The University of Nottingham

PERFORMANCE ANALYSIS OF GROUND SOURCE HEAT PUMPS FOR BUILDINGS APPLICATIONS

By

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ABSTRACT

Geothermal heat pumps (GSHPs), or direct expansion (DX) ground source heat pumps, are a highly efficient renewable energy technology, which uses the earth, groundwater or surface water as a heat source when operating in heating mode or as a heat sink when operating in a cooling mode. It is receiving increasing interest because of its potential to reduce primary energy consumption and thus reduce emissions of GHGs. The main concept of this technology is that it utilises the lower temperature of the ground (approximately <32°C), which remains relatively stable throughout the year, to provide space heating, cooling and domestic hot water inside the building area. The main goal of this study is to stimulate the uptake of the GSHPs. Recent attempts to stimulate alternative energy sources for heating and cooling of buildings has emphasised the utilisation of the ambient energy from ground source and other renewable energy sources. The purpose of this study, however, is to examine the means of reduction of energy consumption in buildings, identify GSHPs as an environmental friendly technology able to provide efficient utilisation of energy in the buildings sector, promote using GSHPs applications as an optimum means of heating and cooling, and to present typical applications and recent advances of GSHPs. The study highlighted the potential energy saving that could be achieved through the use of ground energy sources. It also focuses on the optimisation and improvement of the operation conditions of the heat cycle and performance of the GSHP. It is concluded that GSHP, combined with the ground heat exchanger in foundation piles and the seasonal thermal energy storage from solar thermal collectors, is extendable to more comprehensive applications.

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Nomenclature

ACH	Air changes per hour
GSHP	Ground source heat pump
HRV	Heat recovery ventilator
PRT	Platinum resistance thermometer
1	condenser/heating
2	evaporator
a	air
b	brine
c	coil
cp	Specified heat at constant pressure (kJ/kg K)
Dp	dew point
e	electricity for other uses
f	fan
h	Enthalpy (kJ/kg)
hp	heat pump
hps	heat pump system
hpsf	hps plus fan-coil heater
g	Local acceleration of gravity (m/s^2)
i	inlet
L	latent
m	mean, motor
o	outlet
o/d	outdoor
R	radius
p	pump
S	sensible
tot	total
DC	Direct current
HSPF	Heating season performance factor
SEER	Seasonal energy efficiency ratio
Btu	British thermal unit

EER	Energy efficiency rating
DX	Direct expansion
GS	Ground source
EPA	Environmental Protection Agency
HVAC	Heating, ventilating and air conditioning
DETR	Department of the Environment Transport and the Regions
DTI	Department of Trade and Industry
AFUE	Annual fuel utilisation efficiency rating
ARI	The Air-conditioning and Refrigeration Institute

Designation of variables

COP	Coefficient of performance (%)
N	Air change per hour (ACH) (h^{-1})
P	Pressure (Pa) (kPa)
Q	Heat (thermal energy) (J)
Q_c	Capacity (thermal power) (W)
t	Temperature (Celsius) (°C)
T	Temperature (thermodynamic) (K)
V	Volume (m^3)
V_f	Volume flow (m^3/s)
W	Work (mechanical or electric) (J)
W_p	Power (mechanical or electric) (W)
η	Efficiency (%)
φ	Relative vapour pressure (%)
λ	Thermal conductivity (W/m/K)
ρ	Density (kg/m^3)
τ	Time (h.min.s)

Acronyms

GHP	Geothermal heat pump
GL	Ground loop
GSHP	Ground source heat pump
HP	Heat pump

Some useful figures and conversions

1 kW (kilowatt) is a unit of power, or a rate of energy (A 1 bar fire consumes 1 kW)

There are 3,411 Btus in 1 kWatt i.e., 10 kWatts = 31,400 Btu/hr

1 ton = 12,000 Btu/hr

There are 860 kcal/h in 1 kW

1 kWh (Kilowatt hour) is a quantity of energy

(A 1 kW heater would use 24 kWhr per day)

I kWatt hr = 1 unit of electricity = 1 bar fire used for one hour

Gas bills now use kWhr instead of the old confusing units Thermo, etc.

1 kJoule x 3,600 = 1 kWhr

If 10 kWatts were extracted from water having a flow rate of 0.8 Lit/sec, then the temperature would drop by 3°C (3K)

0°C = 32°F (freezing point of water)

20°C = 68°F (room temperature)

100°C = 212°F (boiling point of water)

(°F-32)/9x5=°C, or °Cx9/5+32=°F

1 lit/sec = 13.19 Gallons (UK)/min

1.0 Introduction

The move towards a low-carbon world, driven partly by climate science and partly by the business opportunities it offers, requires the promotion of environmentally friendly energy sources and alternatives in order to achieve an acceptable stabilisation level of atmospheric carbon dioxide. This requires the harnessing and use of natural resources that produce no air pollution or GHGs and provide comfortable coexistence of humans, livestock, and plants. Exploitation of renewable energy sources, and particularly ground heat in buildings, can significantly contribute towards reducing dependency on fossil fuels and hence achieving this goal. Due to the urgent need to mitigate greenhouse gas emissions, new and more efficient ways of utilising energy in space heating and cooling applications have been actively explored. Although fossil fuel installations and central air-conditioning systems constitute a dominant technology for the buildings sector, geothermal heat pumps establish an attractive alternative.

This study highlights the energy problem and the possible saving that can be achieved through the use of ground sources energy. Also, this study clarifies the background of the study, highlights the potential energy saving that could be achieved through use of ground energy source and describes the objectives, approach and scope of the thesis. It also focuses on the optimisation and improvement of the operation conditions of the heat cycles and performances of the GSHP. It was recommended that GSHPs are extendable to more comprehensive applications combined with the ground heat exchanger in foundation piles and the seasonal thermal energy storage from solar thermal collectors.

1.1 Background

Some emphasis has recently been put on the utilisation of the ambient energy from ground source and other renewable energy sources in order to stimulate alternative energy sources for heating and cooling of buildings. Exploitation of renewable energy sources and particularly ground heat in buildings can significantly contribute towards reducing dependency on fossil fuels. This section highlights the potential energy saving that could be achieved through use of ground energy source.

Under the 1997 Montreal Protocol, governments agreed to phase out chemicals used as refrigerants that have the potential to destroy stratospheric ozone [1]. It was also considered desirable to reduce energy consumption and consequently decrease the rate of depletion of world energy reserves and pollution of the environment. Globally, buildings are responsible for approximately 40% of the total world annual energy consumption. Most of this energy is for the provision of lighting, heating, cooling, and air conditioning. Increasing awareness of the environmental impact of CO_2, NO_x and CFCs emissions triggered a renewed interest in environmentally friendly cooling, and heating technologies.

One way of reducing building energy consumption is to design buildings, which are more efficient in their use of energy for heating, lighting, cooling, ventilation and hot water supply. Passive measures, particularly natural or hybrid ventilation rather than air-conditioning, can dramatically reduce primary energy consumption [1]. Exploitation of renewable energy in buildings and agricultural greenhouses can, also, significantly contribute towards reducing dependency on fossil fuels. Therefore, promoting innovative renewable applications, particularly the ground source energy will contribute to the preservation of the ecosystem by reducing emissions at local and global levels. This will in turn contribute to the amelioration of environmental conditions by replacing conventional fuels with renewable energies that produce no air pollution or greenhouse gases.

Therefore, an approach is needed to integrate renewable energies in a way to meet high building performance. However, because renewable energy sources are stochastic and geographically diffuse, their ability to match demand is determined either by the utilisation of a greater capture area than that occupied by the community to be supplied or the reduction of the community's energy demands to a level commensuratable with the locally available renewable resources [2].

1.2 Alternative energy sources

Utilised renewable resources currently account for about 9%-10% of the energy consumed in the world; most of this is from hydropower and traditional biomass sources [2]. Wind, solar, biomass and geothermal technologies are already cost-effective today in an increasing number of markets and are making important steps to broaden commercialisation. The present situation is best characterised as one of very rapid growth for wind and solar technologies and of significant promise for biomass and geothermal technologies. Each of the renewable energy technologies is in a different stage of research, development and commercialisation and all have differences in current and future expected costs, current industrial base, resource availability and potential impact on energy supply chain.

This study proposes the use of a ground source heat pump (GSHP) system as an alternative system for residential space heating and cooling applications. A demonstration facility was developed as part of this study and extensive data that will assist future GSHP systems designs and reduce uncertainty was gathered and assessed in order to draw a wider picture on the capability of ground source heat pumps to meet the energy needs of buildings.

1.3 Overview of ground source heat pump systems

Ground source heat pump (GSHP) systems (also referred to as geothermal heat pump systems, earth energy systems, and GeoExchange systems) have received considerable attention in the recent decades as an alternative energy source for residential and commercial space heating and cooling applications. The GSHP applications are one of three categories of geothermal energy resources as defined by ASHRAE [2]. These categories are: (1) high-temperature (>150°C) suitable for electric power production, (2) intermediate- and low-temperature (< 150°C) suitable for direct-use applications, and (3) low temperature GSHP applications (generally (32°C). The GSHP applications are distinguished from the others by the fact that they operate at relatively low temperatures. However, GSHPs can also be categorised based on the use of heat source/sink, and this study will explore these in details. The conceptual integration of various warm/cold energy sources combined with thermal energy storage system is illustrated as shown in Figure 1.1. The shapes and numbers of the internal channels and the optimum configuration will obviously depend on the operating characteristics of each installation.

1.4 Objectives of the study

The main objective of this study is to stimulate the uptake of the GSHPs. The GSHPs are well suited to space heating and cooling, and can produce significant reduction in carbon emissions. The tools that are currently available to design a GSHP system require the use of key site-specific parameters such as temperature and the thermal and geotechnical properties of the local area. This study deals with the modelling of vertical closed-loop and hybrid, ground source heat pump systems. The challenges associated with the design of these systems are discussed herein.

A considerable amount of research in the past decade has been geared towards optimising the performance of these types of systems and this study is part of these efforts. Also, this project will provide a service to GSHP users, installers and designers by supplying them with the necessary key design parameters in order to help and reduce design uncertainties. There are therefore four primary tasks to this study. These are to:

- Examine the effects of ground-water flow on closed-loop GSHP systems.
- Develop a design and simulation tool for modelling the performance of a shallow pond as a supplemental heat rejecter with closed-loop GSHP systems.
- Develop a design and simulation tool for modelling the performance of a refrigeration system as a supplemental heat rejecter with closed-loop GSHP systems.

- Identify current total and component costs of GSHPs, and compare the cost of GSHP equipment and installation with similar industry cost.

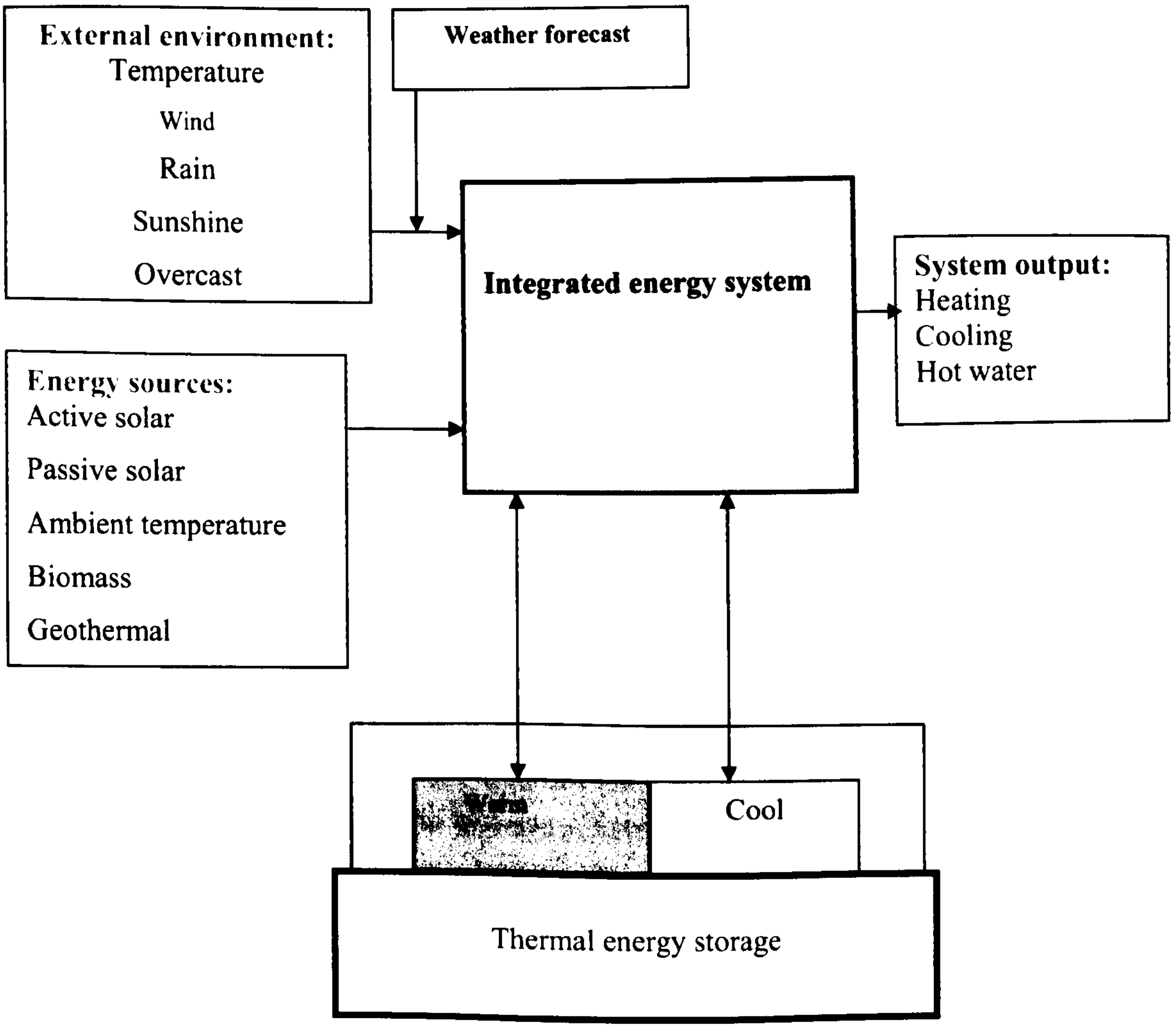


Figure 1.1 Conceptual illustration of an integrated energy system with thermal storage

1.5 Goals

The purpose of this study is to establish the suitability of ground source heat pumps (GSHPs) for heating and cooling and to develop a design tool and document the necessary design parameters, and the savings in energy use and demand that GSHPs may reasonably be expected to achieve. This design tools will be verified using measured data.

1.6 Approach

It was recognised long ago that water source heat pumps were the only likely candidate for cold regions heat pump applications. Demonstration projects were then conducted for groundwater and sewage effluent source heat pumps on several facilities [3]. As part of this research a ground source heat pump (GSHP) was installed at the School of Built Environment of Nottingham University, UK, and experimental measurements were undertaken. Following this initial phase, and as a part of the current study, the facility has now been further developed in order to conduct detailed demonstrations and collect additional data. The GSHP installed for this study was designed taking into accounts the local meteorological and geological conditions. The site is at the School of the Built Environment, University of Nottingham, where the demonstration and performance monitoring efforts were undertaken The study involved development of a design and the performance of the cooling system, which acts as a supplemental heat rejecting system using a closed-loop GSHP system.

1.7 Technology need/justification

Geothermal energy is the natural heat that exists within the earth and that can be absorbed by fluids occurring within, or introduced into, the crystal rocks. Although, geographically, this energy has local concentrations, its distribution globally is widespread. The amount of heat that is, theoretically, available between the earth's surface and a depth of 5 km is around 140×10^{24} joules per day [3]. Only a fraction of this (5×10^{21} joules) can be regarded as having economic prospects, and only about 10% of this is likely to be exploited by the year 2020 [3]. Three main techniques are used to exploit the heat available: geothermal aquifers, hot dry rocks and ground source heat pumps. However, only the ground source heat pumps are considered in this study because the other previous two are expensive.

1.8 Accomplishments

The present ground source heat pump has been designed taking into account the local metrological and geological conditions. This project yielded considerable experience and performance data for the novel methods used to exchange heat with the primary effluent. The heat pump was also fitted in a dry, well-ventilated position where full access for service and monitoring the performance of a number of GSHPs, including one so-called "hybrid" system that included both ground-coupling and a cooling tower, were possible. The site was at the School of the Built Environment, University of Nottingham, where the demonstration project and performance monitoring efforts were carried out in order to obtain the required performance data for the GSHP system.

1.9 Scope of the thesis

Chapter 1 is an introduction to the energy problem and the possible saving that can be achieved through improving building performance and the use of ground energy sources. The relevance and importance of the study is discussed in the chapter. It also highlights the objectives of the study, and the scope of the thesis.

Chapter 2 comprises a comprehensive review of energy sources and discusses the environment and development of sustainable technologies to explore these energy sources. It includes the renewable energy technologies, energy efficiency systems, energy conservation scenarios, energy savings and other mitigation measures necessary to reduce climate change.

Chapter 3 reviews some interactions between buildings and environment. The correct assessment of climate helps to create buildings, which are successful in their external environment, while knowledge of sick buildings syndrome helps to avoid the causes of this from the internal environments. The sections on energy conservation and green buildings suggest how the correct design and use of buildings can improve the total environment. It has also been shown that the exploitation of renewable energy sources, and particularly ground heat in buildings, can significantly contribute towards reducing dependency on fossil fuels.

Chapter 4 provides a detailed literature-based review of the ground source heat pump (GSHP) technology, concentrating on loops, ground systems, and looks more briefly at applications. It is concluded that, despite potential environmental problems, geothermal heat pumps pose little, if any, serious environmental risk when best management practices are applied during the installation, operation, and decommissioning of these systems. Ground heat exchanger configurations are described in some detail here and their design challenges are explained, laying the foundation for the motivation of this study.

Chapter 5 discusses various types of heat exchanger designs, features, sizing, and the characteristics of heat pumps. It also, looks in more detail at the applications of the technology, distribution systems, and the thermal performance of heat pumps.

Chapter 6 describes the different methods and techniques for providing energy for heating and cooling systems. It also, covers the optimisation and improvement of the operation conditions of the heat cycles and performance of the GSHPs.

Chapter 7 deals with the development; design and modelling of vertical closed loop ground source heat pump systems. It also, covers the challenges associated with the design of these systems.

Chapter 8 investigates hydraulic and thermal properties of soils and rocks. The impact of groundwater flow on the estimation of soil/rock thermal conductivity, diffusivity and specific heat capacity were measured and evaluated for different soils.

Chapter 9 describes the details of the prototype GSHP test rig, details of the construction and installation of the heat pump, heat exchanger, heat injection fan and water supply system. It also, presents a discussion of the experimental tests being carried out.

The conclusions drawn, lessons learnt and recommendations for future work are summarised in a closing chapter.

2.0 Clean energies development

2.1 Introduction

This chapter presents a comprehensive review of energy sources, the development of sustainable technologies to explore these energy sources. It also includes potential GSHP, energy efficiency systems, energy savings techniques and other mitigation measures necessary to reduce climate change. The chapter concludes with the technical status of the GSHP technologies.

2.2 Energy sources and use

Over millions of years ago, plants have covered the earth converting the energy of sunlight into living plants and animals, some of which was buried in the depths of the earth to produce deposits of coal, oil and natural gas. The past few decades, however, have experienced many valuable uses for these complex chemical substances and manufacturing from them plastics, textiles, fertiliser and the various end products of the petrochemical industry. Indeed, each decade sees increasing uses for these products. Coal, oil and gas, which will certainly be of great value to future generations, as they are to ours, are however non-renewable natural resources. The rapid depletion of these non-renewable fossil resources need not continue. This is particularly true now as it is, or soon will be, technically and economically feasible to supply all of man's needs from the most abundant energy source of all, the sun. The sunlight is not only inexhaustible, but, moreover, it is the only energy source, which is completely non-polluting [4].

Industry's use of fossil fuels has been largely blamed for warming the climate. When coal, gas and oil are burnt, they release harmful gases, which trap heat in the atmosphere and cause global warming. However, there had been an ongoing debate on this subject, as scientists have struggled to distinguish between changes, which are human induced, and those, which could be put down to natural climate variability. Notably, human activities that emit carbon dioxide (CO_2), the most significant contributor to potential climate change, occur primarily from fossil fuel consumption. Consequently, efforts to control CO_2 emissions could have serious, negative consequences for economic growth, employment, investment, trade and the standard of living of individuals everywhere.

Scientifically, it is difficult to predict the relationship between global temperature and greenhouse gas (GHG) concentrations. The climate system contains many processes that will change if warming occurs. Critical processes include heat transfer by winds and tides, the hydrological cycle involving evaporation, precipitation, runoff and groundwater and the formation of clouds, snow, and ice, all of which display enormous natural variability.

The World Summit on Sustainable Development in Johannesburg in 2002 [4] committed itself to ''encourage and promote the development of renewable energy sources to accelerate the shift towards sustainable consumption and production''. Accordingly, it aimed at breaking the link between resource use and productivity. This can be achieved by the following:

- Trying to ensure economic growth does not cause environmental pollution.
- Improving resource efficiency.
- Examining the whole life-cycle of a product.
- Enabling consumers to receive more information on products and services.
- Examining how taxes, voluntary agreements, subsidies, regulation and information campaigns, can best stimulate innovation and investment to provide cleaner technology.

The energy conservation scenarios include rational use of energy policies in all economy sectors and the use of combined heat and power systems, which are able to add to energy savings from the autonomous power plants. Electricity from renewable energy sources is by definition the environmental green product. Hence, a renewable energy certificate system, as recommended by the World Summit, is an essential basis for all policy systems, independent of the renewable energy support scheme. It is, therefore, important that all parties involved support the renewable energy certificate system in place if it is to work as planned. Moreover, existing renewable energy technologies (RETs) could play a significant mitigating role, but the economic and political climate will have to change first. It is now universally accepted that climate change is real. It is happening now, and GHGs produced by human activities are significantly contributing to it. The predicted global temperature increase of between 1.5 and 4.5^{0}C could lead to potentially catastrophic environmental impacts [5]. These include sea level rise, increased frequency of extreme weather events, floods, droughts, disease migration from various places and possible stalling of the Gulf Stream. This has led scientists to argue that climate change issues are not ones that politicians can afford to ignore, and policy makers tend to agree [5]. However, reaching international agreements on climate change policies is no trivial task as the difficulty in ratifying the Kyoto Protocol and reaching agreement at Copenhagen have proved.

Therefore, the use of renewable energy sources and the rational use of energy, in general, are the fundamental inputs for any responsible energy policy. However, the energy sector is encountering difficulties because increased production and consumption levels entail higher levels of pollution and eventually climate change, with possibly disastrous consequences. At the same time, it is important to secure energy at an acceptable cost in order to avoid negative impacts on economic growth. To date, renewable energy contributes only as much as 20% of the global energy supplies worldwide [5]. Over two thirds of this comes from biomass use, mostly in developing countries, and some of this is unsustainable. However, the potential for energy from sustainable technologies is huge. On the technological side, renewables have an obvious role to play. In general, there is no problem in terms of the technical potential of renewables to deliver energy. Moreover, there are very good opportunities for RETs to play an important role in reducing emissions of GHGs into the atmosphere, certainly far more than have been exploited so far. However, there are still some technical issues to address in order to cope with the intermittency of some renewables, particularly wind and solar. Nevertheless, the biggest problem with relying on renewables to deliver the necessary cuts in GHG emissions is more to do with politics and policy issues than with technical ones [6]. For example, the single most important step governments could take to promote and increase the use of renewables is to improve access for renewables to the energy market. This access to the market needs to be under favourable conditions and, possibly, under favourable economic rates as well. One move that could help, or at least justify, better market access would be to acknowledge that there are environmental costs associated with other energy supply options and that these costs are not currently internalised within the market price of electricity or fuels. This could make a significant difference, particularly if appropriate subsidies were applied to renewable energy in recognition of the environmental benefits it offers. Similarly, cutting energy consumption through end-use efficiency is absolutely essential. This suggests that issues of end-use consumption of energy will have to come into the discussion in the foreseeable future [7-8].

2.3 Role of energy efficiency system

The prospects for development in power engineering are, at present, closely related to ecological problems. Power engineering has harmful effects on the environment, as it discharges toxic gases into atmosphere and also oil-contaminated and saline waters into rivers, as well as polluting the soil with ash and slag and having adverse effects on living things on account of electromagnetic fields and so on. Thus there is an urgent need for new approaches to provide an ecologically safe strategy. Substantial economic and ecological effects for thermal power projects (TPPs) can be achieved by improvement, upgrading the efficiency of the existing equipment, reduction of electricity loss, saving of fuel, and optimisation of its operating conditions and service life leading to improved access for rural and urban low-income areas in developing countries through energy efficiency and renewable energies. Sustainable energy is a prerequisite for development. Energy-based living standards in developing countries, however, are clearly below standards in developed countries. Low levels of access to affordable and environmentally sound energy in both rural and urban low-income areas are therefore a predominant issue in developing countries. In recent years many programmes for development aid or technical assistance have been focusing on improving access to sustainable energy, many of them with impressive results. Apart from success stories, however, experience also shows that positive appraisals of many projects evaporate after completion and vanishing of the implementation expert team. Altogether, the diffusion of sustainable technologies such as energy efficiency and renewable energy for cooking, heating, lighting, electrical appliances and building insulation in developing countries has been slow. Energy efficiency and renewable energy programmes could be more sustainable and pilot studies more effective and pulse releasing if the entire policy and implementation process was considered and redesigned from the outset [9]. New financing and implementation processes, which allow reallocating financial resources and thus enabling countries themselves to achieve a sustainable energy infrastructure, are also needed. The links between the energy policy framework, financing and implementation of renewable energy and energy efficiency projects have to be strengthened and as well as efforts made to increase people's knowledge through training.

2.3.1 Energy use in buildings

Buildings consume energy mainly for cooling, heating and lighting. The energy consumption was based on the assumption that the building operates within ASHRAE-thermal comfort zone during the cooling and heating periods [10]. Most of the buildings incorporate energy efficient passive cooling, solar control, photovoltaic, lighting and day lighting, and integrated energy systems. It is well known that thermal mass with night ventilation can reduce the maximum indoor temperature in buildings in summer [11]. Hence, comfort temperatures may be achieved by proper application of passive cooling systems. However, energy can also be saved if an air conditioning unit is used [12]. The reason for this is that in summer, heavy external walls delay the heat transfer from the outside into the inside spaces. Moreover, if the building has a lot of internal mass the increase in the air temperature is slow. This is because the penetrating heat raises the air temperature as well as the temperature of the heavy thermal mass. The result is a slow heating of the building in summer as the maximal inside temperature is reached only during the late hours when the outside air temperature is already low. The heat flowing from the inside heavy walls could be reduced with good ventilation in the evening and night. The capacity to store energy also helps in winter, since energy can be stored in walls from one sunny winter day to the next cloudy one.

However, the admission of daylight into buildings alone does not guarantee that the design will be energy efficient in terms of lighting. In fact, the design for increased daylight can often raise concerns relating to visual comfort (glare) and thermal comfort (increased solar gain in the summer and heat losses in the winter from larger apertures). Such issues will clearly need to be addressed in the design of the window openings, blinds, shading devices, heating system, etc. In order for a building to benefit from daylight energy terms, it is a prerequisite that lights are switched off when sufficient daylight is available. The nature of the switching regime; manual or automated, centralised or local, switched, stepped or dimmed, will determine the energy performance. Simple techniques can be implemented to increase the probability that lights are switched off [13]. These include:

- Making switches conspicuous and switching banks of lights independently.
- Loading switches appropriately in relation to the lights.
- Switching banks of lights parallel to the main window wall.

There are also a number of methods, which help reduce the lighting energy use, which, in turn, relate to the type of occupancy pattern of the building [14]. The light switching options include:

- Centralised timed off (or stepped)/manual on.
- Photoelectric off (or stepped)/manual on.
- Photoelectric and on (or stepped), photoelectric dimming.
- Occupant sensor (stepped) on/off (movement or noise sensor).

Likewise, energy savings from the avoidance of air conditioning can be very substantial. Whilst day-lighting strategies need to be integrated with artificial lighting systems in order to become beneficial in terms of energy use, reductions in overall energy consumption levels by employment of a sustained programme of energy consumption strategies and measures would have considerable benefits within the buildings sector. The perception often given however is that rigorous energy conservation as an end in itself imposes a style on building design resulting in a restricted aesthetic solution. It would perhaps be better to support a climate sensitive design approach that encompasses some elements of the pure conservation strategy together with strategies, which work with the local ambient conditions making use of energy technology systems, such as solar energy, where feasible. In practice, low energy environments are achieved through a combination of measures that include:

- The application of environmental regulations and policy.
- The application of environmental science and best practice.

- Mathematical modelling and simulation.
- Environmental design and engineering.
- Construction and commissioning.
- Management and modifications of environments in use.

While the overriding intention of passive solar energy design of buildings is to achieve a reduction in purchased energy consumption, the attainment of significant savings is in doubt. The non-realisation of potential energy benefits is mainly due to the neglect of the consideration of post-occupancy user and management behaviour by energy scientists and designers alike. Calculating energy inputs in agricultural production is more difficult in comparison to the industry sector due to the high number of factors affecting agricultural production. However, considerable studies have been conducted in different countries on energy use in agriculture [15-30] in order to quantify the influence of these factors.

2.4 Energy and sustainable development

Sustainability is defined as the extent to which progress and development should meet the need of the present without compromising the ability of the future generations to meet their own needs [31]. This encompasses a variety of levels and scales ranging from economic development and agriculture, to the management of human settlements and building practices. Tables (2.1-2.3) indicate the relationship between energy conservation, sustainable development and environment.

Table 2.1 Energy and sustainable environment [32]

Technological criteria	Energy and environment criteria	Social and economic criteria
Primary energy saving in regional scale	Sustainability according to greenhouse gas pollutant emissions	Labour impact
Technical maturity, reliability	Sustainable according to other pollutant emissions	Market maturity
Consistence of installation and maintenance requirements with local technical known-how	Land requirement	Compatibility with political, legislative and administrative situation
Continuity and predictability of performance	Sustainability according to other environmental impacts	Cost of saved primary energy

The following issues were addressed during the Rio Earth Summit in 1992 [32]:

- The use of local materials and indigenous building sources.

- Incentive to promote the continuation of traditional techniques, with regional resources and self-help strategies.
- Regulation of energy-efficient design principles.
- International information exchange on all aspects of construction related to the environment, among architects and contractors, particularly non-conventional resources.
- Exploration of methods to encourage and facilitate the recycling and reuse of building materials, especially those requiring intensive energy use during manufacturing, and the use of clean technologies.

Table 2.2 Classification of key variables defining facility sustainability [33]

Criteria	Intra-system impacts	Extra-system impacts
Stakeholder satisfaction	• Standard expectations met • Relative importance of standard expectations	• Covered by attending to extra-system resource base and ecosystem impacts
Resource base impacts	• Change in intra-system resource bases • Significance of change	• Resource flow into/out of facility system • Unit impact exerted by flow on source/sink system • Significance of unit impact
Ecosystem impacts	• Change in intra-system ecosystems • Significance of change	• Resource flows into/out of facility system • Unit impact exerted by how on source/sink system • Significance of unit impact

Table 2.3 Positive impact of durability, adaptability and energy conservation on economic, social and environment systems [33]

Economic system	Social system	Environmental system
Durability	Preservation of cultural values	Preservation of resources
Meeting changing needs of economic development	Meeting changing needs of individuals and society	Reuse, recycling and preservation of resources
Energy conservation and saving	Savings directed to meet other social needs	Preservation of resources, reduction of pollution and global warming

And, the following action areas for producers were recommended:

- Management and measurement tools - adopting environmental management systems appropriate for the business.
- Performance assessment tools - making use of benchmarking to identify scope for impact reduction and greater eco-efficiency in all aspects of the business.
- Best practice tools - making use of free help and advice from government best practice programmes (energy efficiency, environmental technology, resource savings).

- Innovation and ecodesign - rethinking the delivery of 'value added' by the business, so that impact reduction and resource efficiency are firmly built in at the design stage.
- Cleaner, leaner production processes - pursuing improvements and savings in waste minimisation, energy and water consumption, transport and distribution, as well as reduced emissions.
- Supply chain management - specifying more demanding standards of sustainability from 'upstream' suppliers, while supporting smaller firms to meet those higher standards.
- Product stewardship - taking the broadest view of 'producer responsibility' and working to reduce all the 'downstream' effects of products after they have been sold on to customers.
- Openness and transparency - publicly reporting on environmental performance against meaningful targets; actively using clear labels and declarations so that customers are fully informed; building stakeholder confidence by communicating sustainability aims to the workforce, the shareholders and the local community (Figure 2.1).

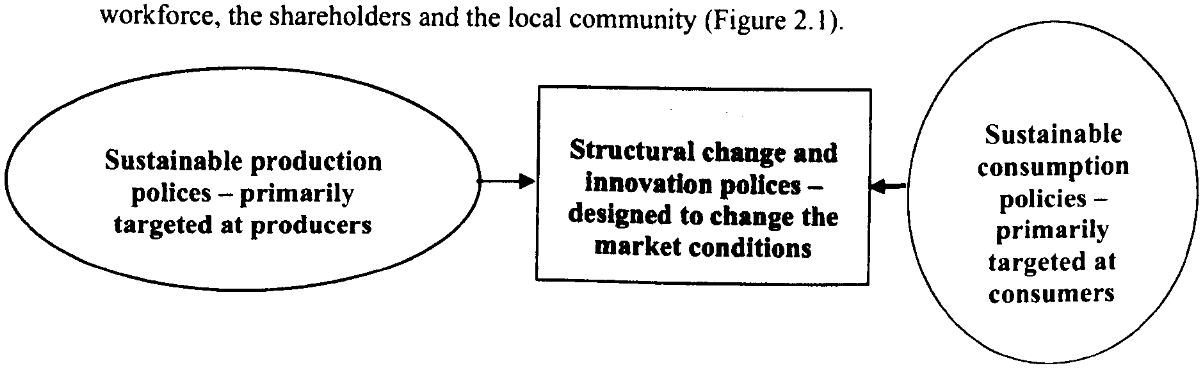


Figure 2.1 Link between resources and productivity

This is the step in a long journey to encourage progressive economy, which continues to provide people with high living standards, but, at the same time helps reduce pollution, waste mountains, other environmental degradation, and environmental rationale for future policy-making and intervention to improve market mechanisms. This vision will be accomplished by:

- 'Decoupling' economic growth and environmental degradation. The basket of indicators illustrated in Table 2.4 shows the progress being made. Decoupling air and water pollution from growth, making good headway with CO_2 emissions from energy, and transport. The environmental impact of our own individual behaviour is more closely linked to consumption expenditure than the economy as a whole.
- Focusing policy on the most important environmental impacts associated with the use of particular resources, rather than on the total level of all resource use.

- Increasing the productivity of material and energy use that are economically efficient by encouraging patterns of supply and demand, which are more efficient in the use of natural resources. The aim is to promote innovation and competitiveness. Investment in areas like energy efficiency, water efficiency and waste minimisation.
- Encouraging and enabling active and informed individual and corporate consumers.

Table 2.4 The basket of indicators for sustainable consumption and production

Economy-wide decoupling indicators
1. Greenhouse gas emissions
2. Air pollution
3. Water pollution (river water quality)
4. Commercial and industrial waste arisings and household waste not cycled
Resource use indicators
5. Material use
6. Water abstraction
7. Homes built on land not previously developed, and number of households
Decoupling indicators for specific sectors
8. Emissions from electricity generation
9. Motor vehicle kilometres and related emissions
10. Agricultural output, fertiliser use, methane emissions and farmland bird populations
11. Manufacturing output, energy consumption and related emissions
12. Household consumption, expenditure energy, water consumption and waste generated

2.5 Global warming

On some climate change issues (such as global warming), there is no disagreement among the scientists (Appendix 2.2). The greenhouse effect is unquestionably real; it is essential for life on earth. Water vapour is the most important GHG; followed by carbon dioxide (CO_2). Without a natural greenhouse effect, scientists estimate that the earth's average temperature would be $-18^{o}C$ instead of its present $14^{o}C$ [33]. There is also no scientific debate over the fact that human activity has increased the concentration of the GHGs in the atmosphere (especially CO_2 from combustion of coal, oil and gas). The greenhouse effect is also being amplified by increased concentrations of other gases, such as methane, nitrous oxide, and CFCs as a result of human emissions. Most scientists predict that rising global temperatures will raise the sea level and increase the frequency of intense rain or snowstorms. Climate change scenarios sources of uncertainty, and factors influencing the future climate are:

- The future emission rates of the GHGs (Table 2.5).

- The effect of this increase in concentration on the energy balance of the atmosphere.
- The effect of these emissions on GHGs concentrations in the atmosphere, and
- The effect of this change in energy balance on global and regional climate.

Table 2.5 West European states GHG emissions [34]

Country	1990	1999	Change 1990-99	Reduction target
Austria	76.9	79.2	2.6%	-13%
Belgium	136.7	140.4	2.8%	-7.5%
Denmark	70.0	73.0	4.0%	-21.0%
Finland	77.1	76.2	-1.1%	0.0%
France	545.7	544.5	-0.2%	0.0%
Germany	1206.5	982.4	-18.7%	-21.0%
Greece	105.3	123.2	16.9%	25.0%
Ireland	53.5	65.3	22.1%	13.0%
Italy	518.3	541.1	4.4%	-6.5%
Luxembourg	10.8	6.1	-43.3%	-28.0%
Netherlands	215.8	230.1	6.1%	-6.0%
Portugal	64.6	79.3	22.4%	27.0%
Spain	305.8	380.2	23.2%	15.0%
Sweden	69.5	70.7	1.5%	4.0%
United Kingdom	741.9	637.9	-14.4%	-12.5%
Total EU-15	4199	4030	-4.0%	-8.0%

This results in the following requirements:

- Relevant climate variables should be generated (solar radiation: global, diffuse, direct solar direction, temperature, humidity, wind speed and direction) according to the statistics of the real climate. The average behaviour should be in accordance with the real climate.
- Extremes should occur in the generated series in the way it will happen in a real warm period. This means that the generated series should be long enough to capture these extremes, and series based on average values from nearby stations.

It has been known for a long time that urban centres have mean temperatures higher than their less developed surroundings. The urban heat increases the average and peak air temperatures, which in turn affect the demand for heating and cooling. Higher temperatures can be beneficial in the heating season, lowering fuel use, but they exacerbate the energy demand for cooling in the summer times. Neither heating nor cooling may dominate the fuel use in a building in temperate climates, and the balance of the effect of the heat is less. As the provision of cooling is expensive with higher environmental cost, ways of using innovative alternative systems, like the mop fan will be appreciated. The solar gains would affect energy consumption. Therefore, lower or higher percentages of glazing, or shading devices might affect the balance between annual heating and cooling loads. In addition to conditioning energy, the fan energy needed to provide mechanical ventilation can make a significant further contribution to energy demand. Much depends on the efficiency of design, both in relation to the performance of fans themselves and to the resistance to flow arising from the associated ductwork. Figure 2.2 illustrates the typical fan and thermal conditioning needs for a variety of ventilation rates and climate conditions.

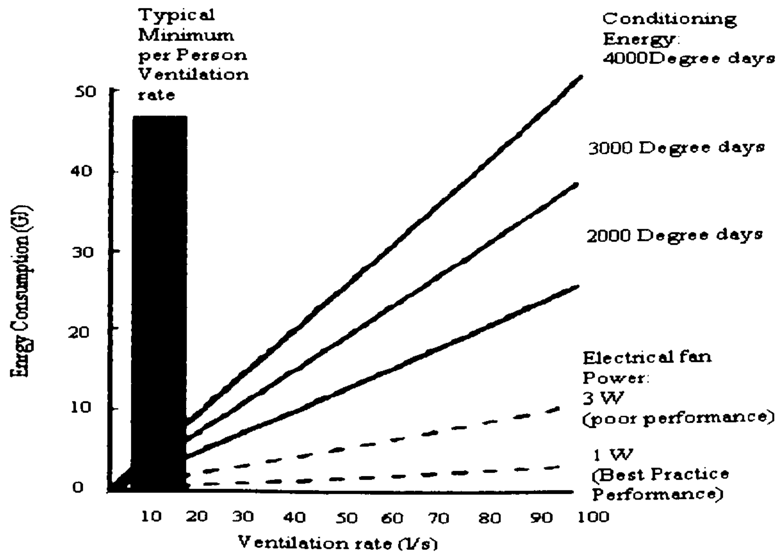


Figure 2.2 Energy impact of ventilation

2.6 Ground source heat pumps

The term "ground source heat pump" has become an all-inclusive term to describe a heat pump system that uses the earth, ground water, or surface water as a heat source and/or sink. Some of the most common types of ground source ground-loop heat exchangers configurations are classified in Figure 2.3. The GSHP systems consist of three loops or cycles as shown in Figure 2.4. The first loop is on the load side and is either an air/water loop or a water/water loop, depending on the application. The second loop is the refrigerant loop inside a water source heat pump. Thermodynamically, there is no difference between the well-known vapour-compression refrigeration cycle and the heat pump cycle; both systems absorb heat at a low temperature level and reject it to a higher temperature level. However, the difference between the two systems is that a refrigeration application is only concerned with the low temperature effect produced at the evaporator, while a heat pump may be concerned with both the cooling effect produced at the evaporator and the heating effect produced at the condenser. In these dual-mode GSHP systems, a reversing valve is used to switch between heating and cooling modes by reversing the refrigerant flow direction. The third loop in the system is the ground loop in which water or an antifreeze solution exchanges heat with the refrigerant and the earth.

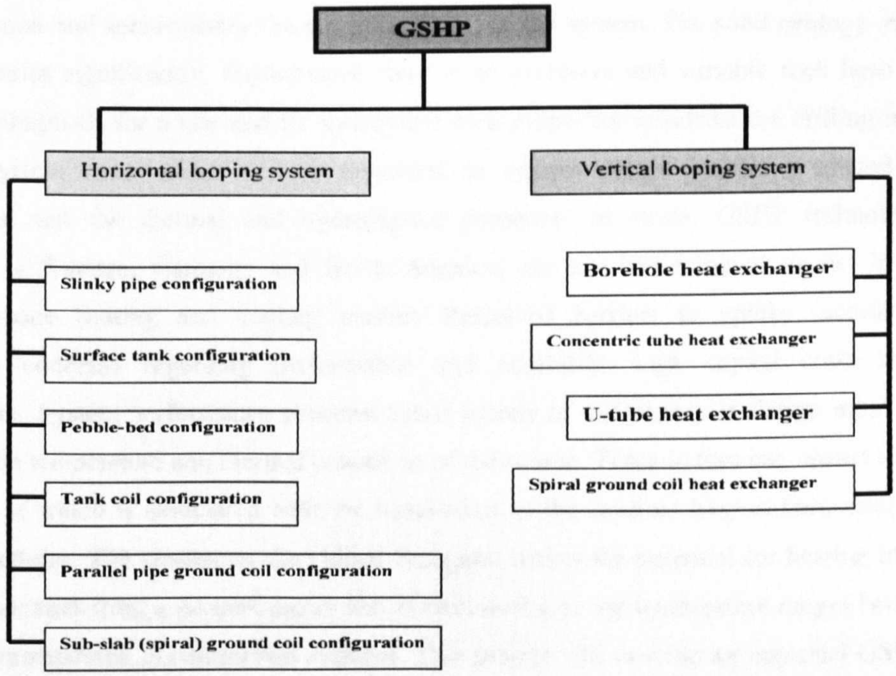


Figure 2.3 Common types of ground-loop heat exchangers

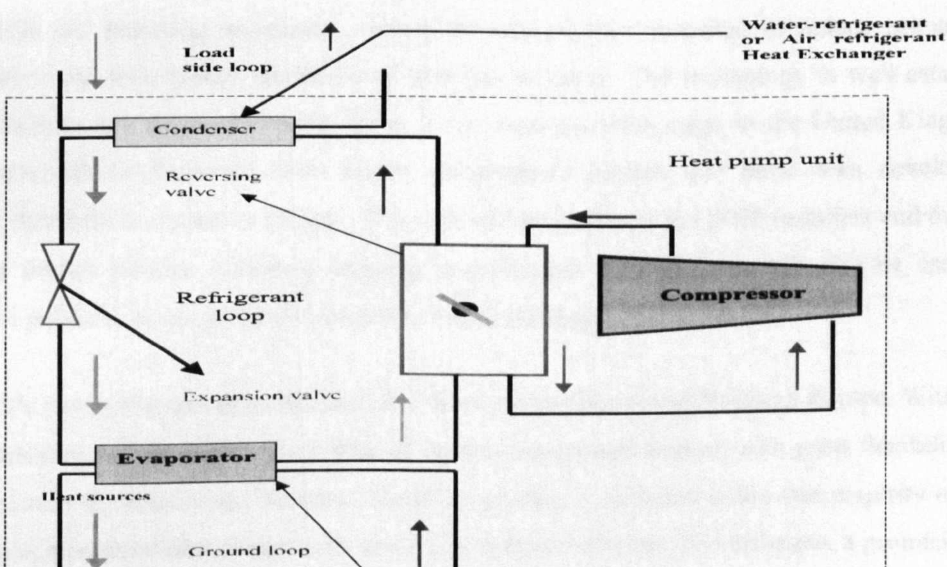


Figure 2.4 Schematic of GSHP system (heating mode operation)

The GSHPs utilise the thermal energy stored in the earth through either vertical or horizontal closed loop heat exchange systems buried in the ground. Many geological factors impact directly on site characterisation and subsequently the design and cost of the system. The solid geology of the United Kingdom varies significantly. Furthermore there is an extensive and variable rock head cover. The geological prognosis for a site and its anticipated rock properties influence the drilling methods and therefore system costs. Other factors important to system design include predicted subsurface temperatures and the thermal and hydrological properties of strata. GSHP technology is well established in Sweden, Germany and North America, but has had minimal impact in the United Kingdom space heating and cooling market. Perceived barriers to uptake include geological uncertainty, concerns regarding performance and reliability, high capital costs and lack of infrastructure. System performance concerns relate mostly to uncertainty in design input parameters, especially the temperature and thermal properties of the source. These in turn can impact on the capital cost, much of which is associated with the installation of the external loop in horizontal trenches or vertical boreholes. The climate in the United Kingdom makes the potential for heating in winter and cooling in summer from a ground source less certain owing to the temperature ranges being narrower than those encountered in continental climates. This project will develop an impartial GSHP function on the site to make available information and data on site-specific temperatures and key geotechnical characteristics.

The GSHPs are receiving increasing interest because of their potential to reduce primary energy consumption and thus reduce emissions of greenhouse gases. The technology is well established in North Americas and parts of Europe, but is at the demonstration stage in the United Kingdom. The information will be delivered from digital geoscience's themes that have been developed from observed data held in corporate records. This data will be available to GSHP installers and designers to assist the design process, therefore reducing uncertainties. The research will also be used to help inform the public as to the potential benefits of this technology.

The GSHPs play a key role in geothermal development in Central and Northern Europe. With borehole heat exchangers as heat source, they offer de-central geothermal heating with great flexibility to meet given demands at virtually any location. No space cooling is included in the vast majority of systems, leaving ground-source heat pumps with some economic constraints. Nevertheless, a promising market development first occurred in Switzerland and Sweden, and now also in Austria and Germany. Approximately 20 years of R and D focusing on borehole heat exchangers resulted in a well-established concept of sustainability for this technology, as well as in sound design and installation criteria. The market success brought Switzerland to the third rank worldwide in geothermal direct use.

The future prospects are good, with an increasing range of applications including large systems with thermal energy storage for heating and cooling, ground-source heat pumps in densely populated development areas, borehole heat exchangers for cooling of telecommunication equipment, etc.

Loops can be installed in three ways: horizontally, vertically or in a pond or lake. The type chosen depends on the available land area, soil and rock type at the installation site. These factors help to determine the most economical choice for installation of the ground loop. The GSHP delivers 3-4 times as much energy as it consumes when heating, and cools and dehumidifies for a lower cost than conventional air conditioning. It can cut homes or business heating and cooling costs by 50% and provide hot water free or with substantial savings. The GSHPs can reduce the energy required for space heating, cooling and service water heating in commercial/institutional buildings by as much as 50%. Figure 2.5 shows the GSHP components.

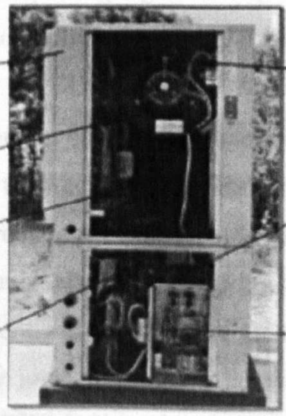


Figure 2.5 GSHPs extract solar heat stored in the upper layers of the earth

Efficiencies of the GSHP systems are much greater than conventional air-source heat pump systems. COP (coefficient of performance) is defined as the ratio of the heat delivered by the heat pump to the electricity supplied to the compressor. A higher COP can be achieved by a GSHP because the source/sink earth temperature is relatively constant compared to air temperatures. Additionally, heat is absorbed and rejected through water, which is a more desirable heat transfer medium because of its relatively high heat capacity. GSHP systems rely on the fact that, under normal geothermal gradients of about (30°C/km), the earth temperature is roughly constant in a zone extending from about (6.1 m) deep to about (45.7 m) deep. This constant temperature interval within the earth is the result of a complex interaction of heat fluxes from above (the sun and the atmosphere) and from below (the earth interior). As a result, the temperature of this interval within the earth is approximately equal to the average annual air temperature [32]. Above this zone (less than about (6.1 m) deep), the earth temperature is a damped version of the air temperature at the earth's surface. Below this zone (greater than about (45.7 m) deep), the earth temperature begins to rise according to the natural geothermal gradient. The storage concept is based on a modular design that will facilitate active control and optimisation of thermal input/output, and it can be adapted for simultaneous heating and cooling often needed in large service and institutional buildings [33]. Loading of the core is done by diverting warm and cold air from the heat pump through the core during periods with excess capacity compared to the current need of the building [32-34]. The cool section of the core can also be loaded directly with air during the night, especially in spring and fall when nights are cold and days may be warm.

2.7 Recommendations

- Encouraging the private sector to assemble, install, repair and manufacture GSHP devices via investment encouragement and more flexible licensing procedures.
- Launching of public awareness campaigns among local investors particularly small-scale entrepreneurs and end users of GSHP to highlight the importance and benefits of renewable, particularly GSHP.
- Amendment of the encouragement of investment act, to include furthers concessions, facilities, tax holidays, and preferential treatment to attract national and foreign capital investment.
- Allocation of a specific percentage of soft loans and grants obtained by governments to augment budgets of R and D related to manufacturing and commercialisation of GSHP.
- Governments should give incentives to encourage the household sector to use GSHP instead of conventional energy. Execute joint investments between the private sector and the financing entities to disseminate the GSHP information and literature with technical support from the research and development entities.
- Availing of training opportunities to personnel at different levels in donor countries and other developing countries to make use of their wide experience in application and commercialisation of GSHP particularly renewable energy.
- The governments should play a leading role in adopting GSHP devices in public institutions, e.g., schools, hospitals, government departments, police stations etc., for water pumping, water heating, cooling and heating.

2.8 Conclusions

The adoption of green or sustainable approaches to the way in which society is run is seen as an important strategy in finding a solution to the energy problem. The key factors to reducing and controlling CO_2, which is the major contributor to global warming, are the use of alternative approaches to energy generation and the exploration of how these alternatives are used today and may be used in the future as green energy sources. Even with modest assumptions about the availability of land, comprehensive fuel-wood farming programmes offer significant energy, economic and environmental benefits. These benefits would be dispersed in rural areas where they are greatly needed and can serve as linkages for further rural economic development.

However, by adopting coherent strategy for alternative clean sustainable energy sources, the world as a whole would benefit from savings in foreign exchange, improved energy security, and socio-economic improvements. With a nine-fold increase in forest – plantation cover, every nation's resource base would be greatly improved while the international community would benefit from pollution reduction, climate mitigation, and the increased trading opportunities that arise from new income sources.

The non-technical issues related to clean energy, which have recently gained attention, include: (1) Environmental and ecological factors, e.g., carbon sequestration, reforestation and revegetation. (2) Renewables as a CO_2 neutral replacement for fossil fuels. (3) Greater recognition of the importance of renewable energy, particularly modern biomass energy carriers, at the policy and planning levels. (4) Greater recognition of the difficulties of gathering good and reliable renewable energy data, and efforts to improve it. (5) Studies on the detrimental health efforts of biomass energy particularly from traditional energy users.
The present study is one effort in touching all these aspects.

3.0 The case for GSHP systems

3.1 Introduction

This chapter reviews some interactions between buildings and the environment. The correct assessment of climate helps to create buildings that have little impact to the external environment. The chapter highlights how the correct design and use of buildings can help to improve the total environment. Exploitation of renewable energy sources and particularly ground heat in buildings can significantly contribute towards reducing dependency on fossil fuels.

The challenge before many cities today is to support large numbers of people while limiting their impact on the natural environment. Buildings in a modern society are significant users of energy and materials and, hence, energy conservation in buildings plays an important role in urban environmental sustainability [36-40]. A challenging task for architects and other building professionals, therefore, is to design and promote low energy buildings in a cost effective and environmentally responsive way. Passive and low energy architecture has been proposed and investigated in different locations around the world [41-66], and design guides and handbooks have been produced for promoting energy efficient buildings [67-70]. However, at present, little information is available for studying low energy buildings designed for densely populated areas. Designing low energy buildings in high-density areas requires special treatment of the planning of urban structure, co-ordination of energy systems, integration of architectural elements, and utilisation of space. At the same time, the study of low energy buildings will lead to a better understanding of the environmental conditions and improved design practices. This may help people to study and improve the quality of the built environment and hence the living conditions.

The term low energy in many demonstration projects and studies is often not uniquely defined [71]. It may mean achieving zero energy requirements for a house or reduced energy consumption in an office building. However, a major goal of low energy building projects and studies is usually to minimise the amount of externally purchased energy, such as electricity and fuel gas. Sometimes the target may focus on the energy costs or a particular form of energy input to the building. However, as building design needs to consider requirements and constraints, such as architectural functions, indoor environmental conditions, and economic effectiveness, a pragmatic goal of low energy building is also to achieve the highest energy efficiency, which requires the lowest possible need for energy within the economic limits of reason. Therefore, since many complicated factors and phenomena influence energy consumption in buildings, it is not easy to define low energy building precisely or to measure and compare the levels of building energy performance. The loose fit between form and performance in architectural design also makes quantitative analysis of building energy use more difficult. Nevertheless, it is believed that super-efficient buildings, which have significantly lower energy consumption, can be achieved through good design practices and effective use of energy efficient technology [72].

In an ideal case, buildings can even act as producers rather than consumers of energy. Besides the operational energy requirements of buildings, it is important to consider two related energy issues. The first one is the transport energy requirements as a result of the building and urban design patterns and the second is the embodied energy or energy content of the building materials, equipment or systems being used. Transport energy is affected by the spatial planning of the built environment, transport policies and systems, and other social and economic factors. It is not always possible to study the effect of urban and building design on transport energy without considering the context of other influencing factors. The general efficiency rules are to promote spatial planning and development, which reduce the need to travel, and to devise and enforce land-use patterns that are conducive to public transport [73]. Embodied energy, on the other hand, is the energy input required to quarry, transport and manufacture building materials, plus the energy used in the construction process. It represents the total life-cycle energy use of the building materials or systems and can be used to help determine design decisions on system or materials selection [74]. At present, the field of embodied energy analysis is generally still only of academic interest and it is difficult to obtain reliable data for embodied energy. However, research findings in some countries, such as Australia, USA, and Canada, indicate that the operating energy often represents the largest component of life-cycle energy use [77]. Accordingly, when studying low energy buildings, most people would prefer to focus on operating energy, and perhaps carry out only a general assessment of embodied energy.

3.2 Climate and energy performance

A fundamental reason for the existence of a building is to provide shelter from the climate patterns, such as the cold and the heat, the wind and the rain. The climate for a building is the set of environmental conditions, which surround that building and links to the inside of the building by means of heat transfer. Therefore, climate has important effects on the energy performance of buildings, in both winter and summer, and on the durability of the building fabric. Although the overall features of the climate are beyond our control, the design of a building can have a significant influence on the climatic behaviour of the building [75-77]. The following measures can be used to enhance the interaction between buildings and climate.

- Selection of site to avoid heights and hollows; and selection of ground surfaces for dryness.
- Orientation of buildings to maximise or minimise solar gains.
- Spacing of buildings to avoid unwanted wind and shade effects.
- Design of windows to allow maximum daylight in buildings.
- Design of shade and windows to prevent solar overheating.
- Selection of trees and wall surfaces to shelter buildings from driving rain and snow.

3.3 Energy conservation

At present, most of the energy used to heat buildings, including electrical energy, comes from fossil fuels such as oil and coal. This energy has originally come from the sun and was used in the growth of plants such as trees. Then, because of changes in the earth's geology, those ancient forests eventually became a coal seam, an oil field or a natural gas field. The existing stocks of fossil fuels on earth cannot be replaced and unless conserved, they will eventually run out. Primary energy is used for building services such as heating, lighting and electricity [72]. Most of the energy consumed in the domestic sector is used for space heating. Reducing the use of energy in buildings will therefore be of great help in conserving energy resources and in saving money for the occupants of buildings.

A recent World Energy Council (WEC) study found that without any change in our current practice, the world energy demand in 2020 would be 50-80% higher than 1990 levels [72]. According to a recent USA Department of Energy (DoE) report, annual energy demand will increase from a current capacity of 363 million kilowatts to 750 million kilowatts by 2020 [72]. The world's energy consumption today is estimated to 22 billion kWh per year, 53 billion kWh by 2020. Enhanced lifestyle and energy demand rise together and the wealthy industrialised economics, which contain 25% of the world's population, consume 75% of the world's energy supply [72]. About 6.6 billion metric tons carbon equivalent of greenhouse gas (GHG) emission are released in the atmosphere to meet this energy demand [72]. Approximately 80% of this is due to carbon emissions from the combustion of energy fuels. At the current rate of usage, taking into consideration population increases and higher consumption of energy by developing countries, oil resources, natural gas and uranium will be depleted within a few decades; so one needs to reduce energy consumption by conserving resources.

3.3.1 Energy efficiency

Large amounts of energy are contained in the world's weather system, which is driven by the sun through wind, oceans, and in heat from the earth's interior, caused by radioactivity in rocks. This energy is widely available at no cost except for the installation and running of conversion equipment. Devices in use include electricity generators driven by wind machines, wave energy and geothermal steam. The total energy of the universe always remains constant but when energy is converted from one form to another some of the energy is effectively lost to use by the conversion process. For example, hot gases must be allowed to go up the chimney flue when a boiler converts the chemical energy stored in a fuel into heat energy and around 90% of the electrical energy used by a traditional light bulb is wasted as heat rather than light.

However, new techniques are being used to improve the conversion efficiency of devices used for services within buildings. Condensing boilers, for example recover much of the latent heat from flue gases before they are released. Heat pumps can make use of low temperature heat sources, such as waste air, which have been ignored in the past. The heating or cooling of a space to maintain thermal comfort is a highly energy intensive process accounting for as much as 60-70% of total energy use in non-industrial buildings [38]. Of this, approximately 30-50% is lost through ventilation and air infiltration [39]. However, estimation of the energy impact of ventilation relies on detailed knowledge of air change rates and the difference in enthalpy between the incoming and outgoing air streams. In practice, this is a difficult exercise to undertake as there is much uncertainty about the value of these parameters [40]. As a result, a suitable datum from which strategic planning for improving the energy efficiency of ventilation can be developed has proved difficult to establish [41]. Likewise, although electrical appliances have a high-energy efficiency at the point of use, the overall efficiency of the electrical system is greatly reduced by the energy inefficiency of large power stations built at remote locations.

The 'cooling towers' of these stations are actually designed to waste large amounts of heat energy. It is possible to make use of this waste heat from power stations both in industry and for the heating of buildings. These techniques of combined heat and power (CHP) can raise the energy efficiency of electricity generation as discussed in chapter 2. CHP techniques can also be applied on a small scale to meet the energy needs of one building or a series of buildings. Electrical energy will still be required for devices such as lights, motors and electronics but need not be used for space heating. Any CHP scheme should be subject to an in depth feasibility study with particular attention being given to the use of the heat produced and the cost and retail price of the power being exported. Also, boiler efficiency should be checked using a flue gas analysis kit. These kits consist of carbon dioxide (CO_2) gas analyser, a flue gas thermometer and a smoke tester. They are simple to use, and with the information gained, the burner can then be set up for optimum operation. Table 3.1 gives target values for CO_2 and Oxygen (O_2). These targets are only a rough guide as individual boilers might have specialist requirements. Boiler efficiency is a key factor to eliminating energy waste.

Table 3.1 Target flue gas

Fuel	Theoretical % CO_2 (dry basis)	Target CO_2 % (dry basis)	Target O_2 % (dry basis)
Bituminous coal	18.6	12.0	7.4
Dry steam coal	19.2	13.0	7.9
Coke	19.5	13.0	7.0
Natural gas	11.7	10.7	2.1
Propane	13.8	12.4	2.1
Butane	14.1	12.7	2.1
35 sec fuel oil	15.4	12.7	3.8

3.3.2 Thermal insulation

External walls, windows, roof and floors are the largest areas of heat loss from a building. The upgrading of insulation in existing buildings can be achieved by techniques of roof insulation, cavity fill, double-glazing, internal wall lining, and exterior wall cladding. Heat pumps perform best in well-insulated buildings. To achieve an efficient performance requires careful consideration of a number of practical issues, such as:

- Whether a heat recovery and ventilation (HRV) system is employed.
- Temperature of water/ antifreeze solution in the ground loop(s).
- Design water temperature for the underfloor heating.
- Structure and thermal mass of the underfloor heating system.
- Floor covering resistances, and control system.

3.3.3 Role of ventilation on energy consumptions/savings where ventilation requires

The warm air released from a building contains valuable heat energy, even if the air is considered stale for ventilation purposes. The heat lost during the opening of doors or windows contribute to a significant energy lost. These ventilation losses are reduced by better seals in the construction of the buildings, by air-sealed door lobbies, and the use of controlled ventilation. Ventilation is essential for securing a good indoor air quality, but, as explained earlier, can have a dominating influence on energy consumption in buildings. Table 3.2 of environmental factors indicates some of the major interactions between different designs. There are four key features of innovative buildings design, which are:

natural ventilation, external day lighting, Heat reclamation if necessary, and use of borehole cooling where affordable.

Table 3.2 Interactions of environmental designs

Some design options	Heating	Ventilation	Lighting	Sound
Sheltered site loss and gain	Less heat	-	Less daylight	Less noise intrusion
Deep building shape	Less heat loss and gain	Reduced natural ventilation	Less daylight	-
Narrow building plan	More heat loss and gain	More natural ventilation	More daylight intrusion	More noise
Heavy building materials	Slower heating and cooling	-	-	Better sound insulation
Increased window area	More heat loss and gain	-	More daylight	More noise intrusion
Smaller, sealed windows	Less heat loss and gain	Reduced natural ventilation	Less daylight	Less noise intrusion

Architects, consultants and contractors have to introduce new initiatives, ideas and concepts to the outlook of air-conditioning and ventilation systems operations. Such innovations and ideas would exist in the areas of:

- Design of energy efficient systems, which would make use of sources of renewable energy as a medium of heat transfer.
- Introduction of solar architectural designs in buildings reducing power consumption through electric bulbs during the day.
- Educating clients and users of buildings to understand the role of their buildings with respect to ozone layer depletion and environmental awareness.

Furthermore, it should be noted that particulate pollutants in buildings can have damaging effects on the health of occupants. Studies have shown that indoor aerosol particles influence the incidence of sick building syndrome [77]. Some airborne particles are associated with allergies because they transport viruses and bacteria. The concentration of indoor aerosol particles can be reduced by using different ventilation strategies such as displacement and perfect mixing. However, there are insufficient data to quantify the effectiveness of these methods, as removal of particles is influenced by particle deposition rate, particle type, size, source and concentrations.

3.3.3.1 Natural ventilation

Generally, buildings should be designed with controllable natural ventilation. A very high range of natural ventilation rates is necessary so that the heat transfer rate between inside and outside can be selected to suit building conditions [78]. The ventilation rates required to control summertime temperatures are very much higher than those required to control pollution. Therefore, any natural ventilation system that can control summer temperatures can readily provide adequate ventilation to control levels of pollution.

3.3.3.2 Mechanical ventilation

Most medium and large size buildings in Europe are ventilated by mechanical systems designed to bring in outside air, filter it, supply it to the occupants and then exhaust an approximately equal amount of stale air. Ideally, these systems should be based on criteria that can be established at the design stage. To return afterwards in an attempt to mitigate problems may lead to considerable expense and energy waste, and may not be entirely successful [78]. The key factors that must be included in the design of ventilation systems are code requirement and other regulations or standards (e.g., fire), ventilation strategy and systems sizing, climate and weather variations, air distribution, diffuser location and local ventilation, ease of operation and maintenance and impact of system on occupants (e.g., acoustically). These factors differ for various building types and occupancy patterns. For example, in office buildings, pollutants tend to come from sources such as occupancy, office equipment, and in office. Occupant pollutants typically include metabolic carbon dioxide emission, odours and sometimes smoking. When occupants (and not smoking) are the prime source. Carbon dioxide acts as a surrogate and can be used to cost-effectively modulate the ventilation, forming what is known as a demand controlled ventilation system. Generally, contaminant sources are varied but, often, well-defined and limiting values are often determined by occupational standards.

3.4 Application of ground sources heat pump (GSHP) systems

There are increasing challenges facing people throughout the world to secure a reliable, safe and sustainable energy supply to meet their needs. In developing countries, the demand for commercial energy is growing quickly. Indeed, these countries are faced with substantial financial, environmental and energy security problems forcing them to explore alternative viable energy sources. In fact, the pressure in both developed and less developed countries is growing to find workable alternatives to traditional energy supplies and to improve the efficiency of energy use in an attempt to limit emissions of gases that cause global climate change. Ground sources heat pumps (GSHP) systems are considered as one viable candidate for alternative energy sources.

The heat pump is the main component of a GSHP system. Most underfloor heating systems use zone valves that reduce the flow-rate. The heat pump can maintain the correct flow-rate in buildings. A buffer tank is suggested to be used. If radiators are to be used, they must be large enough because of enough circulation. Double the normal sizing (as used with a boiler) is a good starting point. Whilst this type of heat pump installation could provide all the heating needs, it is common practice, and often makes economic sense, to have a back-up boiler linked to the system to cope with the very cold periods. Electric back up is not ideal as this puts a high load on the main supply at a time of peak demand when the power station's net fuel efficiency is low [79-80]. The ground pipe system must be planned carefully, especially as it will be there for well over 50 years. Any mistakes may be too difficult or costly to rectify later. The highest energy efficiency will result from systems that do not go below freezing point, therefore, the bigger the pipe system/ground area, the better. However, this is costly and gives diminishing returns. The pressure drop in the pipes should be compatible with standard low-head pumps.

Weather compensation will greatly improve the annual energy efficiency by reducing the heated temperature to the minimum required, depending on the outside temperature. Most heat pumps incorporate this in the controller, though this facility can be retrofitted as an extra. To keep energy efficiency high, the heated water temperature should be kept as low as possible. Also, heat pump compressors like to run for long periods. Stop-starts should be minimised. The use of buffer tanks, correctly set thermostat differentials and correctly positioned cylinder sensors will all help to maximise run periods. Noise could be a problem if not considered properly and this problem should be eliminated at the design stage.

A GSHP is an electrically powered system that takes advantage of the earth's relatively constant ground temperature to provide heating, cooling and hot water for businesses. Figure 3.1 explains the basic principles involved in a GSHP system. There are two types of the GHPS; ground-coupled heat pumps (GCHPs) and the water loop heat pumps (WLHPs) or water source heat pump. They are both widely used commercially and often confused with each other. Although the piping loop inside the building is similar, there are several important differences. Water-to-air heat pumps as WLHP are located throughout the building. Local zone temperature is achieved with conventional on-off thermostats. Ductwork is minimised because the units are in the zone they serve. A central piping loop is connected to all the units. The temperature of this loop is typically maintained between (16°C) and (32°C) [81-85]. A cooling tower is used to remove heat when the loop temperature exceeds (32°C) and heat is added with a boiler if the temperature falls below (16°C) [88]. Generally, the WLHPs are most successful when internal building loads are sufficient to balance the heat loss through the external surfaces and ventilation. If heat losses exceed internal loads, the energy requirements of the WLHPs can become significant, as energy must be added in both the boiler and heat pumps. However, this is not true in cooling because the heat is dissipated through the cooling tower, which only has pump and fan motor requirements [86-88].

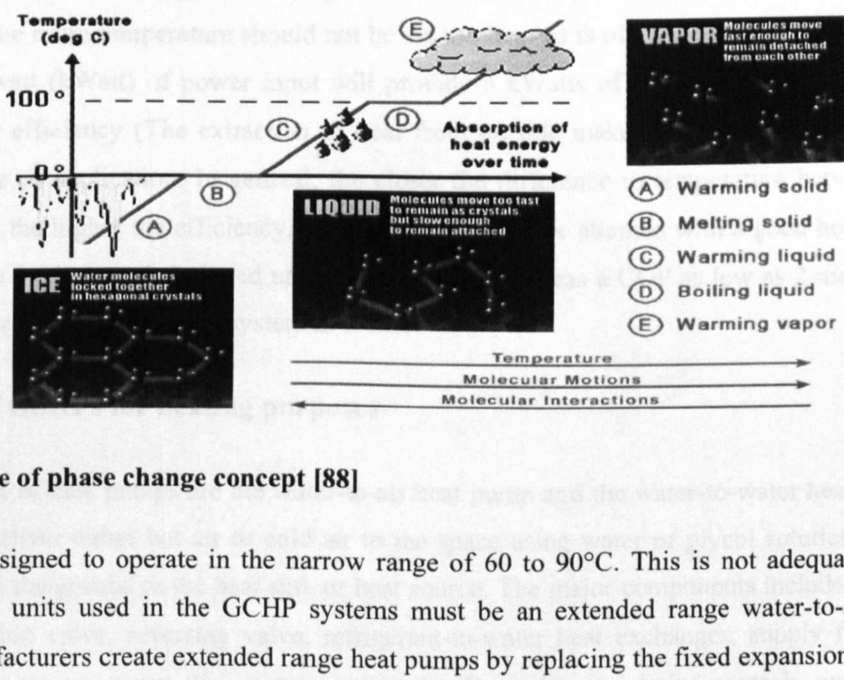


Figure 3.1 Principle of phase change concept [88]

The WLHPs are designed to operate in the narrow range of 60 to 90°C. This is not adequate for a GCHP system. The units used in the GCHP systems must be an extended range water-to-air heat pumps. Some manufacturers create extended range heat pumps by replacing the fixed expansion device of a WLHP with a thermostatic expansion valve (TEV). Others make this modification and add improved compressors, air and water coils, fans, and controls. This has resulted in units that operate with higher efficiencies than conventional WLHPs even when operating with water temperatures outside the 60 to 90°C range. It is obvious that the ground coil can add to the cost of the system. Also many high-rise commercial applications may not have sufficient land area to accommodate a full size ground coil. A hybrid ground-coupled water-loop heat pump (GCWLHP) would be a viable option to reduce the size of the ground coil. The coil should be sized to meet the heating requirement of the building. This is typically one-half the size required for meeting the cooling load.

The following sections summarises the GSHP application for heating and cooling aspects respectively.

3.4.1 Air-conditioning application

Air-to-air systems are used throughout the world for air-cooling. The reversible version of these is the most common type of heat pump; because they are more compact and simple to install. In heating mode, the efficiency is not as good as the water systems. In cooling mode, however, they consume large amounts of energy. In the UK a large ventilation-rate combined with sun shading is more appropriate for cooling, as fans use far less power. If mechanical air-cooling is necessary, then a water- or ground-coupled heat pump system will be the most energy efficient.

If air-conditioning is used, then good housekeeping to reduce energy consumption should not be overlooked. This should include good shading from sunlight by use of automatic or manually controlled blinds. The room temperature should not be set too low, as is often the case. A COP of 3 is typical, i.e., 1 kilowatt (kWatt) of power input will provide 3 kWatts of useful output [87]. This is equivalent to 300% efficiency (The extraction of heat from outside makes this possible) [88]. COP depends on the type of application. In general, the closer the difference in temperature between the source and the sink, the higher the efficiency, e.g., a COP of 5 can be attained with a good heat pump with a spring source feeding well designed underfloor heating, whereas a COP as low as 2 may result in heating bath water from an air source system in winter.

3.5 Integration of GSHPs for heating purposes

The two major types of heat pumps are the water-to-air heat pump and the water-to-water heat pump. Water-to-air units deliver either hot air or cold air to the space using water or glycol solution as the transfer medium and the ground as the heat sink or heat source. The major components include casing, compressor, expansion valve, reversing valve, refrigerant-to-water heat exchanger, supply fan, and connections for the source water "in" source water "out" condensate drain, controls and other accessories (Appendix 3). Figure 3.2 shows a layout of a typical vertical heat pump system. The following specifications usually apply.

- The top pipe is recommended to 0.6 m below the frost line.
- The trench depth is usually 1.5 m, and the distance between the trenches is 2.1 to 2.4 m.
- A horizontal heat exchanger, located under the asphalt surface, may operate at higher temperatures in summer and a lower temperature in winter.
- The building height is not an issue in this vertical design.

- The vertical bore fields require anywhere from 5.4 to 25 sq m of ground-surface area per ton of block load.
- The borehole depths range from 45 to 150 m.
- The spacing between the bores is normally 4.5 m.
- The vertical design is limited to buildings of about six stories or less.

Water-to-water units, on the other hand, produce either chilled water (usually 25°C) or hot water (usually not over 72°C) using water or glycol solution as the heat-transfer medium and the ground as the heat sink or the heat source. The major components of this unit include casing, compressor, expansion valve, reversing valve, refrigerant-to-water heat exchanger, and connections for source water "in" source water "out" system (or load) side-water "supply," system (or load) side-water "return".

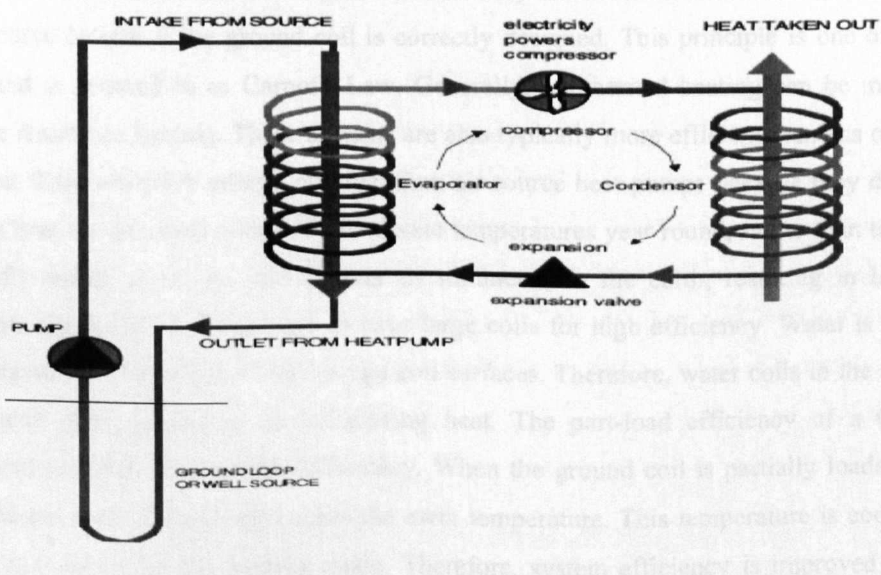


Figure 3.2 layout of a typical vertical heat pump system

3.5.1 Water-to-air versus water-to-water heat pumps

Water-to-air heat pumps are excellent for applications where each individual zone requires a separate control. This application has increased maintenance and electrical demands because there is no way to take advantage of load diversity. Water-to-water heat pumps, on the other hand, are very good candidates where the building occupancies allow the advantage of diversity. Several water to-water heat pumps can be grouped together to create a central cooling and heating plant to serve several air-handling units. The system can be sized for this diversity, rather than for the individual peaks. This application has advantages of better control, centralised maintenance, redundancy, and flexibility.

The disadvantage, however, is that the initial costs tend to be higher, especially if the four-pipe system is used. The water-to-water heat pumps can also be used for pre-heating/pre-cooling and hydronic heating applications.

3.6 Heat pump efficiency

Heat pump efficiency is primarily dependent upon the temperature difference between the building interior and the environment. For a Carnot engine, this is entirely determined by the temperatures of hot and cold reservoirs: $\eta_{Carnot} = 1-(T_c/T_h)$. If this difference can be maximised, heat pumps efficiency (and capacity) will improve. Ground temperatures are almost always closer to room temperature than air temperatures. Therefore, the GSHPs are inherently more efficient than units that use outdoor air as a heat source or sink if the ground coil is correctly designed. This principle is one of Mother Nature's rules and is referred to as Carnot's Law. Generally, geothermal heating can be more efficient than electric resistance heating. These systems are also typically more efficient than gas or oil-fired heating systems. They are more energy efficient than air-source heat pumps because they draw heat from, or release heat to, the earth, which has moderate temperatures year round, rather than to the air (which is generally colder in winter and warmer in summer than the earth, resulting in less effective heat transfer). Secondly, it is important to have large coils for high efficiency. Water is far superior to air with regard to "convection" heat through coil surfaces. Therefore, water coils in the GSHP are smaller and much more "efficient" in transferring heat. The part-load efficiency of a GSHP is actually improved compared to full load efficiency. When the ground coil is partially loaded, the water loop temperature more closely approaches the earth temperature. This temperature is cooler in the cooling mode and warmer in the heating mode. Therefore, system efficiency is improved. Hence, auxiliary power requirement can be reduced significantly compared to conventional systems.

Although it is heavier than air, a given volume of water contains 3500 times the thermal capacity of atmospheric air. Therefore, the pump motors circulating water through a GCHP system are much smaller than outdoor air or cooling tower fan motors of conventional systems. The indoor fan power is also reduced because the units are in the zone and duct runs are very short or non-existent. Therefore, low pressure (and power) fans can be used. Unfortunately, the efficiency ratings used for the GSHPs do not match with the ratings of conventional equipment [89-90].

3.7 Advantages of the GSHPS

Major advantages of the GSHPs are summarised as follows:

3.7.1 Space requirement

The GCHP systems require a small amount of space if properly designed. An 18 kW water-to-air heat pump in a horizontal package can be as small as 50x64x115 cm and easily located above the ceiling in a typical office. Likewise, vertical packages can be placed in small closets. Some units used in the water loop heat pump (WLHP) systems may have excessive noise levels for these locations. However, the improved units recommended for GSHP systems have quieter compressors and large, low velocity fan wheels that reduce noise levels. Also, besides the GSHP, the central distribution system requires relatively little space, and the relative requirements of a high velocity air system, a low velocity air system. This also indicates the required power of the GSHP pump is much smaller than that required by the fans of either air system.

Geothermal heating and cooling equipment is readily available in the marketplace and can be installed by any qualified HVAC contractor. The process is two-fold in that it involves installing the indoor unit and method of delivery, forced hot air or hydronic, and the outside pipe loop. Loop installation can be planned concurrently with other construction activities, so the overall construction schedule should not be affected by choice of system. Some loops will require an additional permit. However, geothermal equipment can be installed with equal ease in both new construction and remodelling projects.

3.7.2 Aesthetics

One pleasant advantage of a GSHP system is the absence of unsightly outdoor equipment. The ground above outdoor coil can become a greenspace or a parking lot. This is especially suited to schools where outdoor equipment may pose a safety hazard to small children or a vandalism target for the not so small children.

3.7.3 Simplicity

The conventional GSHP system is extremely simple. The water-to-air unit consists of a compressor, a small water coil, a conventional indoor air coil, one bi-flow expansion device, and a few electrical controls. The flow control can be either a single circulation pump on each unit (that is turned on with the compressor relay) or a normally closed two-way valve for systems with a central circulation pump.

If the designer chooses an extended range heat pump as recommended, no water regulating control valves are necessary.

3.7.4 Easy to control and operate

Control is also very simple. A conventional residential thermostat is sufficient. Since units are located in every zone, a single thermostat serves each unit. Zones can be as small as 1.8 kW. However, each unit can be linked to a central energy management system if desired. Air volume control is not required. Larger water-to-air heat pumps are available if multi-zone systems are required. However, this would complicate one of the most attractive benefits of the GSHPs, local zone control. The simple system can be installed and serviced by technicians with moderate training and skills. The building owner would no longer be dependent on the controls vendor or outside maintenance personnel. The simple control scheme would interface with any manufacturers' thermostats.

3.7.5 Comfort

The GSHPs eliminate the Achilles' heel of conventional heat pumps in terms of comfort, namely "cold blow". Commercial systems can be designed to deliver air temperatures in the 38° to 41°C range without compromising efficiency [90]. Moisture removal capability is also very good in humid climates. The previously discussed advantage of local zone control is also critical to occupant comfort.

3.7.6 Less repairs and maintenance requirement

One of the most attractive benefits of the GSHPs is the low level of maintenance. The heat pumps are closed packaged units that are located indoors. The most critical period for a heat pump compressor is start-up after defrost. The GCHPs do not have a defrost cycle. The simple system requires fewer components. Logic dictates that the fewer components, the lower the maintenance requirements. Not a great deal of data is available to support the claim of low maintenance in commercial buildings because of the limited amount of data for the GSHPs. However, a detailed study of a water loop heat pump (WLHP) system was conducted by Ross [91] and the median service life of compressors in perimeter heat pumps was projected to be 47 years [92].

3.8 Disadvantages of the GSHPS

Some disadvantages of the GSHP systems are as summarized below.

3.8.1 New and innovative application of the GSHPS

Geothermal heat pumps (GHPs) are a relatively new application that can save homeowners money. The GSHPs use the natural heat storage capacity of the earth or ground water to provide energy efficient heating and cooling. However, the GSHPs face the typical barriers of any new application in the heating and cooling industry. Air source heat pump and natural gas heating applications have been successful [92]. A great deal of research and development has also been successfully devoted to improving the technology [92].

Furthermore, the GSHP technology faces an additional barrier in the lack of the infrastructure to bridge two unrelated networks: the HVAC industry and the drilling/trenching industry. There is little motivation on either side to unite. The HVAC industry prefers to continue marketing a proven technology and well drillers continue to profit on existing water well, environmental monitoring well, and core sampling work. It is the task of the two sectors that benefit the most from the GSHPs, customers and electric utilities, to force a merger of the two networks.

3.8.2 Limited profit for HVAC equipment manufacturers

Some equipment manufacturers are resistant to the GSHPs because of the reduced need of their products. Water-to-air heat pumps are relatively simple and potentially inexpensive devices. The control network of GSHP is especially simple and inexpensive. There will be no need for manufacturer's technicians to trouble-shoot and service control systems. There will be no need to lock into one manufacturer's equipment because of incompatibility. The GSHPs are not expensive. However, approximately 50% of the system's initial cost must be shared with a driller/trencher. Therefore, some HVAC manufacturers may be reluctant to support the implementation of the GCHPs.

3.9 Limited commercial installations

The choice of installation type depends on the available land area and the soil and rock type at the installation site. Very few building owners, engineers, and architects consider GSHPs because in the past implementation was difficult. There were very few qualified loop installers, design guides were hard to find, and the traditional HVAC and residential network balked at the thought of linking equipment to plastic pipe buried in the ground. However, the experiences of those who tried the most recent concepts have led to a sound methodology for the design and installation of highly reliable and efficient systems. One such firm is the Pennsylvania GSHP Firm, which operates in USA [88]. This firm designs, installs and operates GSHP systems. The ground coils are typically 6 to 167 m deep with 4 cm polyethylene U-bends. Drilling in the area is very difficult compared to the rest of the USA [89]. However, several successful systems have been and are continuing to be installed and operated. A listing is given in Table 3.3.

Table 3.3 List of GSHP systems installed and operated by Pennsylvania GCHP Firm [89]

Building Type	Area (m^2)	Capacity (tons)	Units	Bores
Bank	5,500	13	3	3
Retired Community	420,000	840	316	187
Elementary School	24,000	59	21	20
Doctor's Office	11,800	35	7	7
Condominiums	88,000	194	74	40
Middle School	110,000	412	96	106
Restaurant	6,500	36	6	7
Office/Lab	104,00	252	43	62
Elderly Apts.	25,000	89	76	12
Life Care Comm.	390,000	1,100	527	263
Ron. McDonald House	2,000	5	4	1

Similar firms are operating profitably in areas all over the USA. Texas has several new schools and other commercial buildings that have GCHPs. Activities in Canada are very high compared to the USA with utilities promoting the technology with rebates and technical assistance. Oklahoma, a state that derives much of its income from oil and gas, is in the process of installing a GCHP system to heat and cool its state capital complex [89].

The common thread in successful GCHP programmes appears to be an individual or set of individuals in a particular location who recognise the advantages of the GCHPs. These individuals have the initiative to push forward in spite of the many skeptics who contend that GCHPs will not work [90]. However, there are several factors that help to determine the most economical choice for installation of the smaller sizes [89] such as:

- The cooling requirement of commercial buildings with high lighting and internal loads usually exceeds the heating requirement.
- In the heating mode only about 70% of the heat requirement of the building must come from the ground coil. The remaining 30% comes from the power input to the compressor and fan motors. So the coil transfers about 2675 kWatts. In cooling the coil must transfer the building

load and the added heat of the motors. This means 130% or 4970 kWatts must be moved through the ground coil [89].

- The heating requirement of commercial buildings is often in the form of a morning "spike" followed by a reduced load. Ground coils are well suited to handling spikes because of the large thermal mass of the earth. Therefore, lengths can be reduced compared to systems designed for continuous loads. Since the ground coil for a GCWLHP would not be able to meet the cooling load in most climates, a downsized cooling tower would be added to the loop.

The GCHPs can also be integrated into "free cooling" or thermal storage schemes. For example, hydronic coils could be added to core heat pumps of a GCWLHP system. When the outdoor temperature was cold enough, the cooling tower could be started. This would bring the loop temperatures below 10°C to cool the core zones without activating the compressors. The heat pumps in perimeter zones could operate simultaneously in the heating mode if required. A variety of other systems are possible because of the simplicity and flexibility of ground-coupled heat pumps.

3.10 Cost of GSHP

This summarises the costs of GSHP:

3.10.1 Initial cost of GSHP

The initial cost of a geothermal heat pump system varies greatly according to local labour rates, geological profile, type of system installed, and equipment selected. Therefore, the initial cost of GHP systems does come at a premium when compared to air source heat pump systems. Generally, the cost of installed ducts should be identical for the two systems. However, equipment costs can be 50-100% more expensive for a GHP system when the circulating pump, indoor tubing, and water source heat pump are considered. This 50-100% premium translates to £1000 - £2000 for a 10.5 kW system. The ground loop is generally the most expensive component of the geothermal heat pump system and is highly dependent on the local labour rates and drilling conditions. An installed ground loop stubbed out in a home can run between £1000 and £3000 per installed ton. Overall, one could expect to pay between £4000 and £11000 more for a turnkey 10.5 kW GHP system than for an air source heat pump system. Many consumers justify this initial investment with the savings they expect to realize on their heating and cooling bills over the lifetime of the system.

Indeed, the high installation cost is currently the most formidable barrier to the application of GCHP systems. While this is especially true in the residential sector, it also applies to commercial applications. Residential premiums compared to a standard electric cooling/natural gas heating system (9.0 for the seasonal energy efficiency ratio (SEER), 65% for annual fuel utilisation efficiency rating (AFUE) are typically £600 to £800 per ton for horizontal systems and £800 to £1000 per ton for vertical systems. Simple payback is typically five to eight years [92]. The percent increase is somewhat less for commercial GCHPs as shown in the following section.

3.10.2 Installation cost of GSHP

High installation costs have been identified as a major barrier to wider application of GSHPs often referred to as geothermal heat pumps. The primary reason cited for higher cost is the ground loop. Other factors may be high costs of GSHP heat pump units and supplies, interior installation, and limited competition.

Nevertheless, reductions in GSHP system cost, improvements in installation quality, greater competition, and improved market penetration have occurred primarily in the areas that have been involved with GSHPs for several years. The installation cost of GSHPs in areas that do not have established contractors and designers is often prohibitively high. Many potential customers cannot economically justify these relatively high costs. Thus, the GSHP heat pump industry in these areas does not develop sufficiently to support loop and HVAC contractors in order to invest in the equipment and training necessary to install GSHPs effectively.

However, the average cost of ground-source heat pump systems ranges from 10.5 kW (horizontal) to 17.5 (vertical) [94]. The cost can be subdivided by components as follows (Figure 3.3):

Ground loop = 27.2% to 34.2%
Heat pump = 27.3% to 30.2%
Indoor installation = 19.2% to 21.1%
Ductwork = 13.5% to 14.5%
Pumps = 6.2% to 7.1%
Borehole drilling cost for vertical heat exchangers: 20-55 (£/m).
The total cost for an installed ground collector including materials and backfilling, etc., varies between 25 - 50 £/m.
The cost of maintenance is between 1.08 - 5.38 £/m^2/per year.

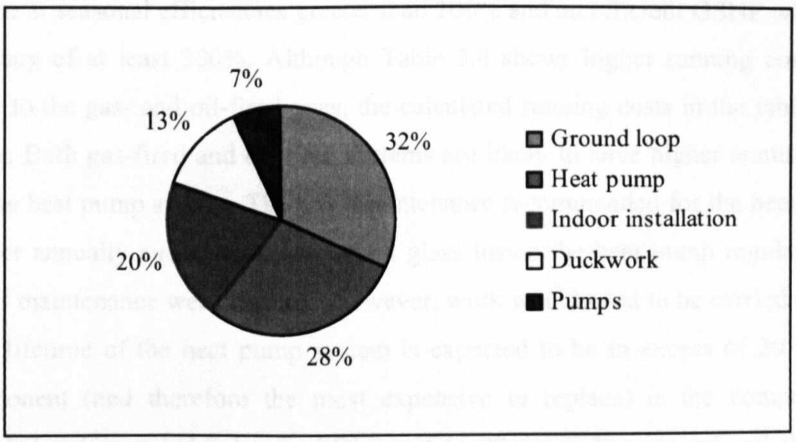


Figure 3.3 Average cost of GSHP

The reasons for these high costs and lost market opportunities appear to be:

1. High cost of ground loops.
2. Higher cost for GSHP heat pump equipment and supplies.
3. Higher cost of HVAC installation.
4. Limited competition.

The potential for improvement (in terms of performance and lower costs) must be evaluated thoroughly before the industry's limited research resources are unwisely expended.

Alternatives should have the following characteristics.

1. Very durable during and after installation.
2. Able to be installed with low cost, low maintenance, and compact equipment.
3. Require moderate volumes of antifreeze solutions in cold climates.
4. Must not require heat pumps with larger refrigerant charges, complicated controls or complex refrigerant circuits.
5. Be evaluated based on long periods (one year) with higher than average loads.
6. Constructed of materials that can be fabricated with conventional materials that will not decay in soils.
7. Able to be installed and serviced by technicians with moderate skills.

It should be noted that the best gas-condensing boiler has a seasonal efficiency of approximately 85% compared with an efficiency of about 73% for a conventional boiler. Heat pump systems, on the other hand, can operate at seasonal efficiencies greater than 100% and an efficient GSHP will operate with a seasonal efficiency of at least 300%. Although Table 3.4 shows higher running cost for the GSHP systems relative to the gas- and oil-fired ones, the calculated running costs in the table do not include annual servicing. Both gas-fired and oil-fired systems are likely to have higher annual servicing costs than those for the heat pump system. The only maintenance recommended for the heat pump system is to clean the filter annually and to check the sight glass inside the heat pump regularly (about every three months). If maintenance were required, however, work would need to be carried out by a suitable local firm. The lifetime of the heat pump system is expected to be in excess of 20 years. The most important component (and therefore the most expensive to replace) is the compressor, which is hermetically sealed and expected to have a lifetime of 15-20 years. The ground coil should last longer (coils are being guaranteed for up to 50 years) [94]. Despite this, the heat pump was only supplied with a two-year guarantee. In order to overcome the effect of fuel cost fluctuations over time and across regions, all the fuel prices are three-year averages taken from the Government's Standard Assessment Procedure (SAP, 2009) [93].

Table 3.4 Costs and CO_2 emissions of the ground source system compared with other alternatives [94]

System	Capital cost installed (£)	Energy consumption (kWh)	Annual running cost (£)	Annual CO_2 emissions ($kgCO_2$)
Ground source heat pump	**1800**	7825	420	3600
All electric2 (efficiency 100%)		18690	545-1100	8590
Regular oil-fired boiler (efficiency 70%)	**1280**	**26686**	**380**	**7210**
Regular oil-fired boiler (efficiency 79%)		**23646**	**340**	**6390**
Gas-fired condensing boiler (efficiency 85%)		21976	365	4260

Figure 3.4 shows the domestic fuel cost per useful kWh of heat provided versus fuel utilisation efficiency. This graph can be useful at the early decision making stage. Also, maintenance costs for the GSHPs are minimal. There is no requirement for an annual safety inspection as there is for combustion equipment, for example. The discounted payback period (DPP) is a method of comparing alternative investments or for evaluating a single investment in payback analysis. Payback period is the time required for the total accumulated savings or benefits of a system to offset investment costs. Since the time value of money must be considered in payback computations, all the costs must be discounted to calculate the discounted payback period. Then, the payback is achieved when the total accumulated present value (PV) savings are enough to offset the total PV costs of an alternative. The discounted payback period is simply the total elapsed time between the point when the savings begin to accrue and

the point at which payback will occur. Figure 3.5 shows that, in terms of the number of year of discounted payback period, the combined GSHP and gas heating system is less attractive compared with an electric heater heating system and gas-fired condensing boiler, with the payback period of 5.5 years and 25 years respectively.

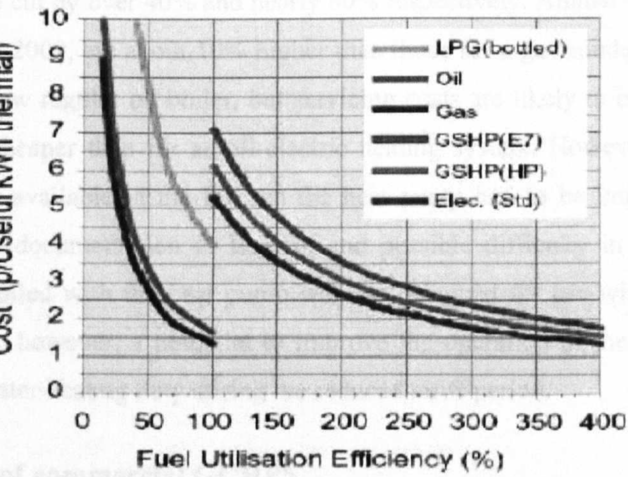


Figure 3.4 Fuel cost versus fuel utilisation efficiency [94]

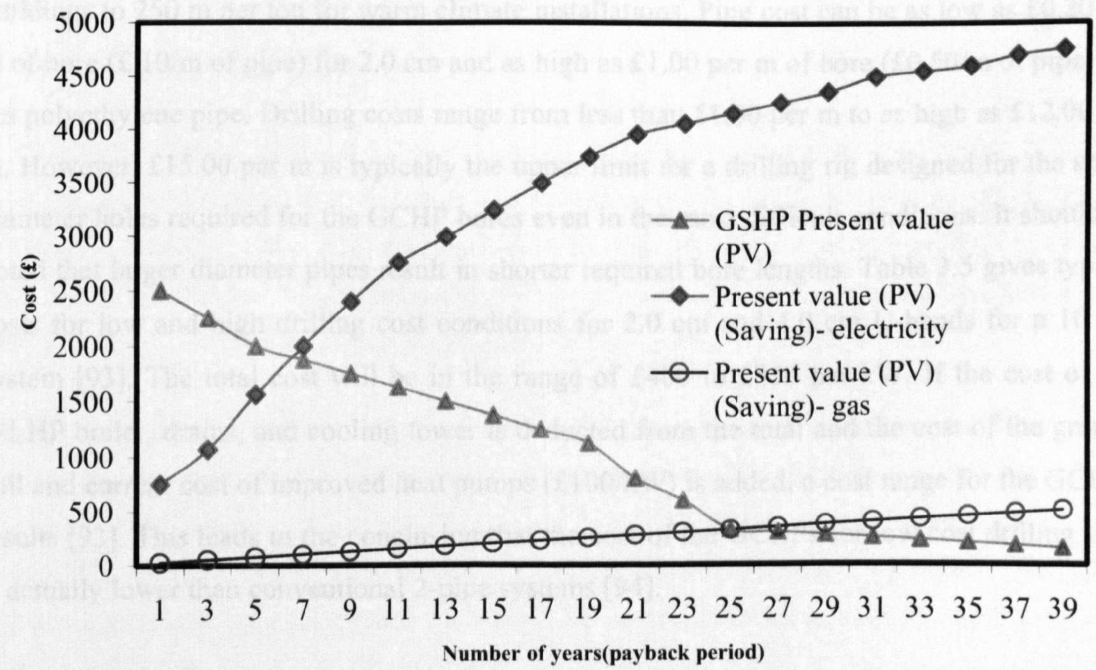


Figure 3.5 Comparison of present values of different energy sources

As can also be seen in Table 3.4, the GSHP system is responsible for lower CO_2 emissions than alternative heating systems. For example, the table shows that, compared with a gas-condensing boiler, the heat pump system resulted in 15% lower CO_2 emissions (assuming a CO_2 emission factor for electricity of 0.46 kg/kWh). When compared with new oil fired boiler system or all-electric systems, the emissions of CO_2 are cut by over 40% and nearly 60% respectively. Annual fuel costs, based on the fuel prices given in SAP 2009, are about 10% higher than those for a gas condensing boiler and about 20% higher than for a new regular oil boiler, but servicing costs are likely to be lower. Also, running costs are substantially cheaper than for an all-electric heating system. However, at present, suitable products are not readily available in the UK, so the heat pump had to be imported. This had some drawbacks, e.g., limited documentation in English and possible difficulty in obtaining spare parts. Also, the controller supplied with the heat pump was not designed for use with an Economy 7 type tariff structure. There is, however, a potential to improve the operation of the system by scheduling more of the space and water heating duty during the reduced tariff period.

3.10.3 Projected cost of commercial GCHPS

The cost of vertical ground coil ranges between £2.00 to £5.00 per m of bore. Required bore lengths range between 125 m per ton for cold climate, high internal load, and commercial buildings to 250 m per ton for warm climate installations. Pipe cost can be as low as £0.20 per m of bore (£.10/m of pipe) for 2.0 cm and as high as £1.00 per m of bore (£0.50/m of pipe) 4.0 cm polyethylene pipe. Drilling costs range from less than £1.00 per m to as high as £12.00 per m. However, £15.00 per m is typically the upper limit for a drilling rig designed for the small diameter holes required for the GCHP bores even in the most difficult conditions. It should be noted that larger diameter pipes result in shorter required bore lengths. Table 3.5 gives typical costs for low and high drilling cost conditions for 2.0 cm and 4.0 cm U-bends for a 10 ton system [93]. The total cost will be in the range of £400 to £850 per kW. If the cost of the WLHP boiler, drains, and cooling tower is deducted from the total and the cost of the ground coil and current cost of improved heat pumps (£100/kW) is added, a cost range for the GCHPs results [93]. This leads to the conclusion that the cost of the GCHPs for low cost drilling sites is actually lower than conventional 2-pipe systems [94].

Table 3.5 Cost of vertical ground coils [93]

System	£1.50/m Drilling cost	£4.00/m Drilling cost
	(2.0 cm) (2000 m)	(4.0 cm) (1700 m)
Drilling	£3000	£2550
Pipe	£600	£1360
Fittings	£300	£300
Total	£3900	£4210
Cost/ton	£390	£421

3.10.4 Running costs

Geothermal heat pumps offer high efficiency and low operating cost. Hence, they can save homeowners 30-70% on heating and 20-50% on cooling costs over conventional systems. Limited data is available documenting the operating cost of the GCHPs in commercial applications. The steady state and part load cooling efficiencies of vertical GCHPs appear to be superior to high efficiency central systems. The heating efficiencies are very good, especially when the ground coil is sized to meet the cooling requirement. However, these high efficiencies will not be realised if ground coils are undersized or low and moderate efficiency water-to-air heat pumps are used. A comprehensive study of the GCHP operating costs in commercial buildings must be conducted. Such a study is needed to expand the limited design guidelines currently available for the GCHPs.

3.10.5 Facing the competition with GCHPS

Electric utilities may argue that the above arguments for GCHP systems may be exaggerated. There is, of course, a strong element of truth in this. For example, naturally, air source heat pumps do not heat well in cold weather (Mother Nature will not allow it). Also, air heat pumps do blow large amounts of air at temperatures below body temperature. Hence, in the heating mode, the air heat pump consumes more net energy than high efficiency gas furnaces.

However, the electrical utility has focused the bulk of its response on aggressive marketing that, in some cases, can be criticised as misleading. This marketing includes advertising and reduced rates for customers who choose electric systems. To a lesser degree, the response has included development of advanced heat pumps. In the commercial sector, this has generally excluded the GCHPs. Most of the developmental activity for the GCHPs has been confined to the residential market, where the electric utility would be the benefactor. They offer all of the many advantages of conventional electric heat pumps plus higher efficiency, simplicity, reliability, reduced demand, removal of unsightly outdoor equipment, comfort, and long life. They offer a system whose performance cannot be matched by natural gas equipment.

3.11 Conclusions

GSHPs are receiving increasing interest because of their potential to reduce primary energy consumption and reduce emissions of GHGs. The technology is well established in North America and parts of Europe, but is still at the demonstration stage in the United Kingdom. Benefits to the community at large will result from the reduction in fossil consumption and the resulting environment benefits. By reducing primary energy consumption, the use of the GSHPs has the potential to reduce the quantity of CO_2 produced by the combustion of fossil fuels and thus to reduce global warming. The choice of horizontal or vertical system depends on the land area available, local ground conditions and excavation costs. As costs for trenching and drilling are generally higher than piping costs it is important to maximise the heat extraction per unit length of trench/borehole. The piping material used affects life, maintenance costs, pumping energy, capital cost and heat pump performance. Both gas-fired and oil-fired systems are likely to have higher annual servicing costs than those for the heat pump systems. The performance of the heat pump system could also be improved by eliminating unnecessary running of the integral distribution pump. This would improve both the economics and the environmental performance of the system. More generally, there is still potential for improvement in the performance of heat pumps and seasonal efficiencies for GSHPs. It is also likely that unit costs will fall as production volumes increase. GSHPs can provide an energy-efficient, cost-effective way to heat and cool building facilities.

4.0 Ground source technologies description only

4.1 Introduction

This chapter provides a detailed literature-based review of the ground source heat pump (GSHP) technology, concentrating on loops, ground systems, and looks more briefly at applications. It is concluded that, despite potential environmental problems, geothermal heat pumps pose little if any serious environmental risk when best management practices are applied during the installation, operation, and decommissioning of these systems. Ground heat exchanger configurations are described in some detail here and their design challenges are explained, laying the foundation for the motivation of this study.

4.1 Overview

The GSHPs provide a new and clean way of heating buildings. They make use of renewable energy stored in the ground, providing one of the most energy-efficient ways of heating buildings [95]. They are also suitable for a wide variety of building types and particularly appropriate for low environmental impact projects. They do not require hot rocks (geothermal energy) and can be installed in most of the world, using a borehole or shallow trenches or, less commonly, by extracting heat from a pond or lake. Heat collecting pipes in a closed loop, containing water (with a little antifreeze) are used to extract this stored energy, which can then be used to provide space heating and domestic hot water. In some applications, the pump operation can be reversed in the summer to provide an element of cooling. The only energy used by the GSHP systems is electricity to power the pumps. Typically, a GSHP will deliver three or four times as much thermal energy (heat) as is used in electrical energy to drive the system [95]. For a particularly environmental solution, green electricity can also be purchased to operate the pumps. The GSHP systems have been widely used in some parts of the world, including North America and Europe, for many years. Typically, they cost more to install than conventional systems; however, they have a very low maintenance cost and can be expected to provide reliable and environmentally friendly heating for more than 20 years [95]. The GSHPs work best with heating systems, which are optimised to run at a lower water temperature than is commonly used in the UK boiler and radiator systems. As such, they make an ideal partner for under-floor heating systems. Also, geothermal heating can be more efficient than electric resistance heating. These systems are also typically more efficient than gas or oil-fired heating systems. They are more energy efficient than air-source heat pumps because they draw heat from, or release heat to, the earth, which has moderate temperatures the year round, rather than to the air (which is generally colder in winter and warmer in summer than the earth, resulting in less effective heat transfer). Hence, it is argued that heat pumps are highly energy efficient, and therefore environmentally benign.

Generally, heat pumps can, indeed, offer the most energy efficient way to provide heating and cooling in many applications, as they can use renewable heat sources in their surroundings. Even at temperatures considered to be cold, air, ground and water contain useful heat that is continuously replenished by the sun. By applying a little more energy, a heat pump can raise the temperature of this heat energy to the level needed. Similarly, heat pumps can also use waste heat sources such as from industrial processes, cooling equipment or ventilation air extracted from buildings. A typical electrical heat pump will just need 100 kWh of power to turn 200 kWh of freely available environmental or waste heat into 300 kWh of useful heat [95]. Because heat pumps consume less primary energy than conventional heating systems, they are an important technology for reducing emissions of gases that harm the environment, such as carbon dioxide (CO_2), sulphur dioxide (SO_2) and nitrogen oxides (NO_x). However, the overall environmental impact of electric heat pumps depends very much on how the electricity is produced. Heat pumps driven by electricity from, for instance, hydropower or renewable energy reduce emissions more significantly than if the electricity is generated by coal, oil or gas fired power plants.

Climate change is a real threat to the future, and its major cause is the use of fossil fuels to power homes and businesses. Renewable energy, combined with energy efficiency, offers a viable and potent solution to countering the effects of global warming. By installing any one of the renewable energy technologies, one will be making a major personal contribution to the well being of the future generations and could also benefit from lower fuel bills. Greater use of renewable energy and increased energy efficiency are considered key to limiting greenhouse gas (GHG) emissions. However, wind, solar, biomass, and water are not the only sources of clean, environmentally friendly energy. Other energy sources can also provide heat, light, and electricity without polluting the air or disturbing large areas of land or water. Geothermal energy is one new technology, which is likely to become mainstream sources of energy in the approaching decades.

4.3 Earth energy systems

Geothermal heating and cooling systems are known by a variety of names, such as earth energy systems, GeoExchange systems, GSHPs, GeoExchange heat pumps, ground-coupled groundwater source heat pumps, well water heat pumps, solar energy heat pumps, and a few other variations. Some names are used to describe more accurately the specific application; however, most are the result of marketing efforts and the need to associate (or disassociate) the heat pump systems from other. However, they are essentially heat pumps that collect and transfer heat from the earth through a series of fluid-filled, buried pipes running to a building, where the heat is then concentrated for inside use. The GSHPs do not generate heat through combustion - they simply move the heat from one place to another. Their principal aims are to:

- Promote the concept of using the GSHPs as an environmentally preferable means of heating and cooling buildings.
- Assist in developing standards for, and provide support to, the growing industry of manufacturers, importers and installers of the GSHPs.

The GSHPs offer a different kind of heating. Unlike conventional forced-air furnaces, geothermal units offer a steady heat. There is no "blast" of hot air and it provides a constant and clean heat. There's no residue or dust around the house like the case with a forced-air heating systems in homes in big cities. Geothermal units are also extremely efficient in cooling homes.

A GSHP operates much like the common air-source heat pump by transferring heat, rather than generating it. Unlike air-source, a GSHP transfers heat to and from the earth to provide cooling and heating for the homes at all atmospheric conditions. For example, below the frost line, the temperature of the earth in Nebraska stays fairly constant at 12.5°F [95]. In summer, the soil temperature is cooler than the outside air. In winter, it's warmer. A GSHP uses this constant temperature to heat and cool homes very efficiently.

4.3.1 Geothermal energy

A GSHP uses the earth or ground water or both as the sources of heat in the winter, and as the "sink" for heat removed from the home in the summer. For this reason, the GSHP systems have come to be known as earth-energy systems (EESs). Heat is removed from the earth through a liquid, such as ground water or an antifreeze solution, upgraded by the heat pump, and transferred to indoor air. During summer months, the process is reversed: heat is extracted from indoor air and transferred to the earth through the ground water or antifreeze solution. A direct-expansion (DX) earth-energy system uses refrigerant in the ground-heat exchanger, instead of an antifreeze solution.

Earth-energy systems are available for use with both forced-air and hydronic heating systems. They can also be designed and installed to provide heating only, heating with "passive" cooling, or heating with "active" cooling. Heating-only systems do not provide cooling while passive-cooling systems provide cooling by pumping cool water or antifreeze through the system without using the heat pump to assist the process. People have known since ancient times that the earth's interior is very hot. The temperature of the earth's core is estimated to be between 3000 and 5000°C (scientists are still not sure what the exact temperature is). This heat is generated by the slow breakdown of radioactive elements, and by the immense gravitational pressures acting on the rocks and minerals of the earth's interior. Temperatures in excess of 500°C can be found in the earth's crust just a few thousand metres below the surface, but geothermal heat right at the surface of the land is barely detectable [96].

Geothermal heat has been used to heat homes and businesses on a commercial scale since the 1920s. In most cases, communities take advantage of naturally occurring geysers, hot springs, and steam vents (called fumaroles) to gather hot water and steam for heating. Geysers and fumaroles occur when ground water seeps through cracks and comes in contact with volcanically heated rocks. In Iceland for instance, wells are drilled into volcanic rocks to extract hot water and steam. The hot water or steam is carried to communities in insulated pipes and used to heat homes and businesses. In some cases, the water is superheated (heated under pressure to temperatures greater than 100°C). Superheated water quickly turns to high-pressure steam, which can turn high-speed turbines that drive electrical generators.

Earth energy systems such as GSHPs, GeoExchange, or Geothermal heat pump systems are considered to be the most energy-efficient, environmentally clean and cost-effective heating and cooling systems available. This is because the ground is generally warmer in the middle of winter and cooler in the middle of summer than the outside air. However, the temperature of the ground is fairly constant below the frost line (Figure 4.1). A single efficient system can be used for both heating and cooling, eliminating the need for separate furnace and air-conditioning systems. It can also heat water at no additional cost. An earth energy system uses a series of buried pipes to transfer the heat from the ground into a building during winter, converting it into warm air and distributing it through ducts. In summer, the system is reversed to transfer heat out of the building, where it uses the cooler ground as a heat sink. The system can be configured as either a closed or open loop, and the loop itself can be either horizontal or vertical. Closed-loop systems circulate a fluid mixture within the buried pipes, while open-loop systems circulate well or surface water.

As the GSHPs do not create heat through combustion; they simply move solar heat that is stored in soil or water from one place to another, they can reduce greenhouse gas emissions by 66% or more compared with conventional heating and cooling systems that use fossil fuels [96]. Also, earth energy systems use up to 75% less electricity than conventional heating or cooling systems, while maintenance costs for this type of technology can be cut in half and operating costs reduced one-quarter of that of a conventional system [97]. GSHP systems for domestic heating are a relatively new concept in Britain; however the technology is widely used in an industrial capacity. Across Europe, hundreds of thousands of domestic heat pump units are in use, and the technology is tried, tested and reliable [102].

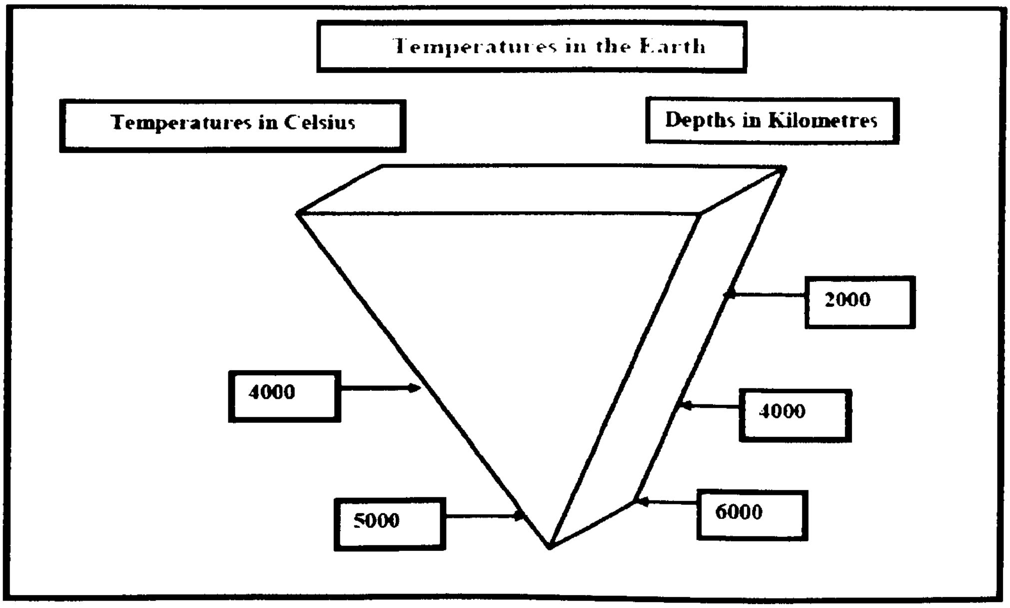


Figure 4.1 Geothermal heats comes from pressure and nuclear reactions at the earth's core

4.4 Geothermal heat pump system

A geothermal heat pump system includes three principle components – (1) an earth connection subsystem, (2) heat pump subsystem, and (3) heat distribution subsystem. The earth connection subsystem usually includes a closed loop of pipes that is buried, horizontally or vertically. A fluid is circulated through these pipes, allowing heat, but not fluid, to be transferred from the building to the ground. The circulating fluid is generally water or a water/antifreeze mixture. However, less commonly, the earth connection system includes an open loop of pipes connected to a surface water body or an aquifer, that directly transfers water between the heat exchanger and water source (pond or aquifer).

For heating, the heat pump subsystem removes heat from the circulated fluid, concentrates it, and transfers it to the building. The process is reversed for cooling, applications. The heat distribution subsystem is the conventional ductwork used to distribute heated or cooled air throughout the building.

The US Department of Energy (USDOE) estimated that over two-thirds of the US electrical energy and greater than 40% of natural gas consumption is used inside buildings [97]. In residential and commercial buildings, space heating and cooling and water heating consume greater than 40% of electrical power. The US Environmental Protection Agency (USEPA) estimated that geothermal heat pumps can reduce energy consumption by up to 44% compared to air-source heat pumps and up to 72% compared to conventional electrical heating and air conditioning. For most areas of the USA, geothermal heat pumps are the most energy efficient means of heating and cooling buildings [97].

For vertical, closed loop systems, heat exchange between the fluid and ground depends upon the thermal properties of the material in the borehole. The borehole may be backfilled with soil cuttings or grout. In Illinois, for example, the borehole must be backfilled with bentonite grout or neat cement [98]. Standard bentonite grout has a thermal conductivity that is lower than most soils or geologic materials (0.43 kW/hr m °C vs. 0.8 to 1.8 kW/hr m °C), thus it acts as an insulator around the heat exchange pipes [98]. Thermally enhanced bentonite grouts have been developed and have thermal conductivities of 0.85 to 1.4 kW/hr m °C [99], while retaining low hydraulic conductivity (<10-7 cm/sec), based on technical data from manufacturers. However, in order to boost the thermal conductivity of grouts, manufacturers mix silica sand and bentonite, and at times, other materials such as cement and super-plasticiser [100-101].

One of the most energy efficient methods of domestic heating is to use heat pumps. This is why the GSHPs use a heat pump to transfer heat from the ground into a building to provide space heating (Figure 4.2) and, in some cases, to pre-heat domestic hot water. Heat pumps use electrical energy to reverse the natural flow of environmental heat from cold to hot. A typical heat pump requires only 100 kWh of electrical power to turn 200 kWh of freely available environmental heat into 300 kWh of useful heat. In every case, the useful heat output will be greater than the energy required to operate the pump itself. Generally speaking, 3-4 units of heat are produced for every unit of electricity used to pump the heat. Heat pumps also have a relatively low carbon dioxide output, less than half than that of electric, oil and gas heat production. As well as the GSHPs, air source and water source heat pumps are also available.

A heat pump is a mechanical device used for heating and cooling. It operates on the principle that heat can be moved from a warmer temperature to a cooler temperature. The heat pump moves heat from a low temperature source to a high temperature source. The process of elevating low temperature heat to over 38°C and transferring it indoors of a building involves a cycle of evaporation, compression, condensation and expansion. A non-CFC refrigerant is used as the heat transfer medium, which circulates within the heat pump (Figure 4.3).

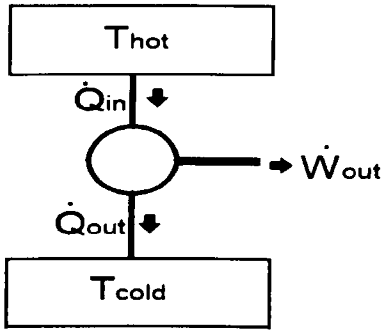


Figure 4.2 Diagram of heat engine

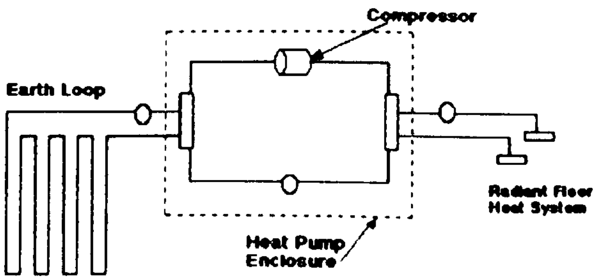


Figure 4.3 heat pump cycles

Refrigeration is the 'artificial' extraction of heat from a substance in order to lower its temperature to below that of its surroundings. Primarily, heat is extracted from fluids such as air and many liquids, but ultimately from any substance. In order to extract heat a region of 'cold' has to be created. A number of effects can be used:

- The Peltier effect (reverse of thermocouples).
- Endothermic chemical reactions.
- Induced vaporisation of a liquid.

However, in thermodynamic terms a refrigerator is simply a reversed heat engine i.e., heat may transfer from a cold reservoir to a hot reservoir by expending work (Figure 4.4). Therefore, a heat pump is no different in principle from a refrigerator apart from its purpose. This is to say that a heat pump is used to provide 'heat' whereas a refrigerator is used to obtain 'cold'.

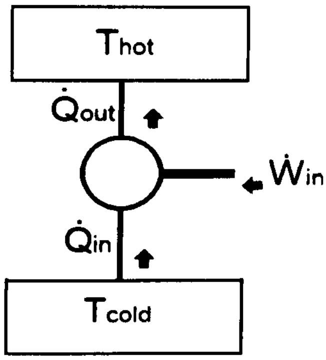


Figure 4.4 Reversed heat engine (refrigerator)

4.5 Heat pump development

A heat pump can save as much as 30% to 40% of the electricity used for heating. It is therefore more reasonable to consider installing an energy-efficient heat pump system for homes. Heat pumps collect heat from the air, water, or ground outside the house and concentrate it for use inside. They are particularly the most efficient form of electric heating in mild and moderate climates, providing two to three times more heating than the equivalent amount of energy they consume in electricity. Air source heat pumps are recommended for mild and moderate climate regions, where the winter temperatures usually remain above -1°C [102]. Ground source (also known as geothermal) heat pumps are more efficient and economical to operate when compared to conventional air source heat pumps, especially in climates with similar heating and cooling loads. Three types of heat pumps are typically available for residents: (1) air-to-air, (2) water source, and (3) ground source. Heat pumps also operate in reverse mode to cool homes by collecting the heat inside the house and pumping it outside effectively [103].

Heat pumps have both heating and cooling ratings in terms of capacity as well as efficiency. Heating efficiency for air source heat pumps is indicated by the heating season performance factor (HSPF). The HSPF tells the ratio of the seasonal heating output in kW's divided by the seasonal power consumption in Watt-hours (Wh). Heat pump efficiency varies with outdoor temperature. The performance of an air source heat pump in heating mode decreases with the drop in outside air temperature. The actual seasonal efficiency (as opposed to the rating) is, therefore, higher in a mild climate than in a severe cold climate. In the cooling mode, a heat pump operates exactly like a central air conditioner. The seasonal energy efficiency ratio (SEER) is analogous to the HSPF but tells the seasonal cooling performance. Federal efficiency standards require that conventional heat pumps have an HSPF rating of at least 6.8 and a SEER rating of at least 10.0. The most efficient air source heat pumps have an

HSPF rating between 9.0 and 10.0 and a SEER above 14 or so, rendering the GSHP as more efficient and environmentally friendly when compared to other systems, as shown in Table 4.1.

Table 4.1 Comparison of different heating systems

System	Primary Energy Efficiency (%)	CO_2 emissions ($kg\ CO_2/kWh$ heat)
Oil fired boiler	60 - 65	0.45 – 0.48
Gas fired boiler	70 - 80	0.26 – 0.31
Condensing Gas Boiler + low temperature system	100	0.21
Electrical heating	36	0.9
Conventional electricity + GHSP	120 - 160	0.27 – 0.20
Green electricity + GHSP	300 - 400	0.00

As with air-source heat pumps, earth-energy systems are available with widely varying efficiency ratings. Earth-energy rating systems (EER) intended for groundwater or open-system applications have heating Coefficient of performance (COP) ratings ranging from 3.0 to 4.0, and cooling EER ratings between 11.0 and 17.0. Those intended for closed-loop applications have heating COP ratings between 2.5 and 4.0, and EER ratings range from 10.5 to 20.0 [103]. The minimum efficiency in each range is regulated in the same jurisdictions as the air-source equipment. There has been a dramatic improvement in the efficiency of earth-energy systems efficiency over the past five years. Today, the same new developments in compressors, motors, and controls that are available to air-source heat pump manufacturers are resulting in higher levels of efficiency for earth-energy systems (Figures 4.5).

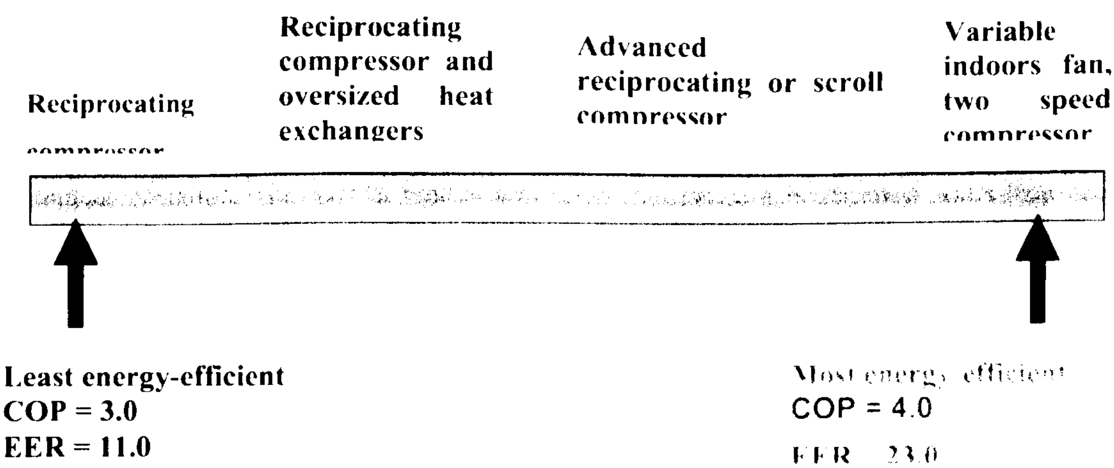


Figure 4.5 Open system earth-energy system efficiency (at an entering water temperature of 10°C)

In the lower to middle efficiency range, earth-energy systems use single-speed rotary or reciprocating compressors, relatively standard refrigerant-to-air ratios, but oversized enhanced-surface refrigerant-to-water heat exchangers. Mid-range efficiency units, on the other hand, employ scroll compressors or advanced reciprocating compressors, while units in the high efficiency range tend to use two-speed compressors or variable speed indoor fan motors or both, with more or less the same heat exchangers.

4.6 Classification of ground source heat pumps

A typical GSHP system design applied to a commercial facility is illustrated in Figure 4.6. It is important to remember that the primary equipment used for groundsource heat pumps are water-source heat pumps. This makes a ground source heat pump different (unique, efficient, and usually more expensive to install) for each ground-coupling system.

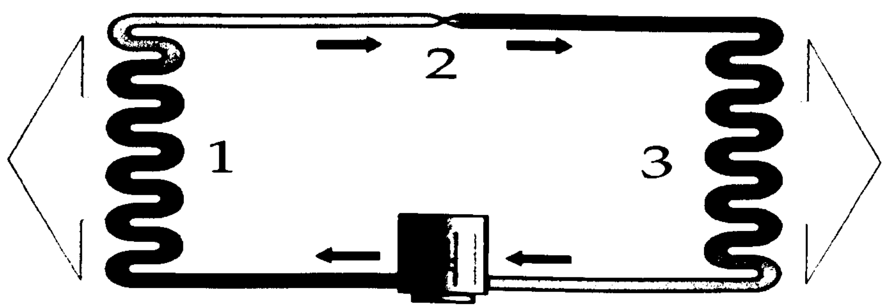


Figure 4.6 Diagram of a phase change heat pump: 1) condensator coil 2) expansion valve 3) evaporator coil and 4) compressor

A conventionally designed water-source heat pump system would incorporate a boiler as a heat source during the winter heating operation and a cooling tower to reject heat (heat sink) during the summer cooling operation. This system type is also sometimes called a boiler/tower water-loop heat pump system. The water loop circulates to the entire water source heat pumps connected to the system. The boiler (for winter operation) and the cooling tower (for summer operation) provide a fairly constant water-loop temperature, which allows the water-source heat pumps to operate at high efficiency. A conventional air-source heat pump uses the outdoor ambient air as a heat source during the winter heating operation and as a heat sink during the summer cooling operation. However, air-source heat pumps are subject to higher temperature fluctuations of the heat source and heat sink. They also become much less effective (and less efficient) at extreme ambient air temperatures. This is particularly true at low temperatures. Generally, heat transfer using air as a transfer medium is not as effective as water systems because of the lower thermal mass of air.

The GSHPs take advantage of the thermodynamic properties of the earth and groundwater and use the ground (or in some cases groundwater) as the heat source during the winter heating operation and as the heat sink during the summer cooling operation. The GSHPs may be subject to higher temperature fluctuations than conventional water-source heat pumps but not as high as air-source heat pumps. Consequently, most manufacturers have developed extended-range systems. The extended-range systems operate more efficiently while subject to the extended-temperature range of the water loop. Like water-source heat pumps, ground-source heat pumps use a water loop between the heat pumps and the heat source/heat sink (the earth). The primary exception is the direct-expansion ground-source heat pump. Temperatures below the ground surface do not fluctuate significantly through the day or the year, as do ambient air temperatures. Indeed, the ground temperature a few feet below the surface stays relatively constant throughout the year. For this reason, the GSHPs remain extremely efficient throughout the year in virtually any climate.

The ground system links the heat pump to the ground and allows for extraction of heat from the ground or injection of heat into the ground. These systems can be classified generally as open or closed systems, with a third category for those not truly belonging to one or the other.

Open systems: Groundwater is used as a heat carrier, and is brought directly to the heat pump. There is no barrier between rock/soil, ground water, and the heat pump evaporator, hence this type is called ''open"

Closed systems: Heat exchangers are located under the ground (either in a horizontal, vertical or oblique fashion), and a heat carrier medium is circulated within the heat exchangers, transporting heat from the ground to the heat pump (or vice versa). The heat carrier is separated from the rock/soil and groundwater by the wall of the heat exchanger, making it a ''closed" system.

Other systems: The system cannot always be attributed exactly to one of the above categories, e.g., if there is a certain distinction between groundwater and the heat carrier fluid, but no true barrier. Standing column wells, mine water or tunnel water are examples for this category.

To choose the right system for a specific installation, several factors have to be considered: Geology and hydrogeology of the underground (sufficient permeability is a must for open systems), area and utilisation on the surface (horizontal closed systems require a certain area), existence of potential heat sources like mines, and the heating and cooling characteristics of the building(s). In the design phase, more accurate data for the key parameters for the chosen technology are necessary to size the ground system in such a way that optimum performance is achieved with minimum cost. The individual types of ground systems are described in more detail below:

4.6.1 Closed systems

The closed system easiest to install is the horizontal ground heat exchanger (synonym: ground heat collector, horizontal loop). Due to restrictions in the area available, in Western and Central Europe, the individual pipes are laid in a relatively dense pattern, connected either in series or in parallel (Figure 4.7) [104].

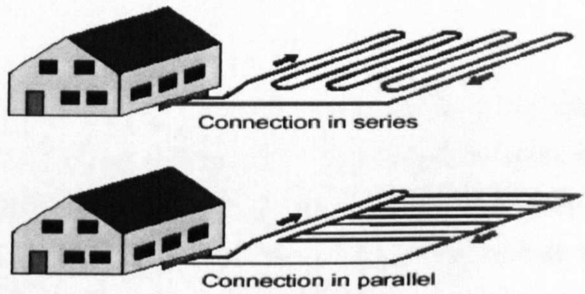


Figure 4.7 Horizontal ground heat exchanger (European style)

4.6.1.1 Horizontal-loop systems

For the ground heat collectors with dense pipe pattern, usually the top earth layer is removed completely, the pipes are laid, and the soil is distributed back over the pipes. In Northern Europe and North America, where land area is cheaper, a wide pattern (''loop") with pipes laid in trenches is preferred (Figure 4.8) [105]. Trenching machines facilitate installation of pipes and backfilling. To save surface area with ground heat collectors, some special ground heat exchangers have been developed exploiting a smaller area at the same volume. These collectors are best suited for heat pump systems for heating and cooling, where natural temperature recharge of the ground is not vital. Hence these collectors are widely used in Northern America, and one type only, the trench collector (Figure 4.9), achieved a certain distribution in Europe, mainly in Austria and Southern Germany [105]. For the trench collector, a number of pipes with small diameter are attached to the steeply inclined walls of a trench some meters deep.

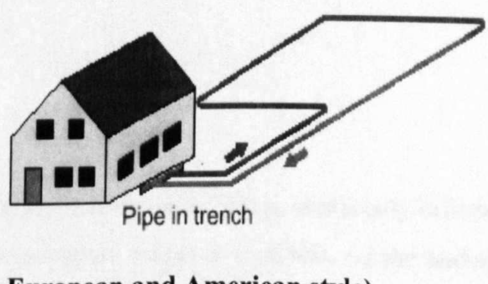


Figure 4.8 Horizontal ground heat exchanger (North European and American style)

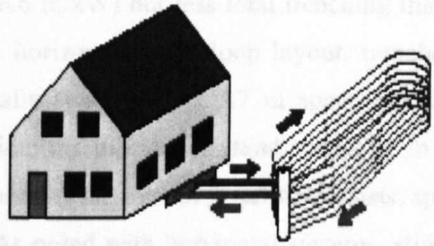


Figure 4.9 Trench collector

The main thermal recharge for all horizontal systems is provided mainly by the solar radiation to the earth's surface. It is important not to cover the surface above the ground heat collector, or to operate it as a heat store, if it has to be located, for example, under a building. A variation of the horizontal ground source heat pump is direct expansion. In this case, the working medium of the heat pump (refrigerant) is circulating directly through the ground heat collector pipes (in other words, the heat pump evaporator is extended into the ground). The advantage of this technology is the omission of one heat exchange process, and thus a possibility for a better system efficiency. In France and Austria, direct expansion has also been coupled to direct condensation in the floor heating system. Direct expansion (DX) requires good knowledge of the refrigeration cycle, and is restricted to smaller units. The horizontal-loop systems can be buried beneath lawns, landscaping, and parking lots. Horizontal systems tend to be more popular where there is ample land area with a high water table.

- **Advantages:** Trenching costs typically lower than well-drilling costs as well as flexible installation options.
- **Disadvantages**: Large ground area required; ground temperature subject to seasonal variance at shallow depths; thermal properties of soil fluctuate with season, rainfall, and burial depth; soil dryness must be properly accounted for in designing the required pipe length, especially in sandy soils and on hilltops that may dry out during the summer; pipe system could be damaged during backfill process; longer pipe lengths are required than for vertical wells; antifreeze solution viscosity increases pumping energy, decreases the heat transfer rate, and thus reduces overall efficiency; lower system efficiencies.

4.6.1.2 Spiral loops

A variation on the multiple pipe horizontal-loop configuration is the spiral loop, commonly referred to as the "slinky". The spiral loop consists of pipe unrolled in circular loops in trenches and the horizontal configuration. Another variation of the spiral-loop system involves placing the loops upright in narrow vertical trenches. The spiral-loop configuration generally requires more piping, typically 166 to 330 m per system cooling ton (43.3 to 86.6 m/kW) but less total trenching than the multiple horizontal-loop systems described above. For the horizontal spiral-loop layout, trenches are generally 0.9 to 1.8 m wide; multiple trenches are typically spaced about 3.7 m apart. For the vertical spiral-loop layout, trenches are generally 15.2 cm wide; the pipe loops stand vertically in the narrow trenches. In cases where trenching is a large component of the overall installation costs, spiral-loop systems are a means of reducing the installation cost. As noted with horizontal systems, slinky systems are also generally associated with lower-tonnage systems where land area requirements are not a limiting factor.

- **Advantages**: Requires less ground area and less trenching than other horizontal loop designs; installation costs sometimes less than other horizontal loop designs.
- **Disadvantages**: Requires more total pipe length than other ground coupled designs; relatively large ground area required; ground temperature subject to seasonal variance; larger pumping energy requirements than other horizontal loops defined above; backfilling the trench can be difficult with certain soil types and the pipe system could be damaged during backfill process.

4.6.1.3 Vertical loops

Measurements show that, the temperature below a certain depth (''neutral zone", at 15-20 m depth) remains constant over the year [106]. This fact, and the need to install sufficient heat exchange capacity under a confined surface area, favours vertical ground heat exchangers (borehole heat exchangers). In a standard borehole heat exchanger, plastic pipes (polyethylene or polypropylene) are installed in boreholes, and the remaining room in the hole is filled (grouted) with a pumpable material. In Sweden, boreholes in hard, crystalline rock usually are kept open, and the groundwater serves for heat exchange between the pipes and the rock [106]. If more than one borehole heat exchanger is required, the pipes should be connected in such a way that equal distribution of flow in the different channels is secured. Manifolds can be in or at the building, or the pipes can be connected in trenches in the field (Figure 4.10).

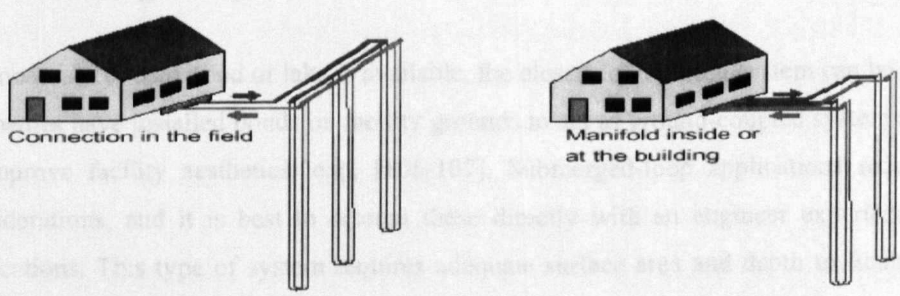


Figure 4.10 Borehole heat exchangers (double-U-pipe)

Several types of borehole heat exchangers have been used or tested; the two possible basic concepts are:

- U-pipes, consisting of a pair of straight pipes, connected by a 180° turn at the bottom. One, two or even three of such U-pipes are usually installed in one hole. The advantage of the U-pipe is the low cost of the pipe material, resulting in double U pipes being the most frequently used borehole.
- Coaxial (concentric) pipes, either in a very simple way with two straight pipes of different diameter, or in complex configurations.

Vertical loops are generally considered when land surface is limited. Wells are bored to depths that typically range from 22.9 to 91.4 m deep. The closed-loop pipes are inserted into the vertical well. Typical piping requirements range from 66 to 200 m per system cooling ton (17.4 to 52.2 m/kW), depending on soil and temperature conditions. Multiple wells are typically required with well spacing not less than 4.6 m in the northern climates and not less than 6.1 m in southern climates to achieve the total heat transfer requirements. A 300-500 ton capacity system can be installed on one acre of land, depending on soil conditions and ground temperature. There are three basic types of vertical-system heat exchangers: U-tube, divided-tube, and concentric-tube (pipe-in-pipe) system configurations.

- **Advantages**: Requires less total pipe length than most closed-loop designs; requires the least pumping energy of closed-loop systems; requires least amount of surface ground area; ground temperature typically not subject to seasonal variation.
- **Disadvantages**: Requires drilling equipment; drilling costs frequently higher than horizontal trenching costs; some potential for long-term heat build-up underground with inadequately spaced boreholes.

4.6.1.4 Submerged loops

If a moderately sized pond or lake is available, the closed-loop piping system can be submerged. Some companies have installed ponds on facility grounds to act as ground-coupled systems; ponds also serve to improve facility aesthetics, e.g., [106-107]. Submerged-loop applications require some special considerations, and it is best to discuss these directly with an engineer experienced in the design applications. This type of system requires adequate surface area and depth to function adequately in response to heating or cooling requirements under local weather conditions.

In general, the submerged piping system is installed in loops attached to concrete anchors. Typical installations require around 300 feet of heat transfer piping per system cooling ton (26.0 m/kW) and around 330 m^2 of pond surface area per ton (79.2 m^2/kW) with a recommended minimum one-half acre total surface area. The concrete anchors act to secure the piping, restricting movement, but also hold the piping 22.9 to 45.7 cm above the pond floor, allowing for good convective flow of water around the heat transfer surface area.

It is also recommended that the heat transfer loop be at least 1.8 to 2.4 m below the pond surface, preferably deeper. This maintains adequate thermal mass even in times of extended drought or other low-water conditions. Rivers are typically not used because they are subject to drought and flooding, both of which may damage the system.

- **Advantages**: Can require the least total pipe length of closed-loop designs; can be less expensive than other closed-loop designs if body of water IS available.
- **Disadvantages**: Requires a large body of water and may restrict lake use (i.e., boat anchors).

4.6.2 Open-loop systems

Open-loop systems use local groundwater or surface water (i.e., lakes) as a direct heat transfer medium instead of the heat transfer fluid described for the closed-loop systems. These systems are sometimes referred to specifically as "groundwater-source heat pumps" to distinguish them from other GSHPs. Open-loop systems consist primarily of extraction wells, extraction and reinjection wells, or surface water systems. A variation on the extraction well system is the standing column well. This system reinjects the majority of the return water back into the source well, minimising the need for a reinjection well and reducing the amount of surface discharge water. There are several special factors to consider in open-loop systems. One major factor is water quality. In open-loop systems, the primary heat exchanger between the refrigerant and the groundwater is subject to fouling, corrosion, and blockage. A second major factor is the adequacy of available water. The required flow rate through the primary heat exchanger between the refrigerant and the groundwater is typically between 1.5 and 3.0 gallons per minute per system cooling ton (0.027 and 0.054 L/s.kW). This can add up to a significant amount of water and can be affected by local water resource regulations. A third major factor is what to do with the discharge stream. The groundwater must either be re-injected into the ground by separate wells or discharged to a surface system such as a river or lake. Local codes and regulations may affect the feasibility of open-loop systems.

This type is characterised by the fact that the main heat carrier, ground water, flows freely in the underground, and acts as both a heat source/sink and as a medium to exchange heat with the solid earth. Main technical part of open systems is ground-water wells, to extract or inject water from/to water bearing layers in the underground (''aquifers"). In most cases, two wells are required (''doublette"), one to extract the groundwater, and one to re-inject it into the same aquifer it was produced from (Figure 4.11).

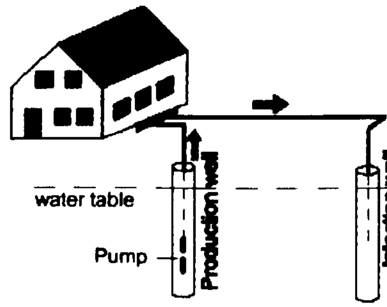


Figure 4.11 Groundwater heat pump doublette

Depending on the well configuration, open-loop systems can have the highest pumping load requirements of any of the ground-coupled configurations. Open systems tend to be used for larger installations. The most powerful ground source heat pump system worldwide uses groundwater wells to supply ca. 10 MW of heat and cold to a hotel and offices. In ideal conditions, however, an open-loop application can be the most economical type of ground-coupling system. With open systems, a powerful heat source can be exploited at comparably low cost. On the other hand, groundwater wells require some maintenance, and open systems in general are confined to sites with suitable aquifers. The main requirements are:

- Sufficient permeability to allow production of the desired amount of groundwater with little draw down.
- Good groundwater chemistry, e.g., low iron content to avoid problems with scaling, clogging and corrosion.

- **Advantages**: Simple design; lower drilling requirements than closed loop designs; subject to better thermodynamic performance than closed-loop systems because well(s) are used to deliver groundwater at ground temperature rather than as a heat exchanger delivering heat transfer fluid at temperatures other than ground temperature; typically lowest cost; can be combined with potable water supply well; low operating cost if water already pumped for other purposes, such as irrigation.

- **Disadvantages**: Subject to various local, state, and Federal clean water and surface water codes and regulations; large water flow requirements; water availability may be limited or not always available; heat pump heat exchanger subject to suspended matter, corrosive agents, scaling, and bacterial contents; typically subject to highest pumping power requirements; pumping energy may be excessive if the pump is oversized or poorly controlled; may require well permits or be restricted for extraction; water disposal can limit or preclude some installations; high cost if re-injection well required.

4.7 Measured performance

In order to optimise performance and improve efficiency throughout the year, the GSHPs replace the need for a boiler in winter by utilising heat stored in the ground; this heat is upgraded by a vapour-compressor refrigeration cycle. In summer, heat from a building is rejected to the ground. This eliminates the need for a cooling tower or heat rejecter, and also lowers operating costs because the ground is cooler than the outdoor air. Water-to-air heat pumps are typically installed throughout a building with ductwork serving only the immediate zone; a two-pipe water distribution system conveys water to and from the ground-source heat exchanger. The heat exchanger field, on the other hand, consists of a grid of vertical boreholes with plastic u-tube heat exchangers connected in parallel. Simultaneous heating and cooling can occur throughout the building, as individual heat pumps, controlled by zone thermostats, can operate in heating or cooling as required. The GSHP was installed near the Energy Learning Centre (ELC), at the School of the Built Environment, University of Nottingham. The measurement was carried out at the ELC. Figures 4.12 shows the typical annual hourly building heating and cooling loads. The peak-cooling load was about 40 kW, while the peak heating load approached 60 kW, but only for short periods of the cold months, namely January, February, November and December.

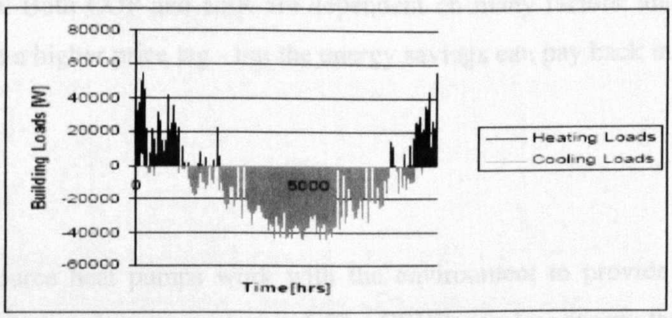


Figure 4.12 Annual hourly building heating and cooling loads

During the summer, the system takes heat from indoors and dumps it back into ground. Annual air temperature, moisture content, soil type and vegetative cover (i.e., trees and plants) have an effect on ground soil temperature. Figure 4.13 shows the monthly variation of the ground and the ambient temperatures.

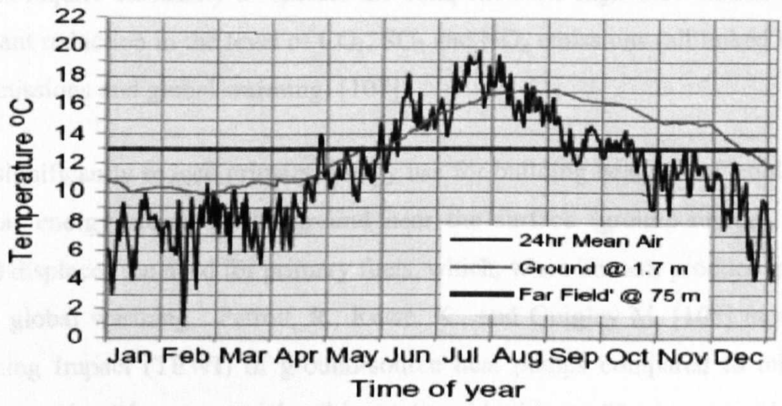


Figure 4.13 Air and ground temperatures

In general, energy efficiency is calculated as the "useful work" or "energy delivered" divided by the amount of energy supplied to do that work. With heat pumps, energy efficiency is measured in two different ways, namely heating and cooling efficiency [108].

Heating efficiency is expressed as a Coefficient of Performance (COP). The higher the COP, the more efficient is the system. For example, a residential-sized geothermal system might have a COP of 3.4 or higher, meaning for every one unit of energy used to power the system, more than three units are put back into the home as heat. This compares to efficiencies of 0.92 for a high-efficiency natural gas furnace.

Cooling efficiency is measured as an Energy Efficiency Ratio (EER). The higher the EER, the more efficient is the system. Both COP and EER are dependent on many factors, and that high-efficiency equipment comes with a higher price tag - but the energy savings can pay back in the difference in just a few years.

4.8 Loops benefits

Geothermal/ground source heat pumps work with the environment to provide clean, efficient, and energy saving heating and cooling the year round. The GSHPs use less energy than alternative heating and cooling systems, helping to conserve natural resources. Additionally, ground source heat pumps are housed entirely within the building and underground. Hence, they are quiet, pollution free and do not detract from the surrounding landscape. Governments and energy planners prefer Earth Energy, EE, technology because it is an environmentally benign technology, with no emissions or harmful exhaust. The EE industry was the first to move away from damaging chlorofluorocarbons (CFCs). Although EE units require electricity to operate the components, a high COP means that EE systems provide a significant reduction in the level of CO_2, SO_2 and NO_x emissions (all linked with the issue of greenhouse gas emissions and global warming) [107].

Heat pumps can significantly reduce primary energy use for building heating and cooling. by utilising renewable or solar energy stored in the ground near the surface (ground-source). The renewable component (66%) displaces the need for primary fuels, which, when burned, produce greenhouse gases and contribute to global warming. Petrov, R., Rowe, K., and Quigley M. [108] modelled the Total Equivalent Warming Impact (TEWI) of ground-source heat pumps compared to other heating and cooling systems in residential, commercial and institutional buildings. The impact of heating only was examined in residential buildings, whereas both heating and cooling impacts were examined in commercial and institutional buildings. The modelling results showed significant emission reductions.

Additionally, the environmental protection agency claims that residential fossil fuel heating systems for the models they studied produced anywhere from 1.2 to 36 times the equivalent CO_2 emissions of the ground-source heat pumps. CO_2 emission reductions from 15% to 77% were achieved through the use of ground-source heat pumps [108]. The GSHP equipment is widely available throughout Europe. The equipment is competitive on a life cycle cost basis with other systems, particularly in those markets where air-conditioning is desired. And, indeed, there is unlikely to be any larger mitigating effect on greenhouse gas emissions (and the resulting global warming) impact of buildings from any other current, market-available single technology, than from ground-source heat pumps.

4.9 Advantages/disadvantages of ground loops

The following considerations are summarises regarding economic of ground loops:

4.9.1 Cost

Earth energy technology may be more expensive to install than some natural gas, oil or electric heating units, but they are very competitive with any type of combination heating/cooling system. For this reason, heat pumps are most attractive for applications requiring both heating and cooling. An open-loop water-source system for an average residence may cost £10,000, while a closed-loop ground-source system may cost as much as £20,000. However, annual operating costs would be as low as £850 compared to £2,000 or more for conventional heating/cooling systems [108]. The savings available with an EE heat pump will reflect the size of the building, its heat loss and level of insulation, as well as the sizing of the EE unit, its balance point, its COP, local climate and energy costs, lifestyle habits, the efficiency of alternate heating systems, configuration of loop, interior temperature setting, ductwork (on retrofits), site accessibility for equipment, and the options selected.

4.9.2 Customers benefits

Geothermal/ground source heat pumps offer customers a heating, cooling, and hot water system that are cost saving, reliable, efficient, and environmentally sound. The unique flexibility of the GSHPs allows them to be used for residential and commercial buildings all across the United States, Canada, and Europe. The GSHP systems can be installed in new buildings and as retrofits in older buildings.

4.9.3 Utilities

Geothermal/ground source heat pumps are a proven and highly efficient technology. The GSHP systems help electric utilities stabilise demand loads and become more competitive with other energy sources. They are fast becoming the most reliable and competitive heating systems available.

4.10 The Future

Energy prices have increased significantly since the second half of 1999. Plans already drafted at the end of the 1990s, but partly delayed, by Indonesia, Philippines and Mexico aim at an additional 2,000 MW_e before 2010. In the direct use sector, China has the most ambitious target: substitution of 13 million tons of polluting coal by geothermal energy [108]. The short to medium term future of geothermal energy is encouraging, providing some hurdles that have recently slowed its growth are overcome. Among them are the Far Eastern economic crisis (especially in Indonesia and Philippines, which had ambitious development plans); the strong production decline at the Geysers field in USA and the extended period of low energy prices. However, actions are being taken to improve the situation where possible. At the Geysers, for example, an effluent pipeline (to be completed by 2020) is under construction from the town of Santa Rosa in order to inject back into the reservoir as much wastewater as is being produced, thus increasing the field potential [109].

Improved use of hydrothermal resources, limitation of front-end costs and increased ground heat extraction are the keys to a steady development of conventional geothermal energy. Installation of a large number of binary power plants will increase electricity production from wide geographical areas underlain by medium-temperature resources. A good example is the Altheim plant just inaugurated in

Austria, which has added power production to district heating with 106°C water. Therefore, heat readily available in spaces can be optimised by adding compatible uses. Additionally, new horizons for geothermal energy can be opened up with fresh applications, for example drinking water production on islands and in coastal areas with scarce resources. Finally, the GSHP systems can also be replicated in many parts of the world.

4.11 Conclusions

A geothermal heat pump can transfer heat stored in the earth into a building during the winter, and transfer heat out of the building during the summer. Furthermore, special geological conditions, such as hot springs, are not needed for successful application of geothermal heat pumps. The GSHPs are receiving increasing interest because of their potential to reduce primary energy consumption and thus reduce emissions of the GHGs. The GSHP is generally recognised to be one of the most outstanding technologies of heating and cooling in both residential and commercial buildings, because it provides high coefficient of performance (COP), up to 3-4 for an indirect heating system and 3.5-5 for a direct heating system. The main benefit of using the GSHPs is that the temperature of the subsurface is not subject to large variations experienced by air. It is currently the most common thermal energy source for the heat pumps, and so would allow construction of more efficient systems with superior performance. The GSHPs do not need large cooling towers and their running costs are lower than conventional heating and air conditioning systems. As a result, the GSHPs have increasingly been used for building heating and cooling with annual rate of increase of 10% in recent years.

5.0 Description of the heat pump components

5.1 Introduction

This chapter discusses various types of heat exchanger designs, features, sizing, and the characteristics of heat pump system tested. It also, looks in more detail at the applications of the technology, distribution systems, and the thermal performance of heat pumps.

The earth's surface acts as a huge solar collector, absorbing radiation from the sun. In the UK, the ground temperature is nearly constant around 11-13°C at 3 metres below the surface all the year round [110]. Among many other alternative energy resources and new potential technologies, the ground source heat pumps (GSHPs) are receiving increasing interest because of their potential to reduce primary energy consumption and thus reduce emissions of greenhouse gases [111].

Direct expansion GSHPs are well suited to space heating and cooling and can produce significant reduction in carbon emissions (Figure 5.1). In the vast majority of systems, space cooling has not been normally considered, and this leaves ground-source heat pumps with some economic constraints, as they are not fully utilised throughout the year. The tools that are currently available for design of a GSHP system require the use of key site-specific parameters such as temperature gradient and the thermal and geotechnical properties of the local area. A main core with several channels will be able to handle heating and cooling simultaneously, provided that the channels to some extent are thermally insulated and can be operated independently as single units, but at the same time function as integral parts of the entire core. Loading of the core is done by diverting warm and cold air from the heat pump through the core during periods of excess capacity compared to the current needs of the building [110-111]. The cold section of the core can also be loaded directly with air during the night, especially in spring and fall when nighttimes are cooler and daytimes are warmer. The shapes and numbers of the internal channels and the optimum configuration will obviously depend on the operating characteristics of each installation. Efficiency of a GSHP system is generally much greater than that of the conventional air-source heat pump systems. Higher COP (coefficient of performance) is achieved by a GSHP because the source/sink earth temperature is relatively constant compared to air temperatures. Additionally, heat is absorbed and rejected through water, which is a more desirable heat transfer medium due to its relatively high heat capacity. The GSHPs in some homes also provide: Radiant floor heating, heating tubes in roads or footbaths to melt snow in the winter, hot water for outside hot tubs and energy to heat hot water.

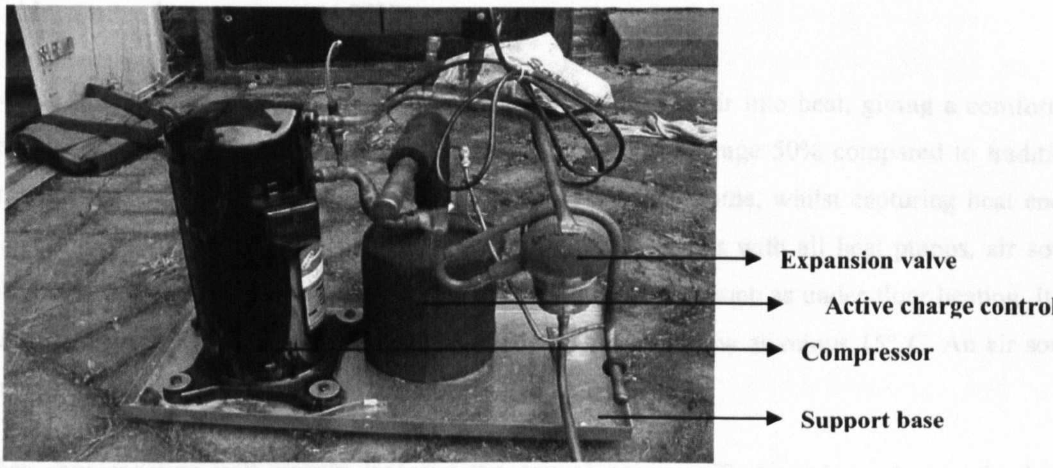


Figure 5.1 A photograph showing the connection of GSHP installed at the School of Built Environment

The GSHP is called such, because it pumps heat. Through the use of a simple, yet tried and tested refrigeration system, it pumps heat from the warm earth in the winter and places it in homes or businesses. In the summertime the process is reversed. Since it costs far less to move heat than to make it, much less energy is consumed. This results in huge reductions in energy costs and greatly reduces the environmental impact of space conditioning. For closed loop systems, water or an antifreeze solution is circulated through plastic pipes buried beneath the earth's surface. During the winter the fluid collects heat from the earth and carries it through the system and into the building. During the summer the system reverses itself to cool the building by pulling heat from the building, carrying it through the system and placing it in the ground. Open systems operate on the same principle as closed loop systems and can be installed where an adequate supply of suitable water is available and open discharge is feasible. Benefits similar to the closed loop system are realised: requires less mechanical room space, requires less outdoor equipment, does not require roof penetrations, maintenance decks or architectural blends, quiet operation, and reduces operation and maintenance costs.

Limitations: requires surface area for heat exchanger field, higher initial cost, requires additional site co-ordination/supervision, and higher design cost.

5.2 Heat pump types

There are various types of ground source heat pumps

5.2.1 Air source heat pumps (ASHP)

Air source heat pumps convert the energy created by the outside air into heat, giving a comfortable temperature inside the home and reducing heating costs by on average 50% compared to traditional systems. Exhaust air heat pumps provide hygienic air inside the home, whilst capturing heat energy from lighting, people and domestic appliances, and recycling it. As with all heat pumps, air source models are most efficient when supplying low temperature systems such as under-floor heating. It can extract heat from the air even when the outside temperature is as low as minus 15° C. An air source heat pump system is compact, and requires no storage space for fuel.

Weather compensation will greatly improve the annual energy efficiency by reducing the heated temperature to the minimum required, dependent on outside temperature. Most heat pumps incorporate this in the controller; however, this facility can be retrofitted if necessary. To keep energy efficiency high, the heated water temperature should be kept as low as possible, and some zone valves fully open and control the temperature down by carefully adjusting the weather compensation controller. If there is no weather compensation controller installed, the water temperature should be kept as low as possible so that adequate heating is attained. If domestic hot water is provided by the heat pump, then a larger than normal cylindrical water storage tank is needed so that the water can be stored at a slightly lower temperature. "Thermal store" type systems should be avoided, as they require temperatures higher than heat pumps can efficiently provide. Heat pump compressors should be low maintenance and reliable as they are likely to run for long periods; stop-starts should be minimised. The use of buffer tanks, correctly set thermostat differentials and correctly positioned cylinder sensors will all help to maximise run periods.

5.2.2 Ground source heat pumps (GSHP)

The GSHPs take heat from the ground rather than the outdoor air. In winter, the ground is usually warmer than ambient air temperature. There is more heat available from the ground to pump into the house, reducing the need for auxiliary heat. So, a GSHP may be significantly less expensive to operate over the course of the year. In cold climates where winter air temperatures are too low for air-source heat pumps to be effective, GSHPs may be the most practical heat pump application. A properly installed GSHP may last longer than an air-source heat pump. It causes less wear on the compressor because it operates over a narrower range of temperatures, following more uniform ground temperatures throughout the year. Furthermore, the GSHP does not need defrosting, resulting in improved operating efficiency. There are, however, three main disadvantages:

The first is the initial cost. The GSHPs typically cost more to install than air-source heat pumps. Unless one has a large house with a large heating load, the energy savings might not offset the additional installation cost during the lifetime of the heat pump.

The second disadvantage is that it is difficult to find a qualified installer in the area and there may be a long wait when the system emergency service is needed. There are few installers because most installations require unique designs. For example, sites must be carefully evaluated for soil temperatures, moisture levels and heat conductivity. This is important, as the system must be designed to keep the soil near the house from freezing when the heat pump extracts heat from the ground.

The third disadvantage is that installation requires some excavation or drilling. Some systems require extensive trenching and expensive landscape repairs. Others are installed with a drill in a fairly stationary location, causing less damage. Additionally, it can be expensive if the underground piping requires repair, and the landscaping options may be reduced.

A basic description of the component parts of the heat pump is given below:

- A heat pump packaged unit: DX GSHP type (approximate the size of a small fridge).
- The heat source, which is usually a closed loop of copper pipe, contains a glycol antifreeze solution. This pipe is buried in the ground in vertical boreholes or horizontal trenches. The trenches take either straight pipe or coiled (Slinky) pipe, buried about 1.5 to 2m below the surface. A large area is needed for this.
- The heat distribution system: This is either underfloor heating pipes or conventional radiators of large area connected via normal water pipes.
- Electrical input and controls: The system will be require an electrical input energy, three-phase being preferred, but single phase is perfectly adequate for smaller systems. A specialised controller is required to provide temperature and timing functions of the system.

This type of installation offers many advantages:

- The ground source heat pump unit is a sealed and reliable self-contained unit.
- There are no corrosion or degradation issues with buried copper pipes.
- The system will continue to provide the same output even during extremely cold spells.
- The installation is fairly invisible, i.e., no tanks or outside unit to see, and no regular maintenance is required.

5.2.3 Water source heat pump (WSHP)

Water-source heat pumps use a body of water for their heat source. They typically use well water, but sometimes they use lakes or streams. Water source heat pumps - particularly those using well water - have the same advantages as GSHPs. The water they use is usually warmer than winter air and temperatures are more stable. Water-source heat pumps also share a disadvantage with GSHPs - they are more expensive to install than air-source systems (unless an existing well can be used), and may not recover this additional expense unless the house has a large heating load. Hence, water source systems should be carefully evaluated in light of the following points.

- If the water-source is a stream or lake, then check if it is legal to use it as a heat source. Some areas have environmental laws that prevent this use of water (or have restrictions that make it more expensive), as the water gets too cold to use in the winter.
- If the water-source is a well, then it should have adequate flow and temperature to meet the heat pump requirements.
- Some localities require disposing the water via the sewer, which can increase the sewer bill. Others may require having a second well to return the water to the aquifer.

The efficiency of the system will be greatly improved if the temperature of the heated water is kept as low as possible. For this reason, underfloor heating is preferred to radiators. It is vital to ensure that the underfloor layout is properly designed to use low water temperatures, i.e., plenty of pipe and high flow-rates. Note that heat pumps have a different design emphasis to boiler systems. Most underfloor systems use zone valves that reduce the flow-rate. To maintain the correct flow-rate through the heat pump, a buffer tank is suggested to achieve that. If radiators are to be used, they must be large enough. Double the normal sizing (as used with a boiler) is a good starting point. Whilst this type of heat pump installation could provide all the heating needs, it is common practice, and often economical, to have a back-up boiler linked to the system to cope with the very cold periods. Electric back up is not ideal as it puts a high load on the mains supply at a time of peak demand, when the power station's net fuel efficiency is already low. Therefore, the ground pipe system must be planned carefully, especially as it will be there for well over 20 years. Any mistakes may be too difficult or costly to rectify later on. The highest energy efficiency will result from systems that do not go below freezing point. Accordingly, the bigger the pipe system to ground area, the better the system will be. However, this is costly and gives diminishing returns. Also, the pressure drop in the pipes should be compatible with standard low-head pumps.

5.3 Heat pump features

The heat pumps have the following features:

5.3.1 Supplemental heat lockout

Outdoor thermostats sense the outdoor temperature and lock out the use of secondary heating devices (supplemental heat) unless the temperature drops below a preset point (except when the heat pump is not working and needs emergency heat). The advantage of this strategy is that it is a positive lockout that will not be defeated by "thermostat fiddlers".

5.3.2 Smart thermostats

Smart thermostats (microprocessor controlled) sense only the indoor temperature. They will not turn on supplemental heat unless the heat pump is unable to keep the house at the desired temperature. The advantage of this strategy is that it is tied to indoor comfort. There is considerable debate about which is the better strategy. But either one is clearly better than no lockout at all.

5.3.3 Staged supplemental heat

Most heat pumps have controls that cause all of the supplemental heat to be on at the same time. However, there are important benefits to staging supplemental heat. Staging refers to turning the supplemental heat on in two or more stages. The first stage comes on in mild temperatures just below the heat pump balance point. If the temperature falls below a point that the first stage is not enough, the second stage provides more heat. There are two important benefits of staging supplemental heat. First, more comfortable and second, it benefits utility ratepayers. One of the major costs of operating an electric utility is the cost of "peak" power as defined by a high point of electrical customer demands. This peak occurs during the winter when lots of heating systems need power. By staging the backup heat, the utility's peak is likely to be lower, reducing utility operating costs. These savings are particularly important when they can help to avoid the cost of expensive new electrical generating facilities. Depending on the control system, staging supplemental heat may reduce the on/off cycles of the heat pump. Reduced cycling can increase the longevity of the heat pump. Staging supplemental heat increases the comfort of a heat pump. As it gets colder outside the refrigeration components produce less heat, so then, when the supplemental heat is not on, the temperature of the air coming out of the registers gets lower as it gets colder outside. The supplemental heat adds more heat to the air, making it more comfortable. If all supplemental heat comes on at once, it may run only for a short time. The delivered air temperature drops as soon as it goes off. When only one stage of supplemental heat comes on, it stays on longer. Staged supplemental heat provides higher temperature air for longer periods of time, so the house will be more comfortable during winter cold spells.

5.3.4 Defrost control

There are many types of defrost controls. They can be grouped into two categories. First, time and temperature and, second, demand. Time and temperature controls turn on the defrost cycle at specified intervals whenever the outdoor temperature reaches a predetermined point. It is assumed that below a certain outdoor temperature there will be frequent frost formation and defrost will be necessary. Unfortunately this can result in unnecessary defrost cycles, which waste energy. There may not actually be frost during the times specified. Demand controls actually detect the presence of frost on the outdoor coils. When the controls sense frost, they initiate the defrost cycle. When the frost is melted, the defrost cycle is terminated. Since the defrost cycle is only used when needed, this is much more efficient and reduces heating costs.

5.3.5 Emergency heat indicator

"Emergency heat" comes on when the heat pump breaks down. Auxiliary heat provides all the heat to the house. A break down could be caused by a mechanical failure or by the operation of the safety switches. Since the house will still be warm when emergency heat is on, occupants may not realise that the heat pump is not working. The emergency electric heat is more expensive to operate than the heat pump. Many thermostats come with a light that turns on when the emergency heat is on, indicating that the heat pump is not working when it should. This is a highly desirable feature as it serves as a reminder that the heat pump needs attention.

The terms "emergency heat," "auxiliary heat" and "supplemental heat" are often used interchangeably, since they all refer to the heating unit(s) that add to, or take over from, the heat pump when needed. Manufacturers are understandably reluctant to put a light called "emergency heat" on their equipment, so the emergency heat indicator may have a different name. Nevertheless, a thermostat with an emergency heat light should be specified, even if it goes by a different name. A supplemental heat indicator, called "auxiliary heat" indicator on some thermostats, tells when the supplemental heat is on. Unlike emergency heat, supplemental heat is a normal occurrence. The heat pump keeps working while the supplemental heat is on.

5.3.6 Safety switches

To prevent compressor damage, a heat pump should have pressure sensors that indicate either excessively high or dangerously low refrigerant pressures. If either condition occurs, the heat pump should automatically shut down, and switch on the emergency heat if needed. These adverse conditions are often accompanied by high temperature. Accordingly, those in the heat pump business often call these pressure/temperature switches.

5.3.7 Accumulator

Heat pump compressors are designed to compress gases, not liquids. Liquids are much more difficult to compress than gases. If liquid refrigerant enters the compressor, it may damage the compressor. Since compressors are very expensive to replace, heat pumps should be protected with an accumulator. The accumulator traps liquid refrigerant to prevent it from entering the compressor. However, scroll compressors are the exception to this rule as they can handle some liquid refrigerant without being damaged, so they do not require an accumulator.

5.3.8 Filter/drier

The filter/drier does two things: It filters the refrigerant to remove dirt and other impurities that can cause damage to the compressor and other heat pump parts. Also, it removes moisture from the refrigerant. Moisture can cause a variety of problems, so it is important to remove it from the system quickly.

5.3.9 Crankcase heater

When the heat pump is off during cold weather, liquid refrigerant can migrate to the compressor crankcase, reducing lubrication effectiveness. When the heat pump comes on, the refrigerant evaporates rapidly. However, foam forms in the oil preventing adequate lubrication of the compressor and shorten its life. The compressor should be equipped with a crankcase heater, which prevents the refrigerant from liquefying in the oil. Most crankcase heaters are on at all times. Some are designed to operate only when needed. Again, the scroll compressor is the exception, as it does not require a crankcase heater to operate safely.

5.3.10 Salt air models

The outdoor unit may have a shorter life in coastal locations where salt air corrosion is a problem. Consequently, some companies manufacture outdoor units designed and built to resist salt air corrosion.

5.4 Types of heat pump technologies

Characteristics of two types of heat pumps are summarised below:

5.4.1 Variable speed heat pumps

A long awaited heat pump has just come on the market (Appendixes 3.1-3.3). It is called a "variable speed" heat pump because it adjusts its output to match the heating or cooling requirement of the home. This allows the heat pump to run continuously rather than starting and stopping frequently during mild weather. This is more efficient and reduces wear. It can also improve comfort since the fan speed is matched to the heat output, reducing drafts when the output is low.

5.4.2 Scroll compressor

Another recent development is a new type of compressor called a "scroll compressor". It has a rotary motion that reduces noise more than any other rotary compressors, due to its unique design. It has a higher efficiency at lower temperatures than reciprocating compressors for better seasonal heating performance. It also tolerates small amounts of liquid refrigerant, so it does not require an accumulator or crankcase heater.

5.5 Proper sizing and installation

It is difficult for the consumer to verify that the contractor properly sizes and installs the system, and they should at least let the contractor know the expected criteria to be met. If it is in a utility-sponsored heat pump programme, the utility may help ensure the system meets these criteria.

5.5.1 Heat pump sizing

There are three reasons that a heat pump should be properly sized for the house, cost, durability and efficiency.

Cost: Large equipment is more expensive. If the system is too large, too much money will be spent on it. On the other hand, if the heat pump is undersized for heating, supplemental heat will operate too often, increasing the electric bill.
Durability: Most wear and tear on a compressor occurs when it starts up. Oversized equipment will cycle on and off more often than accurately sized systems.
Efficiency: Oversized systems have shorter "on" times, which means a greater portion of "on" time is spent getting started, an inefficient part of the heat pump cycle.

5.5.2 Load calculations

The only way to properly size a heat pump is to do heating and cooling load calculations and then match the equipment to the calculated loads. These load calculations should take the following into account:

- The dimensions of the floors, basement walls, above ground walls, windows, doors and ceilings.
- The energy efficiency of these components (insulation, window types, air tightness, etc.).
- Local weather: Loads should be calculated for a cold winter day (but not the coldest on record) and a hot summer day (but not the hottest on record). The local electric utility may be able to recommend appropriate design temperatures.

If the heat pump is for heating use only, then only heat load calculations are needed. If the plan is to do both heating and cooling, both heating and cooling load calculations are needed. It is important to properly calculate the heating and cooling loads and not to guess for the reasons explained in the previous section (Heat pump sizing).

5.5.2.1 Load calculation methods

There are several widely accepted methods of calculating heating and cooling loads. The most popular are based on methods and data developed by the American Society of Heating, Refrigerating and Air conditioning Engineers (ASHRAE). One of the best is called Manual Journal: Load Calculation developed by the Air Conditioning Contractors of America (ACCA). Manufacturers often simplify ASHRAE and ACCA methods so that the process can be speeded up. Most major manufacturers provide forms that help contractors' size their heating equipment. If the forms are based on ASHRAE or Manual Journal, the contractor will probably do a good job of estimating the sizing requirements.

5.5.2.2 Room-by-room load calculations

Load calculations should be done for each "room" in the house, because each room has its own heating and cooling requirement. It's the only way contractors know how much heating or cooling to deliver to each room. Otherwise, they can only guess at duct sizes, and deliver incorrect amounts of heating or cooling. Areas that are open to each other are treated as one "room". For example, one "room" could include kitchen, family and dining areas.

5.5.2.3 Sizing for heating and cooling

In most homes, heat pumps provide both heating and cooling (Appendixes 3.5-3.6). Proper sizing requires calculating both heating and cooling loads as explained above. A heat pump that matches both loads as closely as possible should be chosen.

First, choose equipment that meets the cooling needs of the house. Then check the heat output of the equipment against the heating requirement "Choosing the best size for heating". If the heat output is too small, larger equipment can be chosen as long as it does not oversize the cooling load by more than 25 percent (some utility financing programmes allow 50 percent over-sizing). When sizing for cooling, both sensible and latent cooling loads should be considered. Sensible cooling is most important, and it is the type of cooling people is familiar with - simply reducing the air temperature. Latent cooling is reducing the humidity so that occupants can be comfortable at the temperature they choose for indoor living. Since European summers are typically not humid, latent load is not as important. However, in general, equipment should be chosen to meet sensible plus latent loads. If the equipment matching the heating requirement is not available without over-sizing for cooling, then one of the following strategies may need to be considered: (1) Upgrade the insulation and windows and reduce the air leakage from the house to reduce the winter heating requirement; or (2) Choose a unit that is undersized for heating, realising that the supplemental heat will operate more than optimal, hence, reducing the potential savings.

5.5.2.4 Choosing the best size

Assume that the ideal heating unit in the climate has a typical balance point near -1.2°C. There is a range of 3 to 5 degrees on either side. Two heat pumps in the graph are close enough. The smaller heat pump has a balance point of 0 °C, and the larger one, -2.7 °C.

Figure 5.2 shows the relationship between the heating requirement of the house and the heat output of four hypothetical heat pumps. The four heat pumps are different sizes (they have different heat outputs), so the balance point occurs at different outdoor temperatures for each. This graph can help to choose the best heat pump for heating. None of the units give the exact balance point and the cooling load should be checked to see which one is acceptable. If the larger unit is outside the boundary of 125-150 percent of the cooling load, then the smaller unit would be chosen. If both were in the acceptable range for cooling, the larger unit would be chosen for increased heating economy.

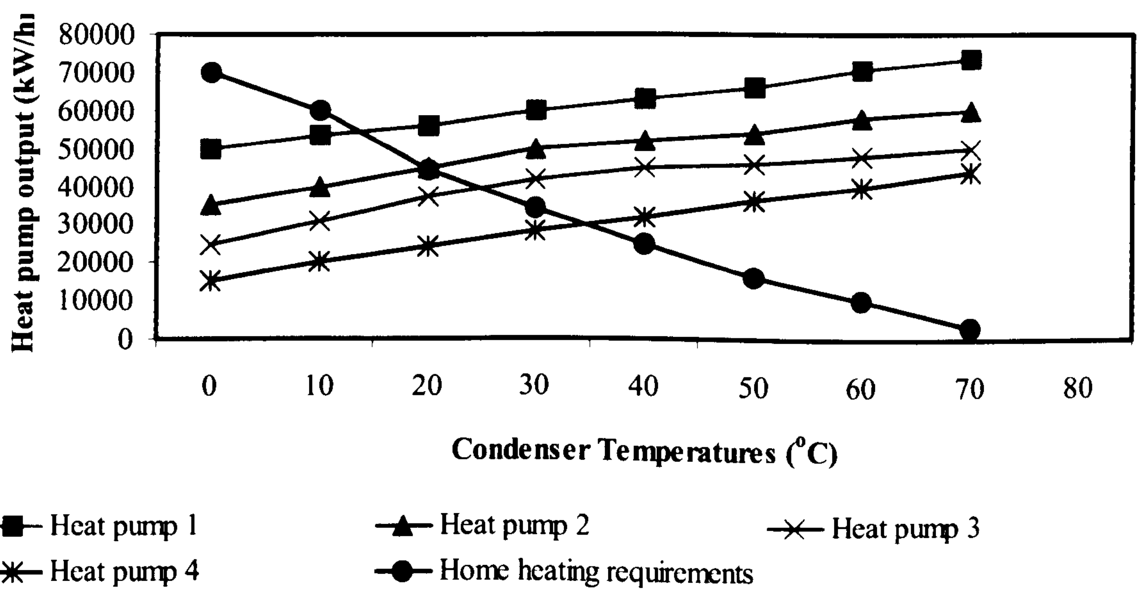


Figure 5.2 The relationship between the heating requirement of the house and the heat output of four hypothetical heat pumps

5.6 The duct systems

The issues relating to the duct systems are summarised below:

5.6.1 Duct sizing

One of the most important aspects of proper installation is to ensure that the ductwork can deliver adequate airflows to maintain comfort in the house. But even more importantly, the airflow needs to be adequate to prevent damage to the heat pump. Airflow must meet the manufacturer's specifications. Otherwise the refrigerant will not be able to get rid of excess heat. If the refrigerant gets too hot, its pressure may exceed the limits of the compressor and cause it to fail. Replacing a compressor is expensive; it costs more than the added cost of properly designing and installing the duct system.

5.6.2 Return air system

Most customers are aware of the warm air supply outlets because they deliver warm air to the house. And it is easy to figure out that there are usually ducts that connect the heat pump to those outlets. However, it is easy to overlook the return side of the system - the ducts and grills that carry air back to the heat pump. In fact, the return airside is often installed as though it's an afterthought [111]. Ideally, there is a return grill and duct in each room where there is a warm air supply. That is usually expensive, but it is worthwhile to get as many returns as practical. At a minimum, there should be one for the main living areas and one for the bedrooms. It is also worth considering separate returns for large living rooms and master bedrooms. A good return air system can help reduce differences in pressure throughout the house, reduce drafts and improve comfort.

5.6.3 Terminals

Terminals are the registers, vents and grills at the ends of the ducts that deliver air to rooms or return air to the heat pump. Terminals should distribute conditioned air properly in each room of the house. The room-by-room heat load calculations mentioned earlier tell the contractor how much airflow each room needs. An important consideration for selecting terminals is the air velocity going through them. In general, larger terminals produce slower velocities. If the velocity is too high, terminals will be noisy and cause drafts. Supply registers and vents should have a velocity of less than 250 mpm and the correct "throw" (distance the air is projected from the terminal, usually about three metres). Return grills should have a velocity of 130 mpm or less. Again, note that consumers probably will not be able to verify that these criteria were met. The best design is to deliver air from the floor parallel to an outside wall.

5.6.4 Dampers

Adjustable duct dampers must be installed so airflow can be set for each room, according to the room-by-room heat load calculations. After the system is installed, the heating contractor should "balance" the system by adjusting each damper for correct air flows. These dampers are usually found in branch ducts near where they take off from the main duct. Once the dampers have been adjusted to balance the system, they are usually not moved unless the system is modified.

5.6.5 Duct air sealing

Air leakage from ducts is typically one of the main sources of heat loss in the house. Ducts should be sealed at joints between sections, along seams in individual duct sections, and where ducts penetrate from unheated to heated areas. Ducts are typically sealed with duct tape. Aluminum tape is more durable than cloth varieties. The energy savings are worth the expense. Sealing is also important for comfort; one may not be comfortable if warm air leaks out of the duct before it gets to the room. Also, eliminating duct leaks is critical for heat pump system efficiency.

5.6.6 Duct insulation

Ducts passing through unheated areas such as garages, crawl spaces and attics should be insulated. Northwest regional conservation standards require sheet metal ducts to be insulated with R-11 insulation and insulated flex duct with two layers of R-4 or one layer of R-11 insulation [112].

5.6.7 Flexible duct

Some contractors use flexible ducts with insulation already built in. Because flexible ducts can be installed by less experienced trades' people than required by sheet metal ones, there is some concern that flexible ducts encourage poor installation practices. However, flexible ducts should be installed according to the following guidelines.

1. Use R-11 or "double wrap" ducts (two layers of R-4).
2. Make connections between sheet metal and flexible ducts with metal or nylon clamps.
3. Seal connections (aluminium duct tape) between flexible and sheet metal ducts.
4. Support flexible ducts so they do not sag (restricting air flow) using supports at least 2.5 cm wide, and stretch duct to its full length so air passages are as smooth as possible.

5.7 The outdoor unit

The outdoor units may require the followings.

5.7.1 Outdoor unit installation

The outdoor portion of the heat pump should be installed on a concrete pad (unless the manufacturer specifies other support), separate from the house foundation. Some units are elevated on legs so air can flow under the unit. In cold climates, the legs should be tall enough so that snow will not block the airflow. The unit should be far enough out from the eaves so snow falling from the roof will not land on it. If possible, someone needs to place the unit so that it is sheltered from prevailing winter winds, and the shrubs do not block airflow.

5.7.2 Outdoor unit location

The outdoor unit should be located where its noise will not bother the neighbours. Likewise, make sure that it is not located under bedroom windows. If it is difficult to find a good location, then one may need a heat pump with special sound reduction features. The outdoor unit should be located to minimise the length of the copper refrigerant lines that connect the indoor and outdoor units.

5.7.3 Refrigerant lines

The lines should be reasonably straight. Any excess lines that need to be coiled should be coiled horizontally so as not to form an oil trap. Also, vertical coils may prevent lubricant from returning to the compressor. However, refrigerant lines should be insulated; to reduce unwanted heat loss and heat gain in order to save energy.

5.7.4 Condensate drain

When the heat pump is in its summer cooling mode, water from air inside the house often condenses on the indoor coil. This water must be drained from the house (but not into the crawl space). Locating the drain where it will work by gravity alone may sometimes be difficult or even impossible. Some systems require condensate pumps.

5.8 Heat distribution system

The heat pump works by promoting the evaporation and condensation of a refrigerant to move heat from one place to another. A heat exchanger transfers heat from the water/antifreeze mixture in the ground loop to heat and evaporate refrigerants, changing them to a gaseous state (Appendix 3.6). A compressor is then used to increase the pressure and raise the temperature at which the refrigerant condenses. This temperature is increased to approximately 40^{o}C. A condenser gives up heat to a hot water tank, which then feeds the distribution system. Lengths of plastic pipe are buried in the ground, either in a borehole or a horizontal trench. The pipe is a closed loop, which is filled with a water/antifreeze mixture. This mixture circulates in the pipe, absorbing heat from the ground.

Horizontal trenches are dug to a depth of 1-2 metres and can cost less than boreholes, but require a greater area of land. Placing coiled piping in horizontal trenches will enhance the performance compared with straight piping. A borehole is drilled to a depth of between 15-100 metres and will benefit from higher ground temperatures than the horizontal trench, although installation costs will be greater.

5.8.1 Installation

A trained engineer should carry out the installation of a GSHP. At present, the UK market is small and there is currently no network of accredited installers as with other technologies. Manufacturers and suppliers should also be able to provide trained engineers but geographical limitations may increase installation costs. The cost of a professionally installed GSHP ranges from about £1,200-£1,700 per kW of peak heat output. This includes the cost of the distribution system. Vertical borehole systems would be at the higher end of this scale, due to higher installation costs. A typical 8 kW system would therefore vary between £9,600-£13,600. The costs will vary from property to property. Depending on the size of the system installed, the heat distribution system chosen and the resulting coefficient of performance (COP). However, GSHPs can generally be a cheaper form of space heating than oil, LPG or electric storage heaters. It is, however, probably more expensive than natural gas. Nevertheless, the GSHP technology is low in maintenance as systems have very few moving parts. Systems can have an operating life of over 20 years.

5.8.2 Running costs

COP is an indicator of the efficiency of a GSHP system. This is the ratio of the number of units of heat output for each unit of electricity input used to drive the compressor and pump for the ground loop. Typical COPs range between 2.5-4. The higher end of this range is for underfloor heating, because it works at a lower temperature (30-35°C) than radiators. If grid electricity is used for the compressor and pump, then an economy 7 tariff usually gives the lowest running costs [112].

5.8.3 Environmental impacts

The main environmental impact of a GSHP system can be summarised as follows:

(1) Emission of Green House gases:

Significant CO_2 savings can be gained by displacing fossil fuels. Even compared to the most efficient gas or oil condensing boilers. A well-designed heat pump with COP of 3-4 will reduce emissions by

30-35%. Further carbon savings can be made if the electricity used to power the pump comes from a renewable energy source such as photovoltaic or a renewable electricity tariff. Also, measures can be taken to reduce the impact of pollution from using grid electricity generated through fossil fuel. For example, one can purchase dual tariff green electricity from a number of suppliers. However, even if ordinary grid electricity is used to run the compressor, the system will still produce less CO_2 emissions than even the most efficient condensing gas or oil boiler with the same output.

(2) Use of refrigerants in the system:
Refrigerants such as hydrochloroflurocarbons (HCFCs) are used in GSHP systems and can pose a threat to the environment through being toxic, flammable or having a high global warming potential. However, new types and blends of refrigerant with minimal negative impacts are being developed. A correctly fitted system will also greatly reduce the potential for leakage, which is why using a professional installer is highly recommended.

The GSHPs reduce energy use and hence atmospheric emissions. Conventional boilers and their associated emissions are eliminated, since no supplementary form of energy is usually required. Typically, single packaged heat pump units have no field refrigerant connections and thus have significantly lower refrigerant leakage compared to central chiller systems. GSHP units have life spans of 20 years or more and the two-pipes water-loop system typically used, allows for unit placement changes to accommodate new tenants or changes in building use. The plastic piping used in the heat exchanger should last as long as the building itself. When the system is disassembled, attention must be given to the removal and recycling of the Hydrochlorofluorocarbon (HCFC) or Higher heating value HFC refrigerants used in the heat pumps themselves and the anti-freeze solution typically used in the ground heat exchanger.

5.9 Heat pump operation

The GHPs use the relatively constant temperature of the ground or water several feet below the earth's surface as source of heating and cooling. They are appropriate for retrofit or new homes, where both heating and cooling are desired. In addition to heating and cooling, geothermal heat pumps can provide domestic hot water. Furthermore, they can be used for virtually any size home or lot in any region of the world.

A GHP system consists of indoor heat pump equipment, a ground loop, and a flow center to connect the indoor and outdoor equipment. The heat pump equipment works like a reversible refrigerator by removing heat from one location and depositing it in another location. The ground loop, which is invisible after installation, allows the exchange of heat between the earth and the heat pump.

Special heat pump features can include variable speed blowers and multiple-speed compressors. These features can improve comfort and efficiency in areas where heating and cooling loads are quite different. Additional features include the capability to produce hot water. Desuperheaters can be added to supplement the production of domestic hot water when there is a demand for space heating or cooling. These devices make use of excess heat during the cooling cycle and use some of the heat during the heating cycle to supplement hot water production. Dedicated water heaters can be added TO operate whenever there is a demand for hot water.

Unlike conventional boiler/cooling tower type water loop heat pumps, the heat pumps used in GSHP applications are generally designed to operate at lower inlet water temperature. They are also more efficient than conventional heat pumps, with higher COPs. Because there are lower water temperatures in the two-pipes loop, piping needs to be insulated to prevent sweating. In addition, a larger circulation pump is needed because the units are slightly larger in the perimeter zones requiring larger flows.

5.9.1 Factors affecting heat pump performance

The performance of heat pumps is affected by a large number of factors. For heat pumps in buildings these include: (1) The climate - annual heating and cooling demand and maximum peak loads. (2) The temperatures of the heat source and heat distribution system. (3) The auxiliary energy consumption e.g., pumps, and controls. (4) The technical standard of the heat pump. (5) The sizing of the heat pump in relation to the heat demands and the operating characteristics of the heat pump. (6) The heat pump control system.

5.10 Heat pump characteristics

The followings need to be considered to enhance heat pump characteristics:

5.10.1 A constant heat

A heat pump delivers a lower supply air temperature than a furnace over a longer period of time to provide a more constant heat. It may give the impression that the system "never stops running", or "it feels like cold air". At times, the temperature of the air coming out of the vents is less than the body temperature so it feels like cold air. But it is still providing heat for the house. And when it can no longer keep-up with the heat loss of the structure, the second stage or auxiliary heat will automatically energise, bringing on a much warmer heat.

5.10.2 Water run-off

During the heating cycle, one may notice water running off the outdoor coil. Moisture from the air is condensed on the outside surface of the coil where it gathers and runs off. This is normal.

5.10.3 Outdoors coil defrosting

At certain conditions (low temperature, high humidity), frost, even ice, may build up on the coil of the outdoor unit. In order to maintain heating efficiency, the system will automatically defrost itself. Steam rising from the outdoor unit is normal and is an indication of proper operation. The vapour cloud will only last for a few minutes. When the defrost cycle is completed, the system will automatically switch back to heating. Supplemental heat is automatically energised to maintain comfort during defrost. Heat flows naturally from a higher to a lower temperature. Heat pumps, however, are able to force the heat flow in the other direction, using a relatively small amount of high quality drive energy (electricity, fuel, or high temperature waste heat). Thus heat pumps can transfer heat from natural heat sources in the surroundings, such as the air, ground or water, or man-made heat sources such as industrial or domestic waste, to a building or an industrial application. Heat pumps can also be used for cooling. Heat is then transferred in the opposite direction, from the application that is cooled, to surroundings at a higher temperature. Sometimes the excess heat from cooling is used to meet a simultaneous heat demand.

In order to transport heat from a heat source to a heat sink, external energy to drive the heat pump is needed. Theoretically, the total heat delivered by the heat pump is equal to the heat extracted from the heat source, plus the amount of drive energy supplied. Electrically driven heat pumps for heating of buildings typically supply 100 kWh of heat with just 20-40 kWh of electricity. Many industrial heat pumps can achieve even higher performance and supply the same amount of heat with only 3-10 kWh of electricity. But, during the cooling cycle, a heat pump will simply remove heat and humidity from the home and will transfer this heat to the outdoor air. Likewise, during the heating cycle, a heat pump will remove heat and humidity from the outdoor air and will transfer this heat to homes. This is possible because, even at 32 degrees Celsius, outdoors air contains a great deal of heat. The heat pump does not generate much heat; it merely transfers it from one place to another.

5.11 Design, construction and operational issues of GSHPs

The most economical application of GSHPs is in buildings that require significant space and water heating and cooling over extended hours of operation. Examples are retirement communities, multi-family complexes and schools. Building types not well suited to the technology are retail shopping malls, office buildings and other buildings where space and water heating loads are relatively small or where hours of use are limited.

A typical seasonal performance factor for a GSHP system with an electrically driven vapour compression cycle heat pump is 3.0 and high efficiency, heating only heat pumps can give seasonal performance factors of 3.8. The highest seasonal performance factors are for systems with horizontal collectors with direct circulation supplying low temperature heating systems, for which seasonal performance factors often exceed 4.0 and are expected to reach 5.0 in the near future.

Capital cost is higher than for alternative systems, mainly because of the costs associated with the ground coil, but costs are being reduced. For commercial applications, where heating and cooling are provided, the additional cost of the ground, cost can be substantially offset by the elimination of other plant and a reduction in the space needed for plantroom. However, capital costs appear to vary considerably between countries and direct comparisons are difficult. For residential systems, costs appear to be lowest in North America and Sweden, which may be partly due to economies scale. In Britain, there are currently too few installations to permit accurate cost assessment. Average energy savings of over 50% compared with direct electric heating and 33% compared with air source heat pump systems have been found for residential systems in the USA, implying a simple payback of between 3-7 years with respect to direct electric systems. Domestic systems in Scandinavia providing heating only, have similar payback periods. In Switzerland, although capital costs are much higher than in the USA, they are only about 25% higher than the alternative oil fired system and running costs are about 25% lower. Payback periods are longer at between 10 and 12 years, but still well within the lifetime of the system. For commercial systems, studies in the USA and Canada, e.g. [112-113], suggest a simple payback period of less than 3 years when compared with a water loop heat pump system and that maintenance costs will also be reduced. Other benefits include low noise, good aesthetics and good security.

A market study estimated the total worldwide stock of the GSHPs to be approximately 400,000 in 1996 with total annual sales of about 45,000 units [113-114]. The market has been mainly new housing but the number of commercial installations is growing fast. Systems operating in parallel with conventional heating systems are also beginning to be installed in existing houses, which theoretically form the largest potential market. Between 1996 and 1998 the rate of installation in Europe more than doubled but generally the market growth has been slow [114]. In most of the countries, which have a significant market, initiatives to overcome these barriers and encourage the use of ground source heat pumps have been taken. Usually the government has played an active part, with initiatives forming part of a national energy policy. An increasingly important factor is the concern for the environment not only at government level but also, particularly in Switzerland, it appears to influence the choice of heating system for individual house owners [115].

The COP of a heat pump is closely related to the temperature lift, i.e., the difference between the temperature of the heat source and the output temperature of the heat pump. The COP of an ideal heat pump is determined solely by the condensation temperature and the temperature lift (condensation - evaporation temperature). Figure 5.3 shows the COP for an ideal heat pump as a function of temperature lift, where the temperature of the heat source is 0°C. Also shown is the range of actual COPs for various types and sizes of real heat pumps at different temperature lifts.

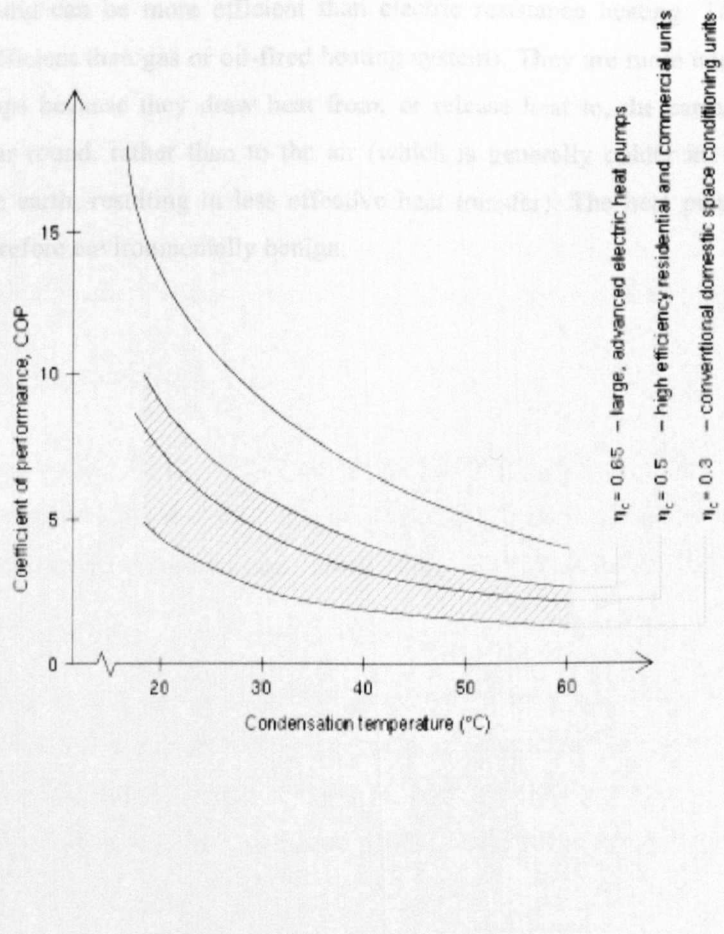


Figure 5.3 COP

5.12 Conclusions

Heat pumps can offer the most energy efficient way to provide heating and cooling in many applications, as they can use renewable heat sources from the surroundings. Even at temperatures considered to be cold, air, ground and water contain useful heat that is continuously replenished by the sun. By applying a little more energy, a heat pump can raise the temperature to the required level. Similarly, heat pumps can also use waste heat sources such as from industrial processes, cooling equipment or ventilation air extracted from buildings. A typical electrical heat pump will just need 100 kWh of power to turn 200 kWh of freely available environmental or waste heat into 300 kWh of useful heat. Because heat pumps consume less primary energy than conventional heating systems, they are an important technology for reducing emissions of gases that harm the environment, such as carbon dioxide (CO_2), sulphur dioxide (SO_2) and nitrogen oxides (NOx). However, the overall environmental impact of electric heat pumps depends also on how the electricity is produced. Heat pumps driven by electricity from, for instance, hydropower or renewable energy reduce emissions more significantly than if the electricity is generated by coal, oil or gas fired power plants.

Geothermal heating can be more efficient than electric resistance heating. These systems are also typically more efficient than gas or oil-fired heating systems. They are more energy efficient than air-source heat pumps because they draw heat from, or release heat to, the earth, which has moderate temperatures year round, rather than to the air (which is generally colder in winter and warmer in summer than the earth, resulting in less effective heat transfer). The heat pumps are highly energy efficient, and therefore environmentally benign.

6.0 Heating and cooling concept

6.1 Introduction

This chapter describes the different methods and techniques for providing energy for heating and cooling systems. It also, covers the optimisation and improvement of the operation conditions of the heat cycles and performance of the GSHPs.

An air-source heat pump is convenient to use and so it is a better method for electric heating. The ambient temperature in winter is comparatively high in most regions, so heat pumps with high efficiency can satisfy their heating requirement [116]. On the other hand, a conventional heat pump is unable to meet the heating requirement in severely cold regions anyway, because its heating capacity decreases rapidly when ambient temperature is below -10°C. According to the weather data in cold regions, the air-source heat pump for heating applications must operate for long times with high efficiency and reliability when ambient temperature is as low as -15°C. Hence, much researches and developments has been conducted to enable heat pumps to operate steadily with high efficiency and reliability in low temperature environments [117]. For example, the burner of a room air conditioner, which uses kerosene, was developed to improve the performance in low outside temperature [118]. Similarly, the packaged heat pump with variable frequency scroll compressor was developed to realise high temperature air supply and high capacity even under the low ambient temperature of –10 to –20°C [119]. Such a heat pump systems can be conveniently used for heating in cold regions. However, the importance of targeting the low capacity range is clear if one has in mind that the air conditioning units below 10 kW cooling account for more than 90% of the total number of units installed in the EU [120].

6.2 Earth-energy systems (EESs)

The earth-energy systems, EESs, have two parts; a circuit of underground piping outside the house, and a heat pump unit inside the house. And unlike the air-source heat pump, where one heat exchanger (and frequently the compressor) is located outside, the entire GSHP unit for the EES is located inside the house.

The outdoor piping system can be either an open system or closed loop. An open system takes advantage of the heat retained in an underground body of water. The water is drawn up through a well directly to the heat exchanger, where its heat is extracted. The water is discharged either to an aboveground body of water, such as a stream or pond, or back to the underground water body through a separate well. Closed-loop systems, on the other hand, collect heat from the ground by means of a continuous loop of piping buried underground. An antifreeze solution (or refrigerant in the case of a DX earth-energy system), which has been chilled by the heat pump's refrigeration system to several degrees colder than the outside soil, circulates through the piping, absorbing heat from the surrounding soil. In some EESs, a heat exchanger, sometimes called a "desuperheater", takes heat from the hot refrigerant after it leaves the compressor. Water from the home's water heater is pumped through a coil ahead of the condenser coil, in order that some of the heat that would have been dissipated at the condenser is used to heat water. Excess heat is always available in the cooling mode, and is also available in the heating mode during mild weather when the heat pump is above the balance point and not working to full capacity. Other EESs heat domestic hot water (DHW) on demand: the whole machine switches to heating DHW when it is required.

Hot water heating is easy with EESs because the compressor is located inside. Because EESs have relatively constant heating capacity, they generally have many more hours of surplus heating capacity than required for space heating. In fact, there are sources of energy all around in the form of stored solar energy, which even if they have a low temperature, can provide the surroundings with enough energy to heat the soil, bedrock and ground water as a heat source for domestic dwellings as shown in Figure 6.1, for example.

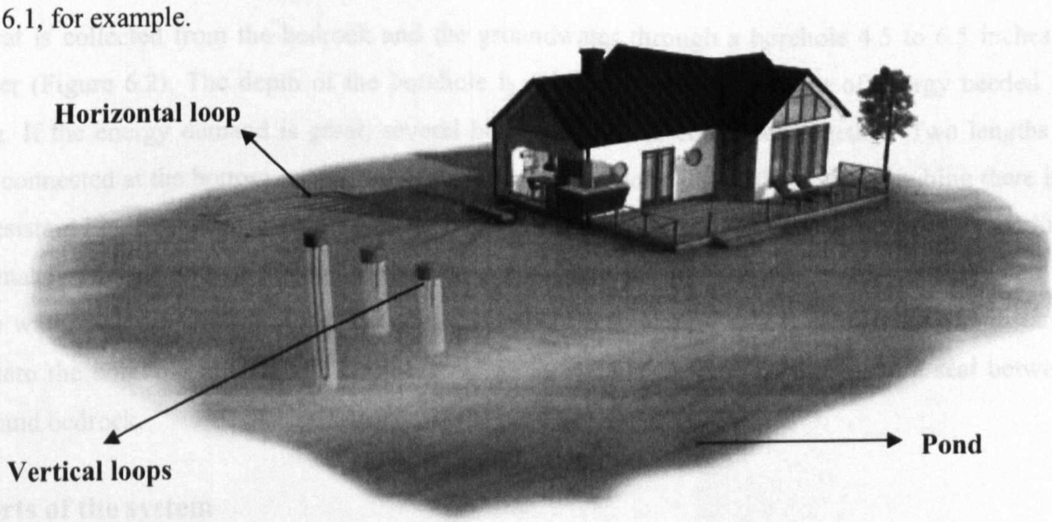


Figure 6.1 Using the soil, bedrock or groundwater as the heat source

6.2.1 Surface soil heat

During the summer, solar heat is stored in the surface layer of the soil. Using that energy for heating is a practical approach for houses with a large plot. The amount of energy that can be extracted is greatest in soils with high water content. The heat is extracted from the soil by means of buried plastic tubing.

An environment-friendly non-freezing liquid circulates in the tubing system and delivers the collected heat to the heat pump. The heat pump converts the heat into high-grade heat for space heating and to produce hot water.

6.2.2 Heat from bedrock

Down in the bedrock there is a source of heat that stays at practically the same temperature all year round. Using heat from the rock is a secure, safe and environment-friendly way of heating all types of building, large and small, public and private. The capital cost is relatively high, but in return one gets a reliable, low-energy form of heating with an extremely long life. The coefficient of performance (COP) is generally good, as high as 4.8. The plant occupies little space and can even be installed on small plots. Very little reinstatement work is needed after drilling the borehole, so the effect on the nearby environment is minimal. The groundwater level is not affected, since no groundwater is used. The heat energy can be transferred to an existing, conventional, water-borne heating system and can also be used to produce hot water.

6.2.2.1 Drilling for energy

The heat is collected from the bedrock and the groundwater through a borehole 4.5 to 6.5 inches in diameter (Figure 6.2). The depth of the borehole is determined by the amount of energy needed for heating. If the energy demand is great, several boreholes can be connected together. Two lengths of tubing connected at the bottom are passed down into the borehole. Inside the collector tubing there is a frost-resistant liquid (cooling medium, brine). The system is completely sealed, so the cooling medium never makes contact with the groundwater. To ensure that the groundwater is not contaminated by surface water running down into the borehole, a steel liner or casing which extends a short distance down into the borehole is installed. Grouting or rubber rings should be used to form a seal between casing and bedrock.

6.3 Parts of the system

As shown in Figure 6.3, earth-energy systems have three main components: the heat pump unit itself, the liquid heat exchange medium (open system or closed loop), and the air delivery system (ductwork) [120]. The GSHPs are designed in different ways. Self-contained units combine the blower, compressor, heat exchanger, and condenser coil in a single cabinet, while split systems allow the coil to be added to a forced-air furnace, and use the existing blower and furnace.

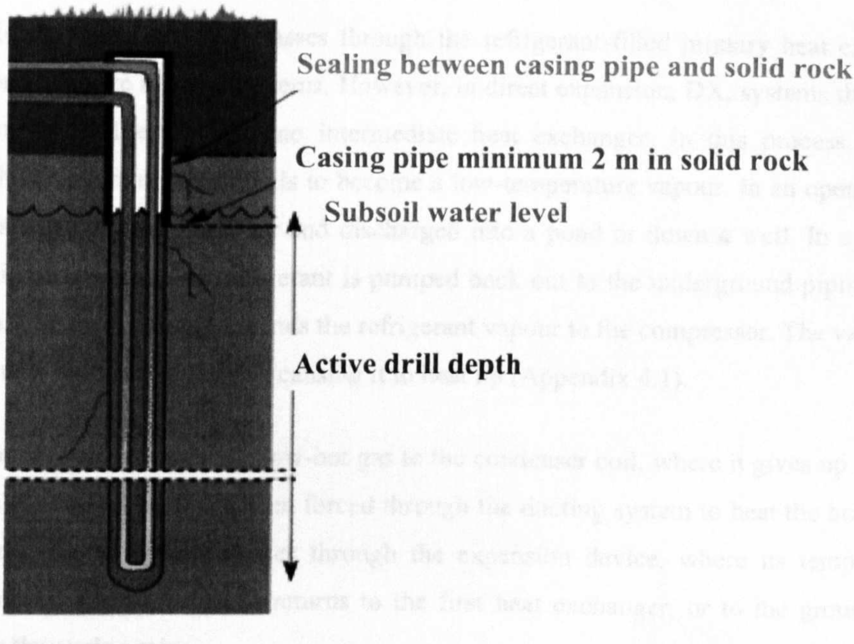


Figure 6.2 Borehole specifications

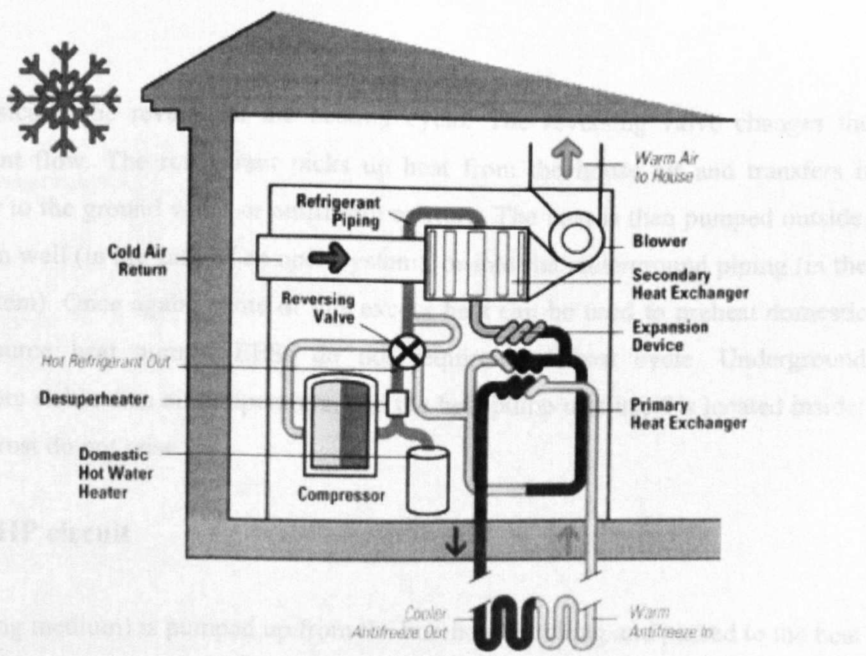


Figure 6.3 Components of a typical GSHP [120]

6.4 The heating cycle

In the heating cycle, the ground water, the antifreeze mixture, or refrigerant, which had circulated through the underground piping system and picked up heat from the soil, are brought back to the heat pump unit inside the house. It then passes through the refrigerant-filled primary heat exchanger for ground water or antifreeze mixture systems. However, in direct expansion, DX, systems the refrigerant enters the compressor directly, with no intermediate heat exchanger. In this process, the heat is transferred to the refrigerant, which boils to become a low-temperature vapour. In an open system, the ground water is then pumped back out and discharged into a pond or down a well. In a closed-loop system, the antifreeze mixture or refrigerant is pumped back out to the underground piping system to be heated again. The reversing valve sends the refrigerant vapour to the compressor. The vapour is then compressed, hence, reduces its volume, causing it to heat up (Appendix 4.1).

Finally, the reversing valve sends the now-hot gas to the condenser coil, where it gives up its heat. Air is blown across the coil, heated, and then forced through the ducting system to heat the home. Having given up its heat, the refrigerant passes through the expansion device, where its temperature and pressure are dropped further before it returns to the first heat exchanger, or to the ground in a DX system, to begin the cycle again.

6.5 The cooling cycle

The cooling cycle is basically the reverse of the heating cycle. The reversing valve changes the direction of the refrigerant flow. The refrigerant picks up heat from the house air and transfers it directly in DX systems or to the ground water or antifreeze mixture. The heat is then pumped outside, into a water body or return well (in the case of an open system), or into the underground piping (in the case of a closed-loop system). Once again, some of this excess heat can be used to preheat domestic hot water. Unlike air-source heat pumps, EESs do not require a defrost cycle. Underground temperatures are much more stable than air temperature, and the heat pump unit itself is located inside; therefore, problems with frost do not arise.

6.6 Function of the GSHP circuit

The collector liquid (cooling medium) is pumped up from the borehole in tubing and passed to the heat pump. Another fluid, a refrigerant, circulates in the heat pump in a closed system with the most important characteristic of having a low boiling point. When the refrigerant reaches the evaporator, which has received energy from the borehole, the refrigerant evaporates. The vapour is fed to a compressor where it is compressed. This results in a high increase in temperature. The warm refrigerant is fed to the condenser, which is positioned in the boiler water. Here the refrigerant gives off its energy to the boiler water, so that its temperature drops and the refrigerant changes state from gas to liquid. The refrigerant then goes via filters to an expansion valve, where the pressure and temperature are further reduced. The refrigerant has now completed its circuit and is once more fed into the evaporator where it is evaporated yet again due to the effect of the energy that the collector has carried from the energy source (Figure 6.4) [120].

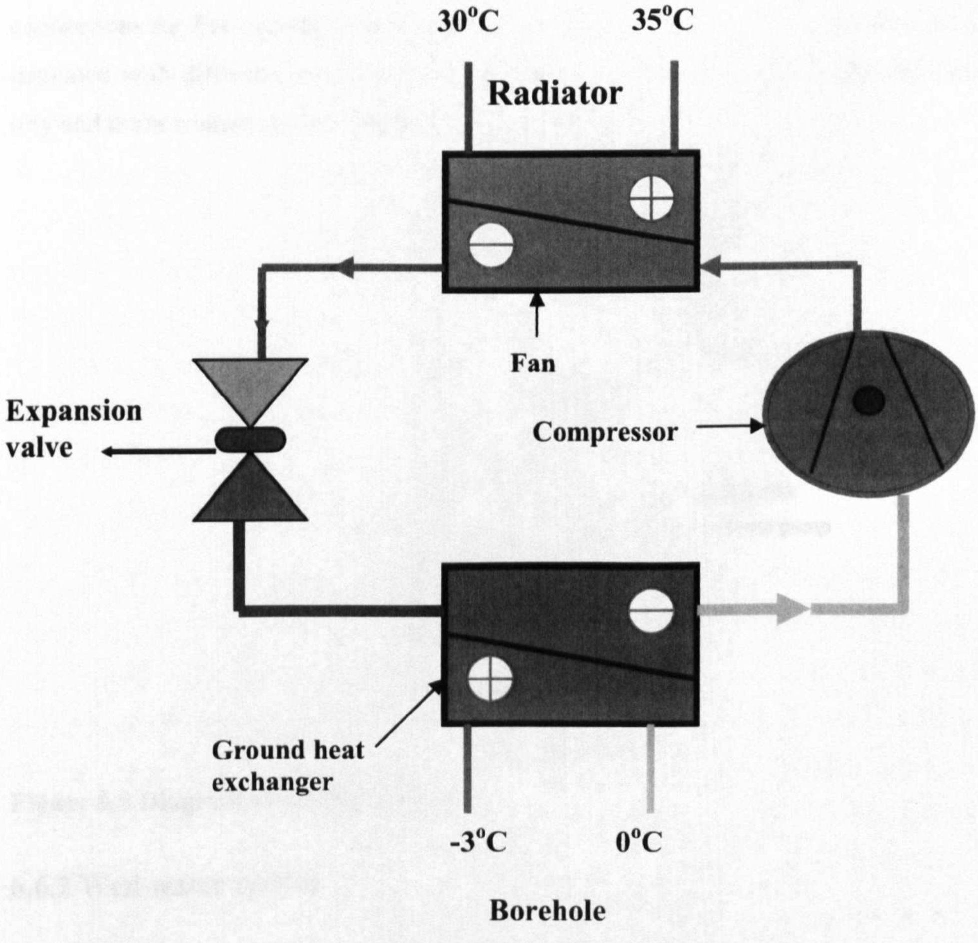


Figure 6.4 Detail of the GSHP circuit [120]

The GSHPs come in 15 models from 4 kW up to 30 kW (even up to 300 kW when connected in parallel). At least 65% of the heating and hot water energy consumption of a house can be saved (65-75% of heating costs with a heat pump) as a result of using such a system. However, sizing of the heat pump and the ground loops is essential for the efficient operation of the system. If sized correctly, a GSHP can be designed to meet 100% of space heating requirements. The sizing of the system is very sensitive to heat loads and should therefore be installed into properties with high-energy efficiency standards, particularly new build. It is a good and practical idea to explore ways of minimising space heating and hot water demand by incorporating energy efficiency measures (Appendix 4.2).

6.6.1 Free cooling

The installation can additionally be fitted with fan convectors, for example, in order to allow connections for free cooling (Figure 6.5). To avoid condensation, pipes and other cold surfaces must be insulated with diffusion proof material. Where the cooling demand is high, fan convectors with drip tray and drain connection are needed.

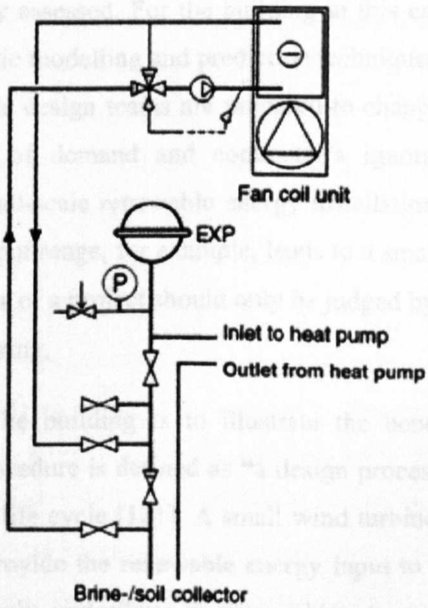


Figure 6.5 Diagram of cooling system

6.6.2 Well-water system

As its name suggests, this system utilises two wells and underground water. Water from one well is pumped through the heat pump, then returned to a second well or discharged into a pond. This system requires three to five gallons of water per minute to operate. Because water is returned to the earth, the underground water supply is not depleted by the heat pump's operation. In the heating season, ground-source heat pump supplies three to four units of heat to the home for every unit of electrical energy required to operate the system. This is equivalent to two to three kilowatt hours (kWh) of free energy for every one kWh of electrical energy spent. In other words, a ground-source heat pump is 300% to 400% efficient.

6.7 Combining GSHP with wind and solar energy

The integration of renewable energy sources into a project requires an analysis of all energy using and energy generating equipment to assess their impact on the prospective annual energy balance. "Bolting on" some photovoltaic panels to a conventional design does not make a building sustainable. Energy use of equipment often neglected by services engineers such as passenger lifts, maintained emergency lighting, kitchen equipment, and even fire alarms, needs analysing [121].

Adopting an integrated design approach is necessary if the benefits of, for example, increased insulation levels are to be properly assessed. For the building in this case-study the available budget only allowed for relatively simplistic modelling and prediction techniques. Larger projects justify more careful modelling only if the whole design teams are prepared to change their designs in response to the results provided. Also, lack of demand and contractor's ignorance of installation methods contribute to the high costs of small-scale renewable energy installations. The lack of availability of wind turbines in the 3 – 20kW output range, for example, leads to a smaller than desired turbine being specified. However, the real success of a project should only be judged by its performance in operation, after at least a year detailed monitoring.

The overall design strategy for the building is to illustrate the benefits of an integrated design approach. An integrated design procedure is defined as "a design process, which considers all aspects of a building, its environment and life cycle [121]. A small wind turbine, roof-mounted photovoltaics and evacuated tube solar panels provide the renewable energy input to the building, whilst a ground source heat pump is used to supply underfloor heating. This approach examines the options for interlinking the energy generating and energy using equipment and why the chosen system was adopted, as well as providing a more general assessment of incorporating small-scale renewable installations into services designs. An initial review of building performance is also provided. The environmental desires are to "practice that preach" and showcase 'green' solutions.

6.8 Ground-coupling with water source heat pumps

Ground-coupled heat pumps (GCHPs) have been receiving increasing attention in recent years. In areas where the technology has been properly applied, they are the system of choice because of their reliability, high level of comfort, low demand, and low operating costs. Initially these systems were most popular in rural, residential applications where heating requirements were the primary consideration. However, recent improvements in heat pumps units and installation procedures have expanded the market to urban and commercial applications.

The GCHPs are a subset of ground-source heat pumps (GSHPs), which also include groundwater and lake water heat pumps. The distinguishing feature of GCHPs is that they are connected to a closed-loop network of tubing that is buried into the ground [121]. The most common method of ground coupling is to bury thermally fused plastic pipe either vertically or horizontally [121]. A water or antifreeze solution is circulated through the inside of the tubing and heat is released to, or absorbed from, the ground. No water enters the system from the ground. Water- to- air heat pumps are located inside the building and are connected to the water loop with a circulator pump. This type of system is referred to as a secondary fluid GCHP since there is an intermediate liquid between the refrigerant and the ground.

A less frequently used system is referred to as a direct expansion (DX) GCHP. Refrigerant lines are buried in the ground in either a vertical or horizontal arrangement. Thus the intermediate heat exchanger and fluid are eliminated. The possibility of higher efficiency than secondary fluid GCHPs does exist. However, larger charges of refrigerant are required and system reliability is compromised. Therefore, the future of DX GCHP is not clear because of environmental concerns. GCHPs are often confused with a much more widely used commercial system, the water loop heat pump (WLHP) or water source heat pump (WSHP). Although the piping loop inside the building is similar, there are several important differences. Water-to-air heat pumps are located throughout the building. Local zone temperature is achieved with conventional on-off thermostats. Ductwork is minimized because the units are in the zone they serve. A central piping loop is connected to all the units. The temperature of this loop is typically maintained between 16°C and 32°C. A cooling tower is used to remove heat when the loop temperature exceeds 32°C and heat is added with a boiler if the temperature falls below 16°C. WLHPs are most successful when internal building loads are sufficient to balance the heat loss through the external surfaces and ventilation. If heat losses exceed internal loads, the energy requirements of WLHPs can become significant. Energy must be added in both the boiler and heat pumps. This is not true in cooling because the heat is dissipated through the cooling tower, which only had pump and fan motor requirements.

The boiler, the cooling tower, and the associated pump and heat exchanger have been replaced with the buried piping system. The only remaining auxiliary is the loop circulation pump. Heat is added to or removed from the ground at no cost and no energy is required to operate a boiler or cooling tower. WLHPs are designed to operate in the narrow range of 16°C and 32°C. They will not perform adequately in a GCHP system. The units used in GCHP systems must be extended range water-to-air heat pumps. Some manufacturers create extended range heat pumps by replacing the fixed expansion device of a WLHP with a thermostatic expansion valve (TEV). Others make this modification and add improved compressors, air and water coils, fans, and controls. This has resulted in units that operate with higher efficiencies than conventional WLHPs even when operating with water temperatures outside the 16°C and 32°C range.

It is obvious that the ground coil can add to the cost of the system. Also many high-rise commercial applications may not have sufficient land area to accommodate a full size ground coil. In this case, a hybrid ground-coupled water-loop heat pump (GCWLHP) would be a viable option to reduce the size of the ground coil. The coil would be sized to meet the heating requirement of the building. This is typically one-half the size required for meeting the cooling load. There are several reasons for the smaller size as summarised below.

The cooling requirement of commercial buildings with high lighting and internal loads usually exceeds the heating requirement.

The heating requirement for commercial buildings is often in the form of a morning "spike" followed by a reduced load. Ground coils are well suited to handling spikes because of the large thermal mass of the earth. Therefore, lengths can be reduced compared to systems designed for continuous loads. Since the ground coil for a GCWLHP would not be able to meet the cooling load in most climates, a downsized cooling tower would be added to the loop.

The GCHPs can also be integrated into "free cooling" or thermal storage schemes. For example, hydronic coils could be added to core heat pumps of a GCWLHP system. When the outdoor temperature was cold enough the cooling tower could be started. This would bring the loop temperatures below 10°C to cool the core zones without activating the compressors. The heat pumps in perimeter zones could operate simultaneously in the heating mode if required. A variety of other systems are possible because of the simplicity and flexibility of ground-coupled heat pumps.

6.9 Refrigeration and heat pumps

The pressure (ps) is a function of how rapidly vapour can be removed through suction or formed through pressure. At equilibrium, the rate at which vapour is formed (determined by Q) equals the rate at which it is removed. Therefore, both the heat transfer rate into the liquid (Q) and the vapour removal rate (suction pump capacity) determines the pressure and hence Tsat(s) (Figure 6.6). This is governed by the following set of equations.

$$Q = m\, h_{fg} \tag{6.1}$$

$$m = \rho g\, V \tag{6.2}$$

$$Q = \rho g V h_{fg} \quad (6.3)$$

$$Q = V h_{fg}/v_g \quad (6.4)$$

Both h_{fg} and v_g depend on the saturation temperature (or pressure) as assumed in Figure 6.7, which describes the relationship represented by eqn. 6.4.

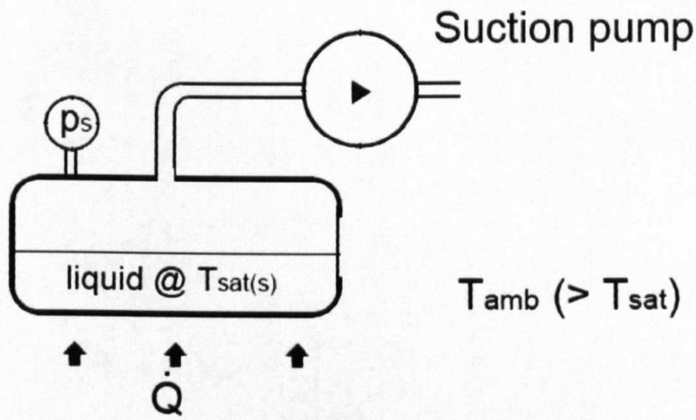


Figure 6.6 Refrigeration Cycle

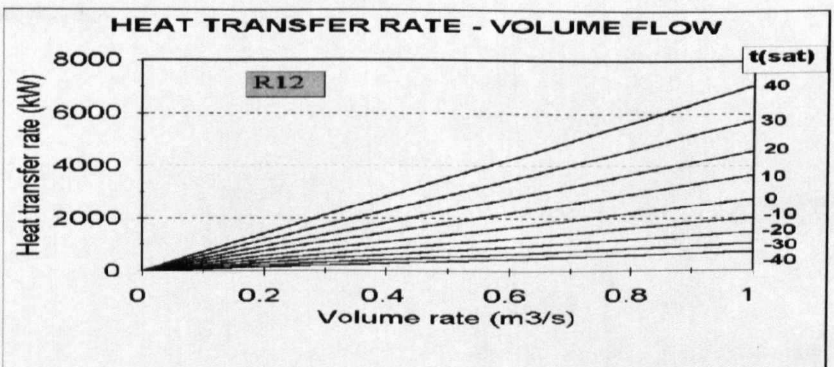
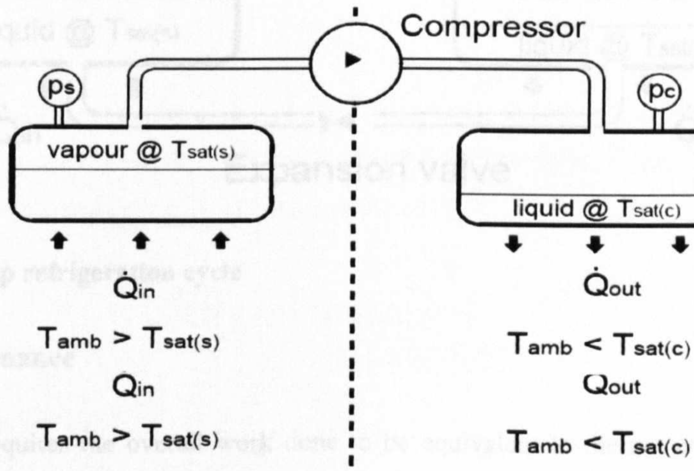


Figure 6.7 Heat transfer rate versus volume rate

The RHS of the Figure 6.8 is the 'converse' of the LHS, and constitutes a heat pump. Heat is 'pumped' from the LHS to the RHS. The main difference is that the vapour, after compression, will almost certainly be superheated and must cool to Tsat(c) before condensing will occur. The same reasoning (in converse) applies to the RHS as previously applied to LHS. Obviously, with the above system, the entire refrigerant would eventually end up on the RHS, and the heat pumping (& refrigeration) effect would cease.

Clearly, to ensure that the system can operate continuously liquid refrigerant needs to be fed from the RHS back to the LHS. This can be achieved by simply allowing it to flow back under its natural pressure difference. In this way a continuous closed circuit refrigeration (Or heat pump) system is obtained (Figure 6.9).



pc = Condenser or 'high side' pressure

ps = Evaporator, 'low side', or suction pressure

Figure 6.8 Heat pumps

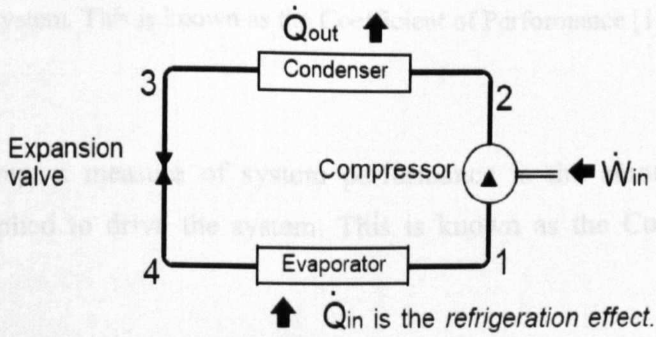


Figure 6.9 Simplified refrigeration system diagram

Control of the liquid flow rate is needed to ensure that it equals the vapour formation rate, and an appropriate balance of liquid quantities in the evaporator and condenser is maintained. When the liquid passes through the expansion valve it experiences a sudden drop in pressure, which causes instantaneous boiling (known as flashing). Vapour is formed using the liquid's sensible heat, which causes the liquid to drop in temperature to Tsat(s). A saturated liquid/vapour mixture will enter the evaporator. Figure 6.10 explains this cycle in practice.

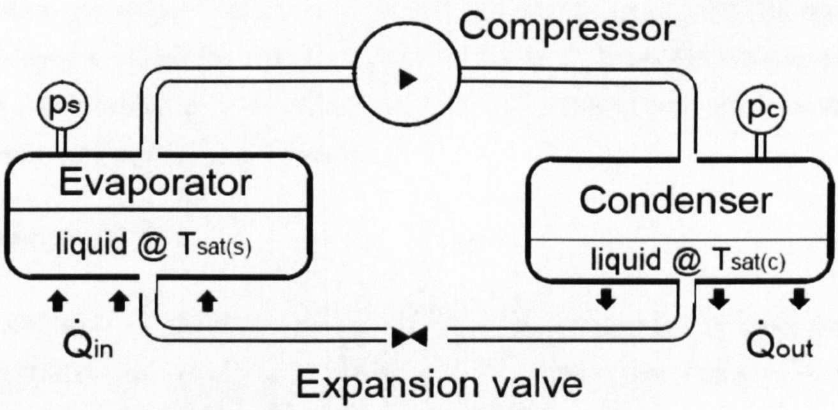


Figure 6.10 Heat pump refrigeration cycle

6.9.1 System performance

The system balance requires the overall work done to be equivalent to the net energy used by the system. Hence,

$$Q_{out} - Q_{in} = W_{in} \quad (6.5)$$

For operation as a refrigerator, a measure of system performance is the amount of heat absorbed per unit work supplied to drive the system. This is known as the Coefficient of Performance [121].

$$COP_{ref} = Qin / Win \quad (6.6)$$

For operation as a heat pump, a measure of system performance is the amount of heat delivered per unit work supplied to drive the system. This is known as the Coefficient of Performance [121].

$$COP_{hp} = Qout / Win \quad (6.7)$$

It follows that (for the same system):

$$COP_{hp} = COP_{ref} + 1 \quad (6.8)$$

6.9.2 Vapour compression refrigeration

The term "vapour compression refrigeration" is somewhat of a misnomer, it would be more accurately described as 'vapour suction refrigeration'. Vapour compression is used to reclaim the refrigerant and is more aptly applied to heat pumps. Vapour compression refrigeration exploits the fact that the boiling temperature of a liquid is intimately tied to its pressure. Generally, when the pressure on a liquid is raised its boiling (and condensing) temperature rises, and vice-versa. This is known as the saturation pressure-temperature relationship (Appendix 4.3).

6.9.3 Refrigerant properties

In practice, the choice of a refrigerant is a compromise, e.g., Ammonia is good but toxic and flammable while R12 is very good but detrimental to the Ozone layer. Figure 6.11 shows some commonly used refrigerants and their typical ranges of usability.

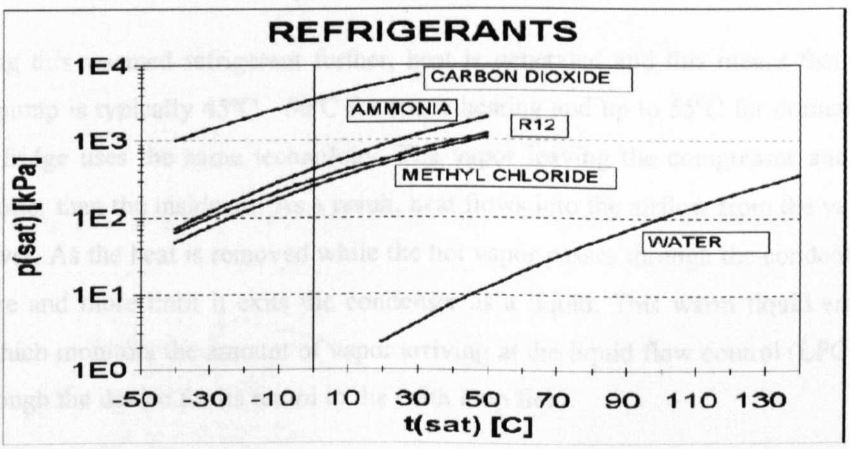


Figure 6.11 Refrigerant chart

Ideally, a refrigerant will have the following characteristics.

- Non-toxic - for health and safety reasons.
- Non-flammable - to avoid risks of fire or explosion.
- Operate at modest positive pressures - to minimise pipe and component weights (for strength) and avoid air leakage into the system.
- Have a high vapour density – to keep the compressor capacity to a minimum and pipe diameters relatively small.
- Easily transportable - because refrigerants are normally gases at SSL conditions they are stored in pressurised containers.
- Environmentally friendly - non-polluting & non-detrimental to the atmosphere, water or ground.

- Easily re-cycleable, and relatively inexpensive to produce.
- Compatible with the materials of the refrigeration system - non-corrosive, miscible with oil, chemically benign.

6.9.4 Heating mode

The average ground temperature just below the surface, in the UK is between 8°C and 13°C; this temperature remains constant throughout the year. A water and food grade Glycol mix is circulated through pipes buried either horizontally or vertically in the ground. The temperature of the water in the pipes is lower than the surrounding ground and so it warms up slightly. This low-grade heat is pumped to the heat pump, where it is used to heat up a refrigerant.

By compressing this warmed refrigerant further, heat is generated and this means that water output from the heat pump is typically 45°C - 50°C for space heating and up to 55°C for domestic hot water. The domestic fridge uses the same technology. The vapor leaving the compressor and entering the condenser is hotter than the inside air. As a result, heat flows into the airflow from the vapor as the air passes the blower. As the heat is removed while the hot vapor passes through the condenser, the vapor condenses more and more until it exits the condenser as a liquid. This warm liquid enters the flow control unit, which monitors the amount of vapor arriving at the liquid flow control (LFC), and meters liquid only through the device for its return to the earth loop field.

6.9.5 Cooling mode

In the cooling mode, cool vapor arrives at the compressor after absorbing heat from the air in the building. The compressor compresses the cool vapor into a smaller volume, increasing its heat density. The refrigerant exits the compressor as a hot vapour, which then goes into the earth loop field (Appendixes 4.4-4.5). The loops act as a condenser condensing the vapor until it is virtually all liquid. The refrigerant leaves the earth loops as a warm liquid. The flow control regulates the flow from the condenser such that only liquid refrigerant passes through the control. The refrigerant expands as it exits the flow control unit and becomes a cold liquid.

6.9.6 Heat pump antifreeze

A potential negative effect of all geothermal heat pumps is the release of antifreeze solutions to the environment. Antifreeze solutions are required in colder climates to prevent the circulating fluid from freezing. Antifreeze chemicals include methanol, ethanol, potassium acetate, propylene glycol, calcium magnesium acetate (CMA), and urea. These chemicals are generally mixed with water when used as a heat exchange fluid. These chemicals can be released to the environment via spills or corrosion of system components. Approved antifreezes include methanol, ethanol, propylene glycol, calcium chloride, or ethylene glycol. These antifreezes must be mixed with water, at concentrations of 20% or less. Geothermal heat pumps for a single-family residence and the antifreezes for these units were evaluated by Heinonen et al., (1996) [122]. These authors evaluated total energy consumption, corrosion due to the antifreeze, and the operational and environmental effects of six antifreeze solutions, namely methanol, ethanol, potassium acetate, propylene glycol, CMA, and urea. However, the excluded salt solutions, such as sodium and calcium chloride, from their study because they pose serious potential corrosion problems. The differences in total energy consumption for the studied antifreezes were considered minimal. Nevertheless, Heinonen et al, recommended that propylene glycol was a good choice based on its low health, fire, and environmental risks (Table 6.1). Unfortunately, these authors did not assess the leak potential of these antifreezes in the plastic pipe (e.g., HDPE & CPVC SDR-11) commonly used for the ground loop [123].

Table 6.1 Cost and risk factors for heat pump antifreeze (Heinonen et al., 1996) [122]

Factor	**Antifreeze**					
	Methanol	Ethanol	Propylene glycol	Potassium Acetate	CMA	Urea
Life cycle cost	**3**	**3**	**2**	**2**	**2**	**3**
Corrosion risk	**2**	**2**	**3**[a]	**2**	**2**	**1**
Leakage risk	**3**	**2**	**2**[a]	**1**[b]	**1**	**1**
Health risk	**1**	**2**	**3**	**3**	**3**	**3**
Fire risk	**1**[a]	**1**[c]	**3**	**3**	**3**	**3**
Environmental risk	**2**	**2**	**3**	**2**	**2**	**3**
Risk of future use	**1**	**2**	**3**	**2**	**2**	**2**

Notes:

Ratings- 1 means potential problems and caution required, 2 means minor potential for problems, 3 means little or no potential problems

a) DOWFROST HD; b) GS-4; c) Pure fluid only. Diluted antifreeze (25% solution) is rated 3.

6.9.7 Antifreeze and grout compatibility

The hydraulic conductivity of bentonite grouts can be altered by changes in the pore fluid, especially some of the fluids used as antifreeze [124-126]. Salt solutions such as calcium chloride and magnesium chloride solutions, at concentrations used for antifreeze applications, can increase the hydraulic conductivity of bentonite by approximately three orders of magnitude [127]. Pure organic liquids such as ethanol and heptane also can increase the hydraulic conductivity of bentonite and other clays by two to three orders of magnitude [128]. Mixtures of ethanol and water, up to 60% ethanol solutions, were found to decrease the hydraulic conductivity of bentonite while 100% ethanol solutions (pure ethanol) increased the hydraulic conductivity of bentonite by more than two orders of magnitude [129]. The causes of this behavior involve differences in fluid viscosity and clay mineralogy, which are beyond the scope of this study. In summary, some antifreeze solutions, if leaked from piping, will alter the hydraulic conductivity of bentonite grouts, which are designed to contain any leakage [130]. Additional research is needed for some antifreeze solutions, such as CMA and propylene glycol, because data for their potential to alter the hydraulic conductivity of bentonite grouts is not known.

Geothermal heat pumps with vertical boreholes may pose environmental threats. If these boreholes are not properly grouted or the grout fails, groundwater could be contaminated by surface water infiltration, interaquifer flow, or antifreeze leakage. These boreholes are usually grouted with bentonite, neat cement, or a mixture of these materials. Laboratory tests of the hydraulic conductivity of grout materials range from 10^{-10} to 10^{-7} cm/sec. Hydraulic conductivity values of 10^{-7} cm/sec are considered impermeable. For the grout and conductor pipe systems, values of hydraulic conductivity of 10^{-8} to 10^{-7} cm/sec have been reported [123].

The low hydraulic conductivity of grout/pipe system can be compromised by poor bonding between the grout and the borehole or poor bonding between the grout and the heat conductor pipe [123]. The bond between the grout and conductor pipe is considered more likely to be compromised [123], and can fail by thermal contraction of the conductor pipe. Because the grout and pipe have significantly different coefficients of thermal expansion, the conductor pipe can contract from the grout at low temperatures, forming a conductive pathway for contaminant transport. Neat cement grouts with water/cement ratios of 0.4 to 0.8 failed in this manner during lab experiments where low temperature fluids were pumped through the pipe [124]. A thermally enhanced grout (Mix 111), on the other hand, did not fail, maintaining hydraulic conductivities of less than 10^{-7} cm/sec during these experiments. Mix 111 is a mixture of cement, water, silica sand, and small amounts of superplasticiser and bentonite. However, the bond between the grout and borehole can be compromised by desiccation of the geologic materials near the borehole, as the heat from the borehole lowers the moisture content of the geologic materials and these materials contract. In areas with thick unsaturated zones, the bentonite grout may dry out over time, compromising the seal.

To improve heat exchange, some advocate the use of spacers, which moves the heat conductor pipe to the side of the borehole, putting it in contact with the geologic materials. However, the use of spacers appears to increase the environmental risk of antifreeze leaking into groundwater, by reducing or removing the bentonite between the heat conductor pipe and geologic materials. The risk of groundwater contamination is primarily controlled by the low hydraulic conductivity of the grout. Thus, grouts must be mixed and placed according to manufacturer's specifications and those procedures defined by industry groups such as the International Ground Source Heat Pump Association, Electric Power Research Institute (EPRI and NRECA, 1997) [125], and the National Ground Water Association [125].

6.9.8 Air distribution

The air distribution system can make a big difference in both the cost and the effectiveness of geothermal heating and cooling. It also has an important effect on personal comfort and health. The air-handling component is either a separate cabinet or is part of the cabinet that houses the geothermal heat pump, and includes the blower assembly that forces air through the ductwork. The supply ductwork carries air from the air handles to the rooms. Typically, each room has at least one supply duct and larger rooms may have several. The return ductwork moves air from the room back to the air handler. Most buildings have one or more main return ducts located in a central area. The cold liquid refrigerant is circulated through the air handler where it absorbs and removes the unwanted heat from the air and vaporizes the refrigerant to a gas. The gas is compressed to increase its temperature and then the underground/underwater coils act as a condenser rather than an evaporator (as in the heating cycle) (Figure 6.12). The heat in the refrigerant is transferred to the ground/water as the refrigerant condenses.

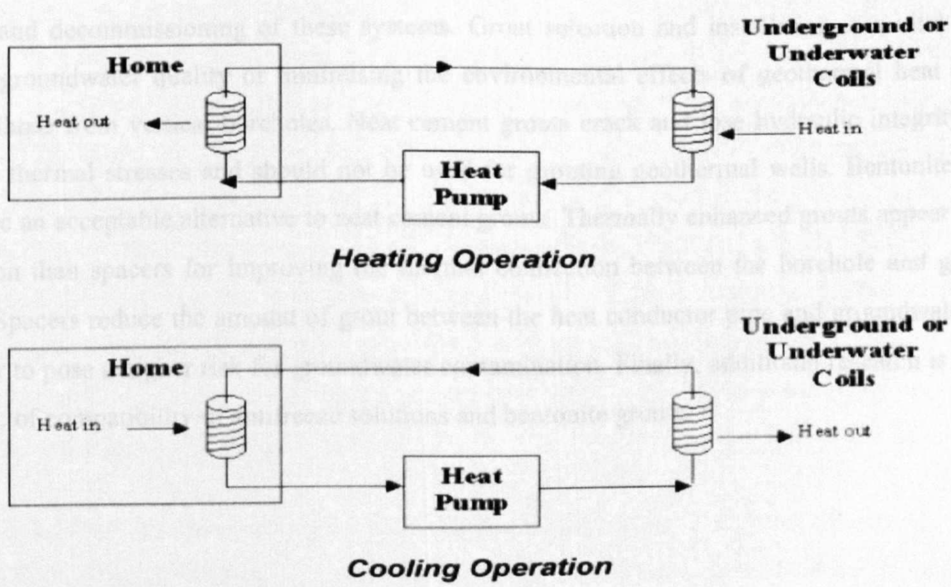


Figure 6.12 Heating and cooling operations

Refrigerants are present in GSHP systems and so present the threat of HCFCs and toxicity. However, new types and blends of refrigerant (some using CO_2) with minimal negative impacts are approaching the market as shown in Table 6.2. Because GSHPs raise the temperature to around 40° they are most suitable for underfloor heating systems or low-temperature radiators, which require temperatures of between 30° and 35°. Higher outputs, such as to conventional radiators requiring higher temperatures of around 60° to 80° can be obtained through use of the GSHP in combination with a conventional boiler or immersion heater.

Table 6.2 CO_2 emissions [131-132]

System	Primary Energy Efficiency (%)	CO_2 emissions (kg CO_2/kWh heat)
Oil fired boiler	60 – 65	0.45 – 0.48
Gas fired boiler	70 – 80	0.26 – 0.31
Condensing gas boiler + low temperature system	100	0.21
Electrical heating	36	0.9
Conventional electricity + GHSP	120-160	0.20-027
Green electricity + GHSP	300-400	0.00

6.10 Conclusions

It is concluded that, despite potential environmental problems, geothermal heat pumps pose little if any serious environmental risk when best management practices are applied during the installation, operation, and decommissioning of these systems. Grout selection and installation is a vital step in protecting groundwater quality or minimising the environmental effects of geothermal heat pumps, especially those from vertical boreholes. Neat cement grouts crack and lose hydraulic integrity when exposed to thermal stresses and should not be used for grouting geothermal wells. Bentonite grouts appear to be an acceptable alternative to neat cement grouts. Thermally enhanced grouts appear to be a better option than spacers for improving the thermal connection between the borehole and geologic materials. Spacers reduce the amount of grout between the heat conductor pipe and groundwater, thus they appear to pose a higher risk for groundwater contamination. Finally, additional research is needed on the topic of compatibility of antifreeze solutions and bentonite grouts.

7.0 Modelling Approach

7.1 Introduction

This chapter deals with the development of a design and modelling of ground source heat pump systems. It also, covers the challenges associated with the design of these systems

A considerable amount of research over the past decade has been geared towards opitising the performance of GSHP systems [133-136], and this study is part of those efforts. These research activities identified the soil thermal characteristics, especially the thermal conductivity, borehole resistance and undisturbed ground temperature, are essential parameters, as essential parameters for the design of thermally efficient and economically sized borehole heat exchanger systems.

The idea of the multi-level heating and cooling pulses classical geothermal response testing (GRT) with regard to the effects of groundwater flow is that the apparent or effective conductivity will increase when the difference between the fluid temperature and groundwater temperature is large. The "true" conductivity can then be estimated from the experiment period with the smaller temperature difference [137-141]. The effect of groundwater flow (if present) will become even bigger at greater temperature differences and hence the magnitude of the effect can become a practically useful measure of the groundwater flow rate. However, if groundwater flow does not play an important role in the heat transport, the estimates of soil conductivity should then be the same as, or at least within, the heating or cooling pulse. It has been shown that it is possible to distinguish the effects in the different thermal energy pulses under no groundwater flow and groundwater flow regimes within the same pulse differences in heat transfer occur during earlier and later times [141]. Using both heating and cooling pulses is interesting because it widens the range of the experimental temperatures. Also, convection effects, if present, can be distinguished by comparing the heat injection with heat extraction results. If there is an appreciable vertical temperature gradient (near the surface or near the bottom of the heat exchanger), effects on the heat transport will be different for heating and cooling pulses [142]. The test described in [142] would be able to separate such effects as well.

The highest conductivity values were found in [142] for the groundwater extraction dataset during the heat extraction pulse even though the difference between fluid and ground temperature was not very great. As temperatures were well above freezing, no heat of fusion was released. Perhaps some residual heat from previous heat injection pulses was transported to the borehole heat exchanger, but then the effect would be expected to diminish with time, which was not the case. The experiments described, was repeated with the order of heating and cooling pulses inversed so that the dependence on the pulse order can be investigated. The datasets, which were assembled using groundwater extraction, could be used to calibrate numerical models incorporating both heat and mass transport. The effects of more uniform groundwater flow, for several typical geohydrological situations, can then be simulated using such models. Using such simulated GRT data, the effects on actual test data can be improved and optimal energy levels for an experiment can be selected.

7.2 Development, design and simulation

A model is a physical or a mathematical representation of an actual system. American Society for Testing and Materials (ASTM) defines a mathematical model as mathematical equations expressing the physical system behaviour and including simplifying assumptions [146]. Mathematical models are solved analytically or numerically using manual or computer methods.

7.3 Model description

Models, energy analyses and comparisons are presented for advanced and basic geothermal heat pump arrangements for heating purposes. The analysis includes investigations into how varying compressor, pump, and motor efficiency affect the system performance. Variations in operating conditions are investigated, with the inclusion of condenser and evaporator pressure, and the degree of subcooling and superheating at the condenser and evaporator exit. The model for each system is composed of two different loops including the heat pump cycle and ground loop heat exchanger, commonly referred to as the ground loop. The arrangement and analysis process for the ground loop is identical for each of the three systems. A vertical borehole ground loop connection is utilised within the study. The brine in the ground loop is taken to be a water/propylene glycol mixture.

The borehole design consists of a main flow through the evaporator, a single pump, and multiple parallel loops. A cool water/glycol (brine) mixture flows from the evaporator to the pump, where the pressure is increased to the required level. The brine flow is then split into the parallel loops, and absorbs heat from the surrounding ground. The heat pump cycle (Figure 7.1) consists of an evaporator, compressor, condenser and expansion valve, coupled with an electric motor for the compressor and a ground loop with a pump. Refrigerant enters the evaporator where thermal energy is transferred to it from the ground loop. The refrigerant exits the evaporator as superheated vapour and enters the compressor, where the pressure increases and the refrigerant exits as a high pressure superheated vapour. The refrigerant enters the condenser where thermal energy is extracted from the refrigerant and supplied to the space.

GHP systems are comprised of three main components that work together to supply heat to a building as can be seen in Figure 7.2. There are five major components in a GHP (Figure 2): a compressor, an expansion valve, a reversing valve and two heat exchangers.

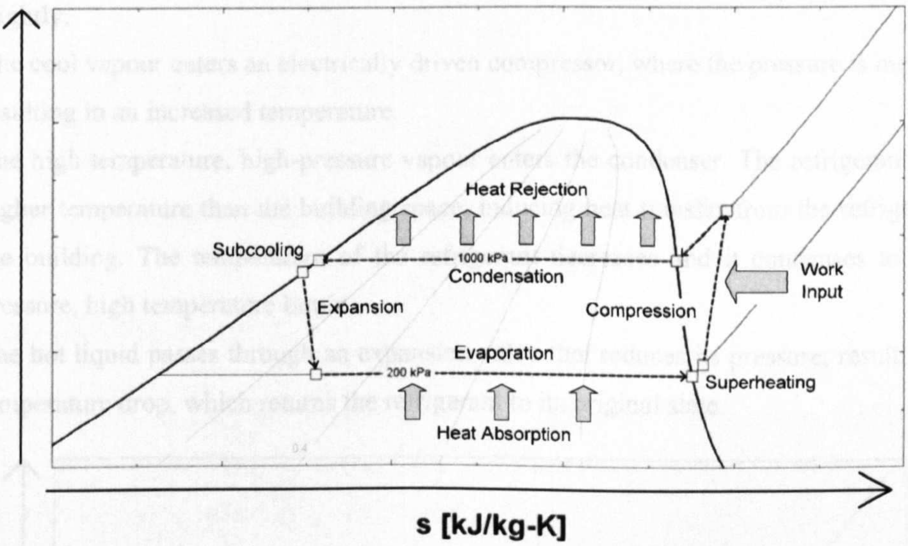


Figure 7.1 Main components of a GHP system: (1) heat pump unit, (2) earth connection, (3) heat distribution system in a building

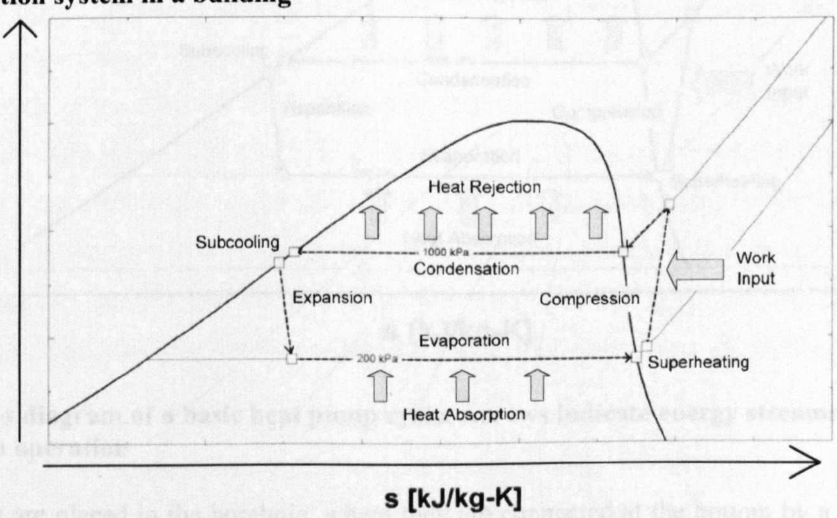


Figure 7.2 Basic layout of a typical ground heat pump system

Heat pumps used for heating operate with the following steps, which are illustrated on a temperature-specific entropy (*T-s*) diagram in Figure 7.3:

1. Heat is absorbed in the earth loop and transported to the evaporator.
2. Within the heat pump, cold refrigerant, mainly in the liquid state, enters the evaporator. The temperature of the refrigerant is lower than the fluid from the earth connection allowing heat to flow from the earth connection loop to the refrigerant, causing the refrigerant to boil and become a low-pressure vapour; the temperature increases only slightly.
3. The cool vapour enters an electrically driven compressor, where the pressure is increased, resulting in an increased temperature.
4. The high temperature, high-pressure vapour enters the condenser. The refrigerant is at a higher temperature than the building space, inducing heat transfer from the refrigerant to the building. The temperature of the refrigerant decreases and it condenses to a high pressure, high temperature liquid.
5. The hot liquid passes through an expansion valve that reduces its pressure, resulting in a temperature drop, which returns the refrigerant to its original state.

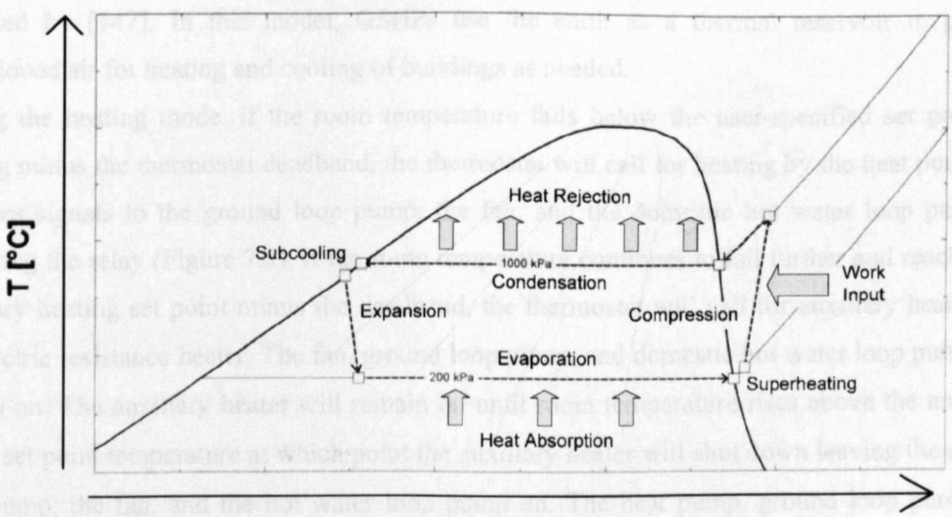


Figure 7.3 *T-s* diagram of a basic heat pump cycle. Arrows indicate energy streams involved in heat pump operation

Pairs of pipes are placed in the borehole, where they are connected at the bottom by a U-shaped connector (Figure 7.4). Heat transfer fluid thus exchanges heat with the ground over a pipe length that is double the borehole depth.

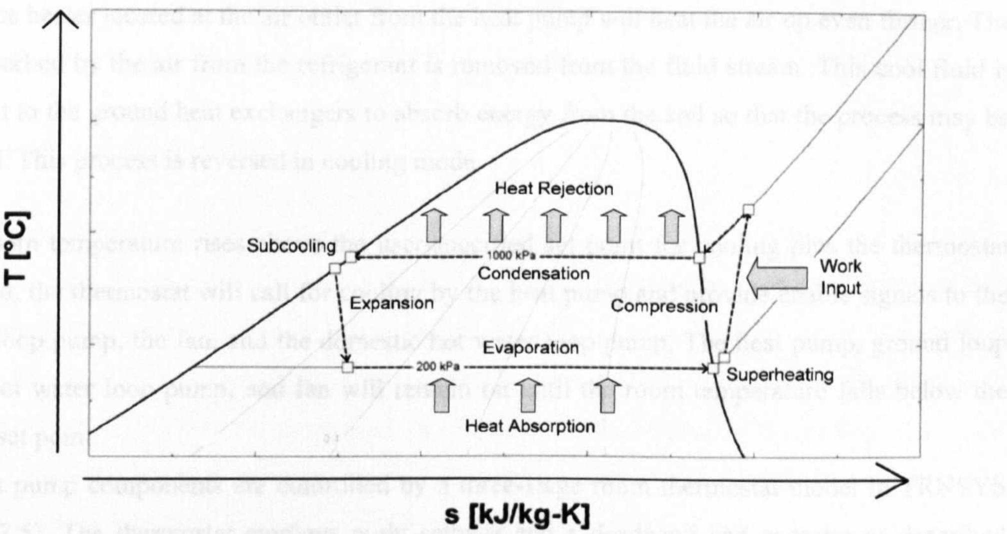


Figure 7.4 A vertical closed loop heat exchange configuration for a ground heat pump system

7.3.1 Model TRNSYS description

The TRNSYS simulation programme has been used to model the GSHP system for HVAC as specified by [147]. In this model, GSHPs use the earth as a thermal reservoir to provide conditioned air for heating and cooling of buildings as needed.

During the heating mode, if the room temperature falls below the user-specified set point for heating minus the thermostat deadband, the thermostat will call for heating by the heat pump and provides signals to the ground loop pump, the fan, and the domestic hot water loop pump by activating the relay (Figure 7.5). If the room temperature continues to fall further and reaches the auxiliary heating set point minus the deadband, the thermostat will call for auxiliary heating by the electric resistance heater. The fan, ground loop pump, and domestic hot water loop pump will remain on. The auxiliary heater will remain on until room temperature rises above the auxiliary heater set point temperature at which point the auxiliary heater will shut down leaving the ground loop pump, the fan, and the hot water loop pump on. The heat pump, ground loop pump, hot water loop pump, and fan will remain on until the room temperature rises above the heating set point.

When the thermostat calls for heating, the fan will move air from the building to the heat pump where it is heated as it crosses the heating coil. This warm air is then dumped back into the building until the thermostat is satisfied. If the thermostat calls for auxiliary heating, an electric resistance heater located at the air outlet from the heat pump will heat the air up even further. The heat absorbed by the air from the refrigerant is removed from the fluid stream. This cool fluid is then sent to the ground heat exchangers to absorb energy from the soil so that the process may be repeated. This process is reversed in cooling mode.

If the room temperature rises above the user-specified set point for cooling plus the thermostat deadband, the thermostat will call for cooling by the heat pump and provide enable signals to the ground loop pump, the fan, and the domestic hot water loop pump. The heat pump, ground loop pump, hot water loop pump, and fan will remain on until the room temperature falls below the cooling set point.

The heat pump components are controlled by a three-stage room thermostat model in TRNSYS (Figure 7.5). The thermostat employs night setback and a deadband and operates as described below.

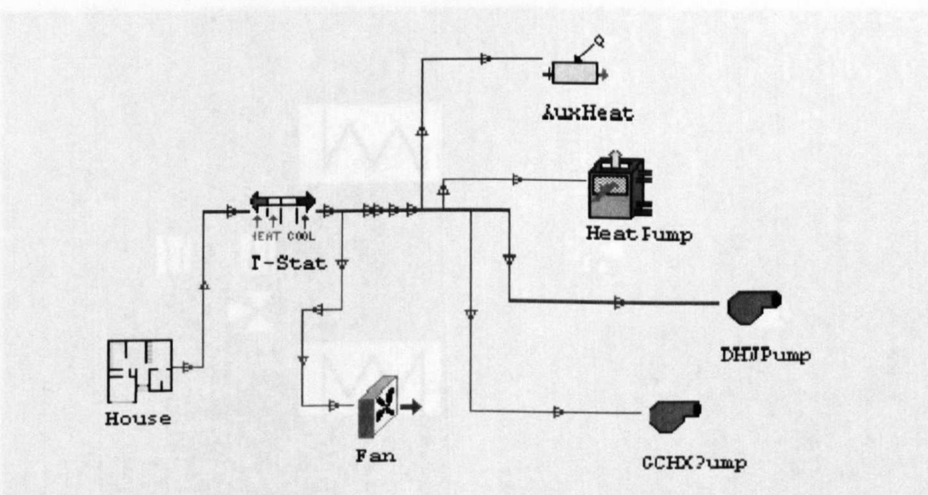


Figure 7.5 Modelling of closed loop GSHP

When the thermostat calls for cooling, the fan will move air from the building to the heat pump where it is cooled as it crosses the cooling coil. The cool air is then dumped back into the building until the thermostat is satisfied. The heat removed from the air and transferred to the refrigerant is then rejected to a cooling fluid stream (typically water in southern climates, i.e., South Europe). This hot fluid is then pumped to ground heat exchangers that are buried in the earth where the heat is transferred to the soil.

The heat pump for this simulation has an option for heating hot water by the use of a desuperheater. While operating in either heating or cooling mode, cool water is removed from the bottom of the hot water storage tank and passed across the desuperheater of the heat pump.

Energy is transferred from the refrigerant to the water by the desuperheating of the refrigerant. The hot water is then pumped back to the top of the hot water storage tank for later use.

7.3.2 Modelling the building

There are traditionally several different building models in TRNSYS that could be chosen to perform the load calculations (detailed multi-zone building, detailed single-zone building model, degree-day building model, etc.). However, in the present study, a building is modelled with a new lumped capacitance-building model written by Thermal Energy System Specialists of Madison, W.I. [162]. This new subroutine represents a simpler approach to building simulation than the standard TRNSYS models (Figure 7.6), but in extremely quick simulation times. The icons represent components and the lines/arrows represent the connections.

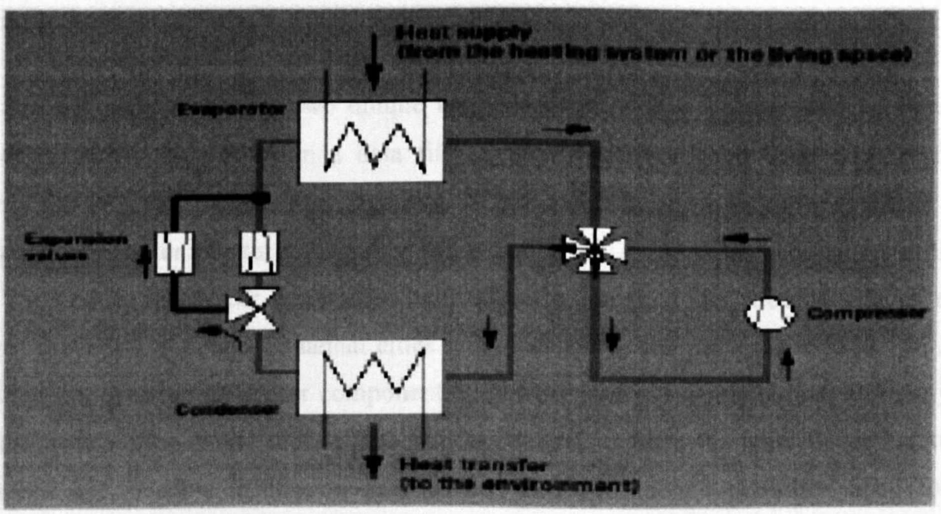


Figure 7.6 Schematic diagram of TRNSYS Simulation

a. Loads estimations

The loads that the ground source heat pump system must meet are dependent on several important factors: the weather, occupancy schedule, lighting schedule, infiltration, internal gains, and ventilation effects (Figure 7.7). Unlike most of the major simulation programmes on the market today, TRNSYS does not decouple the loads from the HVAC system. The loads and the system response are solved simultaneously providing a much more accurate solution.

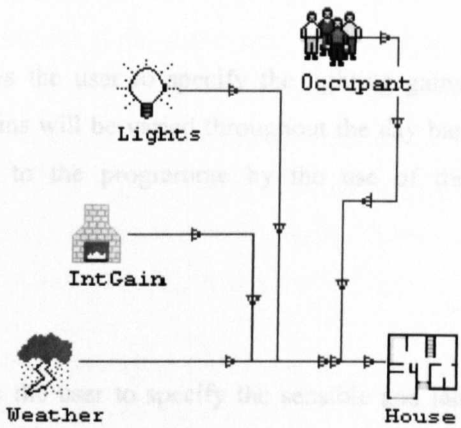


Figure 7.7 Factors affecting GSHP load

b. Weather

The TRNSYS programme has two unique methods of providing weather data to simulations. Weather data may be read from a data file (Typical Meteorological Year weather files are available for TRNSYS), or weather data may be generated based on monthly averages of solar radiation, ambient temperature, humidity ratio, and wind speed. This simulation utilises the TRNSYS weather generator component subroutine to integrate the files. A file of monthly averages for 330 U.S.A and Canadian cities is included with the programme [149-156]. In this simulation, the weather generator component allows the user to quickly choose from any of the 330 sites with a click of the mouse. The building model requires the ambient temperature (for skin losses and sensible infiltration gains/losses) and the ambient humidity ratio (for latent infiltration gains) as inputs.

c. Internal loads

The building model allows the user to specify the internal gains to the space. In the present simulation, the internal gains will be varied throughout the day based on a pre-defined schedule. This schedule was input to the programme by the use of the TRNSYS forcing function component.

d. Lighting loads

The building model allows the user to specify the lighting gains to the space. In the present simulation, the lighting gains will be varied throughout the day based on a pre-defined schedule. This schedule was input to the programme by the use of the TRNSYS forcing function component.

e. Occupancy gains

The building model allows the user to specify the sensible and latent gains to the space. In the present simulation, the occupancy was varied throughout the day based on a pre-defined schedule. This schedule was input to the programme by the use of the TRNSYS forcing function component.

f. Infiltration

The infiltration gains/losses were calculated by the simple ASHRAE approach to infiltration method. These loads are then input to the building model.

7.4 Modelling of the ground loop

When heating or cooling is required of the heat pump, the ground loop pump will move fluid from the ground heat exchangers to the heat pump (Figure 7.8). The heat pumps will then add/remove heat from the fluid and return the fluid to the ground loop where this heat must be rejected to/absorbed from the earth.

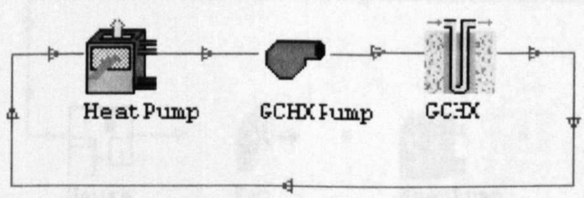


Figure 7.8 GSHP system operations

The key components in any ground source heat pump application are the ground heat exchangers. In this study, two U-tube ground heat exchangers were used to reject/absorb heat to/from the ground. U-tube ground heat exchangers are relatively simple devices. The heat exchanger consists of a long piece of pipe formed into a "U" shape. This U-tube is then inserted into the borehole, a deep hole drilled into the ground. After the U-tube has been placed in the ground, the borehole was backfilled with soil or a thermal-enhanced grout. The two ground heat exchangers were hooked up in parallel and are typically buried about 5 meters apart. The ground heat exchanger design is critical in these systems. If the ground heat exchangers are too short, the temperature of the fluid returning to the heat pump is too hot cooling mode or too cold in heating mode; causing performance degradation and possible equipment failure.

In the present study, the thermal and hydraulic effects of the horizontal pipes leading to and from the ground heat exchangers are ignored since they typically account for only a small fraction of the overall heat transfer. The ground heat exchangers are modelled with a very detailed model written at the University of Lund, Sweden [146-148]. This model accounts for the thermal properties of the fluid, pipes, backfill, and soil. It is considered the finest ground heat exchanger model in the world today. This model has been incorporated into TRNSYS as part of this study to take advantage of the many TRNSYS benefits derived from modular simulation.

7.4.1 Air system

The air system in the present simulation is relatively simple. When heating or cooling is required, a thermostat control signal will enable the fan, which draws conditioned air from the building (Figure 7.9). The room air then passes over the heating/cooling coil of the heat pump; which then heats or cools the air (taking into account both sensible and latent heat considerations). The air leaving the heat pump passes over the auxiliary heating coil, which is controlled by the thermostat based on the room temperature, and is returned to the building.

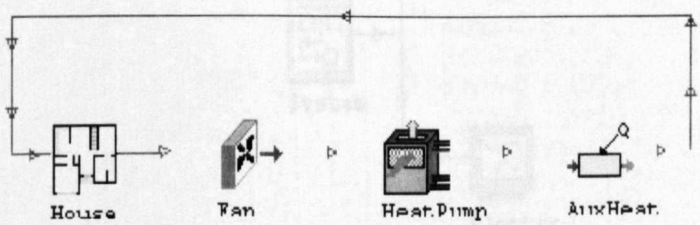


Figure 7.9 Air pump systems

7.4.2 Hot water

The heat pump for this simulation has an option for heating hot water for use in the building by the use of a desuperheater (Figure 7.10). When the heat pump is operating (in either heating or cooling mode), a pump draws cool water from the bottom of the storage tank, passes the water across the desuperheater where it is heated, and returns the hot water to the top of the storage tank. Energy is transferred from the refrigerant to the water by the desuperheating of the refrigerant. The hot water is then pumped back to the top of the hot water storage tank for later use.

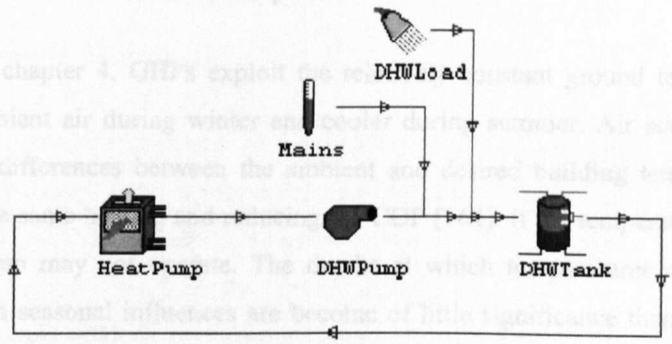


Figure 7.10 Hot water systems

7.4.3 Output of the model

Using a special TRNSYS component for simulation, the following variables were plotted as the simulation progressed. Figure 7.11 presents components of output.

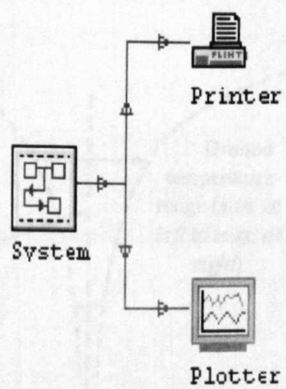


Figure 7.11 Diagram of output

7.5 Earth connections

There are two main types of heat pumps depending on heat source; air source and geothermal. Air source heat pumps use the ambient air as a heat source while geothermal heat pumps use the surrounding ground. Ambient air temperatures exhibit high variations throughout the year, even on a daily basis, while ground temperatures do not. The temperature of the ground does not change significantly over the course of a day or year, except near the surface. For example, while ground temperatures fluctuate significantly at depths of 0.3-0.8 m on a daily basis, the variations decrease considerably at lower depths [162-163]. Consequently, the variations are more pronounced on a seasonal rather than daily basis.

As explained in chapter 4, GHPs exploit the relatively constant ground temperature, which is warmer than ambient air during winter and cooler during summer. Air source heat pumps are subject to large differences between the ambient and desired building temperatures, requiring more work for the same heating and reducing the COP [164]. If the temperature difference is too large, a heat pump may not operate. The depths at which temperatures stabilise indicate the interface at which seasonal influences are become of little significance than the heat flowing to the surface from deep within the earth [165-166]. Although the movement of heat from the deep within the earth allows for constant temperature at greater depths, the performance and COP are independent of the actual heat transfer intensity of a particular gradient [167]. Table 7.1 outlines the design temperature for different heating systems. Figure 7.12 shows the variation of ground temperature with increasing depth for Nottingham, UK. It can be seen that as the depth increases, the outlying warm and cold temperatures converge. Depending on factors like incoming solar radiation, snow cover, air temperature, precipitation and ground thermal properties, there exists a depth at which there is little or no temperature variation [168].

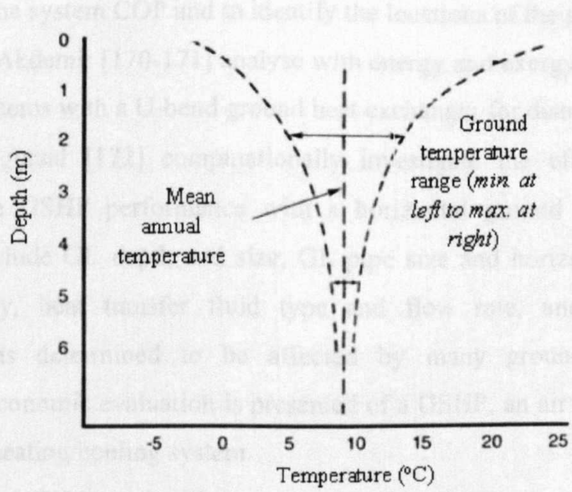


Figure 7.12 Annual range of ground temperature with depth below the ground surface, and mean annual temperature

Table 7.1 Design temperatures for selected heat distribution methods

System type	Indoor design range
100% radiant floor	18-21°C
Mixed radiant floor/forced air	20-22°C
Baseboard	20-22°C

7.5.1 Recent ground heat pump research

The literature on ground source heat pumps appears to be limited mainly to aspects of use and operation and to focus on basic vapour compression systems. Nevertheless, comparisons between ground- and air-source heat pumps have been reported in [168]. Energy and exergy analyses have been carried out for the basic heat pump arrangement, using both simulation and experimental methods. Few investigations have been reported on the effects of varying operating conditions of a ground source heat pump or advanced ground source heat pump systems and the impact of variations in components and arrangements.

The most significant studies of relevance to the present chapter [168–177]. The latter four of this list provided information used in the current chapter for validation purpose.

- Hepbasli and Balta [169] experimentally determine the performance of a heat pump system using low temperature geothermal resources. Energy and exergy analyses are used to determine the system COP and to identify the locations of the greatest irreversibilities.
- Hepbasli and Akdemir [170-171] analyse with energy and exergy methods ground source heat pump systems with a U-bend ground heat exchanger for district heating purposes.
- Healy and Ugursal [172] computationally investigate the effect of various system parameters on GSHP performance with a horizontal ground loop (GL). Parameters considered include GL depth and size, GL pipe size and horizontal pipe spacing, heat pump capacity, heat transfer fluid type and flow rate, and ground type. GSHP performance is determined to be affected by many ground loop parameters. A comparative economic evaluation is presented of a GSHP, an air source heat pump and a conventional heating/cooling system.
- Kulcar, et al., [173] describe the economics of exploiting heat from low-temperature geothermal sources for high-temperature heating of buildings using a heat pump, and demonstrate for a specific system that district heating of buildings is viable economically.

- Kara [174] experimentally determines the performance of a ground source heat pump (GSHP) system in heating mode in the city of Erzurum, Turkey. The system has a single U-tube ground heat exchanger made of polyethylene pipe (similar to that considered the present work).
- Wang, et al., [175] investigate the effects of compressor and motor cooling, where the heat is transferred to the refrigerant for preheating, in a heat pump system. The characteristics of different refrigerants for motor cooling are explored.
- Ma and Chai [176] propose an improved heat pump cycle that incorporates an economiser into the vapour compression cycle with two compression processes between the condenser and evaporator. The new system is optimised and compared to a conventional heat pump system.
- Ma and Zhao [177] extend the work of Ma and Chai [176] by experimentally comparing the improved heat pump cycle with a similar cycle that employs a flash tank with vapour separation and includes two compression processes.

7.5.2 Investigation approach

Each analysis is performed with a common set of assumptions for each system arrangement. When the effect of varying a particular operating condition is explored, all assumptions are applied, except those affecting the condition being varied. Conditions are varied only over practical ranges, based on data in the literature or system operation limitations. In the analyses, heat pump and system COPs are compared, as are ground loop characteristics such as length and other system characteristics. Trends are identified and the sensitivities to particular parametric changes are compared for all systems. The heat pump for System 1 utilises a basic vapour compression cycle, which is widely utilized due to its simplicity and ease of design. The heat pump cycle consists of an evaporator, compressor, condenser and expansion valve, coupled with an electric motor for the compressor and a ground loop with a pump.

7.5.3 Assumptions and data

General assumptions made in this chapter are listed below:

- Pressure drops are neglected within the heat pump unit.
- All processes are treated as adiabatic, except heat exchange processes.
- Changes in elevation are negligible.
- The system operates at steady state, with steady flow conditions.

Additional assumptions specific to the heat pump and ground loop are noted (Tables 7.2-7.3).

7.5.4 System configuration

Three configurations are investigated in this research. The heat pump for System 1 utilises a basic vapour compression cycle, which is widely utilised due to its simplicity and ease of design [178-180]. The heat pump cycle (Figure 7.13) consists of an evaporator, compressor, condenser and expansion valve, coupled with an electric motor for the compressor and a ground loop with a pump. Figure 7.13 shows that the refrigerant at state 1 enters the evaporator where thermal energy is transferred to it from the ground loop. At state 2, the refrigerant exits the evaporator as superheated vapour and enters the compressor, where the pressure increases and the refrigerant exits as a high pressure superheated vapour at state 3. The refrigerant enters the condenser where thermal energy is extracted from the refrigerant and supplied to the space. The subcooled liquid at state 4 passes through an expansion valve that reduces its pressure to that of the evaporator. The systems in Figures 7.13 - 7.15 are analysed assuming a single centralised heat pump system that supplies the entire space with the required heat. A constant heating load is assumed. Other arrangements exist where multiple heat pump units cool and heat different building spaces, but are not considered here.

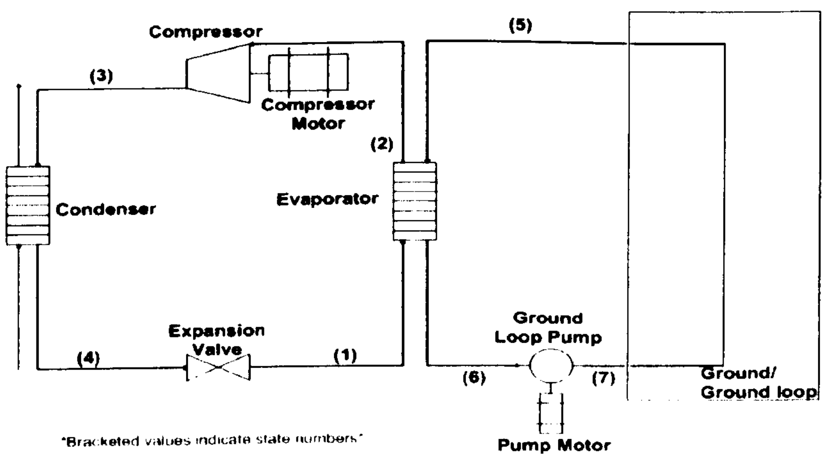


Figure 7.13 Heat pump system 1

The subcooled liquid at the state 4 passes through an expansion valve that reduces its pressure to that of the evaporator.

System 2 (Figure 7.14) is identical to system 1 except for a modified flow path used for motor cooling. The new path directs the refrigerant to the compressor electric motor assembly where wasted heat is recovered, increasing the energy content of the refrigerant at the evaporator inlet.

System 3 (Figure 7.15) incorporates an economiser, following the work of Ma and Chai [176]. In the economiser heat exchanger, heat is transferred between two refrigerant flows. The new flow path, called the supplementary circuit, includes an expansion valve that allows the flow to exist at an intermediate pressure between the evaporator and condenser pressure. Heat is extracted from the main refrigerant circuit by the supplementary circuit, and the main flow passes through an expansion valve lowering its pressure to the evaporator pressure. The supplementary circuit flow passes from the economiser to the compressor through a supplementary inlet. For ease of analysis, Ma and Chai [176] as well as Ma and Zhao [177] suggest interpreting the compression process as quasi two-stage compression with an intermediate mixing chamber [149-155].

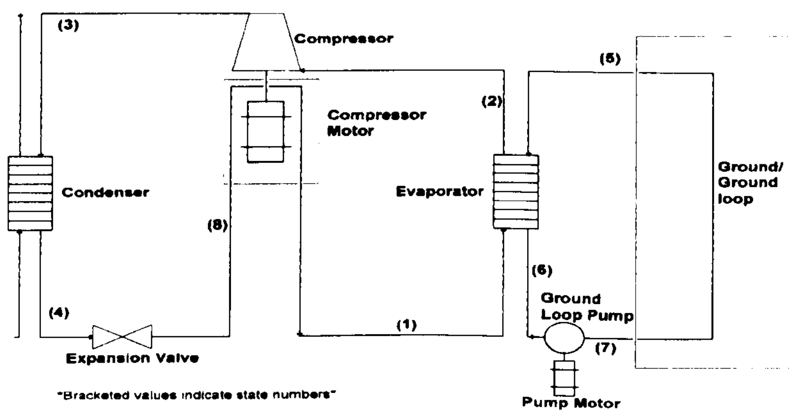


Figure 7.14 Heat pump system 2

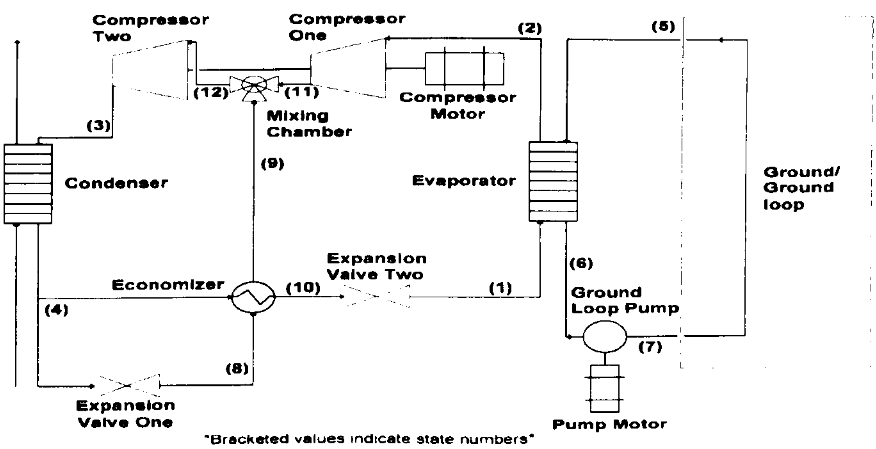


Figure 7.15 Heat pump system 3

This section describes the assumed parameter values used as input for the three systems considered and their operation. There are two loops within the system: the heat pump cycle and the ground loop. The arrangement and analysis for the ground loop is identical for the three systems. The borehole depth is assumed at 30 m and the borehole is assumed 143 mm (vertical system). The rest of the system parameters for the heat pump systems and the ground loop are given in Tables 7.2 and 7.3 respectively were determined from a set of initial measurements performed to determine suitable ranges.

Table 7.2 Assumed parameter values for the heat pump system

Parameter	Value
Refrigerant	R134a
Condenser pressure	1000 kPa
Evaporator pressure	200 kPa
Intermediate pressure	400 kPa
Degree of subcooling	5°C
Degree of superheating	5°C
Extra degree of subcooling	5°C
Compressor efficiency	75%
Pump efficiency	90%
Electric motor efficiency	80%

Table 7.3 Assumed parameter values for the ground loop

Parameter	Value
Evaporator inlet temperature (GL side)	7.3°C
Evaporator outlet temperature (GL side)	1.3°C
Flow rate through individual parallel GL	0.3 kg/s

7.5.5 Basic comparison

The systems considered are compared in terms of compressor and pump work rate, heat transfer rate from the ground loop system, overall ground loop length, and performance (for heat pump and system COPs). The state conditions for systems 1 to 3 are provided in Tables 7.4, 7.5 and 7.6 respectively. The main operation factors for the heat pumps are compared in Table 7.7.

Table 7.4 Conditions for system 1 for states in figures 7.13

State	Fluid	Temperature (°C)	Pressure (kPa)	Specific enthalpy (kJ/kg)	Mass flow rate (kg/s)
1	Refrigerant	-10.09	200	99.92	0.5136
2	Refrigerant	-5.093	200	248.7	0.5136
3	Refrigerant	61.16	1000	294.6	0.5136
4	Refrigerant	34.37	1000	99.92	0.5136
5	Brine	7.3	150	170.9	3.758
6	Brine	1.3	150	150.6	3.758
7	Brine	2.111	223.6	150.6	3.758

Table 7.5 Conditions for system 2 for states in figures 7.14

State	Fluid	Temperature (°C)	Pressure (kPa)	Specific enthalpy (kJ/kg)	Mass flow rate (kg/s)
1	Refrigerant	-10.09	200	111.4	0.5136
2	Refrigerant	-5.093	200	248.7	0.5136
3	Refrigerant	61.16	1000	294.6	0.5136
4	Refrigerant	34.37	1000	99.92	0.5136
5	Brine	7.3	150	170.9	3.468
6	Brine	1.3	150	150.6	3.468
7	Brine	2.111	223.6	150.6	3.468
8	Refrigerant	-10.09	200	99.92	0.5136

7.6 Results

System 3 is observed to have the highest COPs, with a heat pump (HP) COP of 4.265 and a system COP of 3.369, mostly due to its lower compressor work. System 3 also requires the most heat from the ground, leading to it having the longest round loop and consequently the greatest pump work. The increase in pump work reduces the system COP slightly. The HP COP and system COP for system 3 exceed those of system 1 by 0.54% and 0.54%, respectively. In system 3, only part of the refrigerant flowing through the condenser is compressed from the lowest to highest pressure, reducing the work required by the first compressor. System 3 yields the same compressor exit temperature with a lower pressure ratio between the condenser and evaporator pressure, which further reduces compressor work if its exit temperature is set to that of systems 1 and 2.

Table 7.6 Conditions for system 3 for states in figures 7.15

State	Fluid	Temperature (°C)	Pressure (kPa)	Quality	Specific enthalpy (kJ/kg)	Mass flow rate (kg/s)
1	Refrigerant	-10.09	200	0.2632	92.66	0.4905
2	Refrigerant	-5.093	200	1	248.7	0.4905
3	Refrigerant	61.86	1000	1	295.3	0.5117
4	Refrigerant	34.37	1000	0	99.92	0.5117
5	Brine	7.3	150	0	170.9	3.764
6	Brine	1.3	150	0	150.6	3.764
7	Brine	2.111	200	0	150.6	3.764
8	Refrigerant	8.91	400	0.1878	99.92	0.02119
9	Refrigerant	22.41	400	1	268.1	0.02119
10	Refrigerant	29.37	1000	0	92.66	0.4905
11	Refrigerant	22.41	400	1	268.1	0.4905
12	Refrigerant	22.41	400	1	268.1	0.5117

Table 7.7 Heat pump and ground loop characteristics for systems

Characteristic	System 1	System 2	System 3
Pressure ratio	5	5	5
Compressor work rate (kW)	23.57	23.57	23.45
Compressor motor electricity rate (kW)	29.46	29.46	29.31
Pump work rate (kW)	0.2978	0.2749	0.2983
Pump motor electricity rate (kW)	0.3723	0.3436	0.3729
Heat rate supplied by GL system (kW)	76.43	70.54	76.55
Total GL length	3346	3088	3352
COP_{HP}	4.242	4.242	4.265
COP_{System}	3.352	3.355	3.369

7.7 Theory

The analyses performed are explained in this section: one for each heat pump in the three systems and one for the ground loop, which is common for each system.

The electric motor provides mechanical work to the compressor and its rate of electrical energy consumption can be evaluated as follows [156]:

$$E_{comp, motor} = W_{comp} / \eta_{em} \quad (7.1)$$

Where: $E_{comp, motor}$ is electrical power consumed by compressor and pump motors, kW W_{com} is electrical power consumed by compressor motor, kW; η_{em} is the efficiency of the electric motor.

The COP for the heat pump can be written as [157]:

$$COP_{HP} = Q_{load} / W_{comp} \quad (7.2)$$

Where: COP_{HP} is the coefficient of performance of the heat pump cycle with the exclusion of motor and pump work and Q_{load} is the building-heating load. The COP can alternately be expressed as [158]:

$$COP_{HP} = Q_{load} / (Q_{load} - Q_{evap}) \quad (7.3)$$

Where: Q_{evap} is the rate of heat transfer to the refrigerant through the evaporator.

The system coefficient of performance COP_{system} is similar to the heat pump COP, but employs the electrical energy supply rate in the denominator [159]:

$$Q_{evap} = m_{main} (h_2 - h_1) \quad (7.10)$$

Where h_1 is the specific enthalpy at state 1, h_2 is the actual specific enthalpy at states 2.
The heat transfer to the ground loop fluid per unit length is:

$$Q = (T_1 - T_2)/R_{total} \quad (7.11)$$

Where: T_1 denotes the temperature on the outer wall of the grout (ground temperature) and T_2 the mean fluid temperature. R_{total} is total thermal resistance, °C/W.

7.8 System component analysis

This section investigates and compares the effects of varying several heat pump component parameters, including compressor, pump and electric motor efficiencies. The condenser and evaporator pressure for each system remain fixed at those for the basic systems.

7.8.1 Compressor efficiency analysis

The mechanical efficiency is started from 65% for each of the heat pump systems, following the range given by Cengel, et al., [181] for low to high efficiency compressors. The results depicted in Figure 7.16 show that HP COP increases nearly linearly with compressor efficiency. The curves for systems 1 are identical to those for system 2, but slightly different for systems 3, with the COP of system 3 increasing more rapidly with compressor efficiency.

The differences in heat pump COP range from 3.81 to 5.32 (or by 1.51) for systems 1 and 2 and from 3.80 to 5.42 (or by 1.62) for system 3. System 3 is more sensitive to variations in compressor efficiency than systems 1 and 2. This behaviour stems from the design and operation of system 3, which includes two stages of compression. For compressor 2, the conditions at the inlet (state 12) change with compressor efficiency, unlike compressor 1 which has static inlet conditions over the entire range of efficiencies. Hence, when the efficiency is low, the work required by system 3 exceeds that required by system 1 to achieve the same condenser pressure.

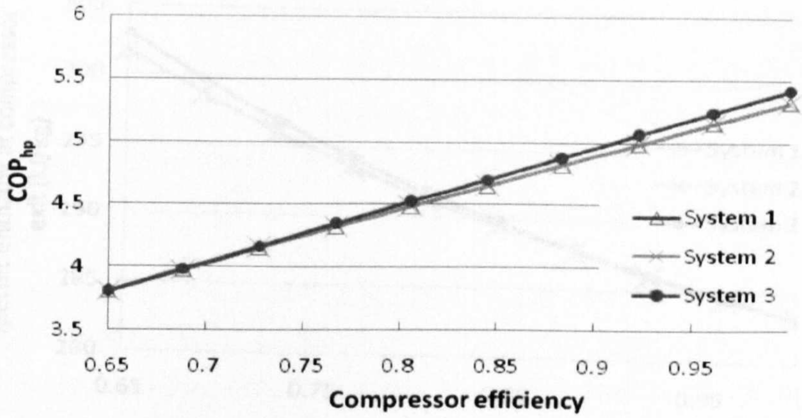


Figure 7.16 Effect of changing compressor efficiency on heat pump COP for each system

As the efficiency is varied the mass flow rate of the refrigerant through the condenser varies as well, in relation to the specific enthalpy at state 3. Figure 7.17 shows that the specific enthalpy at state 3 for systems 1 and 2 are identical. Overall the specific enthalpy with regard to the same state within system 3 exceeds that of system 1 and progressively approaches the values observed for the basic system as efficiency increases.

The trend is inverted when the mass flow rate is considered (Figure 7.18). As the compressor efficiency increases the refrigerant flow rate increases. The flow rate for system 3 is always below that of the other two systems until the efficiency of the compressor is 100%, at which point the flow rates are equal.

When the compressor efficiency is 100%, the compressor work in system 3 is lower than for the other two systems (Figure 7.19). The trend of decreasing compressor work and increasing mass flow rate through the evaporator seem to be contrdictive. The trend of reducing compressor work with increasing flow rate results from a slight change in refrigerant flow rate over the range of compressor efficiencies. It can also be observed in Figure 7.17 that system 3 is the most sentitive to changes in compressor efficiency as it covers the largest range of COP values. The economiser arrangement, within system 3, is best utilised when high efficiency compressors are available.

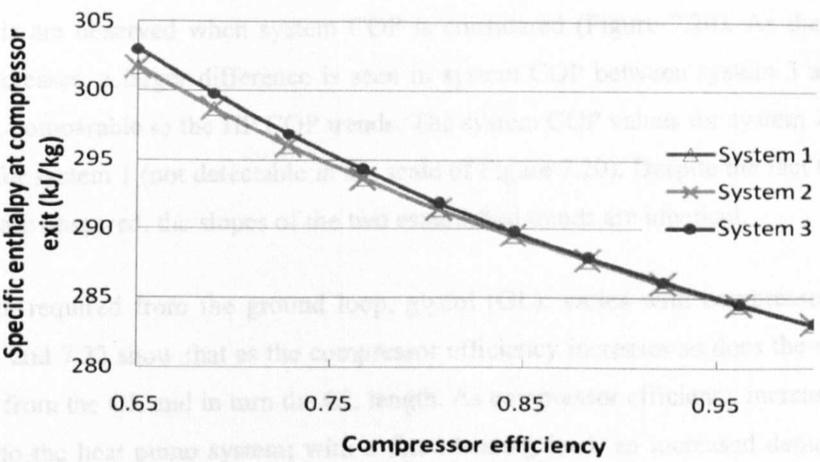


Figure 7.17 Effect of varying compressor efficiency on specific enthalpy at condenser inlet for each system

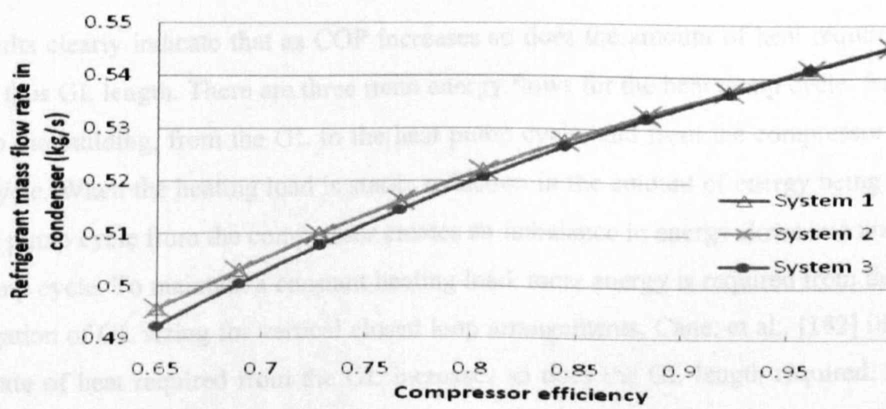


Figure 7.18 Effect of varying compressor efficiency on condenser flow rate for each system

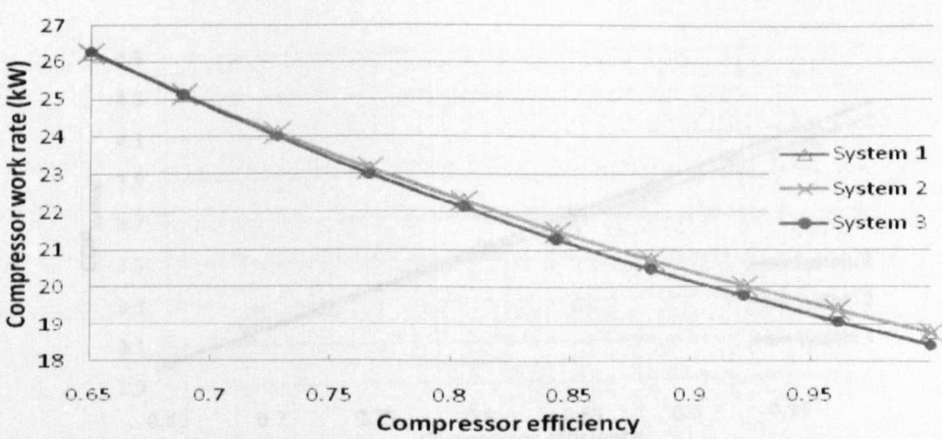


Figure 7.19 Effect of varying compressor efficiency on rate of compressor work required for each system

Similar trends are observed when system COP is considered (Figure 7.20). As the compressor efficiency increases, a larger difference is seen in system COP between system 3 and the other two systems, comparable to the HP COP trends. The system COP values for system 2 are slightly higher than for system 1 (not detectable in the scale of Figure 7.20). Despite the fact that different COP values are observed, the slopes of the two established trends are identical.

The heat rate required from the ground loop, glycol (GL), varies with compressor efficiency. Figures 7.21 and 7.22 show that as the compressor efficiency increases so does the required heat transfer rate from the GL and in turn the GL length. As compressor efficiency increases less work is provided to the heat pump system; with a fixed heating load, an increased demand from the ground loop exists. It can be seen that system 3 has the largest range in heat transfer rate from the GL, attributable to the fact that system 3 exhibits the largest range in COP.

The results clearly indicate that as COP increases so does the amount of heat required from the GL and thus GL length. There are three main energy flows for the heat pump cycle: from the heat pump to the building, from the GL to the heat pump cycle, and from the compressor to the heat pump cycle. When the heating load is static, reduction in the amount of energy being supplied to the heat pump cycle from the compressor creates an imbalance in energy flows into and out of the heat pump cycle. To maintain a constant heating load, more energy is required from the GL. In an investigation of GL sizing for vertical closed loop arrangements, Cane, et al., [182] illustrate that as the rate of heat required from the GL increases so does the GL length required. RETScreen International [183] also provides information that suggests that there is a direct relationship between the COP of a heat pump system and the length required for the ground loop.

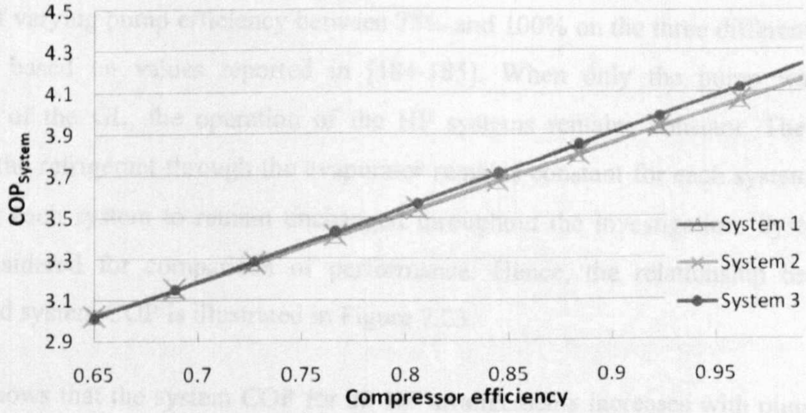


Figure 7.20 Effect of varying compressor efficiency on system COP for each system

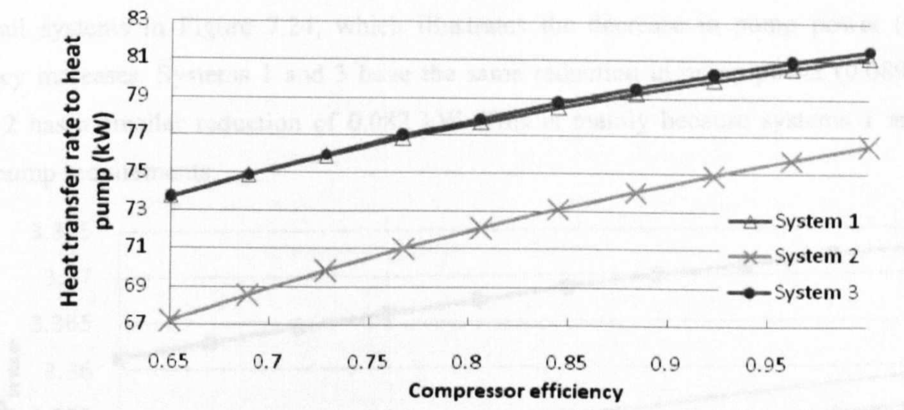


Figure 7.21 Effect of varying compressor efficiency on the rate of heat transfer to the heat pump from the ground loop

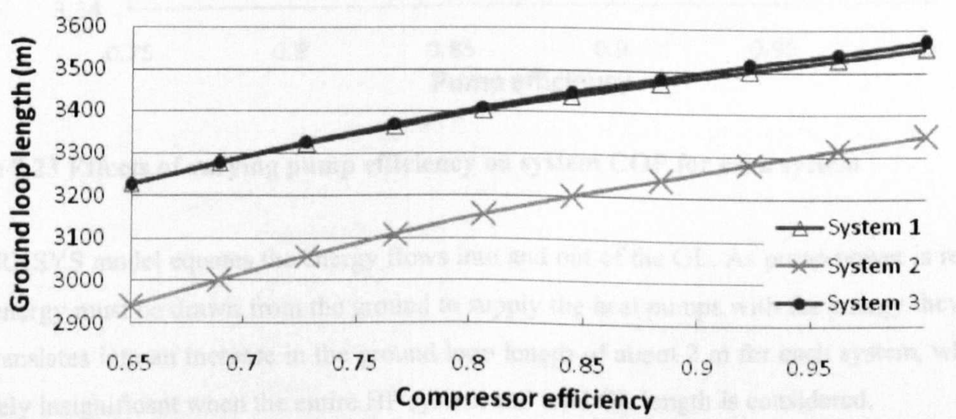


Figure 7.22 Effect of varying compressor efficiency on ground loop length for each system

7.8.2 Pump efficiency analysis

The effect of varying pump efficiency between 75% and 100% on the three different systems was investigated based on values reported in [184-185]. When only the pump was considered independent of the GL, the operation of the HP systems remains constant. The rate of heat required by the refrigerant through the evaporator remains constant for each system, causing the HP COP for each system to remain unchanged throughout the investigation. System COP can only be considered for comparison of performance. Hence, the relationship between pump efficiency and system COP is illustrated in Figure 7.23.

The figure shows that the system COP for all HP arrangements increases with pump efficiency. Each system has an overall COP change of 0.013 for the range of efficiencies considered, which is relatively small. This increase in system COP is in fact due to a reduction in the pump power within all systems in Figure 7.24, which illustrates the decrease in pump power (W) pump efficiency increases. Systems 1 and 3 have the same reduction in pump power (0.089 kW) and system 2 has a smaller reduction of 0.082 kW. This is mainly because systems 1 and 3 have higher pump requirements.

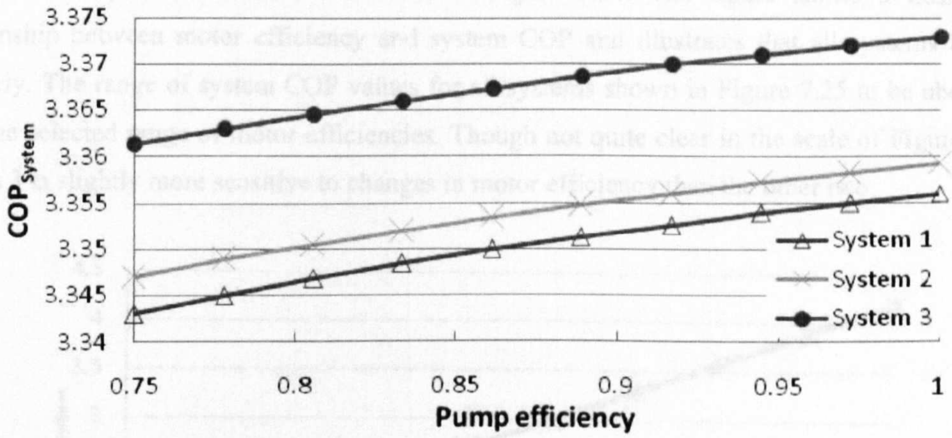


Figure 7.23 Effects of varying pump efficiency on system COP for each system

The TRNSYS model equates the energy flows into and out of the GL. As pump power is reduced more energy must be drawn from the ground to supply the heat pumps with the energy they need. This translates into an increase in the ground loop length of about 2 m for each system, which is relatively insignificant when the entire HP system and total GL length is considered.

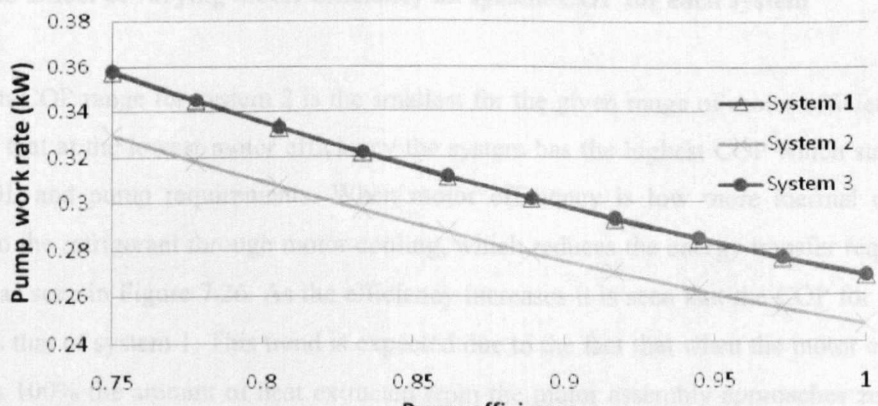


Figure 7.24 Effects of varying pump efficiency on rate of pump work required for each system

7.8.3 Motor efficiency analysis

Electric motors are coupled to the compressors and pumps. The motor efficiency was varied from 35% to 100% based on the suitable range reported in [186]. As in the pump analysis, varying motor efficiency affects the system COP as Figure 7.26. The figure shows a near-linear relationship between motor efficiency and system COP and illustrates that all systems behave similarly. The range of system COP values for all systems shown in Figure 7.25 to be about 2.7 over the selected range of motor efficiencies. Though not quite clear in the scale of Figure 7.25, system 3 is slightly more sensitive to changes in motor efficiency than the other two.

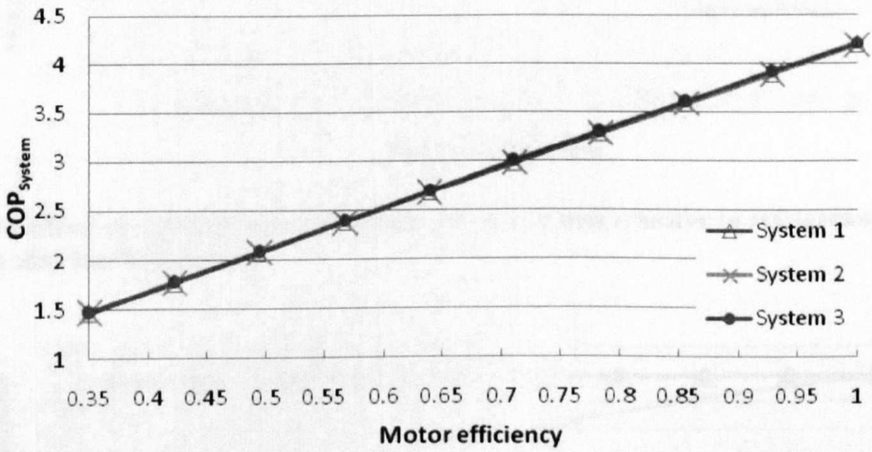


Figure 7.25 Effect of varying motor efficiency on system COP for each system

The system COP range for system 2 is the smallest for the given range of motor efficiencies due to the fact that at the lowest motor efficiency the system has the highest COP which stems from lowered GL and pump requirements. When motor efficiency is low more thermal energy is available to the refrigerant through motor cooling, which reduces the energy transfer requirement of the GL as seen in Figure 7.26. As the efficiency increases it is seen that the COP for system 2 approaches that of system 1. This trend is expected due to the fact that when the motor efficiency approaches 100% the amount of heat extracted from the motor assembly approaches zero. If no heat is supplied to the system by the motor, all of the required heat must come from the ground.
While rates of heat transfer through the evaporators in systems 1 and 3 do not change with efficiency. The rate of heat transfer for system 2 is affected significantly by the motor efficiency by design, as motor waste heat contributes to the heat requirement of the HP system. Identical trends are found for the GL length and pump power requirement as those found for the heat

requirement from the evaporator (Figure 7.27). This is because when the GL load is reduced the GL length and pumping requirements associated also decrease allowing system 2 to have the highest system COP at low motor efficiencies as discussed earlier.

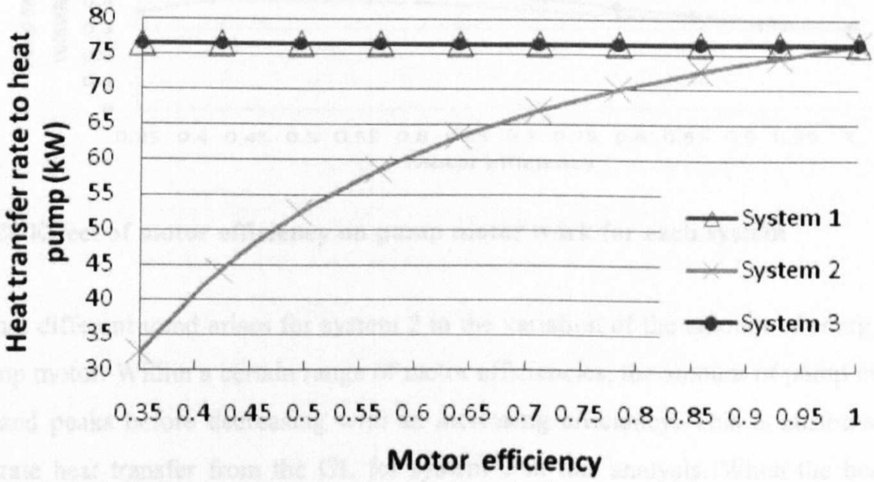


Figure 7.26 Effect of varying motor efficiency on rate of heat transfer to refrigerant through the evaporator for each system

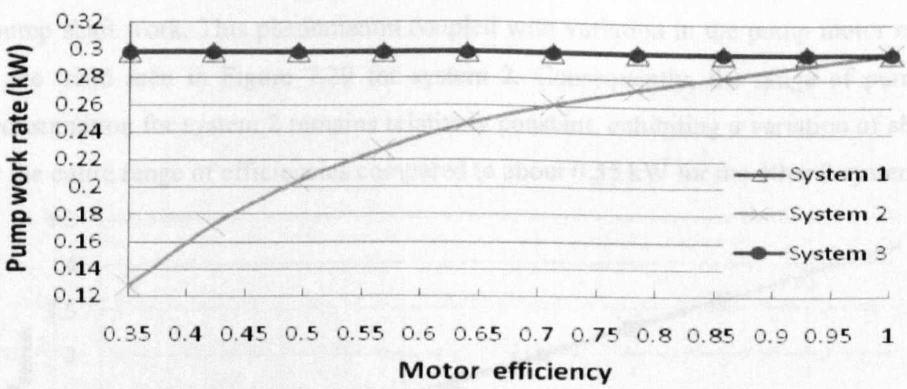


Figure 7.27 Effect of motor efficiency on pump work rate required within the ground loop for each system

Figure 7.28 illustrates the varyiation of the amount of energy consumed by the pump motor with motor efficiency. For systems 1 and 3 the trends are similar, with the amount of energy required by the pump motor decreasing with increasing motor efficiency. This trend is expected since the motor efficiency directly determines, for a given output, the amount of energy it requires, for a given output. More energy is consumed by a motor with low efficiency compared to high efficiency one.

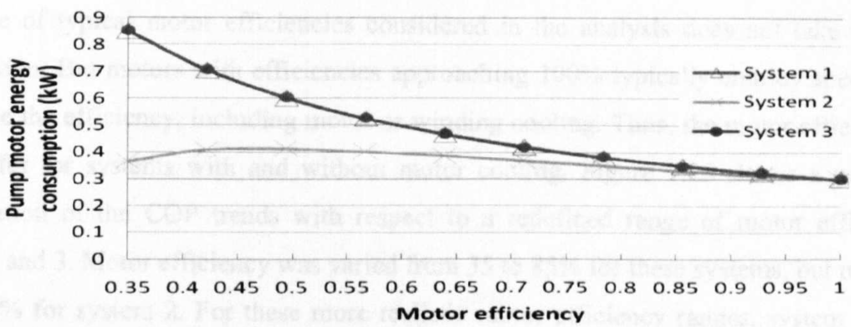


Figure 7.28 Effect of motor efficiency on pump motor work for each system

A somewhat different trend arises for system 2 in the variation of the amount of energy required by the pump motor. Within a certain range of motor efficiencies, the amount of pump motor work increases and peaks before decreasing with an increasing efficiency. This is attributable to the changing rate heat transfer from the GL for system 2 in this analysis. When the heat transfer requirement changes so does the GL length, with the variation in the GL length directly affecting the power required by the pump to move the brine around the loop. The pump power also decreases when the GL length is reduced; thus reducing the requirement of the pump motor to supply pump shaft work. This phenomenon coupled with variation in the pump motor efficiency leads to the trend seen in Figure 7.29 for system 2. Consequently, the range of pump motor energy consumption for system 2 remains relatively constant, exhibiting a variation of about 0.11 kW over the entire range of efficiencies compared to about 0.55 kW for the other 2 systems.

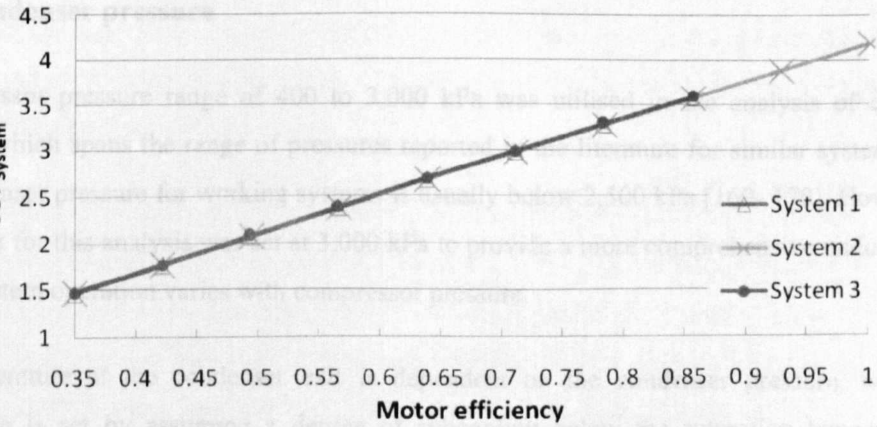


Figure 7.29 Effect of motor efficiency on system COP for each system, considering revised efficiency ranges

$$COP_{system} = Q_{load} / E_{motor,\ total} \quad (7.4)$$

Where: $E_{motor,\ total}$ is the total rate of electrical energy consumed by the compressor and pump motors. The total rate of electrical consumption is [160]:

$$E_{motor,\ total} = E_{comp,\ motor} + E_{motor,\ pump} \quad (7.5)$$

Where: $E_{comp,\ motor}$ and $E_{motor,\ pump}$ are the rates of electrical energy consumption of the compressor motor and pump motor, respectively.

The available waste energy from the compressor motor is the difference between the compressor work rate and the electrical energy consumption rate of the motor [161]:

$$E_{motor,\ waste} = E_{comp,\ motor} - W_{comp} \quad (7.6)$$

Where: $E_{motor,\ waste}$ is the rate waste energy of the compressor motor, $E_{comp,\ motor}$ is the rate of electrical energy consumption for the motor, and W_{comp} is the rate of work required by the compressor.

When motor cooling is incorporated, the heat pump COP is slightly modified so that the heat supply rate to the refrigerant from the motor is included [162]:

$$COP_{HP} = Q_{load} / (Q_{load} - (Q_{evap} + Q_{waste\ heat})) \quad (7.7)$$

The mass flow rate of refrigerant can be found with a condenser energy rate balance:

$$Q_{load} = m_{ref}\,(h_3 - h_4) \quad (7.8)$$

Where: Q_{load} is the specified heating load, m_{ref} is the refrigerant mass flow rate, and h_3 and h_4 are the specific enthalpies for states 3 and 4, respectively.

The rate of heat transfer from the ground loop to the refrigerant through the evaporator is calculated as follows:

$$Q_{evap} = m_{ref}\,(h_3 - h_2) \quad (7.9)$$

Where: m_{ref} is the mass flow rate of refrigerant, and h_2 and h_3 are the specific enthalpies for states 2 and 3, respectively. The rate of heat transfer to the refrigerant is equal to the rate of heat removal from the GL brine through the evaporator.

The heat transfer rate required from the GL for this arrangement is determined as:

The range of typical motor efficiencies considered in the analysis does not take into account motor design. But motors with efficiencies approaching 100% typically employ special methods to increase the efficiency, including motor or winding cooling. Thus, the motor efficiency ranges likely differ for systems with and without motor cooling. Figure 7.25 shows a more realistic representation of the COP trends with respect to a redefined range of motor efficiencies for systems 1 and 3. Motor efficiency was varied from 35 to 85% for these systems, but maintained at 35 to 100% for system 2. For these more realistic motor efficiency ranges, system 2 exhibits a larger potential for a high system COP, since the system COP values extend past those of systems 1 and 3. Although systems 1 and 3 are general affected the most by varying motor efficiency since they exhibit the largest variations in system COPs within a given efficiency range as discussed earlier, system 2 was found to have the largest range of system COPs when a realistic motor efficiencies were employed for system 1 and 3.

7.9 Operating conditions analysis

The impact on the performance of the heat pump units was investigated by varying several operating conditions, including condenser and evaporator pressure as well as the degree of superheating and subcooling at the outlet of the evaporator and evaporator, respectively. System 3 utilises an intermediate pressure between the evaporator and condenser pressure; the effect of varying this intermediate pressure was also investigated.

7.9.1 Condenser pressure

A compressor pressure range of 400 to 3,000 kPa was utilised in the analysis of condenser pressure, which spans the range of pressures reported in the literature for similar systems [169]. The condenser pressure for working systems is usually below 2,500 kPa [169- 170]. However, an upper limit for this analysis was set at 3,000 kPa to provide a more comprehensive understanding of how system operation varies with compressor pressure.

The temperature at the condenser exit is dependent on the condenser pressure, where the temperature is set by assuming a degree of subcooling below the saturation temperature of refrigerant at the specified pressure. At low condenser pressures, the temperatures at the condenser inlet and exit (states 3 and 4 for all system arrangements) become too low for use with the conventional heat distribution systems utilised in building design. Figure 7.30 shows the condenser inlet and exit temperatures for pressures between 400 and 3000 kPa. The inlet and outlet condenser temperatures are generally low for all systems at low condenser pressures, e.g., at 400 kPa the inlet and outlet temperatures for all the systems are about 22°C and 4°C, respectively. Then, temperature starts to increase gradually with condenser pressure as shown in the figure.

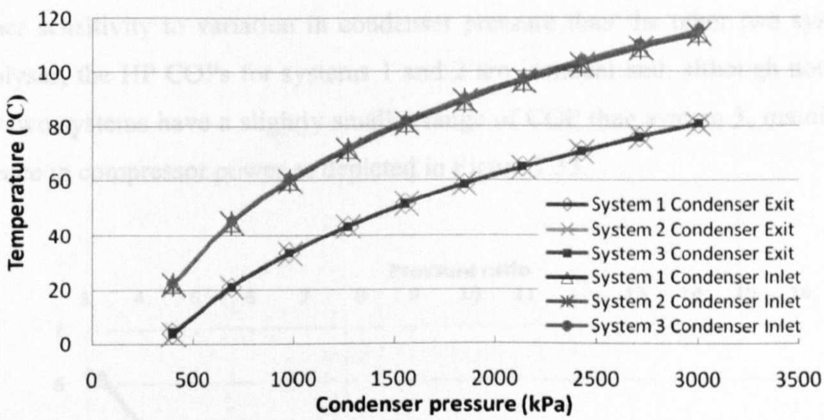


Figure 7.30 Effect of varying condenser pressure on condenser inlet and outlet temperatures for each system

Of all the heat distribution arrangements, hydronic heat distribution systems typically have the lowest design temperature, usually 18-22°C. The inlet and outlet temperatures of the condenser on the building side using a hydronic heat distribution system should not be below this temperature range [176, 183, 184, and 185]. Thus the lowest temperatures at the condenser inlet and exit for the heat pump cycle should ideally be within or above the temperature range for hydronic systems to allow for proper heat transfer across the condenser between the heat pump and the building heat distribution system.

Consequently, the analysis below considers pressures between 650 and 3000 kPa, allowing appropriate temperatures across the condenser. For this range of condenser pressures, the HP and system COPs for all the systems decrease with increasing condenser pressure. All systems follow similar trends as pressure increases; with a rapid decrease in COP initially followed by a gradual decrease in COP (Figures 7.31 and 7.32). This trend is attributable to the compressor power over the range of condenser pressures. The increase in compressor power as pressure increases is notable at low condenser pressures and levels off at higher pressures (Figure 7.33). Also increasing condenser pressure raises the temperature at the inlet and exit of condenser. The condenser inlet and exit temperatures vary differently with condenser pressure. Figure 7.34 shows that the condenser inlet temperature increases more than the condenser exit temperature over the same range of condenser pressures, which in turn reduces the refrigerant flow rate through the condenser. These two factors lead to the trends observed for compressor work and, in turn, the behaviour of the heat pump HP and system COP's. It can be seen in Figures 7.31 and 7.32 that the COP decreases with increasing pressure ratio. It also worth noting that system 3 exhibits a slightly higher sensitivity to variation in condenser pressure than the other two systems. As in previous analyses, the HP COPs for systems 1 and 2 are identical and, although not clear in the figure, these two systems have a slightly smaller range of COP than system 3, mainly due to the small difference in compressor power as depicted in Figure 7.33.

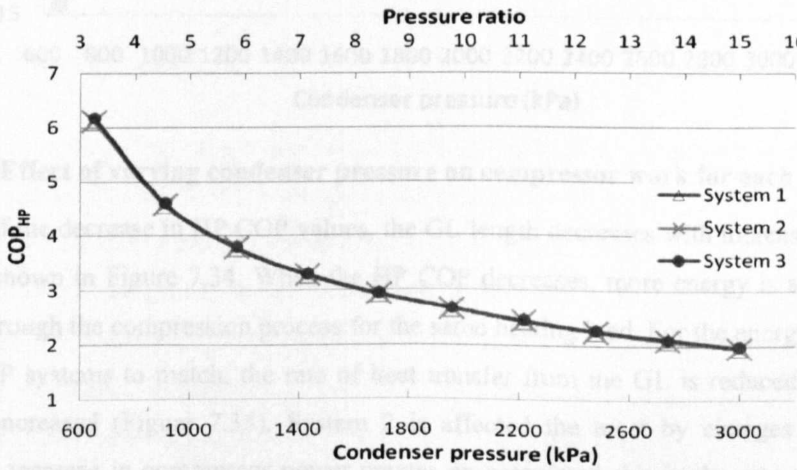


Figure 7.31 Effect of varying condenser pressure on heat pump COP for each system

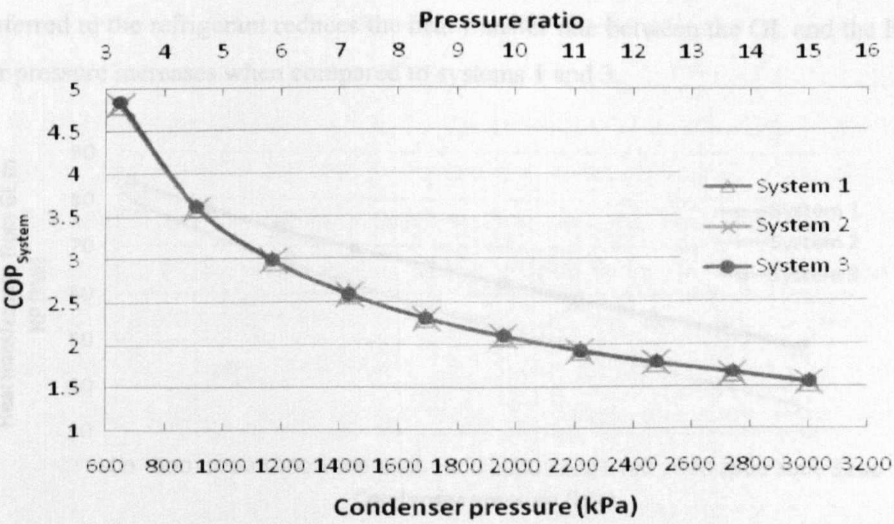


Figure 7.32 Effect of varying condenser pressure on system COP for each system

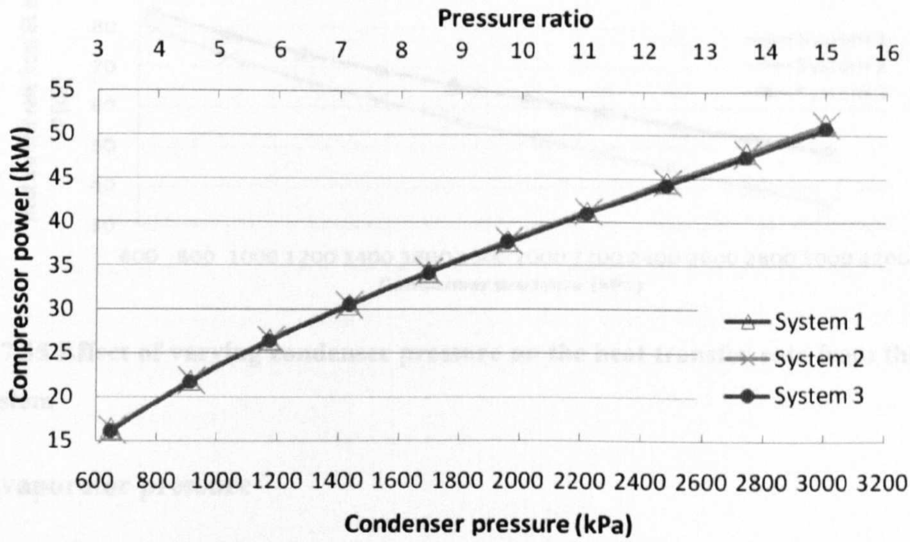


Figure 7.33 Effect of varying condenser pressure on compressor work for each system

As a result of the decrease in HP COP values, the GL length decreases with increasing condenser pressure as shown in Figure 7.34. When the HP COP decreases, more energy is supplied to the HP cycles through the compression process for the same heating load. For the energy flows in and out of the HP systems to match, the rate of heat transfer from the GL is reduced as condenser pressure is increased (Figure 7.35). System 2 is affected the most by changes in condenser pressure. An increase in compressor power creates an associated rise in the rate of compressor motor energy consumption, which is directly associated with an increase of available waste energy from the compressor motor for preheating the refrigerant in system 2. The motor waste heat transferred to the refrigerant reduces the heat transfer rate between the GL and the HP as the condenser pressure increases when compared to systems 1 and 3.

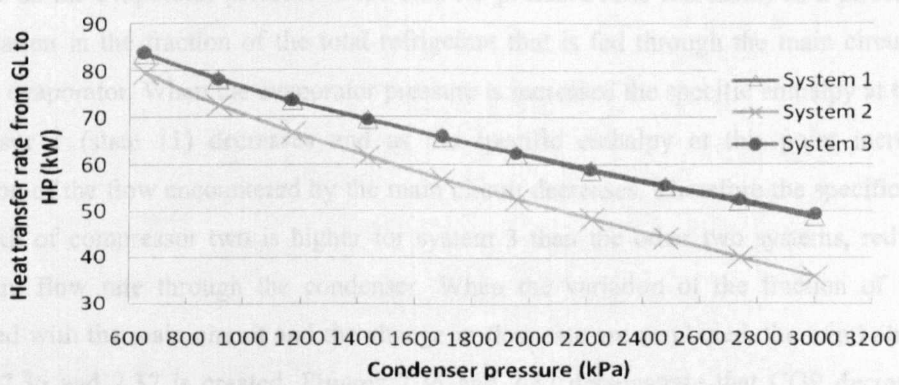


Figure 7.34 Effect of varying condenser pressure on ground loop length for each system

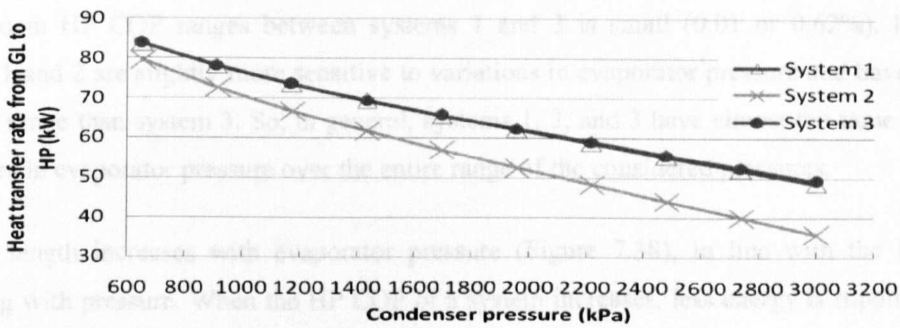


Figure 7.35 Effect of varying condenser pressure on the heat transfer rate from the GL for each system

7.9.2 Evaporator pressure

The effect of varying evaporator pressure on the systems was considered with a minimum evaporator pressure fixed so that the refrigerant temperature at the evaporator inlet was above the freezing temperature of the brine solution in the ground loop (-13.08ºC). The maximum pressure was set so that the refrigerant temperature at the evaporator exit does not exceed the brine temperature at the evaporator inlet and so that the refrigerant evaporator inlet temperature was below that of the brine evaporator exit temperature in order to allow for proper heat transfer. An evaporator pressure range of 178 to 305 kPa satisfies theses conditions.

As evaporator pressure increases, HP and system COPs increase almost linearly for all systems (Figures 7.36 and 7.37). The trends are similar to the ones observed in the condenser pressure analysis. However, as the pressure ratio between the condenser and evaporator increases, the HP and system COPs for the systems decrease. Hence, the difference in HP COP for systems 1 and 3 increases as the evaporator pressure is lowered (as pressure ratio increases) as a direct result of the alteration in the fraction of the total refrigerant that is fed through the main circuit and, in turn, the evaporator. When the evaporator pressure is increased the specific enthalpy at the exit of compressor 1 (state 11) decreases and as the specific enthalpy at this point increases the proportion of the flow encountered by the main circuit decreases. Therefore the specific enthalpy at the exit of compressor two is higher for system 3 than the other two systems, reducing the refrigerant flow rate through the condenser. When the variation of the fraction of flow rate associated with the main circuit and the change in flow rate are combined, the trend observed in Figures 7.36 and 7.37 is created. Figures 7.36 and 7.37 demonstrate that COP decreases with decreasing evaporator pressure and associated increase in pressure ratio. Also note that the difference in HP COP ranges between systems 1 and 3 is small (0.01 or 0.62%). However, Systems 1 and 2 are slightly more sensitive to variations in evaporator pressure and have a larger HP COP range than system 3. So, in general, systems 1, 2, and 3 have almost the same response to changes in evaporator pressure over the entire range of the considered pressures.

The GL length increases with evaporator pressure (Figure 7.38), in line with the HP COP increasing with pressure. When the HP COP of a system increases, less energy is supplied to the HP cycles as compression work for the same heating load. For the energy flows in and out of the HP systems to be equal, the thermal energy extracted from the GL increases as evaporator pressure is increased (Figure 7.39).

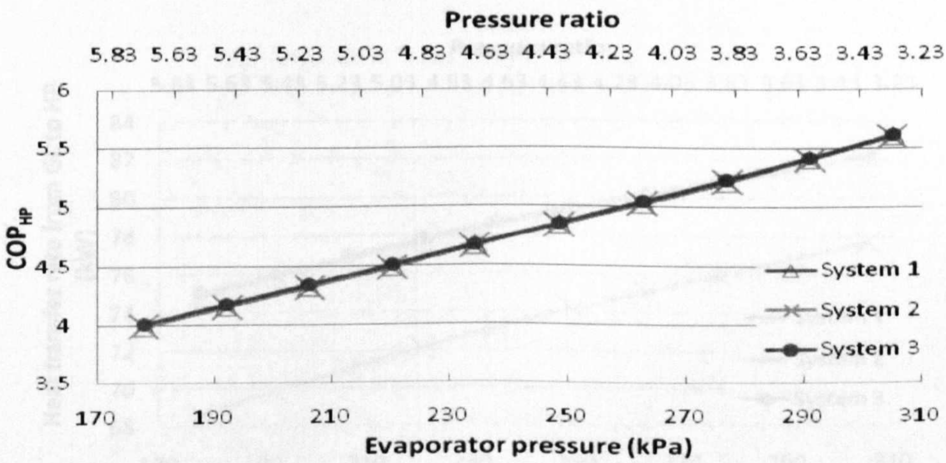


Figure 7.36 Effect of varying evaporator pressure on heat pump COP for each system

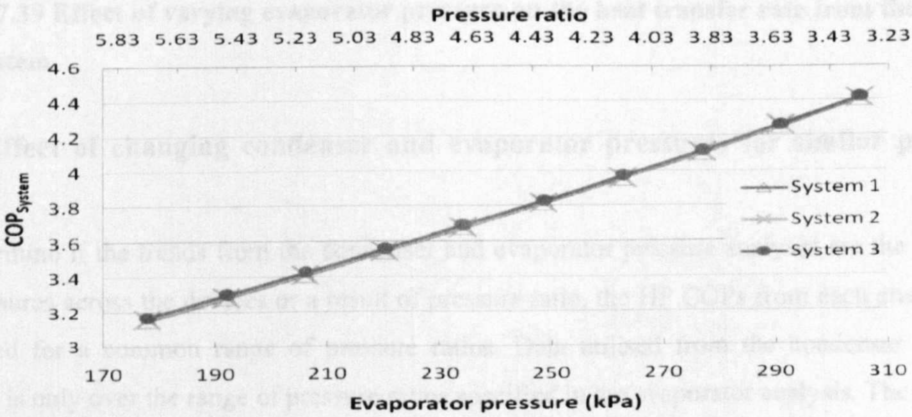


Figure 7.37 Effect of varying evaporator pressure on system COP for each system

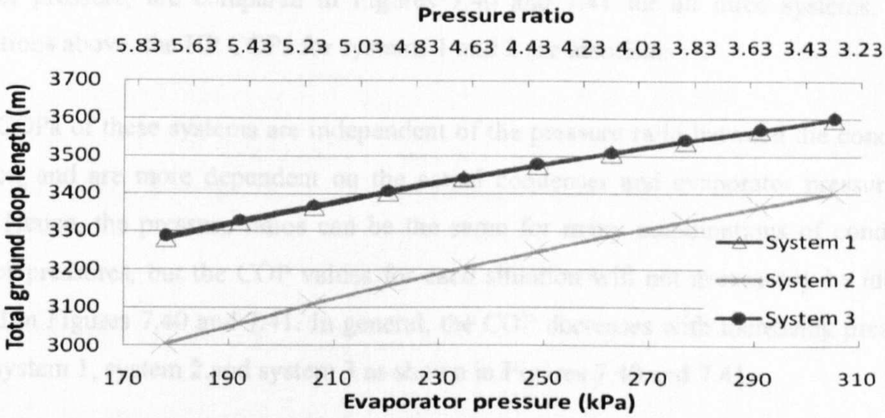


Figure 7.38 Effect of varying evaporator pressure on total GL length for each system

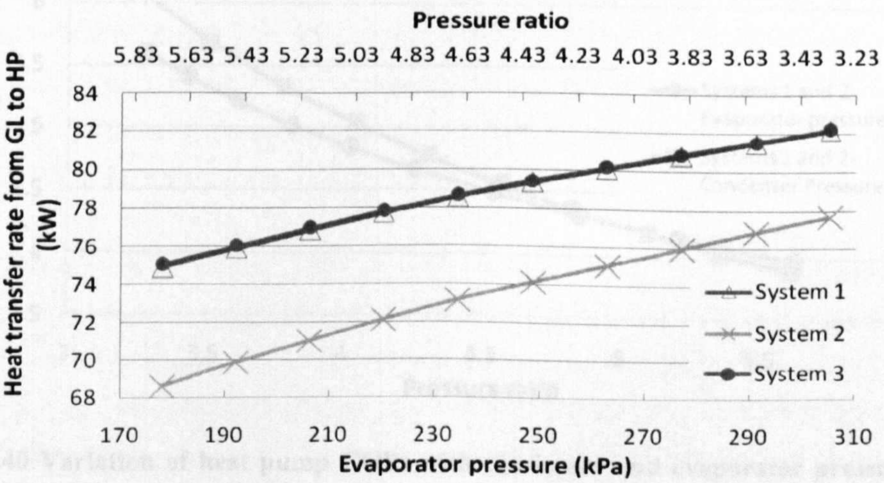


Figure 7.39 Effect of varying evaporator pressure on the heat transfer rate from the GL for each system

7.9.3 Effect of changing condenser and evaporator pressures for similar pressure ratios

To determine if the trends from the condenser and evaporator pressure analyses are the result of the pressures across the devices or a result of pressure ratio, the HP COPs from each analysis are compared for a common range of pressure ratios. Data utilised from the condenser pressure analysis is only over the range of pressure ratios specified in the evaporator analysis. The pressure ratios coincide with varying evaporator pressure and a fixed condenser pressure of 1000 kPa and the pressure ratios corresponding to varying condenser pressure with a fixed evaporator pressure of 200 kPa. The trends with changing pressure ratios, due to changing either condenser or evaporator pressure, are compared in Figures 7.40 and 7.41 for all three systems. As in the investigations above, the HP COPs for systems 1 and 2 are identical.

The HP COPs of these systems are independent of the pressure ratio between the condenser and evaporator, and are more dependent on the actual condenser and evaporator pressures for the systems. Hence, the pressure ratios can be the same for many combinations of condenser and evaporator pressures, but the COP values for each situation will not necessarily be identical, as illustrated in Figures 7.40 and 7.41. In general, the COP decreases with increasing pressure ratio for both system 1, system 2.and system 3 as shown in Figures 7.40 and 7.41.

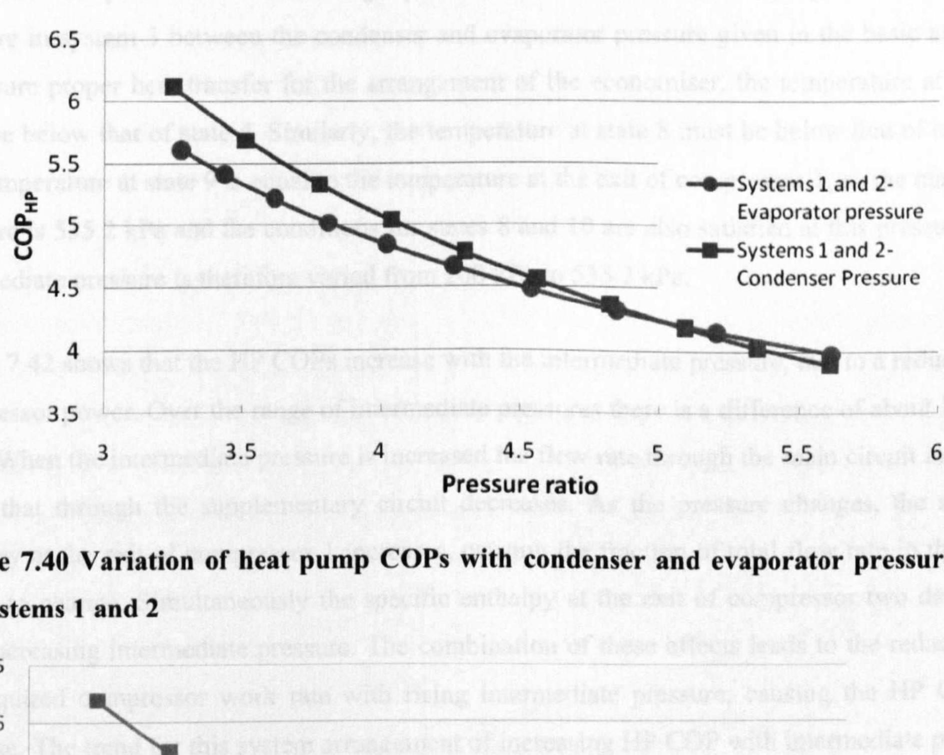


Figure 7.40 Variation of heat pump COPs with condenser and evaporator pressure ratio, for systems 1 and 2

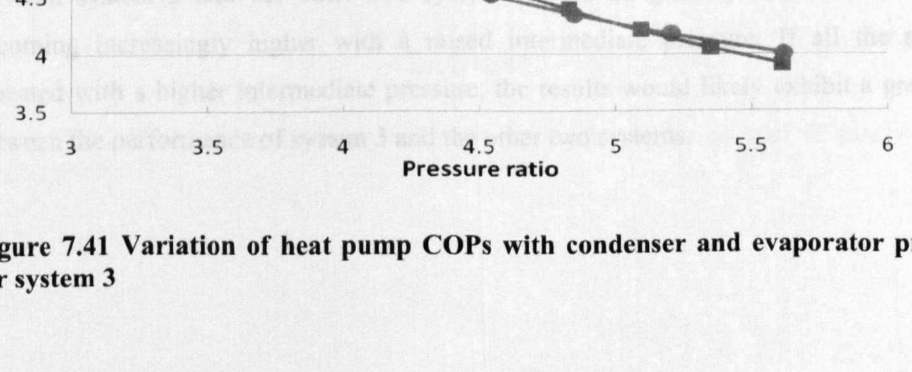


Figure 7.41 Variation of heat pump COPs with condenser and evaporator pressure ratio, for system 3

Heat pump efficiency is primarily dependent upon the temperature difference between the building interior and the environment. For a Carnot engine, this is entirely determined by the temperatures of hot and cold reservoirs: $\eta_{Carnot} = 1-(T_c/T_h)$. If this difference can be maximised, heat pumps efficiency (and capacity) will improve. It can also be observed that the HP COP is more sensitive to the variation in condenser pressure compared to the variation of evaporator pressure.

7.9.4 Intermediate pressure in system 3

The effect on performance and design parameters is examined of varying the intermediate pressure in system 3 between the condenser and evaporator pressure given in the basic analysis. To ensure proper heat transfer for the arrangement of the economiser, the temperature at state 9 must be below that of state 4. Similarly, the temperature at state 8 must be below that of state 10. The temperature at state 9 is equal to the temperature at the exit of compressor 1, so the maximum pressure is 535.2 kPa and the conditions for states 8 and 10 are also satisfied at this pressure. The intermediate pressure is therefore varied from 200 kPa to 535.2 kPa.

Figure 7.42 shows that the HP COPs increase with the intermediate pressure, due to a reduction in compressor power. Over the range of intermediate pressures there is a difference of about 1.3% in COP. When the intermediate pressure is increased the flow rate through the main circuit increases while that through the supplementary circuit decreases. As the pressure changes, the specific enthalpy at the exit of compressor 1 increases, causing the fraction of total flow rate in the main circuit to change. Simultaneously the specific enthalpy at the exit of compressor two decreases with increasing intermediate pressure. The combination of these effects leads to the reduction in the required compressor work rate with rising intermediate pressure, causing the HP COP to increase. The trend for this system arrangement of increasing HP COP with intermediate pressure is consistent with the trends found by the theoretical of Ma and Chai [176]. If an increased intermediate pressure is used in the basic comparison of the systems, the difference in COPs between system 3 and the other two systems would be greater, with the COP of system 3 becoming increasingly higher with a raised intermediate pressure. If all the analyses were repeated with a higher intermediate pressure, the results would likely exhibit a greater variation between the performance of system 3 and the other two systems.

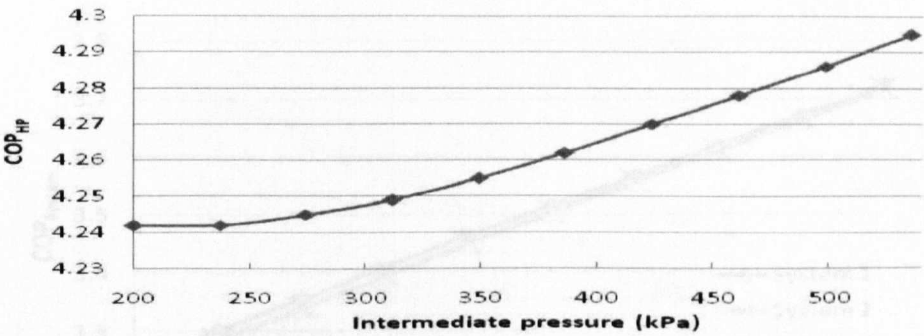


Figure 7.42 Effect of varying intermediate pressure on heat pump COP for system 3

7.9.5 Subcooling at condenser outlet

The effect of the degree of subcooling at the condenser on the performance and operation of the three systems considered is investigated in this section. The temperature at the condenser exit was limited to a reasonable minimum to allow for proper heat transfer within the heat distribution system. Hence, a degree of subcooling varying from 0 to 20°C for a fixed condenser pressure of 1000 kPa was considered. The HP and system COPs both increase almost linearly with increasing degree of subcooling (Figures 7.43 and 7.44), mainly because of a reduction in mass flow rate through the condenser in all the systems. When the temperature at the condenser exit is increased, the mass flow rate reduces according to equation 7.8. The variation of the refrigerant flow rate through the condenser with degree of subcooling is nearly linear (Figure 7.45).

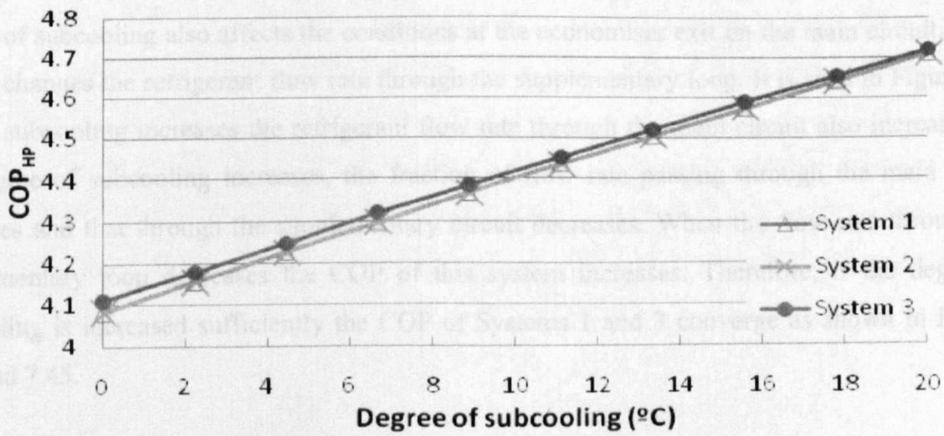


Figure 7.43 Effect of varying degree of subcooling at condenser exit on heat pump COP for each system

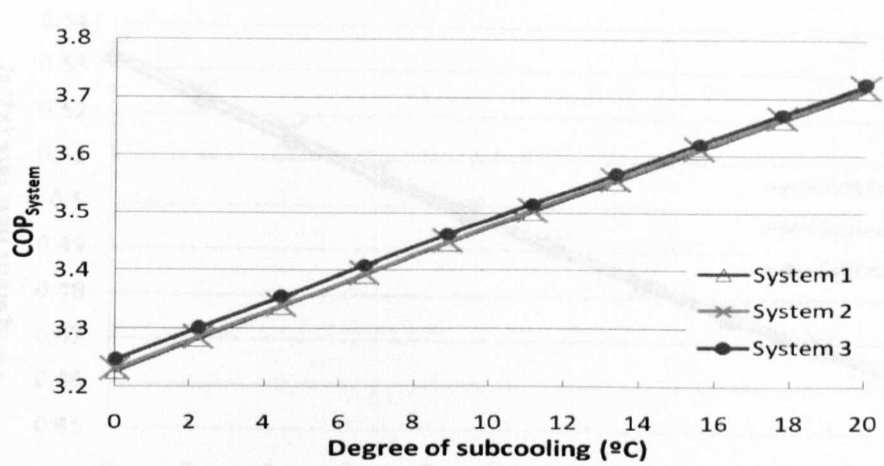


Figure 7.44 Effect of varying degree of subcooling at condenser exit on system COP for each system

Systems 1 and 2 are observed to be identical and more sensitive to subcooling than System 3. For a variation in subcooling of 20ºC, the HP COP changes by 0.63 for systems 1 and 2 and by 0.61 for system 3. On a normalised basis, the HP COP changes by about 0.031 and 0.030 per degree of subcooling for systems 1 and 3, respectively. The system COP for system 2 exhibits the greatest sensitivity to variations in the amount of subcooling at the condenser exit, but the difference between systems 1 and 2 is small.

System 3 is the least affected by subcooling because of its supplementary circuit. In system 3 the degree of subcooling also affects the conditions at the economiser exit on the main circuit, which in turn changes the refrigerant flow rate through the supplementary loop. It is seen in Figure 7.46 that as subcooling increases the refrigerant flow rate through the main circuit also increases. As the degree of subcooling increases, the fraction of flow rate passing through the main circuit increases and that through the supplementary circuit decreases. When the flow rate through the supplementary loop decreases the COP of this system increases. Therefore, if the degree of subcooling is increased sufficiently the COP of Systems 1 and 3 converge as shown in Figures 7.44 and 7.45.

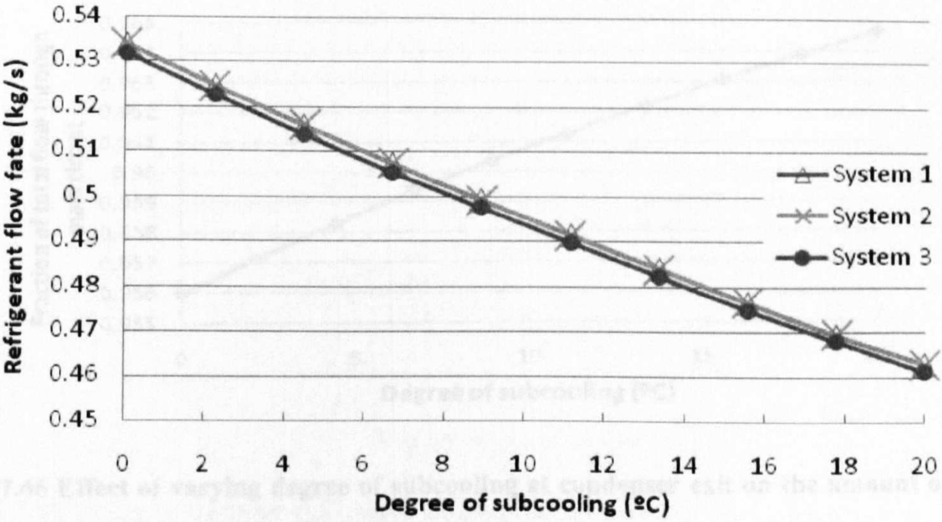


Figure 7.45 Effect of varying degree of subcooling at condenser exit on refrigerant flow rate for each system

7.9.6 Superheating at evaporator outlet

The effect of varying the degree of superheating on the performance and operation of the three systems was also investigated. The range of superheating was limited to between 0 and 17°C to ensure the temperature of the refrigerant leaving the evaporator was below that of the warm brine entering the evaporator in order to allow for proper heat transfer. Figures 7.46 and 7.47 show that, the HP system COPs increase with increasing degree of superheating. This is because of the reduced requirement of the compressor power. The difference in the range of COP values given by the different systems is relatively small. For example, for a variation of 17°C, the HP COP changes by 0.036 for systems 1 and 2 and by 0.033 for system 3 as Figure 7.47 shows. On a normalised basis, these amount to changes of about 0.0021 and 0.0019 per degree of superheating for systems 1 and 3, respectively.

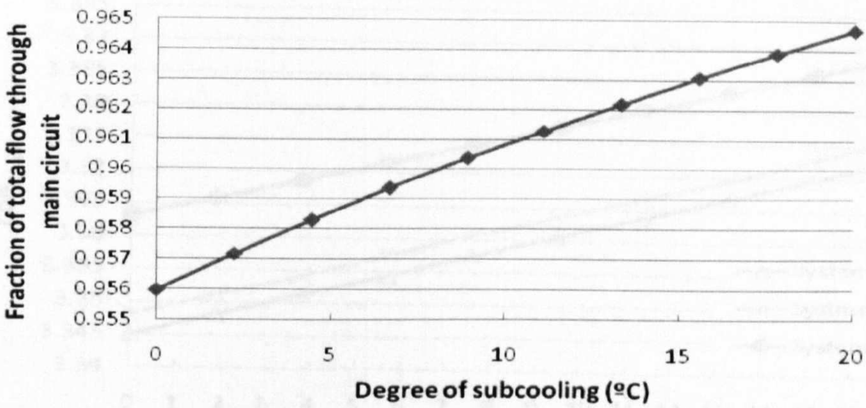


Figure 7.46 Effect of varying degree of subcooling at condenser exit on the amount of flow utilised in the main circuit of system 3

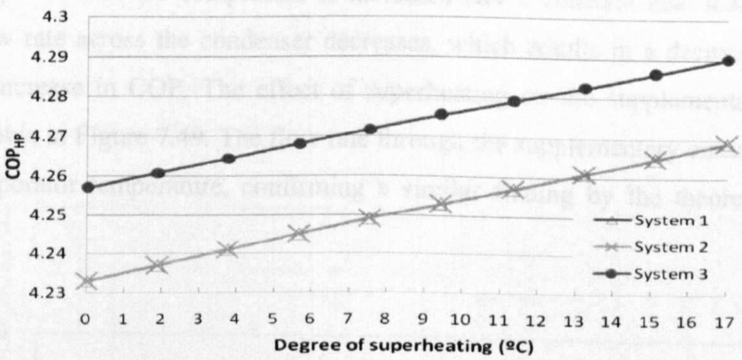


Figure 7.47 Effect of varying the degree of superheating at evaporator exit on heat pump COP for each system

The figure 7.48 also indicate that the ranges of HP and system COPs for systems 1 and 2 are greater than that for system 3, suggesting that systems 1 and 2 are the most affected by changing the amount of superheating after evaporation. These differences between the systems are due to the varying division of flow rate through the main and supplementary circuit within system 3, as shown and concluded above for other cases.

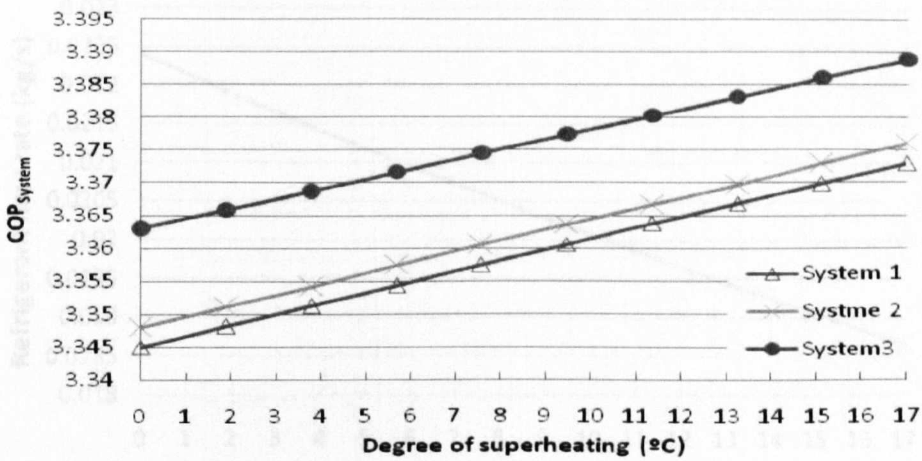


Figure 7.48 Effect of varying the degree of superheating at the evaporator exit on system COP for each system

When the temperature at the compressor is increased (for a constant heat load), the necessary refrigerant flow rate across the condenser decreases, which results in a decrease in compressor work and an increase in COP. The effect of superheating on the supplementary flow rate for system 3 is shown in Figure 7.49. The flow rate through the supplementary circuit decreases with increasing evaporator temperature, confirming a similar finding by the theoretical of Ma and Zhao [176].

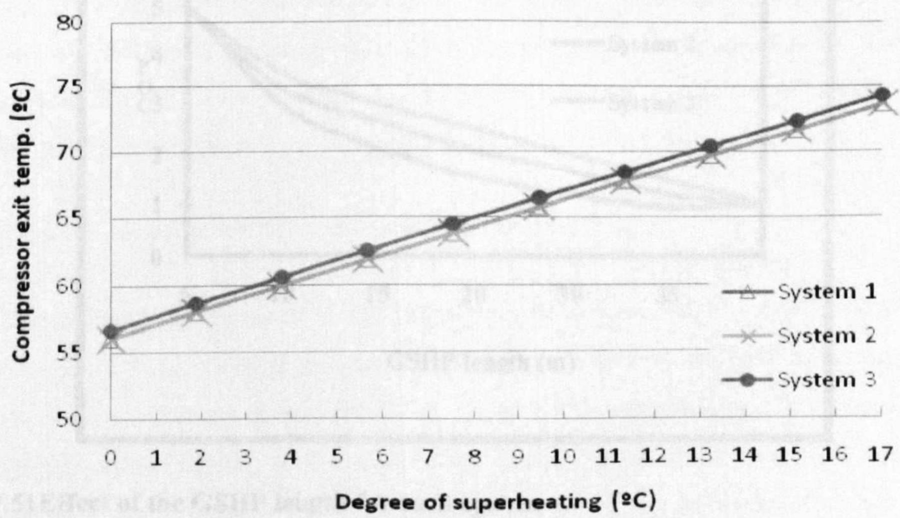


Figure 7.49 Effect of varying the degree of superheating at the evaporator exit on the compressor exit temperature

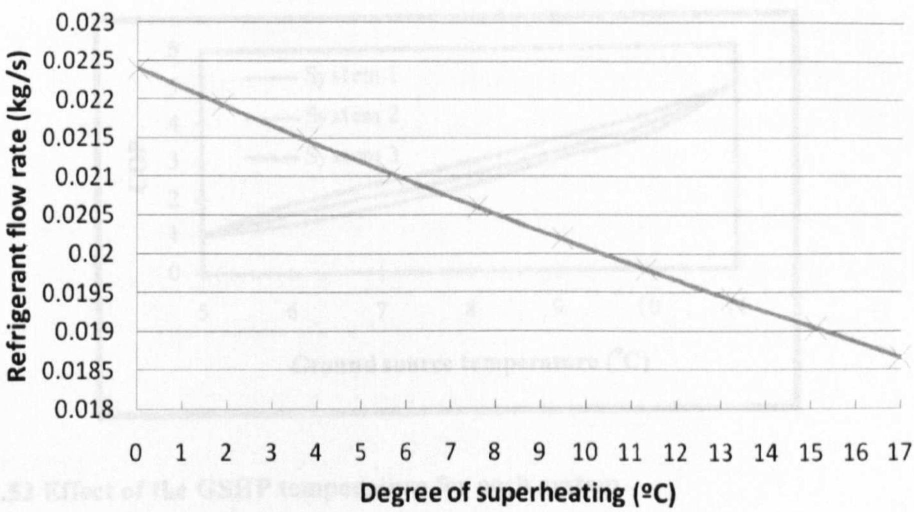


Figure 7.50 Effect of superheating on supplementary circuit flow rate

The trends suggest that it is beneficial to have a high degree of superheating (higher compressor inlet temperature), which can be accomplished by utilising a warmer ground source, thereby permitting a broader range for the degree of superheating. Figures 7.51 and 7.52 the effects of the GSHP loop length and temperatures for each system.

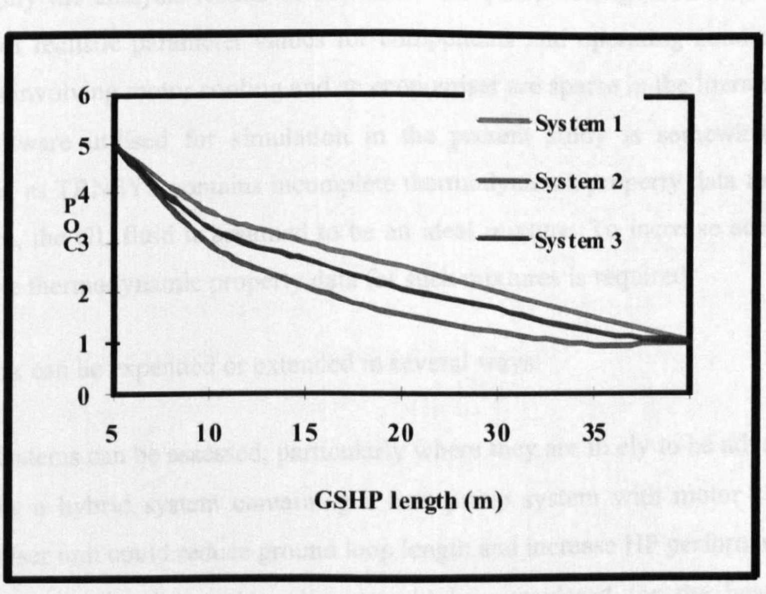


Figure 7.51Effect of the GSHP length for each system

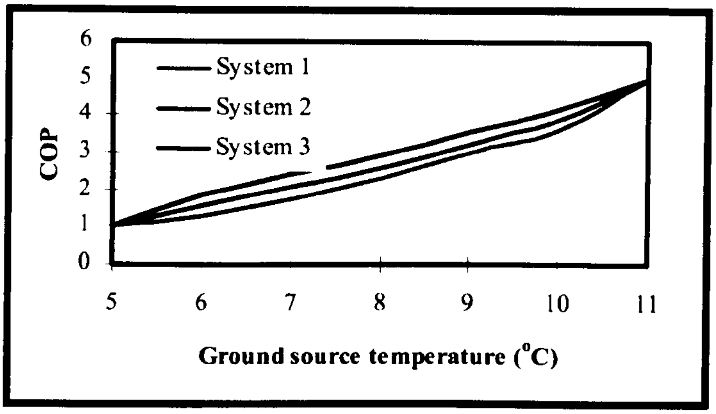


Figure 7.52 Effect of the GSHP temperature for each system

7.10 Limitations of analysis and potential enhancements

The analyses in this chapter provide insight into ground heat pump systems and their operation, but the work has some limitations and several enhancements are possible:

- A wide range of operational data should be attained and utilised to verify more thoroughly the analysis results of the three heat pump arrangements, and to refine the ranges of realistic parameter values for components and operating conditions. Data for systems involving motor cooling and an economiser are sparse in the literature.
- The software utilised for simulation in the present study is somewhat limited. For instance, as TRNSYS contains incomplete thermodynamic property data for water/glycol mixtures, the GL fluid is assumed to be an ideal mixture. To increase accuracy, a more complete thermodynamic property data for such mixtures is required.

The present work can be expanded or extended in several ways:

- Other systems can be assessed, particularly where they are likely to be advantageous. For example, a hybrid system containing a heat pump system with motor cooling and an economiser unit could reduce ground loop length and increase HP performance.
- Supplementary heating and cooling should be considered for the heat pump units. Supplementary heating provides external heat to the HP cycle beyond that from the GL, while supplementary cooling uses a typical HP cycle with a cooling tower. Both concepts could potentially reduce heating or cooling loads on the GL and thereby enhance ground source heat pump systems.

- Since the parameter variations considered affect economic in addition to technical conditions, corresponding economic assessments are needed to provide better context for the results. Economic values determine the suitability of systems for industrial and other applications, and are essential for optimisation efforts.
- Since space cooling is required in many climates, especially during summer months, cooling aspects of the systems need to be investigated. Such evaluations could assist in the selection of a systems and operating conditions that are most favourable over the entire year.

7.11 Conclusions

The characteristics of three geothermal heat pump systems that provide space heat had been assessed, and parametric studies have been performed to determine the sensitivities of the results to parameter variations. Several important findings and conclusions have been identified.

1) Heat pump designs with an economiser have the potential for high efficiency, based on the observation that system 3 attains the highest COPs for the ranges of the variables investigated.
2) Heat pump system that utilises motor cooling/refrigerant preheating can reduce ground loop requirements without sacrificing performance relative to the basic vapour compression cycle. For instance, the ground loop length of system 2 is generally less than for system 1, although heat pump and system COPs are similar.
3) The COPs for heat pump designs that utilise an economiser are the least sensitive to variations in evaporator pressure, degree of subcooling and degree of superheating, relative to basic vapour compression cycles and compression cycles with motor cooling. Systems with an economiser are also the most resilient to parameter variations, since system performance differs the least relative to the other arrangements.
4) Heat pump designs that utilise the basic vapour compression cycle or a compression cycle with motor cooling are the least sensitive to changes in compressor efficiency, motor efficiency and condenser pressure, compared to heat pump cycles with an economiser. The basic heat pump and the heat pump with motor cooling are the most resilient to changes in the parameters considered, with the performance of the systems differing the least relative to the economiser unit.
5) Condenser pressure has the greatest effect on COPs for all systems considered. And the effect on system COP of the other parameters can be ranked from highest to lowest as

motor efficiency, evaporator pressure, compressor efficiency, degree of subcooling, degree of superheating and pump efficiency.

6) Heat pump COPs and ground loop lengths are directly related, with required ground loop length increasing when the heat pump COP increases.

The findings and trends can assist design and optimisation activities for ground heat pump systems, providing insights into possible improvements. The information provided on how systems react to variations in operating parameters is important in such activities. Since the advanced systems covered in this chapter are not extensively investigated in the literature, the present results and findings enhance the available information on the systems and their operation.

8. Soil thermal properties and its influence of GSHP operation

8.1 Introduction

One of the fundamental tasks in the design of a reliable ground source heat pump system is proper sizing of the ground source heat exchanger length (i.e., depth of boreholes). Recent research efforts have produced several methods and commercially available design software tools for this purpose [187-189]. These design tools are based on principles of heat conduction and estimate of the ground thermal conductivity and volumetric specific heat. These parameters are perhaps the most critical to the system design, yet adequately determining them is often the most difficult task in the design phase.

A further complication in the design of ground source heat pump systems is the presence of ground water. Where groundwater is present, flow occurs in response to hydraulic gradients and the physical process affecting heat transfer in the ground, such as heat diffusion (conduction) and heat advection by moving ground water is inherently coupled. In general, groundwater flow can be expected to be beneficial to the thermal performance of closed-loop ground heat exchangers since it will have a moderating effect on borehole temperatures in both heating and cooling modes.

This chapter investigates hydraulic and thermal properties of soils and rocks. The impact of groundwater flow on the estimation of soil/rock thermal conductivity, diffusivity and specific heat capacity were measured and evaluated for different soils.

8.2 Ground properties

Applications of GSHP require information on the depth of soil cover, the type of soil or rock and the ground temperature. The depth of soil cover may determine the possible configuration of the ground coil. If bedrock is within 1.5 m of the surface or there are large boulders, it may not be possible to install a horizontal ground loop. For a vertical borehole the depth of soil will influence the cost as, in general, it is more expensive and time consuming to drill through overburden than rock as the borehole has to be cased.

The temperature difference between the ground and the fluid in the ground heat exchanger drives the heat transfer so it is important to determine the ground temperature. At depths of less than 2 m, the ground temperature will show marked seasonal variation above and below the annual average air temperature. As the depth increases the seasonal swing in temperature is reduced and the maximum and minimum soil temperatures begin to lag the temperature at the surface. At a depth of about 1.5 m, the time lag is approximately one month [189]. Below 10 m the ground temperature remains effectively constant at approximately the annual average air temperature (i.e., between 10°C and 14°C in the UK depending on local geology and soil conditions). The annual variation in ground temperatures at a depth of 1.7 m comparable to the daily average air temperature measured at the site. It also shows the ground temperature at a depth of 75 m [189].

In order to determine the length of heat exchanger needed to meet a given load the thermal properties of the ground will be needed. The most important difference is between soil and rock as rocks have significantly higher values for thermal conductivity. The moisture content of the soil also has a significant effect as dry loose soil traps air and has a lower thermal conductivity than moist packed soil. Low-conductivity soil may require as much as 50% more collector loop than highly conductive soil. Water movement across a particular site will also have a significant impact on heat transfer through the ground and can result in a smaller ground heat exchanger.

8.3 Influence of groundwater flow on soil thermal properties and/or GSHP

Underground water occurs in two zones, the saturated and unsaturated zones. The term 'groundwater' refers to water in the saturated zone. The surface separating the saturated zone from the unsaturated zone is known as the 'water table'. At the water table, water in soil or rock pore spaces is at atmospheric pressure. In the saturated zone (below the water table), pores are fully saturated and water exists at pressures greater than atmospheric. In the unsaturated zone, pores are only partially saturated and the water exists under tension at pressures less than atmospheric. Groundwater is present nearly everywhere, but it is only available in usable quantities in aquifers. Aquifers are described as being either confined or unconfined. Unconfined aquifers are bounded at their upper surface by water table. Confined aquifers are bounded between two layers of lower permeability materials. In practice, the boreholes of ground-loop heat exchangers may partially penetrate several geological layers.

The governing equation describing flow through porous media is given by Darcy's Law [190]:

$$q = S\,(dh/dx) \qquad (Jm^{-2}) \qquad (8.1)$$

Where q is the specific discharge, (volume flow rate per unit of cross-sectional area), S is the hydraulic conductivity, h is the hydraulic head and x is the depth. The specific discharge is related to average linear groundwater velocity, v (ms^{-1}), by:

$$v = q/n \qquad (8.2)$$

Where n is the porosity and is introduced to account for the difference between the unit cross-sectional area and the area of the pore spaces through which the groundwater flows [191-192]. By applying the law of conservation of mass to a control volume and by making use of Darcy's Law (Eq. 8.1), an equation defining the hydraulic head distribution can be derived. Transient groundwater flow with constant density can then be expressed in Cartesian tensor notation as [192]:

$$S_s \frac{\partial h}{\partial t} - \frac{\partial}{\partial x_i}\left(K_{ij} \frac{\partial h}{\partial x_i} \right) = R^* \qquad (8.3)$$

Where: S_s is the saturated conductivity, t is the time (s), h is the hydraulic head, x is the depth, R^* is the soil resistance and k_{ij} is the thermal conductivity.

Since groundwater at 43.3°C (an extreme temperature limit expected in GSHP applications) has a specific gravity of approximately 0.991, the assumption of constant density flow for low-temperature geothermal applications may be considered valid. Figure 8.1 shows the variation of ground thermal conductivity with ground depths (x).

8.4 Heat transport in groundwater

Heat can be transported through a saturated porous medium by the following three processes:

- Heat transfer through the solid phase by conduction.
- Heat transfer through the liquid phase by conduction, and
- Heat transfer through the liquid phase by advection.

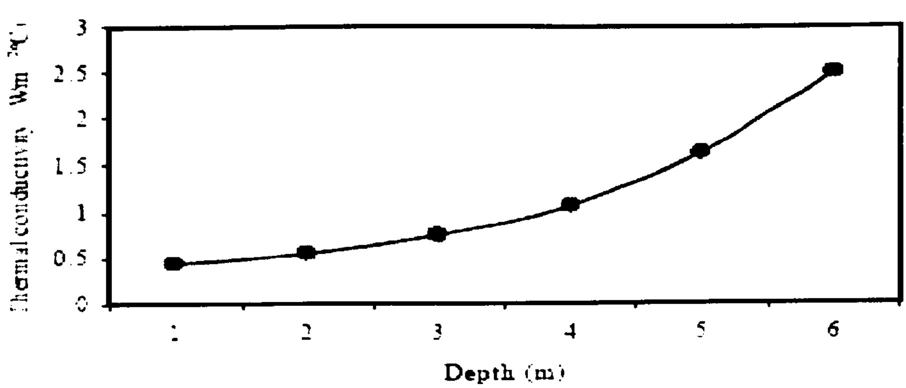


Figure 8.1 Variation of ground thermal conductivity with ground depths (x)

The governing equation describing mass or heat transport in groundwater is a partial differential equation of the advection-dispersion type [193]. By applying the law of conservation of energy to a control volume, an equation for heat transport in groundwater can be found and can be expressed as [193]:

$$nR\frac{\partial T}{\partial t}+v_i\frac{\partial T}{\partial x_i}-\frac{\partial}{\partial x_i}\left(D_{ij}\frac{\partial T}{\partial x_i}\right)=Q^{*} \tag{8.4}$$

Where the velocity v_i is determined from the solution of Eqs. 8.1-8.3 and T is the temperature of rock/water matrix, D_{ij} is the diffusion coefficient; $(\delta T/\delta t)$ is the rate of change of temperature of the water, v (ms^{-1}) is the groundwater velocity, Q^* is the heat transfer, n is the porosity, and R is the soil resistance. If the groundwater velocity is zero, Eq. 8.4 reduces to a form of Fourier's Law of heat conduction [194-196]. The diffusion coefficient tensor D_{ij} is modeled as an effective thermal diffusivity given by:

$$D_{ij} = k_{eff}/\rho_l C_l \tag{8.5}$$

Where C_l is the heat capacity of groundwater, and, ρ_l is the specific heat capacity of groundwater.

The effective thermal conductivity k_{eff} is a volume-weighted average thermal conductivity of the saturated rock matrix and can be expressed using the porosity as:

$$k_{eff} = nk_l + (1-n)k_s \tag{8.6}$$

Where K_s is the thermal conductivity of saturated rock, k_l is the hydraulic conductivity, and n is the porosity.

It is necessary to distinguish between the conductivity and thermal capacity of the water and soil/rock in this way to account for the fact that heat is stored and conducted through both the water and soil/rock, but heat is only advected by the water. Similarly, it is necessary to define a retardation coefficient (R) accounting for retardation of the thermal plume, which results from, differences in the liquid and solid volumetric heat capacities [193]:

$$R=\frac{1+(1-n)\rho_s C_s}{n\rho_l c_l} \tag{8.7}$$

Where ρ_s is the density of the solid soil, ρ_l is the specific heat capacity of groundwater, n is the porosity, C_s is the heat capacity of solid soil and C_l is the heat capacity of groundwater.

Darcy's Law indicates that flow is dependent on both the local hydraulic gradient and the hydraulic conductivity of the geologic material. Heat transfer is dependent on the flow velocity and the thermal properties of the material. The thermal properties of soils and rocks are functions of mineral content, porosity and degree of saturation. Of these, porosity may be considered as the most important property simply because of the origin and nature of soils and rocks. Rocks originate under higher heat and pressure environments than soils and consequently generally possess lower porosities.

Equations (8.1- 8.7) are used for estimations of the thermal properties of soil and rocks, porosity and degree of saturation. Of these, porosity may be considered the most important property simply because of the origin and nature of soils and rocks. Rocks originate under higher heat and pressure environments than soils and consequently generally possess lower porosities. Lower porosities in rocks result in higher contact area between gains and therefore higher thermal conductivities than soil, regardless of mineral content. For saturated materials, increased porosity results in increased heat capacities and therefore lower thermal diffusivities. The thermal properties of common ground types are given in Table 8.1 [194]. The most important difference is between soil and rock because rocks have significantly higher values for thermal conductivity and diffusivity.

Table 8.1 Typical thermal properties of soil [194]

Material	Conductivity ($Wm^{-1}K^{-1}$)	Specific heat ($kJkg^{-1}K^{-1}$)	Density (kgm^{-3})	Diffusivity (m^2d^{-1})
Granite	2.1-4.5	0.84	2640	0.078-0.18
Limestone	1.4-5.2	0.88	2480	0.056-0.20
Marble	2.1-5.5	0.80	2560	0.084-0.23
Sandstone				
Dry	1.4-5.2	0.71	2240	0.074-0.28
Wet	2.1-5.2			0.11-0.28
Clay				
Damp	1.4-1.7	1.3-1.7		0.046-0.056
Wet	1.7-2.4	1.7-1.9	1440-1920	0.056-0.074
Sand				
Damp		1.3-1.7		0.037-0.046
Wet*	2.1-26	1.7-1.9	1440-1920	0.065-0.084

* Water movement will substantially improve thermal properties

The main consideration with installation of the ground coil is to ensure good long-term thermal contact. Only standard construction equipment is needed to install horizontal ground heat exchanger, i.e., bulldozers or backhoes and chain trenchers. In larger installation in Europe, track type machines have been used to plough in and backfill around the pipe in continuous operation. Drilling is necessary for most vertical heat exchanger installations. The drilling equipment required is considerably simpler than the conventional equipment for drilling water wells. Drilling methods commonly used are listed in Table 8.2. For the design of thermally efficient and economically sized borehole heat exchanger systems the soil thermal characteristics, especially the thermal conductivity, borehole resistance and undisturbed ground temperature are essential parameters (Table 8.3). As stated earlier, the design and economic feasibility of these systems critically depend upon the estimate of the ground thermal conductivity. The actual values are listed by case number in Figure 8.2.

Table 8.2 Drilling methods for the installation of vertical collectors [195]

Type of ground soil	Drilling method	Remarks
Soft, sand	Auger	Sometimes temporary casing required
Gravel	Rotary	Temporary casing or mud additives required
Soft, silt/clay	Auger	Usually the best choice
	Rotary	Temporary casing or mud additives required
Medium	Rotary	Roller bit, sometimes mud additives required
	DTH*	Large compressor required
Hard	Rotary	Button bit, very slow
	DTH	Large compressor required
	Top hammer	Special equipment
Very hard	DTH	Large compressor required
	Top hammer	Special equipment
Hard under soft	ODEX#	In combination with DTH

- Down-the-hole-hammer, # Overburden drilling equipment (Atlas Copco, Sweden)

Table 8.3 Actual values of thermal conductivity

Case number	Simulation duration (hr)	Ground thermal conductivity predicted by numerical model Austin et al., 2000 [16] (W/m°C)
1	50	1.11
2	50	1.12
3	50	1.26
4	50	1.98
5	50	6.33
6	50	10.51
7	168	1.08
8	168	1.20
9	168	1.66
10	168	3.89
11	168	14.24
12	168	26.14

A constant heat flux of 2500 W was applied during simulation time periods (50 hours to one week). The model time step was 2.5 minutes and the initial temperature was 17.2 °C. Twelve cases were simulated as listed in Table 8.3. Resulting temperature responses for 12 cases are plotted in Figure 8.2, which shows that the ground water flow in coarse sand significantly impacts the average borehole fluid temperature during ground thermal conductivity test. As ground thermal conductivity increases, the time to reach steady-state conditions decreases and the steady-state temperature decreases.

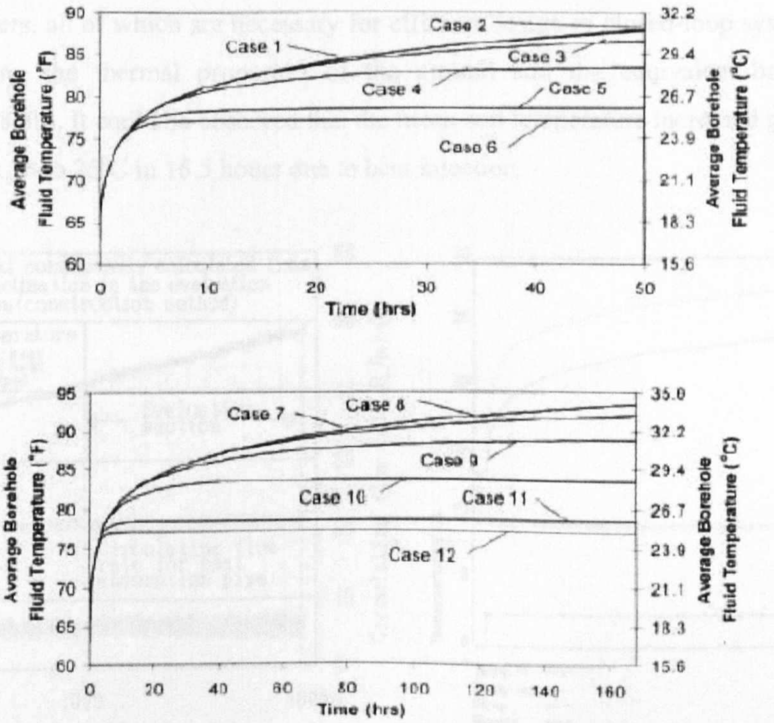


Figure 8.2 Average borehole fluid temperatures for the (12 cases) ground thermal conductivity test cases in coarse sand for (a) 50 hours (b) one week

Based on existing information regarding Sapporo's subsurface geology (using geologic columnar section (Figure 8.3a), etc.), thermal conductivity for the soil, which is typically found in the range 0 to 30 m deep underground, were estimated. The theme undertakes an evaluation of heat absorption properties in the soil, and carries out a performance test for a unit heat pump and a simulated operation test for the system. In fact, these procedures are necessary for identifying operational performance to obtain technical data on the heat pump system. Under these circumstances, the study estimated the thermal properties of the soil. The measurements have been carried out using KD2 Pro thermal analyser at Forest Field, Nottingham (Forest Field, Nottingham (Latitude 52° 56' 15.89" N, Longitude 1° 11' 45.43" W, Altitude 68 m) at depth 1-2 m. The measured thermal conductivity for the soil is given in Table 8.4. The test is aimed at identifying applicable areas for ground source heat pump system.

A thermal response test (TRT) is used to determine in-situ thermal properties. This involves injecting a finite amount of heat energy into a closed-loop borehole over a period of several days. During the test the principal parameters measured are the incoming and outgoing temperatures of the heat transfer fluid; the flow rate of the fluid; and the heat energy input. Test data can be interpreted to provide the following parameters, all of which are necessary for efficient design of closed-loop systems: the initial ground temperature, the thermal properties of the ground and the equivalent borehole thermal resistance (Figure 8.3b). It could be observed that the mean soil temperature increased gradually during the test from about 16 to 25°C in 16.5 hours due to heat injection.

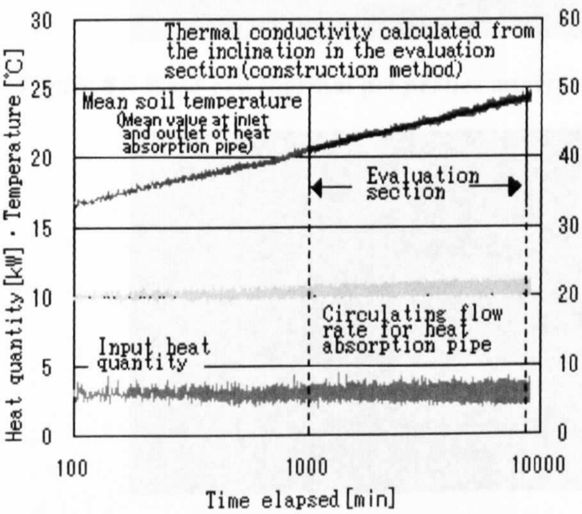


Figure 8.3a Thermo response test

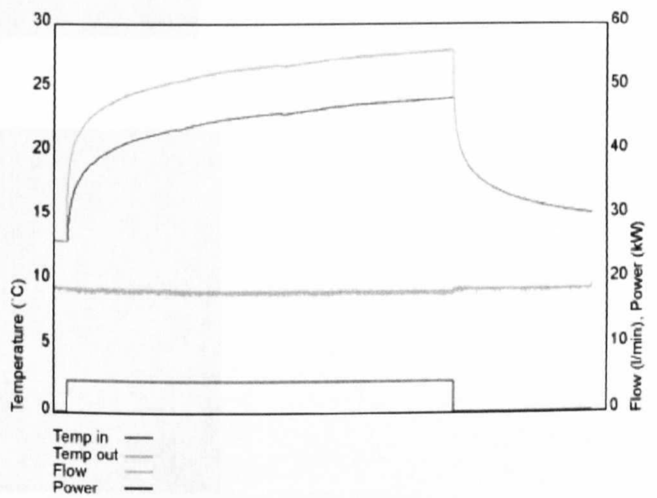


Figure 8.3b Thermo response test data

Table 8.4 Observed value and estimated value of soil thermal conductivity

Evaluation method	Thermal conductivity ($Wm^{-1}K^{-1}$)
Observed value by thermo response test	1.37
Estimation value by geologic columnar section	1.27

8.5 Soil thermal measurements

In this research work, the soil thermal measurements were carried out using KD2 Pro thermal properties analyser (Figure 8.4). The KD2 Pro is a hand-held device used to measure thermal properties of materials. It is battery-operated, menu-driven device that measures thermal conductivity and resistivity, volumetric specific heat capacity and thermal diffusivity. The device consists of a hand-held controller and sensors inserted into the medium to be measured. The single-needle sensors measure thermal conductivity and resistivity, while the dual-needle sensor also measures volumetric specific heat capacity and diffusivity (Figures 8.5 - 8.7). Other types are summarised in Figure 8.8.

Figure 8.4 KD2 Pro thermal properties analyser

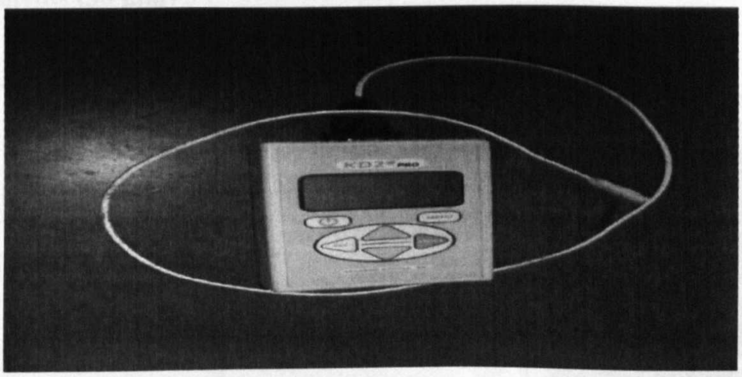


Figure 8.5 Single-needle sensors for thermal conductivity and resistivity measurements (6 cm) for liquids

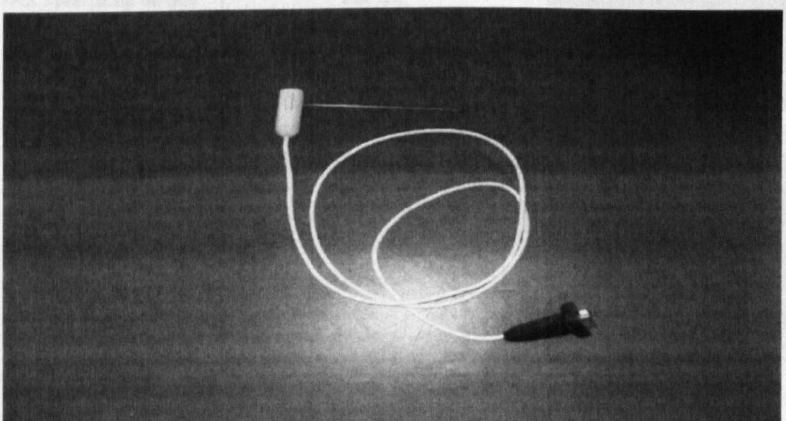


Figure 8.6 Extended single-needle sensors for thermal conductivity and resistivity measurements (10 cm) for use in hard materials

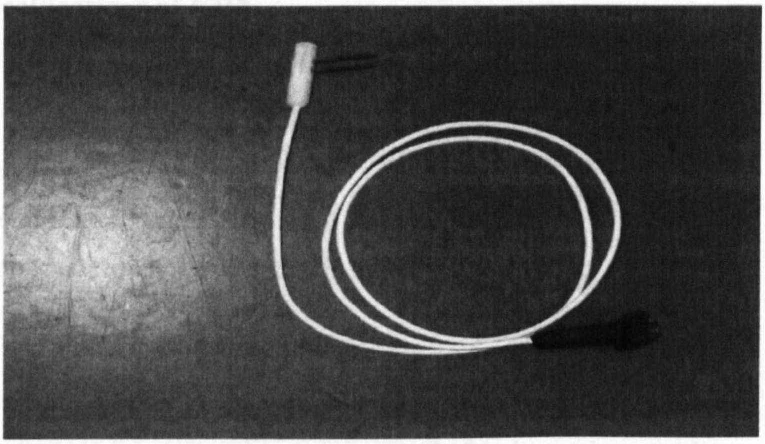


Figure 8.7 Dual-needle sensors for volumetric specific heat capacity and diffusivity measurements (30 mm)

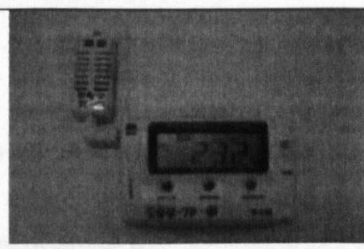
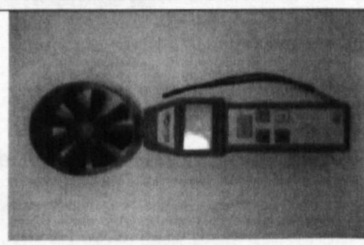
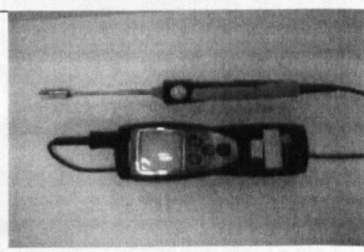
Device Type	Name of equipment	Images
Thermometer / Hygrometer	Thermal recorder TR-72U T&D Corp. Japan	
Air current Measuring device	Velocity calculator TSI Inc. USA	
Thermometer of surface area	testo 925 Testo AG Germany	

Figure 8.8 Types of thermo/hygrometer and air current measurement devices

8.5.1 Specifications of KD2

KD2 Pro has been designed for ease of use and maximum functionality. Operating conditions are:

Controller temperature range: 0-50 °C
Sensors temperature range: -50 to +150 °C
Battery life 1800 readings in constant use
Accuracy ±5%

If the temperature of the sample medium is different from the temperature of the needle, the needle must equilibrate to the surrounding temperature before beginning a reading.
Carslaw and Jaeger [196] modified temperature surrounding an infinite line heat source with constant heat output and zero mass in an infinite medium. According to this model, when a quantity of heat Q (Jm^{-1}) is instantaneously applied to the line heat source, the temperature rise at distance r (m) from the source is given by [196]:

$$\Delta T = \frac{Q}{4\prod kt}\exp\left(\frac{-r^2}{4Dt}\right) \tag{8.8}$$

Where Q is heat flux, π is 3.14, k the thermal conductivity (W/m-K), D the thermal diffusivity (mm^2/s), r is radius and t is time (s). If a constant amount of heat is applied to a zero mass heater over a period of time, rather than as an instantaneous pulse, the temperature response is:

$$\Delta T = \frac{q}{4\prod k} Ei\left(\frac{-r^2}{4Dt}\right) \qquad 0<t \le t_1 \tag{8.9}$$

Where q is the rate of heat dissipation (W/m), t_1 is the heating time and Ei is the exponential integral [197]. The temperature rise after the heat is turned off is given by:

$$\Delta T = \frac{q}{4\prod k}[-Ei\left(\frac{-r^2}{4Dt}\right) + Ei\left(\frac{-r^2}{4D(t-t_1)}\right)] \qquad t>t_1 \tag{8.10}$$

Material thermal properties are determined by fitting the time series temperature data during heating to Eq. 8.9 and during cooling to Eq. 8.10. Thermal conductivity can be obtained from the temperature of the heated needle (single needle), with r taken as the radius of the needle. Diffusivity is best obtained by fitting the temperatures measured a fixed distance from the heated needle (the KD2 Pro uses 6 mm); k is also determined from these data. Volumetric specific heat C (W/m^3 °K) is determined from k and D as follows.

$$C = k/D \tag{8.11}$$

In each case, k and D are obtained by a non-linear least squares procedure [198], which searches for values of k and D, which minimise the difference between modeled and measured sensor temperatures. Most experiments will not occur under constant temperature conditions. An additional linear drift factor is included in the inverse procedure. This reduces errors substantially.

Kluitenberg et al., [200] give solutions for pulsed cylindrical sources that are not ideal line heat sources. For a heated cylindrical source of radius a (m) and length 2b (m), with temperature measured at its centre, the temperature rise during heating (zero<$t \leq t_l$) is [199]:

$$\Delta T = \frac{q}{4\prod k} \int_{r^2/4Dr}^{\infty} U^{-1} \exp(-U) \exp[-(a/r)^2 U] I_o(2au/r) erf\left(\frac{b}{r}\sqrt{u}\right) du \qquad (8.12)$$

During cooling ($t>t_l$) it is:

$$\Delta T = \frac{q}{4\prod k} \int_{r^2/4Dr}^{r^2/4D(t-t_l)} U^{-1} \exp(-U) \exp[-(a/r)^2 U] I_o(2au/r) erf\left(\frac{b}{r}\sqrt{u}\right) du \qquad (8.13)$$

Where $I_o(x)$ represents a modified Bessel function of order zero, erf(x) is the error function and u is an integration variable. As pointed out by Kluitenberg et al., [200], exp [-(a/r) ^{2}u] I_o (2au/r) approaches unity as a/r approaches zero, and $erf\left(\frac{b}{r}\sqrt{u}\right)$ approaches unity as b/r approaches infinity, reducing Eqs. (8.12 and 8.13) to Eqs. (8.9 and 8.10).

A geotechnical survey can be used to reduce the uncertainty associated with the ground thermal properties. More accurate information could result in a reduction in design loop length and easier loop installation. For large schemes where multiple boreholes are required, a trial borehole and/or a thermal properties field test may be appropriate.

8.6 Soil thermal properties

The ground source heat pump system, which uses a ground source with a smaller annual temperature variation for heating and cooling systems, has increasingly attracted market attention due to lower expenses for installing underground heat absorption pipes and lower costs of dedicated heat pumps, supported by environmentally oriented policies.

8.7 Test of soil thermal conductivity

According to the measurement result shown in Table 8.4, the observed soil thermal conductivity was slightly higher than the thermal conductivity estimated by the geologic columnar section. The future plan is to predict system operational performance at each observation point, based on the relationship between estimated soil thermal property and measured soil thermal conductivity, an example of which is shown in Figures 8.9 - 8.10. The sample soil thermal conductivity-measuring instrument was produced to measure the soil thermal conductivity from rises in underground temperature thermo response test when a certain amount of heat was conducted into heat absorption soil. Table 8.5 shows the type of soil at different depth, as revealed from the test. Using a compilation of typical hydraulic and thermal properties of soils and rocks, a preliminary analysis of the effects of groundwater flow on the design and performance of closed-loop ground source heat pump systems has been made.

Table 8.5 Geologic columnar sections (provided the drilling company -Jackson Engineers)

Depth	Type of soil
5 m	Top soil or surface soil and volcanic ash
18 m	Gravel mixed with clay
30 m	Gravel mixed with volcanic ash
40 m	Clay mixed with grave and sand
46 m	Gravel
63 m	Volcanic ash mixed with gravel and clay
78 m	Clay mixed with volcanic ash
100 m	Sand and clay

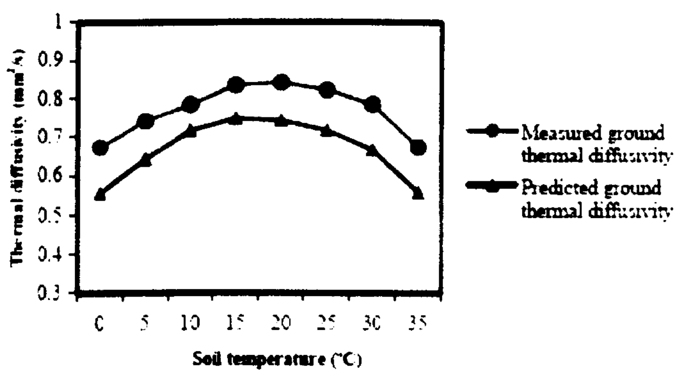


Figure 8.9 Measured and predicted data of the soil (gravel) thermal diffusivity using equation 8.5

A vertical strip or scale drawing of the strip taken from a given area or locality showing the sequence of the rock units and their stratigraphic relationship, and indicating the thickness, lithology, age, classification, and fossil content of the rock units. 0.25 m -1.75 m from the surface is estimated to be a layer of embankment. At some of the investigation points, the earth contains traces of gravel, and the density of soil is inconsistent across several investigation points. From approximately 0.25 m to 1.75 m below ground level, a layer, which seems to be a sandy clay stratum, starts. The firmness of the ground is relatively consistent but at investigation point, the 2 m layer from the surface is soft.

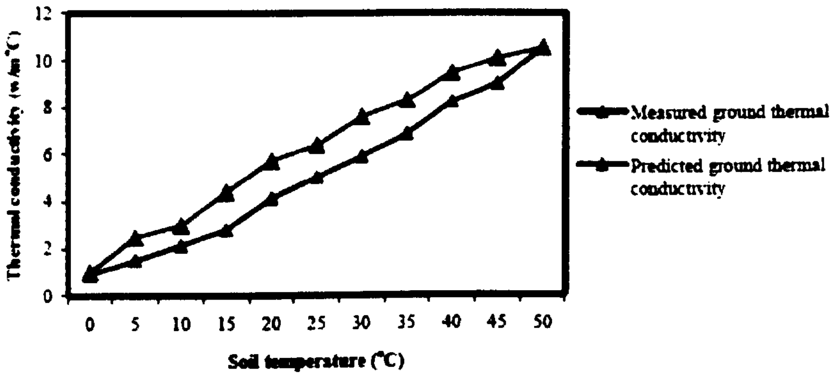


Figure 8.10 Measured and predicted data of soil (gravel) thermal conductivity using equations 8.3

Figure 8.11 shows the relationship between the soil temperature and its conductivity for different materials (measured). It is seen from the figure that temperature drops much faster for granite and slower for the coarse graveled soil. This is mainly due to the fact that coarse graveled material has a higher thermal storage capacity or lower thermal diffusivity than granite. Therefore, the high thermal energy stored found in the coarse graveled can provide longer heat extraction as shown in Figure 8.11.

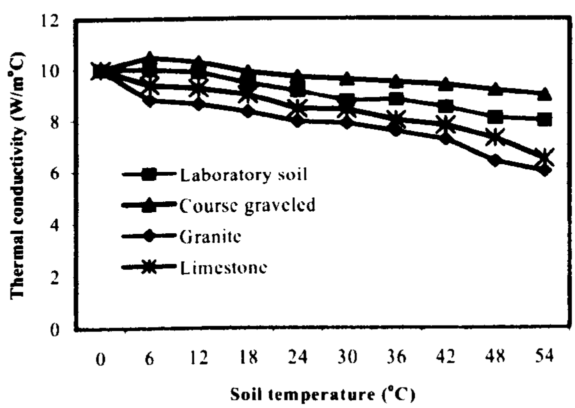


Figure 8.11 Comparison of measured thermal conductivity for different soils using KD2 Pro thermal properties analyser

Figures 8.12-8.13 show a summary of the soil thermal properties. The temperature difference between the ground and the fluid in the ground heat exchanger drives the heat transfer so it is important to determine the ground temperature. At depths of less than 2 m, the ground temperature will show marked seasonal variation above and below the annual average air temperature. As the depth increases, the seasonal swing in temperature is reduced and the maximum and minimum soil temperatures begin to lag the temperature at the surface. The effects of the soil properties on the groundwater temperature and soil temperature at initial temperature 10°C and heat extraction rate of 2.2 kW are shown in Figure 8.14.

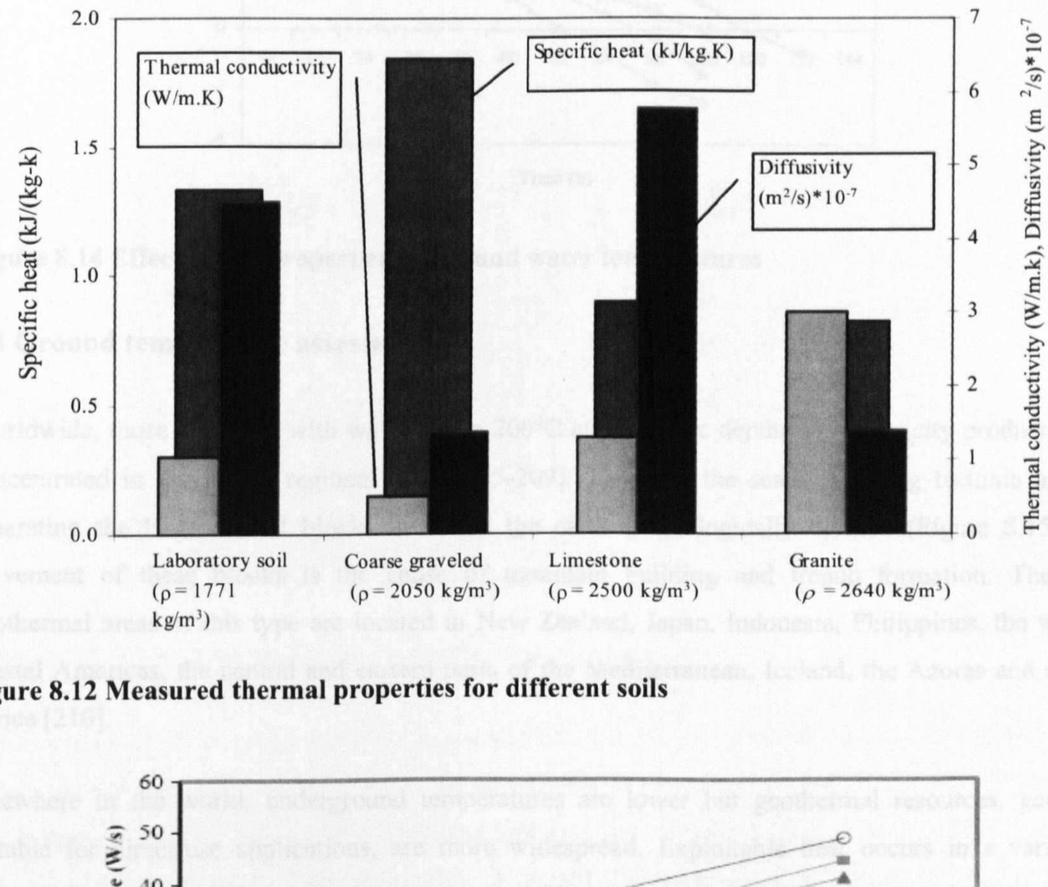


Figure 8.12 Measured thermal properties for different soils

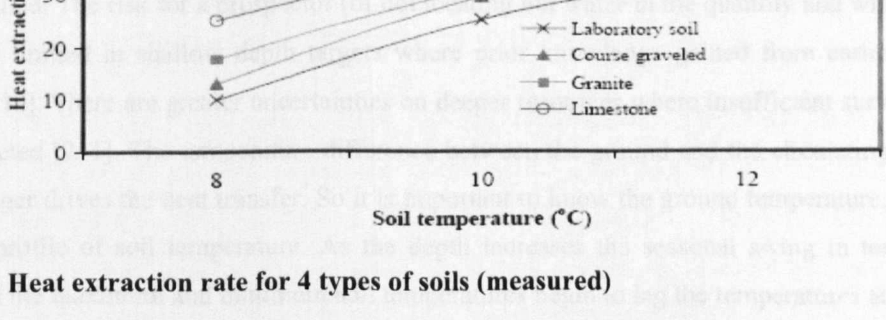


Figure 8.13 Heat extraction rate for 4 types of soils (measured)

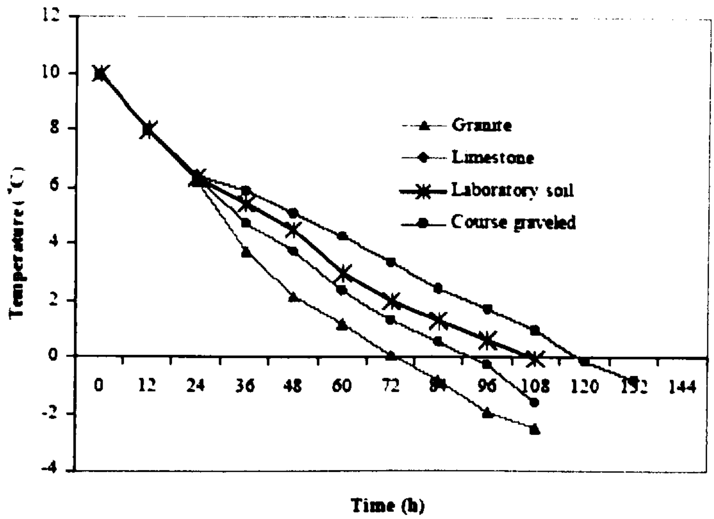


Figure 8.14 Effect of soil properties on ground water temperatures

8.8 Ground temperature assessment

Worldwide, those hot areas with water above 200°C at economic depths for electricity production are concentrated in the young regional belts [205-209]. They are the seats of strong tectonic activity, separating the large crustal blocks in which the earth is geologically divided (Figure 8.15). The movement of these blocks is the cause of mountain building and trench formation. The main geothermal areas of this type are located in New Zealand, Japan, Indonesia, Philippines, the western coastal Americas, the central and eastern parts of the Mediterranean, Iceland, the Azores and eastern Africa [210].

Elsewhere in the world, underground temperatures are lower but geothermal resources, generally suitable for direct-use applications, are more widespread. Exploitable heat occurs in a variety of geological situations. It is practically always available in the very shallow underground where GSHPs can be installed. The risk for a prospector (of not locating hot water in the quantity and with the quality required) is limited in shallow depth targets where prior knowledge gained from earlier surveys is available [210]. There are greater uncertainties on deeper resources where insufficient survey work has been conducted [211]. The temperature difference between the ground and the circulating fluid in the heat exchanger drives the heat transfer. So it is important to know the ground temperature. Figure 8.13 shows the profile of soil temperature. As the depth increases the seasonal swing in temperature is reduced and the maximum and minimum soil temperatures begin to lag the temperatures at the surface. An empirical formula suggested by Eggen, 1990 [203] is:

$$T_m = T_o + 0.02\ H \quad (8.14)$$

Where:

Tm is the mean ground temperature (°C).

To is the annual mean air temperature (°C).

H is the depth below the ground surface (m).

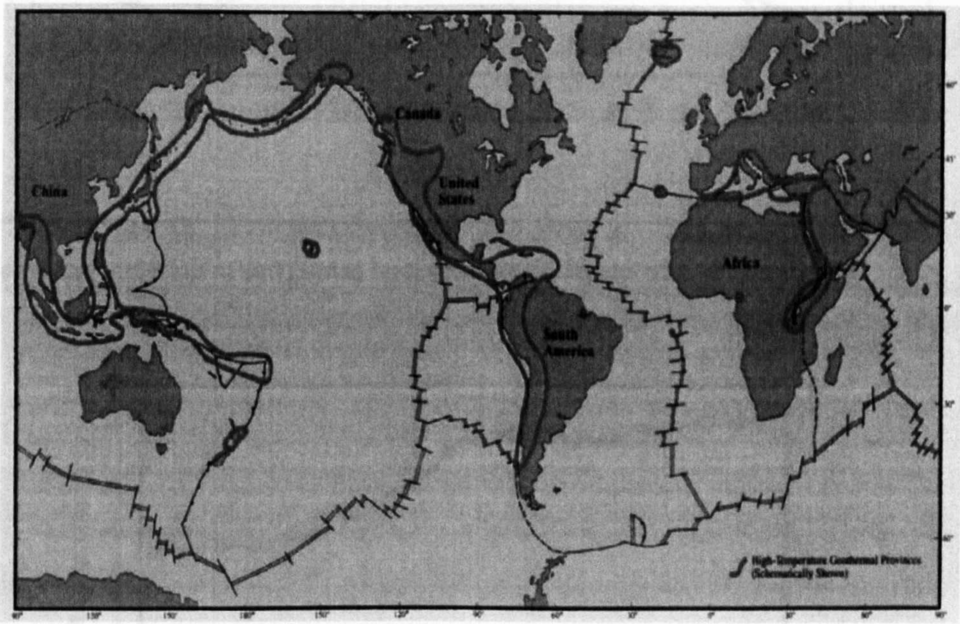


Figure 8.15 World high temperature geothermal provinces [204]

The temperature variation gradually disappears at lower depth and remains effectively constant below 10 m at approximately the annual mean air temperature. Figure 8.16 shows the monthly variation of soil temperature at different depths. The measurements have been carried out using KD2 Pro thermal analyser at Forest Field Ground, Nottingham (Forest Field, Nottingham (Latitude 52° 56' 15.89" N, Longitude 1° 11' 45.43" W, Altitude 68 m) at depth 0.02 m and 1 m. It can be observed that the temperature variation was higher at shallow depth compared to deeper one.

As Figure 8.17 shows, at a depth of about 1 m, the time lag is approximately one month. Below 10 m the ground temperature remains effectively constant at approximately the annual average air temperature (i.e., between 10°C and 14°C depending on local geology and soil conditions). The annual variation in ground temperatures at a depth of 1.7 m compares to the daily average air temperature measured at the site (University Park, Nottingham). The ground temperature increases with the depth, as the effect of ambient is less influential at deeper depths.

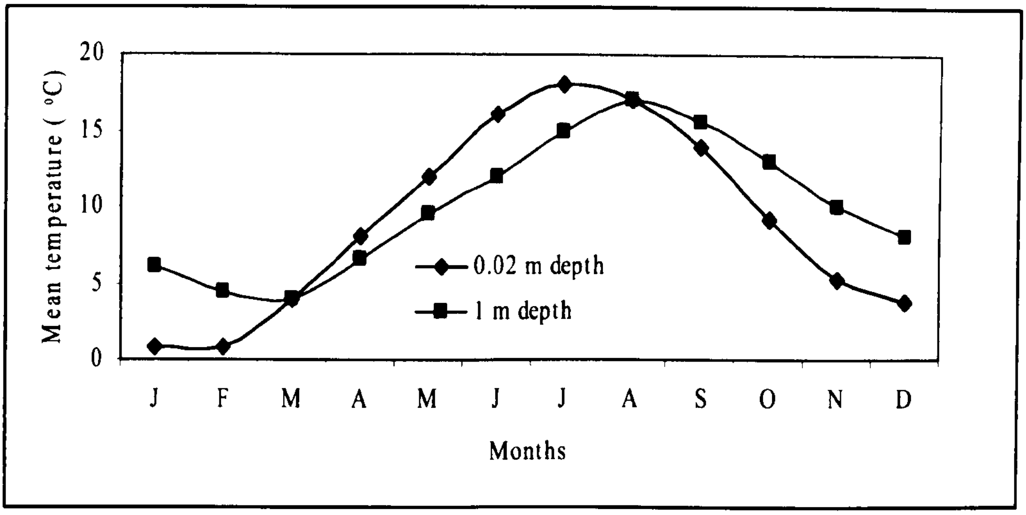


Figure 8.16 Seasonal variation of soil (sand) temperature at depths of 0.02 m and 1 m

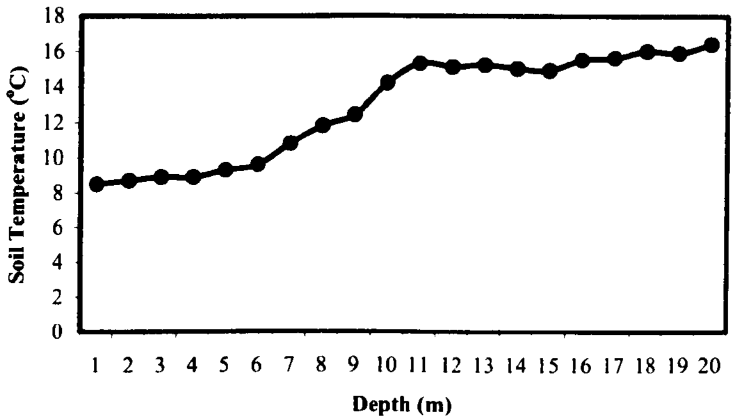


Figure 8.17 Variation of soil (sand) temperature with ground depth

It is important to maximise the efficiency of a heat pump when providing heating, not only to have less variable/stable heating distribution temperature but also to have as high a source temperature as possible. Overall efficiencies for the GSHPs are inherently higher than for air source heat pumps because ground temperatures are higher than the mean air temperature in winter and lower than the mean air temperature in summer. The ground temperature also remains relatively stable allowing the heat pump to operate close to its optimal design point whereas air temperatures vary both throughout the day and seasonally and are lowest at times of peak heating demand. For heat pumps using ambient air as the source, the evaporator coil is also likely to need defrosting at low temperatures. It is therefore important to determine the depth of soil cover, the type of soil or rock and the ground temperature. The depth of soil cover may determine the possible configuration of the ground coil. In order to determine the length of heat exchanger needed to meet a given load the thermal properties of the ground will be needed. The most important difference is between soil and rock as rocks have significantly higher values for thermal conductivity (Table 8.6). The moisture content of the soil also has a significant effect as dry loose soil traps air and has a lower thermal conductivity than moist packed soil [202]. Low-conductivity soil may require as much as 50% more collector loop than highly conductive soil. Water movement across a particular site will also have a significant impact on heat transfer through the ground and can result in a smaller ground heat exchanger.

Table 8.6 Peclet numbers corresponding to typical values of thermal properties of soils and rocks [202]

Porous medium	Peclet number L= a typical borehole spacing of (4.5 m)
Soil	
Gravel	5.72E+02
Sand (coarse)	1.34E+01
Sand (fine)	1.15E+00
Silt	1.28E-02
Clay	3.2E-05
Rocks	
Limestone, Dolomite	5.92E-03
Karst limestone	5.28E+00
Sandstone	1.77E-03
Shale	1.05E-06
Fractured igneous and metamorphic	6.32E-02
Unfractured igneous and metamorphic	1.00E-07

Latent heat during phase changes between freezing soil and thawing soil was regarded as an inner heat source described as follows [201]:

$$WH\,(\sigma_d)\,\delta f_s/\delta t_s = q_s \tag{8.15}$$

$$(\delta T/\delta t)\,\sigma + U_x\,\delta T_f/\delta x = \alpha_t\,\Delta^2 T + qt/\,(\rho C_p) \tag{8.16}$$

Where:

C_p is the specific heat (J kg^{-1} K^{-1}); q is the internal heat source (Wm^{-3}), W is the water content in soil (%); T is the temperature (°C), H is the condensation latent heat of water (J kg^{-1}), t is the times (s); U is the velocity (ms^{-1}), f_s is the solid phase ratio, *s* refers to soil; *f* refers to groundwater, Ψ is the porosity, α is the convective heat transfer coefficient ($Wm^{-2}K^{-1}$), δ is volumetric specific heat ratio, and ρ is the density (kg m^{-3}).

Heat transfer between a GSHP and its surrounding soil is illustrated in Figure 8.18, and shows the daily measured cold energy charged to and discharged from its surrounding soil using DX-GSHP at different days as part of the current study. The daily cold energy charged in the initial five pre-cooling periods sharply decreased, while increased gradually during the normal operating period. Consequently, the building-cooling load also slightly increased.

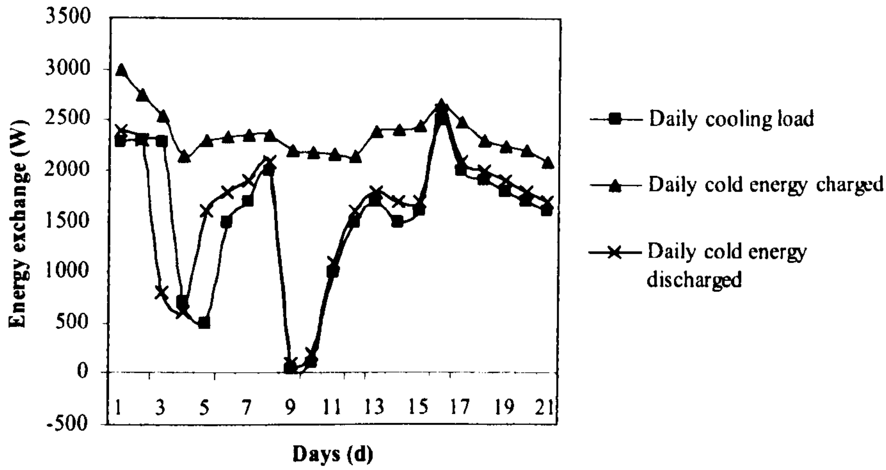


Figure 8.18 Daily measured cold energy charged and discharged from its surrounding soil using the GSHP at different days

8.9 The effects of the soil properties on the soil temperature

For the design of thermally efficient and economically sized borehole heat exchanger systems, the soil thermal characteristics, especially the thermal conductivity, borehole resistance and undisturbed ground temperature, are essential parameters. Figures 8.19-8.20 compare results of predicted and of laboratory measurement of the average soil temperatures at all points along the heat flow carried out.

It can be seen from Figure 8.21 that the temperature drops much faster for granite and slower for the coarse graveled soil. This is mainly due to the fact that coarse graveled material has a higher thermal storage capacity or lower thermal diffusivity than granite. Therefore, the high thermal energy stored found in the coarse graveled can provide longer heat extraction operation for the storage water.

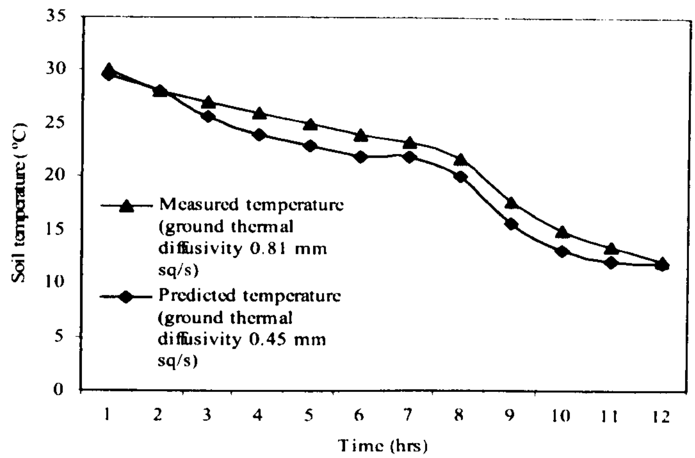


Figure 8.19 Variation of the measured and predicted soil (sand) temperatures with specified diffusivity

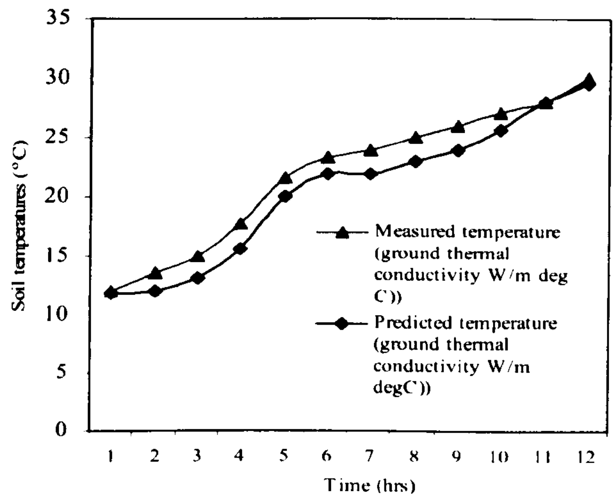


Figure 8.20 Variation of the measured and predicted soil (sand) temperatures with specified conductivity

The groundwater flow in coarse sand significantly impacts the average borehole fluid temperature. The effective thermal conductivity values measured are plotted against the corresponding groundwater flow velocity as shown in Figures 8.22 - 8.23. Measurements conditions are:

- Soil was a homogeneous porous medium with its mass force, heat radiation effect and viscosity dissipation neglected.
- The local temperature of groundwater and soil arrived at the thermal equilibrium instantly.

- The thermal and physical properties of soil and its temperature at the far-field boundary remained constant.
- Because the diameter of the pipe was very small, the only temperature variation of the working fluid inside the pipe was considered.

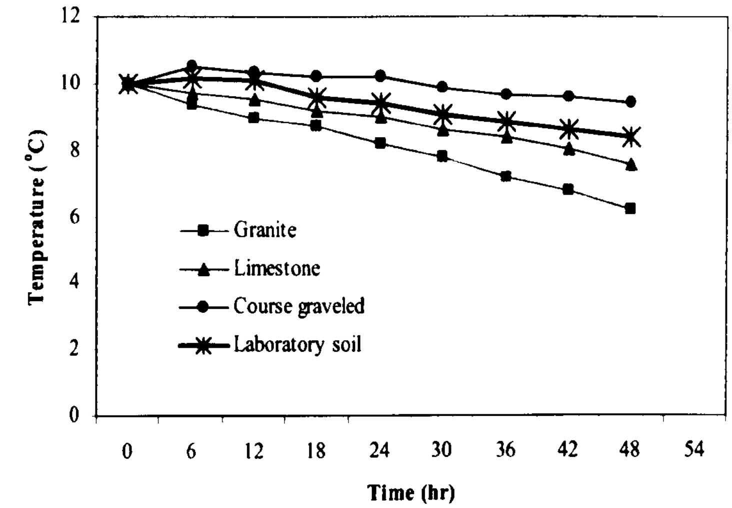


Figure 8.21 The effect of soil properties on soil temperature due to heat extraction

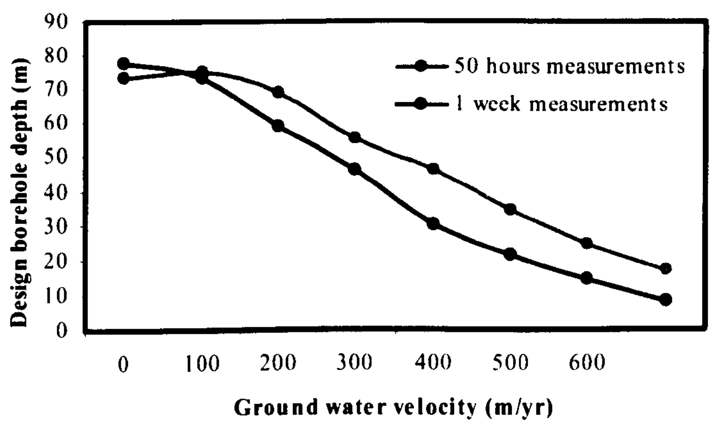


Figure 8.22 Variation of the design borehole depths with the groundwater flow velocity for 50 hours and week measurements

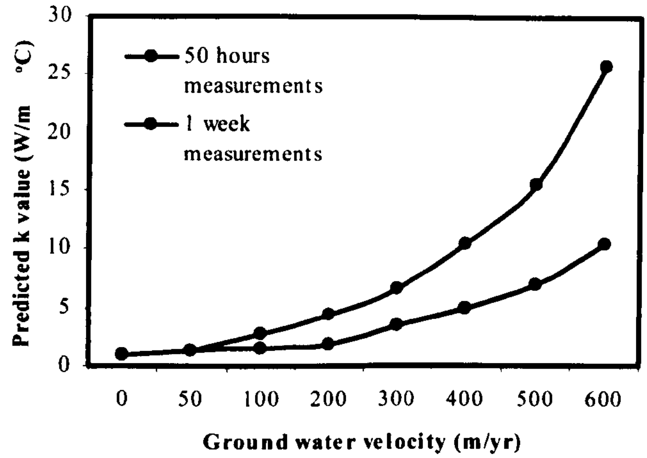


Figure 8.23 Measurements of ground thermal conductivity values versus groundwater flow velocity for 50 hour and 1 week

Figure 8.24 shows the influence of temperature and relative humidity inside the pit. When the relative humidity is low and the temperature is high, the moisture content of the soil has a significant effect on its thermal properties.

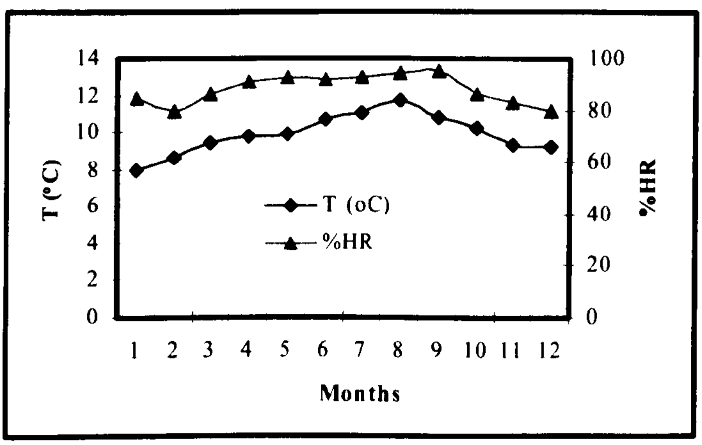


Figure 8.24 Experimental temperature and relative humidity values for the air inside the pit at an average depth of 3 m

8.10 Discussion

The two-rock/soil properties, which most affect the design of a heat pump system, are the thermal conductivity and the thermal capacity. The thermal diffusivity is a measure of the ground's ability to conduct thermal energy relative to its ability to store thermal energy. The most important difference is between soil and rock as rocks have significantly higher values of thermal conductivity and diffusivity. As the vertical collector may pass through several soil layers, it is therefore important that these are correctly identified.

The moisture content of the soil also has a significant effect on its thermal properties. When water replaces the air between particles it reduces the contact resistance. Consequently, the thermal conductivity can vary from 0.25 W/m/K for dry soil to 2.5 W/m/K for wet soil. However, the thermal conductivity is relatively constant above a specific moisture threshold. In fact, where the water table is high and cooling loads are moderate, the moisture content is unlikely to drop below the critical level. In Nottingham, where the present study was conducted, soils are likely to be damp for much of the time. Hence, thermal instability is unlikely to be a problem. Nevertheless, when heat is extracted, there will be a migration of moisture by diffusion towards the heat exchanger and the thermal conductivity will increase.

Indeed, the net energy exchange in the soil after one year of operation was only 3% of the total cold energy charged. This shows that there was no acute soil temperature changing after the whole year operation of the GSHP system. Therefore, the system is feasible technically and the operation mode is reasonable.

8.11 Conclusions

GSHP systems use less energy than alternative heating and cooling systems, helping to conserve the natural resources. The heat transfer between the GSHP and its surrounding soil affected by a number of factors such as working fluid properties (e.g., glycol) and its flow conditions, soil thermal properties, soil moisture content and groundwater velocity and properties, etc. Soil was a homogeneous porous medium, with its mass force, heat radiation effect and viscosity dissipation neglected. The local temperature of groundwater and soil arrived at a thermal equilibrium instantly. The thermal and physical properties of soil and its temperature at the far-field boundary remained constant.

9.0 Experimental investigation of use of the GSHP

9.1 Introduction

This chapter describes the details of the prototype GSHP test rig, details of the construction and installation of the heat pump, heat exchanger, heat injection fan and water supply system. It also, presents the results of the experimental tests, and comparison with the theoretical estimations.

The construction of the experimental rig was undertaken in three steps. The first step includes drilling three boreholes (each 30 meter deep, and diameter 143 mm), digging out the pit and connection of the manifolds and preparation of coils. Holes were grouted with bentonite and sand. The pipes were laid and tested with nitrogen. Then, the pit was backfilled and the heat pump was installed. The second part involved setting up of the main experimental rig: construction and installation of the heat injection fan, water pump, expansion valve, flow meter, electricity supply, heat exchanger and heat pump. The third stage was an installation of refrigerator and measurements.

The GSHP installed for this study was designed taking into account the local meteorological and geological conditions. The site is at the School of the Built Environment, University of Nottingham, where the demonstration and performance monitoring efforts were undertaken. The study involved development of the design and the performance analysis of the cooling system, which acts as a supplemental heat rejecting system using a closed-loop GSHP system. With the help of the Jackson Refrigeration (Refrigeration and Air Conditioning engineers) the following connection has been made:

- The ground loops are connected to the heat pump (Figure 9.1).
- The heat pump is connected to the heat exchanger (Figure 9.2).
- Vacuum is applied on the system.
- The refrigeration loop is charged with R407C refrigerant.

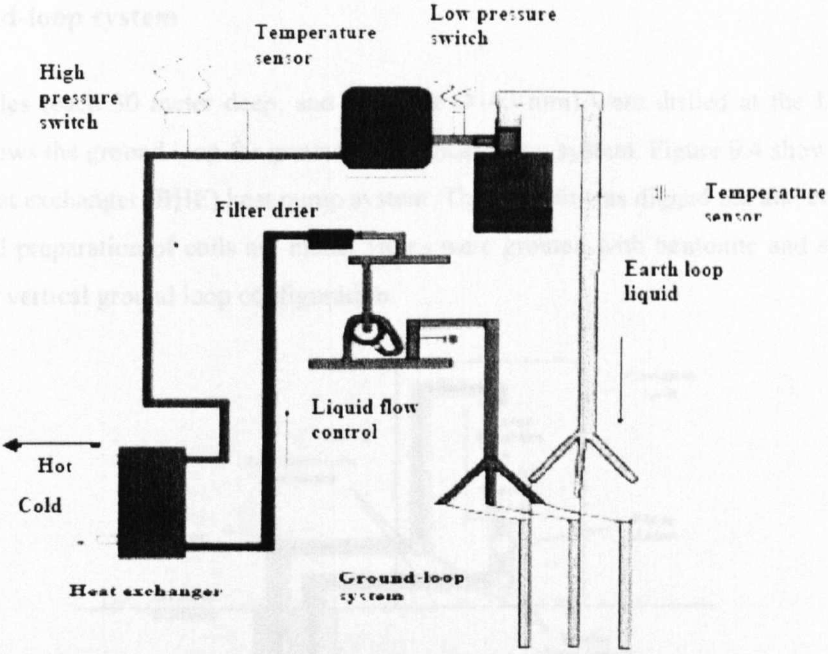


Figure 9.1 The whole heat pump system installation

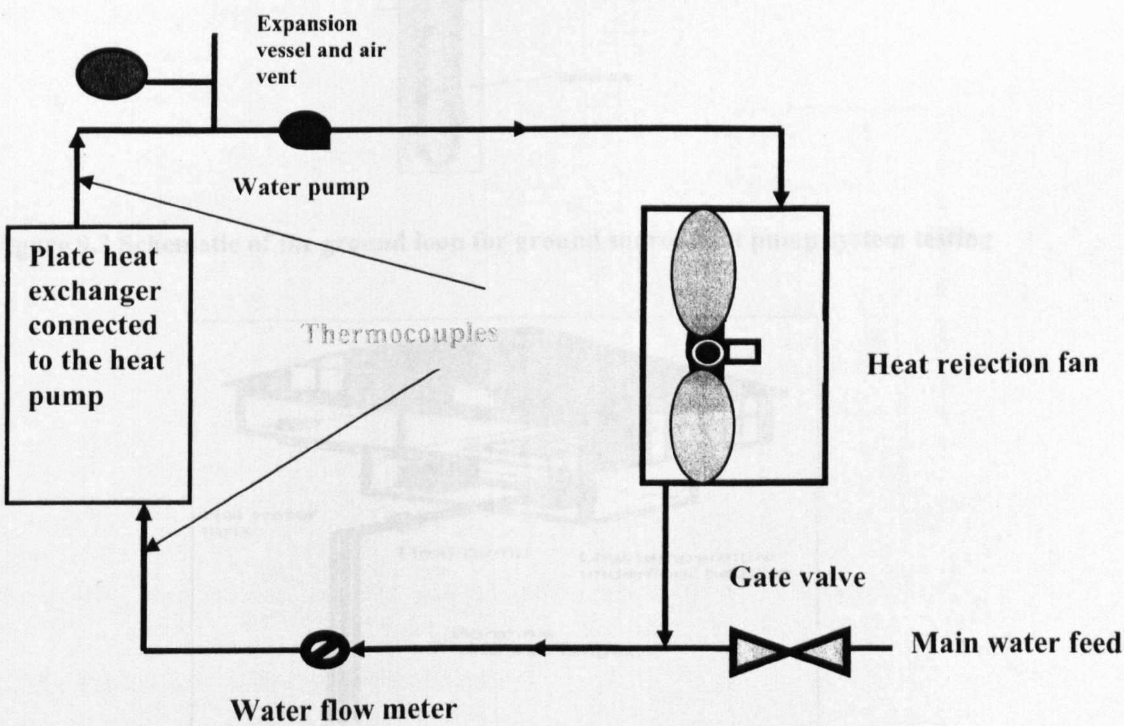


Figure 9.2 Sketch of installing heat pump above the ground

9.1.1 Ground-loop system

Three boreholes (each 30 meter deep, and diameter Φ143 mm) were drilled at the University Park. Figure 9.3 shows the ground loop for ground source heat pump system. Figure 9.4 shows application of a borehole heat exchanger (BHE) heat pump system. Then the pit was digged out and connection of the manifolds and preparation of coils are made. Holes were grouted with bentonite and sand. Figure 9.5 shows typical vertical ground loop configuration.

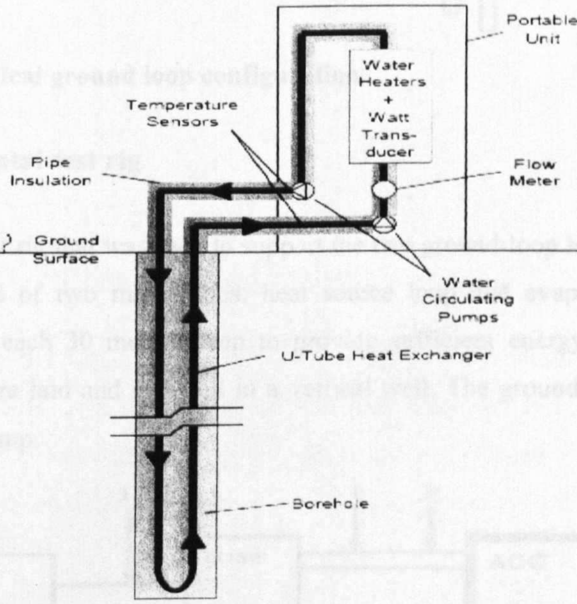


Figure 9.3 Schematic of the ground loop for ground source heat pump system testing

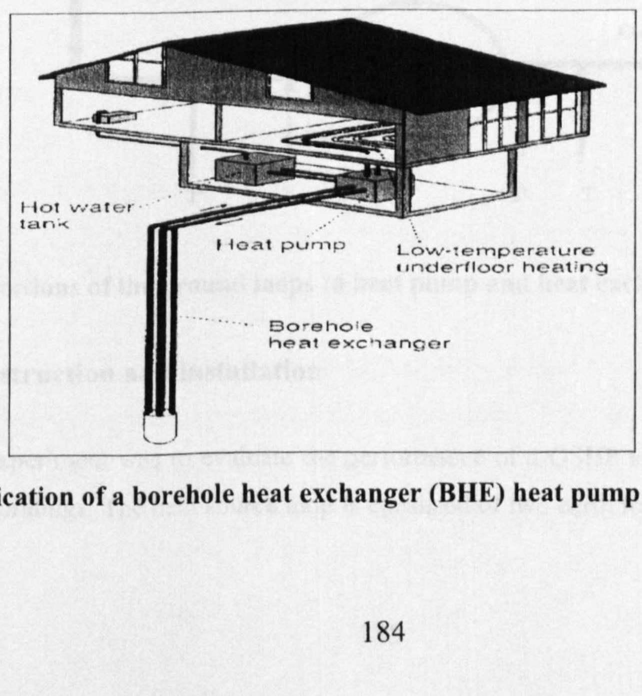


Figure 9.4 Application of a borehole heat exchanger (BHE) heat pump system

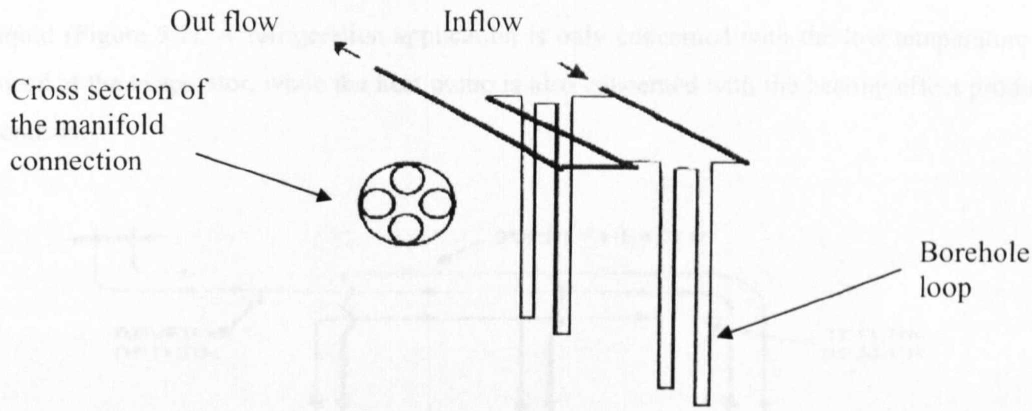


Figure 9.5 Typical vertical ground loop configuration

9.1.2 Main experimental test rig

The schematic of the test rig that was used to support the two ground-loop heat exchangers is shown in Figure 9.6. It consisted of two main loops: heat source loop and evaporation heat pump. Three horeholes were drilled each 30 meters deep to provide sufficient energy for cooling system. The closed-loop systems were laid and installed in a vertical well. The ground-loop heat exchaners were connected to the heat pump.

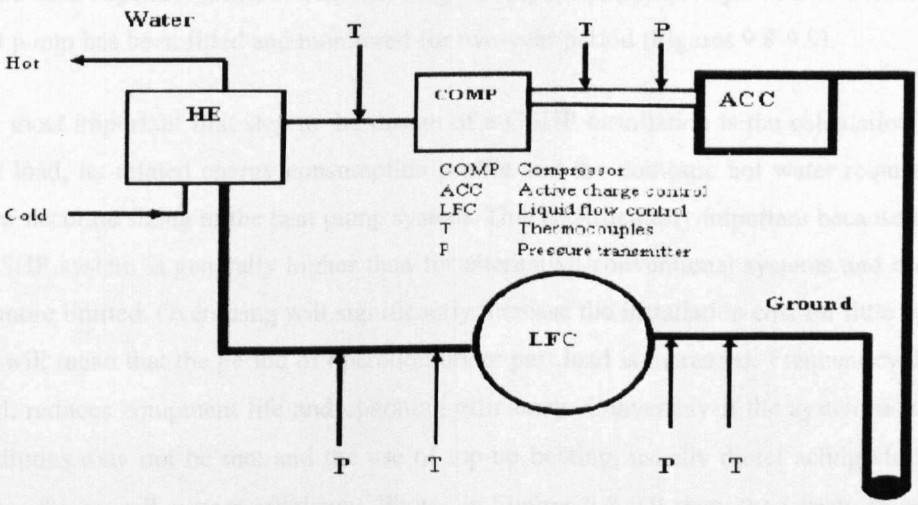


Figure 9.6 Connections of the ground loops to heat pump and heat exchanger (HE)

9.2 Design, construction and installation

The aim of the experiment was to evaluate the performance of a GSHP system for providing heating and cooling for buildings. The heat source loop is consisted of two earth loops, one for vapour and one for liquid (Figure 9.7). A refrigeration application is only concerned with the low temperature effect produced at the evaporator, while the heat pump is also concerned with the heating effect produced at the condenser.

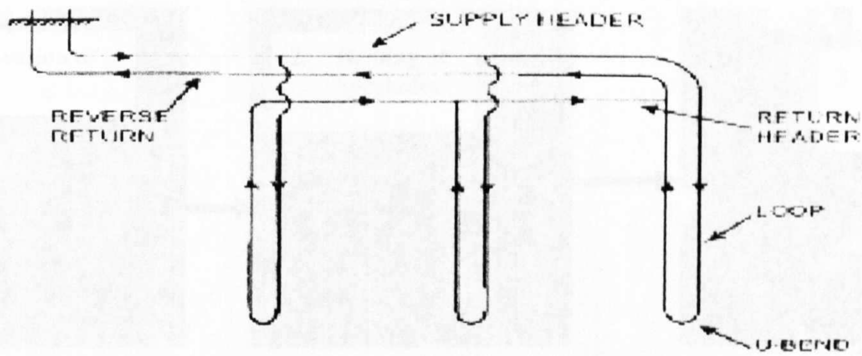


Figure 9.7 Layout of the vertical ground source system loops

Installation of the heat pump system and especially the ground heat exchanger needs to be carefully programmed so that it does not interfere with or delay any other construction activities. The time for installation depends on soil conditions, length of pipe, equipment required and weather conditions. The heat pump has been fitted and monitored for two-year period (Figures 9.8-9.9).

The most important first step in the design of a GSHP installation is the calculation of the building's heat load, its related energy consumption profile and the domestic hot water requirements. This will allow accurate sizing of the heat pump system. This is particularly important because the capital cost of a GSHP system is generally higher than for alternative conventional systems and economies of scale are more limited. Oversizing will significantly increase the installation cost for little operational saving and will mean that the period of operation under part load is increased. Frequent cycling, on the other hand, reduces equipment life and operating efficiency. Conversely if the system is undersized design conditions may not be met and the use of top-up heating, usually direct acting electric heating, will reduce the overall system efficiency. Photos in Figures 9.8-9.9 show the variety stages of drilling and system installation.

The water supply system consisted of water pump, boiler, water tank, flow metre and expansion valve (Figure 9.9). A thermostatically controlled water heater supplies warm water, which was circulated between the warm water supply tank and warm water storage tank using a pump to keep the surface temperature of the trenches at a desired level. The output from the GSHP provides indirect heating via an exchange coil in the domestic hot water cylinder (Figure 9.9). Because of the relatively high output temperature required (55°C minimum is recommended for stored water to avoid the risk of legionella) the efficiency for water heating may be reduced. Water heating is normally provided in addition to space heating and provides a year-round load and therefore improves the load factor for the heat pump.

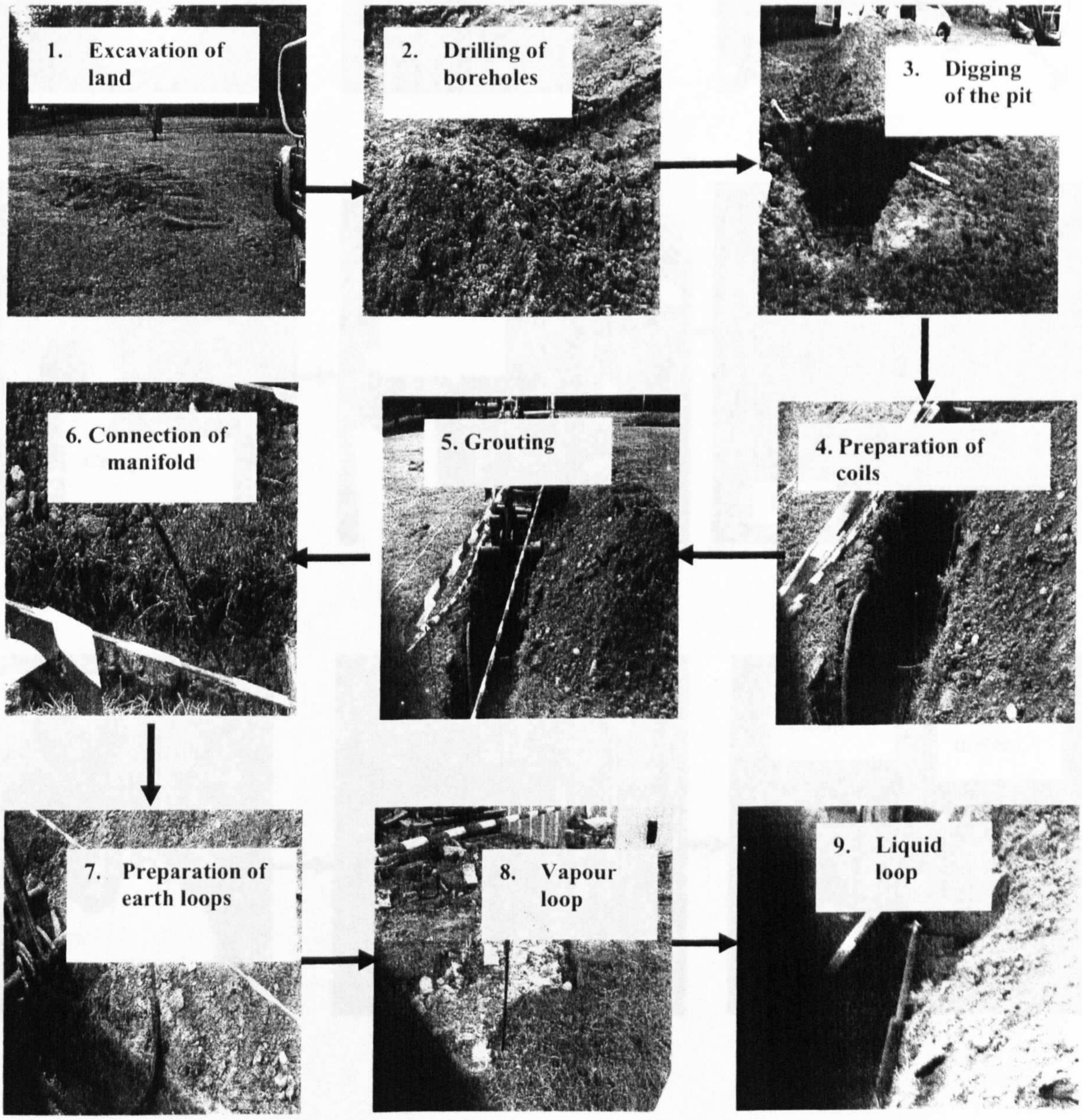


Figure 9.8 Pictures showing the stages of the drilling (1-2), digging of the pit (3), preparation of the coils (4), grouting, (5), connection of the manifolds (6), the source loop, which consists of two earth loops: one for vapour and one for liquid (7-9)

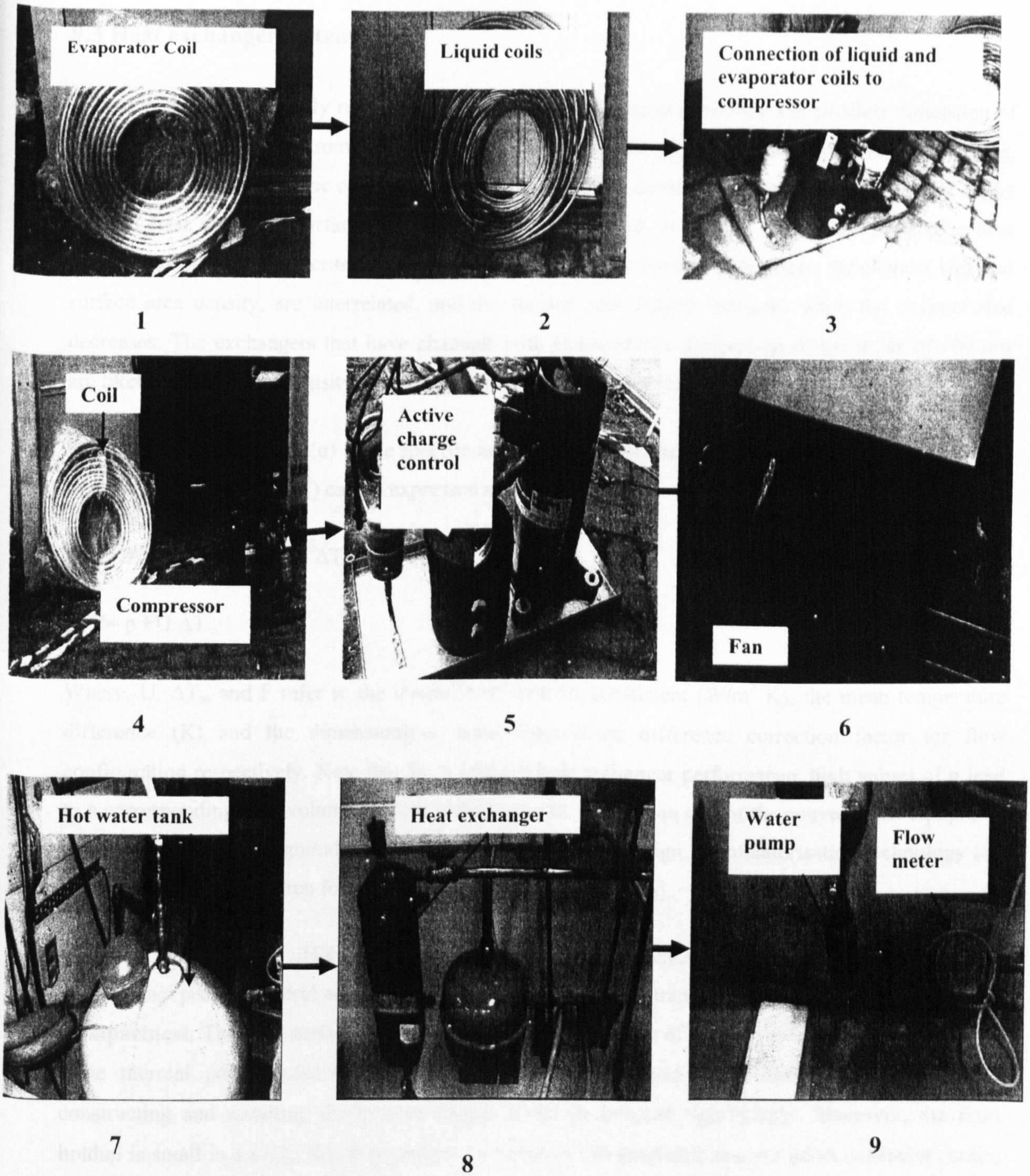


Figure 9.9 Pictures showing the stages of the preparation of coils (1-3), installation of heat pump (4-6) and connection of water supply system (water pump, flow metre, expansion valve and the boiler) (7-9)

9.3 Heat exchanger system

A heat exchanger is usually referred to as a micro heat exchanger (μHX) if the smallest dimension of the channels is at the micrometer scale, for example from 10 μm to 1 mm. Beside the channel size, another important geometric characteristic is the surface area density ρ (m^2/m^3), which is defined as the ratio of heat exchange surface area to volume for one fluid. It reflects the compactness of a heat exchanger and provides a criterion of classification. Note that the two parameters, the channel size and surface area density, are interrelated, and the surface area density increases when the channel size decreases. The exchangers that have channels with characteristic dimensions of the order of 100 μm are likely to get an area density over 10 000 m^2/m^3 and usually referred to as μHXs [212-215].

By introducing efficiency (α) in the specific heat exchanger performance equation, the volumetric heat transfer power P/V (W/m^3) can be expressed as follows:

$$P = FUA\,\Delta T_m = FUA\,\rho\,\alpha\,V\,\Delta T_m \qquad (9.1)$$

$$P/V = \rho\,FU\,\Delta T_m \qquad (9.2)$$

Where, U, ΔT_m and F refer to the overall heat transfer coefficient (W/m^2 K), the mean temperature difference (K) and the dimensionless mean temperature difference correction factor for flow configuration respectively. Note that for a specific heat exchanger performance, high values of α lead to a corresponding high volumetric heat transfer power, larger than that of the conventional equipment by several orders of magnitude. As a result, heat exchanger design by miniaturisation technology has become a common research focus for process intensification [216].

The main advantages of μHX design are "compactness, effectiveness and dynamic". These properties enable exact process control and intensification of heat and mass transfer [217]:

Compactness. The high surface area density reduces the volume of the heat exchanger needed for the same thermal power substantially. As a result, the space and costly material associated with constructing and installing the heat exchanger could be reduced significantly. Moreover, the fluid holdup is small in a μHX; this is important for security and economic reasons when expensive, toxic, or explosive fluids are involved.

Effectiveness. The relatively enormous overall heat transfer coefficient of μHXs makes the heat exchange procedure much more effective. In addition, the development of microfabrication techniques [218] such as LIGA, stereolithography, laser beam machining, and electroformation allows designing a μHX with more effective configurations and high pressure resistance.

Dynamic. The quick response time of a μHX provides a better temperature control for relatively small temperature differences between fluid flows. The quick response (small time constant) is connected to the small inertia of the heat transfer interface (the small metal thickness that separates the two fluids). On the other hand, the exchanger as a whole, including the "peripheric" material, usually has a greater inertia than conventional exchangers, entailing a large time-constant. Thus the response of one fluid to a temperature change of the other fluid comprises two "temperature-change waves", with very distinct time-constants. In conventional exchangers, it is possible that the two responses are blurred into one.

However, μHXs are not without shortcomings. On the one hand, the high performance is counterbalanced by a high pressure drop, a rather weak temperature jump and an extremely short residence time. On the other hand, those fine channels (~100 μm) are sensitive to corrosion, roughness and fouling of the surfaces. Moreover, the distinguishing feature of the μHXs is their enormous volumetric heat exchange capability accompanied with some difficulties in realisation. μHXs design optimisation lies, on the one hand, in maximising the heat transfer in a given volume taking place principally in microchannels, while, on the other, minimising the total pressure drops, the dissipations, or the entropy generation when they function as a whole system. Moreover, difficulties such as the connection, assembly, and uniform fluid distribution always exist, all of which should be taken into account at the design stage of μHXs. All these make the optimisation of μHXs design a multi-objective problem, which calls for the introduction of multi-scale optimization method in order to bridge the microscopic world and the macroscopic world [219]. In recent years, the fractal theory [220] and constructal theory [221] were introduced to bridge the characteristics of heat and mass transfer that mainly takes place in micro-scale and the global performance of the heat exchanger system in macro-scale [222].

The concept of multi-scale heat exchanger is expected to have the following characteristics [223]:

- A relatively significant specific heat exchange surface compared to that of traditional exchangers;
- A high heat transfer coefficient, as heat transfer is taking place at micro-scales and meso-scales;
- An optimised pressure drop equally distributed between the various scales;
- A modular character, allowing assembly of a macro-scale exchanger from microstructured modules.

Some difficulties still exist. On the one hand, the properties of flow distribution in such an exchanger are still unknown [224]. A lot of research work still needs to be done for the equidistribution optimization. On the other hand, 3-D modelling of heat transfer for such an exchanger requires a thorough knowledge of the hydrodynamics and profound studies on elementary volume (smallest scale micro channels). Finally, maintenance problems for this type of integrated structures may become unmanageable when fouling; corrosion, deposits or other internal perturbations are to be expected. Figures 9.10-9.12 show the connections of the heat exchanger, water pump, heat rejection fan expansion valve, and the power supply to heat injection fan (Figure 9.13).

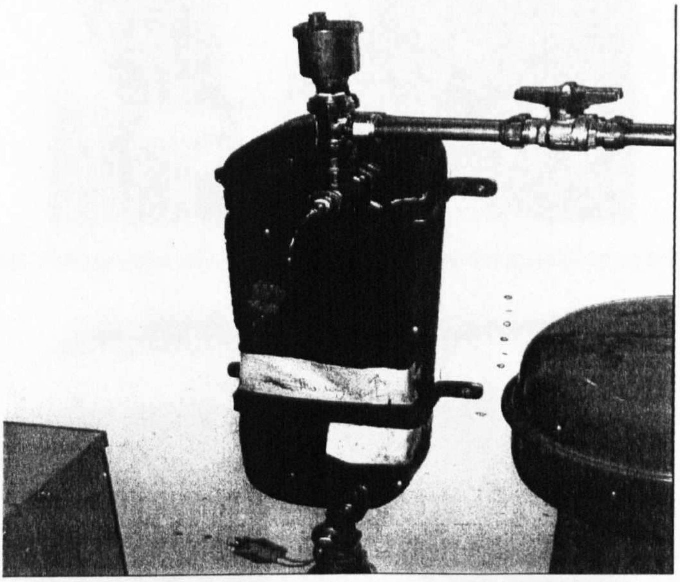


Figure 9.10 shows the heat exchanger

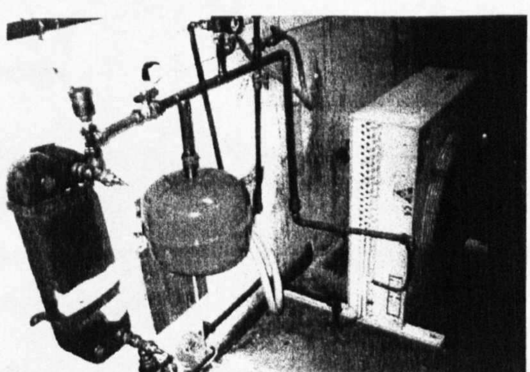


Figure 9.11 shows the connections of the heat exchanger, water pump, heat rejection fan and expansion valve

This project yielded considerable experience and performance data for the novel methods used to exchange heat with the primary effluent. The heat pump was also fitted in dry, well-ventilated position where full access for service and monitoring the performance of a number of GSHPs, including one so-called "hybrid" system that included both ground-coupling and a cooling tower is possible.

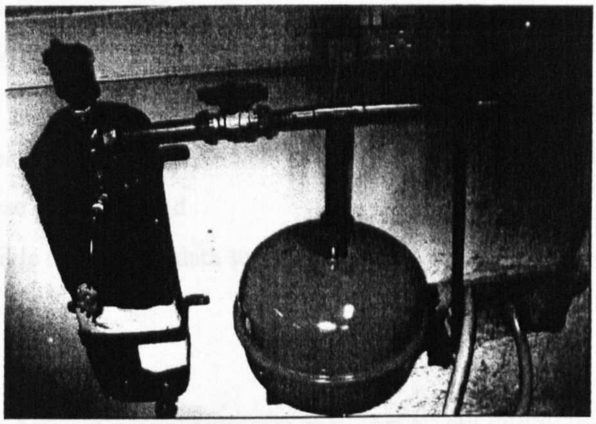


Figure 9.12 Shows the connections of the heat exchanger and expansion valve

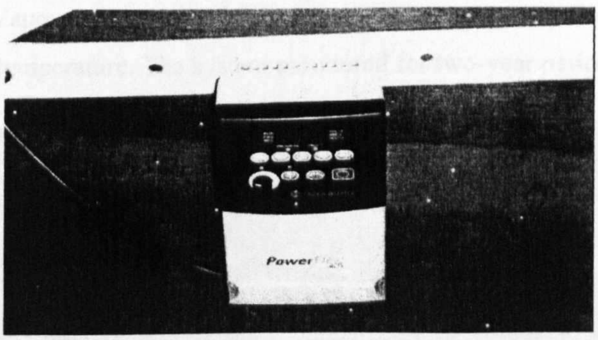


Figure 9.13 Shows the power supply to heat injection fan

9.4 Data acquisition system

With the debate on climate change, the preference for real measured data has been changed. The analyses of climate scenarios need an hourly weather data series that allows for realistic changes in various weather parameters. By adapting parameters in a proper way, data series could be generated for the site. Weather generators were useful for:

- Calculation of energy consumption (no extreme conditions are required).
- Design purposes (extremes are essential), and
- Predicting the effect of climate change, such as increasing the annual average of temperature.

This resulted in the following requirements:

- Relevant climate variables should be generated (solar radiation: global, diffuse and direct solar direction, temperature, humidity, wind direction and speed) according to the statistics of the real climate.
- The average behaviour should be in accordance with the real climate.
- Extremes should occur in the generated series in the way it will happen in a real warm period. This means that the generated series should be long enough to ensure the occurrence of these extremes, and
- It should be possible to generate data series based on average values from nearby stations.

9.4.1 Test procedures

The measurements of the different parameters have been carried out during the testing period using the data logger (DT 500) shown in Figure 9.14. The following were tested: (1) Indoor temperature (2) Pit temperature (3) Vapour temperature (4) Condenser temperature (5) Compressor temperature and (6) Heat exchanger temperature. The system monitored for two-year period.

Figure 9.14 Data logger

9.4.2 Measurement undertaken

The system was operated continuously, and monitored for the entire period of the experiment. Indoor temperature, pit temperature, vapour temperature, condenser temperature, compressor out let temperature, heat exchanger temperature, energy input and output, air temperatures and relative humidity were all continuously measured and automatically saved by a computer. The data were measured a 5 second interval and then averaged over 15 minutes period, and saved in the computer. The test rig was assembled as shown in Figure 9.15.

The data logger has the following features:

- Working voltage 5±0.2V DC, output voltage 1.0-3.0V DC, and maximum current 2mA.
- Accuracy 25-90% RH at 25°C.
- Storage temperature –40 to 50°C.
- Operation up to 100% relative humidity (RH).
- Easy installation, good long term reliability, and cost effective performance.

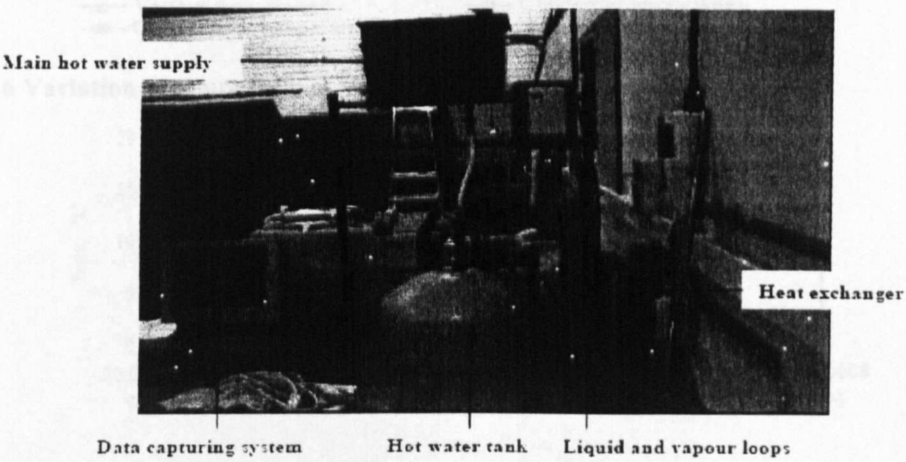


Figure 9.15 Data capturing /monitoring of the system

9.5 Results of the experiment

Figures 9.16 - 9.22 show summary result of the data collected, at specific periods of the tests. Temperature T_1, T_2, T_3, T_4, T_5 and T_6 shown in Figures 9.17 to 9.22 indicate Heat exchanger temperature out let, compressor temperature, condenser temperature, vapour temperature, indoor temperature, and pit temperature respectively.

The performance of the heat pump is inversely proportional to the difference between the condensation temperature and the evaporation temperature (the temperature lift). These are stable operating conditions, but not true steady state conditions. At output temperatures greater than 40°C, the heat pump was providing heating to the domestic hot water. The variation is largely due to variations in the source temperatures (range 0.2°C to 4.3°C). These results indicate that the system performance meets the specified rating for the heat pump of 2.5 kW at an output temperature in the range of 45 (older systems) and 65°C (newer systems) [224].

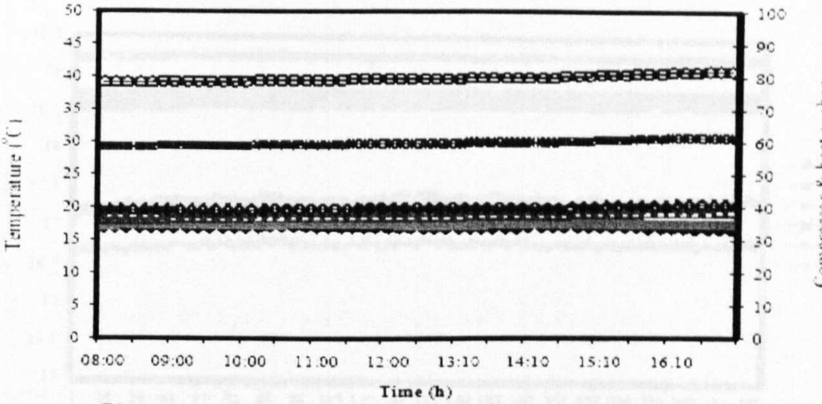


Figure 9.16 Variation of temperatures per day for the GSHP system

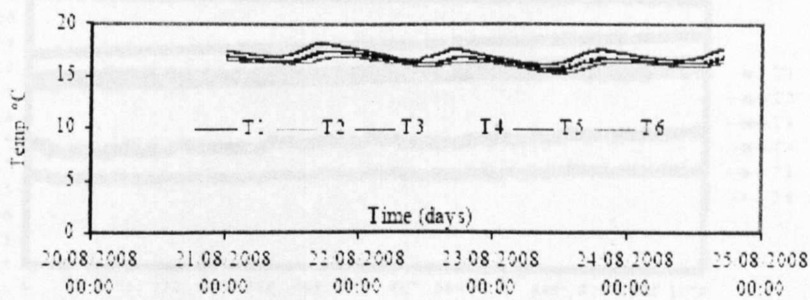


Figure 9.17 Variation of temperatures per 6 days for the GSHP system

Two different control mechanisms for the supply of energy from the heat pump for space heating were tested. From March 2007 until July 2008, the supply of energy from the heat pump to the space heating system was controlled by a thermostat mounted in the room. From August 2008, an alternative control using an outside air temperature sensor was used in order to reduce the need for the auxiliary heater. This is because the amount the auxiliary heater is used has a large effect on the cost of the system. This resulted in the heat pump operating more continuously in cold weather and in considerably less use of the auxiliary heater as planned. Using the outdoor air temperature sensor results in the return temperature being adjusted for changes in the outdoor temperature and good prediction of the heating requirement. Very stable internal temperatures were maintained. The same period of the year has been compared, using the room temperature sensor and an outdoor air temperature sensor. The operating conditions were not identical, but the average 24-hour temperatures for the two periods were quite similar at 9.26°C and 9.02°C respectively. Figures 9.16 -9.20 show variation of the daily system temperatures for a sample day in each period and the periods of operation of the auxiliary heater and the immersion heater.

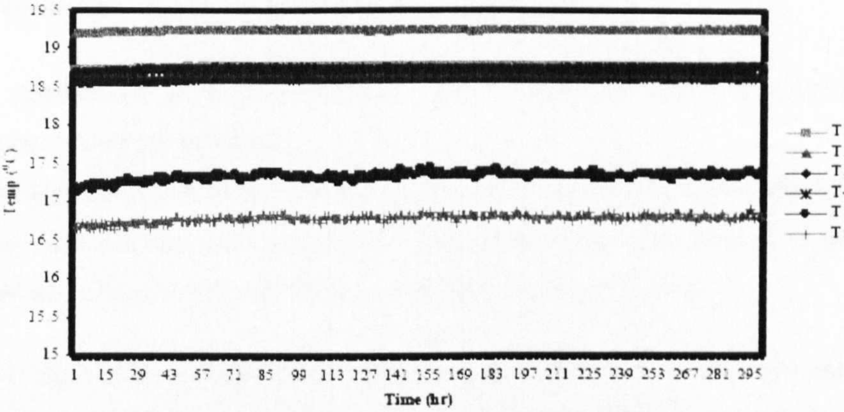


Figure 9.18 Variation of temperatures for heat exchanger for two weeks

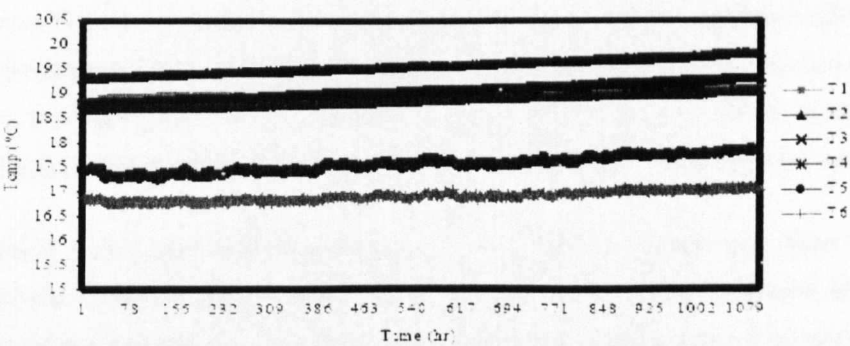


Figure 9.19 Variation of temperatures for heat exchanger for 45 days

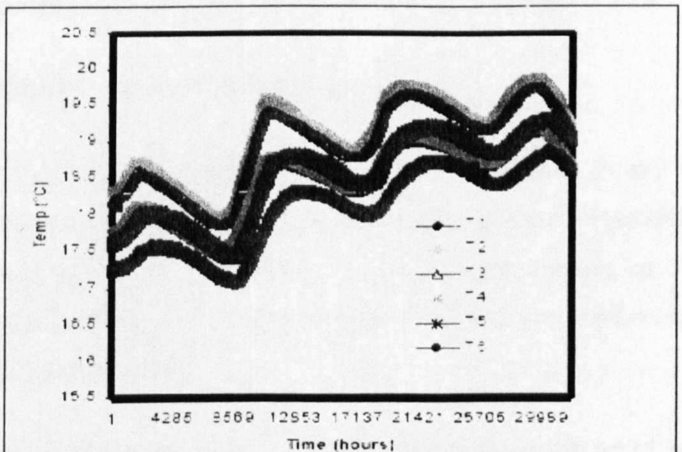


Figure 9.20 Variation of temperatures for heat exchanger for year

9.5.1 Heat pump performance

The performance of the heat pump depends on the performance of the ground loop and vice versa. Some of the factors that may affect performance of GSHP include:

- The underground pipes/boreholes may create undesirable hydraulic connections between different water bearing strata.
- Undesirable temperature changes in the aquifer that may result from the operation of a GSHP.
- Other issue that may need to be taken into consideration is the pollution of groundwater that might occur from leakage of additive chemicals used in the system.

Efficiencies of the GSHPs can be high because the ground maintains a relatively stable temperature allowing the heat pump to operate close to its optimal design point. In contrary in air source heat pumps, the air temperature varies both throughout the day and seasonally such that air temperatures, and therefore efficiencies, are lowest at times of peak heating demand. Heat pump efficiencies improve as the temperature differential between 'source' and demand temperature decreases, and when the system can be 'optimised' for a particular situation. The relatively stable ground temperatures moderate the differential at times of peak heat demand and provide a good basis for optimisation.

The refrigerant is circulated directly through the ground heat exchanger in a direct expansion (DX) system but most commonly GSHPs are indirect systems, where a water/antifreeze solution circulates through the ground loop and energy is transferred to or from the heat pump refrigerant circuit via a heat exchanger. This application will only consider closed loop systems. The provision of cooling, however, will result in increased energy consumption and the efficiency it is supplied with.

9.5.2 Coefficient of performance (COP) of the system

Heat pump technology can be used for heating mode, or for cooling mode, or in a 'reversible' mode for both heating and cooling depending on the demand. Reversible heat pumps generally have lower COPs than heating only heat pumps. They will, therefore, result in higher running costs and emissions. The heat delivered by the heat pump is theoretically the sum of the heat extracted from the heat source and the energy needed to deliver the cycle.

For electrically driven heat pumps the steady state performance at a given set of temperatures could be assessed in terms of the coefficient of performance (COP). It is defined as the ratio of the heat delivered by the heat pump and the electricity supplied to the compressor [225]:

COP = [heat output (kW_{th})] / [electricity input (kW_{el})] (9.3)

Figure 9.21 shows the daily total space heating from the heat pump and the auxiliary heater for the two heating control systems.

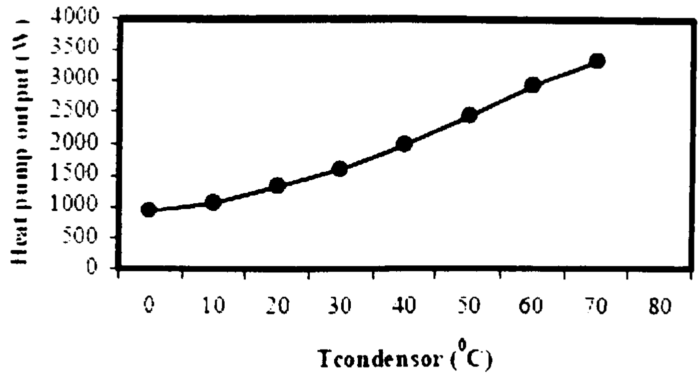


Figure 9.21 Variation of heat pump output with condenser temperature

For an ideal heat pump the heat output, however, is determined solely by the condensation temperature and the temperature lift (condensation temperature – evaporation temperature) [226]:

COP = [condensing temperature (°C)] / [temperature lift (°C)] (9.4)

Figure 9.22 shows the COP of heat pump as a function of the evaporation temperature. Figure 9.23 shows the COP of heat pump as a function of the condensation temperature. As can be seen, the theoretical measured is strongly dependent on the temperature lift. It is important not only to have as high a source temperature as possible but also to keep the sink temperature (i.e., heating distribution temperature) as low as possible. In practice, the achievable heat pump COP is lower than the ideal COP because of losses during the transportation of heat from the source to the evaporator and from the condenser to the room and the compressor. However, technological developments are steadily improving the performance of the heat pumps.

The first law of thermodynamics is often called the law of conservation of energy. Based on the first law or the law of conservation of energy for any system, open or closed, there is an energy balance as:

[Net amount of energy added to system] = [Net increase of stored energy in system] (9.5)

Or

[Energy in] – [Energy out] = [Increased of stored energy in system] (9.6)

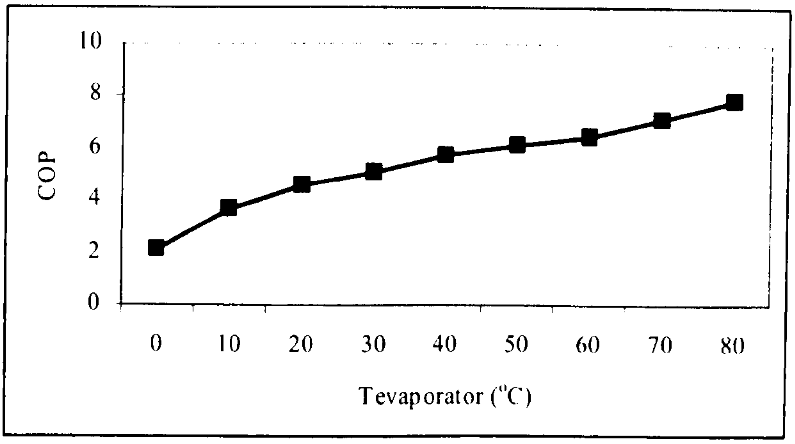


Figure 9.22 Heat pump performance vs evaporation temperature (°C)

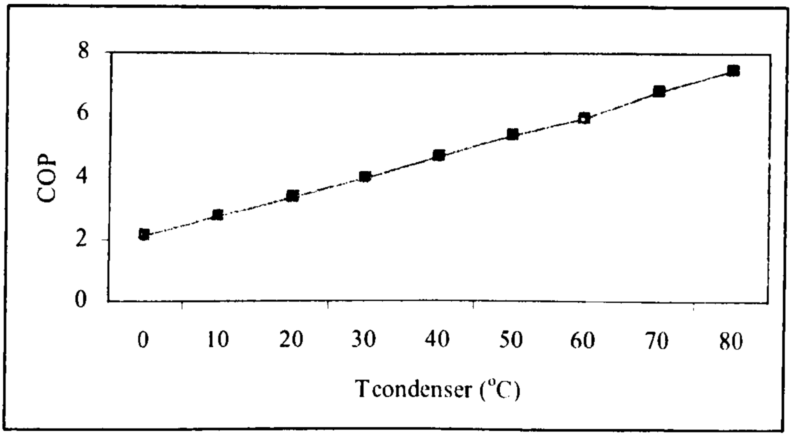


Figure 9.23 Heat pump performance vs condensation temperature (°C)

In a cycle, the reduction of work produced by a power cycle (or the increase in work required by a refrigeration cycle) equals the absolute ambient temperature multiplied by the sum of irreversibilities in all processes in the cycle. Thus, the difference in reversible and actual work for any refrigeration cycle, theoretical or real, operating under the same conditions becomes [227]:

$$W_{actual} = W_{reversible} + T_o \sum I \tag{9.7}$$

Where:

I is the irreversibility rate, kW/K.

T_o is the absolute ambient temperature, K

Refrigeration cycles transfer thermal energy from a region of low temperature to one of higher temperature. Usually the higher temperature heat sink is the ambient air or cooling water, at temperature T_o, the temperature of the surroundings. Performance of a refrigeration cycle is usually described by a coefficient of performance (COP), defined as the benefit of the cycle (amount of heat removed) divided by the required energy input to operate the cycle:

COP = [Useful refrigeration effect] / [Net energy supplied from external sources] (9.8)

For a mechanical vapour compression system, the net energy supplied is usually in the form of work, mechanical or electrical and may include work to the compressor and fans or pumps. Thus,

$$COP = [Q_{evap}] / [W_{net}] \quad (9.9)$$

In an absorption refrigeration cycle, the net energy supplied is usually in the form of heat into the generator and work into the pumps and fans, or:

$$COP = (Q_{evap}) / (Q_{gen} + W_{net}) \quad (9.10)$$

In many cases, work supplied to an absorption system is very small compared to the amount of heat supplied to the generator, so the work term is often neglected. Applying the second law of thermodynamic to an entire refrigeration cycle shows that a completely reversible cycle operating under the same conditions has the maximum possible COP. Table 9.1 lists the thermodynamic properties of the refrigerant at the various measuring points of the cycle. The mass flow of the refrigerant is the same through all the components, so it is only computed once through the evaporator. Departure of the actual cycle from an ideal reversible cycle is given by the refrigerating efficiency:

$$\eta_R = COP / (COP)_{rev} \quad (9.11)$$

Table 9.1 Computed thermodynamic properties of R-22

State	Pressure (kPa)	Temperature (°C)	Specific enthalpy (kJ/kg)	Specific entropy (kJ/kg K)	Specific volume (m^3/kg)
1. Evaporator	310	-10	402.08	1.78	0.075
2. Suction line	304	-4	406.25	1.79	0.079
3. Compressor	1450	82	454.20	1.81	0.021
4. Discharge line	1435	70	444.31	1.78	0.019
5. Condenser	1410	34	241.40	1.14	0.0008
6. Liquid line	1405	33	240.13	1.13	0.0008
7. Expansion device	320	-12.8	240.13	1.15	0.0191

Figures 9.24-9.26 show COP of the ground source heat pump for different applications, and show that this increases slightly with condenser temperatures. The increase is more apparent with the evaporator temperature as shown in Figure 9.26. As expected, the achievable COP is lower in cooling mode than in heating mode (Figure 9.24).

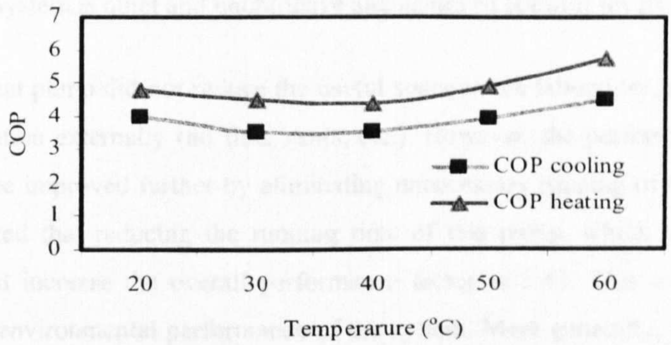


Figure 9.24 COP Vs condenser temperatures for different applications (°C)

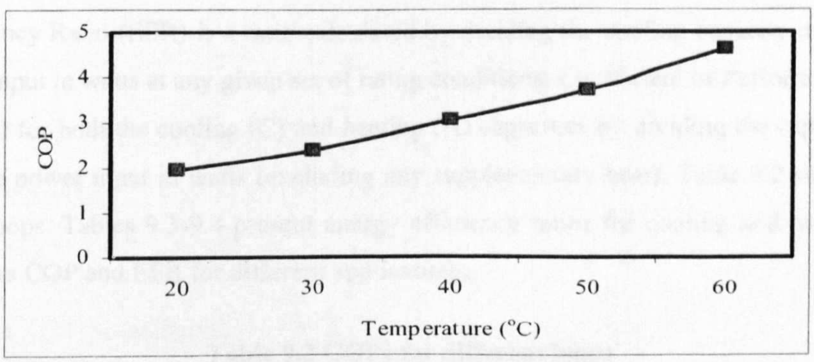


Figure 9.25 COP Vs temperature lifted (condensation temperatures-evaporation temperatures °C)

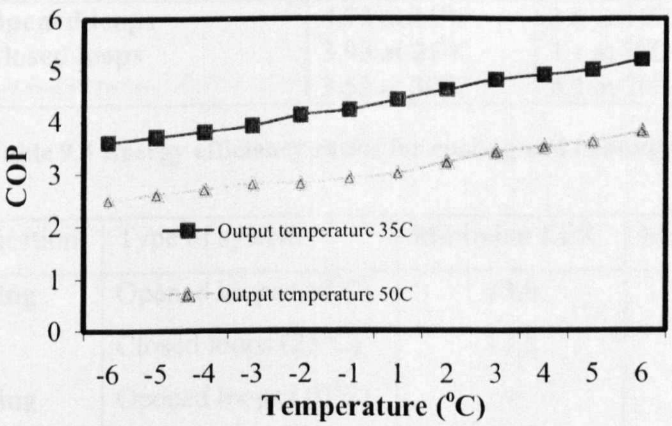


Figure 9.26 COP of GSHPs Vs evaporator temperatures (°C)

Over its first year of operation, the ground source heat pump system has provided 91.7% of the total heating requirement of the room and 55.3% of the domestic water-heating requirement, although only sized to meet half the design-heating load. The heat pump has operated reliably and its performance appears to be at least as good as its specification. The system has a measured annual performance factor of 3.16. The system is quiet and unobtrusive and achieved comfort levels.

Additionally, the heat pump did not reduce the useful space in the laboratory, and there are no visible signs of the installation externally (no flue, vents, etc.). However, the performance of the heat pump system could also be improved further by eliminating unnecessary running of the integral distribution pump. It is estimated that reducing the running time of this pump, which currently runs virtually continuously, would increase the overall performance factor to 3.43. This would improve both the economics and the environmental performance of the system. More generally, there is still a potential for improvement in the performance of the heat pump, and seasonal efficiency for ground source heat pumps of 4.0 might be possible. It is also likely that unit cost will fall as production volumes increase.

Energy Efficiency Ratio (EER) is a ratio calculated by dividing the cooling capacity in watts per hour by the power input in watts at any given set of rating conditions. Coefficient of Performance (COP) is a ratio calculated for both the cooling (C) and heating (H) capacities by dividing the capacity expressed in watts by the power input in watts (excluding any supplementary heat). Table 9.2 summarises COP for different loops. Tables 9.3-9.4 present energy efficiency ratios for cooling and heating purposes. Table 9.5 shows COP and EER for different applications.

Table 9.2 COPs for different loops

Type of system	COP_C	COP_H
Opened loops	4.75 at 15°C	3.6 at 10°C
Closed loops	3.93 at 25°C	3.1 at 0°C
[illegible]	3.52 at 30°C	4.2 at 20°C

Table 9.3 Energy efficiency ratios for cooling and heating applications

Application	Type of system	Minimum EER	Minimum COP
Cooling	Opened loops (10°C)	13.0	-
	Closed loops (25°C)	11.5	-
Heating	Opened loops (10°C)	-	3.1
	Closed loops (0°C)	-	2.8

Table 9.4 Direct expansion closed loop ground or water source heat pumps

Application	Type of system	Minimum EER	Minimum COP
Cooling	Opened loops (10°C)	11.0	3.2
	Closed loops (25°C)	10.5	3.1
Heating	Opened loops (10°C)	-	3.0
	Closed loops (0°C)	-	2.5

Table 9.5 Key energy star criteria for ground-source heat pumps

Product Type	Minimum EER	Minimum COP	Water Heating (WH)
Closed-loop	14.1	3.3	Yes
With integrated WH	14.1	3.3	N/A
Open-loop	16.2	3.6	Yes
With integrated WH	16.2	3.6	N/A
DX	15.0	3.5	Yes
With integrated WH	15.0	3.5	N/A

Ground storage systems can be classified in many different ways. One of the most important classifications is in accordance with the temperature of the storage. According to this classification, the ground storage systems are classified as follows:

- GSHPs, without artificially charging the soil - temperature about 10°C.
- Low temperature ground storage - temperature < 50°C.
- High temperature ground storage - temperature > 50°C.

9.5.3 Seasonal performance factor (SPF)

There are primary two factors to describe the efficiency of heat pumps. First, the coefficient pf performance (COP) is determined in the test stand with standard conditions for a certain operating point and/or for a number of typical operating points. Second, the seasonal performance factor (SPF), describes the efficiency of the heat pump system under real conditions during a certain period, for example for one year. The SPFs in this case are the ratio of the heat energy produced by the heat pump and the back-up heater and the corresponding energy required of the heat pump. SPF = heat delivered (kWh/season / energy supplied (kWh/season). The SPF for individual months and an average value for the year 2008 for the present GSHP are shown in Figure 9.27. The assessment of the 2008 measurement data for the GSHP in the buildings providing both heating and cooling reveals a seasonal performance factor (SPF) of 3.8. The SPF of the present system was in the range of 3.0-4.6.

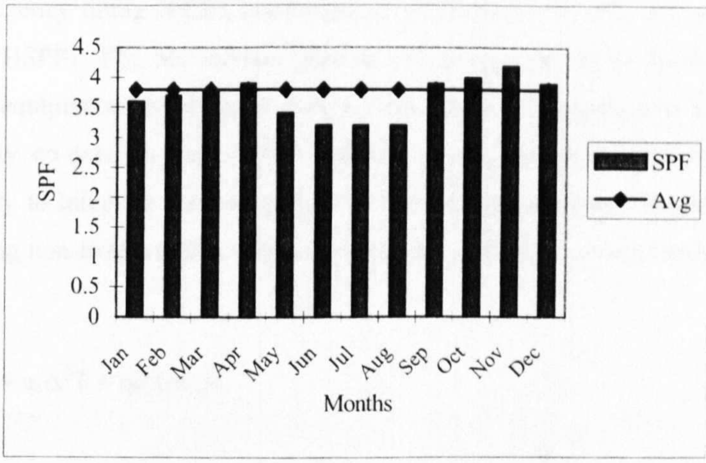


Figure 9.27 Seasonal performance for individual months and average for 2008

The preliminary results show that the GSHP are especially promising when it comes to reaching high efficiencies under real conditions. However, there is still a need for optimisation in the integration of the unit in the supply system for the house and for the control strategies of the heat pump. Thus, a poorly integrated heat source or an incorrectly designed heat sink can decrease the seasonal performance factor of the heat pump.

9.5.4 Comparison of numerical simulation and experiments

GSHPS are generally more expensive to develop, however they have very low operating cost to justify the higher initial cost. Therefore, it is necessary to have an idea of the energy use and demand of these equipments. The performances are normally rated at a single fluid temperature (0°C) for heating COP and a second for cooling EER (25°C). These ratings reflect temperatures for an assumed location and ground heat exchanger type, and are not ideal indicators of energy use. This problem is compounded by the nature of ratings for conventional equipment. The complexity and many assumptions used in the procedures to calculate the seasonal efficiency for air-conditioners, furnaces, and heat pumps (SEER, AFUE, and HSPF) make it difficult to compare energy use with equipment rated under different standards. The accuracy of the results is highly uncertain, even when corrected for regional weather patterns. Additionally, these values are not good indicators for demand since they are seasonal averages and performance at severe conditions is not adequately weighted.

Consequently, the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) [228] recommends a weather driven energy calculation, like the bin method, in preference to single measure methods like seasonal energy efficiency ratio (SEER), seasonal performance factor

(SPF), energy efficiency rating (EER), coefficient of performance (COP), and annual fuel utilisation efficiency rating (HSPF). The bin method permits the energy use to be calculated based on local weather data and equipment performance over a wide range of temperatures [229]. Both solid and liquid parts usually co-exist in one control volume of non-isothermal groundwater flow. It was, therefore, necessary to integrate the two parts into one energy equation. Accordingly, the governing equations describing non-isothermal groundwater flow in a saturated porous medium can be written as follows [230].

$$T\,(\Delta v) + (\delta T/\delta t)\,\sigma = \alpha_t \Delta^2 T + qt/\,(\rho C_p)_f \quad (9.12)$$

and

$$(\rho C_p)_t = \psi\,(\rho C_p)_f + (1-\psi)\,(\rho C_p)_s \quad (9.13)$$

Where:

C_p is the specific heat (J kg^{-1} K^{-1}); q is the internal heat source (Wm^{-3}), W is the water content in soil (%); T is the temperature (°C), H is the condensation latent heat of water (J kg^{-1}), t is the times (s); U is the velocity (ms^{-1}), f_s is the solid phase ratio; s is the soil; f is the groundwater, ψ is the porosity; α is the convective heat transfer coefficient ($Wm^{-2}K^{-1}$), δ is volumetric specific heat ratio; and ρ is the density (kg m^{-3}).

According to these Figures 9.28-9.29, the measured and calculated values are in agreement qualitatively, although the measured temperature distributions are more than those of the calculated ones. The numerical estimations and experiments are conducted for are conducted for unsaturated (US) soil without groundwater flow, saturated soil (SS) without groundwater flow and saturated soil with groundwater (SSG) flow under same conditions and their results are compared under the same condition and their results are compared as shown in Figures 9.30-9.31.

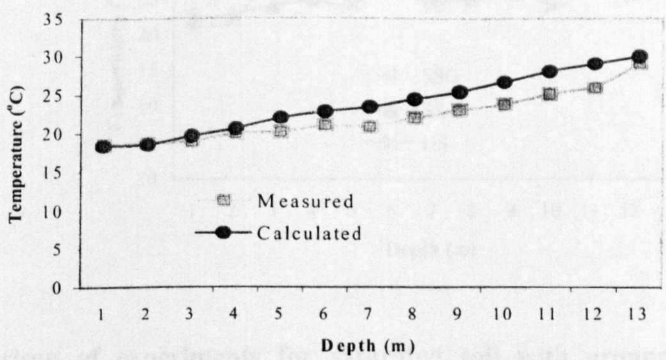


Figure 9.28 Comparison of calculations and experiments for saturated soil with groundwater flow (SSG)

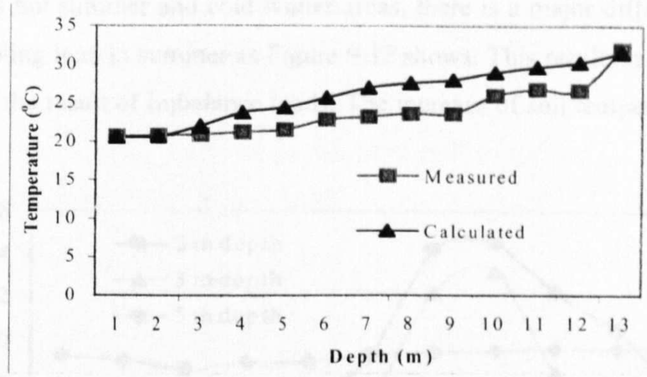


Figure 9.29 Comparison of calculations and experiments for saturated soil without groundwater flow (SS)

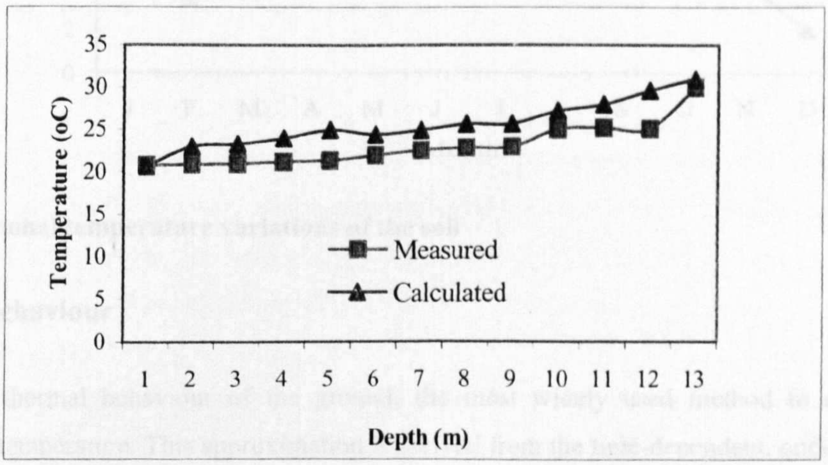


Figure 9.30 Comparison of calculations and experiments for unsaturated soil without groundwater flow (US)

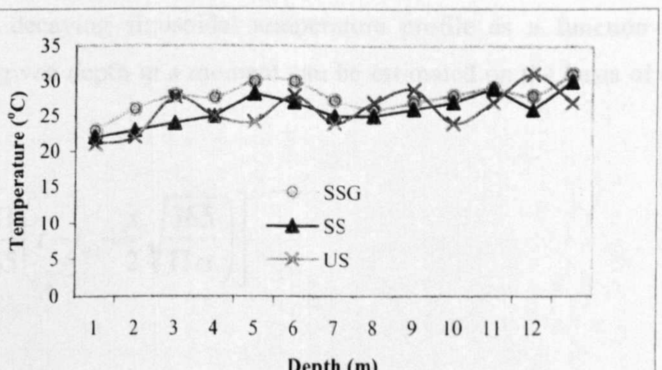


Figure 9.31 Comparison of experiments for saturated soil with groundwater flow (SSG), saturated soil without groundwater flow (SS) and unsaturated soil without groundwater flow (US)

In some zones such as hot summer and cold winter areas, there is a major difference between heating load in winter and cooling load in summer as Figure 9.32 shows. This results in an inefficient recovery of soil temperature as the result of imbalance loads. The increase of soil temperature will decrease the COP of the system.

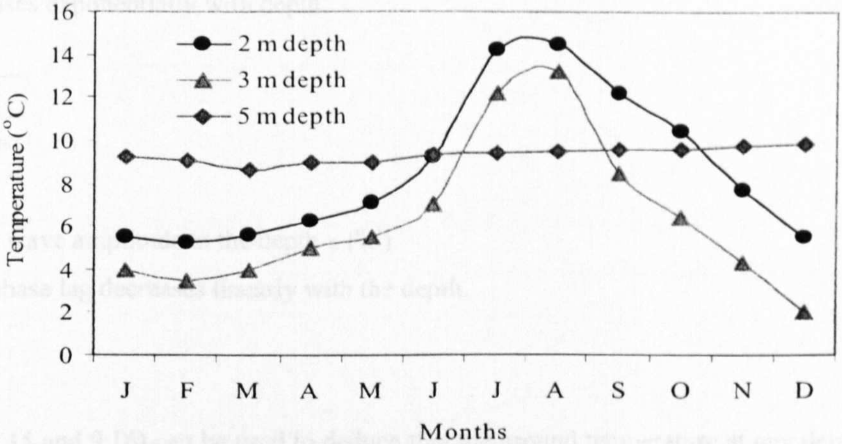


Figure 9.32 Seasonal temperature variations of the soil

9.6 Thermal Behaviour

To explain the thermal behaviour of the ground, the most widely used method to estimate the undisturbed soil temperature. This approximation is derived from the time-dependent, one-dimensional temperature solution for heat flow in a semi-infinite solid with a prescribed surface temperature boundary condition and constant thermal diffusivity [231]. An annual sinusoidal ambient temperature profile and an exponentially decaying sinusoidal temperature profile as a function of depth are assumed. Temperature at any given depth in a moment can be estimated on the basis of the following equation [232-268]:

$$T(x,t)= A_s e^{-x\sqrt{\frac{\Pi}{365\alpha}}} \cos\left[\frac{2\Pi}{365}\left(t-t_o-\frac{x}{2}\sqrt{\frac{365}{\Pi\alpha}}\right)\right] \quad (9.14)$$

Where:

T(x, t) is the soil temperature at the depth (x) and time (t) (°C), T_m is an average soil temperature (°C), A_s is the thermal wave amplitude (°C), x is the depth (m), t is the day of year (in days, where t=0 at midnight on 31 December), t_o is the phase constant (days), and α is the apparent thermal diffusivity (m^3/day).

This simplified model has disadvantages such as the diffusivity of precisely approximating the annual outside temperature as a sine wave or the unevenness of the soil profile. Nevertheless, the application of this equation has provided valid results in comparisons with experimental results from USA [269], Australia [270], and other regions [271]. From equation (9.14), it can be inferred that the wave amplitude decreases exponentially with depth:

$$A_x = A_s \ e^{-x\sqrt{\frac{\Pi}{365\alpha}}} \quad (9.15)$$

Where:

A_x is the thermal wave amplitude at the depth x (°C)

In addition, the phase lag decreases linearly with the depth.

$$t - t_o = \frac{1}{2}\sqrt{\frac{365}{\alpha\Pi}}x \quad (9.16)$$

The equations (9.15 and 9.16) can be used to deduce that the ground temperature at any depth depends on the surface temperature of the soil (mean temperature and amplitude) and of the physical properties of the soil profile: conductivity (k), density (ρ) and specific heat (c), grouped in the apparent thermal diffusivity (α) considering a homogenous soil:

$$\alpha = k/\rho c \quad (9.17)$$

Thus, the soil properties and depth determine the damping and the phase lag of the temperature wave. The greater the depth to which the pit is excavated and the lower the apparent thermal diffusivity of the soil, the greater the stability inside it and the less the external variations will be perceived. Figures 9.33-9.36 are examples in which it can be seen how temperature varies with the depth and thermal diffusivity of an ideal surface temperature of 12°C, annual amplitude of 10°C and phase lag of 20 days.

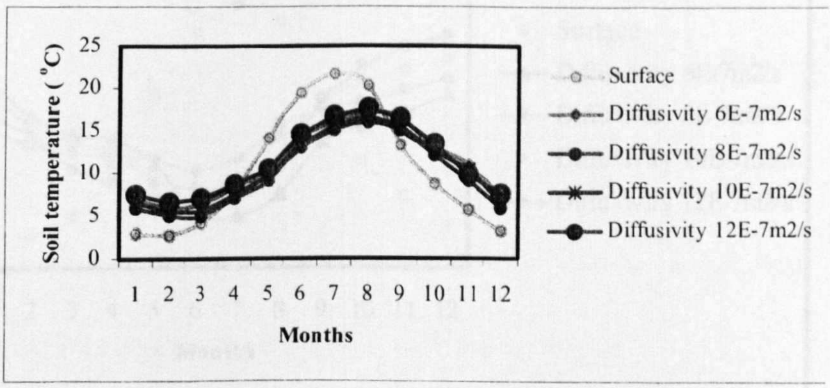


Figure 9.33 Temperature of ground at depth 1 m for different thermal diffusivity

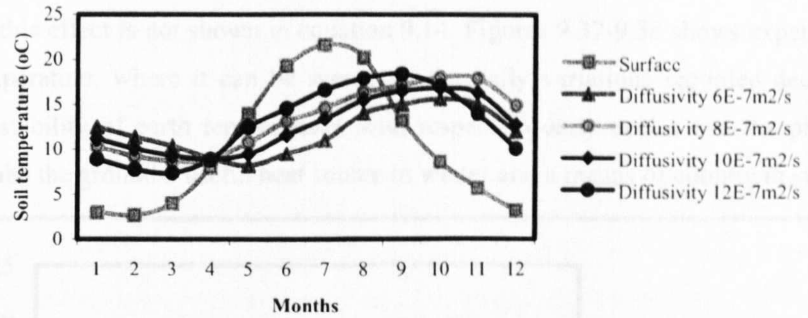


Figure 9.34 Temperature of ground at depth 3 m for different thermal diffusivity

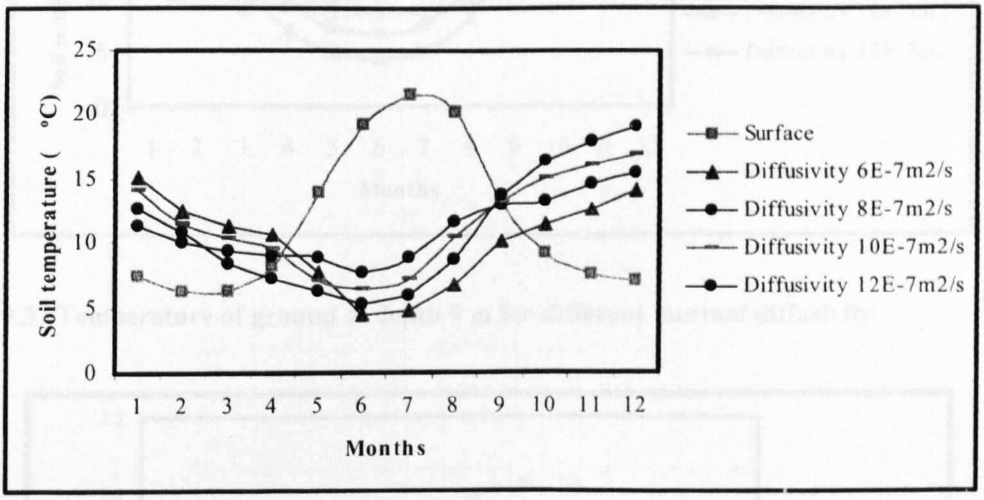


Figure 9.35 Temperature of ground at depth 5 m for different thermal diffusivity

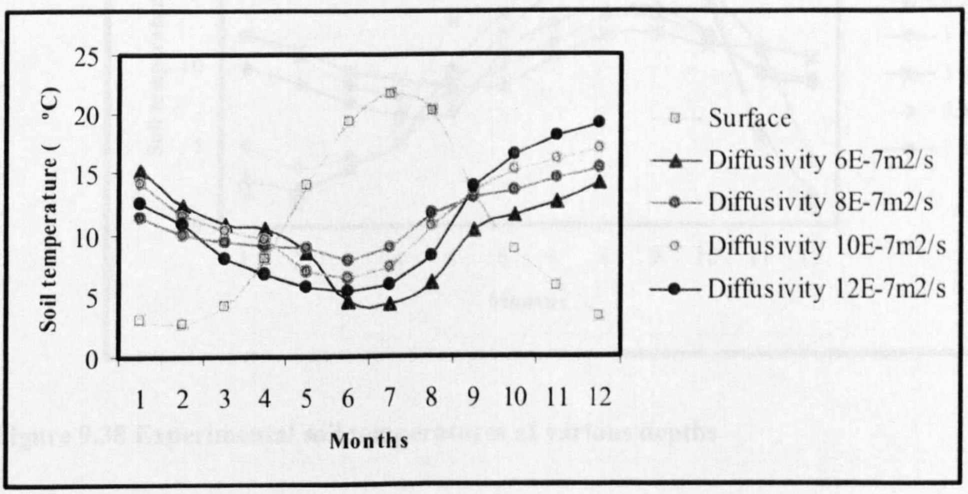


Figure 9.36 Temperature of ground at depth 7 m for different thermal diffusivity

As well as damping the amplitude and phase lag of temperature wave, the oscillations also reduce with depth although this effect is not shown in equation 9.14. Figures 9.37-9.38 shows experimental data of the ground temperature, where it can be seen how the daily variations recorded decrease as depth increases. The stability of earth temperatures with respect to daily cycles and the phase lag of the annual wave make the ground a useful heat source in winter and a means of cooling in summer.

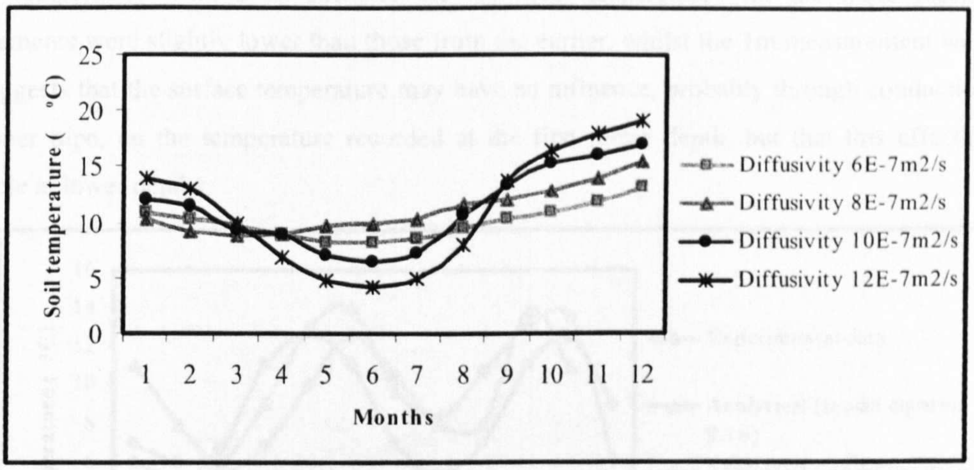


Figure 9.37 Temperature of ground at depth 9 m for different thermal diffusivity

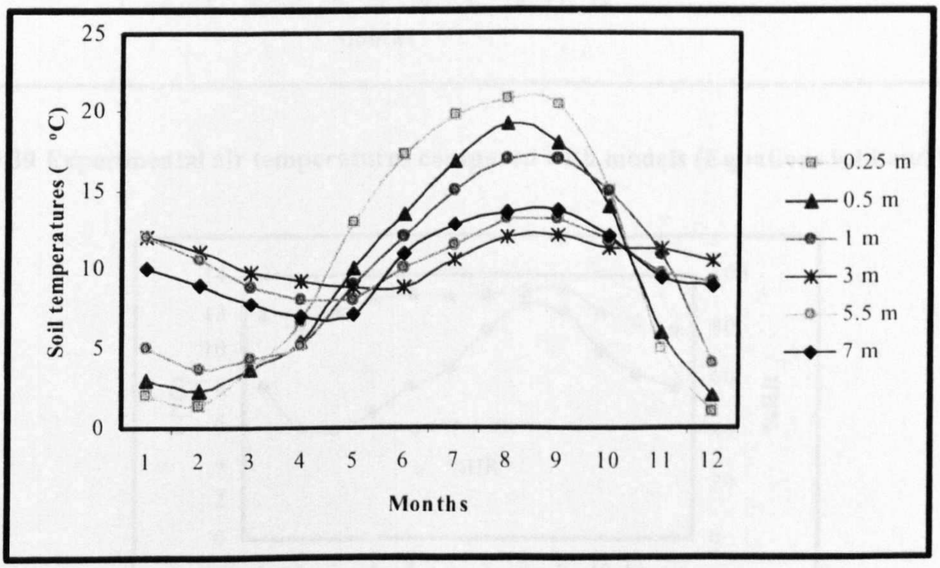


Figure 9.38 Experimental soil temperatures at various depths

$$T(x,t)=(T_m-k)\,A_s e^{-x\sqrt{\frac{\Pi}{365\alpha}}}\cos\left[\frac{2\Pi}{365}\left(t-t_o-\frac{x}{2}\sqrt{\frac{365}{\Pi\alpha}}\right)\right] \quad (9.18)$$

The measured temperatures of the ground loops start at the winter – 14°C are the mixed output of all ground loops (situated at 1 m and 1.7 m and two levels in between) as shown in Figures 9.39-9.40. The surface temperature from 2 m onwards the recorded temperatures for the more recent set of measurements were slightly lower than those from the earlier, whilst the 1m measurement was higher. This suggests that the surface temperature may have an influence, probably through conduction within the copper pipe, on the temperature recorded at the first metre depth, but that this effect becomes negligible at lower depths.

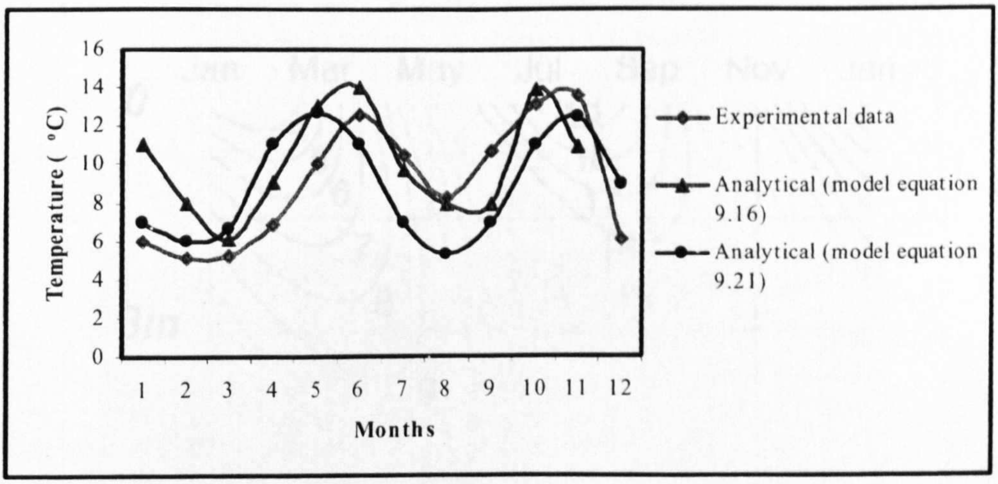


Figure 9.39 Experimental air temperatures compared with models (Equations 9.14 and 9.18)

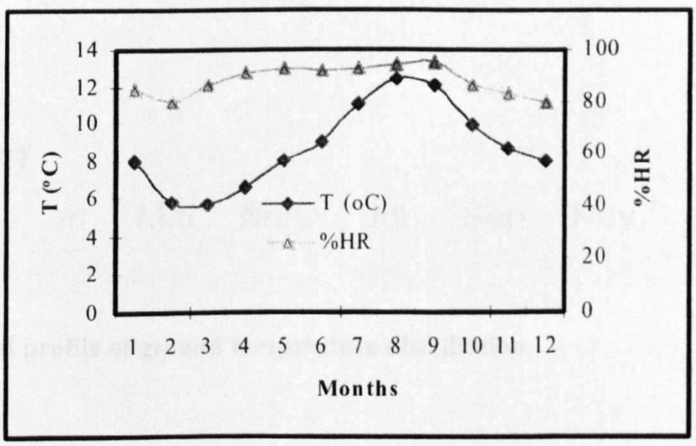


Figure 9.40 Experimental temperature and relative humidity values for the air inside the pit at an average depth of 3 m

There are lots of disturbing factors affecting measurements. Surface topography, vegetation and hydrological conditions affect also to the subsurface temperature. Below surface the temperature profile is being disturbed by changes in groundwater conditions. From the measurements it has been found out that daily variation of surface temperature can be seen in the depth of 2 meters and annual variation of surface temperature can be seen in the depth of 20 meters. Rapid temperature changes are therefore not conveyed very deep so the temperature reconstructions from boreholes do not show rapid temperature changes, but they show how the temperature has varied during decades and centuries. Figure 9.41 shows seasonal profile of ground temperature distribution. Figures 9.42-9.44 shows air temperatures, earth temperatures.

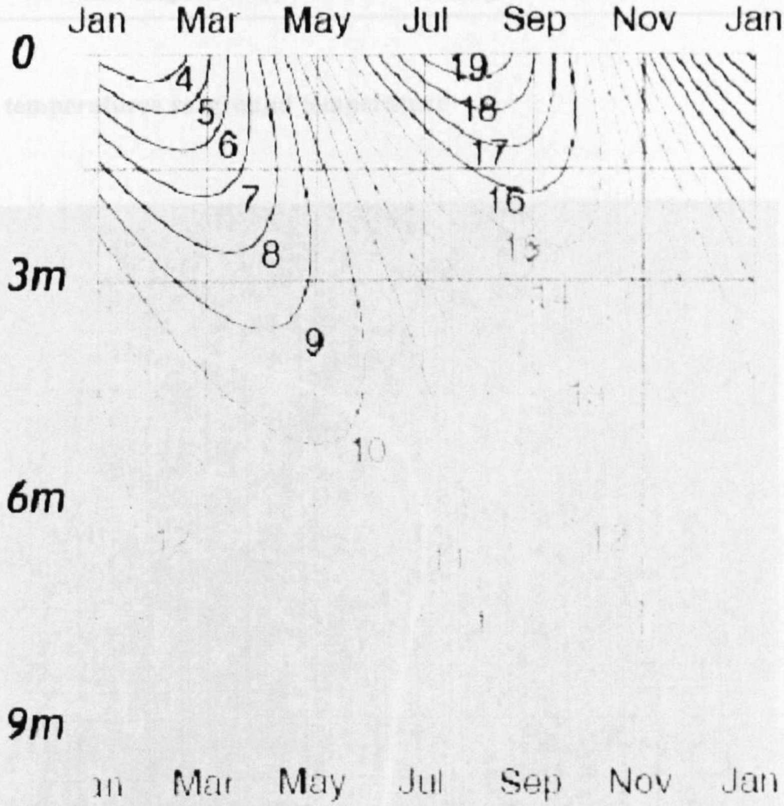


Figure 9.41 Seasonal profile of ground temperature distribution

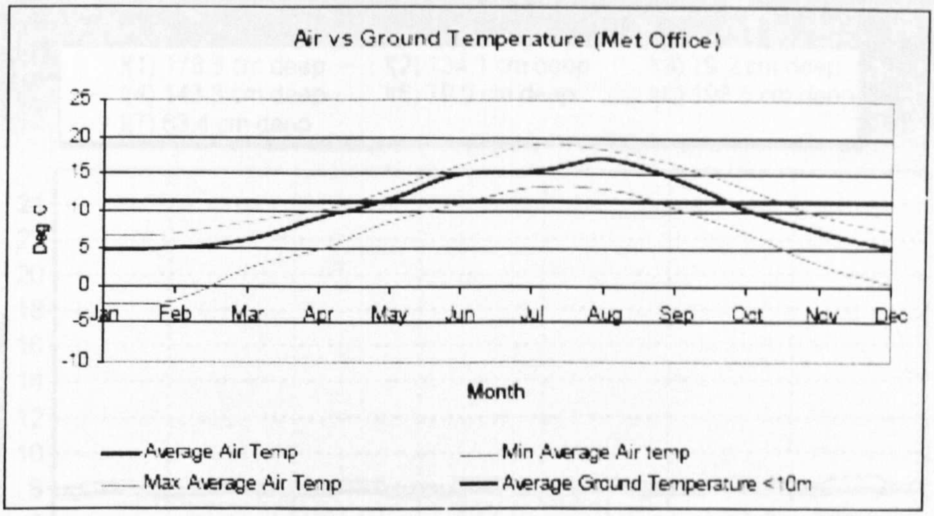


Figure 9.42 Air temperatures vs. ground temperature

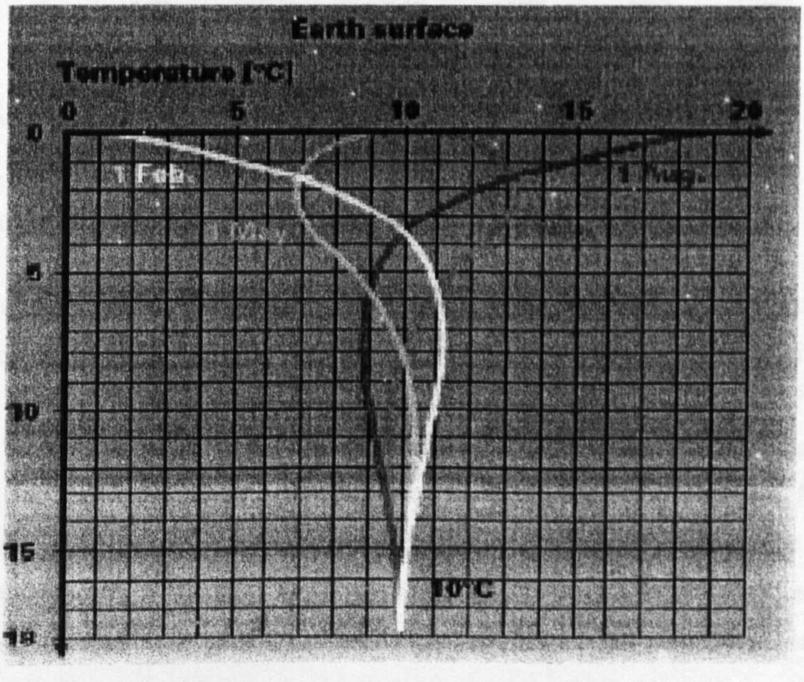


Figure 9.43 Ground temperatures below ~10 m near constant throughout the year

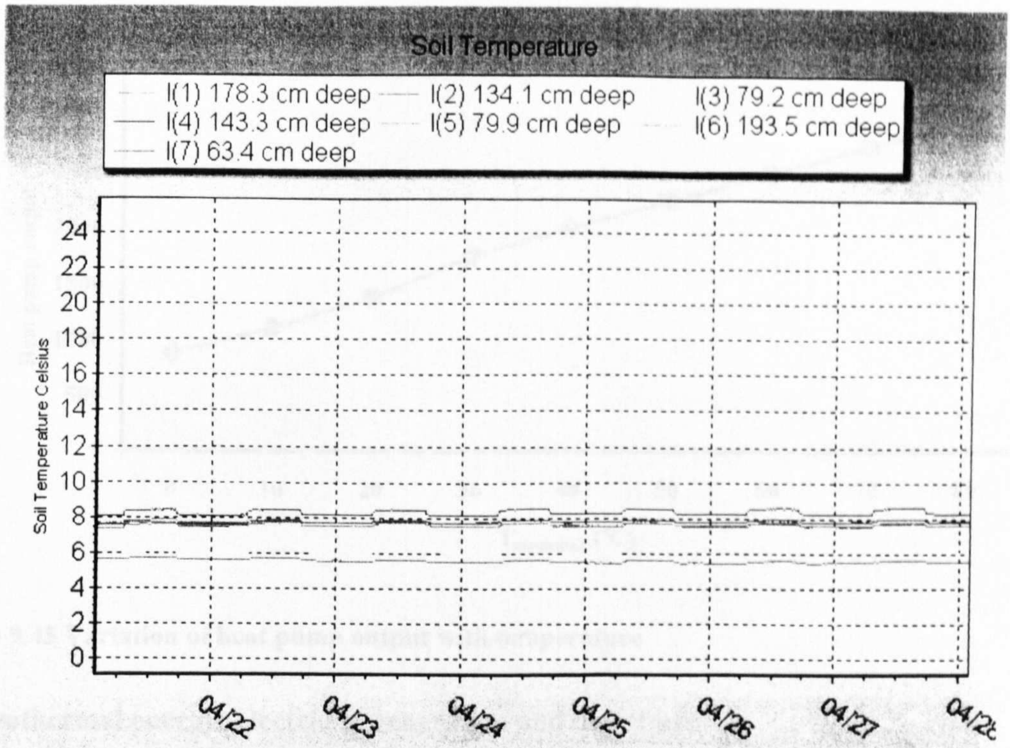


Figure 9.44 Soil temperatures

9.7 Performance of the ground collector

The flow rate in the ground coil is 0.23 l/s. The heat collection rate varies from approximately 19 W to 27 W per metre length of collector coil. In winter, the ground coil typically operates with a temperature differential of about 5°C (i.e., a flow temperature from the ground of 2°C to 3°C and a return temperature to the ground coil of -1°C to -2°C). The ground coil temperatures are considerably higher in summer when, for water heating, the temperature differential is similar but flow and return temperatures are typically 11°C and 6°C respectively. When the heat pump starts, the flow and return temperatures stabilise very quickly. Even over sustained periods of continuous operation the temperatures remained stable. Figure 9.45 shows the variation of ground source heat pump against ground temperatures.

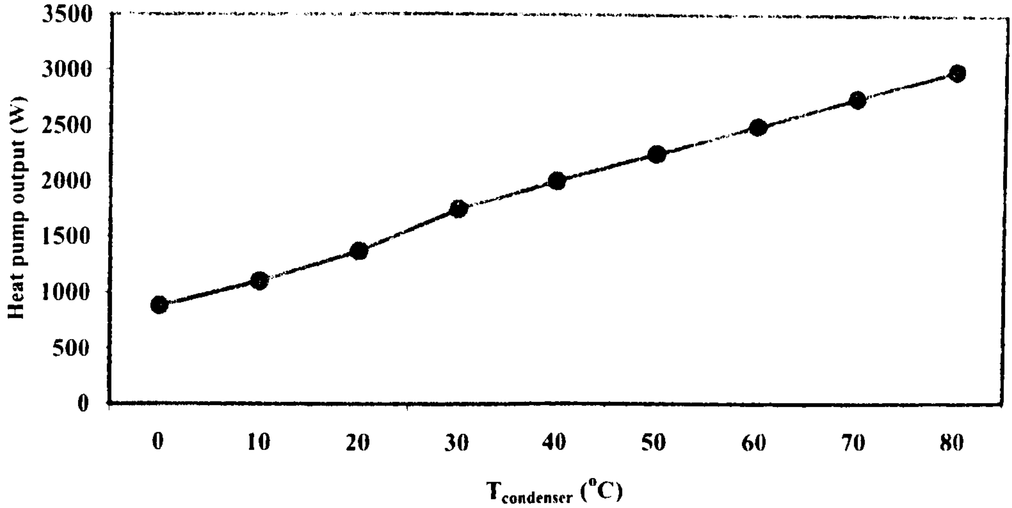


Figure 9.45 Variation of heat pump output with temperature

9.8 Geothermal energy: electricity generation and direct use

Geothermal power is very competitive with other sources of energy when it comes to energy costs. Table 9.6 shows the globally averaged energy costs in 2008 for different energy sources and shows what the potential future energy costs for different sources will be. As the Table 2 shows, geothermal is already generally more financially viable and cost-effective globally than other forms of renewable power, being on par with hydro-electricity (however, it is important to note that costs will vary between countries) [272].

Table 9.6 Comparison of energy costs between different energy sources

Energy source	Energy costs (US¢/kWh)	Potential future energy costs (US¢/kWh)
Hydro	2-10	2-8
Biomass	5-15	4-10
Geothermal	2-10	1-8
Wind	5-13	3-10
Solar	25-125	5-25
Tidal	12-18	4-10
coal	4	0.4

Concerning direct heat uses, the three countries with the largest amount of installed power: USA (5,366 MW_t), China (2,814 MW_t) and Iceland (1,469 MW_t) cover 58% of the world capacity, which has reached 16,649 MW_t, enough to provide heat for over 3 million houses [272]. Out of about 60 countries with direct heat plants, beside the three above-mentioned nations, Turkey, several European countries, Canada, Japan and New Zealand have sizeable capacity. Most systems have less than 15 kWth heating output, and with ground as heat source, direct expansion systems are predominant. Ground-source heat pumps had a market share of 95% in 2006 [272] (Figure 9.46). Figure 9.47 illustrates the monthly energy consumption for a typical household in the United Kingdom.

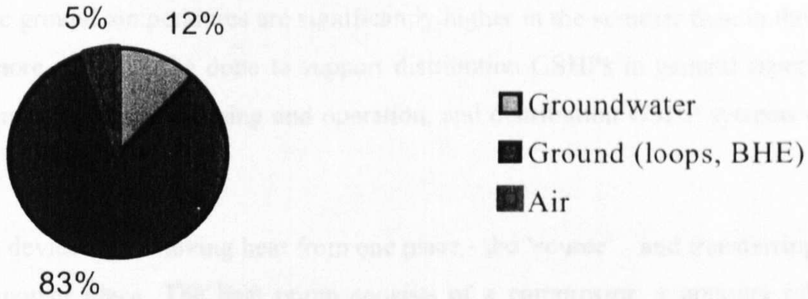


Figure 9.46 Distribution of heat sources for heat pumps (for space heating)

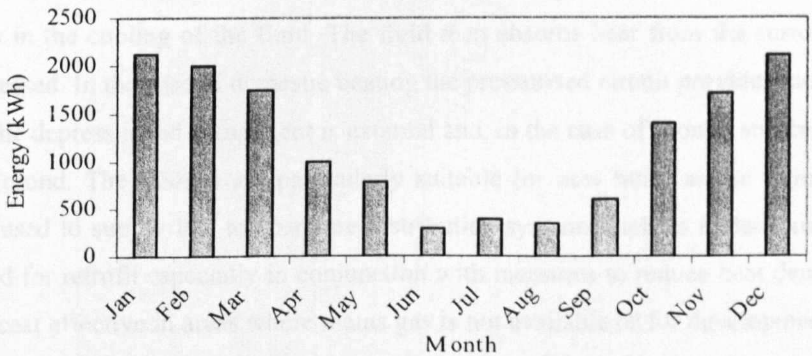


Figure 9.47 Monthly heating energy demands

Geothermal power utilises the heat energy naturally produced within the earth. Its wide abundance and renewable nature make it an attractive alternative energy source to fossil fuels. The environmental impact of geothermal power plants is negligible in comparison to combustion plants and it is progressively becoming more financially viable as emission regulations are tightened. The technology is increasingly being utilised by countries all over the world, as there are many different ways in which geothermal can be harnessed. The energy used to operate this pump could be reduced if it was controlled to operate only when the heat pump was supplying heat. The improvement in efficiency would be greatest in summer when the heat pump is only operating for a short period each day. If this pump was controlled to operate only when the heat pump is operating, it is estimated that the overall annual performance factor of the heat pump system would be 3.43, and that the average system efficiencies for the period November to March and April to September would be 3.42 and 3.44 respectively. Under these conditions, it is predicted that there would only be a small variation in the efficiency of the heat pump system between summer and winter. This is explained by the fact that although the output temperature required for domestic water heating is higher than that required for space heating, the ground temperatures are significantly higher in the summer than in the winter. There is clearly a lot more that must be done to support distribution GSHPs in general especially from the perspective of buildings in the planning and operation, and distribution GSHP systems (Figures 9.48-9.50).

A heat pump is a device for removing heat from one place - the 'source' - and transferring it at a higher temperature to another place. The heat pump consists of a compressor, a pressure release valve, a circuit containing fluid (refrigerant), and a pump to drive the fluid around the circuit. When the fluid passes through the compressor it increases in temperature. This heat is then given off by the circuit while the pressure is maintained. When the fluid passes through the relief valve the rapid drop in pressure results in the cooling of the fluid. The fluid then absorbs heat from the surroundings before being re-compressed. In the case of domestic heating the pressurised circuit provides the heating within the dwelling. The depressurised component is external and, in the case of ground source heat pumps, is buried in the ground. The GSHPs are particularly suitable for new build as the technology is most efficient when used to supply low temperature distribution systems such as underfloor heating. They can also be used for retrofit especially in conjunction with measures to reduce heat demand. They can be particularly cost effective in areas where mains gas is not available or for developments where there is an advantage in simplifying the infrastructure provided. The ground source heat pump system, which uses a ground source with a smaller annual temperature variation for heating and cooling systems, has increasingly attracted market attention due to lower expenses to mine for installing underground heat absorption pipes and lower costs of dedicated heat pumps, supported by environmentally oriented policies. The theme undertakes an evaluation of heat absorption properties in the soil and carries out a performance test for a ground source heat pump and a simulated operation test for the system. In fact, these policies are necessary for identifying operational performance suitable for heating and cooling, in order to obtain technical data on the heat pump system for its dissemination and maintain the system in an effort of electrification. In these circumstances, the study estimated the heat properties of the soil in the city of Nottingham and measured thermal conductivity for the soil at some points in this city, aimed at identifying applicable areas for ground source heat pump system.

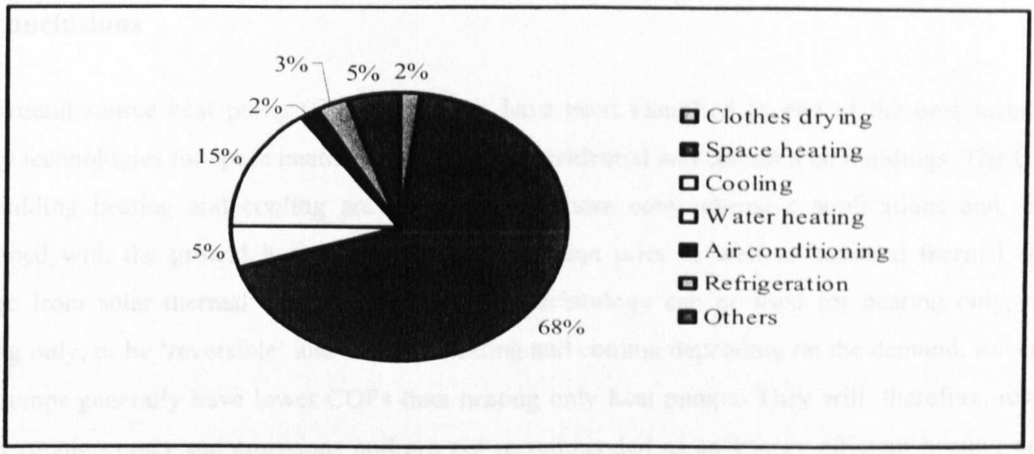


Figure 9.48 Residential energy consumption according to end use

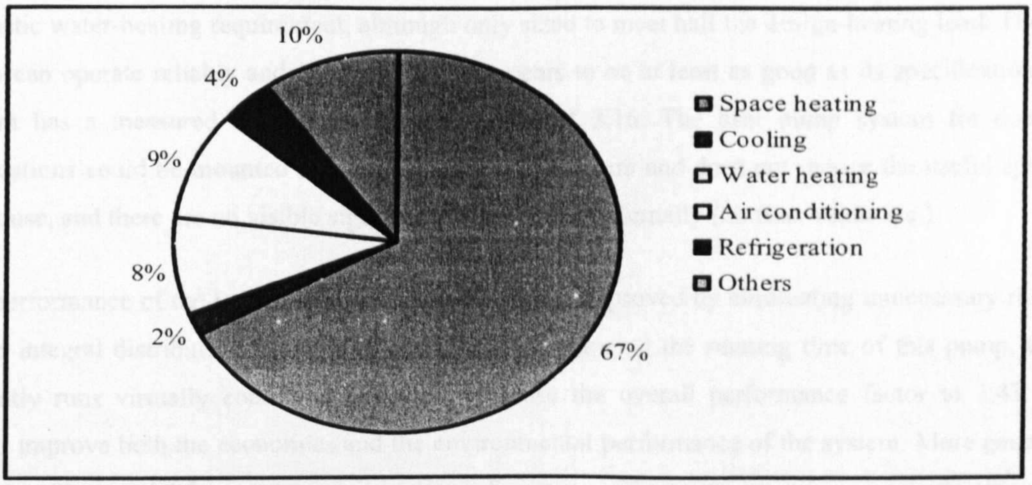


Figure 9.49 Commercial energy consumption according to end use

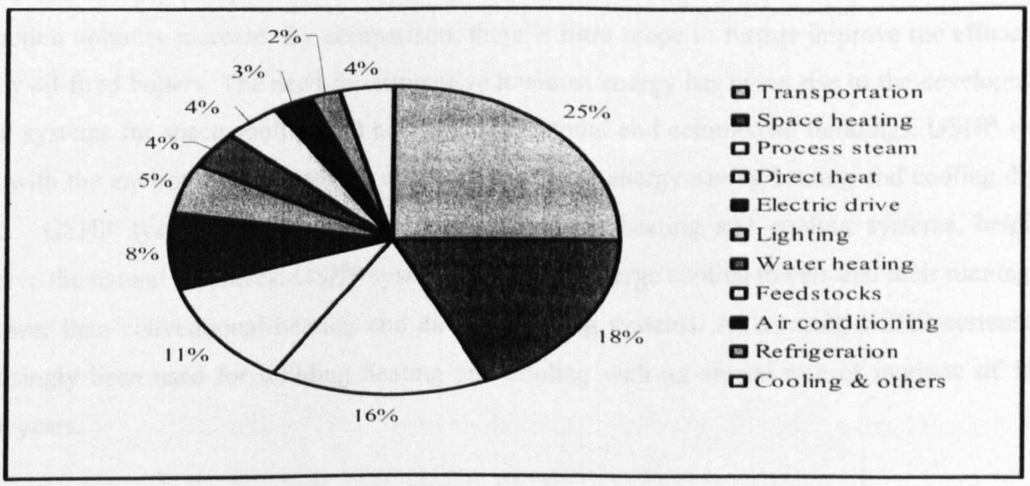


Figure 9.50 Energy consumption according to end use

9.9 Conclusions

The ground source heat pump (GSHP) systems have been identified as one of the best sustainable energy technologies for space heating and cooling in residential and commercial buildings. The GSHPs for building heating and cooling are extendable to more comprehensive applications and can be combined with the ground heat exchanger in foundation piles as well as seasonal thermal energy storage from solar thermal collectors. Heat pump technology can be used for heating only, or for cooling only, or be 'reversible' and used for heating and cooling depending on the demand. Reversible heat pumps generally have lower COPs than heating only heat pumps. They will, therefore, result in higher running costs and emissions and are not recommended as an energy-efficient heating option. The GSHP system can provide 91.7% of the total heating requirement of the building and 55.3% of the domestic water-heating requirement, although only sized to meet half the design-heating load. The heat pump can operate reliably and its performance appears to be at least as good as its specification. The system has a measured annual performance factor of 3.16. The heat pump system for domestic applications could be mounted in a cupboard under the stairs and does not reduce the useful space in the house, and there are no visible signs of the installation externally (no flue, vents, etc.).

The performance of the heat pump system could also be improved by eliminating unnecessary running of the integral distribution pump. It is estimated that reducing the running time of this pump, which currently runs virtually continuously, would increase the overall performance factor to 3.43. This would improve both the economics and the environmental performance of the system. More generally, there is still potential for improvement in the performance of heat pumps, and seasonal efficiencies for ground source heat pumps of 4.0 are being achieved. It is also likely that unit costs will fall as production volumes increase. By comparison, there is little scope to further improve the efficiency of gas- or oil-fired boilers. The need for alternative low-cost energy has given rise to the development of GSHP systems for space cooling and heating in residential and commercial buildings. GSHP systems work with the environment to provide clean, efficient and energy-saving heating and cooling the year round. GSHP systems use less energy than alternative heating and cooling systems, helping to conserve the natural resources. GSHP systems do not need large cooling towers and their running costs are lower than conventional heating and air-conditioning systems. As a result, GSHP systems have increasingly been used for building heating and cooling with an annual rate of increase of 10% in recent years.

Overall conclusions

Conventional heating or cooling systems require energy from limited resources, e.g., electricity and natural gas, which have become increasingly more expensive and are, at times, subjects to shortages. Attention has recently been given to sources of energy that exist as natural phenomena, such as geothermal energy, solar energy, tidal energy, and wind generated energy. While all of these energy sources have advantages and disadvantages, geothermal energy, i.e., energy derived from the earth or ground, has been considered by many authors as the most reliable, readily available, and most easily tapped of the natural phenomena. In particular, GSHPs are receiving increasing interest because of their potential to reduce primary energy consumption and reduce emissions of GHGs. Another benefit of GSHPs is that the performance of the subsurface is not subject to large variations experienced by ambient air. Additionally, by reducing primary energy consumption, the use of the GSHPs has the potential to reduce the quantity of CO_2 produced by the combustion of fossil fuels and thus to reduce global warming.

The installation and operation of a geothermal system may be affected by various factors. These factors include, but are not limited to, the field size, the hydrology of the site the thermal conductivity and thermal diffusivity of the rock formation, the number of wells, the distribution pattern of the wells, the drilled depth of each well, and the building load profiles. The performance of the heat pump system could also be improved by eliminating unnecessary running of the integral distribution pump. This would improve both the economics and the environmental performance of the system.

This study has dealt with the modelling of vertical closed-loop and ground source heat pump systems. The challenges associated with the design of these systems originate from the fact that they present a unique type of heat transfer problems. There are inherent inabilities to make direct observations in the subsurface environment with respect to both space and times as well as heat transfer within the subsurface environment. Consequently, a considerable amount of research in the past decade has been geared towards optimising the design and performance of GSHP systems and this study is part of those efforts.

The characteristics of three geothermal heat pump systems that provide space heat have been assessed, and parametric studies have been performed to determine the sensitivities of the results to parameter variations. Since the advanced systems covered in this study are not extensively investigated in literature, the present results and findings enhance the available information on the systems and their operation.

Several important findings and conclusions have been identified.

1. The results have shown that, heat pump designs with an economiser have the potential for high efficiency for the ranges of variables investigated in this study.
2. A heat pump system that utilises motor cooling/refrigerant preheating can reduce ground loop requirements without sacrificing performance relative to the basic vapour compression cycle. For instance, the ground loop length of system 2 is generally less than for system 1, although heat pump and system COPs are similar.
3. The COPs for heat pump designs that utilise an economiser are the least sensitive to variations in evaporator pressure, degree of subcooling and degree of superheating, relative to basic vapour compression cycles and compression cycles with motor cooling. Systems with an economiser also are the most resilient to parameter variations as system performance differs the least relative to the other arrangements.
4. Heat pump designs that utilise the basic vapour compression cycle or a compression cycle with motor cooling are the least sensitive to changes in compressor efficiency, motor efficiency and condenser pressure, compared to heat pump cycles with an economiser. The basic heat pump and the heat pump with motor cooling are the most resilient to changes in the parameters considered with the performance of the systems differing the least relative to the economiser unit.
5. Condenser pressure has the greatest effect on COPs for all systems considered, and the effect on system COP of the other parameters can be ranked from highest to lowest as motor efficiency, evaporator pressure, compressor efficiency, degree of subcooling, degree of superheating and pump efficiency.
6. Heat pump COPs and ground loop lengths are directly related, with required ground loop length increasing when the heat pump COP increases.

The findings and trends can assist design and optimisation activities for ground heat pump systems, providing insights into possible improvements. The information provided on how systems react to variations in operating parameters is important in such activities.

The results of soil properties investigation have also demonstrated that the moisture content of the soil has a significant effect on its thermal properties. When water replaces the air between particles it reduces the contact resistance. Consequently, the thermal conductivity varied from 0.25 W/m/K for dry soil to 2.5 W/m/K for wet soil. However, the thermal conductivity was relatively constant above a specific moisture threshold. In fact, where the water table is high and cooling loads are moderate, the moisture content is unlikely to drop below the critical level. In Nottingham, where the present study was conducted, soils are likely to be damp for much of the time. Hence, thermal instability is unlikely to be a problem. Nevertheless, when heat is extracted, there will be a migration of moisture by diffusion towards the heat exchanger and hence the thermal conductivity will increase.

Long measurements have shown that, the net energy exchange in the soil after one year of operation was only 3% of the total cold energy charged. This shows that there was no acute soil temperature change after the whole year operation of the GSHP system. Therefore, the system is feasible technically and the operation mode is reasonable.

Further research could be considered, and proposed as recommendations in the following points:

1. Superheating after evaporator is found to enhance GSHP COP, and therefore, whenever it is possible this should be employed.
2. To achieve optimum use of the GSHP, the thermal conductivity of the ground should be enhanced using various techniques studied in this research.
3. Additional validation of the model, using data collected under a wider range of weather conditions (i.e., rain, snow, and ice conditions), would be useful.
4. Additional validation of the model, using data from a working system, would be useful.

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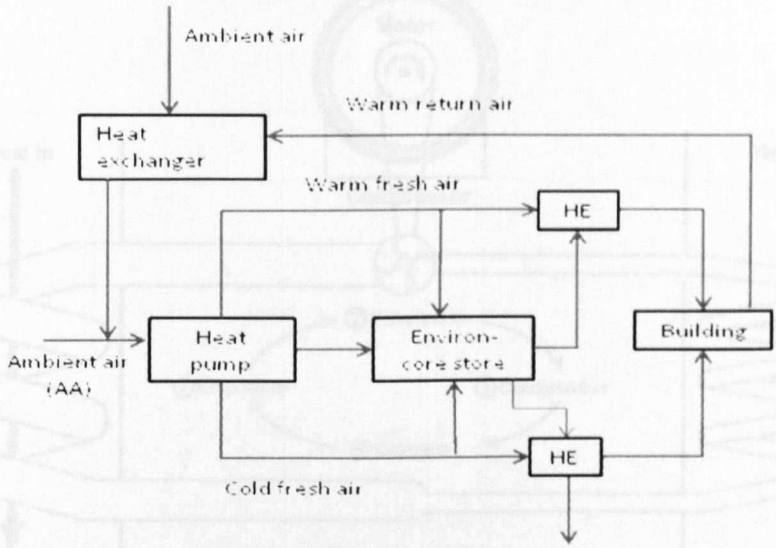
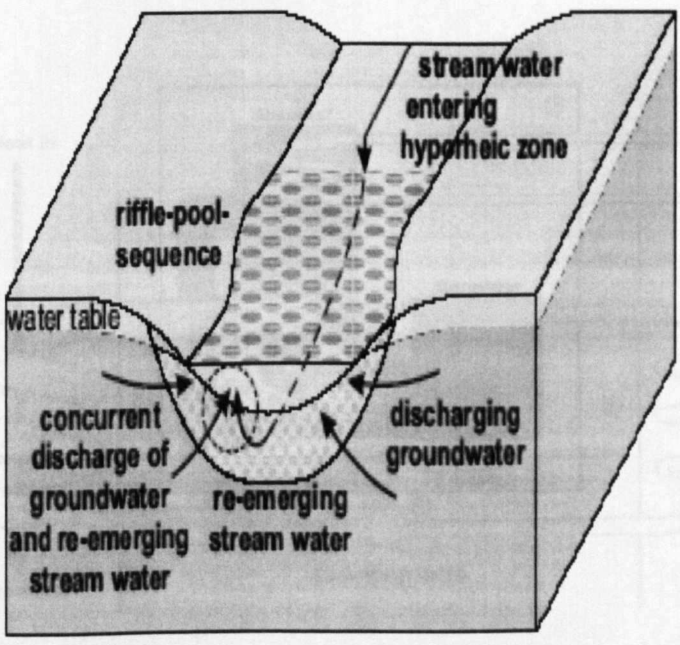
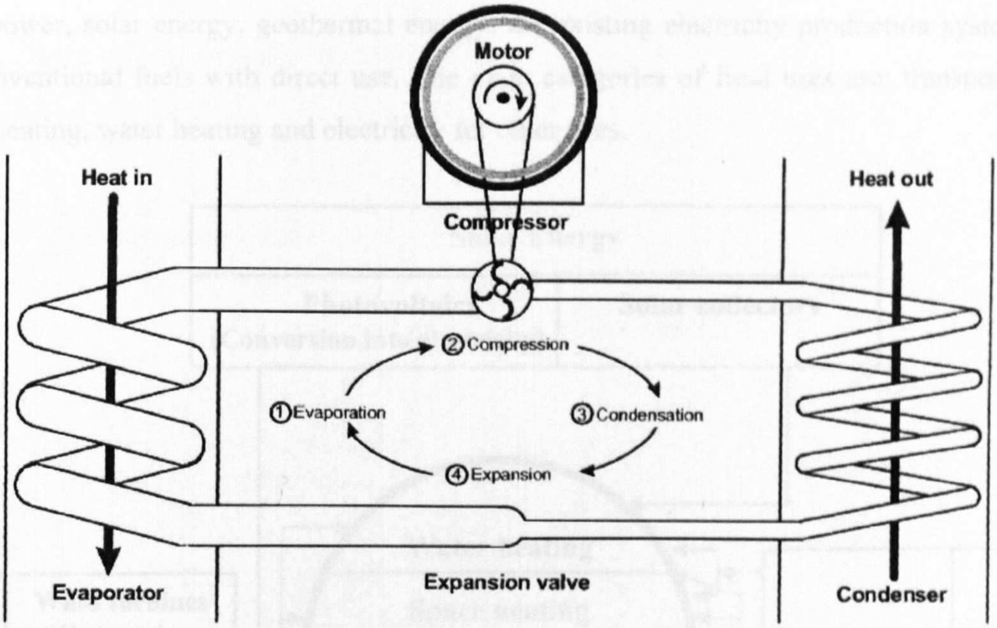
Appendix (1) Flow chart of combined heating and cooling with air-source heat pump and energy recovery from return air in combination with Environ-core thermal storage



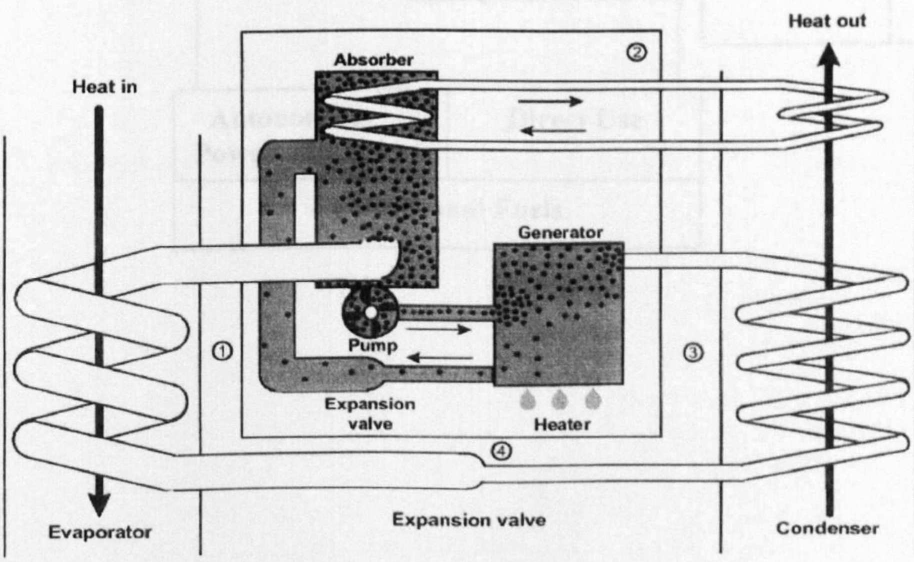
Appendix (1.1) Exchange flows between groundwater and surface water through the hyporheic zone at a riffle-pool-sequence



Appendix (1.2) Closed vapour compression heat pump

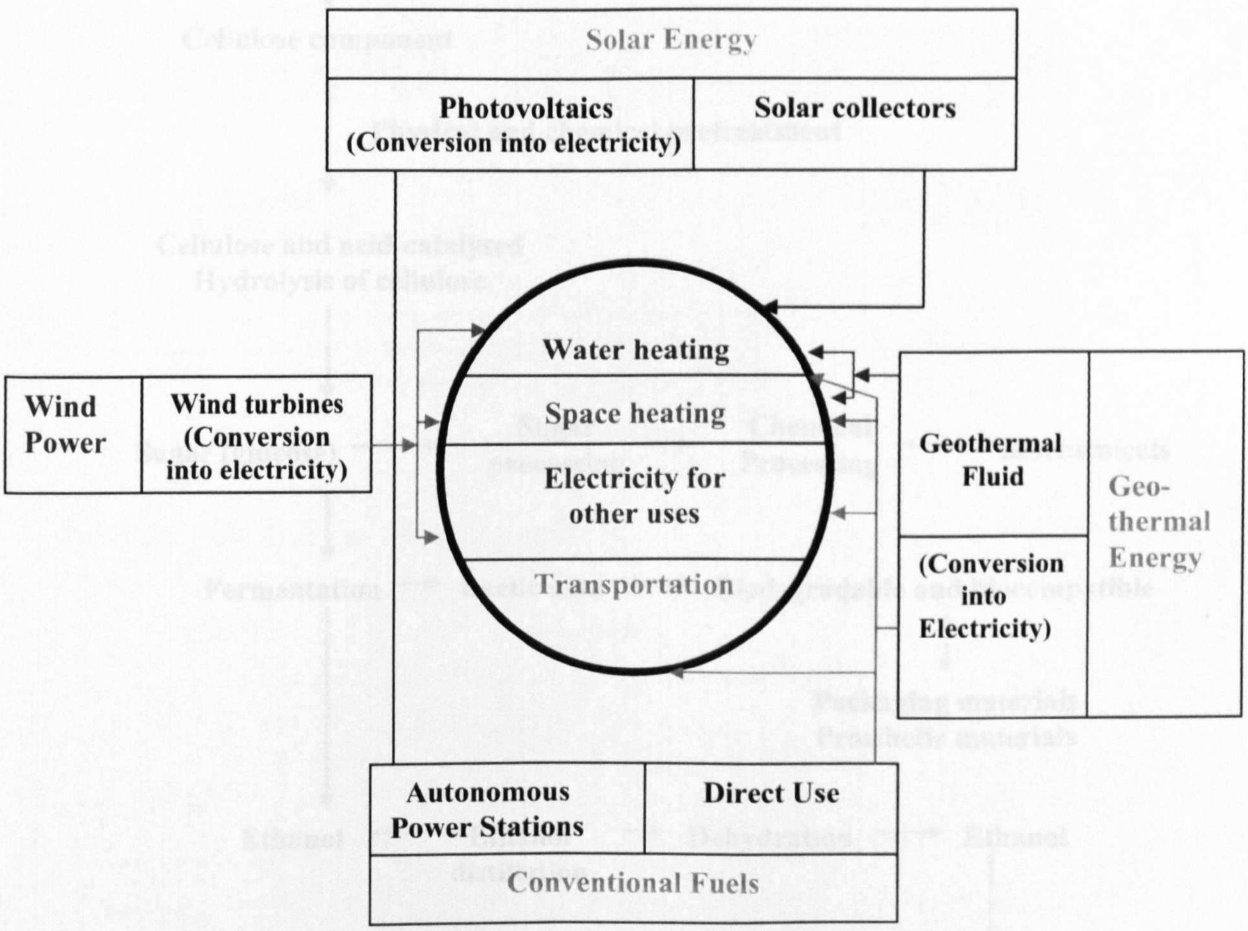


Appendix (1.3) Absorption heat pump

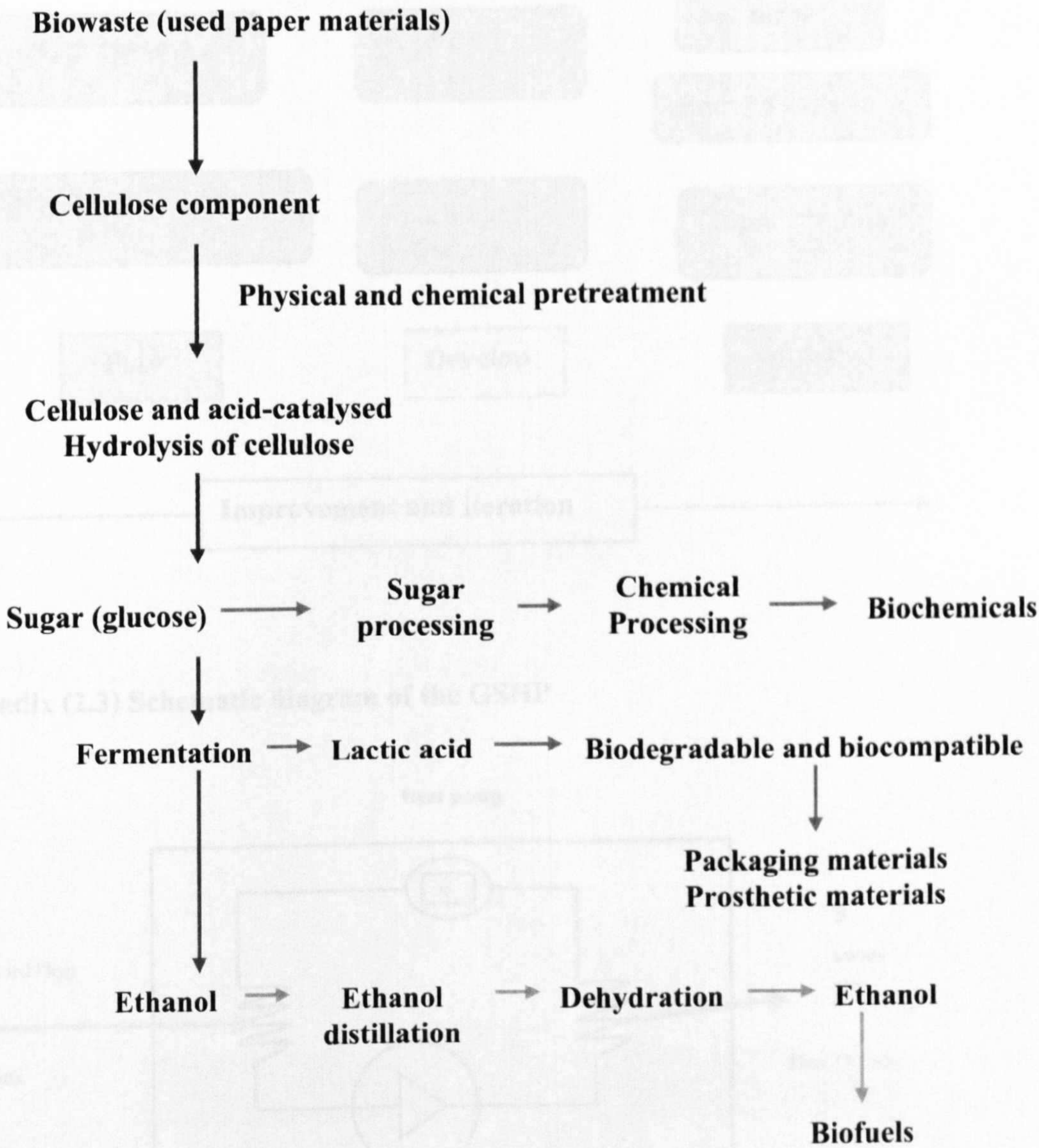


Appendix (2) Energy sources their final uses

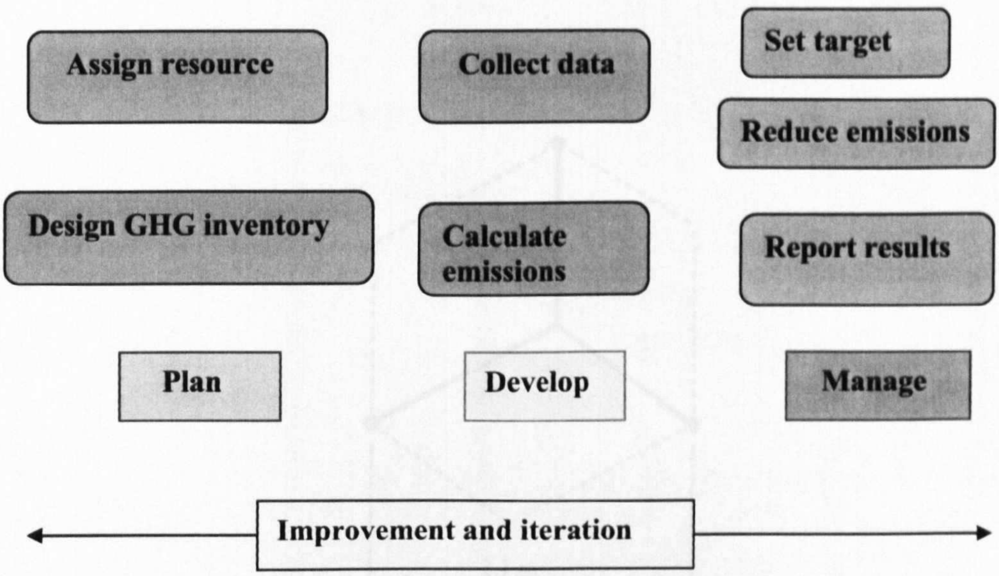
Different sources of energy, which can be used for different final uses. Those sources are: wind power, solar energy, geothermal energy, the existing electricity production system and the conventional fuels with direct use. The main categories of final uses are: transportation, space heating, water heating and electricity for other uses.



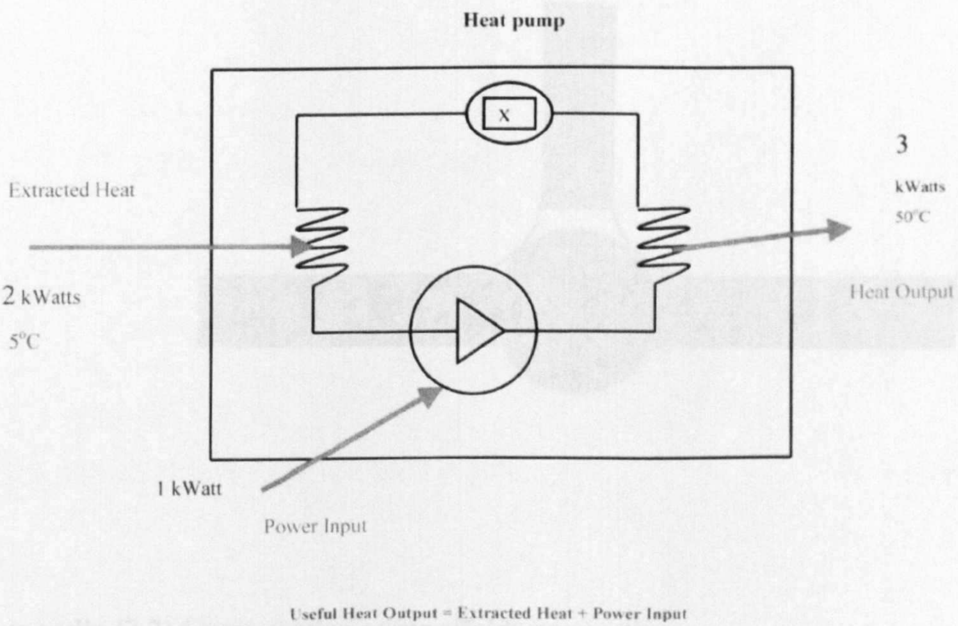
Appendix (2.1) Utilisation of biowaste such as wastepaper materials for bioproduct development



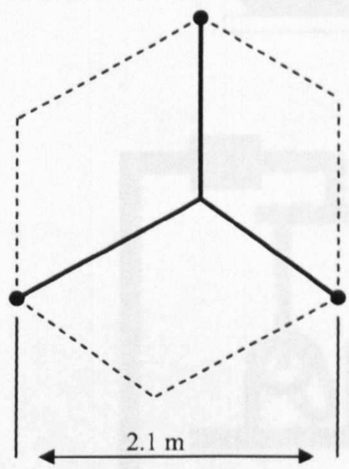
Appendix (2.2) Improvement to tackle global warming



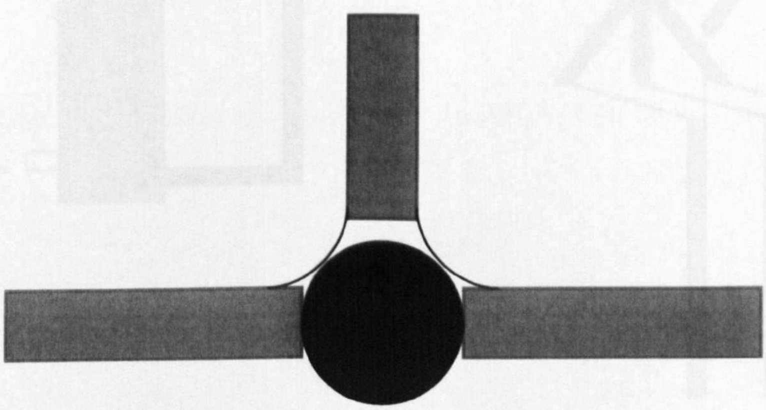
Appendix (2.3) Schematic diagram of the GSHP



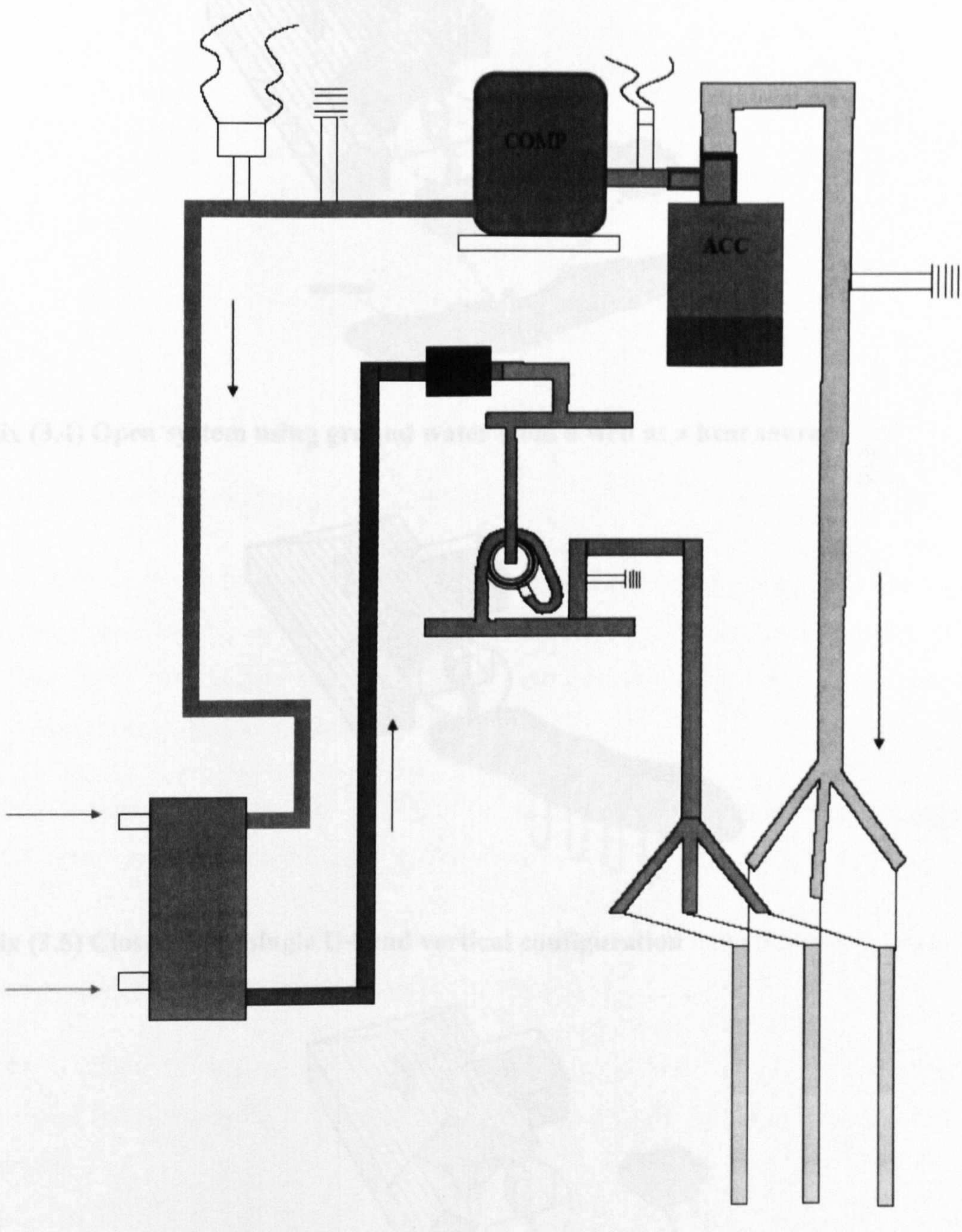
Appendix (3) Schematic of GSHP system (heating mode operation)



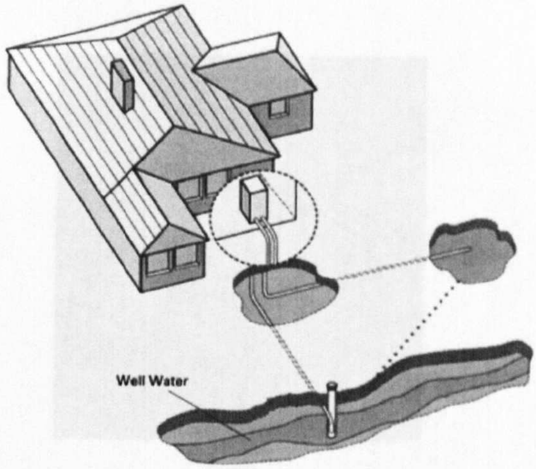
Appendix (3.1) Eight feet diameter manifold pit



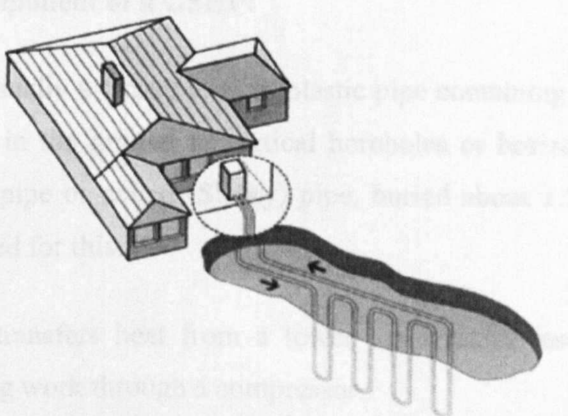
Appendix (3.2) Cross-section of manifolds connection



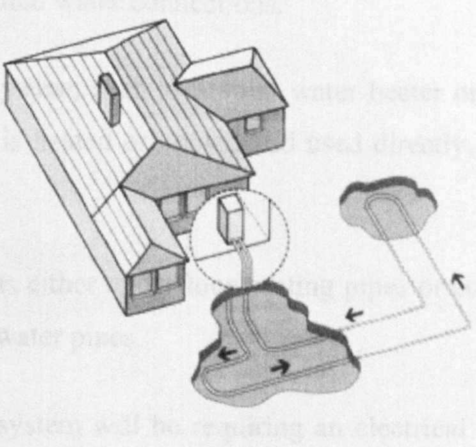
Appendix (3.3) Installation of heat pump



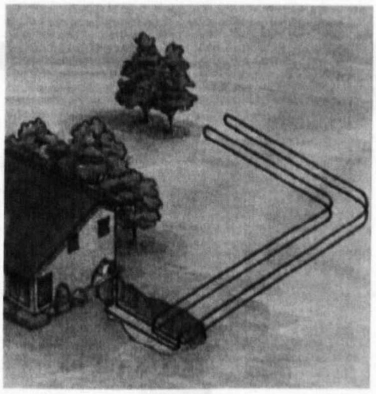
Appendix (3.4) Open system using ground water from a well as a heat source



Appendix (3.5) Closed-loop, single U-bend vertical configuration



Appendix (3.6) Closed-loop, single layer horizontal configuration



Appendix (3.7) Earth loop exchanges heat with the soil

Basic description of the component of a GSHP:

The ground heat source: Is usually a closed loop of plastic pipe containing a glycol antifreeze solution. The pipe is buried in the ground in vertical boreholes or horizontal trenches. The trenches take either straight pipe or coiled (Slinky) pipe, buried about 1.5 to 2m below the surface. A large area is needed for this.

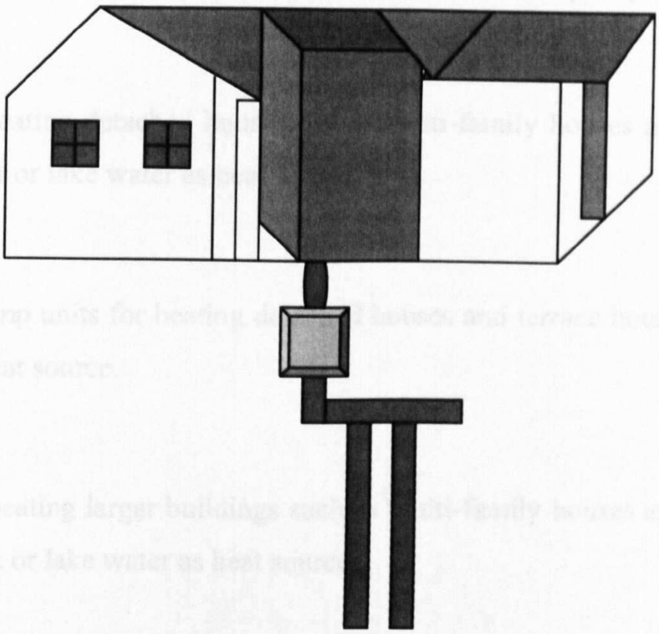
Heat pump: A device that transfers heat from a lower temperature reservoir to a higher temperature reservoir by doing work through a compressor.

A heat pump packaged unit: Water-Water type (Approx. the size of a small fridge) containing two cold water (glycol) and two heated water connections.

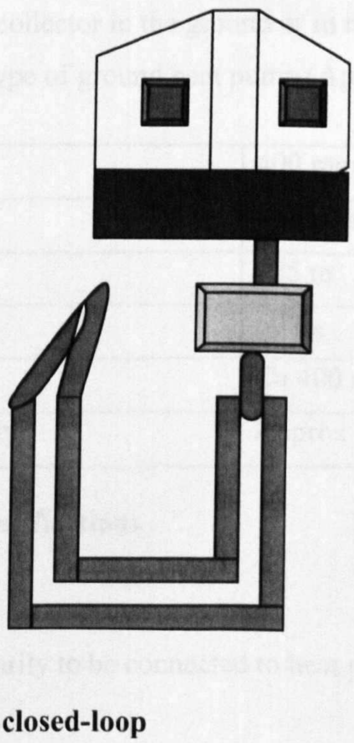
Open loop: A heating or cooling system, such as a solar water heater or ground source heat pump, in which the working fluid is heated or cooled and used directly, not returning to the heating device.

The heat distribution system: This is either underfloor heating pipes or conventional radiators of large area connected via normal water pipes.

Electrical input and controls: The system will be requiring an electrical input energy, three-phase being preferred, but single phase is perfectly adequate for smaller systems. A specilised controller will be incorporated to provide temperature and timing functions of the system.



Appendix (3.8) Vertical closed-loop



Appendix (3.9) Horizontal closed-loop

Appendix (4.1) Types of the commercial ground source heat pumps

FIGHTER 1120

Heat pumps for heating detached houses, small multi-family houses and industrial buildings using soil, bedrock or lake water as heat source.

FIGHTER 1220

Complete heat pump units for heating detached houses and terrace houses using soil, bedrock or lake water as heat source.

FIGHTER 1320

A heat pump for heating larger buildings such as multi-family houses and industrial buildings using soil, bedrock or lake water as heat source.

FLM 30

FLM 30 is an exhaust air module specially designed to combine recovery of mechanical exhaust air with an energy collector in the ground or in rock. FLM 30 is designed to connect to the FIGHTER 1120/1210 type of ground heat pump (Appendix 4.2).

Height	400 mm
Width	600 mm
Depth	625 m
Net weight	60 kg
Max air flow	Ca 400 m^3/h
Max refrigerating capacity	Approx 2 kw

Appendix (4.2) FLM30 specifications

VPA

Water heater intended primarily to be connected to heat pumps.

HPAC

An accessory that turns ground source heat pump range into a complete climate system.

FIGHTER 1120 and FIGHTER 1220	4 [5 kW]	4 [5 kW]	5 [6 kW]	5 [6 kW]
Current total requirement, oil	2,5 m³/year	3 m³/year	3 m³/year	4 m³/year
Current total requirement, elec. *	17500 kWh/year	21000 kWh/year	21000 kWh/year	28000 kWh/year
Geothermal heat, bore depth (active) **	60 - 80 m	60 - 80 m	80 - 100 m	80 - 100 m
Ground heat, hose length **	200 - 300 m	200 - 300 m	250 - 350 m	250 - 350 m
Brine flow	0,25 l/s	0,25 l/s	0,35 l/s	0,35 l/s
Heating water flow	0,10 l/s	0,10 l/s	0,13 l/s	0,13 l/s
Saving**	11400 kWh/year	13100 kWh/year	14200 kWh/year	17700 kWh/year
	7 [9 kW]	7 [9 kW]	8.5 [10 kW]	8.5 [10 kW]
Current total requirement, oil	4 m³/year	5 m³/year	5 m³/year	6 m³/year
Current total requirement, elec. *	28000 kWh/year	35000 kWh/year	35000 kWh/year	42000 kWh/year
Geothermal heat, bore depth (active) **	110 - 130 m	110 - 130 m	130 - 160 m	130 - 160 m
Ground heat, hose length **	325 - 2x225 m	325 - 2x225 m	400 - 2x300 m	400 - 2x300 m
Brine flow	0,48 l/s	0,48 l/s	0,58 l/s	0,58 l/s
Heating water flow	0,18 l/s	0,18 l/s	0,22 l/s	0,22 l/s
Saving**	19300 kWh/year	22300 kWh/year	24500 kWh/year	28400 kWh/year
			10 [12 kW]	10 [12 kW]
Current total requirement, oil			6 m³/year	7 m³/year
Current total requirement, elec. *			42000 kWh/year	49000 kWh/year
Geothermal heat, bore depth (active) **			150 - 180 m	150 - 180 m
Ground heat, hose length **			2x250 - 2x325	2x250 - 2x325
Brine flow			0,65 l/s	0,65 l/s
Heating water flow			0,26 l/s	0,26 l/s
Saving**			29000 kWh/year	29000 kWh/year
Just FIGHTER 1120	11 [12 kW]	11 [12 kW]	13 [15 kW]	13 [15 kW]
Current total requirement, oil	6 m³/year	7 m³/year	7 m³/year	8 m³/year
Current total requirement, elec. *	42000 kWh/year	49000 kWh/year	49000 kWh/year	56000 kWh/year
Geothermal heat, bore depth (active) **	150 - 180 m	150 - 180 m	2x90 - 2x110 m	2x90 - 2x110 m
Ground heat, hose length **	2x250 - 2x325 m	2x250 - 2x325 m	2x300 - 2x400 m	2x300 - 2x400 m
Brine flow	0,65 l/s	0,65 l/s	0,75 l/s	0,75 l/s
Heating water flow	0,31 l/s	0,31 l/s	0,31 l/s	0,31 l/s
Saving**	29000 kWh/year	32800 kWh/year	34500 kWh/year	34500 kWh/year
			15 [17 kW]	15 [17 kW]
Current total requirement, oil			8 m³/year	9 m³/year
Current total requirement, elec. *			56000 kWh/year	63000 kWh/year
Geothermal heat, bore depth (active) **			2x100 - 2x140 m	2x100 - 2x140 m
Ground heat, hose length **			2x350 - 3x300 m	2x350 - 3x300 m
Brine flow			0,86 l/s	0,86 l/s
Heating water flow			0,36 l/s	0,36 l/s
Saving**			39100 kWh/year	43200 kWh/year

* Total energy requirement excluding domestic electricity

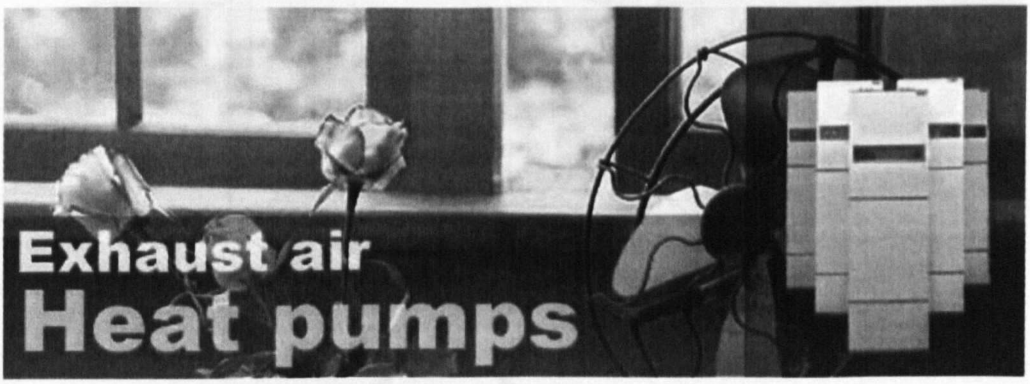
** Stated values are only approximate guide values and have been calculated based on Nordic climate conditions. A milder climate gives a greater saving.

Appendix (4.3) Estimation of what is possible to save with a ground source heat pump. It also provides an approximate guide for dimensioning the bore depth or hose length.

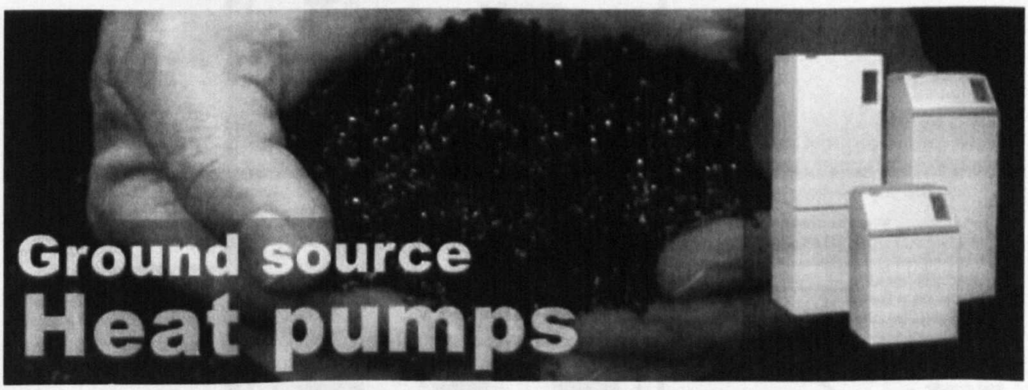
The built-in fan extracts the air from the wet areas of the house to the recovery unit. Energy is transferred to the heat pump from the ground or rock collector. The heat transfer fluid increases in temperature and enhances the heat pump heat factor. When the heat pump is not in operation, energy is stored in the ground or rock collector, which utilises the exhaust air energy to the full. The heat pump capacity is not bound by the amount of air as with an exhaust air heat pump, but the output can be optimally adapted to suit the size of the house

(Appendix 4.3). FLM 30 is best connected directly to FIGHTER 1220 but can also be wall mounted. It provides a total solution for exhaust air and ground and rock heating:

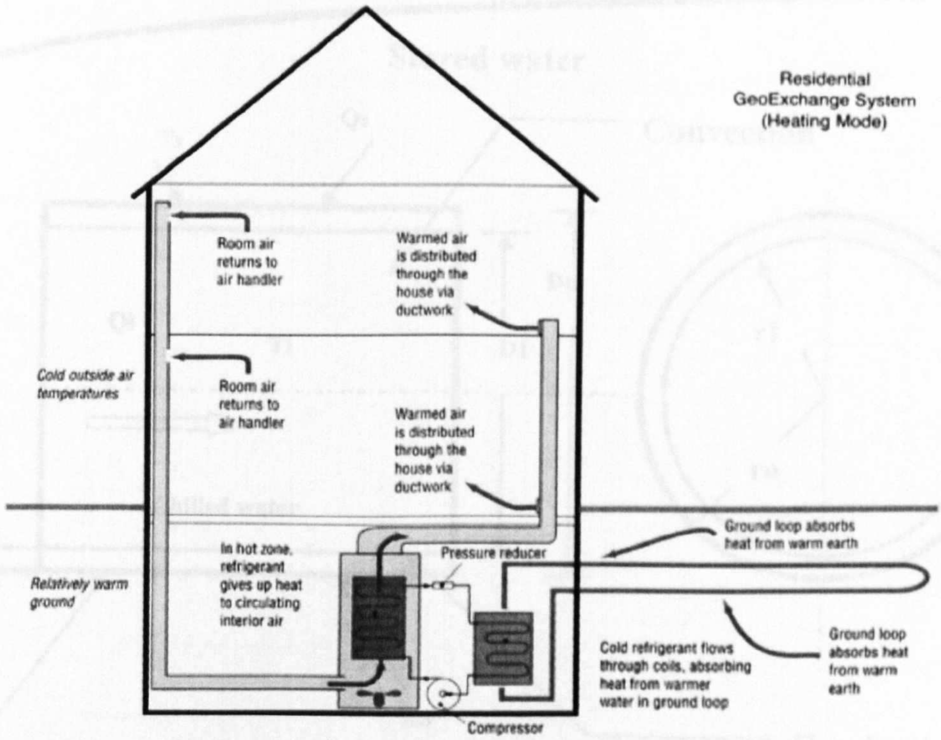
- FLM 30 can be connected to FIGHTER 1120/1210 irrespective of output size.
- Exhaust air energy is accumulated in the ground.
- The collector length can be reduced when required.
- Easy to install.
- High fan capacity and low sound level.



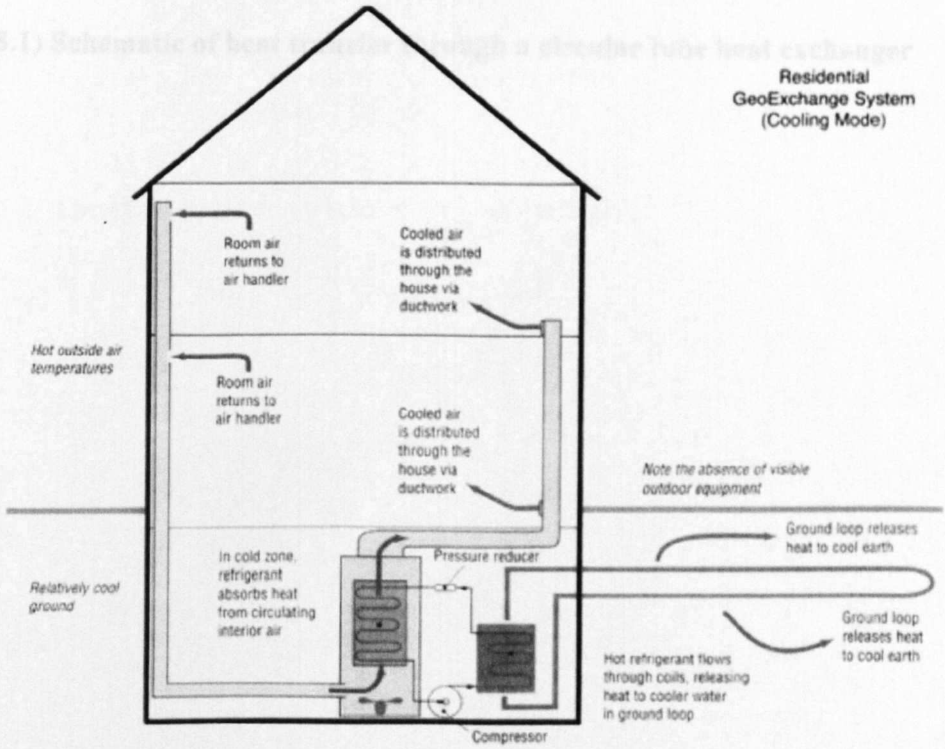
Appendix (4.4) Exhaust heat pumps



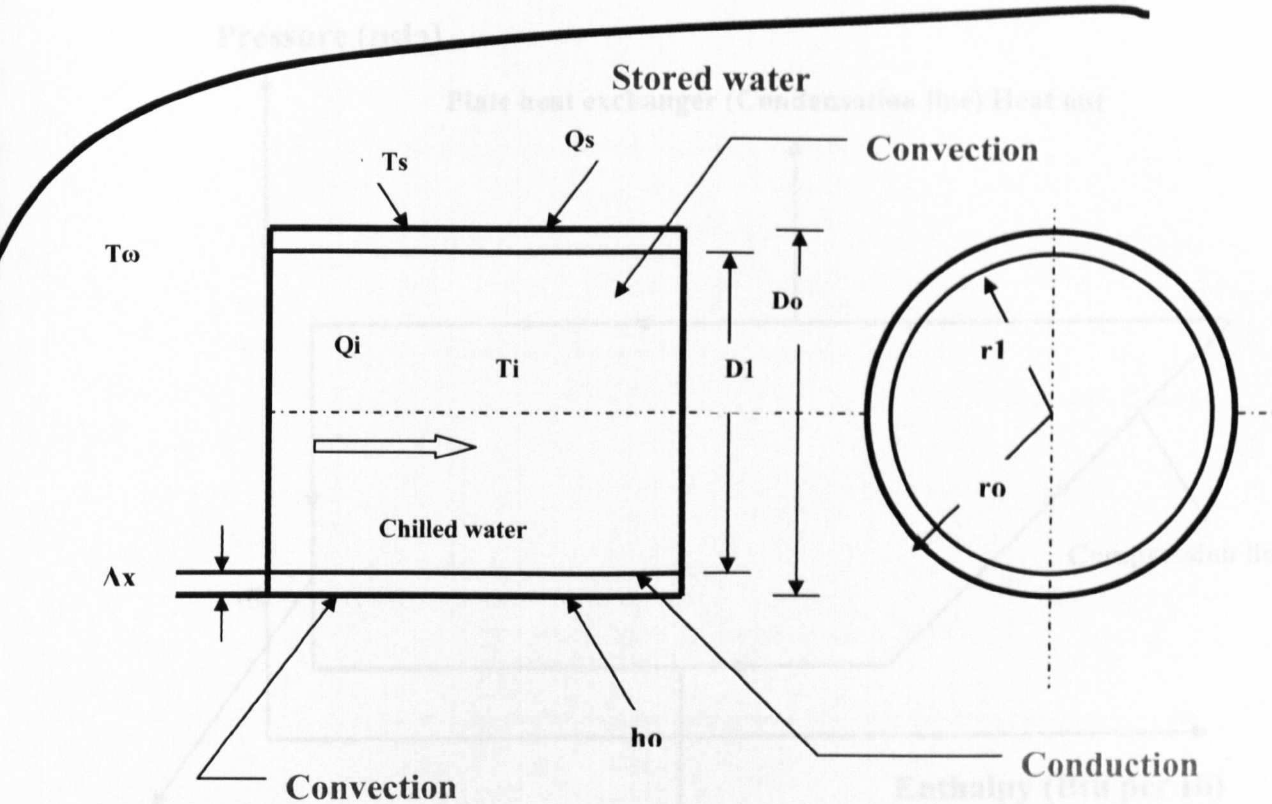
Appendix (4.5) Ground soil



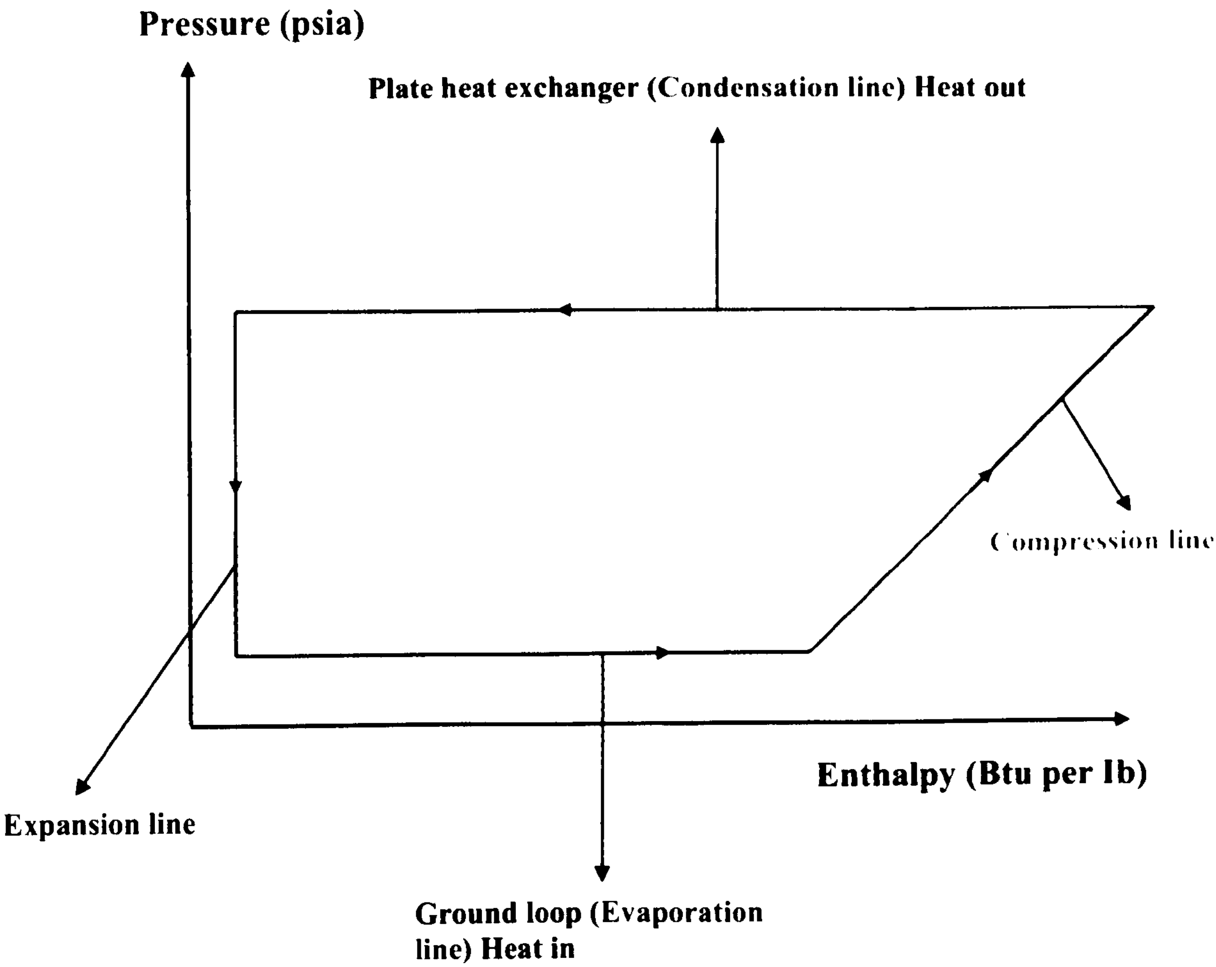
Appendix (4.6) Residential Geoexchange systems (heating mode)



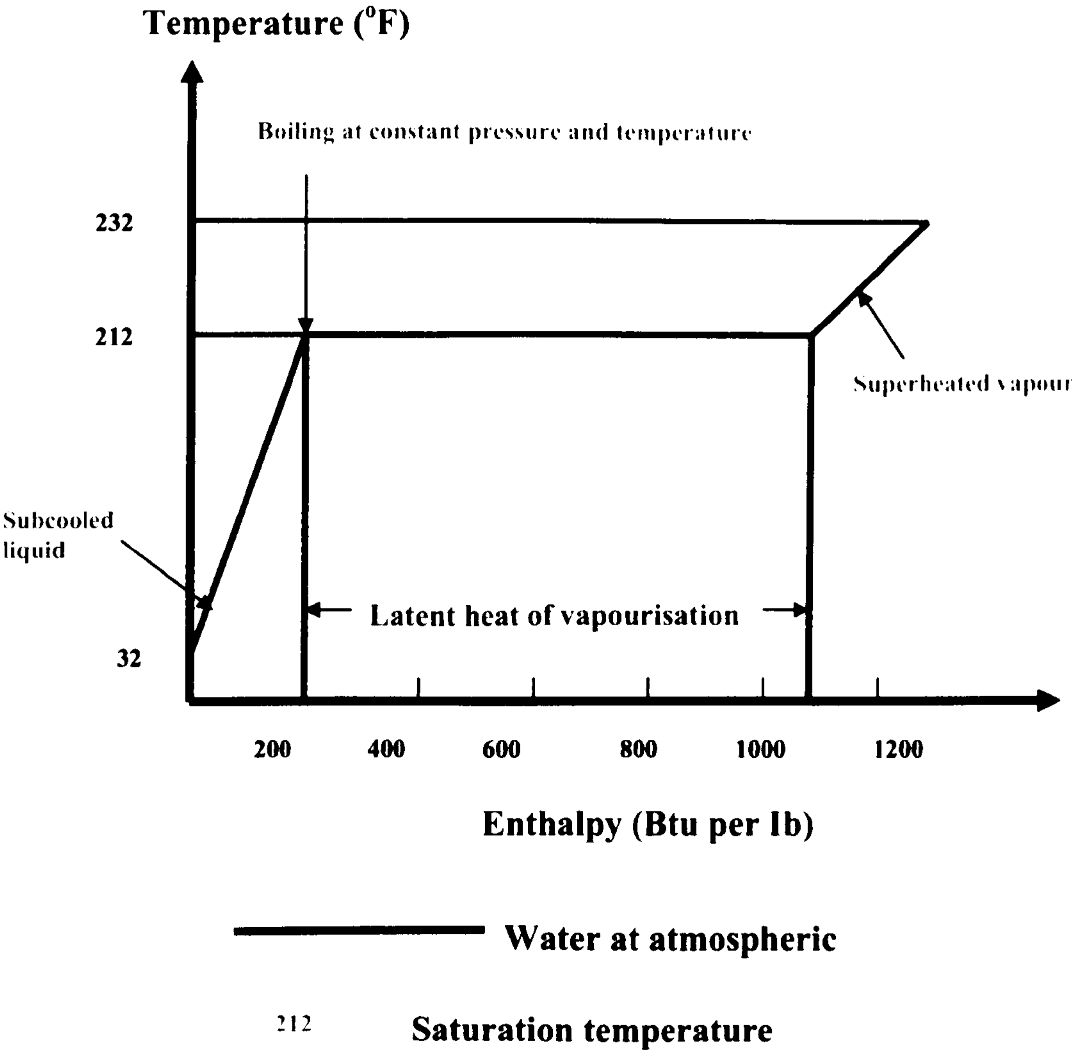
Appendix (4.7) Residential Geoexchange systems (cooling mode)



Appendix (5.1) Schematic of heat transfer through a circular tube heat exchanger



Appendix (5.2) The ideal cycle on Pressure-Enthalpy diagram



Appendix (5.3) Water undergoing a charge of state

Appendix (5.4) Definitions

1) The word "Efficiency" is defined as the ratio of useful heat output to energy input e.g., if an open fireplace loses half its energy up the chimney it is said to be 50% efficient.
2) The COP or "Coefficient of performance" is found by dividing the useful heat output by the energy input e.g., a heat pump that produces 3 kWatts of heat for 1 kWatt of input power has a COP of 3. The open fireplace example with 50% efficiency would have a COP of 0.5 (1/2).
3) The heat "Source" is the outside air, river or ground, wherever the heat is being extracted from. Sometimes referred to as an ambient source.
4) The "Sink" is the name given to the part where the heat is usefully dissipated, such as radiators in the room, underfloor heating, hot water cylinder, etc.

Horizontal collector:
This can be either coiled 'Slinky' or straight pipes that are buried 1.5 m to 2 m deep in open ground (in gardens). The pipe is usually plastic and contains a Glycol antifreeze solution.

Antifreeze:
This is simply an additive to water that makes its freezing point lower. Common salt does the same thing, but Ethylene or Propylene Glycol is more practical for heat pump systems.

Refrigerant:
This is the working fluid within the heat pump. It evaporates in one part and condenses in another. By doing so, heat is transferred from cold to hot. This fluid is sealed in and will not degrade within the heat pumps life.

Heat exchanger:
This is a simple component that transfers heat from one fluid to another. It could be liquid-to-liquid, or liquid-to-air, or air-to-air. Two heat exchangers are housed within the heat pump, one for the hot side (the condenser), one for the cold side (the evaporator).

Slinky:

The name given to the way that ground collector pipes can be coiled before buying in a trench.

Passive heat exchange:

When waste hot water preheats cold input water, it is said to be 'passive'. This costs nothing to run. A heat pump is said to be 'active' it can extract heat from cold waste water but requires a relatively small power input.

Appendix (5.6) Some refrigeration characteristics

The seasonal energy efficiency ratio (SFEE) may be applied to each of the components.

Assuming that KE & PE effects are negligible i.e., the SSFEE is applicable; viz

$$Q + W = m\,\Delta h \tag{5.1}$$

Compressor:

Compression assumed adiabatic:

$$\therefore Q = 0 \tag{5.2}$$

$$W12 = m\,(h2 - h1) \tag{5.3}$$

Or

$$W_{in} = m\,(h2 - h1) \tag{5.4}$$

Condenser:

$$W23 = 0 \tag{5.5}$$

$$\therefore Qout = m\,(h2 - h3) \tag{5.6}$$

Expansion valve:

$W34 = 0 \ \& \ Q34 = 0$ (5.7)

$\therefore h3 = h4$ (5.8)

Evaporator:

$W41 = 0$ (5.9)

$\therefore Q_{in} = m\,(h1 - h4)$ (5.10)

Refrigeration effect

It follows that:

$COP_{ref} = (h1-h3)/(h2-h1)$ (5.11)

$COP_{hp} = (h2-h3)/(h2-h1)$ (5.12)

In order to determine the above equations, the specific enthalpy values will be needed. Because refrigerants work in the liquid/vapour phases appropriate property charts or tables must be used.

Refrigerant properties (Charts and Tables)

Because refrigeration systems basically work between two pressures, and specific enthalpy is one of the most useful properties we need, refrigerant thermodynamic properties are normally presented in the form of a pressure - specific enthalpy (or p-h) chart.

This is done for convenience, and is simply an alternative way of presenting property data. Instead of, e.g., p-V, or T-s, or h-s.

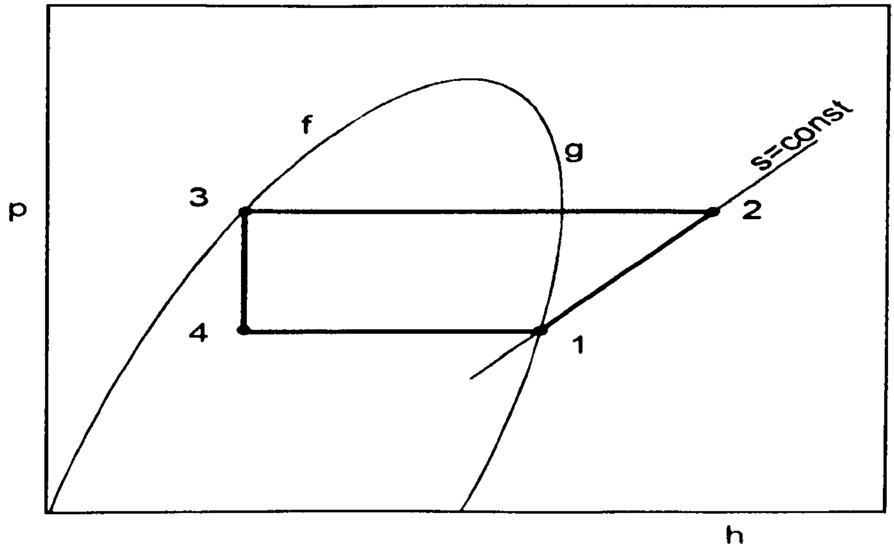
Other useful properties are also shown on the chart, viz: specific entropy, specific volume, temperature and quality. Regard these properties as 'contours'.

The pressure axis (y-axis) is typically logarithmic.

The ideal refrigeration cycle

- Isentropic compression (1 →2)
- Constant pressure cooling/condensation (2 → 3)
- Throttling (3 → 4)
- Constant pressure vaporisation/heating (4 → 1)

The ideal refrigeration cycle plotted on the p-h chart as shown in Appendix 4.5.1.

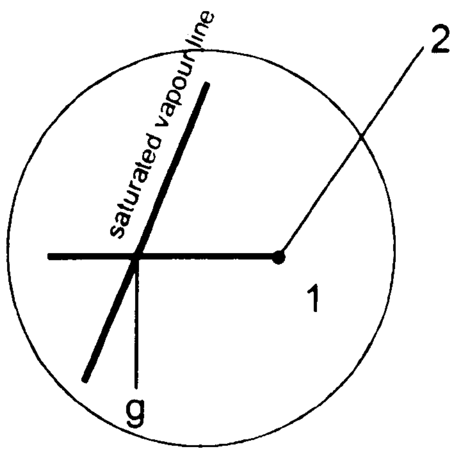


Appendix 5.6.1 Refrigeration cycle

Real Refrigeration Systems

Evaporator superheat

g → 1 Given in K above Tsat(s)

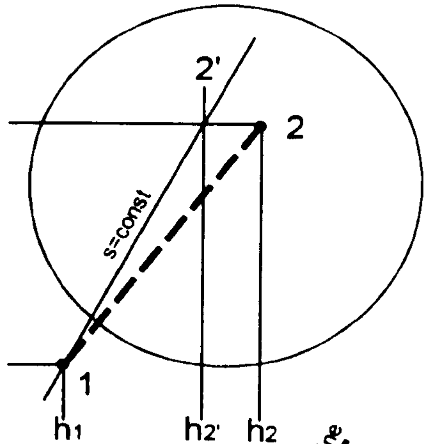


Appendix 5.6.2 Evaporator superheat

Isentropic compressor efficiency

$$\eta_{iscn} = h2'-h1/h2-h1 \qquad (4.13)$$

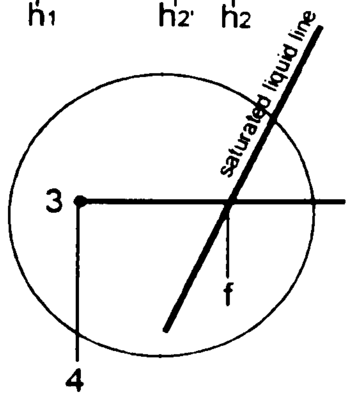
NB: s1 = s2'



Condenser sub-cooling

f → 3 given in K below Tsat(c)

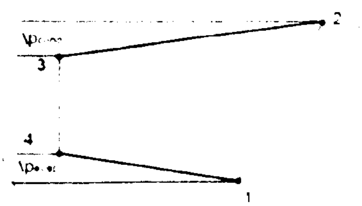
Appendix 5.6.3 Isentropic compressor



Appendix 5.6.4 Condenser sub-cooling

Pressure drops in evaporator and condenser

Clearly, any or all of the above effects can be present, but the pressure drops are often small enough to be neglected.



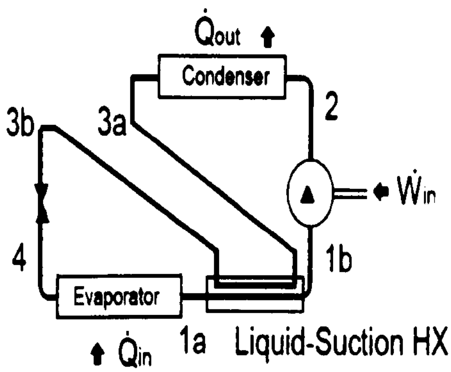
Appendix 5.6.5 Pressure drops in evaporator and condenser

Refrigeration system performance improvement

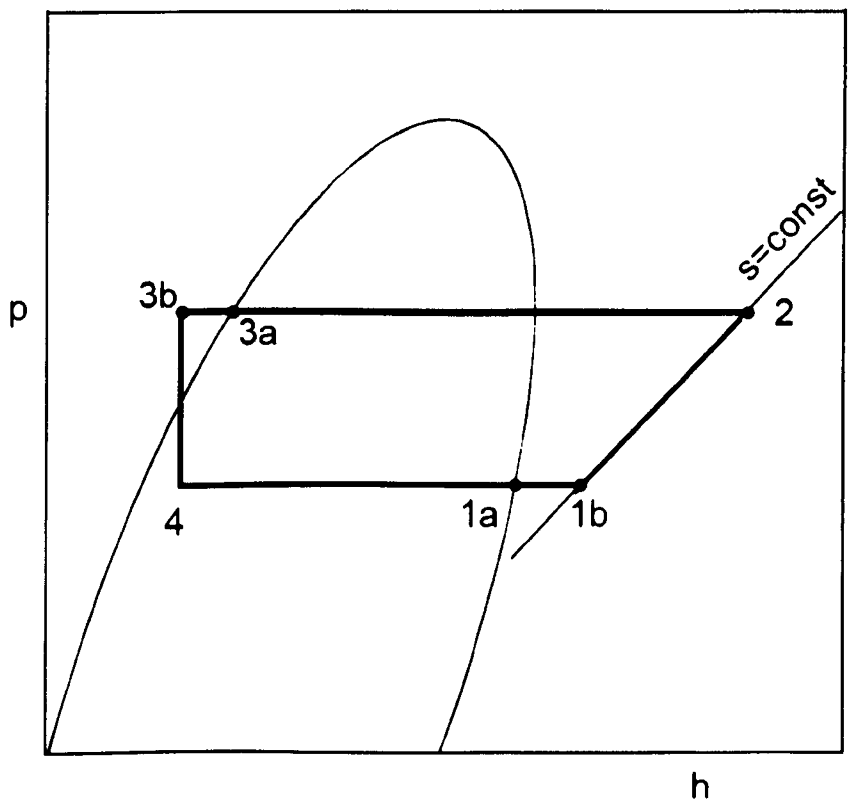
Liquid-Suction heat exchanger

Assuming no losses:

$H_{1b}-h_{1a} = h_{3a}-h_{3b}$ (4.14)

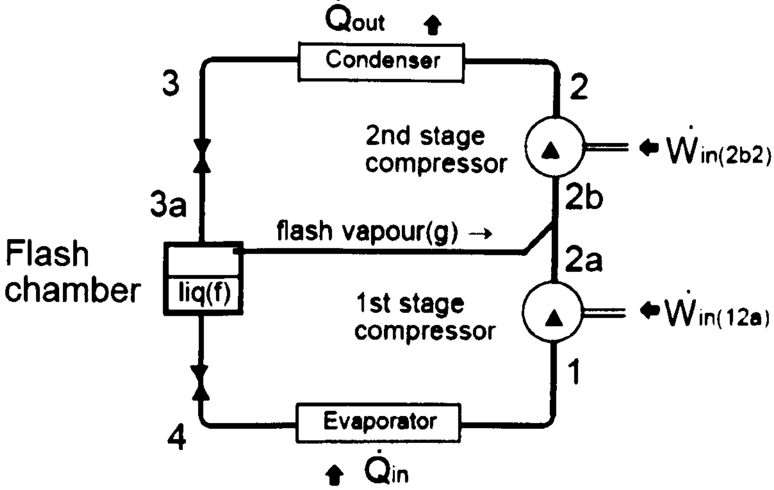


Appendix 5.6.6 Diagram of liquid-suction heat exchanger

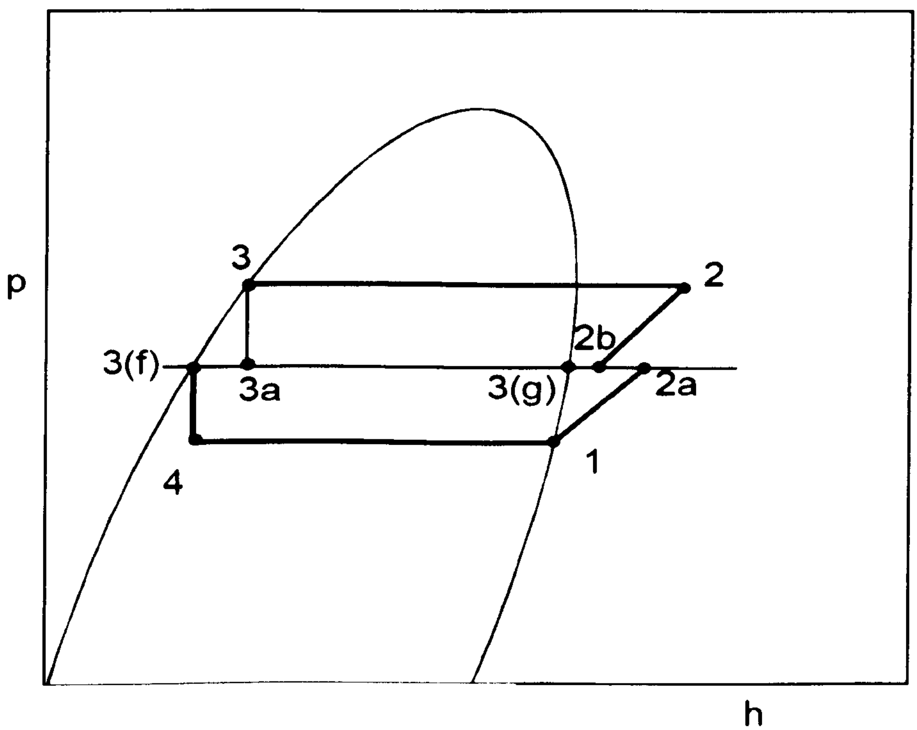


Appendix 5.6.7 Liquid-suction heat exchanger cycle

Multiple compression using flash chambers



Appendix 5.6.8 Diagram of multiple compressions using flash chamber



Appendix 5.6.9 Cycle of multiple compression using flash chamber

At point 3a, have a mixture of vapour and liquid, which is separated, in the flash chamber. The proportion of the total mass flow that is liquid (and proceeds to the evaporator) is given by:

$x_f = h_{3\,(g)} - h_3 / h_{3\,(g)} - h_{3\,(f)}$ (5.15)

The remaining vapour mixes with the discharge from the first stage compressor to give different inlet conditions to the second stage.

Assuming adiabatic mixing:

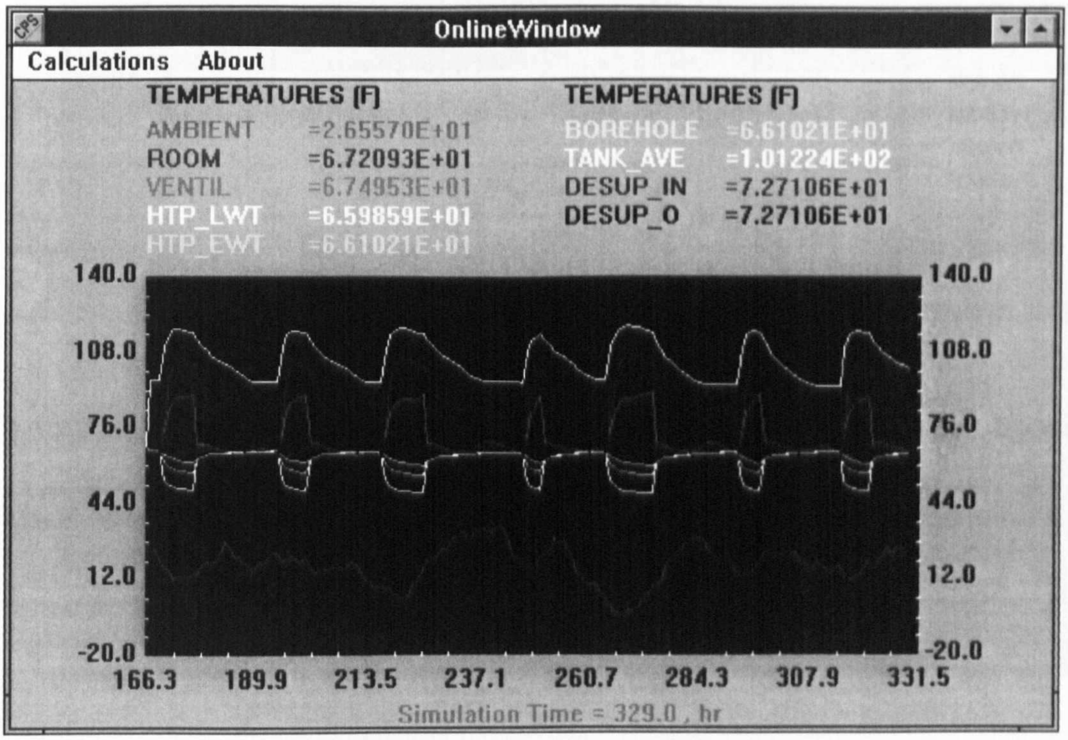
$1 * h_{2b} = x_f h_{2a} + (1 - x_f)\, h3_{(g)}$ (5.16)

A similar equation can be used to find s_{2b}

Finally the COP is given by:

$COP = (x_f (h_1 - h_4)) / (x_f (h_{2a} - h_1) + (h_2 - h_{2b}))$ (5.17)

Appendix 6.1 shows the output of the system

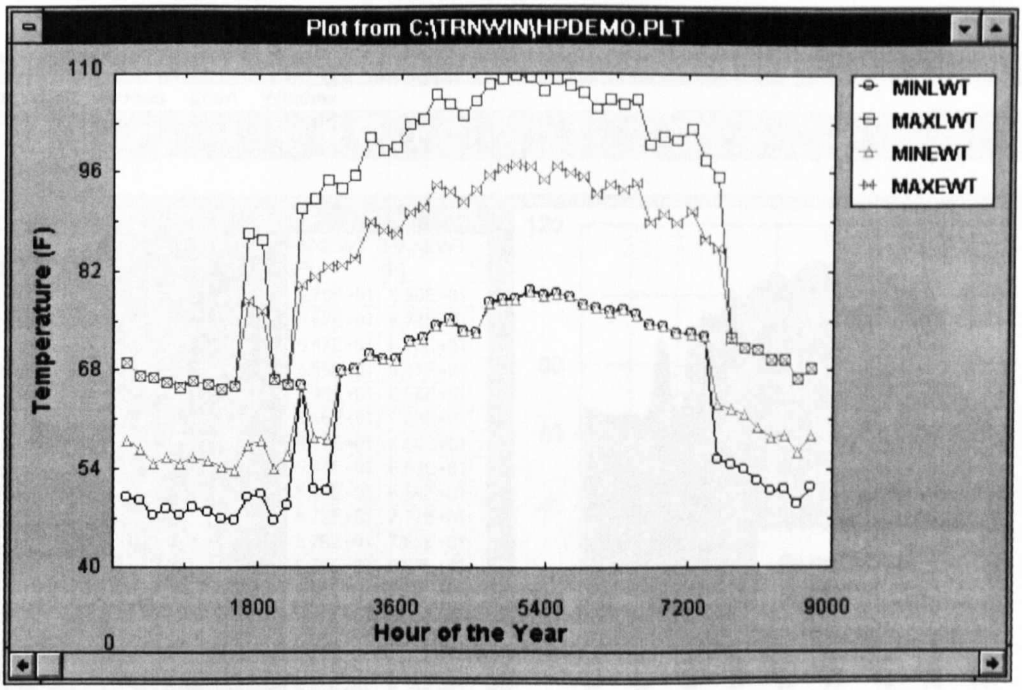


Once the time period and variables have been selected, a plot window is displayed in the TRNSYS programme (Appendix 6.1).

Where:

Ambient	The ambient temperature
Room	The room temperature
Ventil	The room ventilation temperature
HTP_LWT	The temperatures of the water leaving the heat pump
HTP_EWT	The temperatures of the water entering the heat pump
Borehole	The borehole temperature (backfill)
Tank_Ave	The average hot water tank temperature
Desup_In	The temperature of the hot water stream entering the heat pump desuperheater
Desup_O	The temperature of the hot water stream entering the heat pump desuperheater

Appendix 6.2 Water temperatures entering and leaving the heat pump



The features of this plot window may be modified by double-clicking on them with the mouse (symbols, grid lines, scales, titles, legends, etc.). A sample plot window from the simulation is shown in Appendix 6.2. The following items were plotted versus time:

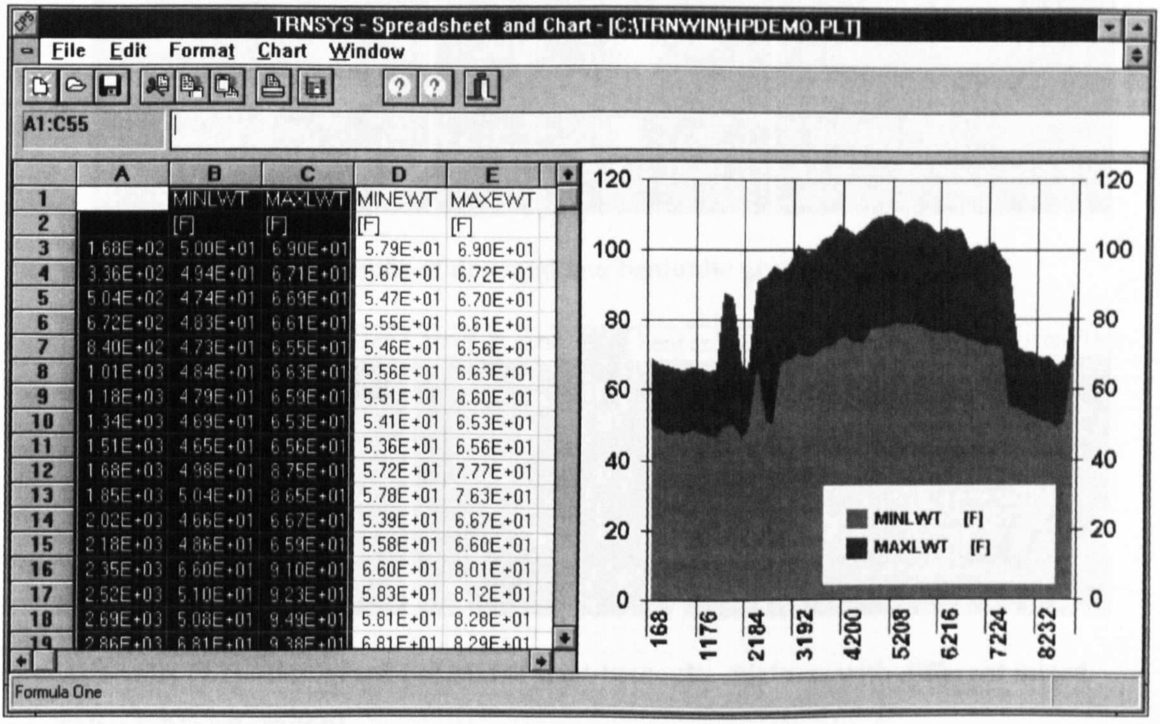
MINLWT - The minimum temperature of the water leaving the heat pump during the week.

MAXLWT - The maximum temperature of the water leaving the heat pump during the week.

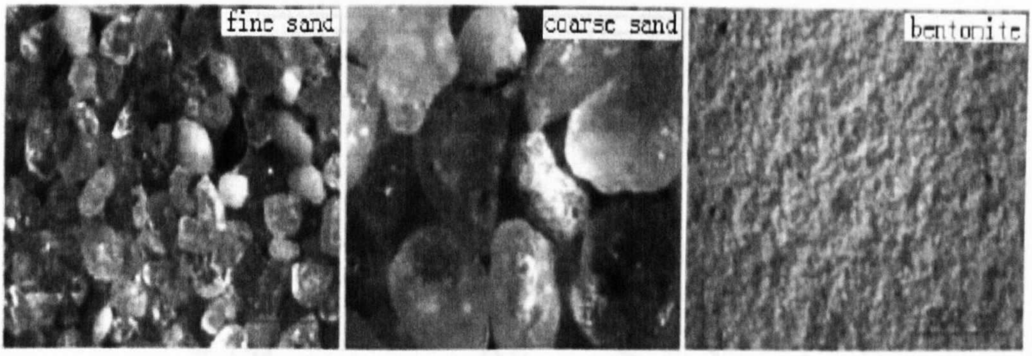
MINEWT - The minimum temperature of the water entering the heat pump during the week.

MAXEWT - The maximum temperature of the water entering the heat pump during the week.

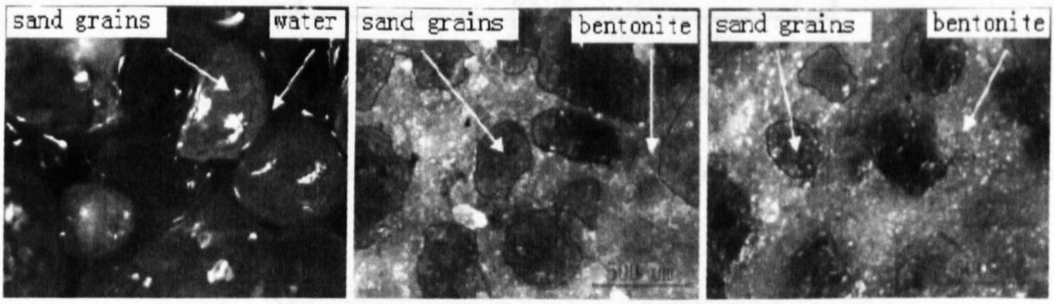
Appendix 6.3 The minimum and maximum temperature of the water entering the heat pump during the week



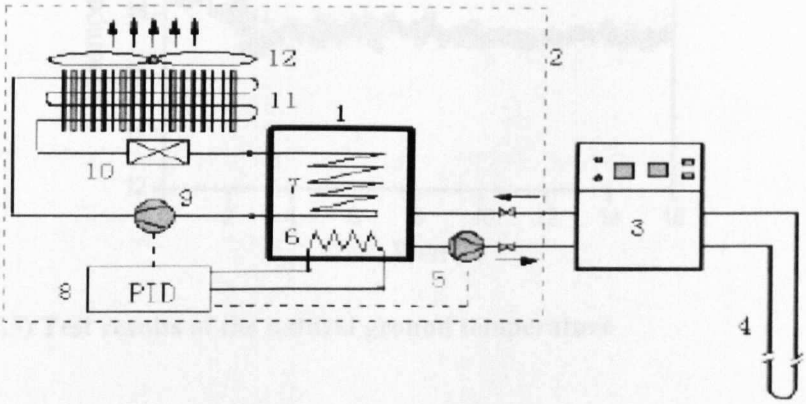
The output file may also be loaded into the TRNSYS Spreadsheet and Plotting programme for further manipulation. The spreadsheet is Excel compatible and features a 3-D (and 2-D) plotting package. The user simply highlights the area of the spreadsheet to be plotted, and selects the type of plot. A sample plot from the programme is shown in Appendix 6.3. The newly created plot may be manipulated in many ways and produces fantastic publication-quality graphics that can be pasted into most Windows applications.



Appendix (7.1) Micrographs of dry sand and bentonite grains

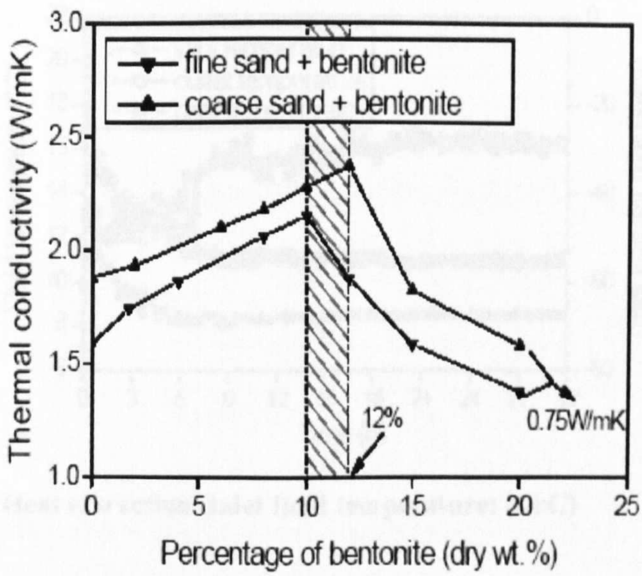


Appendix (7.2) Micrographs of coarse sand-bentonite mixtures with different mixed ratios (80% saturation)

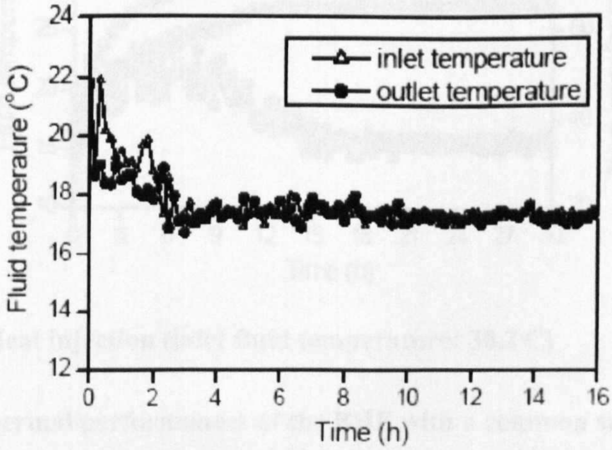


Appendix (7.3) Diagram of the experimental setup testing the thermal performance of a BHE

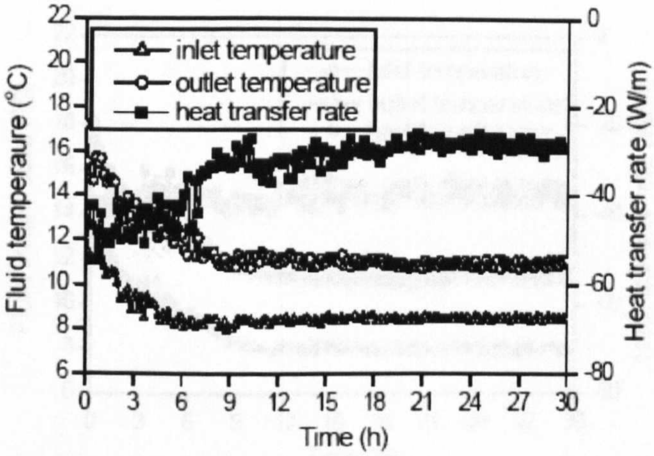
(1: insulated water tank; 2: heat/cold source system; 3: measuring system; 4: borehole heat exchanger; 5: circulating pump; 6: water heater; 7: evaporator; 8: PID controller; 9: compressor; 10: expansion valve; 11: condenser 12: axial cooling fan)



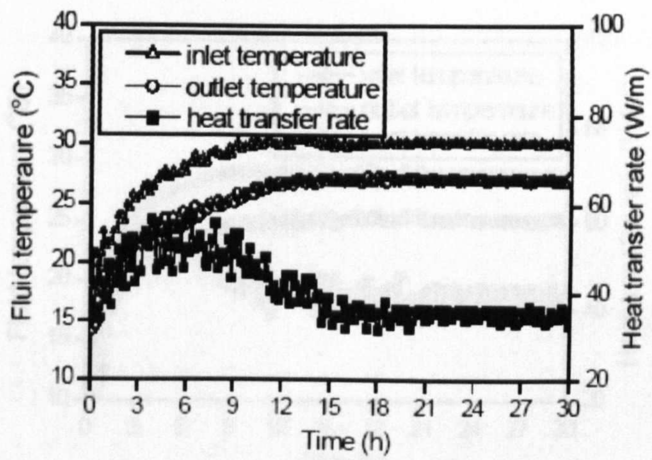
Appendix (7.4) Thermal conductivities of sand-bentonite mixtures with different mixed ratios



Appendix (7.5) Test results of the natural ground temperature

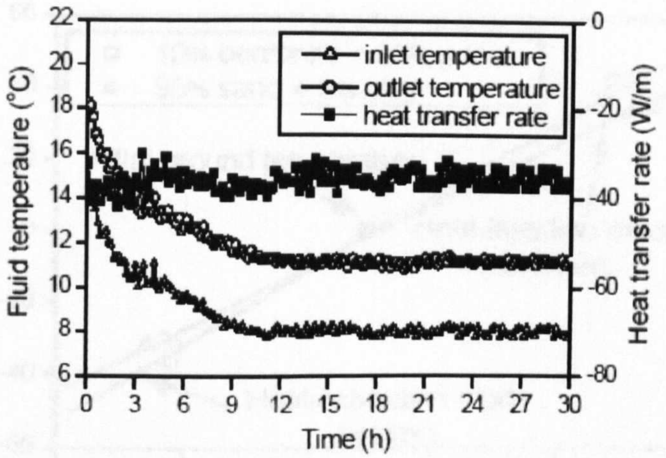


Appendix (7.6a) Heat extraction (inlet fluid temperature: 8.4°C)

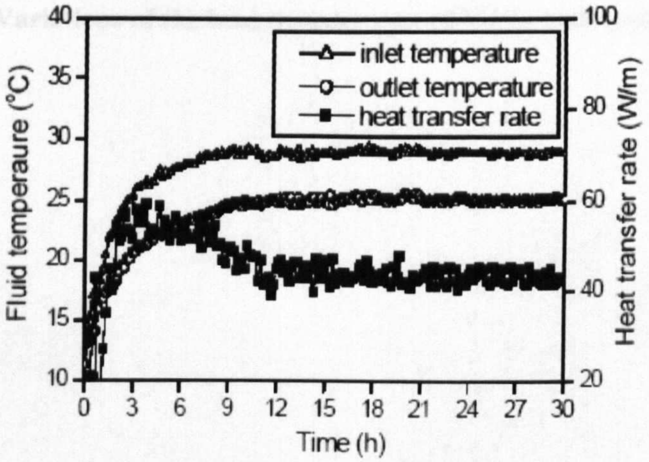


Appendix (7.6b) Heat injection (inlet fluid temperature: 30.2°C)

Appendix (7.6) Thermal performances of the BHE with a common sand-clay backfill material

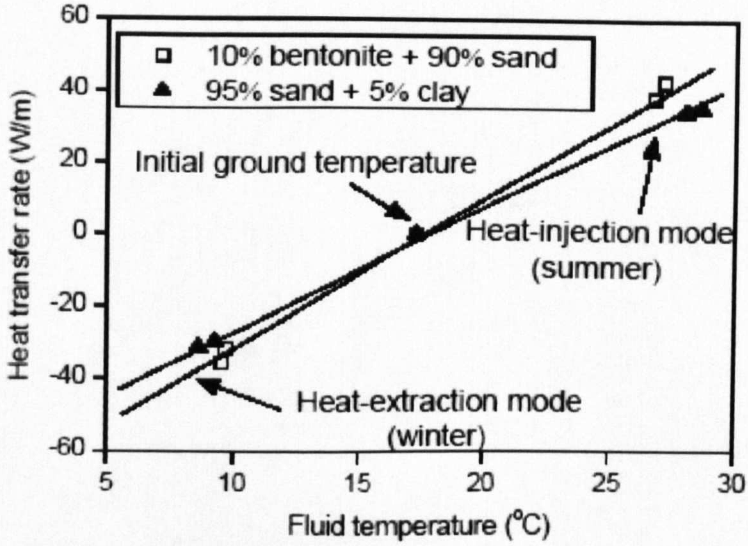


Appendix (7.7a) Heat extraction (inlet fluid temperature: 8.0°C)



Appendix (7.7b) Heat injection (inlet fluid temperature: 28.9°C)

Appendix (7.7) Thermal performances of the BHE with an optimal sand-bentonite backfill material



Appendix (7.8) Variations of the heat transfer rate of BHEs with average fluid temperatures