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Thermal performance of a solar assisted horizontal ground heat exchanger

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Abstract

This paper presents an experimental study of a solar assisted horizontal ground heat exchanger system (HGHEs) operating as a daily heat storage unit. Initially, several soils were assessed as sensible heat storage mediums, with sand and gravel selected as the most appropriate. Then, a HGHEs was designed and connected to a 15m^2 test room with a heating load of 1kW at Nottingham Trent University. Heating cables, simulating solar input, were used to heat the soil in the HGHEs to 70℃, then a heat transfer fluid (HTF), was circulated through a closed loop heat exchanger to extract the stored heat. The parameters of soil backfill and HTF mass flow rate were investigated in the HGHEs. Several output flowrates ranging between 0.1 to 0.6L/min were tested, producing discharge times varying between a few hours to a few days. The HTF mass flowrate was found to be the most significant parameter, affecting the HGHEs thermal capacity and heat exchange rates. The sand filled HGHE produced approximately 50% more hot water (T>35℃) during a longer duration achieving an efficiency of 78% compared to the gravel filled HGHE with a lower system efficiency of 58%. Insulating the HGHE system was found to reduce heat losses and avoid temperature fluctuations in the HGHEs. Overall, the results show the hot water quantity, temperature range and duration produced from the system were in line with low temperature district heating guidelines and can be applied to some household heating applications incorporating low flows and low temperatures.

Keywords: (Energy storage, Horizontal ground heat exchanger, Soils, Building, Space Heating)

1. Introduction

1.1 Background

Over recent years, there has been a shift from conventional resources towards energy efficient renewable sources of energy for building heating purposes (İnallı & Esen 2004). The use of solar energy is of considerable interest because it leads to diminution of fossil fuels consumption and is a non-polluting source of energy (Badescu 2002). Several types of solar energy systems are integrated with heat collection storage systems and have been developed for heating/cooling purposes in residential and commercial buildings. The main heat storage media are water, latent heat materials and ground materials. The ground is a stable heat exchange medium and is essentially unlimited and always available (Ozgener & Hepbasli 2007; İnallı & Esen 2004). Ground heat exchanger systems (GHEs) have gained recognition for improved and easy exploitation of thermal energy from the ground (Esen & Yuksel 2013). Claims made by Garg (1985) are that GHEs can 1) collect heat more efficiently, 2) store more heat at a lower cost, 3) be cheaper to build, and 4) deliver a higher solar fraction with the same collector area compared to a water tank HGHE system maintaining a higher level of performance even in colder climates (Garg 1985; Ozgener & Hepbasli 2007).

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GHEs installed for heating and cooling purposes in buildings have been extensively studied by various authors (Florides & Kalogirou 2007; Luo et al. 2016). Closed ground-loop GHEs can either be installed in vertical (VGHEs) or horizontal (HGHEs) arrangement, and a comparison of HGHEs and VGHEs performance was studied by Lee et al. (2015). In this study, the focus was a solar assisted HGHEs with operating temperatures ranging between 35-70℃ (Wong & Snijders 2006). HGHEs consists of heat exchange pipes, the pipes can come in a variety of configurations including straight, coil, slinky or loops that are buried in shallow ground trenches of up to 1-2m depths. A HTF (water or anti-freeze solution) is circulated through the system to extract the stored heat upon requirement and return the cooled HTF to the ground storage where it gathers further energy, in a continuous cycle. HGHEs are surrounded by soil, and hence the performance of the system is highly dependent on ground heat-transfer characteristics (Ball et al. 1983). Ground thermophysical properties including soil texture, grain size distribution, bulk density, water content and thermal conductivity are correlated and highly influences the heat transfer between the circulating HTF in the GHEs and the surrounding soil, affecting the performance of the system (Bertermann et al. 2015; Luo et al. 2016; Kim et al. 2016; Kavanaugh 2000). HGHEs are preferred over VGHEs for residential installations because of their lower initial installation costs (Naylor et al. 2015). Although HGHEs offer a cost-effective and environmentally friendly alternative compared to other methods, large shallow land areas are required for pipe installations and the system is affected by temperature fluctuations caused by the system's proximity to the ground surface. Most GHEs are equipped with a ground source heat pump (GSHP) to assist the store charge and discharge process and to avoid the extreme high or low temperature conditions that compromise the energy performance of the systems (Wu 2010). Sarbu & Sebarchievici (2015), provided a detailed literature regarding of GSHP systems, and their recent advances. Lund et al. (2005) reported that GSHPs have the largest energy use and installed capacity, according to 2005 data, accounting for 54.4% and 32.0% of the worldwide capacity and use.

Various experimental, numerical, economic and performance prediction studies related to GHEs have been reported in literature. The studies can be categorised into three broad groups: (i) Solar collectors coupled with a GSHP system (Yamankaradeniz & Horuz 1998; Huang & Chyng 2001; Kaygusuz 2000; Reyes et al. 1998; Ball et al. 1983); (ii) Ground heat exchanger systems coupled with a GSHP (Gan et al. 2007; Kim et al. 2016; Luo et al. 2016; Bertermann et al. 2015; İnallı & Esen 2004; Esen et al. 2016; Esen et al. 2015; Cui et al. 2008; Florides & Kalogirou 2007; Naylor et al. 2015; Wu et al. 2010; Ball et al. 1983) (iii) Solar collectors coupled with a GHEs and a GSHP for heating purposes (İnallı & Esen 2004; Ozgener & Hepbasli 2005a; Ozgener & Hepbasli 2005b; Inalli & Esen 2005; Verma & Murugesan 2014; Badescu 2002; Esen et al. 2016). Bose & Smith (1992) developed the first solar GHE, coupled with a GSHP at Oklahoma State University. GHEs coupled with a flat plate collector and GSHP were further developed by Ozgener et al. (2007), Yong & Sumathy (2004) and Kupiec et al. (2015).

Extensive research has been undertaken into HGHEs by various researchers throughout the years, most of which were focused on monitoring HGHEs coupled with a GSHP where the heat pump output and the coefficient of performance (CoP) ratio was calculated to maintain daily indoor temperature. Other studies attempt to enhance the thermal performance of experimental HGHEs by improving the heat transfer between the surrounding soil and the heat exchanging pipes. The methods used to achieve this is by varying the heat exchange pipe properties, type and orientation. Esen & Yuksel (2013) experimentally investigated greenhouse heating by biogas, solar and ground energy in Turkey's climate conditions and concluded that the slinky-type HGHEs occupies less space in the ground and can be successfully used for greenhouse heating purposes. Kim et al. (2016) investigated the performance of HGHE via experiments and numerical analyses in a steel box filled with dried Joomunjin sand, comparing coil-type and slinky-type heat exchange pipes performance in HGHEs and found slinky-type to have better performance. Gonzalez et al. (2012) conducted a study on the interactions between the soil, HGHE and the above ground environment in the UK and the results show that the slinky influences the surrounding soil by significantly decreasing soil temperatures. Koyun et al. (2009) studied the effects of burying aluminum finned pipes in the soil over the traditional plastic polypropylene (PPRC) pipe and concluded that aluminum finned pipe has higher heat transfer values and is therefore more useful in GHEs. İnallı & Esen (2004) carried out experimental measurements of a HGHEs connected to a GSHP to validate the effects of the parameters including the buried depth of soil, the coupled heat exchanger, mass flow rate of the water-antifreeze solution and sewer water on the performance of the system to be used for space heating applications. Results show the CoP of the HGHEs in the different trenches, at 1 and 2 m depths, were different. Wu et al. (2010, 2011) experimentally and numerically studied the thermal performance of a HGHEs ground-coupled GSHP in a UK climate and concluded that heat extraction from the HGHEs increased with ambient temperature and soil thermal conductivity, however it decreased with increasing refrigerant temperature. Kim et al. (2016) also found that GHEs type and soil thermal conductivity are the main factors determining the heat exchange rate of a GHE, whereas the pipe diameter did not have any effect on the GHE performance. Congedo et al. (2012) carried out computer simulations on several HGHEs configurations considering soil thermal conductivity, installation depth, fluid velocity and concluded that the optimal soil type to use around the heat exchanging pipes was that with the highest thermal conductivity. Also, the HGHEs installation depth did not play an important role on the system performance.

1.2 Study Objectives

As evident from Section 1.1, a considerable amount of recent research has been devoted to pipe design characteristics and the addition of GSHP to HGHEs, with much less focus on the ground media used for storage and the air temperature fluctuations caused by the proximity of HGHEs to the ground surface. Moreover, there are limited studies in literature concerning improving the performance of solar PV panels and solar heat collectors assisted HGHEs. Therefore, the objectives of this study are twofold:

- The first objective was to present a comparative study of heat transfer in seven ground media.
- The second objective, was to investigate how excess electricity produced from solar PV panels can be more efficiently stored in an insulated HGHEs to heat a 15m^2 test room with a heating load of 1kW during the typical winter conditions in Nottingham, UK (Temperature of -6℃) without the use of a GSHP. For this purpose, an experimental HGHEs was set-up using two soil types as backfill media including sand (LB) and gravel (GR) and tested under various HTF mass flow rates to evaluate the performance of the system in heating mode (charging) and extracting mode (discharging).

The novelty points of this study are: (1) The system simulates storing excess electricity generated from solar PV panels in the form of heat and/or storing heat obtained directly from a solar heat collectors, (2) Testing and comparing two soil backfill media in a HGHEs under the same working conditions including: the same solar radiation, ambient air temperature, collector materials, insulating materials and HGHE dimensions, (3) The HGHEs is insulated to avoid heat loss to the surroundings and reduce air temperature fluctuations caused by the proximity of HGHEs to the ground surface, and (4) The HGHEs does not use a GSHP to assist in the heating process. These points will assist designers in designing HGHEs.

2. Experimental work

The experimental work was divided into four activities as follows:

- Establishing soil thermophysical properties (Activity 2.1)
- Conducting thermal testing of soils (Activity 2.2)
- The experimental HGHE system set-up (Activity 2.3)
- The soil backfilled HGHE (Activity 2.4)

Seven soils were utilised in this experimental study, these include: Gravel (GR), Leighton buzzard sand (LB), Washed sand (WS), Building sand (BS), Mercia mudstone clay (MM), Gault clay (GA) and Lias clay (LI) as shown in Figure 1. From a designer's point of elevation, the selected soils represent different widely available and abundant soil types in the United Kingdom which are cheap, sustainable and can be purchased from local building merchants.

Figure 1: Soil materials, Top row left to right: LB, BS, WS, GR; Bottom row left to right: LI, MM, G

2.1 *Establishing soil thermophysical properties*

The soils used in this study have fundamental thermophysical properties that determine their energy performance. These thermophysical properties include bulk and particle densities (ρ_b & ρ_p), porosity (n), thermal conductivity (K) and thermal resistivity (R_λ) and are summarised in Table 1. Figure 2 shows the particle size distribution (PSD) curves for each of the tested soils. Soil properties were established using relevant British Standard testing procedures, these are contained within: BS 5930:1981 and BS 1377 for density and particle distribution tests, BS 7591-2:1992 for porosity and BS EN 12667:2001 for thermal testing.

Table 1
Thermophysical properties of selected soils utilized in this study

Soil material & abbreviation	Particle Size (mm)	Gradation Classification	ρ_b (kg/m^3)	ρ_p (kg/m^3)	n (%)	K (W/mK)	R_λ (m°C/W)
Gravel (GR)	2 - 10	Uniform	1451	2464	41.12	0.7	1.43
Leighton Buzzard Sand (LB)	0.6 - 1.18	Uniform	1562	2620	40.40	0.26	3.89
Washed Sand (WS)	0.063 - 5	Uniform	1719	2427	29.15	0.19	5.05
Building Sand (BS)	0.15 - 5	Uniform	1401	1666	15.86	0.14	6.85
Mercia Mudstone Clay (MM)	0-2	Well	1328	1475	10	0.12	8.53
Gault Clay (GA)	0-5	Well	1210	1299	6.86	0.10	9.90
Lias Clay (LI)	0-5	Well	1256	1326	5.27	0.13	7.45

Note: Soils were dried overnight before testing, hence the moisture content for each soil is zero

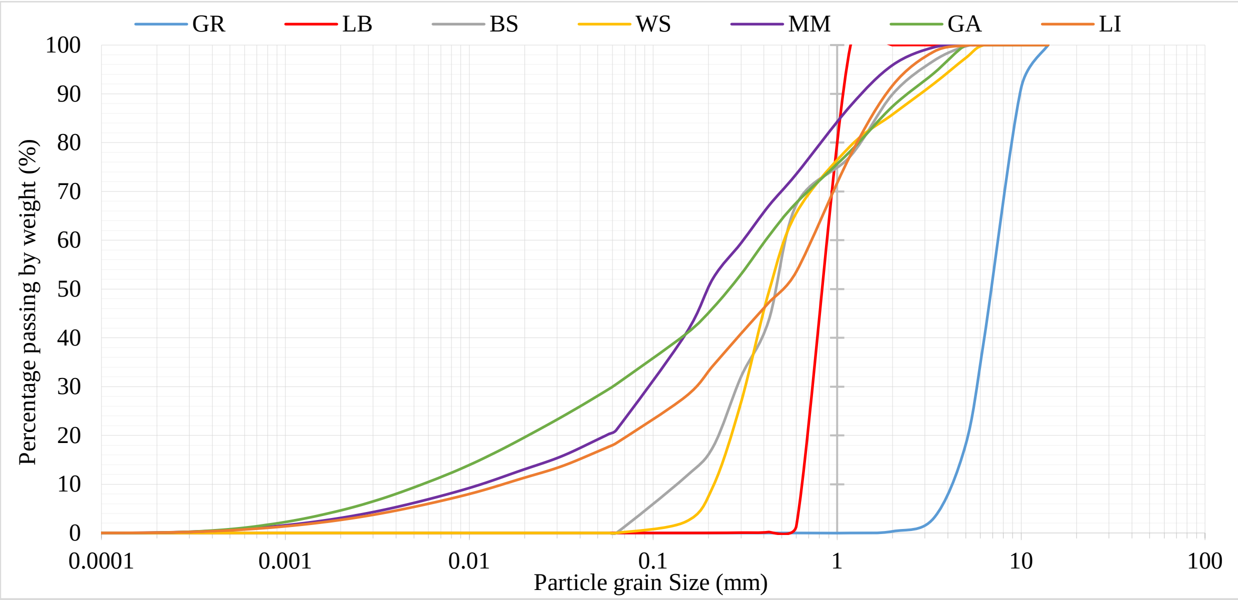

Figure 2: Particle size distribution chart for GR, LB, BS, WS, MM, GA and LI soil gradations

2.2 *Thermal testing of soils*

Each of the soils were tested in 10 litre containers (approximately weighing 15kg each, depending on soil density) to establish heating and cooling patterns. Seven containers were filled to the 10 litre mark with each of the seven soil and placed in an environmental chamber (Model: BRI I/06 Fisons series No 5257) and set to 70°C. RS Pro K-type thermocouples (chromel-alumel) attached to a central data logger were used to monitor temperature. Temperature readings were recorded at 5 minute intervals internally for the environmental chamber (T_{EC}), externally for the room temperature (T_{room}) and at five locations in the containers ($T_{Left}, T_{Midd}, T_{Right}, T_{up}, T_{down}$) as illustrated in Figure 3. After the soil filled containers reached a steady temperature of 70$\pm$2°C, the containers were removed from the chamber and left to cool to ambient room temperature ($\approx$ 20°C). The tests were conducted side by side with a control LB sand filled container and repeated three times to assess comparability.

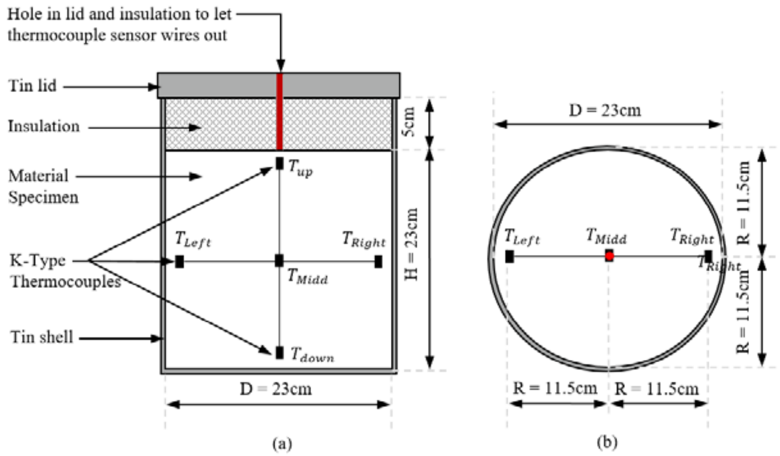

Figure 3: Cross sectional schematic diagram of the 10L containers used for testing (Dimensions in cm) (a) Side elevation, (b) Top elevation

2.3 Experimental HGHE system set-up

An experimental HGHEs was designed and constructed in the soil laboratory facilities at Nottingham Trent University to investigate and evaluate the thermal performance of the system in heating mode (charging) and extracting mode (discharging). A detailed schematic diagram of the main components used in the system is shown in Figure 4. This set-up was designed for a 1kW (test room heating load) at design conditions as calculated in section 4.1. The system consists of 25 individual components with the biggest component being the soil backfilled HGHE storage itself (component 10 on Figure 4). The system has two operation circuits running through it for (a) Heating [charging] HGHE (Red network on Figure 4) and (b) Extracting heat [discharging] from HGHE (Black network on Figure 4). These will be further described in the operation mode section.

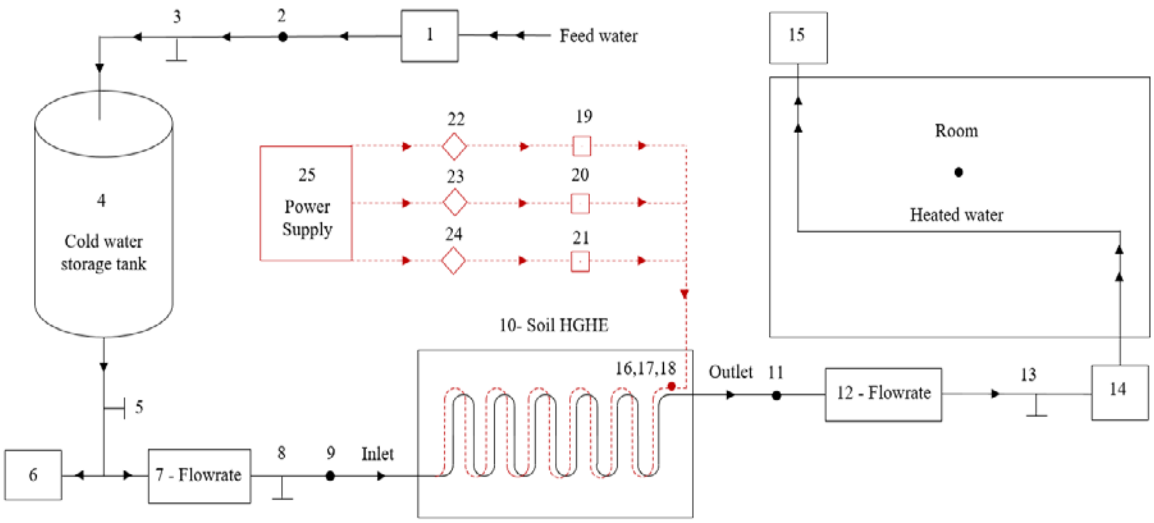

Figure.4: Schematic diagram of the heating system (see additional notes below)

Figure 4 notes: Network A (Red): Heating mode, Network B (Black): Extracting heat mode.

1: Cold water supply, 2: Sensor measures temperature of cold water, 3,5,8,13: Gate valves to control flow of water, 4: Water HGHE tank (capacity 50L), 6: Tank collection drain, 7,12: Water meters to monitor inlet and outlet flow-rate, 9: Sensor measures water inlet temperature of HGHE, 10: Soil HGHE (see Figure 5,6,7 & 8 for further details), 11: Sensor measures water outlet temperature of HGHE, 14: Tap control to alter flowrate of water, 15: Hot water collection drain, 16,17,18: Sensors measures heating cable temperature, 19,20,21: Digitally regulated thermostats to control temperature of heating cables on each of three layers, 22,23,24: Data logger attached to sensors detecting temperature and on/off thermostats timings to monitor the power used in the system, 25: Power supply to heating cable, sensors and digital thermostats.

2.4 Experimental HGHE

Figure. 5 shows a 3D schematic of the soil backfilled HGHE storage used in this study along with material details. Further cross section elevation details are shown in Figure. 6 (plan), Figure. 7 (long) & Figure. 8 (short). The inner dimensions of the HGHE storage are 0.5m wide, 1m long and 0.5m high, allowing a soil capacity of approximately 450kg. The outer dimensions of the HGHE are larger to accommodate for insulation and provide material containment. A 50mm thick extruded polystyrene foam (XEPS) with a low thermal conductivity of 0.033W/mK was used to insulate the HGHE and avoid heat losses to the surroundings during testing. The thermophysical properties of the materials utilised within the HGHE are summarised in Table 2.

Table 2
Thermophysical properties of materials utilized within HGHE storage

HGHE Region	Thickness	Material	ρ (kg/m^3)	K (w/mK)	C_p (J/kg K)
Cover	25mm	Wood (MDF)	700	0.15	1700
Insulation	50mm	Polystyrene (XEPS)	33	0.033	1131
Pipe – Network B	$\emptyset_{ext}$= 10mm & $\emptyset_{int}$= 7mm	Copper	8950	401	385
HTF – Network B	NA	Water liquid	1000	0.6	4200
External environment	NA	Air	1.225	0.0242	1006.43

Where: NA = Not applicable
HTF = Heat transfer fluid
MDF= Modified density fibreboard
XEPS = Extruded expanded polystyrene
$\emptyset_{\text{ext}}$ = external copper pipe diameter
$\emptyset_{\text{int}}$ = internal copper pipe diameter

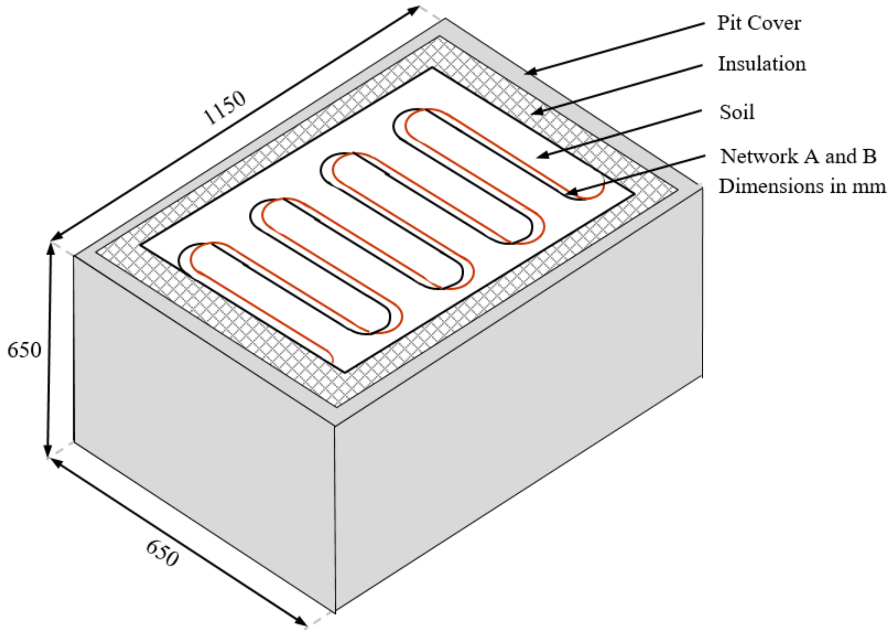

Figure. 5: 3D schematic diagram of the soil backfilled HGHE storage (Dimensions in mm)

2.4.1 Operation modes:

The HGHEs in this study was designed as a daily heat storage unit. During the day, when there is plenty of sunlight, the excess electricity from PV and/or the excess heat collected from solar thermal collectors can be stored in the HGHEs to be later used at night (when heat is required). The HGHE system operates using two networks. Network A is used for heating the storage [HGHE charging] (Red network on Figure’s 4,5,6,7 & 8) and Network B is used for extracting the stored heat from the storage [HGHE discharging] (Black network on Figure’s 4,5,6,7 & 8). The networks are described below.

Network A: HGHE Charging

The soil in the HGHE was heated (charging mode) using electric heating cables (Network A). The cables were 10mm in diameter and follow the pattern shown in Figure. 6 (plan elevation), running on three layers and spaced at 125mm centers as shown in Figure. 7 & 8 (side elevation). The cables were temperature regulated using thermostats to reach temperatures of 65℃ ±5℃ simulating temperatures achieved from either solar thermal collectors and/or excess generated electricity produced from solar PV panels (240W). Once the HGHE reached a homogenous temperature of 65℃ ±5℃, the heating cables were switched off and the heat was extracted using Network B.

Network B: HGHE Discharging

A 10mm diameter copper pipe buried in the soil was used to extract the heat from the HGHE (Network B). The pipe was 15m long (continuous) and ran on three layers in the HGHE at 125mm centres. Copper piping was used due to its suitability for HGHEs as described by Yang (2013). The heat extraction from the HGHE to the heating load is maintained using water as a HTF, which circulates through the pipe work from a water storage tank unit (component 4 on Figure. 4). New fresh water (≈18℃) was used for the start of each test. Water was used due to its low cost, wide availability, and desirable thermal properties. Swardt & Meyer (2001) states that the utilization of water reticulation systems as a heat source/sink is a viable method of optimizing energy usage. Network B runs identically above Network A and follows the path illustrated in Figure. 6 (plan elevation). As illustrated in Figure. 7, the HTF runs through the heated HGHE from the inlet at the top to the outlet at the bottom and is continually heated by the heat exchange occurring between the heated soil and colder fluid in the pipe until the soil loses the stored heat and reaches equilibrium temperature with the input water temperature. In order to increase the heat transfer area between the copper pipe to the surrounding soil, the pipework was formed in a U-bended repeat pattern as illustrated in Figure. 6.

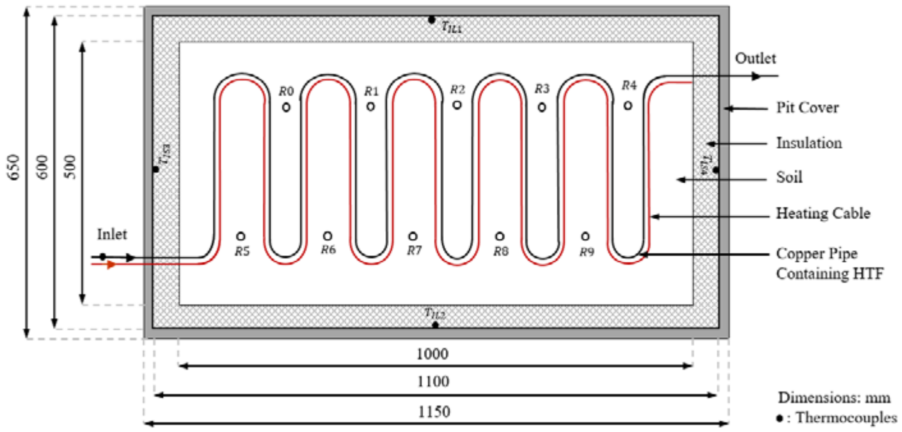

Figure. 6: Schematic diagram of plan elevation of soil filled HGHE (Dimensions in mm)

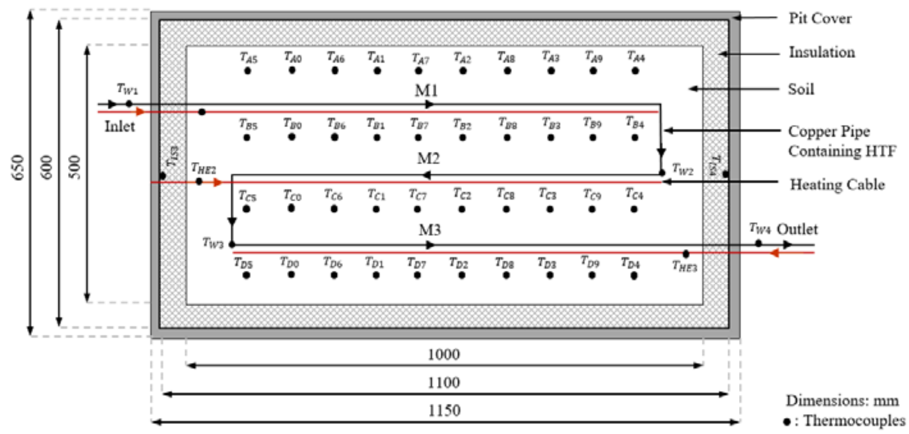

Figure. 7: Schematic diagram of long side elevation of soil filled HGHE (Dimensions in mm)

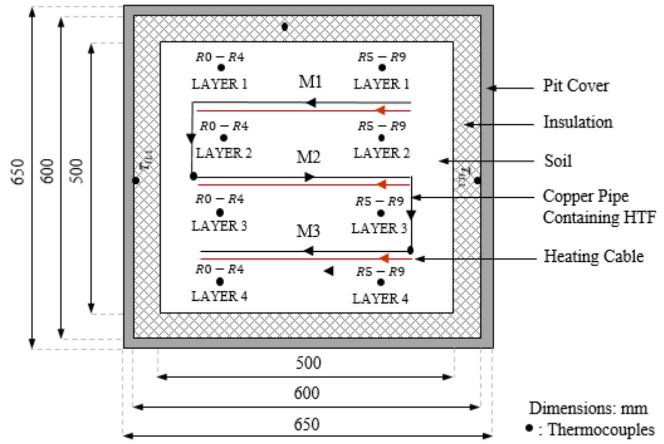

Figure. 8: Schematic diagram of short side elevations of soil filled HGHE (Dimensions in mm)

2.4.2 Measurements

Tests were conducted on the HGHEs between August 2016 to March 2017. The following measured data were recorded from the HGHEs at 5-minute time intervals under steady-state flow conditions;

(a) Temperature of HTF entering and leaving the HGHE by thermocouples.
(b) Temperature of HTF inside the HGHE by thermocouples.
(c) Temperature of experimental room by thermocouples.
(d) Temperature of outer insulation by thermocouples.
(e) Temperature of soil within HGHE (Layers 1,2,3 and 4 – See Figure's 7 & 8) by thermocouples.
(f) Mass flow rate of HTF by a flowmeter.
(g) Electric power input to heating cables and thermostats by a wattmeter.

Figure's 6, 7 and 8 illustrates the layout of 50 K-type (chromel-alumel) thermocouples embedded within the HGHE. Temperatures were recorded with a regular time step of 5 minutes during storage charging and discharging using a datawel acquisition computer based data logger allowing time-temperature relationships to be analyzed. 40 of these thermocouples were distributed in the HGHE storage using ten systematically placed threaded rods (Rods *R0-R9*) to measure the buried soil's temperature as illustrated in Figure 6. Temperature was also recorded at four levels within the HGHE at Layers 1 (437.5mm FB), Layer 2 (312.5mm FB), Layer 3 (187.5mm FB) and Layer 4 (62.5mm FB) (See Figure 8). The ten temperature readings on each layer were averaged to derive an overall time-temperature relationship.

To monitor the circulating HTF temperature, four thermocouples were embedded into the copper pipe, this enabled the temperature of the running HTF to be monitored at the store inlet (T_{w1}), start of M2 (T_{w2}), start of M3 (T_{w3}) and at the store outlet (T_{w4}) as illustrated in Figure 7. A further four thermocouples were sandwiched between the MDF storage cover and insulation layer to assess heat losses from the HGHE. These four sensors were placed in the middle of the 2 long faces (T_{IL1}, T_{IL2}) and 2 short faces (T_{IS3}, T_{IS4}) as illustrated in Figure 6. The ambient air temperature (T_{room}) was also monitored for completeness of data, the T_{room} sensor was kept sheltered to protect the it from direct sunlight.

The HGHEs relied on gravity for HTF circulation from the overhead water storage tank with a head difference of 3m. The maximum HTF output flowrate was 0.7L/min and could be adjusted down to a minimum of 0.1L/min. The flow rate of the circulated HTF through the closed loop system was measured using a flowmeter and controlled by a manual valve mounted to the HGHE. Gate valves were also installed in the system as illustrated in Figure 5 (components 3,5,8,13) allowing the system to be drained at different locations if required. The time-temperature relationships could subsequently relate to flow-rate of the HTF.

3. Uncertainty analysis

An uncertainty analysis has been conducted in this study utilizing the Holman (1994) accepted method stated in the experimental methods for engineers book. Esen et al. (2006) who conducted similar research into GHEs also used this method in determining the uncertainty of data. Holman (1994) states the result 'R' is a given function of the measured independent variables w_1, w_2, … ,w_n considered during testing. If the uncertainties in the independent variables all have the same odds, then the uncertainty w_R in result having these odds is calculated using equation 1. In this study, temperatures, mass flow rates, voltages and amperes were measured with appropriate instruments explained previously. The total uncertainties of the measured parameters are presented in Table 3.

$$w_R = \left[\left(\frac{\partial R}{\partial x_1} w_1\right)^2 + \left(\frac{\partial R}{\partial x_2} w_2\right)^2 + \cdots + \left(\frac{\partial R}{\partial x_n} w_n\right)^2\right]^{1/2} \qquad \text{(eq.1)}$$

Where, $w_1, w_2, \ldots, w_n$ are the uncertainties associated with $x_1, x_2, \ldots, x_n$

Table 3

The experimental results and total uncertainties of the measured parameters

Item	Average Value	Total uncertainty (%)
HTF temperature at HGHE inlet ($T_{wa,i}$)	21°C	± 1.38
HTF temperature at HGHE outlet ($T_{wa,o}$)	70°C	± 1.38
Ambient room temperature (T_{room})	16°C	± 1.38
Insulation temperature on the outside of HGHE (Containers)	20°C	± 1.38
Soil temperature at top layer (layer 1) of HGHE (T_{layer1})	65°C	± 1.38
Soil temperature at top middle layer (layer 2) of HGHE (T_{layer2})	70°C	± 1.38
Soil temperature at bottom middle layer (layer 3) of HGHE (T_{layer3})	68°C	± 1.38
Soil temperature at bottom layer (layer 4) of HGHE (T_{layer4})	62°C	± 1.38
Mass flowrate of HTF	0.0016 – 0.01 L/s	± 2.89
Electric current through system (1 of 3)	0.55 A	± 3.00
Voltage in heating cable (1 of 3)	250 V	± 3.00
Power input to heating cable	240 W	± 3.10

4. Thermodynamic analysis

This section focuses on using the laws of thermodynamics to assess the efficiency of the HGHEs. A list of the notations used in this section is given at the end of the paper. The assumptions made in the analysis presented in this study are:

- A closed system is in operation
- The heat transfer is steady state
- There is a steady flow in operation and assumes processes at constant pressure
- The HTF pressure drops in the pipes connecting the components are ignored, since lengths are short
- The heat is generated uniformly in the resistance electric heating cable
- Constant thermal-physical properties are used for materials (from Table 1 and 2)

4.1 Heating requirement

Calculating the total heat loss from the rectangular test room (with a floor plan $15m^2$) is the first step in determining the heating load requirement before selecting the system components. The construction properties of the test room are given in Table 4. The heating system capacity is sized to meet the needs of the test room under the coldest day of the winter season (outside temperature of -6℃) in Nottingham, UK. The ambient room temperature was recorded to be 15 ℃ on that day. The total required heating load (Q_{thl}) of the room was found to be 0.97kW, approximately 1kW.

Table 4
The construction properties of the test room

Construction	Properties	Value
Window area	Glass, U = 2.8 W/m^2°C	2m^2
Wall area	Brick, U = 0.32 W/m^2°C	39m^2
Floor area	Concrete, U = 0.7 W/m^2°C	15m^2
Ceiling area	Concrete, U = 0.8 W/m^2°C	15m^2
Ventilation	N = 1 Air change/hr ; Air Spht = 0.34	-
Dimensions of the room (V)	5.0mL x 3.0mW x 3.0mH	45m^3

4.2 Energy balance

Based on the first law of thermodynamics, the rate of net energy transfer into the HGHE must equal the rate of energy transfer out by heat from the system as illustrated in equation 2.

$$E_{in} = E_{out} \quad \text{(eq. 2)}$$

Where: E_{in} is the rate of net energy transfer into the HGHE (kW) and E_{out} is the rate of net energy extracted from the HGHE (kW)

The energy required (Q_{req}) to raise the temperature of the soil in the HGHEs from an initial starting temperature of 20℃ to 65℃ was calculated to be 14400kJ using equation 3. From experimental testing, the actual energy inputted into the system (Q_{in}) was calculated using equation 4. Over a heating period of 48 hours, the rate at which electrical energy dissipated from the three heating cables ($\dot{G}$) was 240W as measured from an energy meter. Therefore, the HGHEs was charged with an energy Q_{in} of 41472kJ (excluding heat losses from the system). The steady rate of heat loss (Q_{loss}) through the insulation layer during the charging period (48 hours) was pre-calculated to be 0.075 kW or 12925kJ using equation 5.

$$Q_{req} = m_{soil} \,.\, C_{p,soil} \,.\, \Delta T_{soil} \quad \text{(eq. 3)}$$
$$Q_{in} = (\dot{G} \,.\, \Delta t) - Q_{loss} \quad \text{(eq. 4)}$$
$$Q_{loss} = [k_{ins} \,.\, A_{ins} \,.\, (\Delta T_{ins}/L_{ins})] \,.\, \Delta t \quad \text{(eq. 5)}$$

Where: Q_{req} is the energy required to raise the temperature of the soil mass in the HGHEs (kW); m_{soil} is the mass of soil in HGHEs (kg); $C_{p,soil}$ is the specific heat of soil (J/kgK); ΔT_{soil} is the temperature difference in soil (°C); Q_{in} is the actual energy inputted into the HGHEs (kJ or kW); $\dot{G}$ is the rate at which electrical energy is dissipated from the heating cable (W); Δt is the required time (s); Q_{loss} is the steady rate of heat loss through the HGHEs (kJ or kW); k_{ins} is the thermal conductivity of the insulation XEPS (w/mK); A_{ins} is the area of insulation (m2); ΔT_{ins} is the temperature difference insulation (°C); L_{ins} is the length of insulation (m)

The quantity of heat extracted (Q_{out}) from the HGHEs was calculated using equation 6, which considers the variation in HTF temperature and the quantity of HTF running through the pipe. Several mass flowrates were investigated experimentally, however, for calculation purposes only the lowest flowrate (LF) of 0.0016kg/s or 0.1L/min and highest flowrate (HF) of 0.01kg/s or 0.6L/min were considered. The Q_{out} ranged between 32369kJ (LF) and 13550kJ (HF) for the sand (LB) filled HGHEs and between 24088kJ (LF) and 6775kJ (HF) for the gravel (GR) filled HGHEs. Considering the time taken to extract the heated HTF for each flowrate case, the total heat extracted for both the LB and GR filled HGHEs was calculated to be 0.21kW (LF) and 1.25kW (HF). This means that the heat exchange rate per pipe length is 14W/m and 83W/m for LF and HF respectively.

$$Q_{out} = \dot{m}_{wa} \,.\, C_{p,wa} \,.\, (T_{wa,o} - T_{wa,i}) \quad \text{(eq. 6)}$$

Where: Q_{out} is the quantity of heat extracted from the HGHEs (kJ or kW); $\dot{m}_{wa}$ is the mass flowrate of the HTF (water) (kg/s); $C_{p,wa}$ is the specific heat of the HTF (water) (J/kgK); $T_{wa,o}$ is the outlet average HTF temperature from HGHE (°C); $T_{wa,i}$ is the inlet average HTF temperature from HGHE (°C)

4.3 Energy efficiency

The collection efficiency (η) was calculated using equation 7 for both sand (LB) filled HGHEs and gravel (GR) filled HGHEs to compare output results. Equation 7 takes the ratio of heat extracted quantity from the HGHEs (Q_{out}) to the heat stored in the HGHEs (Q_{in}). The maximum efficiency of the LB and GR filled HGHEs was calculated to be 78% and 58% respectively. It is noted that efficiencies were calculated based on soil temperatures (20℃ to 65℃) and heated HTF temperatures (71℃ to 35℃), which are not instantaneous values.

$$\eta = Q_{out} / Q_{in} \qquad \text{(eq.7)}$$

Where: η is the efficiency of the HGHE system (%)

The calculated energy values from the HGHEs are discussed in the results section.

5. Results and discussion of experimental results

5.1 Soil thermal testing

Preliminary results comparing the seven soil types, as sensible heat storage media's, are summarized as temperature vs. time graphs in Figure. 9 for sands and gravel (LB, BS, WS and GR) and Figure. 10 for clays (LB, MM, LI, GA). All seven soil filled containers were heated in the environmental chamber (EC) to reach a set optimum temperature to within 70℃ ± 2℃ tolerance. The T_{EC} curve shows the internal temperature of the environmental chamber (EC); the point at which the T_{EC} curve heats up corresponds to the time the EC was switched on. Results show that it took 16 hours to heat the soil filled containers where LB achieved the highest peak temperature of 72℃, followed by GR at 71℃, then came BS, GA and LI at 70℃ and finally WS at 69℃. The containers were left for a further 8 hours (total of 24 hours) in the EC to ensure the soils were at a homogenous temperature before removing them.

In Figure's. 9 and 10, the point at which the T_{EC} curve drops is the time the EC was switched off and the containers were removed for cooling. The soils retained their temperatures for the first 2 hours after removing them from the EC, then started to cool down. LB showed the best heat storage properties retaining heat for longer periods and cooling slower than other tested soils. As evident in Figure's 9 and 10, the LB and GR curve had a one to two hour gap between them and other soils. This is because the time it took for each soil to cool down to the same temperature of 35℃ is different, for LB it took seven hours (hr 26 to hr 33), GR took six hours (hr 26 to hr 32), MM, LI, GA took five and a half hours and BS, WS took five hours (hr 26 to hr 31.5). Physical and thermal properties of soil materials (summarized in Table 1) were found to be important parameters in the performance of soils as sensible heat storage media's. Materials with a higher void space (LB and GR ~40%) and that are both poorly graded obtained better results compared to materials with lower void spaces, which is because the voids between the particles are filled with air, air acting as a thermal insulator, allowing the soil to retain heat for longer periods. Overall, it was concluded that the LB and GR soils had the best performance compared to other sands and clays tested for heat storage purposes. Both these soils (LB and GR) were tested as a backfill material in the HGHE to compare the performance of two filled systems.

5.2 HGHEs testing

Methods of storing and extracting heat from a HGHEs was investigated using two soil backfill materials (LB and GR) which were identified previously as better heat storage mediums. For simplicity, the LB filled HGHE is abbreviated to LB-HGHE and GR filled HGHE is abbreviated to GR-HGHE. Table 5 summarizes the experimental results obtained from the LB-HGHE and GR-HGHE under four output flowrates (0.1, 0.2, 0.4 and 0.6L/min). Figure's. 11 to 14 show the results of temperature vs. time graphs for both HGHEs charging and discharging for two of the four output flowrates (Figure. 11: LB-HGHE 0.4L/min FR, Figure. 12: GR-HGHE 0.4L/min FR, Figure. 13: LB-HGHE 0.1L/min FR and Figure. 14: GR-HGHE 0.1L/min FR).

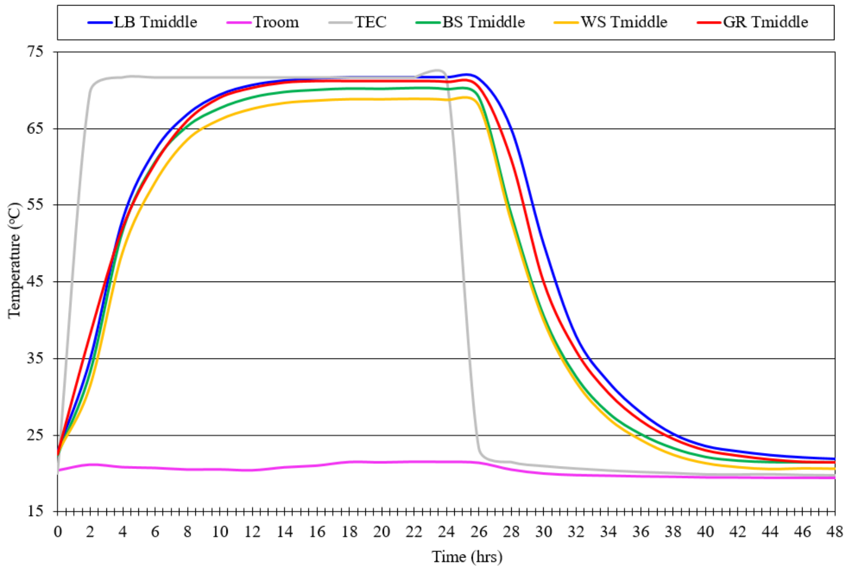

Figure. 9: Temperature vs. time results using sand and gravel (LB, BS, WS and GR) as heat storage media's

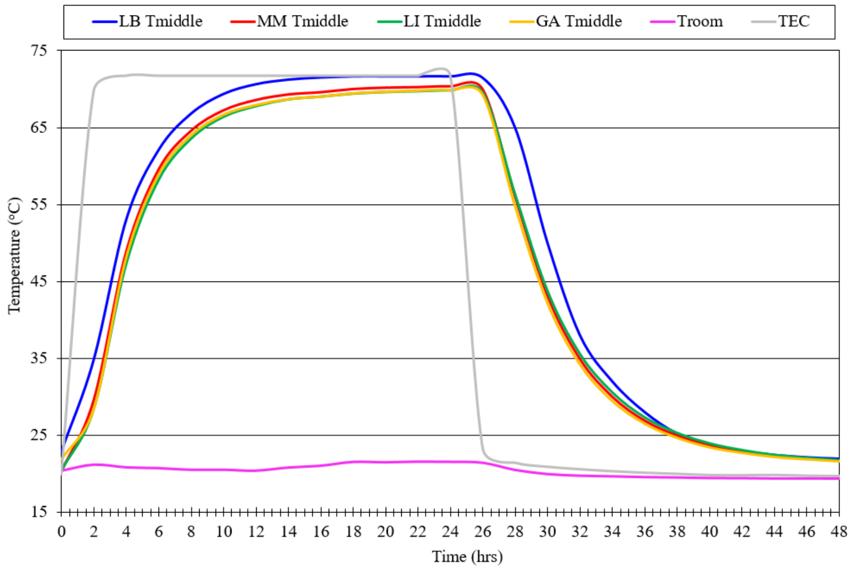

Figure. 10: Temperature vs. time results using sand (LB) and clays (MM, LI, GA) as heat storage media's

5.2.1 HGHEs testing – Charging

Thermocouples buried in the HGHEs showed that both LB-HGHEs and GR-HGHE started with temperatures of 15-22℃ and during charging over the course 28 hours reached temperatures of 69-71℃ using electric cables (see Table 5). The highest temperature values (65-70℃) were recorded in layer 2 and 3 of the HGHEs for both LB-HGHEs and GR-HGHE as illustrated in Figure's. 11-14. Layers 2 and 3 were sandwiched between two layers of heating cable (above and below) and hence reached higher temperatures compared to Layers 1 and 4. Additional tests were conducted to assess the effect on HGHEs temperatures with respect to longer charging periods, however, there was no significant effect on LB-HGHEs temperature. One of the objectives of this research was to reduce the temperature fluctuations in the HGHE due to external colder surroundings, a parameter that currently limits the use of HGHEs. This study, proposed insulating the HGHEs with a recycled XEPS material and installing thermocouples on the outer surface of the XEPS (T_{ins}) to measure heat losses from the HGHEs during charging and discharging. T_{ins} indicates that the temperature of the insulation starts at 14-19℃ and increases to 23-25℃ upon store charging for both LB and GR-HGHEs (Figure's 11-14) indicating a slight heat loss from the system. This means the XEPS insulation did successfully minimize temperature fluctuations heat loss to the surroundings, but, should still be improved in further studies.

Table 5
Comparison of experimental results from LB-HGHEs and GR-HGHEs under different output flowrate

HGHE fill	Water Flow (L/min)	Temperature (℃) (A) Soil Start	(B) Soil Max	(C) Ins Start	(D) Ins Max.	(E) Inlet	(F) Outlet Max.	Time (hrs) (G) Steady HGHE Charge Period	(H) Full HGHE Charge Period	(I) Full HGHE Discharge Period	(J) Hot water HGHE Discharge Period	Quantity (L) (K) Hot Water Output
LB HGHE	0.1 [Fig13]	21	70	19	25	21	69	28	48	74	43	258
	0.2	22	70	18	25	19	70	28	48	29	11	132
	0.4 [Fig11]	22	70	17	24	19	70	28	48	27	5	120
	0.6	22	70	18	25	20	70	28	48	24	3	108
GR HGHE	0.1 [Fig14]	19	71	17	24	19	71	28	48	57	32	192
	0.2	17	71	14	23	17	71	28	48	27	5	120
	0.4 [Fig12]	21	71	16	25	20	71	28	48	20	3	108
	0.6	15	71	13	23	18	71	28	48	17	1.5	54

Note: Table 5 was compiled from interpreting graph data from Figure's 11-14 and refers to lettered regions annotated in Figure. 11 as an example. The letters indicate the following: (A) Starting temperature of soil in HGHE prior to charging; (B) Maximum temperature of soil in HGHE after charging; (C) Starting temperature of insulation in HGHE prior to charging; (D) Maximum temperature of insulation in HGHE after charging; (E) Inlet temperature of HTF (water) entering HGHE when discharging ; (F) Maximum outlet temperature of HTF (water) extracted from HGHE when discharging; (G) Time for HGHE to reach steady temperatures (charging) ; (H) Total charging time of HGHE, soil reaching maximum temperature of 70℃; (I) Total discharging time of HGHE, HTF (water) cools down to 20℃ ; (J) Hot water discharging time from HGHE, HTF (water) cools down to 35℃; (K) Calculated output quantity of hot water extracted from HGHEs (Max -35℃)

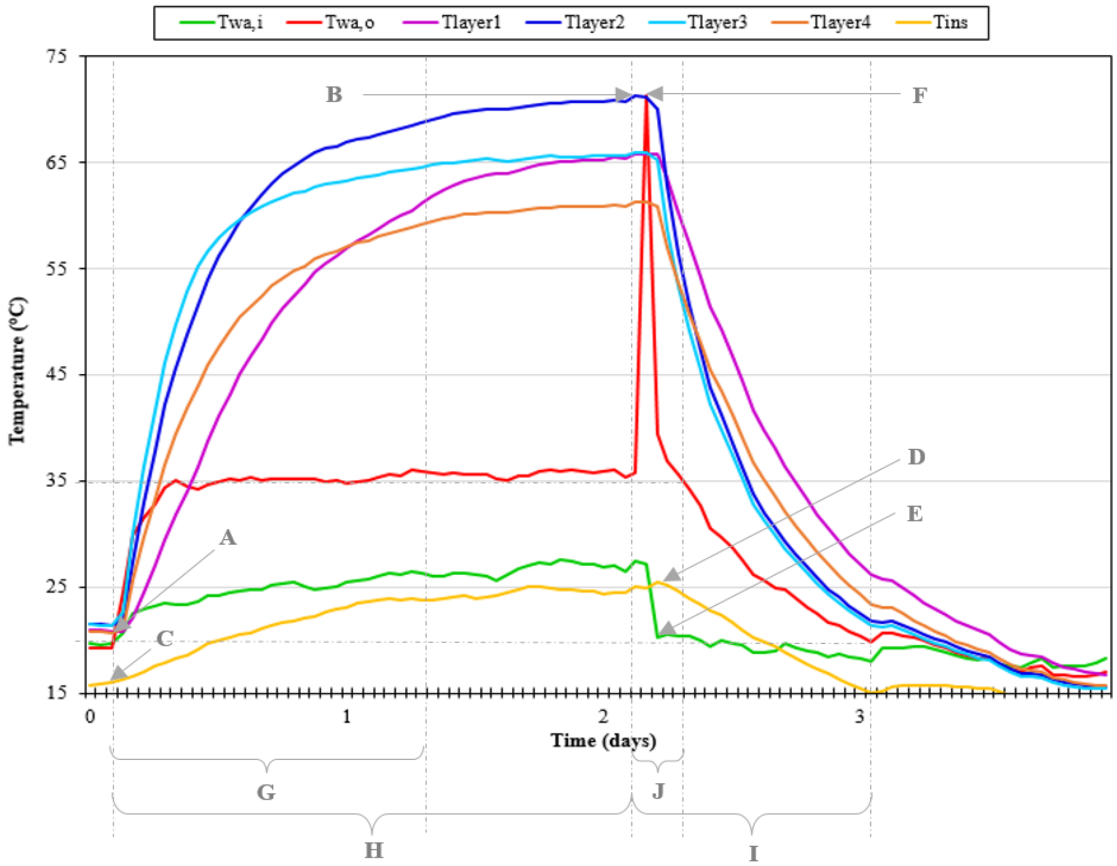

Figure. 11: Temperature vs. time results for sand (LB) filled HGHEs with an output flowrate of 0.4 L/min

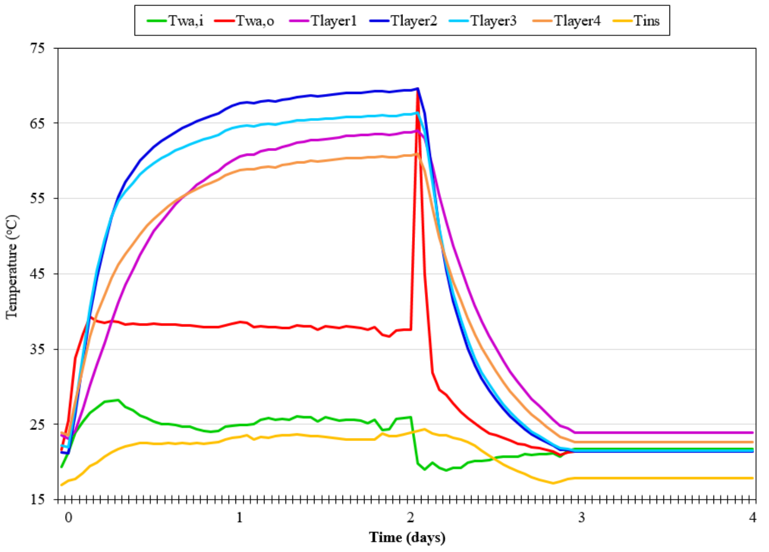

Figure. 12: Temperature vs. time results for gravel (GR) filled HGHEs with an output flowrate of 0.4 L/min

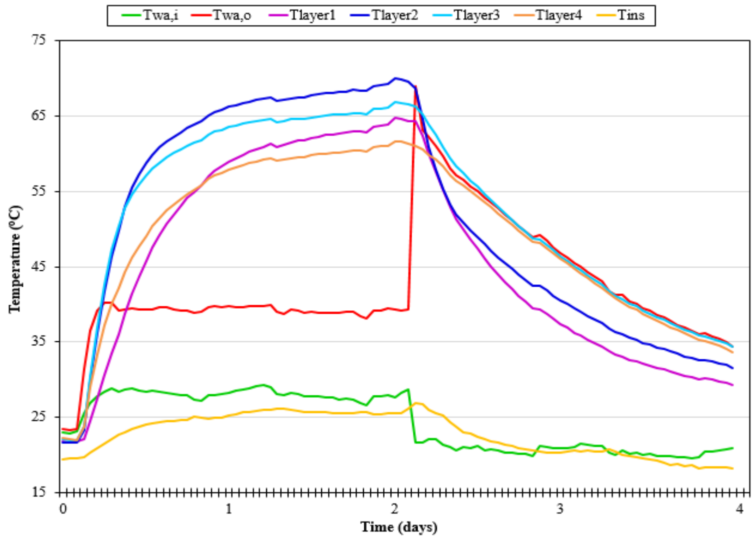

Figure. 13: Temperature vs. time results for sand (LB) filled HGHEs with an output flowrate of 0.1 L/min

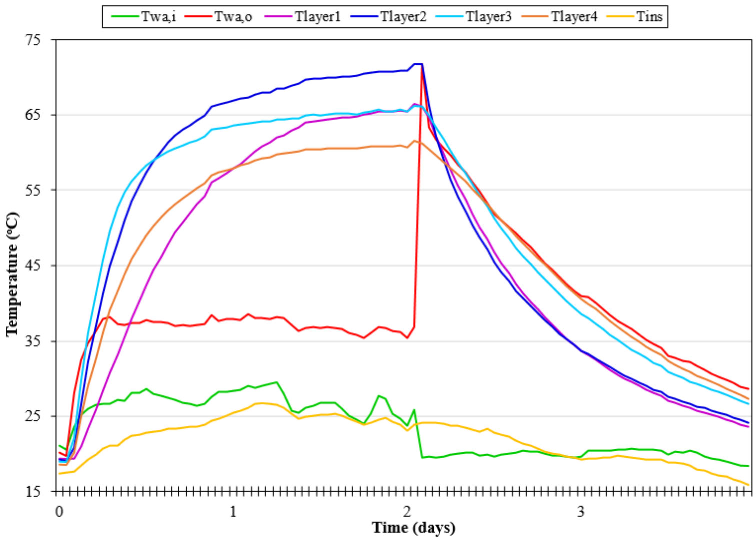

Figure. 14: Temperature vs. time results for gravel (GR) filled HGHEs with an output flowrate of 0.1 L/min

5.2.1 Discharging sand filled HGHEs (LB-HGHEs)

As illustrated in Figure's 11, 13 and Table 5, the HTF entered the LB-HGHE at temperatures ranging between 18-21℃ ($T_{wa,i}$) for all tested flowrates. The maximum HTF output temperature ($T_{wa,o}$) extracted from the system was 70℃ and the total hot water (T>35℃) extracted using a 0.1L/min flowrate was found to be 258L over the course of 43 hours (see Figure 13 & Table 5). Results with a higher output flowrate of 0.6L/min showed the outlet temperature dropped from 70℃ to 35℃ within 3 hours, providing only 108L of extracted hot water (see Table 5). When comparing these results for a 0.1 and 0.6L/min output flowrates from the LB-HGHE, it can be concluded that as the output flowrate increases, there is a reduction in the quantity (decrease of 58%) and duration (decrease of 93%) of extracted hot water for a 0.5L/min flowrate difference. The reason for this is because at lower flower rates there is sufficient time for the heat exchange to occur between the surrounding LB soil to the HTF in the GHE allowing it remain hot for longer periods, conversely, at higher output flowrates, there is a lack of heat exchange between the soil, GHE and HTF and hence the system is cooled down more rapidly. LB-HGHE output flowrate results for 0.2 and 0.4L/min from Table 5 confirm this result trend between 0.1 and 0.6L/min. In addition, Figures. 11, 13 shows that the output water temperature ($T_{wa,o}$) is directly correlated with the temperature of the LB soil layers ($T_{layer1} - T_{layer4}$) in the storage, and that as the heat is extracted from the HGHEs through the HTF, the soil's temperature reduces until all the heat has been extracted from the system (i.e soil media reaches equilibrium with HTF).

5.2.2 Discharging gravel filled HGHEs (GR-HGHEs)

The results from GR-HGHE shows a similar trend to that obtained with LB-HGHE, however the performance of GR-HGHE was overall poorer compared to LB-HGHE. Considering the lowest output flowrate of 0.1L/min in GR-HGHE, the HTF output temperature was roughly similar to that obtained for LB-HGHE at 71℃, but the total heated water (T>35℃) extracted from the GR-HGHEs was found to be 192L over 32 hours (see Figure 14 & Table 5). This means that an additional 66L of hot water was extracted from the LB-HGHEs compared to GR-HGHE at a 0.1L/min flowrate (an increase of approximately ~26%). Results from GR-HGHE with a higher flowrate of 0.6L/min showed that only 54L of hot water was collected during 1.5 hours (see Table 5). Again a similar trend to LB-HGHE was observed for GR-HGHE, whereby when increasing the flowrate from 0.1 and 0.6L/min, the hot water quantity decreased by 72% and the duration by 95%. Results for GR-HGHE with a 0.2 and 0.4L/min output flowrate (see Table 5) further confirm the result trend between 0.1 and 0.6L/min.

Finally, LB-HGHE produced approximately 50% more hot water during a longer duration (50% increase) compared to GR-HGHE. This difference in result is perhaps due to the arrangement of soil particles within the HGHE. A good heat HGHE media must be able to exchange heat to and from the HTF in the copper pipe. LB sand particles are between 0.425 to 1.18mm in size and are rounded in shape, with a density of 1562kg/m^3 (see Table 1). The gradation of the sand means the particles can pack closely together and create a better particle contact surface with the GHE copper piping. Whereas, the GR gravel used in this study consisted of larger particles ranging between 2 and 10mm in size with an overall lower density of 1451kg/m^3 (see Table 1). Due to the larger size and angular nature of the GR particles compared to LB, it appears that the gravel particles did not pack closely together, creating poor and insufficient contact between adjacent particles and the GHE pipe, subsequently reducing the heat transfer occurring. This can explain why less hot water was extracted from GR-HGHEs.

A thermodynamic analysis of both LB-HGHE and GR-HGHE system's was conducted. The total heat stored (Q_{in}) in the HGHEs was calculated to be 41472kJ using material properties specified in Table 1 and 2. The total heat extracted (Q_{out}) from LB and GR-HGHEs was calculated using the quantity of heated water produced from the HGHEs, this was found to be between 0.21kW with a lower flowrate of 0.0016kg/s and 1.25kW with a higher flowrate of 0.01kg/s. The total heating load requirement of the room was calculated to be 1kW, which means that irrespective of soil media, the HGHEs operating at higher flowrates can produce enough hot water to heat the room comfortably. The efficiency of the LB-HGHE is currently operating at 78% compared to the GR-HGHE with a lower efficiency of 58%.

To show accuracy of the system developed in this study, the results were compared to that from comparable studies. A similar HGHE system developed by Kim et al. (2016) and filled with a typical Korean sand (Joomunjin) in a dry condition using sand had similar material properties to the LB sand used in this study, with respect to density, thermal conductivity and specific heat capacity. However, there are three variations in the system compared to this study , these are: (1) the volume of the system is 5m^3 (2) the system uses a spiral coil and (3) the average flow rate of the circulating water was 4-5.5 L/min. Kim et al. (2016) conducted thermal response tests (TRTs) on the HGHEs and found that the temperature of the circulating HTF (water) reached a near steady state after 20h from the beginning of the TRT. This is comparable with the result obtained in this study. Kim et al. (2016) also found that the heat exchange rates of coil-type GHE were 255.3W (or 14.45W/m) and 260.2W (or 10.64W/m) for the slinky-type. These heat exchange rates are similar to that obtained in this study for both the sand and gravel filled systems. A similar three dimensional numerical analysis study simulating the thermal behavior of a horizontal spiral-coil-loop heat exchanger was developed by Go et al. (2016) and showed that when inlet fluid velocity is fast, the heat efficiency decreases due to thermal interference among the pipe. This trend is also evident from the efficiencies obtained in this study with low and high flowrates.

The daily mean household hot water consumption in the UK is 122±18 litres/day and the mean heating time is 2.60±0.35 hours/day (Energy Saving Trust 2008). Although the HGHEs produced in this study was designed on a small scale for experimental purposes only, the hot water quantity, temperature range and duration produced from the system were in line with LTDH guidelines and can be applied to some household heating applications. As discussed, the quantity of hot water produced from the system is distributed over a period of time (variable between hours and days depending on flowrate) and therefore, the system can be used for low required flowrates including underfloor heating applications purposes. In order to meet the standard temperatures for under-floor heating, the inlet temperature has to be 55℃ with a return flow of 45℃ were both satisfied by the results. Standard under-floor heating systems also require a heated water flowrate in the region of 1.55L/min (Antizar-Ladislao et al. 2010). Although the other factors were satisfied, due to the small size of the system, the maximum output flowrate of the HGHE was only 0.6L/min. The system produced in this study will also struggle with a high flowrate demanding operation; for example; running a hot bath, whereby instantaneous delivery of hot water within a short period of time is required.

6. Conclusions

This paper can be summarized in two parts. The first part of this paper presents a comparative study of heat transfer in seven soils to be utilized as sensible heat storage media's. In the second part, an experimental solar simulated HGHEs was installed and tested to investigate the thermal performance of the system using two soils as backfill material with four varying output flowrates. The HGHE was designed for low temperature and low flowrate working conditions. The results obtained from this study are useful to system designers in the selection of an appropriate material for HGHE requirements. The following conclusions and recommendations can be drawn from the results of this study:

1. LB sand and GR gravel soils showed the best heat storage performance properties, retaining heat for longer periods and cooling slower compared to other tested sands and clays (BS, WS, MM, LI, GA). Thermal-physical properties were found to be important parameters in the performance of these soils as heat storage materials.

2. An extensive experimental testing program was conducted on the HGHEs, which operated without problems as a daily heat storage unit. The results indicate that the system can be heated using electrical cables simulating excess electricity produced from PV. Thermocouples buried in the system show that both LB and GR filled systems charged over the course of 28 hours.

3. The stored heat can then be extracted from the HGHEs as hot water production for temperatures of 35-70℃, in line with LTDH standards to meet a test room heating load of 1kW. The present paper contains side by side performance comparisons using LB and GR soil materials as HGHE fill with four output flowrates (0.1, 0.2, 0.4 and 0.6L/min). The discharge time of the HGHE differed with respect to the flowrate and material fill. LB-HGHE

produced approximately 50% more hot water during a 50% longer duration compared to GR-HGHE. This difference is possibly due to the arrangement of soil particles within the HGHE. From a thermodynamic analysis, the efficiency of the HGHE system is 78% and 58% respectively for the LB-HGHE and GR-HGHE. The results obtained from the experimental HGHEs were in reasonable agreement to that from similar studies in literature. The system produced in this study can be applied to meet low temperature and low flow space heating requirements, for example, underfloor space heating applications.

4. The HGHE should be insulated well to avoid heat loss to the ambient surrounding temperature. The XEPS used to insulate the system in this study worked well to retain the heat within the system and needs to be further developed.

5. In a further study, more experimental data are collected using other storage materials. The performance of the HGHE system should be examined over the long term to optimize the storage parameters and improve the overall collection efficiency of the designed HGHEs. Recommendation includes adding a GSHP to the system.

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Disclosure statement

No potential conflict of interest was reported by the authors.

Abbreviations

GHEs	ground heat exchanger system
HGHE	horizontal ground heat exchanger
GSHP	ground source heat pump
MDF	modified density fibreboard
XEPS	extruded polystyrene foam
HTF	heat transfer fluid
PSD	particle size distribution
FB	from bottom of store (baseline)
GR	gravel
LB	leighton buzzard sand
WS	washed sand
BS	building sand
MM	mercia mudstone clay
GA	gault clay
LI	lias clay
LF	low mass flowrate
HF	high mass flowrate
EC	environmental chamber
UK	united kingdom

Nomenclature

ρ	density of material (kg/m^3)
ρ_p	particle density of soil ((kg/m^3)
ρ_b	bulk density of soil (kg/m^3)
C_p	specific heat capacity of material (J/kg K)
n	porosity of soil (%)
K	thermal conductivity of material (W/mK)
R_λ	thermal resistivity of material (m℃/W)
w_R	uncertainty
w_n	independent variables
T_{EC}	temperature inside environmental chamber (°C)
T_{Right}	right of the tin temperature reading (11.5cm from center of 10L tin) (°C)
T_{Middle}	middle of the tin temperature reading (center of 10L tin) (°C)
$T_{outside}$	building external temperature (°C)
T_{room}	ambient room temperature (°C)
$\emptyset_{ext}$	external copper pipe diameter (mm)
$\emptyset_{int}$	internal copper pipe diameter (mm)
P	power input to heating cable (W)
V	voltage input to heating cable (V)
I	ampere input to heating cable (A)
U	heat transfer coefficient (U value) of material (W/m^2°C)
N	number of air change per hour (air rate/hr)
V	internal volume of room (m^3)
E_{in}	the rate of net energy transfer into the HGHE (kW)
E_{out}	the rate of net energy extracted from the HGHE (kW)
Q_{thl}	total heating load requirement of room/total heat loss from room (kW)
Q_{req}	the energy required to raise the temperature of the soil mass in the HGHEs (kW)
Q_{in}	the actual energy inputted into the HGHEs (kJ or kW)
Q_{loss}	the steady rate of heat loss through the HGHEs (kJ or kW)
Q_{out}	the quantity of heat extracted from the HGHEs (kJ or kW)
η	efficiency of the HGHE system (%)
$\dot{G}$	the rate at which electrical energy is dissipated from the heating cable (W)
m_{soil}	mass of soil in HGHEs (kg)
$\dot{m}_{wa}$	mass flowrate of the HTF (water) (kg/s)
ΔT	temperature difference (°C)
Δt	required time (s)
A_{ins}	area of insulation through which heat is lost from the HGHEs (m^2)
L_{ins}	thickness of insulation through which heat is lost from the HGHEs (m)
$T_{wa,o}$	outlet average HTF temperature from HGHE (°C)
$T_{wa,i}$	inlet average HTF temperature from HGHE (°C)
Containers	average insulation temperature on the outside of soil layer in HGHEs (°C)
T_{layer1}	average soil temperature at top layer (layer 1) of HGHE (°C)
T_{layer2}	average soil temperature at top middle layer (layer 2) of HGHE (°C)
T_{layer3}	average soil temperature at bottom middle layer (layer 3) of HGHE (°C)
T_{layer4}	average soil temperature at bottom layer (layer 4) of HGHE (°C)

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