

**Low Energy Ground Cooling System for Buildings in
Hot and Humid Malaysia**

by

Aliyah Nur Zafirah Sanusi
B.Sc., B.Arch., M.Phil.

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ABSTRACT

This thesis presents an investigation into the viability of Low Energy Earth Pipe Cooling Technology in providing thermal comfort in Malaysia. The demand for air-conditioning in buildings in Malaysia affects the country escalating energy consumption. Therefore, this investigation was intended to seek for a passive cooling alternative to air-conditioning. By reducing the air-conditioning demand, there would be a higher chance of Malaysia government to achieve their aim in reducing CO₂ emissions to 40 per cent by the year 2020, compared to 2005 levels. The passive technology, where the ground was used as a heat sink to produce cooler air, has not been investigated systematically in hot and humid countries. In this work, air and soil temperatures were measured on a test site in Kuala Lumpur. At 1m underground, the result is most significant, where the soil temperature are 6°C and 9°C lower than the maximum ambient temperature during wet and dry season, respectively. Polyethylene pipes were buried around 0.5m, 1.0m and 1.5m underground and temperature drop between inlet and outlet were compared. A significant temperature drop was found in these pipes: up to 6.4°C and 6.9°C depending on the season of the year. The results have shown the potential of Earth Pipe in providing low energy cooling in Malaysia. A parametric study on the same experiment was carried out using Energy Plus programme. Energy Plus data agreed with the field work data and therefore, this confirms Energy Plus is reliable to investigate Earth Pipe Cooling in Malaysia. Furthermore, thermal comfort of air at the Earth Pipe outlet was analyzed and the result has shown that the outlet air is within the envelope of thermal comfort conditions for hot/humid countries.

*For my beloved husband Shazlan,
children, Aiman and Sarah
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PUBLISHED PAPERS

The following papers have been published in journal and conference proceedings as a result of this research:

Journal

Sanusi ANZ, Shao L, and Ibrahim N. *Passive Ground Cooling System for Low Energy Buildings in Malaysia (hot and humid climates)*, Renewable Energy (2012), doi:10.1016/j.renene.2012.01.033

Conference Proceeding

Sanusi A., Shao L., and Ibrahim N. *Passive Ground Cooling System for Low Energy Buildings in Malaysia (hot and humid climates)*. Proceedings of World Renewable Energy Congress XI, 25-30 September 2010, Abu Dhabi, United Arab Emirates.

Sanusi A., Shao L., and Ibrahim N. *Earth Pipe Cooling Investigations for Buildings in Hot and Humid Country Malaysia*. Proceedings of SET2009 – 8th International Conference on Sustainable Energy Technologies, 31st August to 3rd September, Aachen, Germany.

Sanusi A., Shao L., Ibrahim N. and Inangda N. *Malaysia Soil Temperature Showing the Potential of Low Energy Earth Tube Cooling Technology*. Proceedings of Renewable Energy 2008 Conference, 13-17 October 2008, Busan, Korea.

CHAPTER 1 INTRODUCTION

In 2004, a report has shown a vast increase in energy consumption in buildings in Malaysia (Chan, 2004). It demonstrated that the energy consumption in Malaysia in the year 2000 is almost tripled the amount of energy consumption in the year 1990 (Figure 1.1).

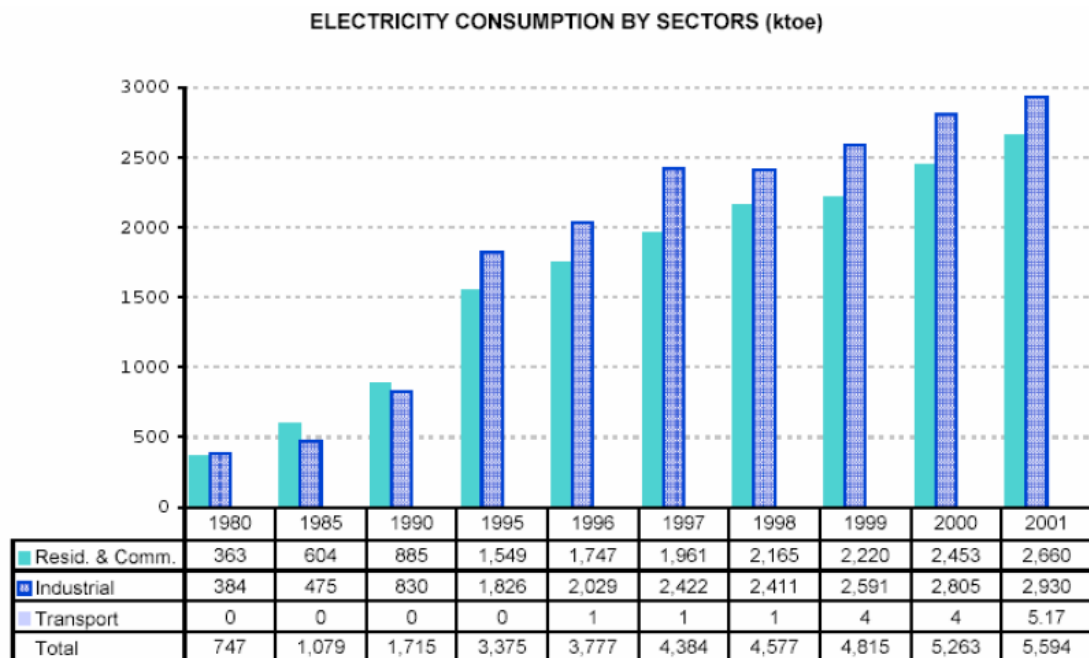


Figure 1.1: Trend of electricity consumption in three different sectors; residential, industrial and transportation from year 1980 to 2001. (Source: Department of Electricity and Gas Supply Malaysia in Chan, 2004).

The same report also stated that the Malaysia Energy Centre (PTM) have foreseen at the time of the report being made, based on the current economic growth rates, that Malaysia would transformed into a net importer of energy by between the year 2010 and 2015 (Figure 1.2)(Chan, 2004).

Ali (2010) presented a report stating Malaysia remained to be a net energy exporter in 2009 with 13.7% of export earnings, which derived from crude oil, liquefied natural gas (LNG) and petroleum products. Referring to the report in 2008, the final

energy demand came up to 44.9Mtoe while the final energy supply in 2008 was 75.5Mtoe. Although the country remains to be a net energy exporter, the energy demand is projected to grow at the rate of 3.4%p.a. According to this projection, the energy demand could reach 92.9Mtoe in 20 years, which is double the energy demand in 2008.

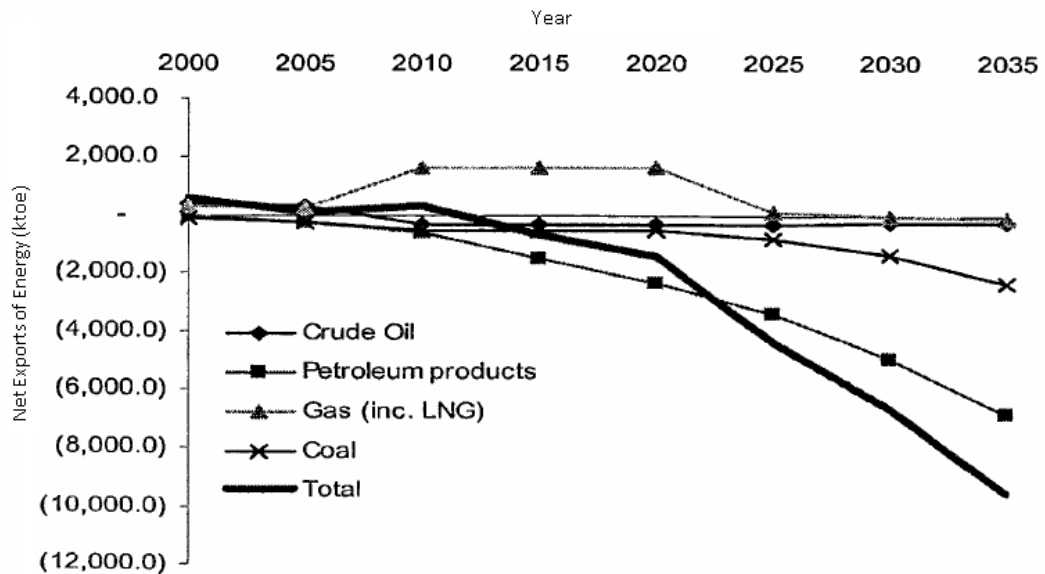


Figure 1.2: Trend of net export/import of energy from year 2000 and prediction up to year 2035 (Source: Chan, 2004).

One of the major factors that are affecting the energy use in buildings in Malaysia is air-conditioning. Being a warm and humid country, cooling of building is in great demand and the majority of building users in Malaysia are depending on air-conditioning to achieve comfort, particularly in non-residential buildings.

In 2003, an energy audit was conducted by Danida and ECO-Energy Systems on a 987m² single storey office building in Malaysia and the report stated that 64% of the energy consumed was for air-conditioning alone (Figure 1.3) (Chan, 2004). Another survey was conducted in a typical Malaysian terraced house of about 180m². The breakdown of energy use was found the refrigerator consumed the most and the air conditioning is the next most energy consuming (Figure 1.4). There is another study that shows refrigerator consumes the most energy in residential sector, followed by air conditioning (Figure 1.5) (Mohd Taha, 2003). The energy consumption of refrigerator is

acceptable because it is an essential home appliance to as food storage in hot and humid weather.

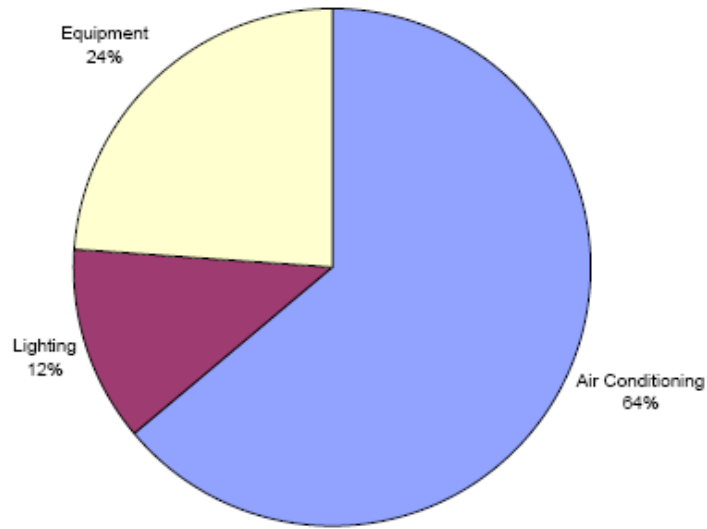


Figure 1.3: Breakdown chart of the energy load in an office building in Malaysia (Source: Chan, 2004).

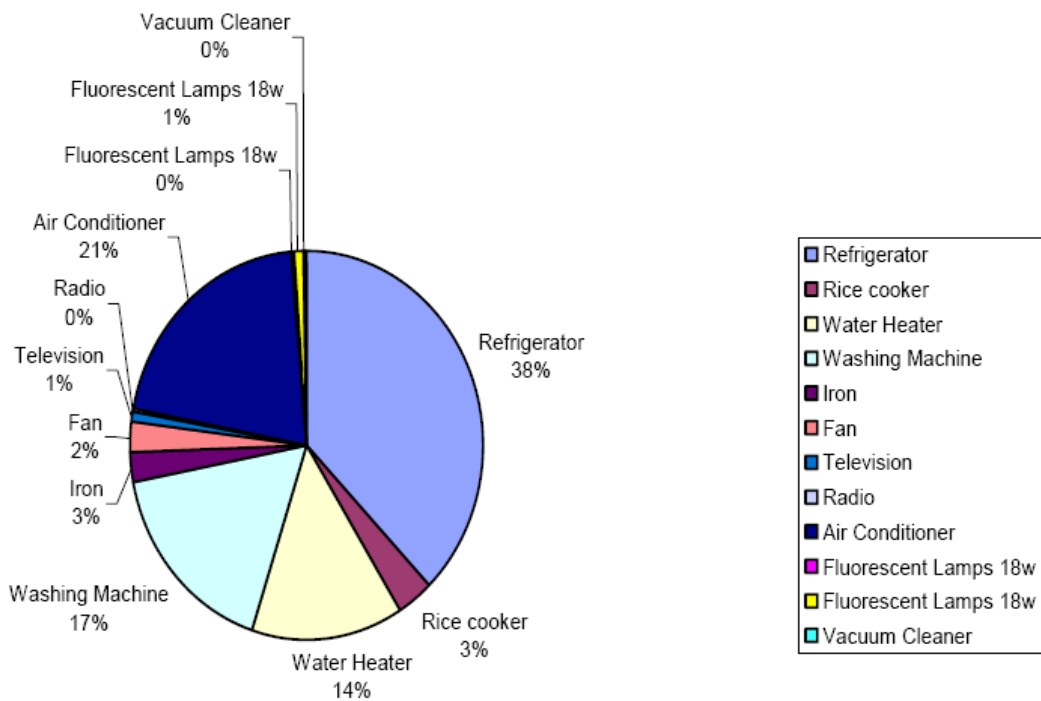


Figure 1.4: Breakdown chart of the energy load in a typical terraced house in Malaysia (Source: Chan, 2004).

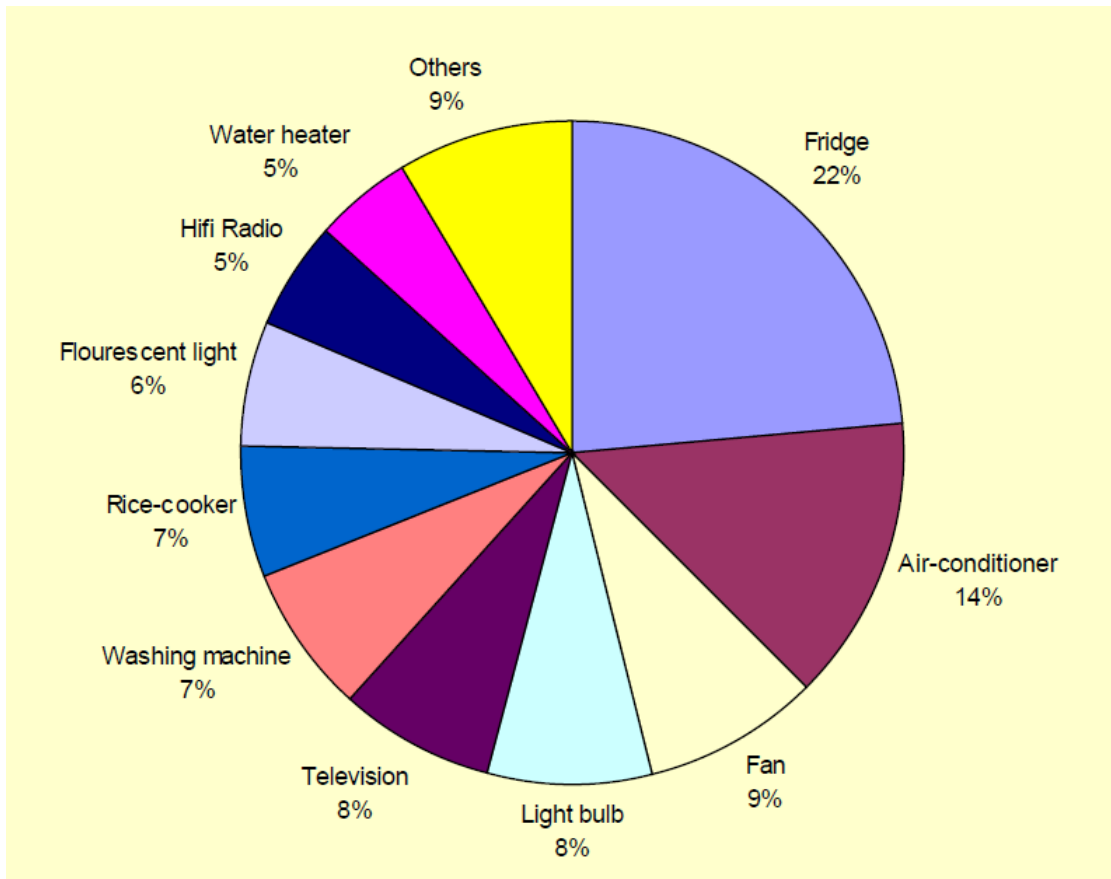


Figure 1.5: Breakdown chart of the energy load in residential sector in Malaysia (Source: Mohd Taha, 2003).

The high percentage of energy consumed by air conditioning in both building types show that there is a potential of significantly reducing energy consumption in the country by reducing the use of air-conditioning in buildings.

In 2009, at the United Nations Climate Change Conference in Copenhagen, Denmark, Malaysia Prime Minister stated the country's aim to reduce CO₂ emissions to 40 per cent by the year 2020, compared to the level in 2005 (Demotix, 2009).

Abdul Rahman and Ismail (2006) stated those in building industry such as architects and engineers and also building owners can play a role in improving the energy issue and reducing energy consumption in buildings. A building can be designed in such a way that it blocks as much as possible sun rays from penetrating into the building interior. The building must also allow as much air movement into the building because of Malaysia weather being warm and humid all year round.

Researchers in Malaysia have carried out investigations in reducing heat gain through the building fabric in Malaysia. Among them are planting creepers onto the building fabric, roof spray mist, wall spray mist, and the fabric colour. Table 1.1 listed the effect of incorporating the innovative radiant heat gain reduction element onto the building fabric towards the thermal performance of the building.

Table 1.1: The effect of incorporating innovative heat gain reduction element onto the building fabric to the maximum indoor air and surface temperature, °C (Source: Abdul Rahman and Ismail, 2006. Location: Malaysia).

Reduce Radiant Heat Gain Element	Before, °C	After, °C	T Difference, °C
Creepers on walls (air temperature)	36.8	27.7	9.1
Roof spray mist (surface temperature)	44.26	33.86	10.40
Roof spray mist (air temperature)	36.30	32.71	3.59
Wall spray mist (air temperature)	35.0	32.0	3.0
White colour – brick (air temperature)	33.5	33.0	0.5

Referring to the first two experiments, which involved creepers and roof spray mist (surface temperature), the latter seem to have more temperature reduction. However, this does not mean the roof spray mist method gives better performance than the creepers. The temperature reduction at the roof spray mist surface before the experiment was very high, and that makes a higher temperature reduction compared to the experiment with creepers.

Differences in indoor air temperature were found between the 2nd and 3rd rows in Table 1.1. This was because the 2nd row recorded indoor surface temperature while the 3rd row recorded indoor air temperature.

The last experiment in Table 1.1 compared the effect of white colour to brick. Referring to Table 2.4 in Chapter 2, white paint has lower solar radiation absorptivity than bricks; white paint is 0.30 while bricks are 0.6 or 0.7 depending on its roughness. Therefore, white paint walls provide lower indoor air temperature (Table 1.1).

To encourage air movement into the indoor environment, this work seeks a better alternative to building cooling in Malaysia, responding to the promotion of using renewable energy and energy efficiently by the Energy Commission in Malaysia (Chan, 2004). Among many innovative low energy building cooling methods, this paper has chosen to investigate the viability of applying Earth Pipe Cooling technology in Malaysia climate. This technology is not very recognized in Malaysia but has been applied in hot arid and temperate countries.

1.1 Research Question

At the initial stage of research, four main research questions arise. The four research questions are as follows:

- a) How is the temperature distribution of Malaysia soil?
- b) How much temperature reduction can be found within the buried pipe?
- c) What is the optimum configuration for pipe burial in Earth Pipe Cooling experiment?
- d) Would the air at the buried pipe outlet provide adequate cooling?

1.2 Research Objective

The research is initiated to explore the feasibility of Earth Pipe Cooling Technology and what it can offer to reduce the hot temperature in Malaysia at daytime and reduces energy consumption at the same time.

The investigation is structured with four objectives in this study. The first objective is to obtain soil temperature data at test site in Kuala Lumpur for various depths. The second objective is to determine the optimum setup for buried pipe. This is followed by the third objective, which is to ascertain temperature reduction performances of buried pipe. The fourth objective is to conduct computer simulation of the soil pipe.

1.3 Research Limitation

As mentioned previously, there has been very few record of this technology being used in Malaysia and information on its performance in hot humid climates is also scarce. The earth pipe cooling technology consists of ambient air being channelled through pipes buried underground. It uses the soil as a heat sink, where heat from the ambient is dissipated to, through conduction via the buried pipe. Its efficiency is largely influenced by temperature difference between ambient and soil temperature and thermal conductivity, followed by air flow inside the pipe, pipe length and diameter. Previous investigations found the optimum depth to bury the pipe is rather great, at 4m underground in many cases in other parts of the world where Earth Pipe Cooling system are often applied. However, for Malaysia climate, this optimum depth to bury the Earth Pipe Cooling system needs to be investigated again.

Data of Malaysia soil temperature is available from the Malaysia Meteorology Department. However, these data is collected at a maximum depth of 1.2 meter below ground, which is not deep enough to get the conclusion on the optimum buried depth of Earth Pipe Cooling system. The initial challenge of commencing the Earth Pipe Cooling Investigation in Malaysia is that there is no reference on soil temperature data at depth lower than 1m underground. Therefore, a separate investigation was added to measure the soil temperature at the same site that was to be used for the Earth Pipe Cooling investigation in Malaysia.

1.4 Thesis Structure

The thesis structure comprises of eight chapters that includes this chapter, Introduction and seven following chapters (Figure 1.6). This section of this chapter briefly introduces the seven following chapters.

Literature Review chapter is divided into two chapters; Chapter 2 and Chapter 3. Chapter 2 explains in detail on background studies of Malaysia and thermal comfort in general and thermal comfort in tropical climate with reference to Malaysia. Chapter 2 begins with the description of Malaysia weather where data obtained from three Meteorology Departments were analysed. This followed by the study of Malaysia Vernacular Architecture, where buildings were designed mainly as the means of shelter

from the surrounding environment. The vernacular architecture responds to the weather condition of Malaysia, which is hot and humid with rainfall. However, the trend of vernacular architecture was taken over by metal and glass buildings in this modern era, where the aesthetic is the main consideration rather than environmental responsive. Even though there are a few buildings designed with low energy cooling system and the next section of Chapter 2 illustrates six case studies on buildings where low energy cooling method was implemented. Chapter 2 continues with the fundamental of thermal comfort which includes the process of thermal interaction between man and the environment, factors of thermal comfort and adaptive thermal comfort. This is followed by thermal comfort analysis in Malaysia and neighbouring countries with similar climate.

Chapter 3 explains the type of passive ground cooling followed by the fundamental of passive low energy Earth Pipe Cooling, which includes the factors that affect the efficiency of the applied Earth Pipe Cooling system, the methods in which the Earth Pipe Cooling has been applied and the limitations found in Earth Pipe Cooling performance. Next section in Chapter 3 explains the common research methods used by previous researchers for Earth Pipe Cooling investigation via field experiments and computer modelling. This is followed by the common research method used to calculate the energy performance of the Earth Pipe Cooling. Chapter 3 ends with a few case studies on hybrid design that incorporates Earth Pipe Cooling into the system.

After examining Malaysia background, thermal comfort and earth pipe cooling, a research methodology for earth pipe cooling investigation was formed in Chapter 4. Chapter 4 begins with description of field work site in Gombak, Malaysia. Gombak is neighbouring Kuala Lumpur. Then, the chapter describes field work on soil temperature measurement and followed by field work methodology on Earth Pipe Cooling experiment in Malaysia. The two field works mentioned were carried out simultaneously throughout the research period on the same site mentioned above. They were carried out in three stages; during the wet season, the hot and dry season and one whole year investigation on one selected buried pipe.

All results from field work experiments were collected, analysed and presented in Chapter 5. The first part of Chapter 5 illustrates results from soil temperature

measurement. Then, the chapter continues by illustrating the results from the Earth Pipe Cooling experiment on the field work site.

Research funding and time limited the Earth Pipe Cooling investigation from carrying out a parametric study. Therefore the parametric study was carried out in computer modelling, which is what Chapter 6 entails. The chapter begins with comparative study between two computer modelling software results against field work result in a few days. After one is chosen, which is the Energy Plus programme, the earth pipe cooling results were plotted against field work data in all months with valid field work data. Then, Chapter 6 illustrates parametric studies as an extended investigation of Earth Pipe Cooling in Malaysia.

The next chapter, Chapter 7 is a general discussion chapter on thermal comfort performance of the Earth Pipe Cooling in Malaysia, using Malaysia thermal comfort temperature range, Auliciems thermal comfort calculation and Khedari's thermal comfort chart. The chapter then discusses the energy efficiency of Earth Pipe Cooling in Malaysia.

All results obtained in each chapter are concluded in the final chapter, which is Chapter 8.

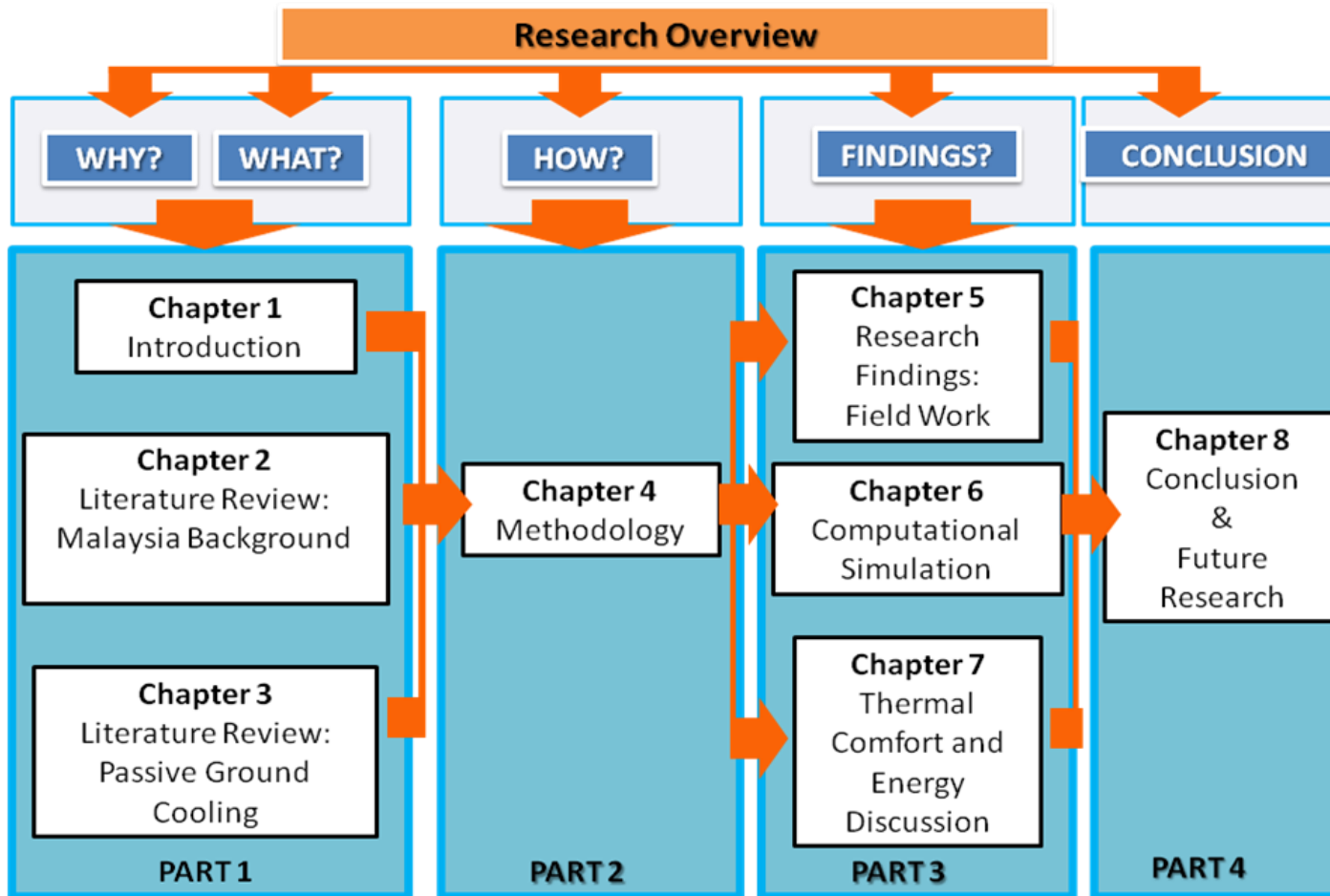


Figure 1.6: Structure of the Thesis.

CHAPTER 2 LITERATURE REVIEW: MALAYSIA BACKGROUND

This chapter is intended to help us improve our knowledge on a) Malaysia location, climate, architecture and cooling system, and b) thermal comfort in general and in hot and humid tropics. This chapter is an essential foundation prior to preparing the research methodology in order to achieve the research objective satisfactorily. This chapter consists of two main sections. The first section studies the background of Malaysia climate, architecture and currently available cooling methods. Further into the chapter, detailed thermal comfort study has been reported. The thermal comfort study covers topic on adaptive thermal comfort and thermal comfort range for occupants in warm and humid tropical countries.

2.1 Malaysia Background Studies

The location of Malaysia on the globe determines its climate and weather distribution throughout the year. Malaysia extends from latitude of 1° N to 7°N and from longitude of 100°E to 120°E (Figure 2.1). Being located close to the equator, and within the tropical region, it has a warm and humid climate, with high air temperature and high humidity level throughout the year. The only seasonal differences in Malaysia are caused by the southwest monsoon, northeast monsoon and the interval period between two monsoons. Southwest monsoon season occurs from the month of May until September. During the southwest monsoon period, the wind is usually at the maximum of 7.7m/s and blows in South Westerly direction. On the other hand, the northeast monsoon season occurs from November until March. During this period, the wind is slightly stronger than in the southwest monsoon season but blows in North Easterly direction. The North Easterly wind can reach up to a maximum of 10.3m/s (<http://www.worldweather.org/020/c00082.htm>).

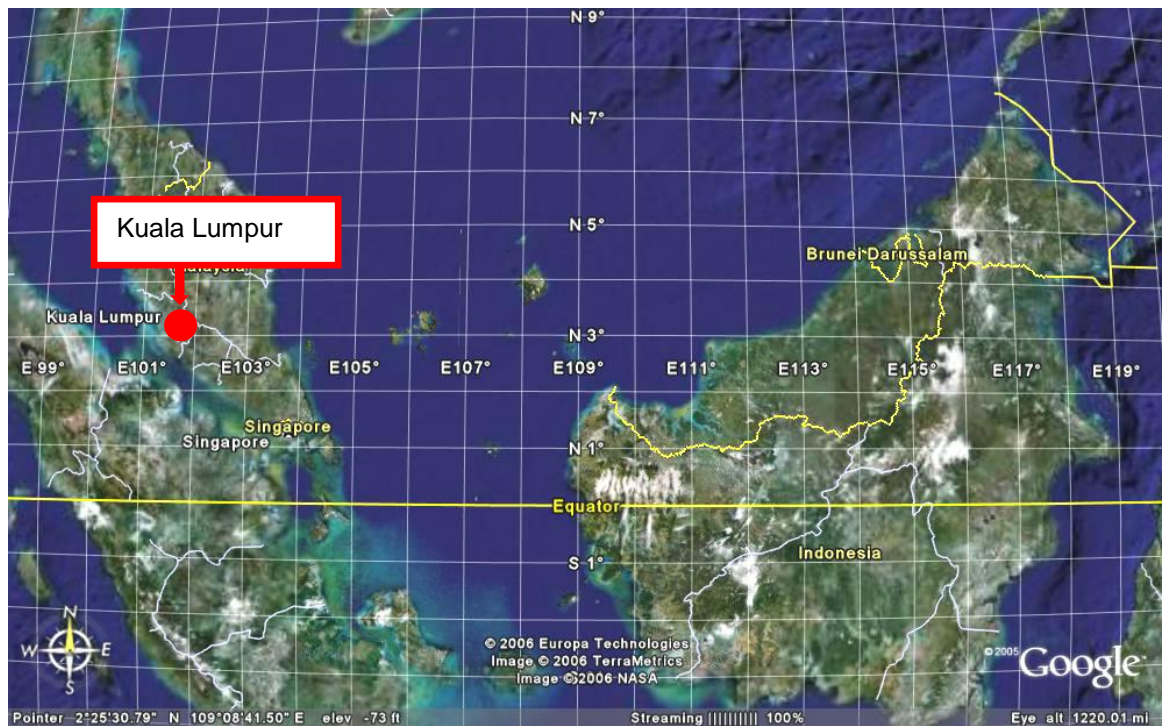


Figure 2.1: Location of Malaysia on the globe, showing its latitude and longitude. (Google Earth. Assessed on the 12th of May 2006).

Malaysia climate is normally considered in terms of five environmental factors: dry bulb temperature ($^{\circ}\text{C}$), relative humidity (%), amount of rainfall (mm), wind speed (m/s) and direction ($^{\circ}$), and solar radiation (MJ/m^2). This climate usually influenced architects to design buildings that were responsive to the local climate. However, when the shelter does not provide adequate comfort, various cooling methods had been applied into the building interior to satisfy the occupants' thermal comfort.

2.1.1 Climate

A study on Malaysia climate was supported by data obtained from local weather stations near Kuala Lumpur. Three weather stations were identified and the data obtained from the three weather stations are being compared with reference to its dry bulb temperature, relative humidity and precipitation. These data were recorded hourly at Sungai Besi, Subang Jaya and Petaling Jaya Weather Stations. Meanwhile, solar radiation data and sunshine hours were only available from Subang Jaya Weather Stations. The three weather stations are located on latitude $3^{\circ} 06' \text{ N}$ and longitude 101°

39' N. Subang Jaya weather station is at 16.5m above M.S.L (Mean Sea Level), while Petaling Jaya weather station is at 60.8m above M.S.L., which is at higher location than Subang Jaya weather station.

Weather data in 2004 were compared between Subang Jaya and Sungai Besi Weather stations, while weather data in 2006 were compared between Subang Jaya and Petaling Jaya weather stations.

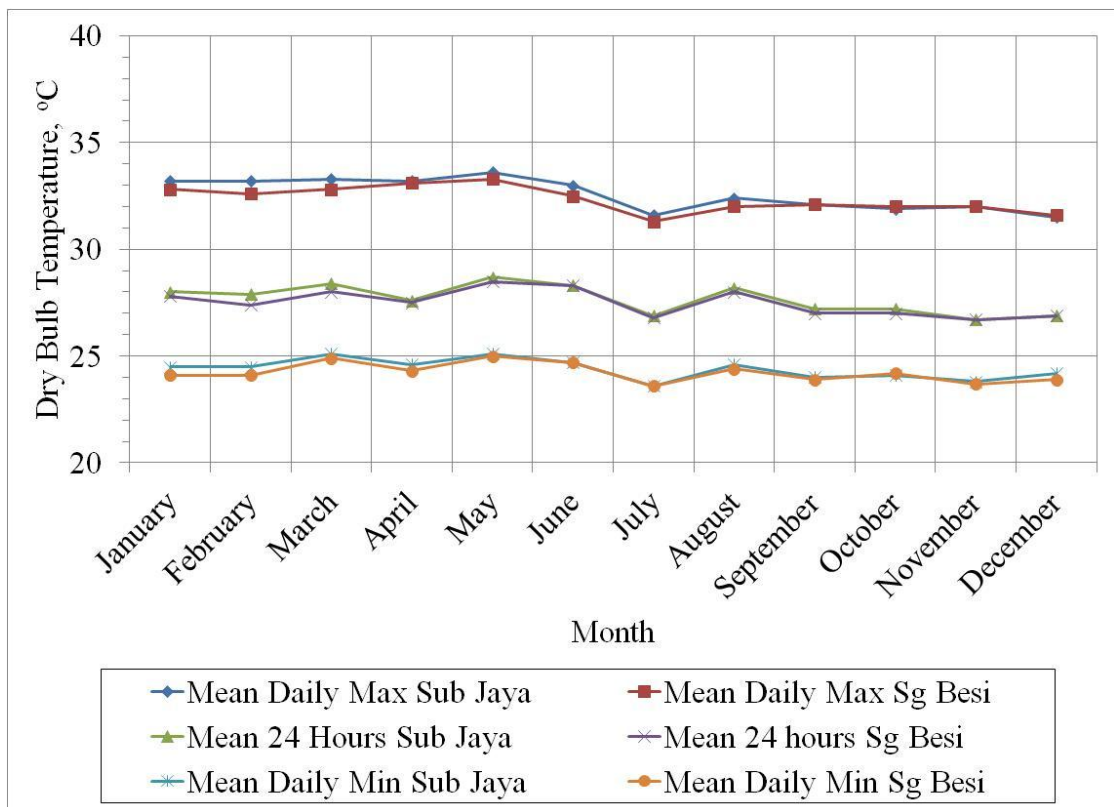


Figure 2.2: Summary of Dry Bulb Temperature in 2004 measured at Subang Jaya and Sungai Besi Weather Station (source: Malaysia Meteorology Department).

Sungai Besi weather station is 23.9km to the East from Subang Jaya weather station. However, referring to Figure 2.2, the dry bulb temperature averages are almost the same, with less than 0.4°C differences. The highest mean daily maximum temperature occurred in May in both weather stations.

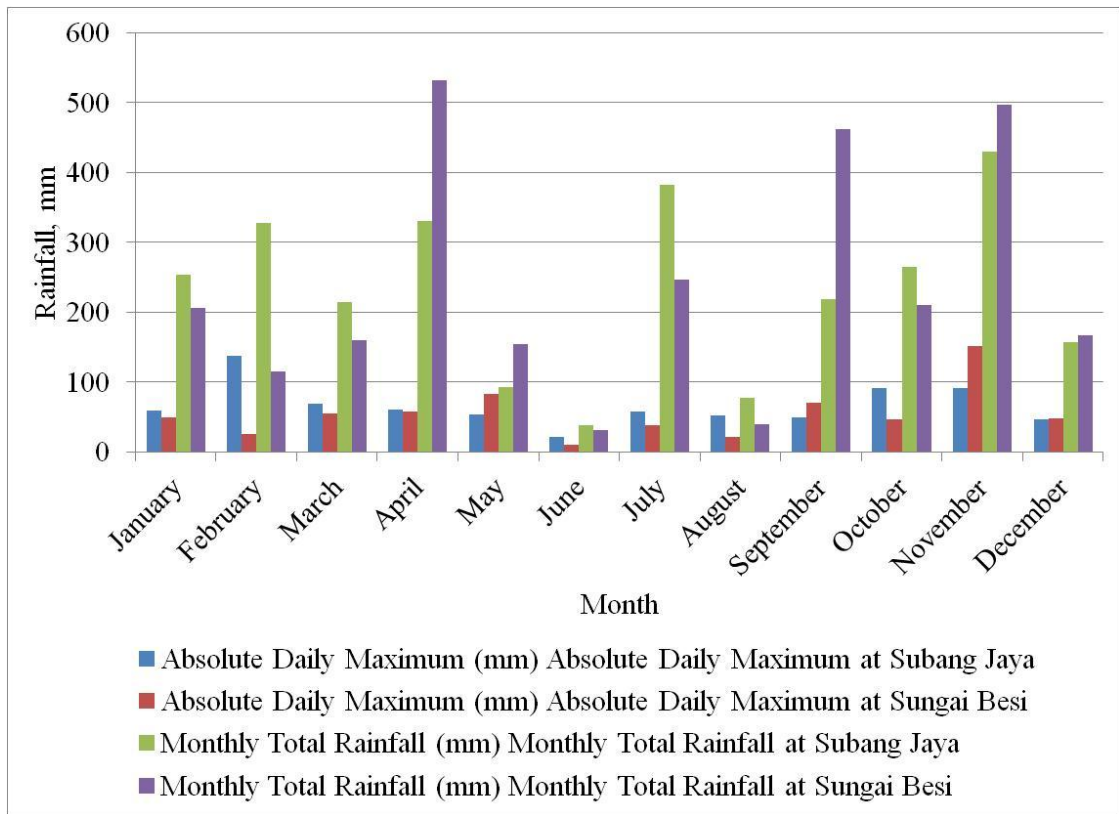


Figure 2.3: Summary of Rainfall in 2004 measured at Subang Jaya and Sungai Besi Weather Station (source: Malaysia Meteorology Department).

Looking at the absolute daily maximum rainfall, both weather stations seemed to have different total of rainfall in each month. However, the monthly total averages for both weather stations in 2004 are almost the same (Figure 2.3). Furthermore, the figure shows that November was the month with most total rainfall at both weather stations and June was the month with the least total rainfall.

Figure 2.4 shows that the average dry bulb temperatures from Subang Jaya and Petaling Jaya weather stations are almost the same and this is because Petaling Jaya weather station is 16.6km to the South East direction from Subang Jaya weather station. The differences in average temperatures are not more than 0.5°C.

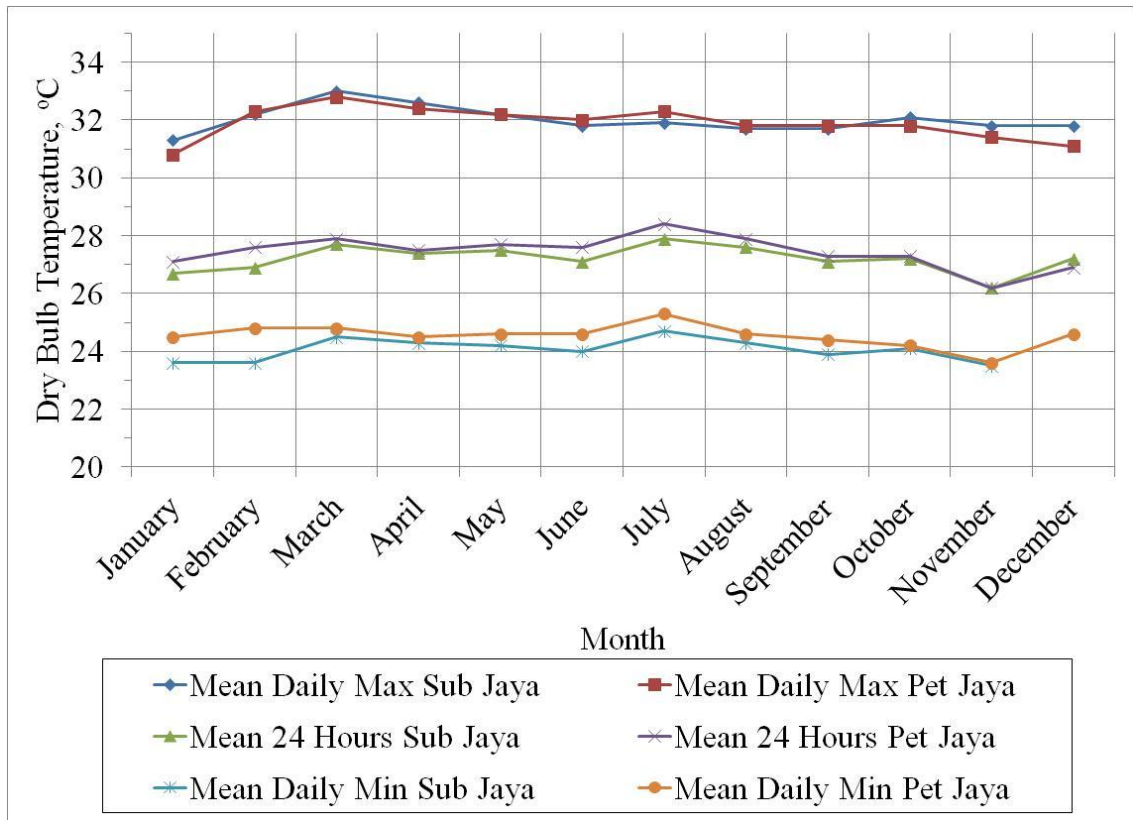


Figure 2.4: Summary of Dry Bulb Temperature in 2006 measured at Subang Jaya and Petaling Jaya Weather Station (source: Malaysia Meteorology Department).

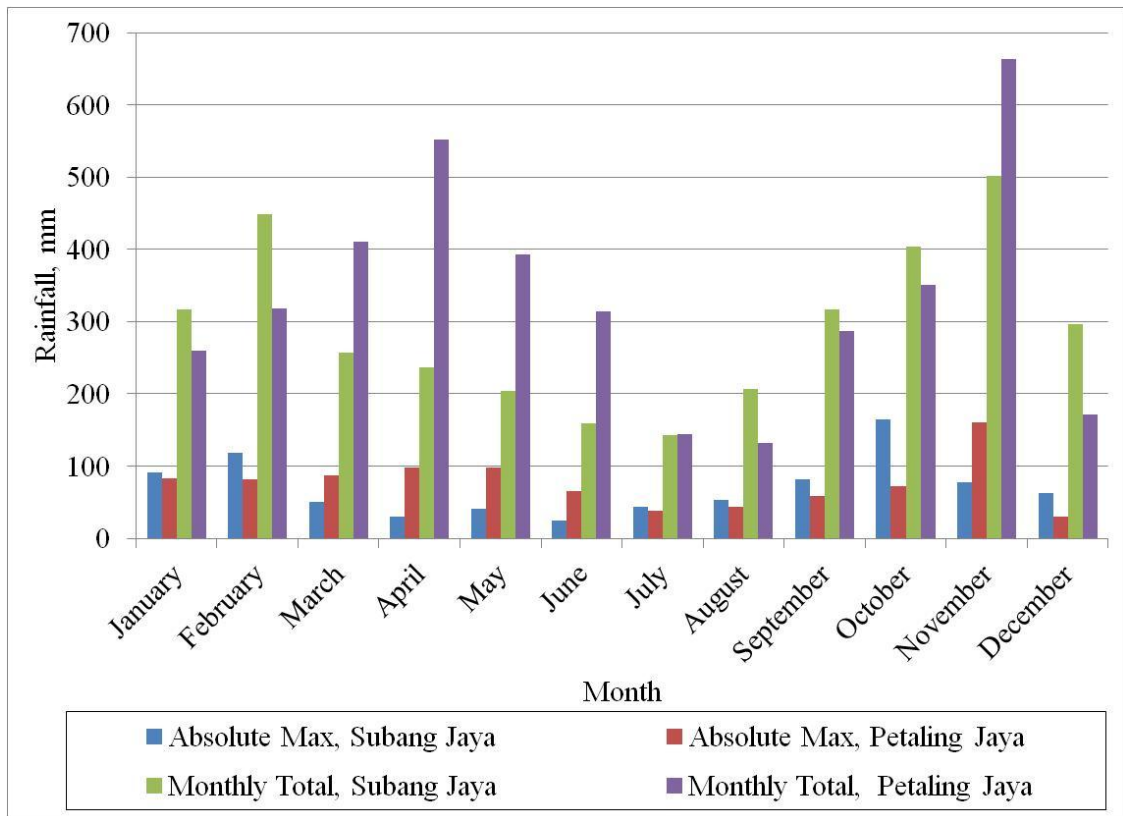


Figure 2.5: Summary of Rainfall in 2006 measured at Subang Jaya and Petaling Jaya Weather Station (source: Malaysia Meteorology Department).

Similar to weather data in 2004, Figure 2.5.2.5 shows that in 2006, the month with most rainfall is November in both Subang Jaya and Petaling Jaya weather stations. The weighting of absolute daily maximum rainfall at both weather stations does not coincide. However, the monthly total rainfall averages in the year are almost the same with approximately 13mm difference. All three weather stations have similar dry bulb temperature trends and monthly average total rainfall. Therefore, either weather station could be used to represent climate of Kuala Lumpur, which is the referred coordinate for this research.

a) *Dry Bulb Temperature*

The illustrated records of Kuala Lumpur air temperature has shown that the maximum dry bulb temperature can reach up to 36.4°C, which occurred in March 2005 (Figure 2.6). The figure is showing the summary of data collected from 2002 to 2008 by the Meteorology Department at Subang Jaya Weather Station.

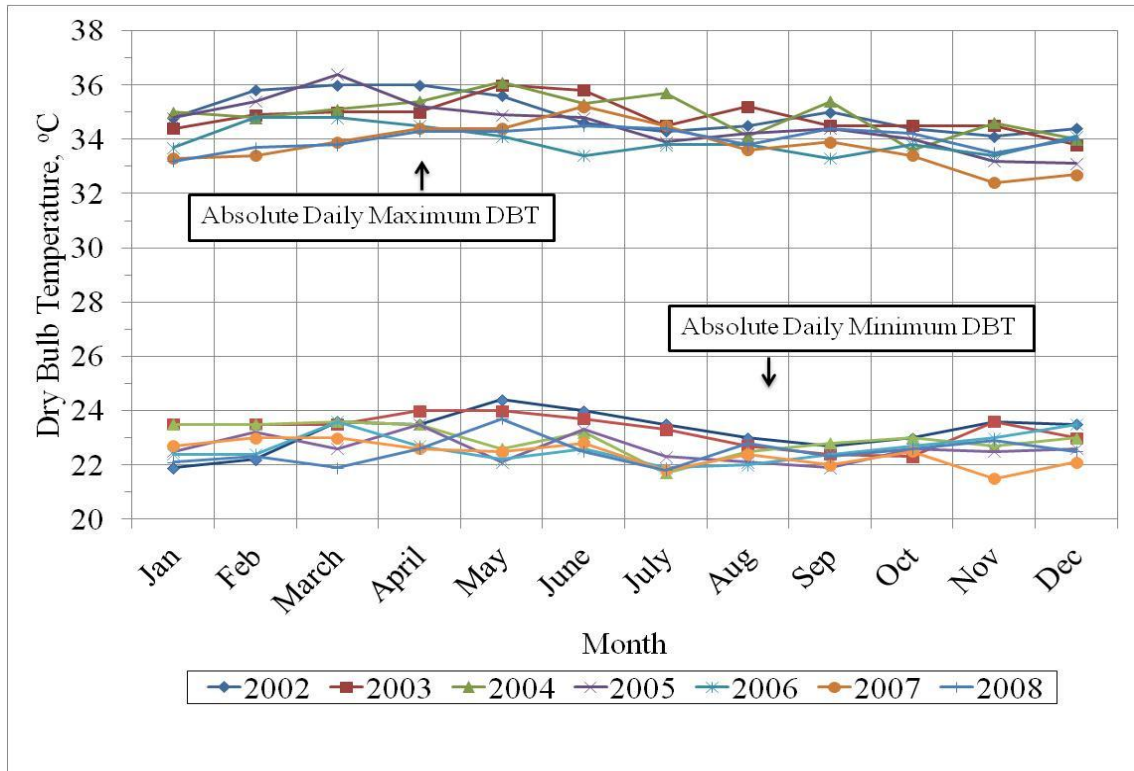


Figure 2.6: Absolute daily maximum and minimum Dry Bulb Temperature from 2002 to 2008 measured at Subang Jaya Weather Station (source: Malaysia Meteorology Department).

Throughout the year 2002 and 2008, the highest absolute and mean daily maximum dry bulb temperature occurred in March, April and May (Figure 2.6 and Figure 2.7). This period is at the end of northeast monsoon season and the beginning of southwest monsoon season.

The lowest absolute daily minimum dry bulb temperature, in six years record, occurred in July, August and September (Figure 2.6). However, the lowest average daily minimum dry bulb temperature occurred in November, which is the northeast monsoon season (Figure 2.7).

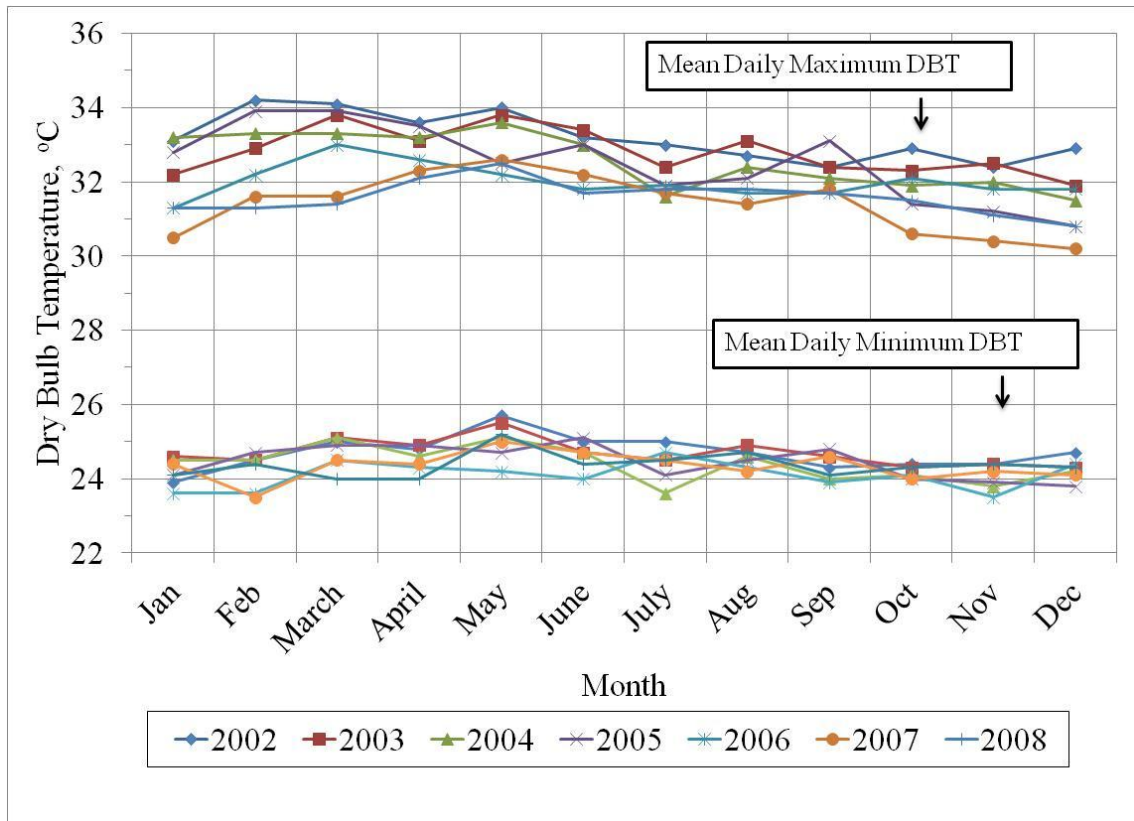


Figure 2.7: Mean daily maximum and minimum Dry Bulb Temperature from 2002 to 2008 measured at Subang Jaya Weather Station (source: Malaysia Meteorology Department).

A study has been carried out on data collected from six Meteorology Department throughout the peninsular of Malaysia from the year 1993 to 2002. The records had shown that the 24 hour mean air temperature ranges from 26.9°C to 28.2°C, where Kuala Lumpur ranking in the middle (Abdullah, 2007). The mean daily maximum ranges from 33.8°C to 35.5°C and the mean daily minimum ranges from 22.0°C to 23.3°C (Abdullah, 2007). Therefore, the air temperature does not differ much more than 2°C in any locations throughout Malaysia.

Malaysia has a uniform sunrise and sunset time throughout the year. The sun rises after 0700 hours and sets around 1900 hours. This is shown later in Figure 2.20 where the solar radiation begins to increase after 0600 hours and reduces back to zero at 1900 hours. Furthermore the daylight hours are illustrated by a stereographic diagram in Figure 2.21.

On the hottest day in 2005, the warmest time in the day was between 1200 hours to 1500 hours. Meanwhile, the coolest time of the day is at 0600 hours, just before the sun rises (Figure 2.8). In Figure 2.8 the temperature range is 11.8°C. Data of 2002 to 2006, obtained from the weather station has shown that the maximum temperature range is 12.4°C. On this day, the maximum temperature was 34.6°C and the minimum was 22.2°C. Meanwhile, the minimum temperature range in the six years record is 2.9°C. On this day, the temperature ranges from 23.3°C to 26.2°C. The maximum temperature was low due to the continuous rainfall from 0800 to 1800 hours. The average daily temperature range in the six years record is 8.14°C.

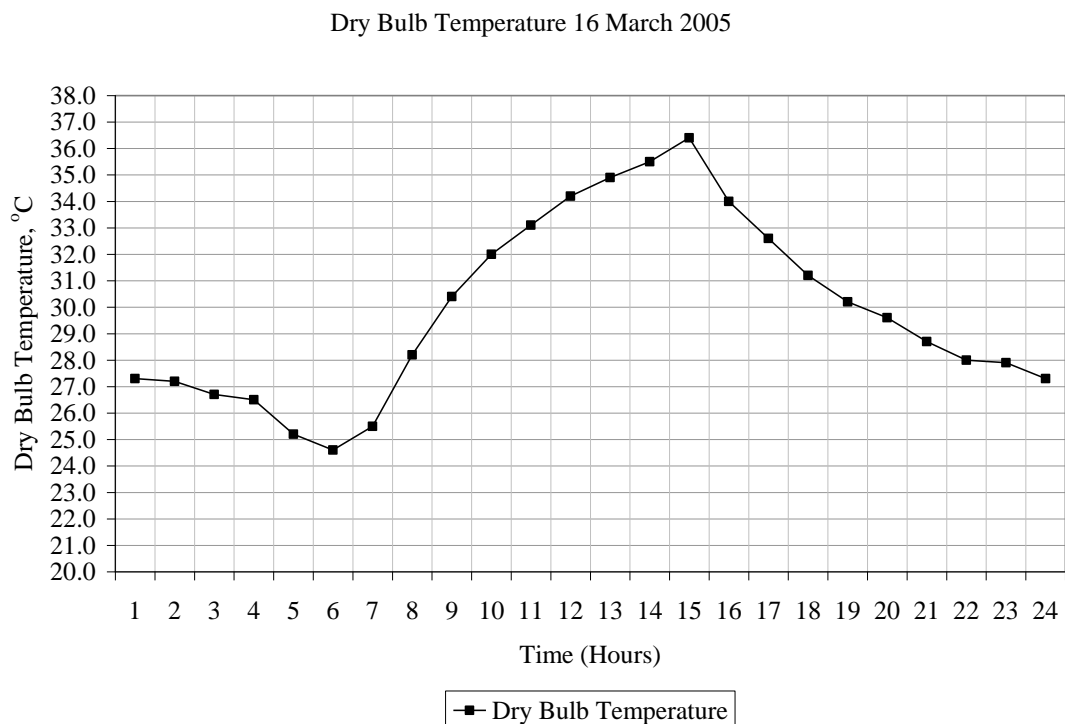


Figure 2.8: A sample of 24 hours dry bulb temperature distribution in March 2005 measured at Subang Jaya weather station (source: Malaysia Meteorology Department).

Referring to the daily average dry bulb temperature in Figure 2.9, the temperature is warmest in the month of May with the 24 hours average dry bulb temperature of 28.4°C. Meanwhile, the lowest 24 hours average dry bulb temperature is found in the month of November with temperature of 26.8°C.

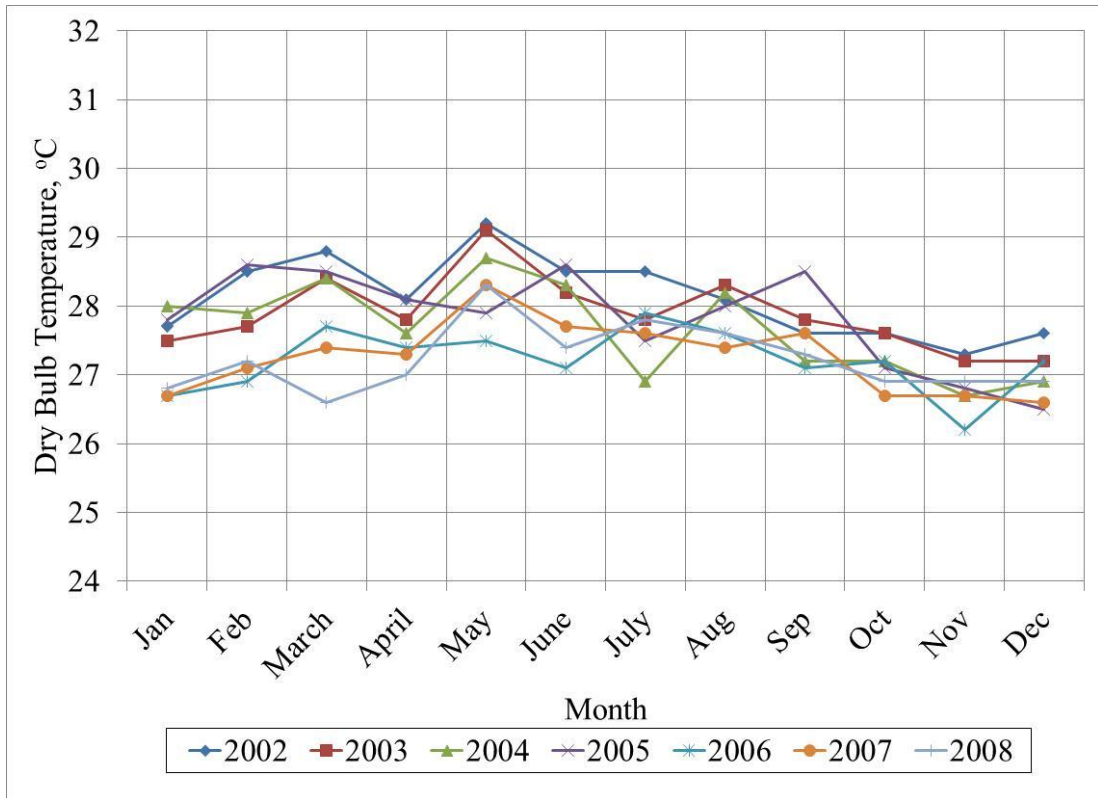


Figure 2.9: 24 hours average dry bulb temperature from 2002 to 2008 measured at Subang Jaya weather station (source: Malaysia Meteorology Department).

b) *Relative Humidity*

Besides dry bulb temperature, relative humidity is another climate factor that influence human thermal comfort. Malaysia is surrounded by sea and there is no part in Malaysia that is further than 80 miles distant from the coast (Abdullah, 2007) as seen in Figure 2.1. That makes it a humid country with high mean daily relative humidity. Records from 2002 to 2008 have shown that the 24 hours average relative humidity ranges from 76.2% to 82.2% (Figure 2.10). These average figures are rather high. The average is at its lowest in the month of February and highest is in the month of November.

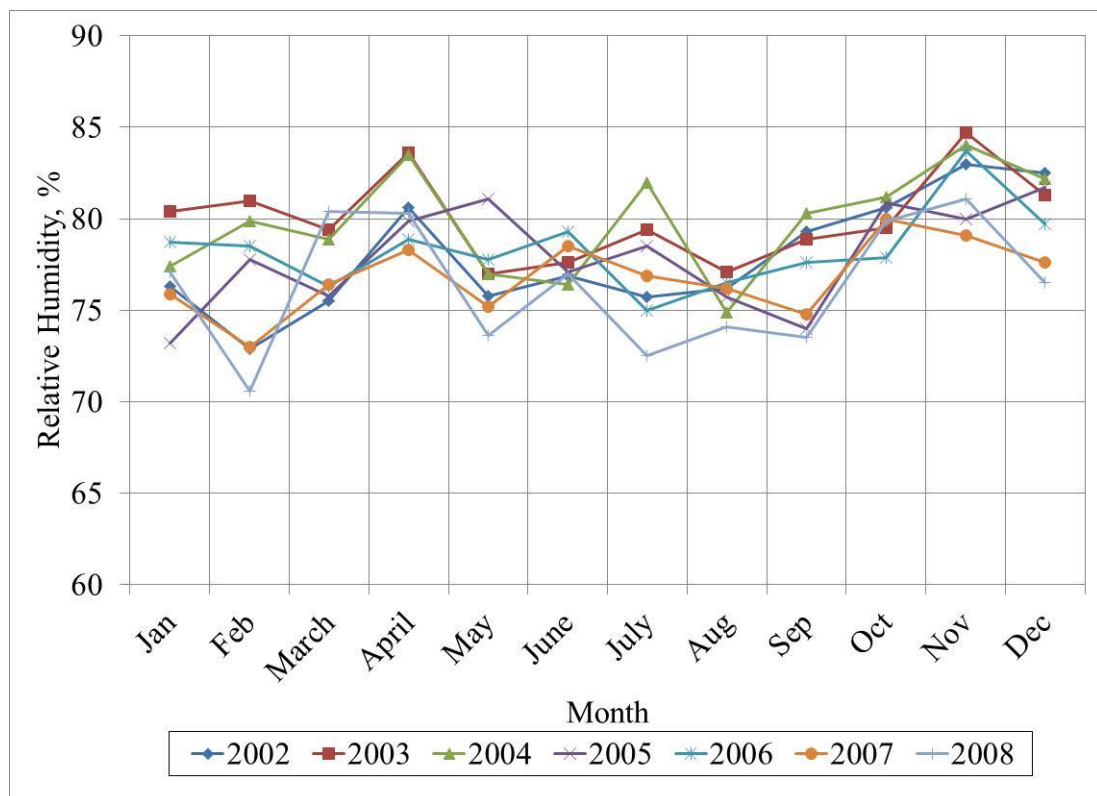


Figure 2.10: 24 hours average Relative Humidity from 2002 to 2008 measured at Subang Jaya weather station (source: Malaysia Meteorology Department).

The highest six years average absolute daily maximum relative humidity occurred in April with average absolute maximum relative humidity of 98.4% (Figure 2.11). Concurrently, the absolute daily minimum relative humidity is 26.0%, which occurred in February 2008 (Figure 2.11).

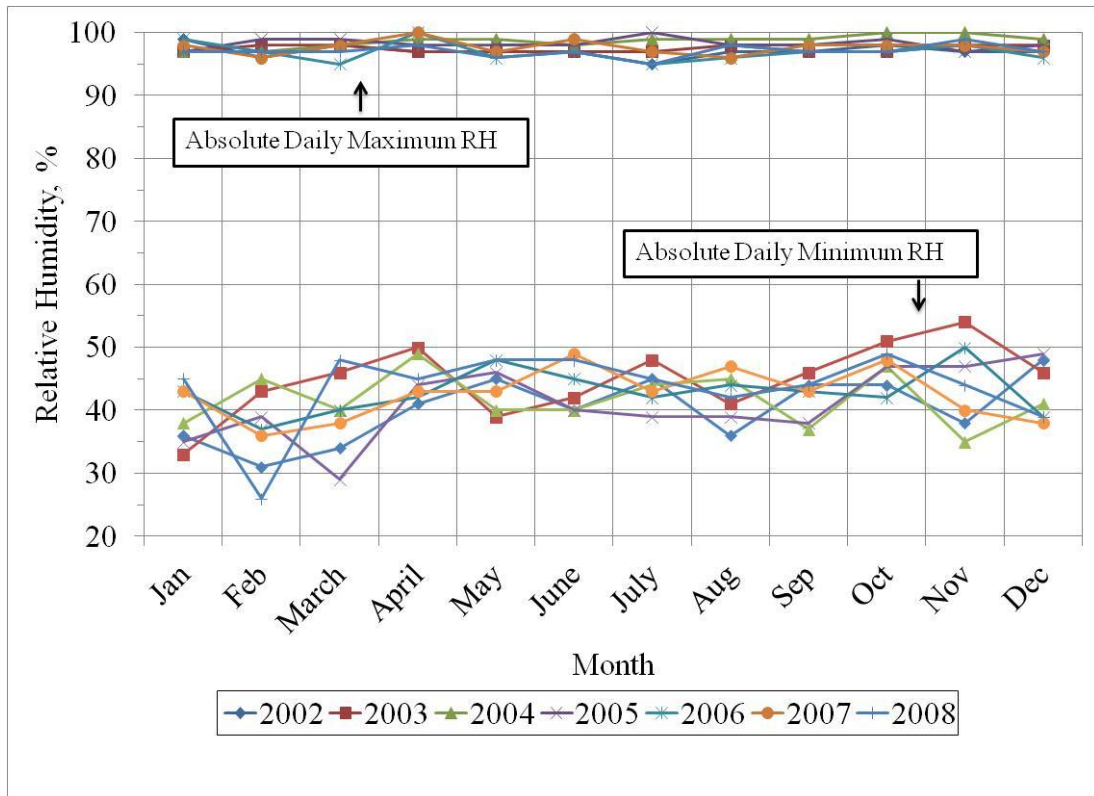


Figure 2.11: Absolute daily maximum and minimum Relative Humidity from 2002 to 2008 measured at Subang Jaya weather station (source: Malaysia Meteorology Department).

Meanwhile, the highest average daily maximum relative humidity is 94.7%, which is in November (Figure 2.12). However, the lowest average daily minimum relative humidity is 52.3%, which is the average of February (Figure 2.12).

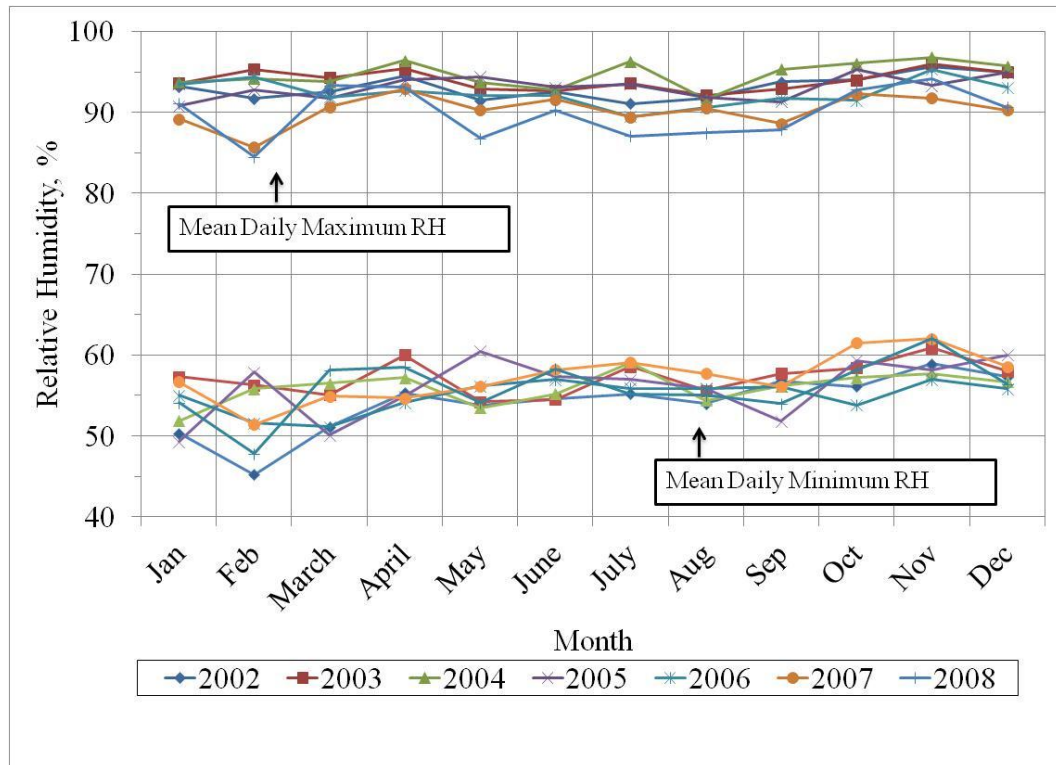


Figure 2.12: Mean daily maximum and minimum Relative Humidity from 2002 to 2008 measured at Subang Jaya weather station (source: Malaysia Meteorology Department).

Figure 2.13 summarises the relative humidity distribution in 2004. From the graph, the daily relative humidity remains the same throughout the year, regardless of the southwest and northeast monsoon seasons. They only differ between day and night, where the relative humidity is higher at night (Figure 2.13). Being a tropical country, Malaysia has a high humidity level, hence the high maximum level in the graph above. In 2004, the maximum relative humidity measured at Subang Jaya weather station was 100%, which occurred a few times during night time and also daytime, in the month of October.

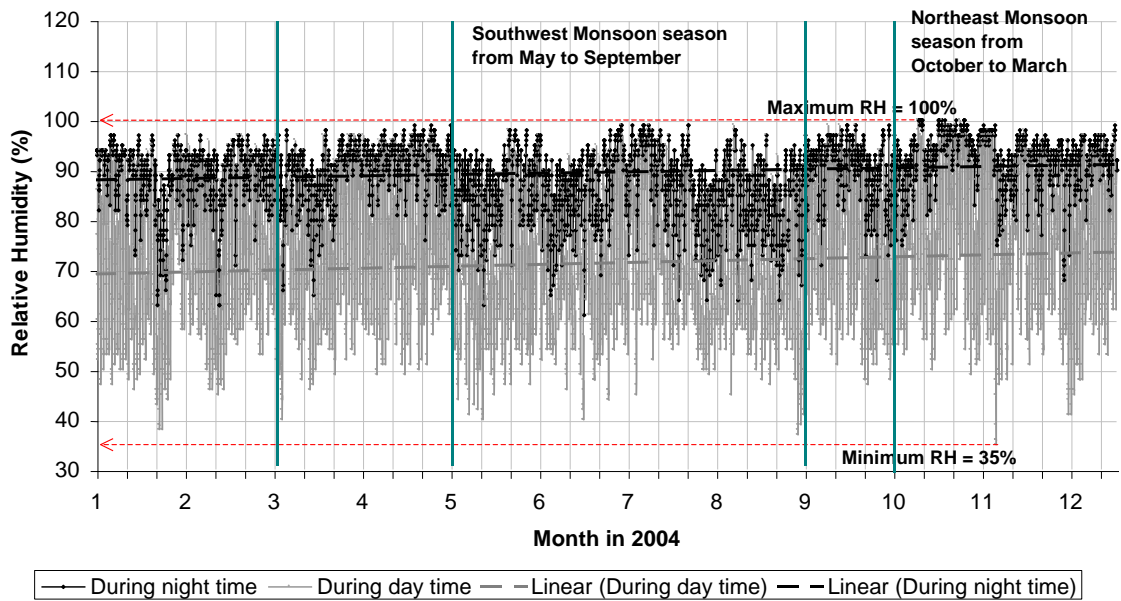


Figure 2.13: A sample of annual Relative Humidity distribution measured at Subang Jaya weather station (source: Malaysia Meteorology Department).

Referring to Figure 2.13, in November, the relative humidity level decreased to its minimum value of 35%. This is considered as a dry environment. However, throughout the year 2004, the relative humidity level is higher than 50% at most times. The two dotted lines on the graph in Figure 2.13 represent the average value for relative humidity during daytime and night time throughout the year 2004. During the night time, the average relative humidity ranged from 88% to 91%, and in the daytime, the average relative humidity ranged from 69% to 74%. Both average relative humidity during night time and daytime were quite high. Therefore, shelters in Malaysia should be able to reduce the humidity level to avoid feeling stuffy and discomfort.

c) Air Velocity

Recorded data from Subang Jaya Weather Station has shown that the air speed in its vicinity could reach an absolute maximum of 12.2m/s. That has happened in September 2003 (Figure 2.14).

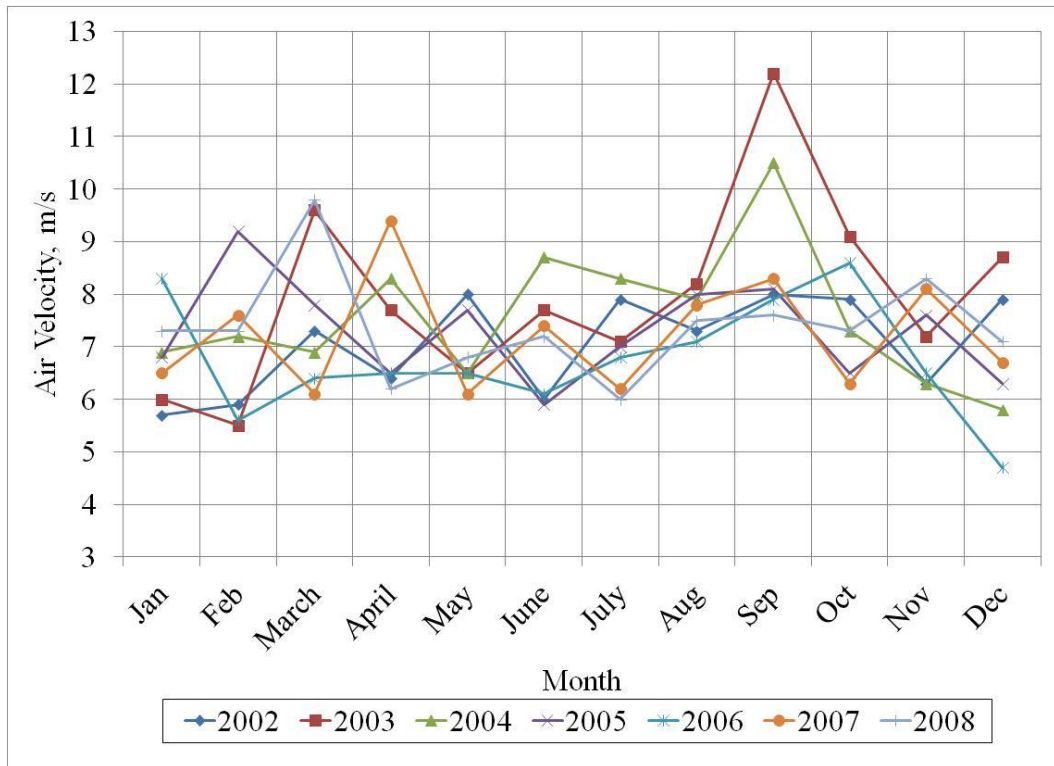


Figure 2.14: Absolute daily maximum air velocity from 2002 to 2008 measured at Subang Jaya weather station (source: Malaysia Meteorology Department).

However, the average daily maximum air speed is only up to 5.6m/s (Figure 2.15). Therefore, a high air speed only happens occasionally. The data was recorded at an airport at the height of 16.5m above M.S.L. (Mean Sea Level). That was the rationale behind a rather high air speed. In terms of the average 24 hours air velocity, it ranges from 1.4m/s to 1.8m/s (Figure 2.16). The average decreases due to calm conditions particularly at night.

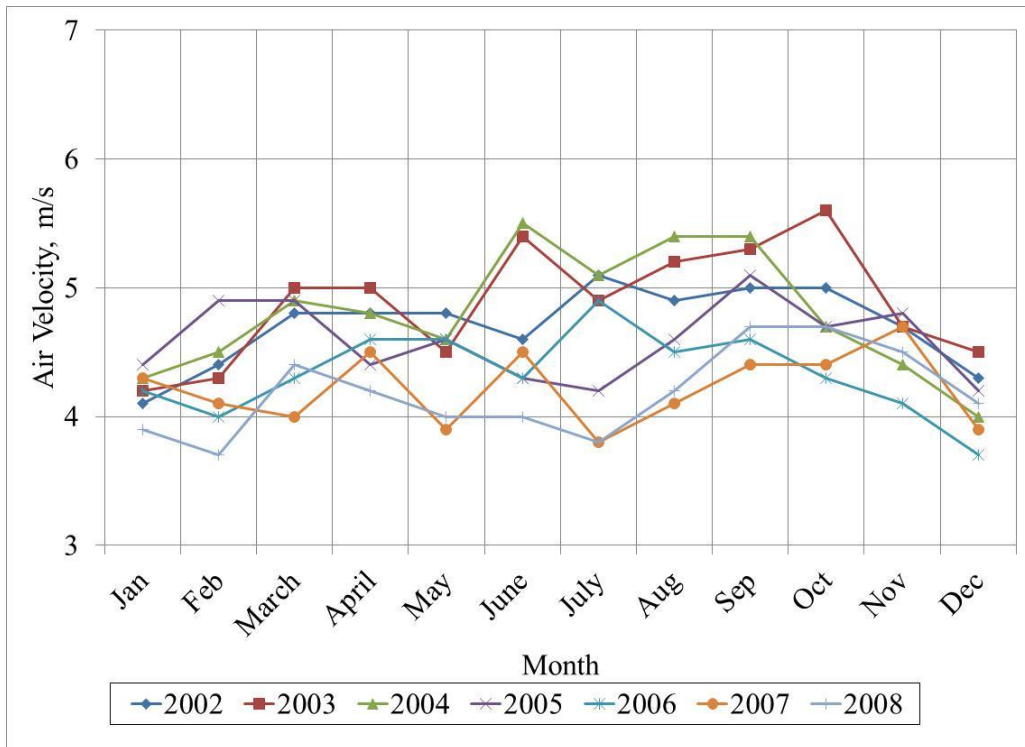


Figure 2.15: Mean daily maximum air velocity from 2002 to 2008 measured at Subang Jaya weather station (source: Malaysia Meteorology Department).

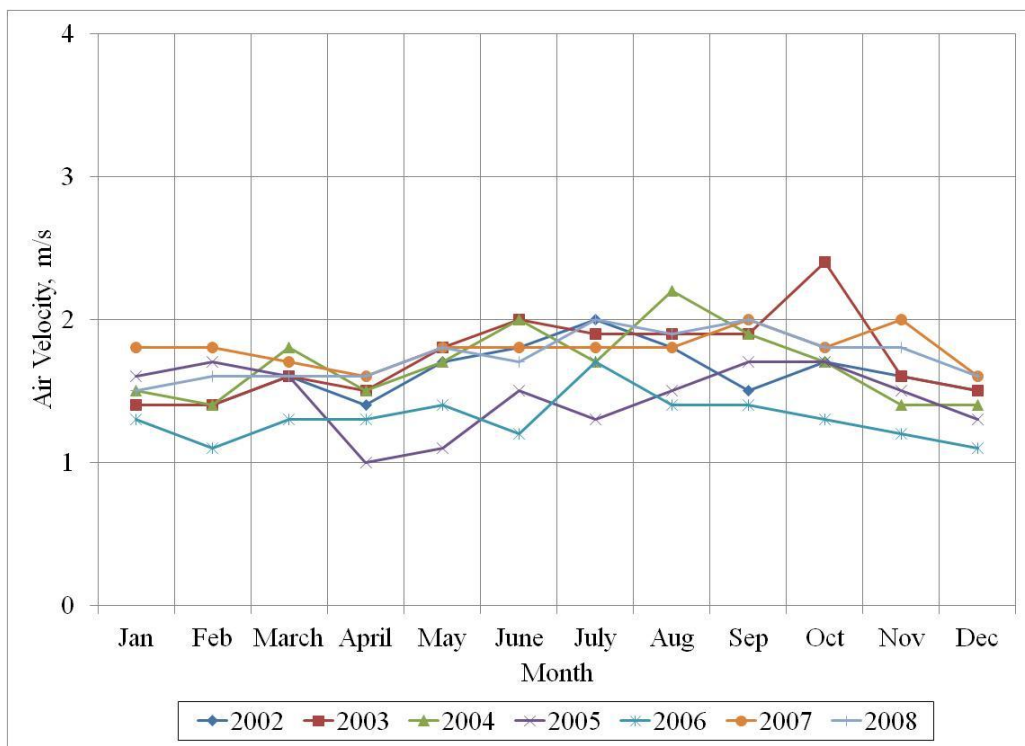


Figure 2.16: 24 hours average Air Velocity from 2002 to 2008 measured at Subang Jaya weather station (source: Malaysia Meteorology Department).

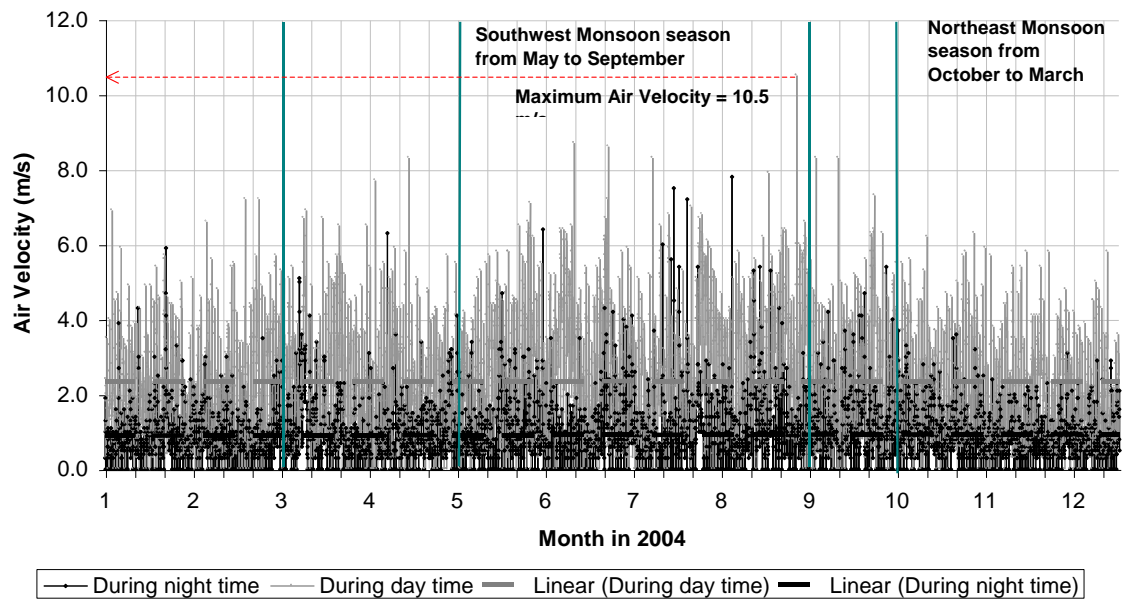


Figure 2.17: A sample of annual air velocity distribution measured at Subang Jaya weather station (source: Malaysia Meteorology Department).

Figure 2.17 shows an annual distribution of hourly air velocity, recorded from Subang Jaya weather station in 2004. The graph separates the data recorded in daytime and night time and it show a fluctuation of air velocity between 0 m/s to a maximum of 10.5 m/s. Although the maximum air velocity was fairly high, the average air velocity was not more than 3 m/s. Referring to the graph, the air velocity was slightly higher in daytime as compared to night time. At night time, the average air velocity was approximately 0.9m/s, whereas in daytime, the average air velocity was approximately 2.3m/s. The two black and grey dotted lines represent these averages (Figure 2.17). Figure 2.17 also shows that there were many occurrences of calm conditions, where the air velocity was 0m/s.

In order to achieve thermal comfort in a room, there should be sufficient air velocity to remove the excess heat gains from the room external fabric, its occupants and the appliances in the room. Thermal comfort can only be achieved when there is a balance between air temperature, humidity and air velocity.

d) *Precipitation*

Being a tropical country, Malaysia experiences rainfall constantly throughout the year but monthly total rainfall differs between seasons. The amount of rainfall was influenced by seasonal change in two different monsoons and two transitional periods between the two monsoon seasons. Figure 2.18 has shown that the southwest monsoon season, which is between May and September, is usually drier than other periods and May is looking to be the month with the least rainfall in most of the years. Meanwhile, November usually has the most total rainfall compared to other months and it is the first half of the Northeast monsoon season.

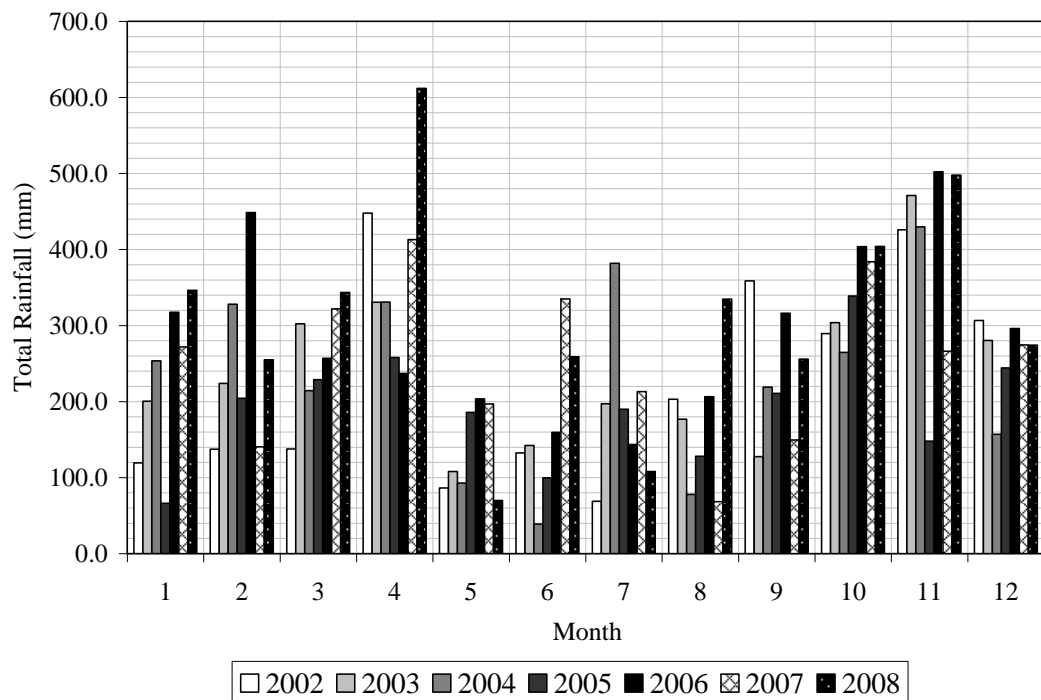


Figure 2.18: Monthly total rainfall from 2002 to 2008 measured at Subang Jaya weather station (source: Malaysia Meteorology Department).

e) *Solar Radiation*

Malaysia is a hot and humid country and therefore it has a relatively high solar radiation throughout the year. Records from Subang Jaya weather station has shown that the daily average over daylight hours of solar radiation from year 2002 to 2006 ranges from 321W/m^2 to 394W/m^2 (Figure 2.19). As the sun rises, the solar radiation increases until the maximum, which occurred mostly at 1200 hours. The solar radiation then gradually decreases until the sun sets (Figure 2.20).

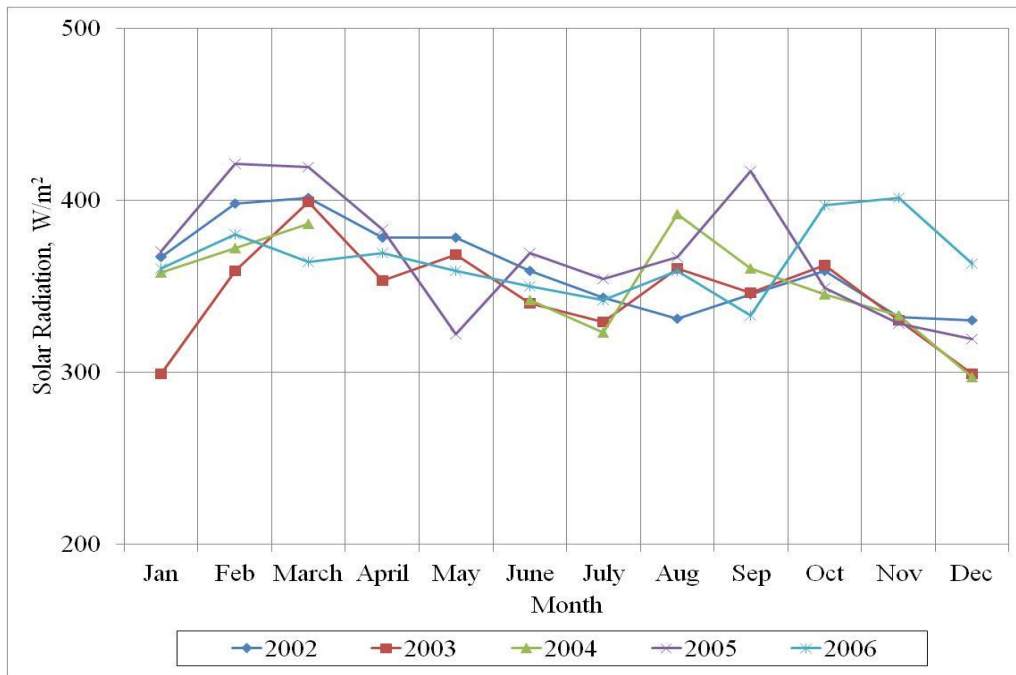


Figure 2.19: Daily daytime average Solar Radiation from 2002 to 2008 measured at Subang Jaya weather station (source: Malaysia Meteorology Department).

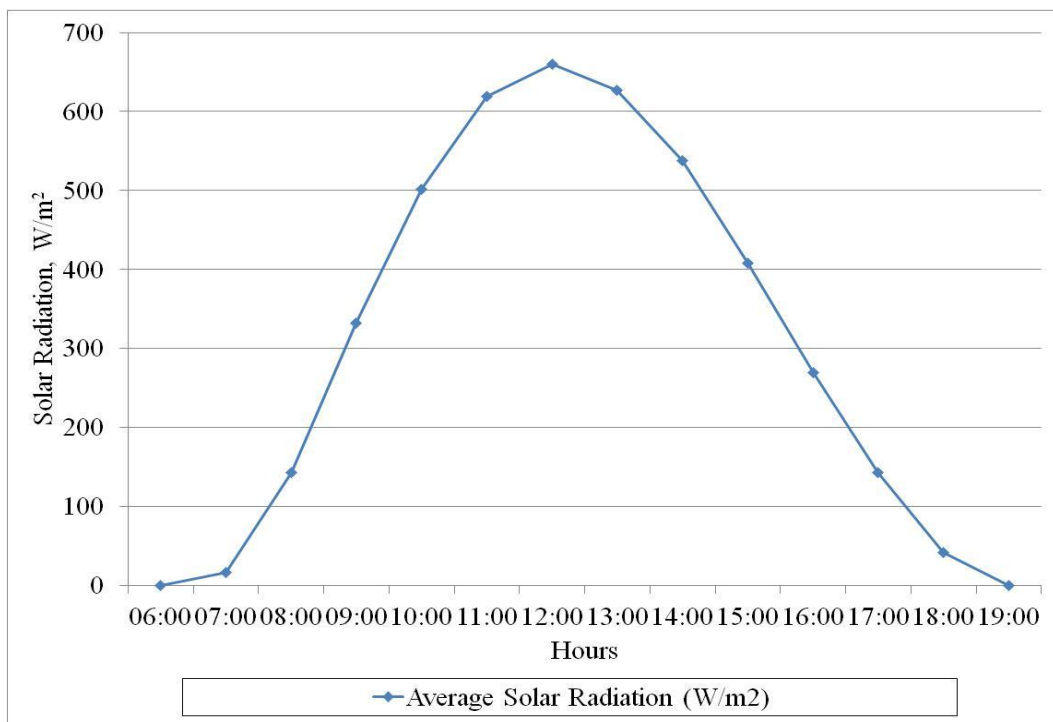


Figure 2.20: Hourly average Solar Radiation from 2002 to 2006 measured at Subang Jaya weather station (source: Malaysia Meteorology Department).

As mentioned earlier, this study has referred to Subang Jaya Weather Station, which is located near Kuala Lumpur at longitude E101.7° and latitude 3.1°N from the equator. Stereographic diagrams that show the sun movement for Kuala Lumpur would be as the diagrams shown in Figure 2.21. A red dot on the diagram shows a sun position in May at approximately 1230 hours.

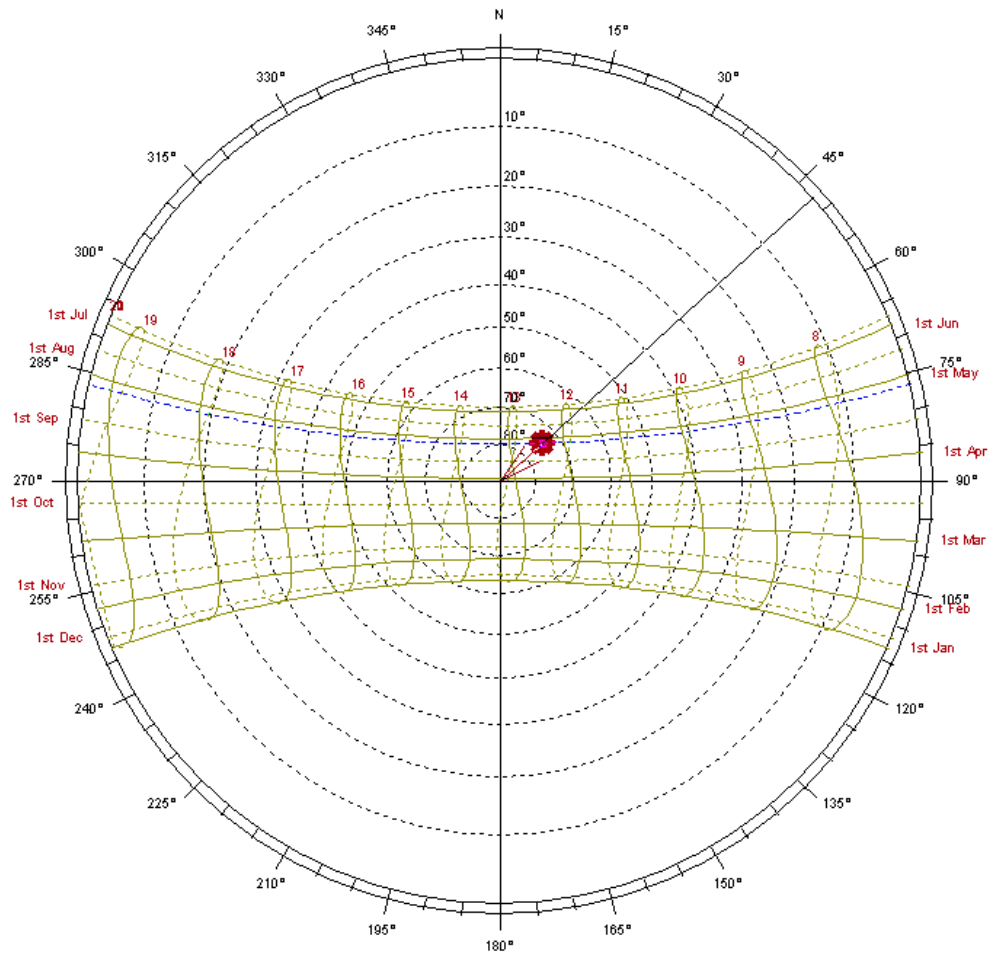


Figure 2.21: A stereographic diagram of Kuala Lumpur with a sun positioned shown was recorded in May at approximately 1230 hours that produce Horizontal Shadow Angle of 47.8° and Vertical Shadow Angle of 79.5° (Ecotect, 2005).

Figure 2.21 is a plan view of a sun path for Kuala Lumpur. In reference to the plan view (Figure 2.21), the lines that cross from east to west are the sun paths from sunrise to sunset within a day where there are series of curvy lines across the diagram, which represent the hours of the day. The diagram also shows a series of circles, which represent the solar altitude. The angle of each solar altitude circle is shown on a straight line that crosses from south to north. The angles on the perimeter of the diagram, from North in a clockwise direction, represent the solar azimuth, which is the sun angle.

These sun paths create the Horizontal Shadow Angle (HSA) and the Vertical Shadow Angle (VSA) upon a building. The curvy lines representing daylight hours on the diagram in Figure 2.21 demonstrates the statement stated earlier in the chapter that the sun rises after 0700 hours and sets around 1900 hours.

The sun apparent movement is governed by the Earth's inclination and the sun angles are determined by the time of the year. Within a year, the annual sun path is divided into four parts, which are bordered by the Vernal and Autumn Equinox Day, Summer Solstice Day and Winter Solstice Day. Vernal Equinox Day falls on the 21st of March, Autumn Equinox Day falls on the 23rd of September, Summer Solstice Day falls on the 22nd of June, and finally, the Winter Solstice Day falls on the 22nd of December (Figure 2.21). These dates differ in Vertical Shadow Angle (VSA) (Table 2.1) and Horizontal Shadow Angle (HSA) (Table 2.2).

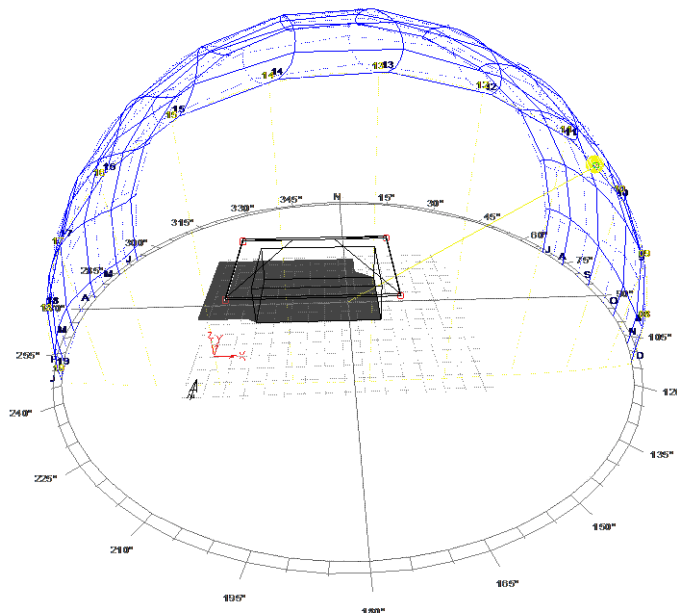


Figure 2.22: An example of a shelter where the Sun was projecting its East facing wall, on a Winter Solstice Day, 22nd of December (Ecotect, 2005).

The values in Table 2.1 and Table 2.2 were obtained from an Ecotect study of a simple building structure (Figure 2.22). The values of Vertical Shadow Angle and Horizontal Shadow Angle were projected onto a wall of a building, which was perpendicular to and faced East.

Table 2.1: Table of Vertical Shadow Angle towards an East-facing wall during the Equinox and Solstice days (Ecotect, 2005).

Date	21/03/04	22/06/04	23/09/04	22/12/04
	Vertical Shadow Angle (°)	Vertical Shadow Angle (°)	Vertical Shadow Angle (°)	Vertical Shadow Angle (°)
1:00	0.0	0.0	0.0	0.0
2:00	0.0	0.0	0.0	0.0
3:00	0.0	0.0	0.0	0.0
4:00	0.0	0.0	0.0	0.0
5:00	0.0	0.0	0.0	0.0
6:00	0.0	0.0	0.0	0.0
7:00	0.0	0.0	0.0	0.0
8:00	12.7	24.5	17.4	10.2
9:00	30.5	47.6	34.9	23.8
10:00	46.3	64.8	50.1	36.6
11:00	60.0	78.3	63.4	48.4
12:00	72.3	90.0	75.5	59.4
13:00	83.9	100.7	87.1	70.1
14:00	95.5	111.4	98.7	80.9
15:00	107.7	122.5	111.1	92.6
16:00	121.1	134.4	125.0	106.2
17:00	136.5	147.2	140.8	123.7
18:00	154.0	160.9	158.8	147.2
19:00	173.3	175.1	178.2	176.8
20:00	0.0	0.0	0.0	0.0
21:00	0.0	0.0	0.0	0.0
22:00	0.0	0.0	0.0	0.0
23:00	0.0	0.0	0.0	0.0
0:00	0.0	0.0	0.0	0.0

Table 2.2: Table of Horizontal Shadow Angle towards an East-facing wall during the Equinox and Solstice

Date	21/03/04	22/06/04	23/09/04	22/12/04
1.00				
2.00				
3.00				
4.00				
5.00				
6.00				
7.00				
8.00	0.8° South	23.3° North	0.5° South	24.5° South
9.00	1.7° South	24.5° North	1.5° South	27.2° South
10.00	2.9° South	27.9° North	2.7° South	32.4° South
11.00	4.8° South	34.9° North	4.7° South	41.4° South
12.00	9.1° South	49.9° North	9.7° South	57.7° South
13.00	33.3° South	80.2° North	64.3° South	84.1° South
14.00	161.4° South	117.2° North	168.2° South	113.3° South
15.00	172.8° South	139.0° North	174.8° South	133.4° South
16.00	175.9° South	149.2° North	177.0° South	144.7° South
17.00	177.5° South	154.1° North	178.3° South	151.1° South
18.00	178.6° South	156.3° North	179.3° South	154.7° South
19.00	179.5° South	156.7° North	179.9° North	156.4° South
20.00				
21.00				
22.00				
23.00				
24.00				

Figure 2.21 shows that, Malaysia is exposed to the East and West sun as well as the South and North sun, throughout the year. The South and North of a building face the sun during mid-day where solar radiation is at its highest. Therefore, building design should include shading the South as well as the North-facing envelope.

However, Table 2.1 shows that the VSA increases to above 45° upward from the East by 11:00 a.m. The sun then starts to set down to below 45° on the West after 4:00 p.m. This occurs throughout the year (Table 2.1).

f) Soil Temperature

Malaysian soil temperatures behave differently to those in Europe. In Europe, the soil temperature fluctuates at shallow depths, which was influenced by the ambient air temperature. The deeper is the soil, the gentler the ground temperature curve varies (Wu et al., 2007). Meanwhile, the soil temperature finds its stability and remains more or less constant beyond a depth of 4m. The temperature of un-shaded soil at this depth is approximately equivalent to the mean annual ambient dry bulb temperature (Building Research Establishment (BRE)). However, when the soil is shaded by forest trees or structure, the temperature at 4m depth underground follows closely its minimum ambient air temperature. This has been confirmed by Givoni (Givoni, 2007). In his study, he proposed an approach of having a raised wooden shack on stilts at approximately 0.6m above the measured soil. During summer months, ambient air temperature in Florida ranges from 24°C to 38°C. During this month, the cooled soil temperature at 1m depth ranges between 24°C and 25°C, which is similar to the minimum ambient air temperature rather than the average.

A study (Abdul Rahim et al., 1986) on Malaysia soil temperature was carried out by Abdul Rahim et al. in 1981 and 1982. It is a comparative study of soil temperature in open land and forested condition, at 5, 10, 20 and 30cm depth underground. The mean daily maximum air temperature is 34.4°C and the corresponding minimum is 18.9°C. Meanwhile, the mean annual air temperature is 26.5°C. Soil temperature at 5cm and 30cm depth underground were measured in both open land and forested condition (Figure 2.23).

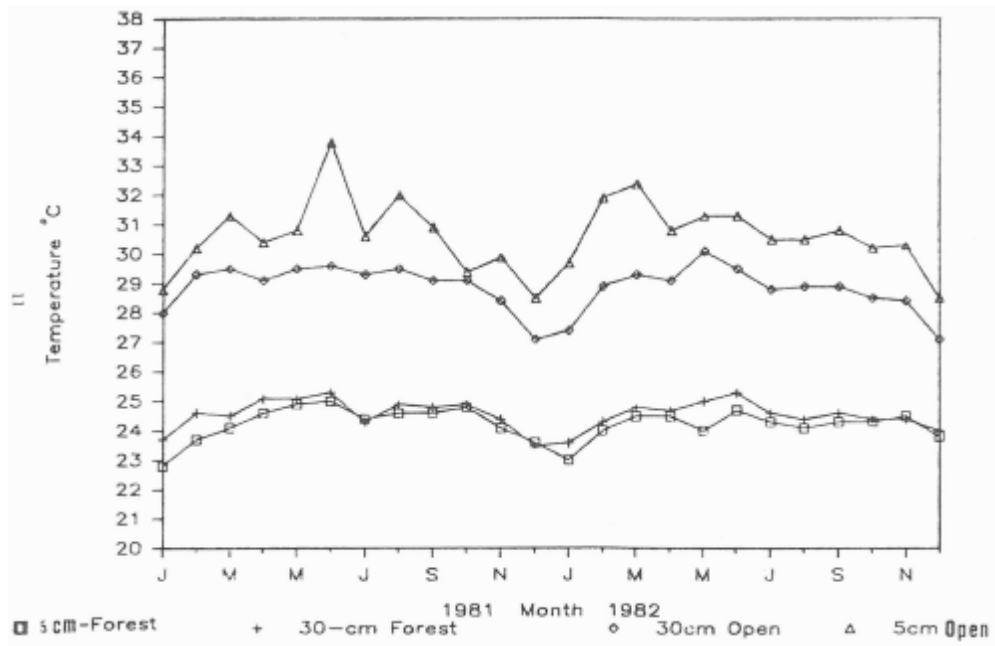


Figure 2.23: Soil temperature distribution at 5cm and 30cm depth underground in both open land and forested conditions (Location: Pahang. Source: Abdul Rahim et al., 1986).

The average soil temperature at 30 cm depth underground for both open land and forested conditions were plotted against the mean air temperature, measured at 1.5m (Figure 2.24) and (Figure 2.25). The two averages follow the mean air temperature closely. The mean monthly air temperature ranges from 25.0°C to 27.5°C. The monthly average soil temperature at 30m depth underground in open land condition ranges from 27.3°C to 30.5°C (Figure 2.24), whereas the corresponding temperature under forested condition ranges from 23.3°C to 25.0°C (Figure 2.25). Therefore, in open land condition, the average soil temperature at 30cm depths underground is higher than the average air temperature, whereas under forested condition, the average soil temperature at the same depth is lower than the average air temperature. In the open land, the ground surface is exposed to the solar radiation from the sun, while in forested land, the ground surface is shaded from the solar radiation by the trees. The main factor for these results is the effect of solar radiation. When the ground surface is exposed to solar radiation during the day, excess heat has been absorbed into the ground, which results in higher average soil temperature than average air temperature in the open land condition. Meanwhile, when the ground surface is shaded by trees, the soil is protected from solar

radiation, which results in lower average soil temperature than the average air temperature in the forested condition.

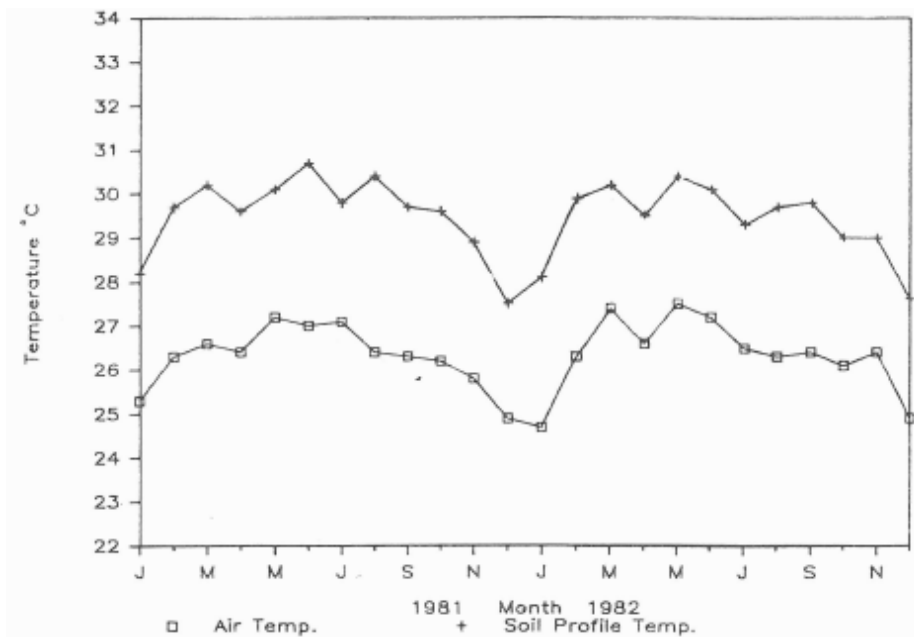


Figure 2.24: Average soil profile temperature at 30cm depth underground plotted against the air temperature at 1.5m high in open land condition (Location: Pahang. Source: Abdul Rahim et al., 1986).

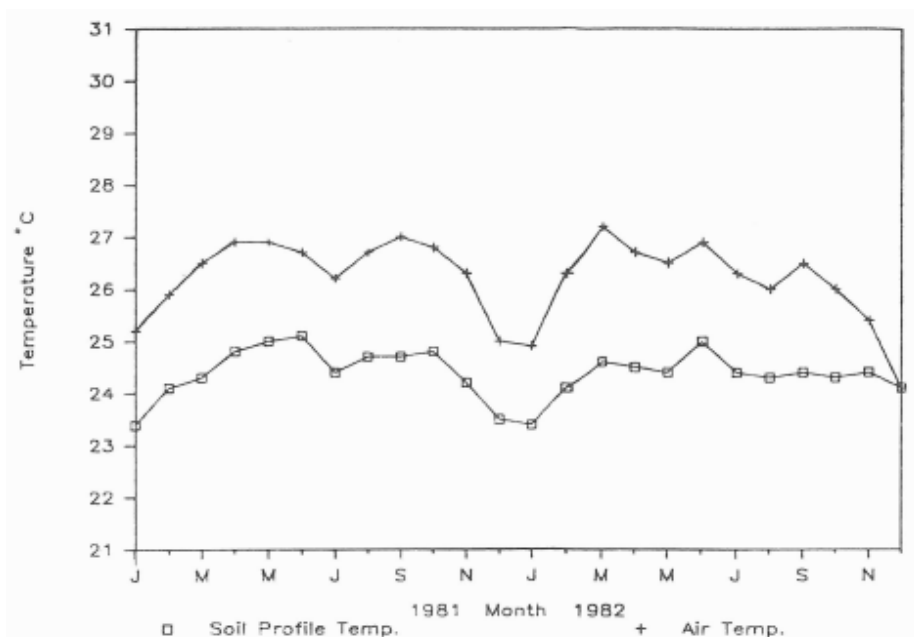


Figure 2.25: Average soil profile temperature at 30 cm depth underground plotted against the air temperature at 1.5m high in forested condition (Location: Pahang. Source: Abdul Rahim et al., 1986).

In 2005, Huat et al. carried out a study on the effect of rain towards soils in Malaysia, which is located above the groundwater table (Huat et al., 2005). As part of their investigations, they have collected measurements on the soil temperature at 30cm depth. The soil temperature at this depth ranges from 28°C to 31°C. This temperature range is similar to the average soil temperature in open condition, recorded by Abdul Rahim in 1981 and 1982.

Records of dry bulb temperature from Subang Jaya Weather Station from year 2002 to 2008, has shown that the 24 hours average dry bulb temperature ranges from 26.8°C to 28.4°C and the mean annual dry bulb temperature is 27.7°C. Therefore, the average soil temperature at 30cm deep underground, in a study carried out by Huat et al. in 2005, is slightly higher than the mean annual air temperature. A study has reported that soil temperature at shallow depth has significant variation in a day and even in a year due to being near to the soil surface (Kusuda and Achenbach, 1965). The study by Kusuda and Achenbach (1965) has shown that the underground earth heat flow is influenced by many factors, which are latitude, altitude, weather conditions, time of the year, shading, landscaping, soil properties and rainfall (Claridge et al., 1993).

Since published records of soil temperature throughout Malaysia at depths greater than 30cm is limited, this research has taken a study of soil temperature measurement at lower depths as a first step of Earth Pipe Cooling investigation.

2.1.2 Malay Vernacular Architecture

Malaysia Architecture, at its origin, is a means of shelter design with primary concepts that response to the local climate condition. Originally, local villagers designed the vernacular houses with great understanding of local climate and their own needs. Following the understanding of the Malaysian climate from previous section, this chapter describes the design strategies of Malay vernacular shelters that should be able to shield the occupants from the unpleasant outside environment. The table below illustrates the primary concepts of a Malay vernacular house (Table 2.3) and their response to the local climate condition.

Table 2.3: Design strategies in Malaysian Vernacular Houses (Lim, 1987).

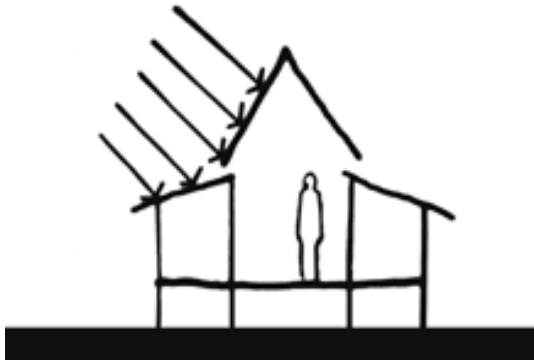
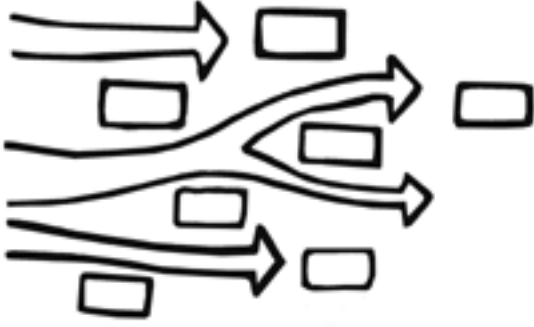

Primary Concepts of a Malay Vernacular House	Responses to Local Climate Condition
<p>1. Low thermal capacity material</p>  <p>The diagram shows a cross-section of a house with a pitched roof. Several arrows point downwards towards the roof, representing solar radiation. A person is standing inside the house on a raised platform. The ground is represented by a thick black line at the bottom.</p>	<p>Due to a high solar radiation during the day, Malay houses were built out of lightweight timber materials. The reason for using lightweight timber construction is because of its low thermal capacity, which holds small amount of heat and releases heat fast into the outside air during night time. This would provide comfortable environment during sleeping time.</p>
<p>2. Widely spread building blocks</p>  <p>The diagram shows several rectangular building blocks arranged in a row. Arrows indicate wind flow from left to right. The arrows curve around the buildings, showing that the wind is not blocked but flows through the spaces between them.</p>	<p>Due to limited air velocity, the buildings are usually spread out to allow uniform wind to flow around each building block.</p>
<p>3. Ventilated Roof</p>  <p>The diagram shows a cross-section of a house with a pitched roof. Arrows indicate air flow: one arrow points upwards from the interior space into the roof cavity, and another arrow points downwards from the roof cavity to the exterior. A person is standing inside the house on a raised platform. The ground is represented by a thick black line at the bottom.</p>	<p>Another strategy to reduce the solar heat gain in a pitched roof is by allowing ventilation of air to flow through the ceiling joints and remove the possibly excess heat collected in the roof.</p>

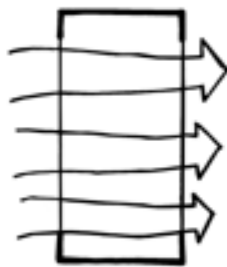
Table 2.3 continues

4. Tall and Thin Vegetation



Due to high solar radiation and limited air velocity, the most suitable type of vegetation is the tall tree such as coconut tree. This tree type provides sufficient shading for the ground and buildings underneath, while simultaneously allowing air to flow freely underneath them.

5. Cross Ventilation



Malay Vernacular houses have openings opposite each other and minimal internal partitions. This is to allow easy access of air velocity from outside to pass through the house.

6. Houses on stilts



Malay Vernacular Houses are raised on stilts. The purpose for this is to allow a higher air velocity into the house by being at a higher level. A common fact is that air velocity is usually higher at a higher level. Another reason for a raised house is to protect the house from flood and animals.

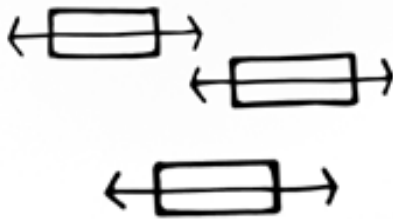
Table 2.3 continues

7. Full length openings



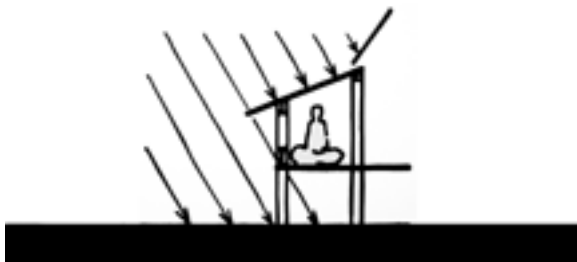
Malay Vernacular houses have openings that open from floor to ceiling. This provides air ventilation at occupant level.

8. East West orientated



Due to low vertical angle of solar radiation in the morning and late afternoon, on the East and West respectively, the Malay Vernacular houses are usually orientated along the East and West direction to minimize solar heat gain from these directions.

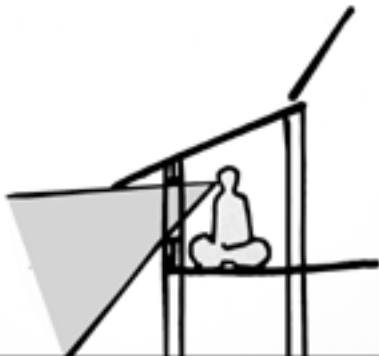
9. Big overhangs



Malay Vernacular houses have big overhangs that shade as much walls and windows from the solar radiation and also rain. This allow windows and doors to be opened at most times of the day during hot days and also rainy days.

Table 2.3 continues

10. Prevention of Glare



The big overhangs also protect the occupants from glare. Another strategy to prevent glare is by having low reflectance ground and wall surfaces of neighbouring buildings: soft landscape and timber walls for example.

11. Lighting performance



Due to large overhangs, the lighting level in a Malay vernacular house is usually not adequate. Despite its lowly lit, it is assumed to have given the occupants the cooling feeling psychologically.

All of the above elements can be applied to a building design in a tropical climate and the next figure is an example of a cross-section of a basic Malay Vernacular house (Figure 2.26).

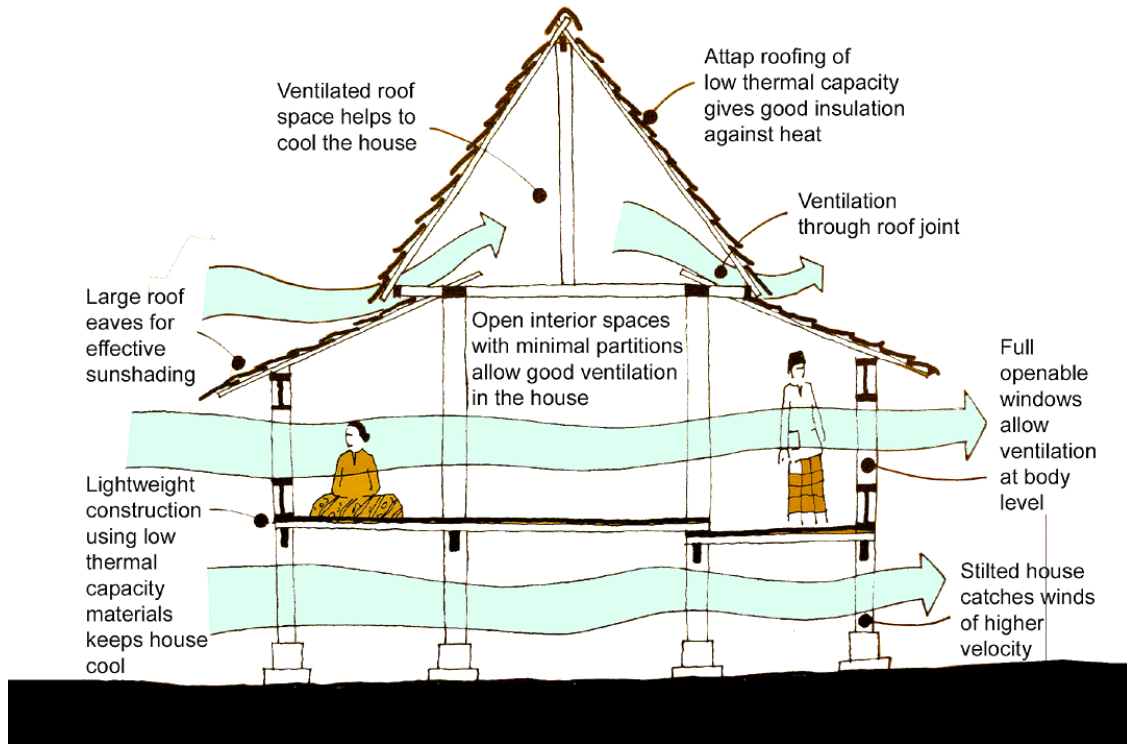


Figure 2.26: A cross section of a typical Malay Venacular House (Lim, 1987)

2.1.3 Cooling Methods Implemented in Malaysia

Having said previously, shelters should be designed responding to local environment and micro climate. Malay vernacular design building is suitable to be built in places with broad land space to accommodate widely spread building blocks and sufficient amount of trees for shading from high solar radiation. Malaysia being a fast developing country has its environment changed rapidly particularly in the city of Kuala Lumpur. The rapid development has result in reduction of vegetation and increase in number of buildings, which makes the place dense with buildings built closely and does not comply with the criteria of vernacular Malay house (Table 2.3 (2)). As a result, natural ventilation does not provide adequate cooling sensation in the building due to the minimal wind flowing around the buildings. Therefore, vernacular Malay design is not suitable for the developed environment of Malaysia. Due to this, occupants have relied on electric fans and air-conditioning. To the extreme, occupants would rather have the building windows shut and depend on air-conditioning for cooling.

As the demand for air-conditioning increases, which contributes to the country energy demand exponential increment, several researchers and architects have come to realize their role in designing modern buildings in Malaysia that can provide thermal comfort with minimal reliance on air-conditioning and less energy demand. The energy efficient building design is also called “Green Building” or “Ecological Design Building” (Yeang, 1999).

“Green” or ecological design here means building with minimal environmental impacts, and, where possible, building to achieve the opposite effect; this means creating buildings with positive, reparative and productive consequences for the natural environment, while at the same time integrating the built structure with all aspects of the ecological systems (ecosystems) of the biosphere over its entire life cycle.” (Yeang, 1999).

a) Old Shop-houses, Melaka

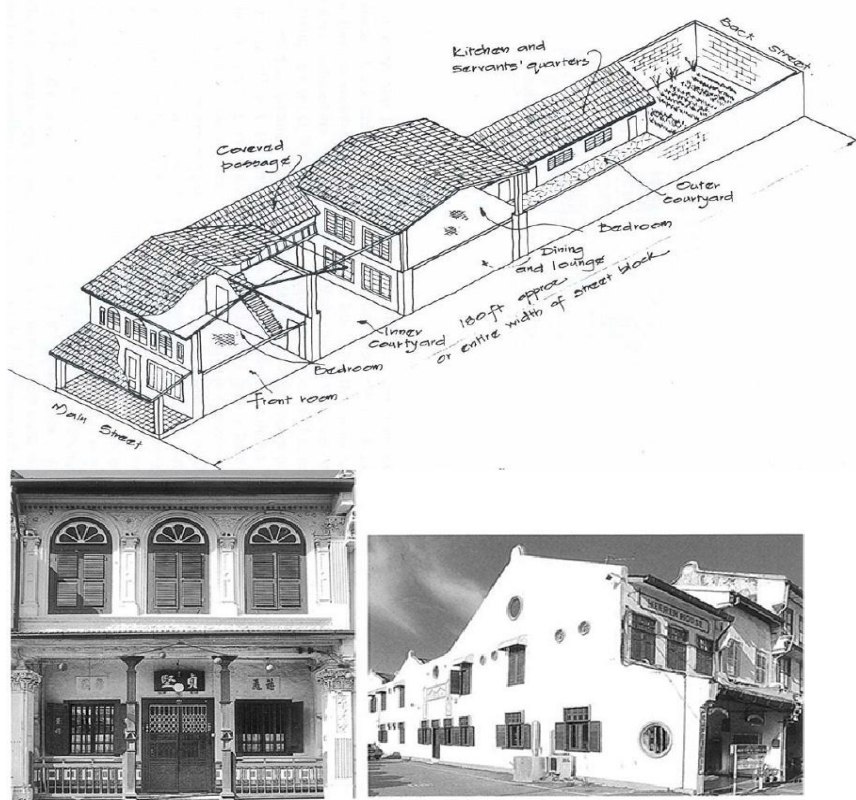


Figure 2.27: An example of old shop-houses in Melaka, Malaysia (Jayapalasingam, 2009).

The old shop-houses design comprises of internal courtyard to provide fresh air and natural daylight into the long building. These shop-houses were first built in the 19th century. Its form has a typical width of within 6 to 7m and typical length of 30m (Figure 2.27). Although there are some with 60m long (Wan Ismail and Shamsuddin, 2005). The rationale behind its form is due to the tax charge according to the width of the façade. Therefore, to reduce paying tax, the width of the building is minimized but with long stretch to the back of the building. These shophouses are also terraced houses and therefore, have minimal exposure to the outdoor environment. As part of passive design, internal courtyards were introduced into the building plan. The number of courtyards depends on the length of the building to provide ample natural ventilation and daylight.

b) IBM Headquarter Mesiniaga Tower, Subang Jaya

One of the earliest energy saving office building was the IBM headquarter Mesiniaga Tower that was erected in 1992 in Subang Jaya, near Kuala Lumpur (Figure 2.28). This sixteen-storey office tower was designed by T.R. Hamzah and Yeang.

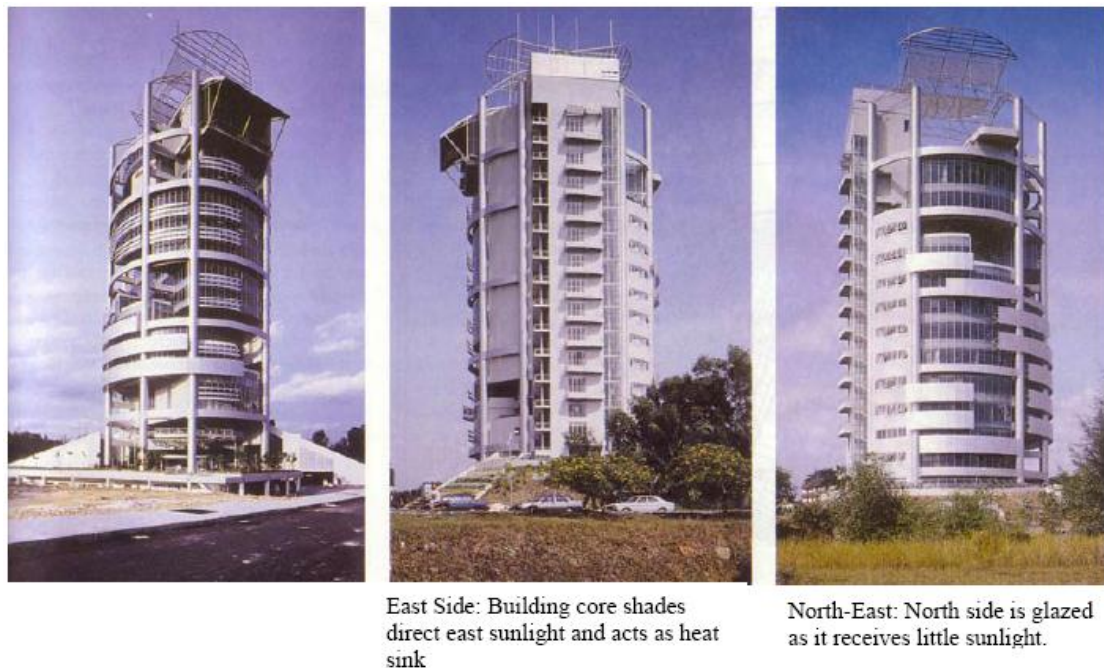
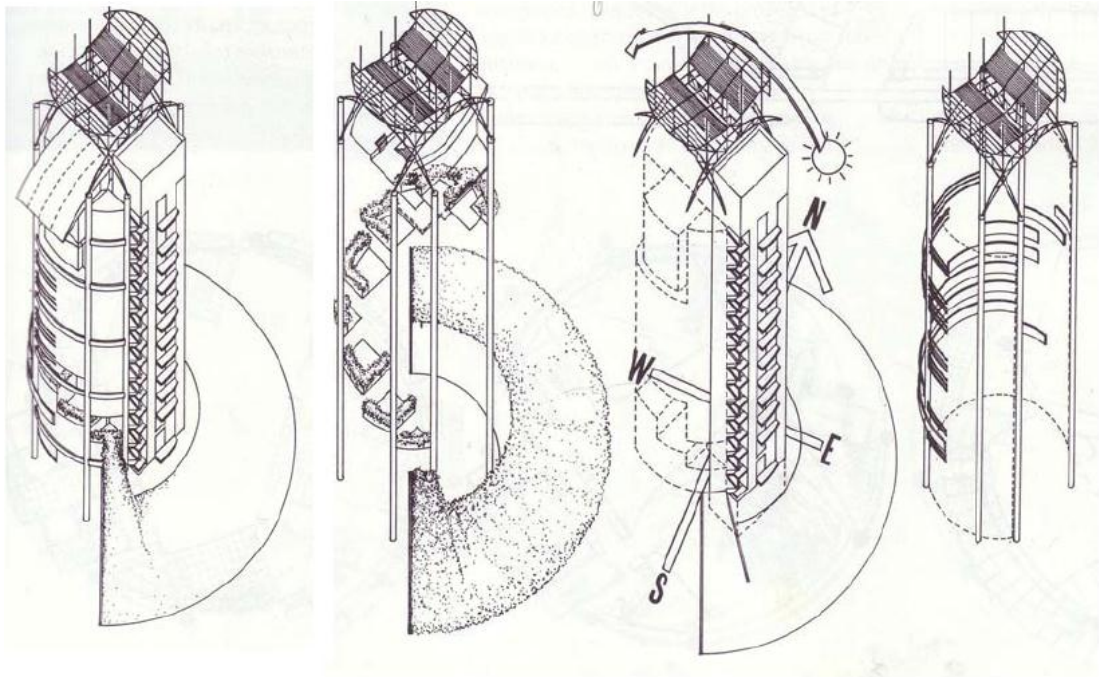


Figure 2.28: Pictures of Mesiniaga Tower in Subang Jaya from three direction (Chan et al., 2004).



Axonometrics: (Left to Right) Built form; Planting & sky gardens; Solar orientation; Shading devices

Figure 2.29: 3d diagram of Mesiniaga Tower illustrating the passive building design scheme (Chan et al., 2004).

Figure 2.29 illustrates part of the building passive design scheme. The Mesiniaga Tower became an energy efficient building by implementing various environmental responsive passive designs. Water conservation system took advantage of the raining season by collecting rainwater for building use. Another passive design strategy is the tower having a naturally ventilated service core, which is placed on the East side of the building to shade the rest of the building from direct east sunlight and provides a heat sink simultaneously. Double-glazed façade can only be found on the North and South side of the building. Furthermore, sky gardens were integrated into the building façade (Figure 2.29) to extend vegetation and also for occupants to relax. On the roof top there is a tubular steel trellis that give shading to the building rooftop and also support the PVC solar panel. The PVC solar panel will absorb solar radiation from the sun and generate electricity for the building (Chan et al., 2004)

b) Securities Commission Building in Malaysia, Kuala Lumpur

The Securities Commission building was completed in 1999 and was designed by Hijjas Kasturi Associates. The building was reviewed as the most energy efficient new building in the ASEAN Energy Awards for Energy Efficient Buildings (AEA) 2001 (Figure 2.30). Its energy efficient features consist of double-glazed thermal flue façade, atrium glass roof, energy-saving light fittings and under-floor air-conditioning system (Securities Commission, 2001). The features were designed to achieve sufficient indoor thermal comfort.



Figure 2.30: Bird's eye view of Securities Commission Building in Kuala Lumpur, showing the triangle-plan atrium at the centre of the building (Abdul Aziz and Mohd Adnan, 2008).

The double-glazed thermal flue façade comprises of a 1.2m air gap that serves the building as ventilated air gap, acoustic buffer zone and maintenance walkway. This walkway has fixed louvered panels as a shading device from solar radiation (Figure 2.31).



Figure 2.31: Securities Commission Building in Kuala Lumpur (Shafii et al., 2006).

Furthermore, the atrium adopts under-floor air-conditioning system at ground level, which provides thermal comfort and good ventilation (Shafii et al., 2006). Thermostat controlled fans are located at the top of the atrium. The function of the fan is to extract hot air and release it to outdoor space via the atrium roof. The overall thermal transfer value (OTTV) of this building is 35Wm^{-2} , which is lower than that of conventional glass building; 45Wm^{-2} (Securities Commission, 2001).

c) UMNO Tower, Penang

UMNO Tower is another building designed by T. R. Hamzah and Yeang, located in North Malaysia. Slightly higher than Mesiniaga Tower, the UMNO Tower comprises of 21 storeys (Figure 2.32). This building is cunningly designed to enhance natural ventilation that provides the indoor environment with approximately 30 air changes per hour. This was achieved by having a large fin or wing wind wall, which creates an artificial pressure zone that allows wind to go in and out of each office floor. The large fin enhanced natural ventilation has reduced the air-conditioning cooling load by 30%.



Figure 2.32: UMNO Tower in Pulau Pinang, showing the large fin or wing wind wall (Abdul Aziz and Mohd Adnan, 2008).

d) Low Energy Office Building LEO, Putrajaya

The LEO building (Figure 2.33) has won 1st prize award in the ASEAN Building Energy Award 2006 (Qahtan et al., 2010). This building was built by the Government of Malaysia with the aid in technical input from Danida International Development Assistance (DANIDA), which house the Ministry of Energy, Water and Communications (MEWC) headquarters. It comprises of 2 building blocks of 6 storey high and 2 basements (Abdul Aziz and Mohd Adnan, 2008).



Figure 2.33: Low energy office building LEO in Putrajaya (Qahtan et al., 2010).

The LEO building have various passive sustainable features such as orientation to minimize solar heat gain into the building, smart internal planning of workspaces to benefit from natural daylight from atrium, thick wall materials, roof insulation, glazing using 12mm thick light green tinted glass and natural ventilation for cooling purposes (Abdul Aziz and Mohd Adnan, 2008). One of the stated passive sustainable features, which is thick wall materials contradicts with one of the climate responsive design strategies of a Malay Vernacular House, lightweight low thermal capacity walls (Table 2.3 (1)). The contradiction is due to the different function of building; one is for living and the other one is an office. Vernacular Malay house design responded to Malay traditional lifestyle, where people worked or studied away from the house most of the day and return to rest in the house in the late evening. Therefore, the priority relied on

the comfort of the house in the late evening and hence the use of low thermal capacity lightweight walls, which quickly released heat from the indoor space and into the outside air during the night.

On the other hand, LEO building, being an office building, is occupied mostly during daytime. It needs a thick wall with high thermal capacity, which could absorb, hold and release heat from outside air into the indoor space slowly during the day. The heat is held long enough in the walls until the sun sets and outside air becomes cooler again.

The natural ventilation is provided by the open space lobby which links to a 5 storey high atrium. The air movement within the atrium is further elevated upwards by the addition of thermal flue at the fifth floor wall, where the walls were painted black. The black wall will absorb heat from the sun, creating hot air, which result in stack effect, where the air flow is further increased upwards naturally without help from any kind of mechanical ventilation (Figure 2.34). The air movement inside the lobby was found to be 6 to 8 air changes per hour (Abdul Aziz and Mohd Adnan, 2008).

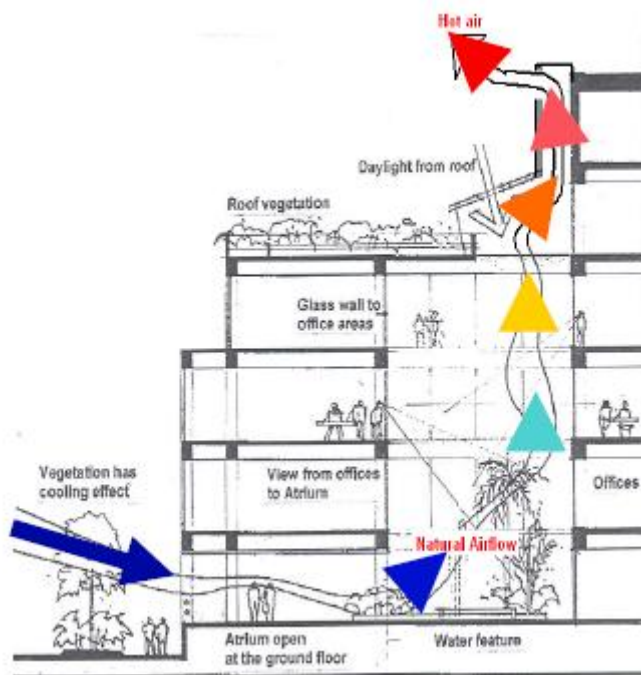


Figure 2.34: A cross section of the LEO building, showing the open space lobby leading to the atrium, the black wall at the fifth floor and the three storey water wall (Abdul Aziz and Mohd Adnan, 2000).

Another passive cooling feature is evaporative cooling provided in the atrium. A series of water mist spray are installed in a row, on the first floor beam to cool down the lobby as the outdoor temperature becomes hot. The evaporative cooling feature coupled with a three storey water wall within the atrium helps maintain the indoor temperature at 24°C (Figure 2.34) (Abdul Aziz and Mohd Adnan, 2008).

The energy consumption of the LEO building is 114kWh/m²year. Typical conventional building energy consumption is within the range of 200 and 300 kWh/m²year while the Malaysian Standard guideline for Energy Efficiency building energy consumption is 140kWh/m²year (MEGTW, 2009). This shows that the LEO building energy consumption is lower than suggested by the Malaysian Standards.

A report also stated that the payback years for the LEO building is 5 years and it makes an annual energy saving of RM600,000, equivalent to GBP120,000 (Shafii, 2007).

e) Green Energy Office Building GEO, Bandar Baru Bangi

The GEO Building is still under construction and scheduled to complete in 2015 (Figure 2.35). The building is built with various green building features such as almost 100% daylighting, floor slab cooling (Figure 2.37), double glazing, insulation, solar energy use and load shifting and a trickling roof cooling tower (Kannan, 2009).



Figure 2.35: A model of GEO building in Bandar Baru Bangi (Kannan, 2009).

In terms of solar energy absorption, the GEO building has a total of 92kW_p of photovoltaics (Shafii, 2007). Four different types of photovoltaic panels were incorporated into the design according to the building zone function (Figure 2.36).

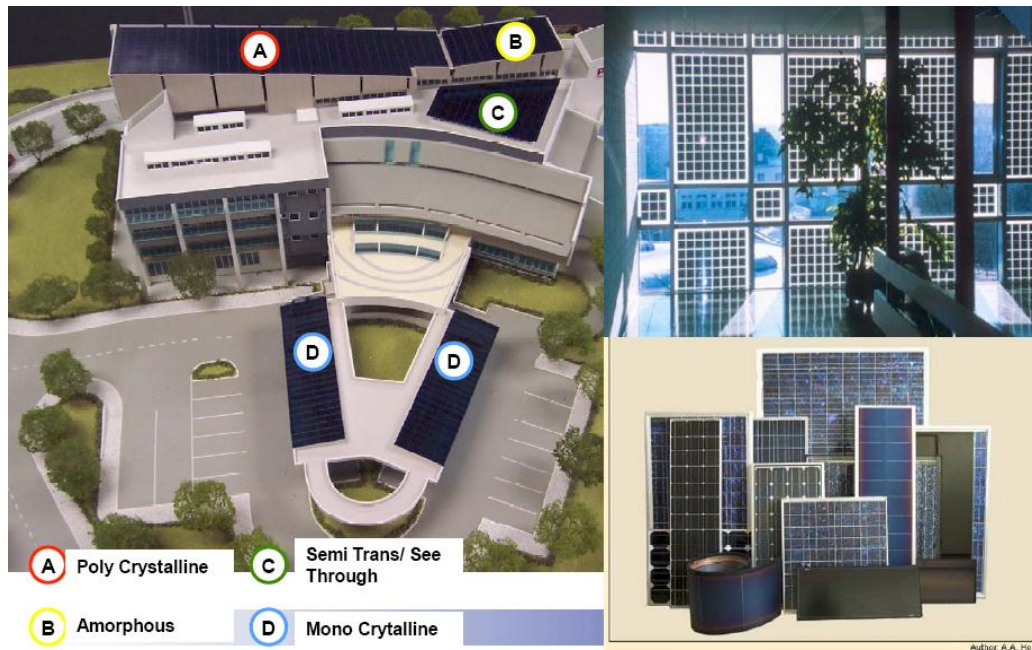


Figure 2.36: Distribution of various types of Photovoltaic panels (Kannan, 2009).

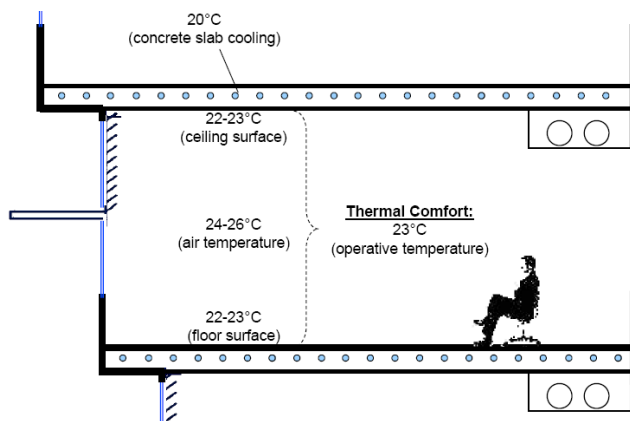


Figure 2.37: A section of the GEO building showing the floor slab cooling and the predicted resulting indoor air temperature (Kannan, 2009).

The GEO building is predicted to consume energy as much as 65kWh/m²year but generates energy as much as 35kWh/m²year in the 2015 (MEGTW, 2009).

2.2 Thermal Comfort

An individual who is experiencing thermal comfort is one who is satisfied and feels thermally comfortable with his surrounding environment. This fact is supported further by a phrase written in the ASHRAE Standard 55-66, which stated the definition of thermal comfort:

“That condition of mind which express satisfaction with the thermal environment.”
(Fanger, 1970).

The study of thermal comfort is crucial in every part of the world and it differs according to the local climate and environment. There are three main reasons behind the study of thermal comfort, which is to achieve user satisfaction, efficient energy consumption and to set a standard with a range of thermal comfort temperature for a particular environment.

The first issue mentioned is to achieve user satisfaction. From personal observation in Malaysia, quite a number of people would bring warm clothes into lecture theatres, cinemas and libraries because the indoor condition was cold as compared to the outdoor environment, which is warm and humid all year round. Furthermore, from personal experience, a library felt too cold because the air-conditioning temperature was set to 18°C. Being an all year round warm and humid country, many commercial buildings are dependent on air-conditioning for cooling the indoor space. Without the knowledge of thermal comfort temperature range, the air-conditioning temperature could be set to be too cold for the occupant and hence the use of warm clothing in a building in warm and humid climate of Malaysia.

With the knowledge of thermal comfort temperature range of a particular environment, energy consumption for heating or cooling could be reduced effectively. A method to calculate heating or cooling requirement for a building is to find the number of ‘degree-days’ within the heating or cooling season, with the aid of local weather data. ‘Degree-days’ can be calculated when thermal comfort temperature and outdoor temperature are known. For a heating season, the ‘Degree-days’ is the number of days multiplied by the temperature drop between the thermal comfort temperature and the outdoor temperature. For a cooling season, the ‘Degree-days’ is the number of days multiplied by the temperature rise between the thermal comfort temperature and the outdoor temperature (CIBSE Guide A, 2006).

Thermal comfort study can also determine the thermal comfort standard that responds to the local weather condition. The comfort standard could reduce the indoor and outdoor temperature differences but maintain indoor comfortable condition. Implementation of comfort standard could introduce efficient energy consumption.

2.2.1 The Processes of Thermal Interaction between Man and the Environment

A healthy body has an internal body temperature of 37°C, with skin temperature that ranges from 25°C up to 37°C. The skin temperature varies in different parts of the nude person and ambient temperature. Figure 2.38 shows the variation of skin temperature, which affected by the different parts of the body and ambient temperature.

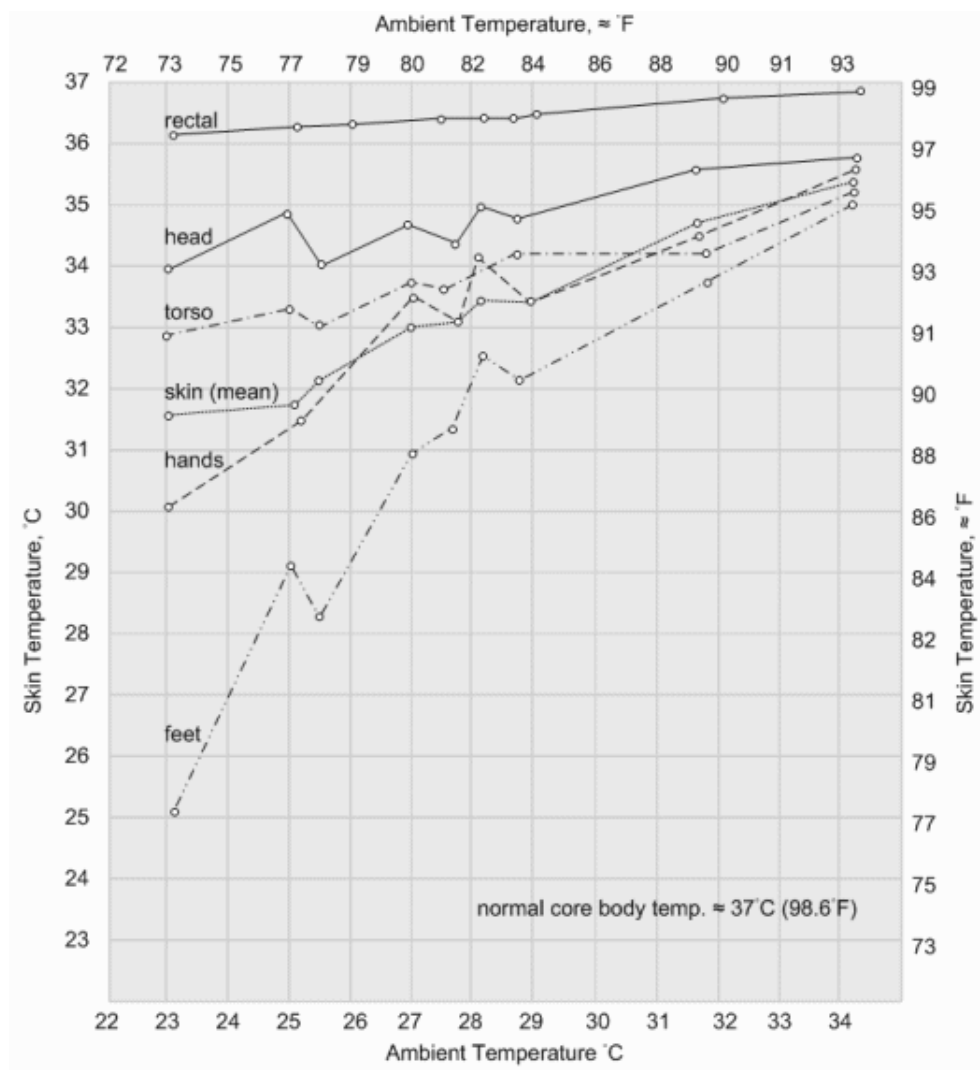


Figure 2.38: Skin temperatures at different parts of person at different ambient temperatures (Olesen, 1982).

In order to avoid discomfort, it is important for the body to maintain a constant internal body temperature. This is where a heat balance of the body occurs, where the production of heat is equivalent to the dissipation of heat (Fanger, 1970). Fanger's (1970) thermal balance equation is shown in Equation 2.1 below.

$$H - E_{is} - E_{sw} - E_{res} - C_{res} = K = R + C \quad (\text{Equation 2.1})$$

Where H is the net metabolic heat production, K is the heat transfer from the human skin to the outer layer of the human's clothing, R is the heat transfer through Radiation, C is the heat transfer through Convection, E_{sw} is the heat loss through Evaporation when sweating and E_{is} is the Evaporation of sensible moisture on the skin. Meanwhile, E_{res} and C_{res} are heat loss from respiratory where C_{res} is a convective heat transfer in the lungs with the value of $0.0014M*(34 - T_a) \text{ Wm}^{-2}$ and E_{res} is an evaporation heat transfer in the lungs with the value of $0.0017M*(59 - p_a) \text{ Wm}^{-2}$. E_{res} is an evaporation from the surface of the lungs, which caused by breathing.

There are four different categories within the processes of thermal interaction between man and environment, which are in terms of physics, physiology, psychophysics and human social behaviour (Nicol, 2008).

The physics aspect of man and environment thermal interaction elaborates most variables in the thermal balance equation (Equation 2.1). The human body loses heat to or gain heat from its surrounding environment through radiation, convection and evaporation. Radiation occurs when there is a heat transfer between two or more objects, with different temperatures, in the form of electromagnetic waves, with no absorbing medium in between the two objects. The calculation of radiation occurred onto a human being in a room is slightly complex because the human is surrounded by objects with various radiant temperature. As an example, inside a room, there could be a warm ceiling but a cold window. The transparency of the windows transmits solar radiation into the room. Different materials have different radiation emissivity or absorptivity and solar radiation reflectivity (Table 2.4). Choosing the correct materials for building envelope can help the building occupant achieve thermal comfort.

Table 2.4: A list of common materials used in building envelope with their average emissivities, absorptivities and reflectivities (Straaten, 1967).

Surface	Emissivity or absorptivity		Reflectivity
	Low-temperature radiation	Solar radiation	Solar Radiation
Aluminium, bright	0.05	0.20	0.80
Asbestos cement, new	0.95	0.60	0.40
Asbestos cement, aged	0.95	0.75	0.25
Asphalt pavement	0.95	0.90	0.10
Brass and copper, dull	0.20	0.60	0.40
Brass and copper, polished	0.02	0.30	0.70
Brick, light buff	0.90	0.60	0.40
Brick, red rough	0.90	0.70	0.30
Cement, white Portland	0.90	0.40	0.60
Concrete, uncoloured	0.90	0.65	0.35
Glass	0.90	—	—
Marble, white	0.95	0.45	0.55
Paint, aluminium	0.55	0.50	0.50
Paint, white	0.90	0.30	0.70
Paint, brown, red, green	0.90	0.70	0.30
Paint, black	0.90	0.90	0.10
Paper, white	0.90	0.30	0.70
Slate, dark	0.90	0.90	0.10
Steel, galvanized, new	0.25	0.55	0.45
Steel, galvanized, weathered	0.25	0.70	0.30
Tiles, red clay	0.90	0.70	0.30
Tiles, black concrete	0.90	0.90	0.10
Tiles, uncoloured concrete	0.90	0.65	0.35

Convection is a heat exchange between the human body and the air surrounding when there is a temperature difference between the human skin or clothing temperature and the air temperature. The heat exchange would create air movement and hence

convection currents are formed. A forced convection current can be set up to increase thermal comfort by accelerating the rate of heat transfer with the aid of a mechanical source (Straaten, 1967).

Evaporation heat transfer occurs when water particles from the human surface evaporates to the air and simultaneously extract latent heat from the surface, which provides cooling effect to the human skin. If the human body is not sweating, evaporation can also occur with the skin moisture. This principle of heat and water vapour relationship forms the basis of psychrometry (Straaten, 1967).

In terms of physiological process of man and environment thermal interaction, heat is endlessly lost to the environment via the skin and the surfaces of the lungs to balance its metabolic heat production, which the human body produces through metabolising food and activities. Heat within a human body is transported around the body via the blood and the temperatures of the internal organs are controlled by the brain, which remain constant. When the core temperature drops, the brain defended the body by setting off vaso-constriction, where the blood circulation is reduced, and so is the heat supply. This then causes the skin temperature reduction, which reduces the heat loss to the environment. When the core temperature drops further, the muscle tension increases, which makes the body shivers (Nicol, 2008).

On the other hand, when the core temperature increases, as a defence, the brain set off vaso-dilation, where the blood circulation increases. This increment leads to the increase in skin temperature and also heat loss from the skin to the environment. When the core temperature increases further, sweating will occur (Nicol, 2008).

The psychophysical thermal interaction of man and the environment is the relationship between the human thermal sensations with the thermal environment.

“The probability that members of a group of people are comfortable will start of low at low temperatures because almost all will be cold. Then rise to a maximum (100%) as temperature increases. Then, fall off again as they become likely to be hot” (Nicol, 2008).

Human social behaviour is an active thermal interaction between man and the environment through changing clothes to suit the climate, changing posture and metabolic rate, movement between different thermal environments and making use of mechanical thermal controls to modify the immediate environment (Nicol, 2008).

2.2.2 Factors of Thermal Comfort

The factors of thermal comfort include environmental factors and personal factors.

Among the various climatic variables in the environment, the main climatic variables, which were usually taken into consideration in environmental responsive building designs were the solar radiation, reflected radiation from the ground, air temperature, humidity, air velocity and precipitation (Givoni, 1976). The precipitation referred to in this study is rain.

a) *Environmental factors*

The first mentioned environmental factor in section 2.2 is solar radiation, which is projected from the sun onto the Earth's surface, when there is no obstruction. Obstructions in the atmosphere cause a decrease in the amount of radiation that reaches the Earth surface, due to absorption, reflection and diffusion.

The direction of sunrays varies with date, time and latitude. As described in Section 2.1, the latitude, date and time of incident determines the sunrays' angle that is projected on to the Earth's surface. Radiation from the ground is emitted to the atmosphere when there is a difference between the radiant temperature of the Earth's surface and the ambient air temperature. This occurs mainly at night when the Earth's surface is warmer than the air temperature in the atmosphere. Solar radiation also create evaporation where there is water on a surface.

The next mentioned environmental variable that affects thermal comfort is the air temperature. It is usually measured in the unit °C. Air temperature is the most crucial environmental factor that could influence the amount of heat released from a human body to achieve comfort. As mentioned before, a healthy internal body temperature is approximately 37°C while the skin surface temperature ranges from 35°C to 37°C depends on the ambient temperature. Please refer to Figure 2.38. A human body continuously release heat produced by its metabolic process, which is an accumulative of its food intake and activities. Therefore, the air temperature must be at a certain level that could help a human body to release heat to the environment to prevent discomfort (Szokolay, 2004).

The humidity of air is determined by the amount of water vapour carried by the atmosphere. This study referred to relative humidity is the percentage of water particles in the ambient air.. The atmosphere collects water vapour due to the evaporation from wet surfaces, vegetation or water features. When the humidity as well as the air temperature is high, discomfort will occur. A range of acceptable relative humidity level is from 30% to 65% (Szokolay, 2004). This thesis investigates buildings in Malaysia, which has a warm and humid climate. Therefore, discomfort due to high relative humidity may occur. In order to prevent discomfort due to high relative humidity, adequate air movement is required to reduce the amount of humidity.

Air speed is measured in the unit m/s. It is created in buildings by the wind, the difference in air temperature and fans. Warmer air is lighter which causes it to rise. This phenomenon is known as the stack effect. The difference in air temperature causes air movement from the warmer surface to a cooler air. This would increase the air velocity. Table 2.5 shows how human reacts to condition with different air speed.

Table 2.5: Human reactions to different air speed (Szokolay, 2004).

<0.1 m/s	stuffy
to 0.2 m/s	unnoticed
to 0.5 m/s	pleasant
to 1.0 m/s	awareness
to 1.5 m/s	draughty
>1.5 m/s	annoying

Another environmental factor that affects human thermal comfort is precipitation, which this study referred to as rain. Precipitation reduces the amount of solar radiation from the sun and causing a cooler atmosphere. This could be due to more cloud covers during rainfall that blocks the solar radiation. Simultaneously, it increases the Relative Humidity as it increases the amount of water vapour in the atmosphere.

These environmental factors play a role in changing the environment and are dependent on and affected by each other.

b) *Personal factors*

Fanger (1970) had listed four personal factors that could affect human thermal comfort. They are the metabolic rate of the occupants, amount of clothing worn by the occupants, the state of health and acclimatisation of the occupants. Even though a group of people occupy a space, which exhibits a uniform environmental condition, they might not have the same thermal comfort perception due to the personal factors.

Metabolic processes are divided into two types, basal metabolism and muscular metabolism. Basal metabolism is a continuous and automatic process, whereas muscular metabolism process occurs when a person is carrying out work. The amount of energy released by a human body depends on the person's activity. The heat output can range from a minimum of 70 Watts, when the body is in a sleeping state, to 700 Watts, when the person is active; playing sports for example (Table 2.6).

Table 2.6: The amount of energy released for different activities (Koenigsberger et al., 1974).

Activity	Energy released (Watts)
Sleeping	Minimum 70
Seating, moderate movement, e.g. typing	130 – 160
Standing, light work at machine or bench	160 – 190
Seating, heavy arm and leg movement	190 – 230
Standing, moderate work, some walking	220 – 290
Walking, moderate lifting or pushing	290 – 410
Intermittent heavy lifting, digging	440 – 580
Hardest sustained work	580 – 700
Maximum heavy work for 30-minutes duration	Maximum 1100

Clothing is another personal factor that would affect occupant's thermal comfort. It is an item that shields the occupants from the environment, and in this study, it was measured in the unit clo-value. Table 2.7 has listed the clo-value of each garment.

Table 2.7: Clo-value of each garment. (Bruel and Kjaer, 1982).

Clothing	Clo-value
Naked	0.0
Briefs	0.06
T-shirt	0.09
Bra and panties	0.05
Long underwear	
upper	0.35
lower	0.35
Shirt	
light, short sleeve	0.14
heavy, long sleeve	0.29
Add 5% for tie or turtleneck	
Skirt	0.22-0.70
Trousers	0.26-0.32
Sweater	0.20-0.37
Socks	0.04-0.10
	0.02-0.08
Light summer outfit	0.3
Working clothes	0.8
Typical indoor winter clothing combination	1.0
Heavy business suit	1.5

In warm weather, occupants would normally wear clothing with low clo-value, to prevent them from getting too warm, whereas in cold weather, occupants would wear clothing with high clo-value to keep themselves warm.

The next personal factor, which would affect thermal comfort of a person, is his or her state of health. When the internal body temperature increases above the air temperature, the body would feel colder. However, this happens very rarely and only when the person is not feeling well.

Another factor, which could affect human thermal comfort, is the acclimatization of the person. The human body is homoeothermic. It is not entirely passive, but it has thermal adjustment mechanisms that enable the body to adapt to its surrounding conditions. The adjustment mechanisms go both ways, either in the cold environment or in the warm environment.

In cold environment, the adjustment mechanism is called vasoconstriction. Here, the blood vessels contract, which reduces the volume of blood flow to the skin. Therefore, the skin temperature is reduced and a reduction in heat dissipation occurs. However, in a warm environment, the mechanism is called vasodilatation. Here, the blood vessels expand, which increases the volume of blood to flow to the skin. Therefore, the heat transport increases, and elevates the skin temperature, which increases the amount of heat dissipation (Szokolay, 2004).

2.2.3 Adaptive Thermal Comfort

Field studies on thermal comfort dates back as early as 1930s. In 1936, Bedford had carried out a field study based on the adaptive approach. In his field study, data of the thermal environment, such as air temperature, relative humidity, radiation, and air movement, were measured. At the same time, when the measurements were recorded, surveys on the occupants' response were carried out (Bedford, 1936).

In 1973, Nicol and Humphreys carried out a study on adaptive comfort. This study involved a range of different locations with different climates. The result had shown that as the indoor temperature, measured from one climate to another, increases, the mean comfort vote did not change as much. The results had proven that the percentage of comfort vote of a warmer climate and a colder climate were similar. Their results had shown that there is a possibility of adaptive comfort.

In 1976, Humphreys carried out another similar study with subjects exposed to a wider variety of climates. Humphreys results had shown that the percentages of comfort

votes were similar, whether they were obtained in a warm climate or a cold climate. This result had supported Nicol and Humphreys conclusion in 1973.

In 1998, Brager and de Dear carried out a field study based on naturally ventilated buildings located in a warm climate. This study used a Predicted Mean Vote (PMV) model and the actual comfort votes from the occupants were also recorded. Their study was to investigate the validity of the Predicted Mean Vote (PMV) model in predicting the thermal comfort in warm climate. The PMV model was created from Fanger's heat balance equation (Fanger, 1970). Their results had shown that the PMV model predicted a lower comfort temperature than the actual comfort votes from the occupants. (Brager and de Dear, 2001). Therefore, they have concluded that the occupants were tolerant to a higher air temperature than what was predicted by the PMV model.

A similar survey using the PMV model was carried out by a group of researchers; Taki, Seden, Ealiwa and Howarth, during the summer of 1997 and 1998. The field study was done in the hot-dry climate of North-Africa, with reference to Ghadames, Libya. During summer, the maximum temperature was up to 47°C, with a minimum night temperature of 30°C. The results of the Adaptive Model showed that, at a range of air temperature from 30°C to 35°C, 80% of the occupants reported they were satisfied. However, the PMV model had predicted a lower comfort temperature (Taki et al., 2001). This had again proven that the occupants in a warm country could tolerate a higher air temperature than what was predicted by the PMV model.

In 2001, McCartney and Nicol carried out another similar type of comfort survey in Europe. The result had concluded that human are able to adapt to their surrounding environment. There are many possibilities for human to adapt to their surrounding environment. It is more of a common sense and natural reaction. A person has a choice, whether to change him or herself to be able to adapt to the environment or to change the environment to suit them. (Nicol and Humphreys, 2001).

The results of an adaptive comfort survey might have possibly been influenced by three main contextual variables. The first variable would probably be the climate itself, which might influence the thermal attitudes and the culture of the community. The second variable would probably relate to the buildings, with respect to their design and the type of building services adopted, either they use individually controlled system

or a centralized system. The third variable would probably be time. Human activities, and the surrounding environment, change continuously through time. Therefore, it is important to take the time frame into consideration.

In 2001, Nicol and Humphreys stated ‘... *people have a natural tendency to adapt to changing conditions in their environment...*’. A phenomenon experienced by Michael Humphreys, which had supported the fact that thermal comfort does not have a fixed range of temperature. He has experienced it for himself during his visit to Pakistan where the outside temperature was approximately 40°C. As he entered a building, he sensed a relief of coolness, assuming the indoor temperature would be around 25°C. When the measurement of the indoor temperature was taken, the actual temperature was found to be 32°C. In United Kingdom, when the indoor temperature reaches 32°C, the indoor space would be considered to be too warm and uncomfortable. (Humphreys and Nicol, 2001).

The studies have shown that different regions on the globe have their own thermal comfort zone. The next section determines the thermal comfort zone for Malaysia and other tropical regions.

2.2.4 Thermal Comfort in Warm and Humid Tropical Countries

The purpose of this section is to determine the thermal comfort zone for Malaysia climate in terms of dry bulb temperature and relative humidity. Malaysian Department of Standards (2001) have suggested thermal comfort range and neutral temperature for air-conditioned non-residential buildings to be from 23°C to 26°C and 24.5°C respectively. The suggested comfort range and neutral temperature agree with ASHRAE (1992) Standard 55 and ISO 7730 (1994). In 2007, the Department of Standards Malaysia (2007) have suggested design value of relative humidity to be between 55% to 70% and air movement to be between 0.15m/s to 0.50m/s. In 2004, ASHRAE Standard 55 has a lower margin of relative humidity that expands the comfort temperature. When the relative humidity is as low as 10%, the suggested comfort range is from 25°C to 28°C, while when the relative humidity is 55%, the suggested comfort range is from 24°C to 27°C (ASHRAE, 2004).

Various researches have been carried out in search of the correct thermal comfort range for warm and humid climate such as Malaysia climate. These researches

investigated on occupants living in naturally ventilated (Table 2.8), air-conditioned or mixed both naturally ventilated and air-conditioned (Table 2.9) buildings.

Table 2.8: Comfort range of occupants in naturally ventilated buildings under hot and humid climate. *ET is Effective Temperature, T of an environment when RH is 50%.

Researcher	Year	Type of Study	Country	No. of Subjects	T _c , Comfort Temp, °C	RH (%), A/V (m/s)
Ellis	1952	Field Study	Between Singapore and Hong Kong	5211	26.1 ET Or T _c = 30°C and lower	50%
Ellis	1953	Field Study	Singapore	118	T _c = 24.4 - 29.4 ET = 21.7 - 27.2	
Webb	1959	Field Study	Singapore	20	T _n = 28.9	70%, A/V = 0.2m/s
Sharma and Ali	1986	Field Study	India (hot and humid)	18	26 - 31°C	30% - 70%
De Dear	1990	Field Study	Singapore	583	T _n = 28.5°C	
Abdul Shukor & Young	1993	Chamber	Penang, Malaysia	142	25.0 - 31.4 T _a	50
Zainal	1993	Chamber and Field Study	Johor, South Malaysia		23.0 - 33.0 T _a	55 - 80 average A/V = 0.15 - 0.2 m/s
Mallick	1996	Field Study	Bangladesh	400	T _n = 28.9	0m/s
					T _n = 31.6	0.45m/s
Abdul Rahman & Kannan	1997	Field Study	Subang Jaya, Malaysia	236	T _n = 27.4°C Comfort Range = 23.4 - 31.5°C	54% to 76%
Nicol et al	1999	Field Study	Pakistan	25	T _{globe} range = 21.0 - 31.0°C	

Table 2.8 continues.						
Abdul Rahman	2000	Field Study	Malaysia		Comfort range = 25.5 – 28.5°C	45% - 90%
					29.5°C	45%
Khedari et al	2000	Field Study	Thailand	183 male 105 female	T _n range = 27 – 31°C. A/V range = 0.1 – 1.68m/s	
Sapian et al.	2001	Field Study	Kuala Lumpur, Malaysia (multi-storey flats)		Comfort Range = 26.0 – 29.5	A/V = 0.5 – 1.0 m/s
Sh Ahmad	2002	Field Study	Malaysia (classroom)		T _n = 26.9°C Comfort Range = 25.1 and 30.1°C	
Wong and Khoo	2003	Field Study	Singapore (classroom)		T _n = 28.8 Comfort Range = 27.1 - 29.3oC	
Sh Ahmad	2005	TAS software	Malaysia		T _n = 26.1oC Comfort range (90% acceptance) = 23.6 – 28.6oC	

Table 2.8 continues.						
Md Zain et al	2007	Auliciem's equation	Malaysia		$T_n = 26.19$	At least A/V 0.7m/s
					Comfort range (80% vote) = 22.7 – 29.2oC	As low as 0m/s
Hussein and Abdul Rahman	2009	Field study	Malaysia	2 schools	$T_n = 28.4$ oC Comfort range = 26.0 – 30.7oC	A/V = 0.3 – 1m/s

Table 2.8 listed the findings of research that was carried out from 1952 to 2009 of the indoor thermal comfort range and neutral temperature for naturally ventilated buildings under warm and humid climate. The overall findings have shown that the neutral temperature, T_n ranges from 26.1°C to 28.9°C and the average T_n is 28.1°C. Meanwhile, the thermal comfort temperature ranges from 22.7°C to 33.0°C and the average upper limit of the thermal comfort temperature is 30.3°C.

Table 2.9 listed the found indoor thermal comfort range and neutral temperature for air-conditioned and mixed naturally ventilated and air-conditioned buildings in warm and humid climate from the year 1990 to 2009. The neutral temperature, T_n for ranges from 24.2°C to 27.5°C and the average T_n is 25.9°C. However, the thermal comfort temperature for air-conditioned or mixed naturally ventilated and air-conditioned room ranges from 20.8°C to 29.5°C. The average upper limit of the thermal comfort temperature is 28.3°C.

Table 2.9: Comfort range of occupants in air-conditioned and mix-mode (naturally ventilated with air-conditioned) buildings under hot and humid climate.

Researcher	Year	Type of Study	Country	No. of Subjects	T _c , Comfort Temp, °C	RH (%) or A/V (m/s)
De Dear	1990	Field Study	Singapore	235	T _n = 24.2	
Busch	1992	Field Study	Thailand	770 (A/C)	Comfort Range = Up to 28°C	
Zain Ahmed et al.	1997	Field Study	Shah Alam, Malaysia	283 (NV + A/C lecture rooms)	T _n = 26.27°C Comfort Range = 24.5 – 28.0°C	73%
Karyono	2000	Field Study	Jakarta, Indonesia	596 in 7 offices (NV, A/C and A/C + NV)	Overall T _n = 26.4°C Overall Comfort Range = 23.3 to 29.5°C	
Ismail & Barber	2001	Field	Penang, Malaysia	501 (100% AC office)	T _n = 24.6 Comfort Range = 20.8 – 28.6	40 – 80
Sh Ahmad and Ibrahim	2003	Field Study	Malaysia	237 (NV and A/C)	T _n = 26.9°C Comfort range = 24.4 – 29.4°C	
Kwong et al	2009	Field Survey, Auliciems equation and CFD simulation	Malaysia	113	T _{oper} range = 25.8 – 28.0°C Mean T _{oper} = 27.3°C T _n = 25.8°C Comfort range (80% acceptance) = 22.3 – 29.3°C	0.1 – 0.2m/s
Daghigh et al	2009	Field survey	Malaysia	14 rooms	T _n = 26.6 – 27.5°C	RH = 60 – 70

Table 2.9 continues.						
Hussein et al	2009	Field survey	Malaysia		$T_n = 24.4^\circ\text{C}$ Comfort range = 23.1 $- 25.6^\circ\text{C}$	

Findings in Table 2.8 and Table 2.9 have shown difference in neutral temperature and thermal comfort temperature range among buildings which are naturally ventilated, fully air-conditioned and mixed naturally ventilated and air-conditioned. The occupants living in air-conditioned building have less tolerance to high dry bulb temperature as compared to occupants living in naturally ventilated building. This is the reason for lower neutral temperature, T_n and thermal comfort temperature range in fully and partially air-conditioned building.

Comparing these results to Fanger's neutral temperature for Malaysia, the results of neutral temperature studies that had been carried out in Malaysia were different from those predicted by Fanger's calculation. The highest tropical neutral temperature found was 28.8°C , derived from the study carried out by Wong and Khoo. That is an increase of 3.1°C from Fanger's neutral temperature for Malaysia. However, the upper boundary of comfort zone ranges from 29.3°C to 30.1°C in Malaysia and Singapore.

2.2.5 Conclusion

This research had looked into innovative technologies, which had been implemented in buildings in Malaysia with aim to provide indoor thermal comfort. The purpose is to identify gaps of research findings specifically for indoor low energy cooling and analyze the viability of low energy Earth Pipe Cooling in providing thermally comfortable air movement. Therefore, this chapter also analyzes the thermal comfort air temperature range for buildings in Malaysia, with reference to results obtained by previous researchers.

CHAPTER 3 LITERATURE REVIEW: PASSIVE GROUND COOLING

Chapter 3 explains the fundamental of the proposed Ground Cooling technology, by analyzing facts gathered from background studies and related literature. After a thorough investigation on Malaysia thermal comfort and current available passive cooling methods in Chapter 2, to help reduce the energy demand in Malaysia, this chapter elaborates another cooling method, with hope it could be a better solution in cooling buildings in Malaysia with less demand on energy consumption. This thesis refers this cooling method as Earth Pipe Cooling Technology, which is a form of ground cooling and it has been successfully applied in temperate and hot and arid countries.

3.1 Heat Flow within the Earth

As a common physics law, heat normally flows from a hot object to a cold object. A simple explanation to this is by referring to a block that is warm at one end and cold at the other end. As the one end of the object warms up, its molecules start to vibrate strongly with increasing magnitude. As the atoms vibrate, their neighbours started to vibrate too until all atoms vibrates equally and achieve stable temperature throughout the block. This process is called Conduction.

A French Physicist named Joseph Fourier formed an equation that calculates the heat flow, Q , conducted through a certain material. Figure 3.1 presents the illustration explaining Fourier's Law of heat flow conduction. The related equation is as below:

$$Q = - \lambda * A * \frac{d\vartheta}{dx}$$

Equation 3.1: Fourier's Law equation on Flow of heat, Q

λ is thermal conductivity of the material, $Wm^{-1}K^{-1}$. A is the corresponding area of the block, m^2 . ϑ is the temperature difference between the cold plate and the warm plate in Figure 3.1, $^{\circ}C$ or $^{\circ}K$. x is the distance, m .

(Source: Banks, 2008).

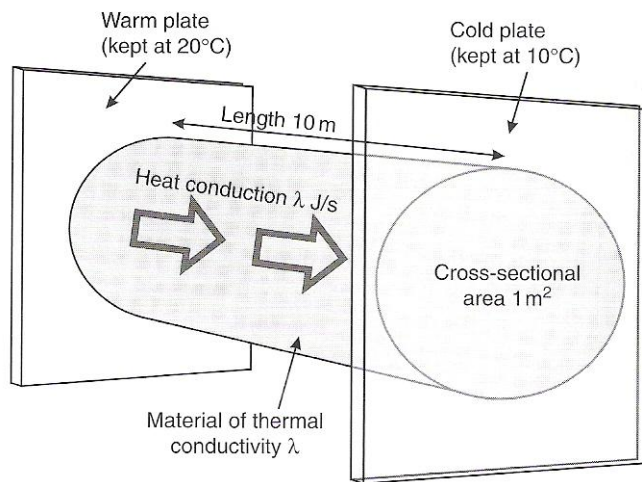


Figure 3.1: A diagram illustrating the conduction heat flow according to Fourier's Law. (Source: Banks, 2008).

Since this research concerns the heat capacity of the earth to store heat, the basic knowledge of heat flow within the earth and the structure of the earth is essential. It was proven there is a geothermal gradient between the earth surface and its core. In the 16th and 17th century, deep mining was initiated and the first geothermic measurements were taken by a French mine, de Gensanne in 1740 (Banks, 2008). The data shows the earth gets warmer with increasing depth below the ground surface. By relating this finding to Fourier's Law, it was reviewed that the earth must experience conduction of heat from the earth core to the earth exterior.

Figure 3.2 shows that the earth structure comprises of four layers. The first layer is the solid inner core, which is a metallic iron-nickel with radius of 1370km. The second layer is a molten outer core, which consists of iron-nickel, with thickness of 2100km. The third layer is the mantel which is composed by ultrabasic iron, Fe and rich amount of magnesium, Mg. The total thickness of the third layer is 2900km. The fourth layer is a relatively very thin crust, which is between 15 to 50km thickness below the continents, and 5 to 8km below the ocean (Banks, 2008).

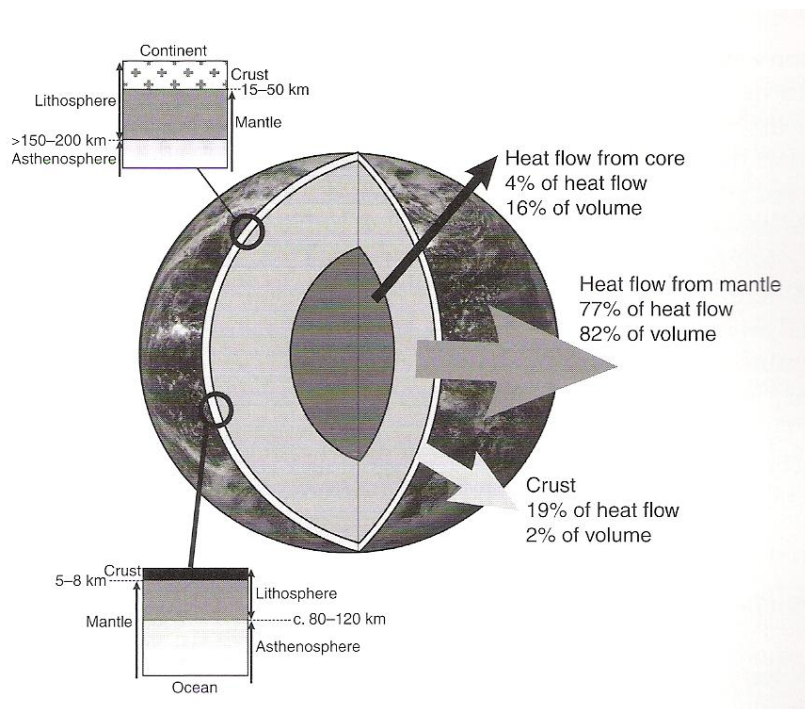


Figure 3.2: Structure of the earth demonstrating the thicknesses of earth surface layers and the percentage of volume and heat flow from each main layer (Source: Banks, 2008).

Referring to Fourier's Law equation, the amount of heat flow through the earth structure should depend on the conductivity of the earth structure.

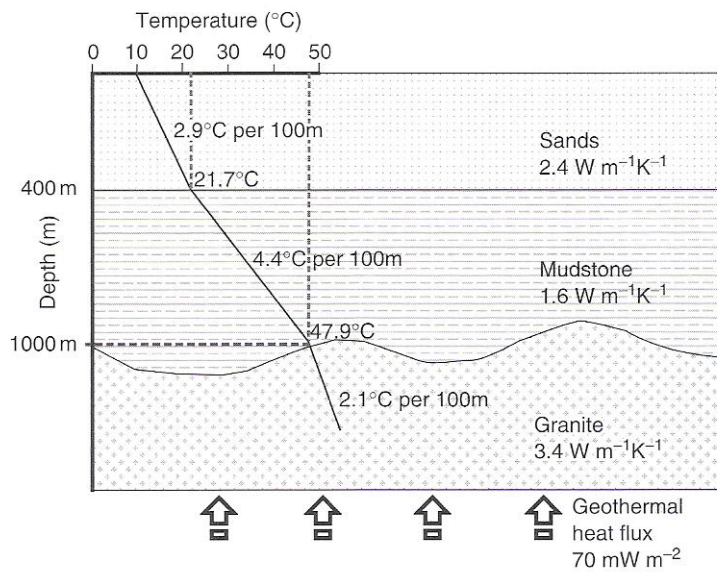


Figure 3.3: An example of geothermal gradient through a sample of earth structure (Source: Banks, 2008).

Figure 3.3 illustrates a sample of heat flow through layers of earth structure with different types of rock. Rocks differ in thermal conductivity and therefore, different rocks perform different geothermal gradient. This figure has shown that the earth gets cooler as the depth decreases. However, the diagram did not consider the heat gain from the solar radiation at the earth surface.

Malaysia weather is hot and humid throughout the year and there is certainly solar radiation in most days apart from rainy periods of the day. Therefore the earth surface of Malaysia certainly gained heat from the sun and with a large heat capacity, earth surface can easily store heat. Therefore at certain point within the shallow depth of earth, there should be equilibrium between the heat flow from the core and the heat gain from the sun through the earth surface.

3.2 Heat Storage Capacity of the Earth Subsurface

The previous section has led to the study of heat storage capacity of the earth subsurface, the shallow depth below the earth surface. The subsurface soil temperature depends on the conductivity of the related rock layer and also its heat storage capacity.

Table 3.1: Thermal conductivity and volumetric heat capacity of rocks and air. (Source: Banks, 2008).

Rocks and sediments	Thermal conductivity ($\text{Wm}^{-1} \text{K}^{-1}$)	Volumetric heat capacity ($\text{MJm}^{-3}\text{K}^{-1}$)
Coal	0.3	1.8
Limestone	1.5-3.0 (2.8, massive limestone)	1.9-2.4 (2.3)
Shale	1.5-3.5 (2.1)	2.3
Wet Clay	0.9-2.2 (1.6)	2.4
Basalt	1.3-2.3 (1.7)	2.4-2.6
Diorite	1.7-3.0 (2.6)	2.9-3.3
Sandstone	2.0-6.5 (2.3)	2.0-2.1
Gneiss	2.5-4.5 (2.9)	2.1-2.6(2.1)
Arkose	2.3-3.7 (2.9)	2.0
Granite	3.0-4.0 (3.4)	1.6-3.1 (2.4)
Quartzite	5.5-7.5 (6.0)	1.9-2.7 (2.1)
Air	0.024	1.29×10^{-3} at 1atm

Table 3.1 has shown that the rocks at the subsurface have high value of volumetric heat capacity but low value of thermal conductivity. Therefore, the heat is rather stored than diffuses through the soil in the upstream.

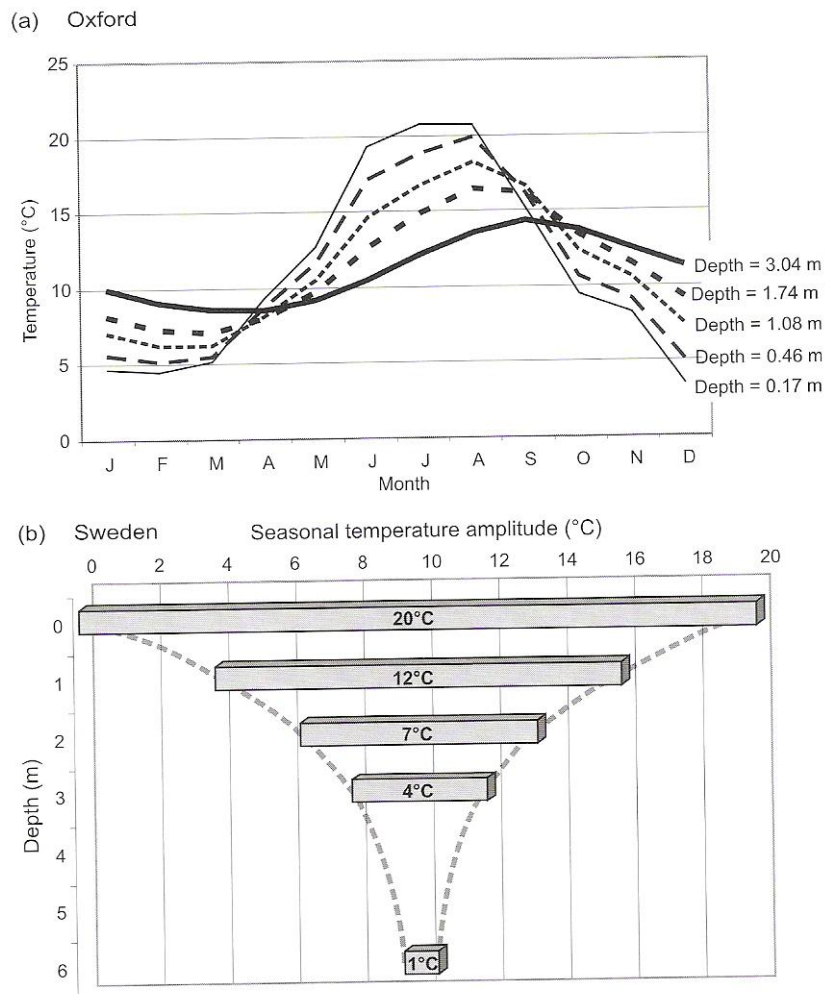


Figure 3.4: Seasonal soil temperature amplitude in Oxford (a) and Sweden (b) at increasing depths below ground. (Source: a) Rambaut, 1900 in Banks, 2008; b) Rosen et al., 2001 in Banks, 2008).

Figure 3.4 (a) shows that the soil temperature amplitude decreases with increasing depth below the ground in Oxford. Oxford is located in a temperate country with winter from December to March, and Summer from June to August. There are several soil temperature behaviour found in the graph in Figure 3.4 (a). The soil temperature was measured and recorded at 0.17m, 0.46m, 1.08m, 1.74m, and 3.04m. In all graphs, the curve peaked during the summer months and reduced to its minimum within the winter months. However, Figure 3.4 (b) shows that the amplitude of the annual monthly average soil temperature decreases with depth. This shows the influence

of the hot ambient air temperature and high solar radiation to the soil. Figure 3.4 (b) shows that the soil temperature is stable at 6m depth underground in Sweden. This research investigated about Malaysia soil temperature gradient at the subsurface.

The knowledge of the heat flow within the earth structure has helped in understanding the heat transfer between the earth and the air flow within a pipe buried underground.

3.3 Passive Ground Cooling

The infinite thermal capacity of earth has made it a very useful heat sink for building cooling or even heating purposes. This fact has been studied and proven by several researchers (Mihalakakou et al., 1995). The rationale behind this is due to the daily and seasonal temperature variations, which is greatly reduced in the ground with increasing depths up to a depth where the soil temperature remains constant throughout the year (Krarti and Kreider, 1996). The constant soil temperature is usually approximately equal to the mean annual air temperature (Labs, 1981 in Krarti and Kreider, 1996). In winter, the soil temperature increases with increasing depth up to a certain depth and hence the use of earth as a heat source. Meanwhile, in summer, the soil temperature decreases with increasing depth, which provides the use of earth as a heat sink (Krarti and Kreider, 1996).

This research is for Malaysia climate, which is hot and humid and therefore, this study will focus on building cooling rather than heating. There are two main strategies for Passive Ground Cooling; the direct earth contact and the indirect earth contact (Jacovides et al., 1996).

“(i) the direct contact, which involves partial or total placing of the building envelope in direct contact with the ground surface, and (ii) the indirect contact, which involves the use of an earth-to-air heat exchanger system through which air from indoor and outdoor of a building or an agricultural greenhouse is circulated and then is brought into the building or the greenhouse.” (Mihalakakou et al.,1997).

The direct earth-to-building contact ground cooling has many advantages in its performance. It is a low maintenance passive cooling strategy with minimal heat gains and solar exposure. Underground houses were built in southern Tunisia and eastern Spain to protect occupants from their hot and arid climates and large houses were

excavated in northern China to cope with severe winter climate (Krarti and Kreider, 1996).

In some places on the globe such as desert and semi-desert countries, large excavation is not suitable due to their geological condition. Therefore, other technique was introduced in Iran (1978), which is the indirect-to-building contact ground cooling. In this country, the air is channeled through tunnels buried underground into the building with the aid of wind towers (Krarti and Kreider, 1996). Krarti and Kreider (1996) also stated that low energy cooling or heating technique using earth became increasingly popular in Europe and America after the oil crisis in 1973.

Despite the advantages of the direct-to-building contact ground cooling, it also creates environmental problem such as indoor condensation and poor indoor air quality (Labs, 1990) and (Jacovides et al., 1996). Malaysia, being a hot and humid climate has a very high humidity level and indoor condensation would be a serious problem to the indoor environment. Furthermore, Malaysia has a low average air velocity throughout the year and having a direct earth contact to the building method would minimize the number of openings, which result in reduction of natural ventilation into the building and hence an even lower air velocity. Therefore, considering the potential consequences of direct earth contact ground cooling and that the indirect earth contact ground cooling was projected to be less risky, this research investigates on the latter ground cooling strategy, which this research refers to as Passive Low Energy Earth Pipe Cooling Technology.

Buried pipes can be arranged in two ways; open loop and close loop. The latter pipe arrangement can reduce the tunnel length since the conditioned air is re-circulated within the buried pipe (Goswami and Biseli, 1993). However, this research investigated on the open loop buried pipe, which helps understand the Earth Pipe Cooling performance better since the system application is rather new in Malaysia. In some cases, the Earth Pipe Cooling system is assisted with a heat pump as a heat exchanger located within the buried pipe. It can increase cooling capacity and hence improve the coefficient of performance (Goswami and Biseli, 1993).

3.4 Passive Low Energy Earth Pipe Cooling

The Earth Pipe Cooling system works with a long buried pipe with one end for the ambient air intake and the other end for providing cooled air to the desired space. The pipe is buried underground at the ultimate depth that could give most efficient results, but with the two pipe ends above ground. This technology uses the ground as a heat sink for cooling purposes in warm countries where the channelled ambient air, via the buried pipe, transfers excess heat to the ground by convection. There should be adequate air flow into the buried pipe intake to produce cool air at the other pipe end for occupants' thermal comfort. If there is insufficient air flow, a fan blower is needed at the buried pipe air intake to stimulate the air flow.

3.4.1 Factors that affect Earth Pipe Cooling performance

As a conclusion from various published literature, the performance of Earth Pipe Cooling are affected by four main parameters and they are:

1. pipe length;
2. pipe radius or diameter;
3. depth of the pipe inserted into the ground;
4. air flow rate inside the pipe.

Many researchers found that the resulting temperature at the buried pipe outlet decreases with increasing pipe length, decreasing pipe diameter, decreasing mass flow rate of flowing air in the pipe and increasing depths up to 4m (Santamouris et al., 1995) and (Ghosal and Tiwari, 2006).

a) Effect of pipe length

Commonly, the results from various researchers in the past have shown that Earth Pipe Cooling systems with different pipe lengths perform differently. The findings have proven that a longer pipe provides lower air temperature at the buried pipe outlet. Mihalakakou et al. (1994) compared Earth Pipes of 30m, 50m and 70m long and found that the pipe exit temperature reduces when the pipe length increases. Santamouris et al. (1995) carried out Earth Pipe Cooling study to cool a 1000m² agricultural greenhouse in

Athens, Greece, comparing two different pipe lengths; 10m and 50m. The result has shown that the air temperature at 50m pipe outlet is 2°C lower than at the 10m pipe outlet. Similar results were found in a study carried out by Ghosal and Tiwari (2006), also at a greenhouse but in Delhi, India. The rationale behind the better performance of a longer pipe was due to the longer pipe allowing the air to circulate underground for a longer time and hence transfer more excess heat into the earth. Meanwhile, pipe lengths are sometimes limited by economic matters. To have the cooling system efficient, it should not be costly and longer pipes tend to cost higher.

Hanby et al. (2005) approached the Earth Pipe Cooling study in a slightly different way. He has combined the system performance with the cost by calculating a payback time to find the efficiency economical. In his study in hot, arid Kuwait, Hanby et al. have found that the optimum pipe length is 56.97m alongside pipe diameter of 0.35m buried at 5.47m deep underground, gives a payback time of 7.24 years to cover the cost of building the Earth Pipe Cooling system (Hanby et al., 2005).

b) Effect of pipe radius or diameter

Another parameter listed as the main factor of Earth Pipe Cooling system performance is the buried pipe radius. Mihalakakou et al. (1994) tested the performance of three buried pipes of different radius; 0.125m, 0.180m and 0.250m. The result found that the increasing pipe radius result in higher air temperature range at the buried pipe outlet. The author concluded the reason for this is because a bigger pipe radius reduces the convective heat-transfer coefficient and hence the higher temperature at the buried pipe outlet (Mihalakakou et al., 1994). Santamouris et al. (1995) has stated that the pipe with the smallest radius performs best. In his opinion, based on his test results, when the radius is small, the centre point of the pipe gets closer to the soil outside, allowing a faster transfer of excess heat from the air to the soil. Ghosal and Tiwari (2006), agreeing with the previous studies, have stated that pipe outlet temperature can be reduced with decreasing pipe diameter.

In a published paper by Krarti and Kreider (1996), they have explained an equation that shows the relationship of heat transfer coefficient, U_s and the buried structure radius r_o ;

$$U_s = k_s/r_o \quad (\text{Equation 3.2})$$

Where k_s = ground conductivity

r_o = radius of the buried structure

(Carslaw and Jaeger, 1959 in Krarti and Kreider, 1996)

From the equation, Krarti and Kreider (1996) concluded that when the buried structure is small, the heat transfer coefficient increases. Therefore, according to the developed Equation 3.2, smaller structure transfers heat more easily into the ground. Krarti and Kreider (1996) carried out a study on the effect of pipe diameter towards the buried pipe outlet temperature using a developed numerical model, which was validated against an experimental data set. The various diameters were 0.1m, 0.2m, 0.4m and 0.8m and the result shows the lowest temperature range at buried pipe outlet were from the 0.1m diameter pipe.

However, when the radius is small, the air pressure inside the pipe increases and hence provides faster air flow. If the air flow inside the pipe is too fast, the channelled air would not have adequate time underground to dissipate the excess heat onto the earth, unless the pipe is long enough. Again, there has to be balance between these parameters to achieve efficient passive cooling.

c) Effect of pipe depth buried underground

Increasing soil depths equals to decreasing amplitude of daily or diurnal soil temperature due to the distance of soil from the soil surface and ambient air. This then influences the temperature of air circulating in the buried pipe. Therefore, the air temperature at the pipe outlet has decreasing amplitude throughout the day or a year with increasing depth it is buried.

Mihalakakou et al. (1994) carried out a study on Earth Pipe Cooling with three different soil depths; 1.2m, 2m, and 3m and has found that pipe buried at 3m provide the lowest temperature range and the pipe outlet. Mihalakakou et al. (1994) carried out another study on buried pipes at different depths; 2.5m, 4m and lower than 4m. The finding shows that the pipe outlet temperature decreases as the depth increases. The pipe outlet temperature stops decreasing when the pipe was buried beyond 4m deep because the ground temperature became stable (Mihalakakou et al. 1994).

d) *Effect of air flow rate inside the pipe*

Similar to other parameters, several researches has found that it does affect the Earth Pipe Cooling performance. In 1994, Mihalakakou et al. also performs investigation on the effect of air flow rate in the buried pipe. They compared three air velocities, namely 5m/s, 10m/s and 20m/s. The findings have shown that increasing air velocity result in increasing air temperature at the buried pipe outlet. The reason given was due to the increased mass flow rate (Mihalakakou et el., 1994).

Krarti and Kreider (1996) also did a parametric study using a developed numerical model on the effect of air flow rate within the buried pipe towards the temperature at the buried pipe outlet. They compared four different air velocities; 3.5m/s, 14m/s, 31.5m/s and 56m/s and 3.5m/s air velocity produce the lowest outlet temperature range. However, the various selected air velocity were unusual.

Another study on the effect of air flow to the performance of Earth Pipe Cooling system was carried out by Bansal et al. (2010) recently. They have tested air velocity ranges from 2m/s to 5m/s. The result agrees with previous researches that when the air velocity is increased, the out temperature in summer increases. This lead to the reduction of temperature difference between pipe inlet and outlet, which then makes the coefficient of performance (COP) reduced (Bansal et al., 2010).

e) *Multiple Parallel Buried Pipes*

Several researches on Earth Pipe Cooling technique have considered the potential of having multiple parallel buried pipes rather than increasing the buried pipe length. This introduces another issue on the adequate distant between the buried pipes to prevent from heat transfer interference. Mihalakakou et al. (1994) investigated the performance of multiple buried pipes arranged in parallel. Various distances between the buried pipes were tested and the distances were 0.5m, 1.5m, 2.5m and 5m. From their result, it has shown that the buried pipe outlet temperature decreases when the distance is further apart.

In 2003, Paepe and Janssens carried out a one-dimensional analytical method to determine optimal dimensions of the buried pipes to perform efficiently with low pressure loss. The study consists of parametric study on number of pipes, pipe diameter, pipe length and pipe arrangement within the soil, whether in parallel or serpentine

manner. In comparison, when there are 3 buried pipes arranged in parallel, with diameter 200mm and length 25m, provided air flow is 2.2m/s, the pressure loss was 8 Pa. Meanwhile, when there is only 1 buried pipe in serpentine manner, with diameter 250mm and length 38m, and provided air flow is 4.2m/s, the pressure loss is 32Pa. This shows that with the slight reduction in pipe diameter and multiplied number of buried pipes, the pressure loss can be reduced by 4 times.

However, when the diameter is halved; 100mm and there were 4 buried pipes in parallel manner, which was 14m long each and provided with air velocity 6.6m/s, the pressure loss increases up to 77Pa. Therefore, the diameter can be reduced but too much reduction would lead to increase in pressure loss. Therefore, it is concluded that with the reduced buried pipe diameter, the Earth Pipe Cooling system performance increases with a possibility of pressure loss increment. To reduce the pressure loss increment, the buried pipe should be multiplied (Paepe and Janssens, 2003).

Fisher and Rees (2005) have investigated the effect of multiple number of boreholes on the performance of a water-to-water ground source heat pump system by modelling the system in a building energy simulation program called EnergyPlus. In the program, Fisher and Rees (2005) compared the wall temperature of three ground loop heat exchanger configurations; 16, 32 and 120 boreholes. Data of 20 years were tabulated onto a graph. It was found that throughout 20 years, the borehole wall temperature increases. However, the configuration with 120 boreholes had the least borehole wall temperature increment over 20 year period. Therefore, multiple loop heat exchanger could help minimize the outlet temperature increment of an Earth-air Heat Exchanger over a period of time.

Recently, Badescu and Isvoranu (2011) studied the performance of multiplied parallel Earth Pipe Cooling system using the simulation software CFD, which the result was validated against experimental results. Apart from reducing heating and cooling load of a building, the objective of the research was also to minimize air pressure drop inside the buried pipe, which could reduce fan energy consumption. Since single pipe requires large air flow rate that leads to large pressure drop, the study recommended the use of multiple parallel buried pipes. However, there are two types of parallel pipes named the Z-path and the π -path. The Z-path channels the outlet air away from the pipe inlet but in the same direction of the air flow into the pipe. Meanwhile, the π -path is

similar to a U-shape buried pipe where the pipe channels the outlet air back to the side of the pipe inlet but in the opposite direction of the air flow into the pipe inlet. From the result, the π -path have less air pressure loss than the Z-path (Badescu and Isvoranu, 2011).

f) *Other parameters: Soil surface condition, pipe material*

Another important factor that could affect the performance of Earth Pipe Cooling system is the surface condition of the ground. A bare ground surface would allow exposure to solar radiation particularly in hot climate like in Malaysia. The heat from the solar radiation onto the ground surface dissipated into the soil, which makes the soil warmer than the soil under grass or shaded ground surface.

In 1994, Mihalakakou et al. carried out a study on Earth Pipe cooling potential of a single and multiple earth-to-air heat exchanger under bare soil and short grass covered soil. The study was carried out using a numerical model which has been validated against a set of experimental data. The validation has proven that the numerical model predicts accurate temperature and humidity of the circulated air, soil temperature and moisture and also the overall thermal performance of Earth Pipe Cooling. From his research findings, he concluded that short grass covered soil provides a higher cooling capacity for both the single and multiple earth-to-air heat exchanger (Mihalakakou et al., 1994). However, both soil conditions provide cooler air temperature at the buried pipe outlet than ambient air temperature.

In 1996, Jacovides et al. carried out an observation on soil temperature profile of two different soil surfaces; short grass covered soil and bare soil in Greece, which was recorded from 1917 to 1990. The results was analysed through Fourier analysis. For the bare surface soil, the monthly mean maximum temperature was 38°C while the minimum was 9°C. On the other hand, the monthly mean maximum temperature for the grass covered soil was 31°C and the minimum was 8°C. The result has shown that during winter, there is only 1°C difference in soil temperature between the two different soils. However, during summer, there was a significant difference of 7°C in soil temperature between the two soils (Jacovides, 1996). The mean air temperature was measured simultaneously as the soil surface temperature and it ranges from 9°C to 31°C. From this result, it has shown that the mean soil surface temperature of bare soil in

summer is higher than the mean air temperature. This must have been the effect of high solar radiation on un-shaded or uncovered soil during the hot summer months.

Givoni has carried out a similar study in 2007. In his paper, he has compared the soil temperatures under two different coverings; shaded by a raised building and by tall grass. The results have shown that the soil temperature under the raised building is around the minimum Dry Bulb Temperature of the day, while the soil temperature under the tall grass is around the average Dry Bulb Temperature of the day. Therefore, the soil under a raised building has a lower temperature than the soil under a tall grass (Givoni, 2007). Givoni's finding can be applied in Malaysia vernacular houses since these houses are mostly built on stilts, hence shading the soil underneath and allowing breeze to pass above the shaded soil (Section 2.1.2, Figure 2.9).

There has been another situation of soil covering that is when the Earth Pipe Cooling system is buried below the building itself. The soil temperature should be different from soil under bare, short grass covered or even shaded condition since the soil is not exposed to any solar radiation as well as night breeze. Mihalakakou et al. (1995) has predicted soil temperature at various depths below a building using a numerical model in TRNSYS environment and the data has been validated with a set of experimental data. This method is described further in Section 2.4.2.

Despite the five parameters, another performance factor is the choice of pipe materials. However, Goswami et al. (1981) has shown that different pipe materials have minor effects on the Earth Pipe Cooling system performance (Goswami and Biseli, 1993). However, the conductivity of each material varies and therefore, this theory was re-assessed again in this thesis.

3.4.2 Application of Earth Pipe Cooling

“High thermal efficiencies associated with the use of buried pipes in which the system's cooling capacity covers 100% of the building's cooling needs....”
(Jacovides et al., 1996)

The above quote was referred to experiments carried out in Athens, Greece, which is a temperate country with large annual ambient air temperature range. Table 3.2 to 3.5 summarizes application and the outcome of Earth Pipe Cooling system in various investigations by other researchers.

Table 3.2: List of applied Earth Pipe Cooling system and the outcome with reference to output temperature in °C.

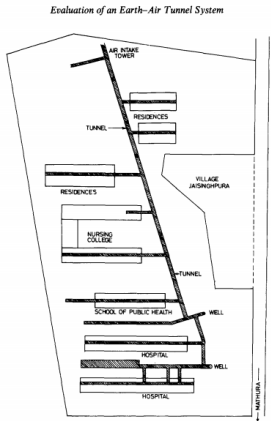
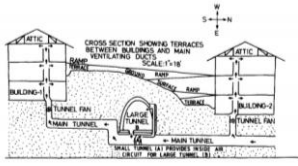
Researcher (year)	Location	Buried Pipe Design	Ambient T, °C	Output T, °C
<p>Sodha et al. (1985)</p>  <p>Schematic Earth-Air tunnel system in Mathura, India (Sodha et al., 1985)</p>  <p>Cross-section of Earth-Air tunnel system in Mathura, India (Sodha et al., 1985)</p>	<p>Mathura, near Delhi, India</p>	<p>1 main tunnel + several subs tunnels = 80m</p> <p>Cross-section area = 1.05 x 0.75m</p> <p>Air velocity = 4.89m/s</p> <p>2 exhaust fans = 500W each connected to skylight.</p>	<p>24°C to 43°C</p> <p>RH = 40% to 53%</p> <p>Inlet DBT = 29.1°C to 36.1°C</p>	<p>Outlet DBT = 23.1°C to 28.2°C</p> <p>Outlet RH = 75% to 89%</p> <p>Therefore, no condensation was observed.</p>

Table 3.2 continues.				
Goswami and Biseli (Summer, 1993)	Florida, USA	0.305m dia, 30.5m long pipe. 2.7m deep. 0.184 kW fan blower and 2 ½ ton heat pump	Summer: 23.9°C to 33.1°C	Reduced from 32.2°C to range of 26.7°C to 28.3°C. 3.9°C to 5.5°C reduction.
Mihalakakou et al. Model for TRNSYS and validated (July and August, 1994)	Greece	4 plastic pipes. 0.125m radius. 30m length. 1.5m depth. Gap between 2 pipes = 1.5m. Air Velocity = 1m/s	July: 23.2°C to 40°C August: 25.3°C to 39.3°C	Outlet Temp.: July: 24.1°C to 28.2°C August: 25.4°C to 29.7°C
Pfafferott Field Experiment (Cooling season 2003)	DB Netz AG (Hamm)	26 Polyethylene Ducts, 67- 107m long. Diameter = 200 and 300mm Air velocity = Approx. 2.2m/s Max Outlet T set to 19°C	Inlet Temperature: 22°C to 34°C	Outlet Temperature: 10°C to 19°C

Table 3.2 continues.				
Pfafferott Field Experiment (Cooling season 2003)	Fraunhofer ISE (Freiburg) (Open loop)	7 Polyethylene Ducts, 95m long Diameter = 250mm Air velocity = 5.6m/s	Inlet Temperature: 22°C to 35°C	Outlet Temperature: 13°C to 24°C
Tiwari et al. (Summer, 2006)	Lamparter (Weilhem) (Close loop)	2 Polyethylene ducts, 90m long each. Diameter = 350mm Air velocity = 1.6m/s.	Inlet Temperature: 22°C to 34°C	Outlet Temperature: 10°C to 22°C
Bansal et al. CFD Model inside FLUENT (Summer, 2010)	Ajmer, Western India	Mild Steel and PVC pipe. 23.42m long each. Depth= 2.7m. A/V= 2-5m/s. Diameter= 0.15m. Blower= 2800RPM and 0.033m ³ /s	Inlet T= 43.1°C	Temperature drop range: 8.0°C to 12.7°C.

Table 3.3: List of applied Earth Pipe Cooling system and the outcome with reference to the optimal system design.

Researcher (year)	Location	Buried Pipe Design	Ambient T, °C	Optimal System Design
Goswami and Biseli (Summer, 1993)	Florida, USA	0.305m dia, 30.5m long pipe. 2.7m deep. 0.184kW fan blower and 2 ½ ton heat pump	Summer: 23.9°C to 33.1°C	Single Pipe = 0.305m diameter Multiple Pipe = 0.203m to 0.254m diameter
Mihalakakou et al. (simulation using TRNSYS, validated against a set of field data) (Summer, 1994)	Athens, Greece Bare soil and short grass covered soil.	Radius: 0.125m, 0.180m, 0.250m Length: 30m, 50m, 70m Depth: 1.2m, 2.0m, 3.0m A/V: 5m/s, 10m/s, 20m/s	Summer: 21°C to 38°C	Soil condition: Short grass cover Radius: 0.125m Length: 70m Depth: 3.00m A/V: 5m/s
Krarti and Kreider (uses a numerical model) (1996)	USA	Radius: 0.1m, 0.2m, 0.4m and 0.8m. A/V: 3.5m/s, 14m/s, 31.5m/s and 56m/s Depth: 1.5m Length: 80m	Mean: 19°C Amplitude: 9°C	Radius: 0.1m A/V: 3.5m/s

Table 3.4: List of applied Earth Pipe Cooling system and the outcome with reference to energy saving.

Researcher (year)	Location	Buried Pipe Design	Ambient T, °C	Energy Saving
Goswami and Biseli (Summer, 1993)	Florida, USA	0.305m dia, 30.5m long pipe. 2.7m deep. 0.184kW fan blower and 2 ½ ton heat pump	Summer: 23.9°C to 33.1°C	Open Loop COP= 12 COP (air-cond)= 1 to 4. COP is coefficient of performance With Heat Pump COP = 13
Kumar et al. (June, 2003)	Mathura, India	Room size: 4x4x4m, 4 occupants Length: 80m Inlet area: 0.53m ² A/V: 4.9m/s		
Sodha et al. (1985)	Mathura, near Delhi, India	1 main tunnel + several subs tunnels = 80m Cross-section area = 1.05 x 0.75m Air velocity= 4.89m/s 2 exhaust fans = 500W each connected to skylight.	24°C to 43°C RH = 40% to 53% Inlet DBT = 29.1°C to 36.1°C	No of rooms can be cooled = 7 of 16m ² floor area of each room. N= (cooling capacity)/(heat flux into the room), N= no of rooms

Table 3.4 continues.

Pfafferott Field Experiment (Cooling season, 2003)	DB Netz AG (Hamm)	26 Polyethylene Ducts, 67-107m long. Diameter = 200 and 300mm Air velocity = Approx. 2.2m/s Max Outlet T set to 19°C	Inlet Temperature: 22°C to 34°C	COP: 88
	Fraunhofer ISE (Freiburg)	7 Polyethylene Ducts, 95m long Diameter = 250mm Air velocity = 5.6m/s Open loop	Inlet Temperature: 22°C to 35°C	COP: 29
	Lamparter (Weilhem)	2 Polyethylene ducts, 90m long each. Diameter = 350mm Air velocity = 1.6m/s. Close loop	2Inlet Temperature: 22°C to 34°C	COP: 380

Table 3.4 continues.				
Bansal et al. CFD Model inside FLUENT (Summer, 2010)	Ajmer, Western India	Mild Steel and PVC pipe. 23.42m long each. Depth= 2.7m. A/V= 2-5m/s. Diameter= 0.15m. Blower= 2800RPM and 0.033m ³ /s	Inlet T= 43.1°C	COP: 1.9 to 2.9

The definition of Coefficient of Performance (COP) is quoted as below;

“Ratio of work or useful output to the amount of work or energy input, used generally as a measure of the energy-efficiency of air conditioners, space heaters and other cooling and heating devices. COP equals heat delivered (output) in British thermal units (Btu) per hour divided by the heat equivalent of the electric energy input (one watt = 3.413 Btu/hour) or, alternatively, energy efficiency ratio divided by 3.413. The higher the efficiency COP, the higher is the efficiency of the equipment.”
(www.businessdictionary.com)

The findings of Earth Pipe Cooling investigation carried out by Pfafferott (2003) in three different location has given three comparative Coefficient of Performance (COP) values; DB Netz AG is 88, Fraunhofer ISE is 29 and Lamparter is 380. The COP of Earth Pipe Cooling system in Lamparter is high due to the large pipe diameter, low air velocity and the close loop system (see Table 3.4). The COP of Earth Pipe Cooling system in DB Netz AG is fairly high also due to the low air velocity through the buried pipe. Meanwhile, the COP of Fraunhofer is comparatively very low because there was a high pressure loss occurred through the buried pipe.

Table 3.5: List of applied Earth Pipe Cooling system and the outcome with reference to payback time.

Researcher	Year	Location	Buried Pipe Design	Ambient T, °C	Payback time (years)
Goswami and Biseli (Summer, 1993)	Summer, 1993	Florida, USA	0.305m dia, 30.5m long pipe. 2.7m deep. 0.184kW fan blower and 2 ½ ton heat pump	Summer: 23.9°C to 33.1°C	Open Loop (Corrugated plastic pipe) = 4
					Open Loop (Steel pipe) = 5
					Heat Pump (Corrugated plastic pipe) = 17
					Heat Pump (Steel pipe) = 22

3.4.3 Limitations

The indirect earth contact ground cooling may get away from having the consequences of high risk indoor condensation but there is the risk of condensation in the buried pipe. The pipe is embedded in a cool soil with warm air passing through the pipe. This allows condensation to occur on the inner surface of the pipe. One way to tackle this problem is by tilting the pipe slightly a few degrees, which could allow the water condensed drain away through a tiny hole (Santamouris et al., 1995).

In 2001, Thanu et al. have recorded the effect on indoor humidity caused by the earth pipe cooling system. The result had shown that there is an increase of 8.7% of relative humidity. The average relative humidity of the ambient air ranges from 18.6% to 66.2% and the average relative humidity of the measured room ranges from 26.5% to 74.9%. Meanwhile, the air inside the buried pipe increased in humidity by 10.9%, comparing the difference in relative humidity between the suction point and delivery point of the buried pipe. However, the maximum relative humidity at the delivery point

was 2% higher than the relative humidity of the measured room. Therefore, there is a reduction of humidity between the delivery point and the whole room (Thanu et al., 2001). From this study, it should be kept in mind that the air could get more humid as it passes through the earth-air-pipe cooling system.

3.5 Common Research Methods for Earth Pipe Cooling Investigation

3.5.1 Field Experiment

a) Soil temperature measurement

Knowledge of soil temperature is important in the design of underground air tunnel system (Goswami and Biseli, 1993). Goswami and Biseli measured soil temperature at 6, 9 and 12 feet (1.83, 2.74 and 3.66m) below the surface in Gainesville and it was found that the soil temperature stays fairly constant, approximately equal to the average annual air temperature, at 10ft (3.05) or more. These data was reported suitable for use in all locations in Florida without significant errors.

Dhaliwal and Goswami (1985) calculated the surrounding soil temperature along a circular pipe using a time increment procedure and the numerical model result is validated against a set of experimental data (Karti and Kreider, 1996). There is a report on the soil temperature within 1.0m proximity of the circular pipe being increased in long term due to the heat dissipation from the pipe effect (Li et al., 2009). Therefore, apart from measuring the undisturbed soil at various depths, soil along the circular pipe within 1.0m proximity is also measured at the same time and both results were compared.

b) Earth pipe cooling experiment

Earth pipe cooling technology investigation is usually carried out either in field experiment or simulation using computer modeling software. However, the latter option of investigation has always been validated against field experiment data.

Goswami and Biseli (1993) investigated the system in a field experiment. At the earth pipe cooling construction, a trench was dug out using a backhoe. The pipe was assembled as much as possible before being buried into the trench. Once the pipe burial completed, a fan blower is attached to one end of the pipe. Part of the investigation is to

look at the system performance with the fan pushing the air and the fan pulling the air through the tunnel. The findings shows that the fan pushing the air through the tunnel worked the best and therefore, the fan blower is best placed at the pipe inlet.

3.5.2 Computer Modelling

In 1995, Mihalakakou et al. developed a parametrical model inside a TRNSYS environment and concluded that the model can accurately predict the thermal performance of the earth pipe cooling by having it validated against a set of experimental data. The necessary inputs for the model is the four parameters, namely pipe length and radius, the air velocity within the pipe and the depth of the buried pipe underground (Mihalakakou et al., 1995)

In the same year, Mihalakakou et al. (1995) has developed another numerical model inside a TRNSYS environment to predict the soil temperature at various depths below a building.

Kumar et al. (2003) developed a numerical model within a different tool, named Matlab through the techniques of Finite Difference and FFT. The researchers improved the model of previous studies by taking into account of other influencing factors such as the soil temperature, soil surface conditions, soil moisture content and design aspects of earth pipe cooling system. The model is then validated against experimental data of a similar earth pipe system set up in Mathura, India and then it is used to predict the performance of Earth Pipe Cooling in India. The improvised model also considers the latent heat transfer between the earth pipe wall and air, which enables the model to predict the humidity variations of air in the earth pipe. Simultaneously, the model also considers heat transfer from the conditioned earth pipe onto the soil surrounding the earth pipe.

Lee and Strand (2006) investigated the performance of an Earth Pipe Cooling System by developing a new module and implementing it into EnergyPlus computer modelling program. EnergyPlus is a simulation engine that comprises a combination of most popular features and capabilities found in simulation software BLAST and DOE-2.1E (Crawley et al., 2005). The simulation engine has a simple input and output if the form of simple text files. The program contains two basic module, which are building system simulation module and heat and mass balance simulation module. Crawley et al.

(2005) have tabulated features and capabilities of all available computer simulation software and EnergyPlus have 71% of all features and capabilities. EnergyPlus Earth Pipe model was validated by plotting alongside the data from experiments carried out by Dhaliwal and Goswami (1984) and Al-Ajmi et al. (2005). The data from EnergyPlus have similar temperature trend with both field experiments data (Figure 3.5) (Lee and Strand, 2008).

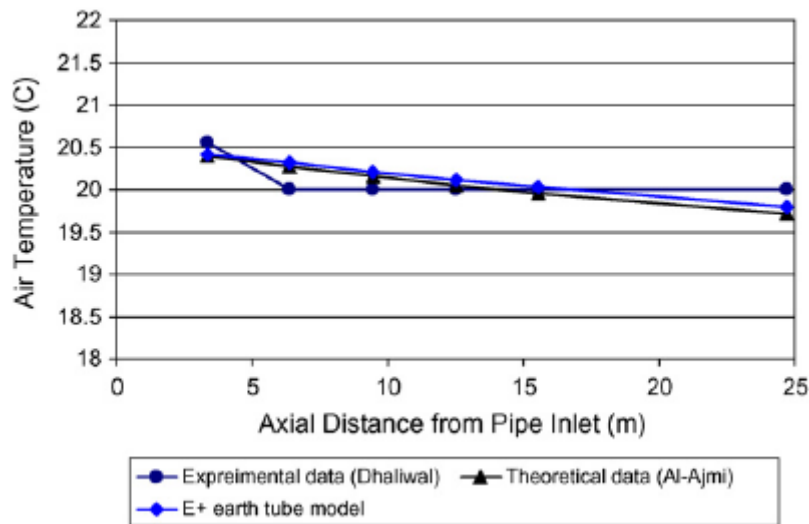


Figure 3.5: EnergyPlus (E+) data validated against two sets of experimental data (Lee and Strand, 2008).

This research uses the software Energy Plus and Buried Pipe as a tool to predict the Earth Pipe Cooling system outlet air temperature.

3.5.3 Energy Calculation

Paepe and Janssens (2003) used the total heat transfer calculation as part of the Earth Pipe Cooling system design calculation:

Total heat transfer to the air when flowing through a buried pipe, Q

$$Q = m_{\text{air}} \times C_{p,\text{air}} (T_{\text{air,out}} - T_{\text{air,in}})$$

Where

$C_{p,\text{air}}$ = thermal capacity for air, J/kgK

Equation 3.3: Total heat transfer equation (Source: Paepe and Janssens, 2003)

Mass flow rate, m_{air}

$$M_{\text{air}} = \rho_{\text{air}} (\pi D^2/4) v_{\text{air}}$$

Equation 3.4: Mass flow rate of air.

Pressure drop equation in a smooth tube:

$$\Delta P = \xi (L/D) \rho (v_{\text{air}}^2/2)$$

Where

$$\xi = 64/Re, Re = (v_{\text{air}}D)/\nu_{\text{air}}$$

v_{air} = speed, m/s

ρ_{air} = density, kg/m³

D = tube diameter, m

L = tube length, m

Equation 3.5: Pressure drop equation.

Pfafferott (2003) calculated the Earth Pipe Cooling system energy efficiency by using the following calculation:

$$\text{Energy Efficiency} = \frac{\text{Energy Gain, } Q_c}{\text{Fan Electricity Demand}}$$

Equation 3.6: Energy Efficiency equation.

Energy gained by the Earth Pipe Cooling system can lead to waste of energy when the supplied energy for cooling or heating is used during times it is not needed (Pfafferott, 2003). There has been a situation when the Earth Pipe Cooling system cools down the incoming air when the ambient air temperature is low and heats up the incoming air when the ambient air temperature is high. This was shown in a graph of cooling and heating energy supply plotted along with the ambient air temperature

(Pfafferott, 2003). In Pfafferott (2003) findings, a control energy gain strategy is essential in order to supply energy when it is needed. The control strategy of Earth Pipe Cooling system operation could either be in terms of time-controlled or temperature controlled or both (Pfafferott, 2003).

In a performance analysis of Earth Pipe Cooling system, Bansal et al. (2010) has calculated the total hourly cooling with the following equation:

$$Q_c = 3600 m C_d C_p (T_{inlet} - T_{exit}), J$$

$$m = (\pi/4) d^2 p v,$$

where, C_d = Coefficient of discharge of the pipe = 0.6

C_p = specific heat capacity of air, J/kg K

d = pipe diameter, m

p = air density, kg/m³

v = air velocity, m/s.

Equation 3.7: An example of equation to calculate the performance of an Earth Pipe Cooling system.

In the calculation used by Bansal et al. (2010), there is an additional coefficient of discharge of the pipe, C_d , with the value of 0.6.

3.6 Hybrid Design for Enhancement of Earth Pipe Cooling System

Tropical Climate of Malaysia is hot and humid throughout the year. However, it has its temperature variation in daily basis that influences the soil temperature regime. Referring to Malaysia climate, the maximum diurnal temperature is up to 12.4°C maximum and the average diurnal temperature is approximately 8.14°C. In 2001, Khedari et al. has carried put an investigation of Earth Pipe Cooling in Thailand, which has hot and humid climate, similar to Malaysia. The Earth Pipe Cooling system consists of 40m long PVC ducts with 30cm diameter, buried at 2m depth underground. Results showed evidence of temperature reduction within the pipe inlet and outlet of Earth Pipe Cooling system. This shows there is a potential of developing the Earth Pipe Cooling system strategy into a hybrid cooling system, coupled with other cooling technology.

Khedari et al. (2001) has further developed their investigation of utilizing the earth as a heat sink by coupling the Earth Pipe Cooling System with an Air Conditioning system. In this study, the earth was used to absorb the heat that usually released to the atmosphere from the condensing unit of an Air Conditioner. The modified condensing unit was buried underground at 1m depth and its copper tube was lengthened to 67m from 22m, which the latter is the typical copper tube length of a conventional air conditioner. Results have shown that the modified condensing unit of an air conditioner consumes less energy as compared to the conventional air conditioner. The coefficient of performance (COP) for the air conditioner with a buried condenser unit is 7.1 during daytime and 8.1 during nighttime. On the other hand, the COP for a conventional air conditioner is less; 2.8 during daytime and 3.1 during nighttime. The temperature leaving the buried condenser is 31°C while the temperature leaving the conventional air condenser is 40°C.

In 2009, Bansal and Mathur carried out a study on enhancing the Earth Pipe Cooling system with the aid of evaporative cooling technology. Alongside this investigation, they performed a parametric studies illustrating the effect of the following parameters on the performance of Earth Pipe Cooling system; pipe length, pipe diameter, volumetric air flow rate, number of pipes and surface-to-volume (s/v) ratio. The evaporative cooler was placed at the inlet of EAHE system and a desired outlet temperature was set according to the comfort temperature range; 22°C to 27°C. In the enhanced Earth Pipe Cooling with evaporative cooler, the pipe length required is 93.5% less than the pipe length required by the Earth Pipe Cooling system alone to achieve the same desired outlet temperature. In terms of effects of variables, the additional of more buried pipes reduced the required length to achieve the same desired outlet temperature by 82.5%. When the s/v increases, the required pipe length reduces exponentially. Furthermore, when the number of buried pipe increases, the pipe diameter reduces, which allow the Earth Pipe Cooling system perform more efficiently (referring to 2.3.1 (b)).

Li et al. (2009) investigated the soil temperature around multiple boreholes with the simulation software, for several years before 2006. The results has shown that if the Earth Pipe system only emits heat into the ground for the whole year, the ground temperature could increase up to 35°C, after 13 years of operation. Meanwhile, if the

Earth Pipe system only extracts heat from the ground for a year, the ground temperature near the Earth Pipe can be reduced to 6°C after 5 years of operation.

Prior to the former investigation outcome, Li et al. (2009) has proposed a solution to alleviate the unwanted heat injected into the ground from the Earth Pipe Cooling system in summer. In the research, Le et al. (2009) introduced a Multi-Function Ground Source Heat Pump System (MFGSHP), which a hybrid of the original Ground Source Heat Pump (GSHP) coupled with Heat Pump for Water Heater. Typical hot water consumption at 65°C by 1 person in 1 household is 100L. The initial water temperature in summer is 24°C. The water supply of hot water is essential even during summer.

The study consists of constructing a 3-dimensional model under a typical climatic condition in Yangtze River, China with the computer fluid dynamic simulation software, FLUENT. For both MFGSHP and GSHP, three points of underground temperature measurement were taken, which was on the borehole wall (Point b), 1m distant from the borehole (Point c) and 2.5m distant from the borehole (Point a). The result of GSHP at the end of the 7th summer showed an increment of 2°C at Point b, 2.2°C at Point c and 1.9°C at Point a. Meanwhile, the result of MFGSHP at the end of the 7th summer showed the ground temperature around the borehole at all three points is close to the initial temperature. Furthermore, the MFGSHP can supply 95% hot water in a house and alleviate the unwanted heat ejected to the ground at the same time.

The hybrid design of Earth Pipe Cooling system is investigated further by Chel and Tiwari (2010) in New Delhi, India. In this hybrid design, a stand-alone Photovoltaic (PV) is integrated with the Earth Pipe Cooling System by utilizing the PV power system that provides daily electrical load partly for the fan blower that generates air flow into the Earth Pipe Cooling system. The rest of the daily electrical load was utilized by ceiling fan, fluorescent tube-light, computer and submersible water pump. The energy generated by a stand-alone Photovoltaic (SAPV) system is 3536kWh/year while the total energy consumed by the electrical load is 3114kWh/year. In terms of alleviating CO₂ emission, the SAPV managed to alleviate 9.4tons/year of CO₂ emission.

The next hybrid design of Earth Pipe Cooling system is proposed by Maerefat and Haghghi (2010) under the climate condition of Iran. The proposed hybrid design coupled the Earth Pipe Cooling system with Solar Chimney (SC). The SC consists of

glass surface captures the heat from solar radiation to heat the air in the SC. This drives the air upwards due to stack effect. The upward airflow then causes driving force, which extracts the outside air through the cooling pipe and into the conditioned room. The ambient outdoor temperature during summer in Iran is 34°C and the undisturbed soil temperature, where it is dry and shaded, is 19°C. With 3 solar chimneys and 1 Earth Pipe Cooling, the conditioned room temperature remains within the range of 28.2°C and 31.9°C, with air change rate of 3-7ACH. Since the room temperature falls within the acceptable comfort range, the integration of Earth Pipe Cooling system and Solar Chimney has been successful.

3.7 Conclusion

This chapter provides reviews on the Earth Pipe Cooling technology investigation carried out by other researchers in various countries. The literature reviews provide guidance in forming the research methodology which consists of field investigation and also simulation work.

CHAPTER 4 METHODOLOGY

Low Energy Earth Pipe Cooling had been often used in buildings in hot and arid and temperate countries. However, speculations were made about the suitability of this technology for hot and humid climate. Therefore, a research methodology was designed to evaluate the potential of applying the technology in hot and humid country, with particular reference to Malaysia.

As a conclusion from the background study on Low Energy Earth Pipe Cooling technology, there are five common design factors that affect the efficiency of this technology. The most crucial factor is the temperature difference between the ambience and its soil, followed by the pipe design, which includes its diameter, length, depth underground and the air flow rate provided inside the pipe. In many hot and arid countries, which utilizes Earth Pipe Cooling in their buildings has buried the pipe system at 4m deep underground due to the soil temperature being stable and fairly constant at that depth. With lack of information on Malaysia soil temperature this research is initiated by finding the optimum depth at which the Earth Pipe should be buried to obtain efficiency in its performance. Currently there are no publications about soil temperature in Malaysia ground at various depths, reaching 4 meter deep. There are data of Malaysia earth temperature available from the Malaysia Meteorology Department but these are daily recorded data of soil temperature at a maximum of 1.2m below ground.

The research methodology is divided into three parts, which consists of soil temperature measurement, earth pipe cooling experiment and earth pipe cooling simulation study using Energy Plus. All three stages are crucial for the following purposes:

- Due to lack of information on Malaysia soil temperature, the initial goal is to obtain soil temperature data at various depths up to 5m deep below ground.
- To analyze the potential of Earth Pipe Cooling application in Malaysia climate with reference to its soil temperature and ambient temperature.
- To determine the optimum depth to bury the Earth Pipe Cooling System below ground for the Earth Pipe Cooling experiment.

- To evaluate the potential of utilizing Earth Pipe Cooling in buildings in Malaysia climate for cooling purposes by referring to the temperature difference between the buried pipe inlet and outlet.
- To conduct more evaluation with extended range of variables with the aid of a computer modeling software Energy Plus, in search for the most efficient Earth Pipe Cooling design for buildings in Malaysia.

The research methodology has been tailored to meet the purposes listed above and Figure 4.1 illustrates an overview of the research methodology.

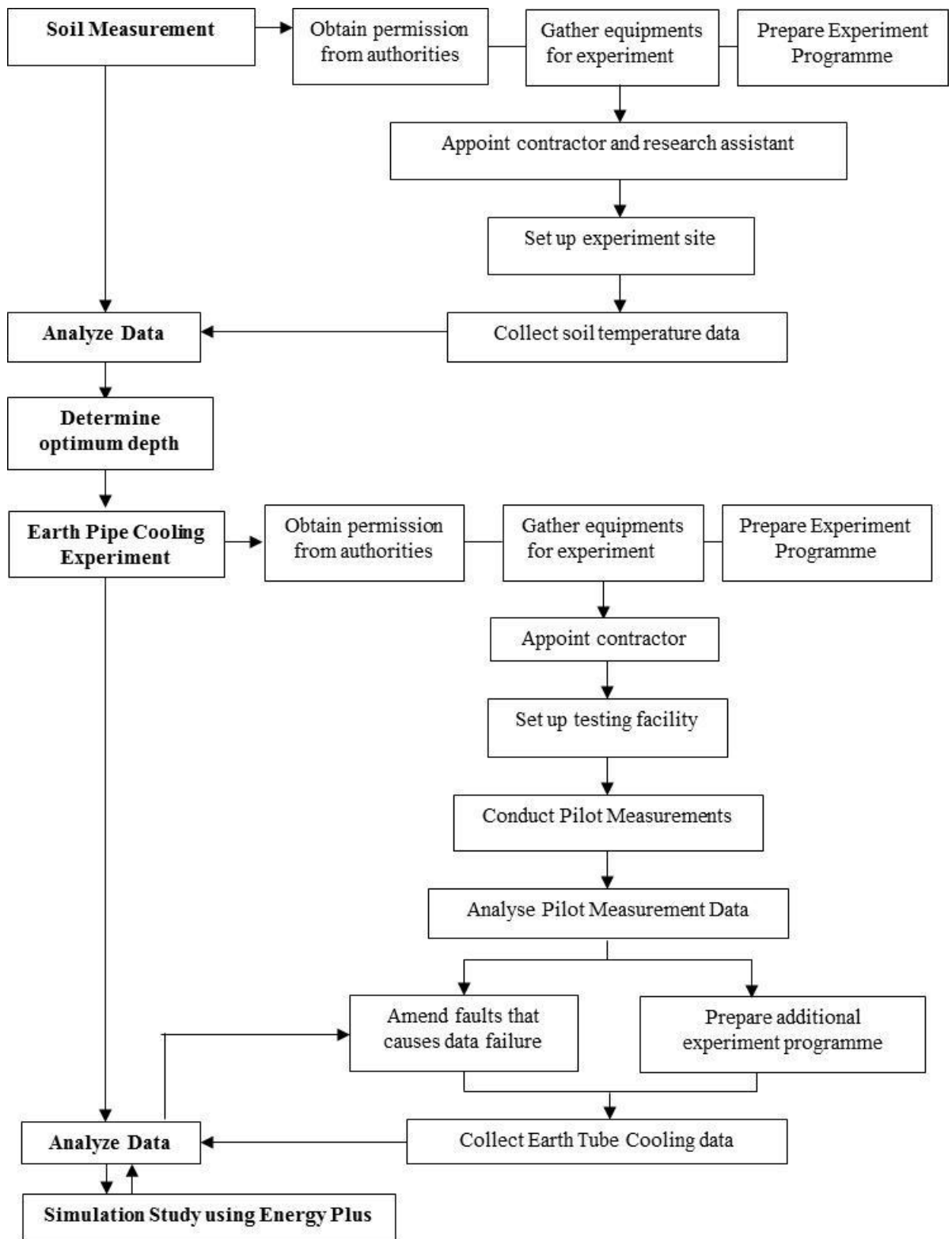


Figure 4.1; An overview of the research methodology for Earth Pipe Cooling investigation.

4.1 Field Work Site

All field work investigations were carried out on the same site within the International Islamic University Malaysia (IIUM) campus, which is located in Kuala Lumpur, Malaysia. Its globe coordinate is near the equator with latitude $3^{\circ} 17' 60''$ N and longitude $101^{\circ} 46' 60''$ E. Figure 4.2 is an illustration of the university campus site map. The field work site is located on the South West of the campus, near the campus perimeter.

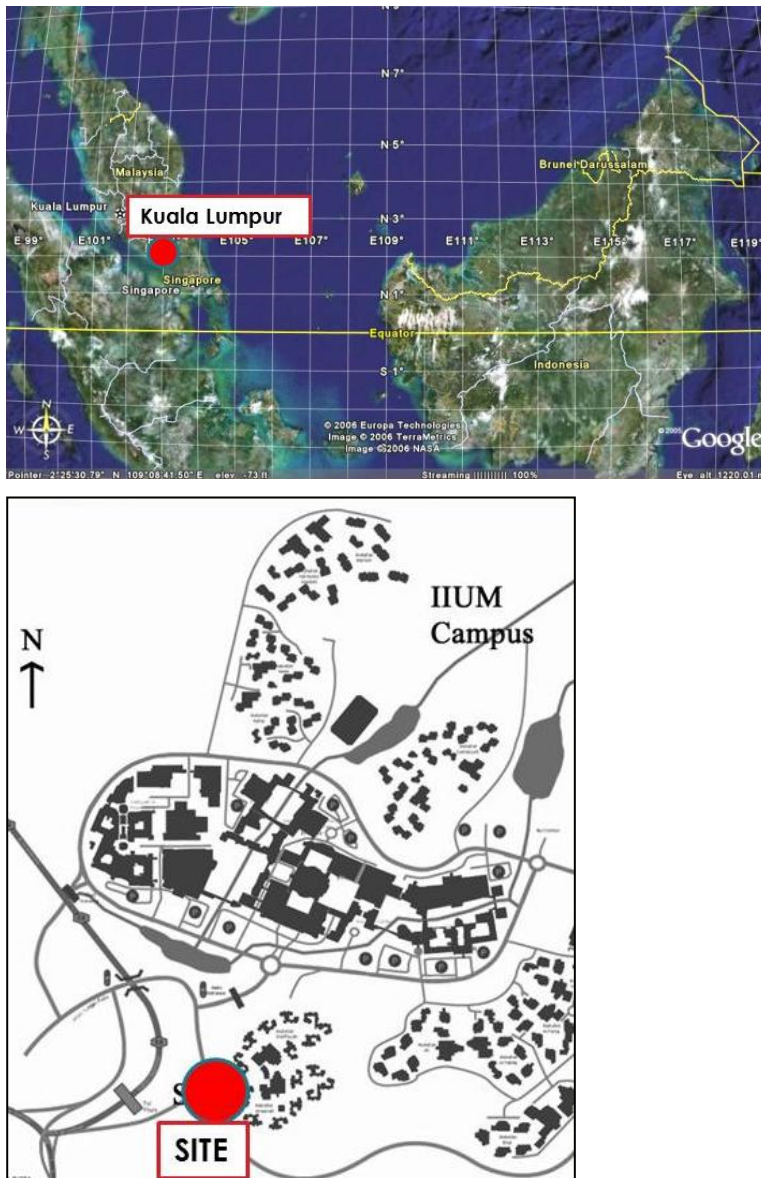


Figure 4.2: Field work site location (red dot) within International Islamic University Malaysia campus.

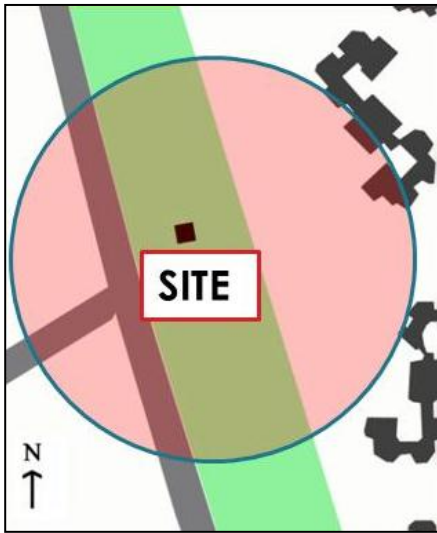


Figure 4.3: Orientation of the experiment shed on site.

The soil at the site is sandy and barely covered with short grass. Hence, the soil is exposed to solar radiation during the day. Figure 4.4 and Figure 4.5 shows the original look of the site before construction was taken place.



Figure 4.4: View of the site from North East before construction.



Figure 4.5: View of the site from South West before construction.

4.2 Field Work 1: Soil Temperature Measurement in Malaysia

This field investigation aims to record temperature of soil in Malaysia at various depths underground, up to 5m deep, purposely to seek potential of applying Earth Pipe Cooling in the country before implementing it. The maximum depth was limited to 5m underground because soil temperature is found to be constant and stable at 4m depth underground in other countries across the globe. Another rationale behind various depths measurement is to determine the optimum depth that could give the most effective result where the pipes were to be buried.

The soil temperature measurement field work has two parts. The first measurement was carried out in October and November 2007 (wet season) whilst the second measurement was carried out in May 2009 (hot and dry season).

4.2.1 Soil temperature measurement in the wet season

The field investigation includes measurements of outdoor dry bulb temperature (DBT), ground surface temperature and soil temperature at 1m, 2m, 3m, 4m and 5m deep below ground.

Before the investigation commenced, permission to use the site was obtained from the Development Division and Student Affairs Division of the International Islamic University. Permission from Student Affairs Division was required due to the site being located within a student resident compound and to use the facilities readily available on site for the experiment, which includes power supply.

The experiment intended to record seven different measurements simultaneously and therefore requires a multi-channel data logger. An 8 channel data logger called USB TC-08 Thermocouple Data Logger was used (Courtesy of Department of Mechatronics Engineering in the International Islamic University) (Figure 4.6). It is a product of Pico Technology Limited. Table 4.1 shows the data logger specifications and further information is available in Appendix 4.1.



Figure 4.6: USB TC-08 Thermocouple Data Logger from Pico Technology Limited.

Table 4.1: Specifications of USB TC-08 Thermocouple Data Logger.

Number of channels	8
Temperature accuracy	The sum of $\pm 0.2\%$ and $\pm 0.5^{\circ}\text{C}$
Voltage accuracy	The sum of $\pm 0.2\%$ and $\pm 10\mu\text{V}$
Overload protection	$> \pm 30\text{V}$
Input range	$\pm 70\text{mV}$
Reading rate	Up to 10 readings per Second
Input connectors	Miniature thermocouple
Output connector	USB1.1 connector
Dimensions	85 x 145 x 25mm

The experiment equipment was completed with 7 K-type thermocouple wires connected to the 8 channel data logger. The wire is made of Teflon and its size is 0.32mm. The K-type thermocouple wire measures temperature ranges from -270°C to

1300°C. Each of the 7 thermocouple wires was connected to the data logger by a Type K Miniature Male Connector. A sample of one day data obtained from the USB TC-08 Thermocouple Data Logger is shown in Figure 4.7.

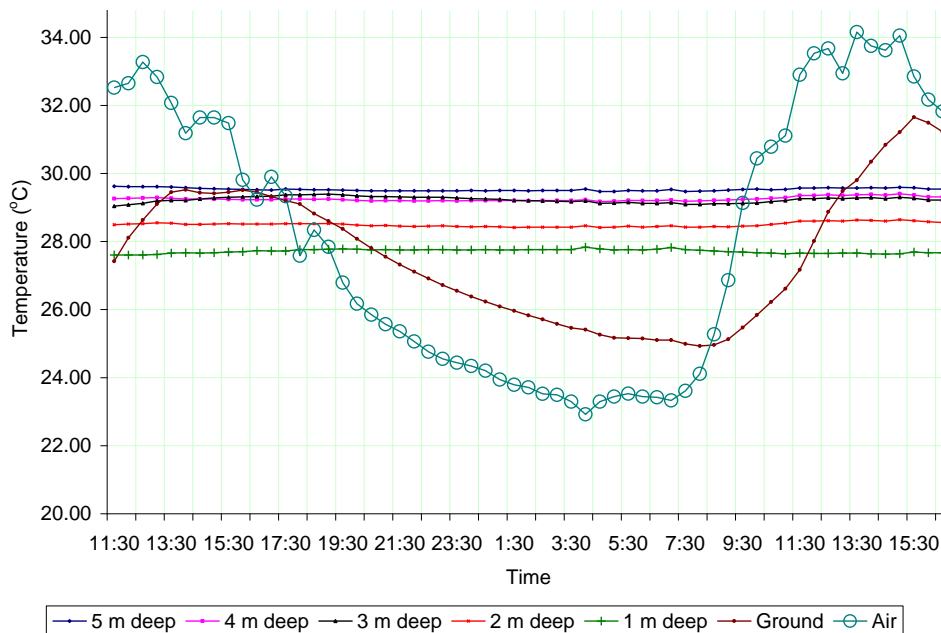


Figure 4.7: Soil and air temperature one day data sample measured with USB TC-08 Thermocouple Data Logger (November, International Islamic University Malaysia, Kuala Lumpur)

The sample graph in Figure 4.7 illustrates hourly temperature distributions in 28 hours in the month November. The data is recorded at the air, ground surface, 1m, 2m, 3m, 4m and 5m deep below ground. Figure 4.7 shows the ambient air temperature ranges from 22.5°C to 34.2°C and ground surface temperature follow closely to the trend of ambient air temperature but with smaller amplitude. From 1m deep underground, the soil temperature remains constant for the whole day despite the oscillation of ambient air and ground surface temperature. Figure 4.7 also shows the soil is warmer as it gets deeper underground. Further explanation and extensive graphs are displayed in Chapter 5.

A contractor was appointed to drill a 15cm hole in the ground to bury the 6 thermocouple wires at 5m, 4m, 3m, 2m, 1m below ground and ground surface (Figure

4.8). One thermocouple wire was set up to measure the ambience dry bulb temperature (Figure 4.9).



Figure 4.8: Thermocouple wires were buried underground at ground surface, 1m, 2m, 3m, 4m and 5m deep.

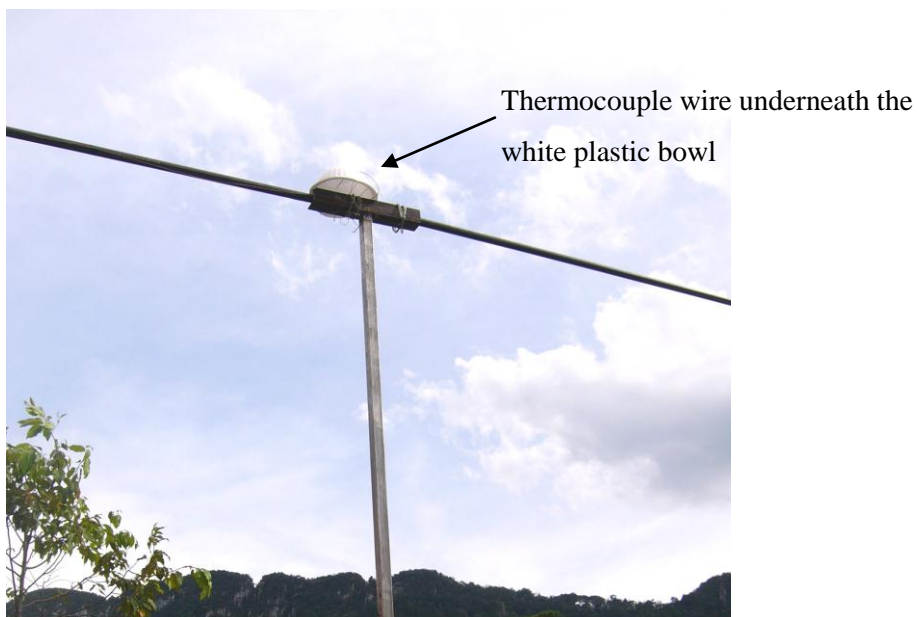


Figure 4.9: One thermocouple wire measuring the ambient dry bulb temperature, shaded by a white plastic bowl.

The measured data were logged from the 5th of October to the 14th of November 2007 and readings were taken daily at 10 minutes interval.

4.2.2 Soil temperature measurement in hot and dry season

Referring back to Chapter 3, Malaysia weather is warm and humid throughout the year. However, the weather does vary in terms of dry and wet seasons and the months October and November falls during the wet season. Hot and dry season are often in the month of May and June. The second field work aims to measure the soil temperature during the hot and dry season.

The result from the previous experiment shows that the soil temperature is lowest and also stable at 1m depth over 5 weeks of recorded data. Therefore, the field work in May measures soil temperature around 1m depth below ground at smaller gaps between two measuring points. The equipment was placed at 0.3m, 0.5m, 0.8m and 1.0m below ground. The ambience dry bulb temperature (DBT) was also measured simultaneously.

In this field work, portable and wireless data loggers were buried at the measuring points below ground. The data logger is called HOBO Pendant Temp Logger (UA-001-64), a product by Onset Computer Corporation (Figure 4.10). The logger specification is listed in Table 4.2 and further information regarding the logger can be found in Appendix 4.2.



Figure 4.10: HOBO Pendant Temp Logger (UA-001-64)

Table 4.2: Specifications for HOBO Pendant Temp Logger (UA-001-64). (Source: Tempcon Instrumentation)

Measurement range	-20° to 70°C (-4° to 158°F)
Accuracy	±0.47°C at 25°C (see Figure 4.11)
Resolution: Temperature	0.10°C at 25°C (see Figure 4.11)
Drift	Less than 0.1°C/year
Response time (airflow of 2m/s)	10 minutes, typical to 90%
Response time (water)	5 minutes, typical to 90%
Time accuracy	±1 minute per month at 25°C (see Figure 4.12)
Operating range (in water/ice)	-20° to 50°C
Operating range (in air)	-20° to 70°C
Water depth rating	30m from -20° to 20°C (see Figure 4.13)
Battery life	1 year typical use
Memory	64K bytes (approximately 52K sample and event readings)
Materials	Polypropylene case; stainless steel screws; Buna-N o-ring
Weight	18 g
Dimensions	58 x 33 x 23 mm
The CE marking identifies this product as complying with the relevant directives in the European Union (EU)	

Figure 4.11 and Figure 4.12 illustrate the performance curves of the HOBO Pendant Temp Logger (UA-001-64). This pendant data logger is waterproof at temperature range from -20°C to 50°C at up to 10m depth (Figure 4.13).

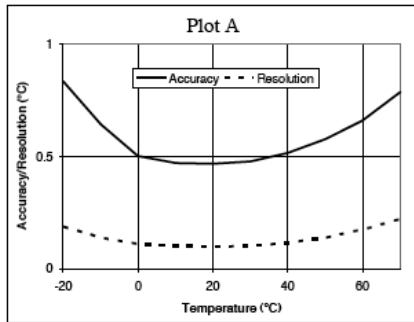


Figure 4.11: Trend of accuracy and temperature resolution of HOBO Pendant Temp Logger (Source: Tempcon Instrumentation).

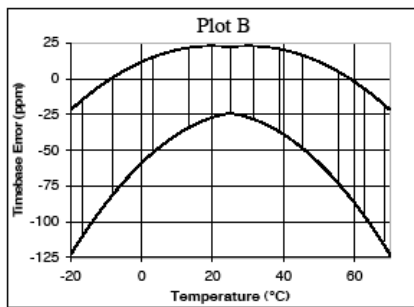


Figure 4.12: Trend of time accuracy for HOBO Pendant Temp Logger. *PPM stands for parts per million (Source: Tempcon Instrumentation).

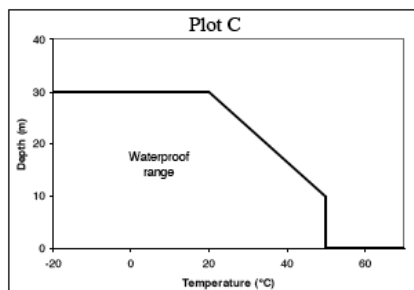


Figure 4.13: The range of depth and temperature where the HOBO Pendant Temp Logger is waterproofed (Source: Tempcon Instrumentation).

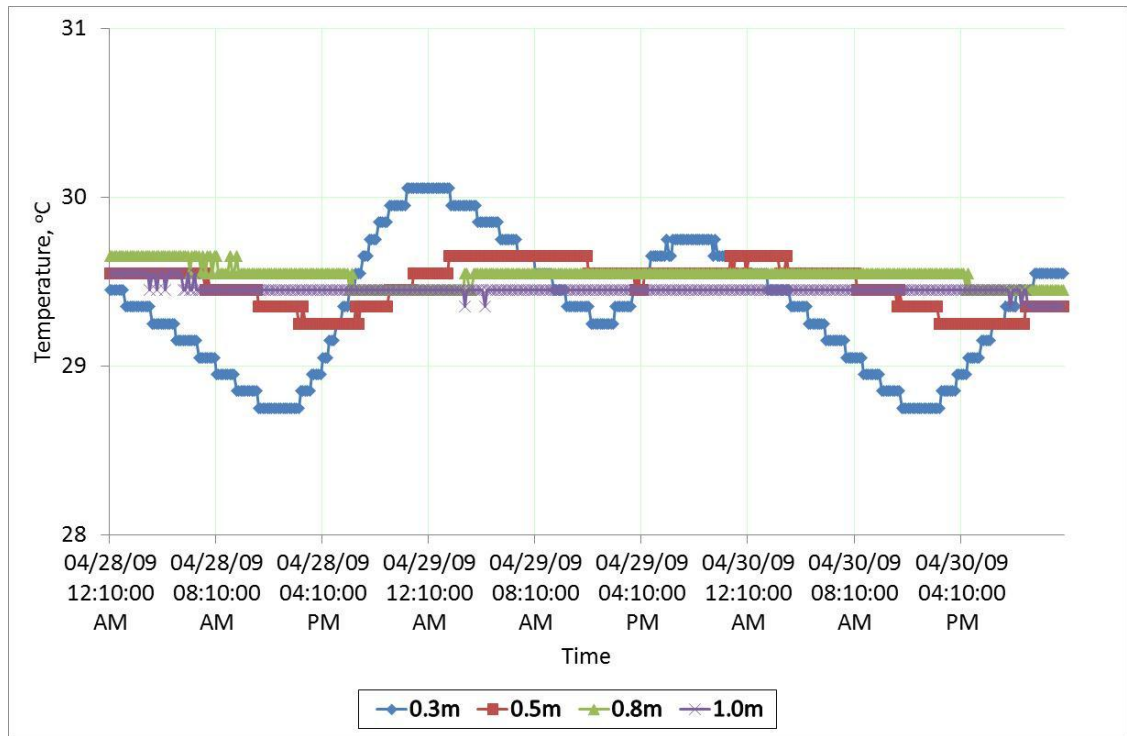


Figure 4.14: Soil temperature data sample measured with HOBO Pendant Temp Logger over 3 days (April, International Islamic University Malaysia, Kuala Lumpur)

The graph in Figure 4.14 presents soil temperature data at various depths in four continuous days. It is shown that soil temperature at 0.3m underground fluctuate the most among the other measured depths because it is the most shallow depth among the four, which was influenced by the effect of cool ambient air at night and warm ambient air and solar radiation during the day.

The equipment that was used to measure the ambience dry bulb temperature is HOBO U12-012 Temp/RH/Light/Ext. It is also a product from Onset Computer Corporation (Figure 4.15).



Figure 4.15: HOBO U12-012 Temp/RH/Light/Ext (Source: Temcon Instrumentation).

The logger in Figure 4.15 was placed just outside an experimental shed, shaded from direct solar radiation, by an opaque plastic bowl. The logger specification is listed in Table 4.3 and further information regarding the logger can be found in Appendix 4.3.

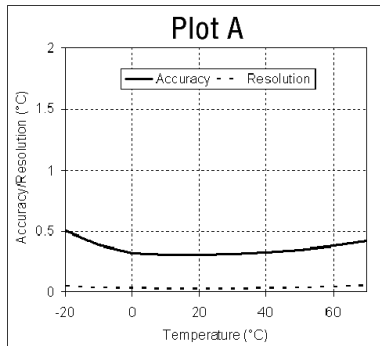


Figure 4.16: Trend of temperature accuracy and resolution for HOBO U12-012 Temp/RH/Light/Ext (Source: Tempcon Instrumentation).

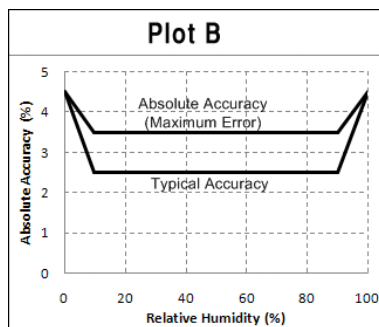


Figure 4.17: Trend of RH accuracy for HOBO U12-012 Temp/RH/Light/Ext (Source: Tempcon Instrumentation).

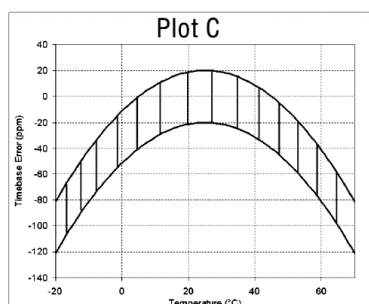


Figure 4.18: Trend of time accuracy for HOBO U12-012 Temp/RH/Light/Ext (Source: Tempcon Instrumentation).

Table 4.3: Specifications for HOBO U12-012 Temp/RH/Light/Ext (Source: Tempcon Instrumentation).

Measurement range (temperature)	-20° to 70°C
Measurement range (RH)	5% to 95% RH
Light intensity	1 to 3000 footcandles (lumens/ft ²)
External input channel	0 to 2.5 DC Volts
Accuracy (temperature)	±0.35°C from 0° to 50°C (see Figure 4.15)
Accuracy (RH)	±2.5% from 10% to 90% RH (typical) (see Figure 4.16)
Accuracy (Light intensity)	Designed for indoor measurement of relative light levels (see Figure 4.17)
Accuracy (external input channel)	±2mV ±2.5% of absolute reading
Resolution (temperature)	0.03°C at 25°C (see Figure 4.15)
Resolution (RH)	0.03% RH
Drift (temperature)	0.1°C/year
Drift (RH)	<1% per year typical; RH hysteresis 1%
Response time in airflow of 1m/s (temperature)	6 minutes, typical to 90%
Response time in airflow of 1m/s (RH)	1 minute, typical to 90%
Time accuracy	±1 minute/month at 25°C (see Figure 4.18)
Operating temperature (logging)	-20° to 70°C
Operating temperature (launch and readout)	0° to 50°C, per USB specification
Battery life	1 year typical use
Memory	64K bytes
Weight	46 g
Dimensions	58 x 74 x 22 mm
The CE marking identifies this product as complying with the relevant directives in the European Union (EU)	

The HOBO Pendant Temp Loggers and HOBO U12-012 Temp/RH/Light/Ext were used to start measure on 27 April 2009 and stop on 16 May 2009. All data were recorded throughout each day at 10 minutes interval. Figure 4.19 shows an example of data recorded from the HOBO U12-012 Temp/RH/Light/Ext.

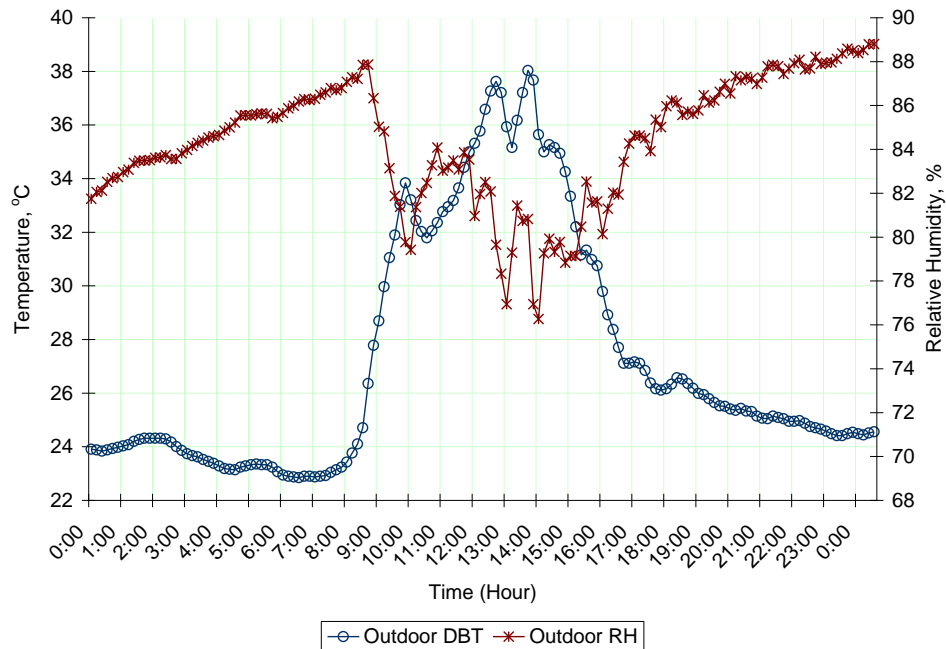


Figure 4.19: Sample data of ambient dry bulb temperature and relative humidity (RH) measured with HOBO U12-012 Temp/RH/Light/Ext over 24 hours (Location: International Islamic University Malaysia, Kuala Lumpur).

4.2.3 Soil temperature measurement in one year

As explained in the results chapters, the study of soil temperature has narrowed down to the depths of 1.5m maximum. The reason is because, during the first period of testing (wet season), it was found that the average soil temperature at 1m is lower than the average soil temperature at 4m. Even though, the soil temperature at 1m depth has the potential to increase in the hot and dry season due for being less stable than the soil temperature at 4m depth, it provides the benefit of low average soil temperature during the wet season. With reference to soil temperature at 1m depth underground, the results obtained from soil temperature measurement in both wet and hot and dry seasons were compared and the finding shown a difference in average soil temperature of the two

seasons. The average soil temperature is slightly higher in May as compared to the average soil temperature in November and December. Building on this result, the study of Malaysia soil temperature was resumed in the same site but for the duration of one year at 0.5m, 1.0m and 1.5m depth underground.

The soil temperatures at three levels were measured using HOBO Pendant Temp Logger (Figure 4.10). Simultaneously, outdoor dry bulb temperature (DBT) was also recorded using the same type of data logging equipment. Initially, the data logger that measured the outdoor DBT was hung under the roof just outside the experimental shed (Figure 4.20). At this moment, the datalogger was facing East and slightly towards North East.



Figure 4.20: The location of HOBO Pendant Temp data logger that measured the outdoor dry bulb temperature (DBT) from March until July (Location: International Islamic University Malaysia, Kuala Lumpur).

Initial analysis of the outdoor DBT showed maximum daily temperature reaching over 40°C (Figure 4.21), which is above the levels of the local Met Office data and this could be the effect of warm air beneath eaves of roof towards the HOBO data logger that was measuring the outdoor DBT.

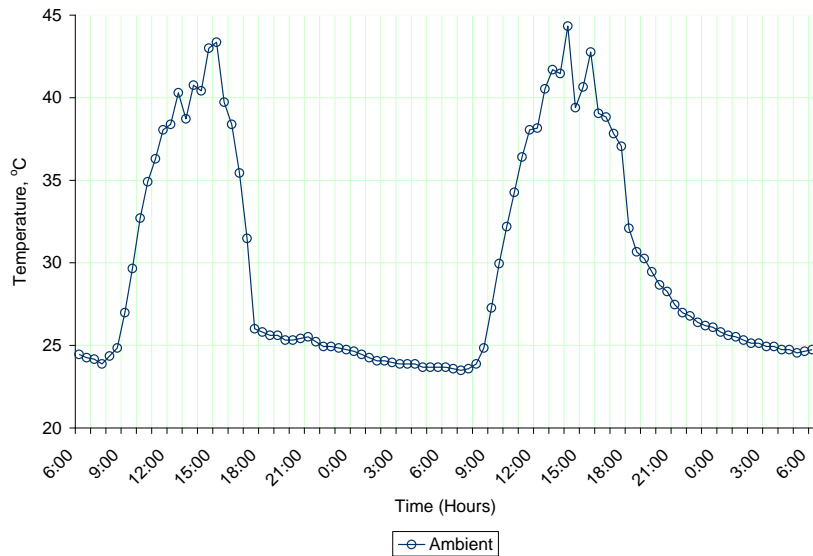


Figure 4.21: Sample data of outdoor dry bulb temperature (DBT) measured with HOBO Pendant Temp data logger (Location: International Islamic University Malaysia, Kuala Lumpur).

In August, the data logger was relocated to a more shaded area, under a tree near the experiment shed and Figure 4.22 illustrates sample of the data measured.

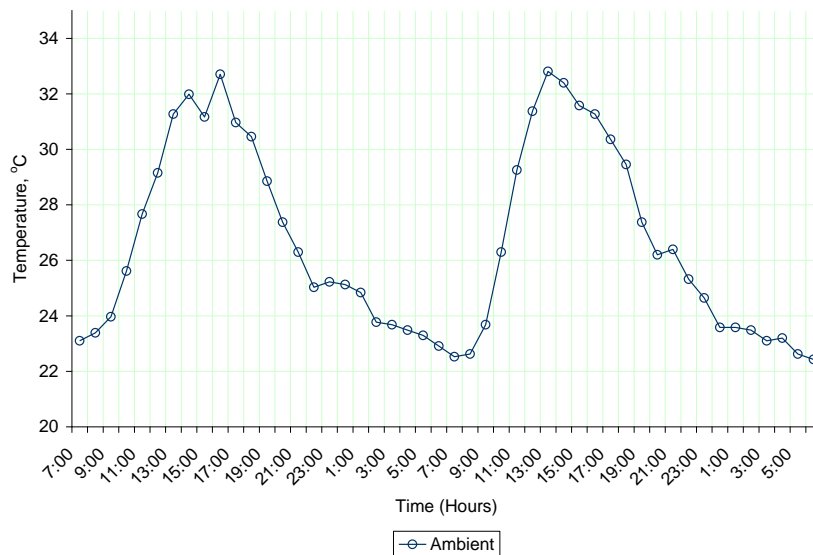


Figure 4.22: Sample data of outdoor dry bulb temperature (DBT) measured under the shade of a tree with HOBO Pendant Temp Datalogger (Location: International Islamic University Malaysia, Kuala Lumpur).

The soil temperature mentioned above was measured at the site of the experiment shed but slightly away from the buried pipe. These data loggers that measured soil temperature for one whole year at 0.5m, 1.0m and 1.5m depth underground were buried on the West of the experiment shed. Two studies reported slight increment of temperature at the soil surrounding the buried pipe as a long term effect of Earth Pipe Cooling (Dhaliwal and Goswami (1985) in Krarti and Kreider, 1996 and Li et al., 2009). Therefore, this research has also carried out a field study to investigate the relationship of soil temperature surrounding the buried pipe or away from the pipe. In this soil comparison investigation, the three data loggers buried underground away from the experiment shed remain at the same location. Another three HOBO Pendant Temp Dataloggers were buried 0.1m away from the buried pipes at 0.5m, 1.0m and 1.5m depth underground (Figure 4.23). The data was logged in November, December, January and February, which were then compared to the data from the other location of the other three dataloggers. Figure 4.24 shows a sample of the data measured.



Figure 4.23: An excavated hole where the three HOBO Pendant Temp Loggers were buried at 0.5m, 1.0m and 1.5m, 0.1m away from the buried pipes (Location: International Islamic University Malaysia, Kuala Lumpur).

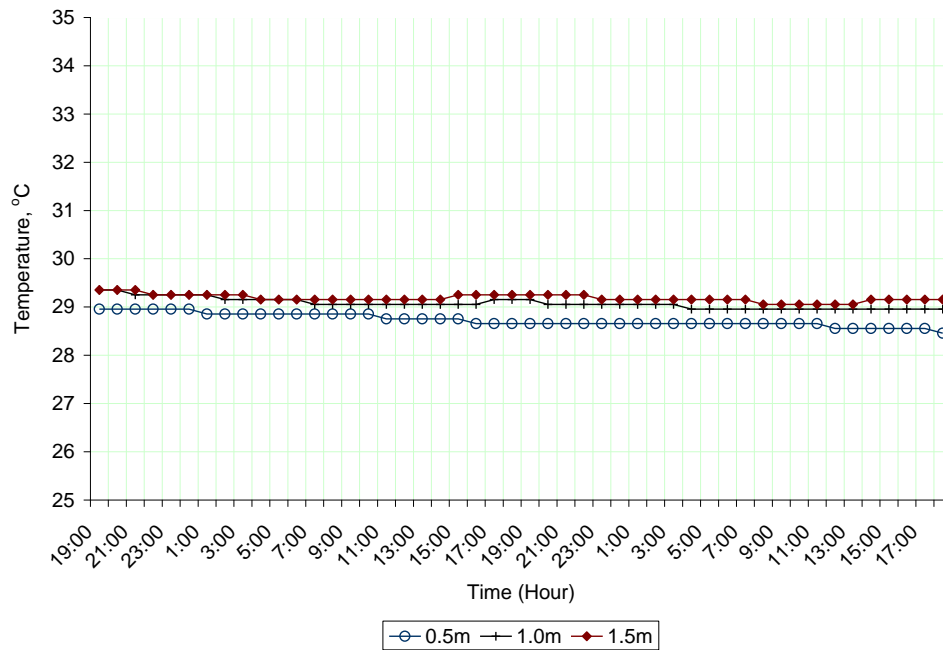


Figure 4.24: Sample data of soil temperature 0.1m distance from buried pipe measured with HOBO Pendant Temp Loggers (Location: International Islamic University Malaysia, Kuala Lumpur).

4.3 Field Work 2: Earth Pipe Cooling Experiment in Malaysia

Published literatures have shown that main parameters affecting the result of Earth Pipe Cooling performances include depth of tube buried underground, length and diameter of buried tube and the air flow rate inside the buried tube. Furthermore, various pipe materials have been used in the experiments published by other researcher.

The second part of field work is the main Earth Pipe Cooling Experiment. Initially, the investigation was carried out in two parts. The first part investigated the performance of Earth Pipe Cooling in November and December, which represents the wet season. The second part investigated the performance of Earth Pipe Cooling in April and May, which represents the hot and dry season. Due to the field experiment located in Malaysia while the research base is in United Kingdom, the initial plan was to investigate the Earth Pipe Cooling performance for one and a half month for each season. This planned decision was made assuming the data produced would be similar for both season since Malaysia climate is hot and humid all year round. However, the findings have shown otherwise. There are differences in the pipe outlet temperature

when the data collected in November and December were compared to the data collected in April and May. Therefore, the investigation of Earth Pipe Cooling resumes and collected data for one whole year and a research assistant on-site was appointed to monitor the experiment once a fortnight.

Field Work 2 involves a bigger construction work compared to soil temperature measurement field work. The experiment set up includes burial of long pipes into the ground and building of an experiment shed. The set up involved four construction workers who brought in a digger, which is a large and heavy vehicle, into the site compound. Therefore, in order to carry out Field Work 2, a new permission was needed from authorities from three departments in International Islamic University. They were Development Division, Student Affairs and Security Officers.

Once permission had been sought, construction work begins. The following figures (Figure 4.25 to 4.34) show some of construction work progress from burying the pipes to finishing the experiment shed.



Figure 4.25: Construction work commenced.



Figure 4.26: PVC pipes buried at 1.0m, 1.5m and 2.0m.



Figure 4.27: The PVC pipe buried at 1.0m depth is 50m long while the other pipes were only 30m long.



Figure 4.28: The inlets and outlets of PVC pipes buried at 0.5m, 1.0m, 1.5m and 2.0m.



Figure 4.29: Construction of an experiment shed containing the equipment and earth pipe in/outlets commenced.



Figure 4.30: Progress in the experiment shed construction work.



Figure 4.31: Ceiling construction in progress showing its insulation materials.

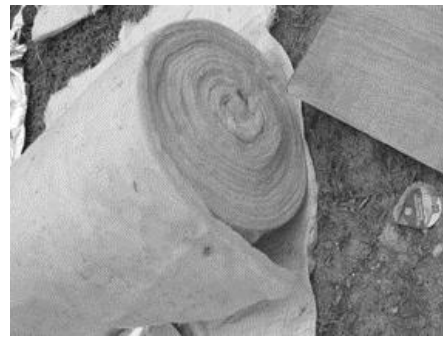


Figure 4.32: Fibre glass insulation to be fitted inside the walls of experiment shed.



Figure 4.33: There is a gap under the roof for ventilation in the experiment shed. However, main purpose of building shed is for security of the equipment purposes.



Figure 4.34: Inlets of the PVC pipes are connected to one fan blower that has three variable speeds. The fan blower extract air from outside and blow the air into the pipe inlets.

The figures above has shown that initially, the experiment uses four PVC pipes buried at 0.5m, 1.0m, 1.5m and 2.0m depth below ground level. Once the set up were completed, each pipe outlet was tested to see if there is airflow going through it when the fan was switched on. Unfortunately, it was found that only one pipe released air at its outlet, which was the pipe buried at 0.5m depth. The other three pipes did not release any air from their outlets. Water was found in the three pipes, all in the same level of 0.63m below ground level. The three pipes were dug out (Figure 4.35). The PVC pipes were then replaced by Polyethylene pipes (Figure 4.36). They were buried at 0.5m, 1.0m and 1.5m depth below ground (Figure 4.42).



Figure 4.35: Broken PVC pipes due to incapability to support soil weight at depth below 0.6m underground. The PVC pipe buried at 0.5m is intact and remains where it is.



Figure 4.36: Polyethylene pipes were used to replace the broken PVC pipes.



Figure 4.37: Three polyethylene pipes were buried at 0.5m, 1.0m and 1.5m.



Figure 4.38: An example of 50m polyethylene pipe buried at 1.0m below ground.

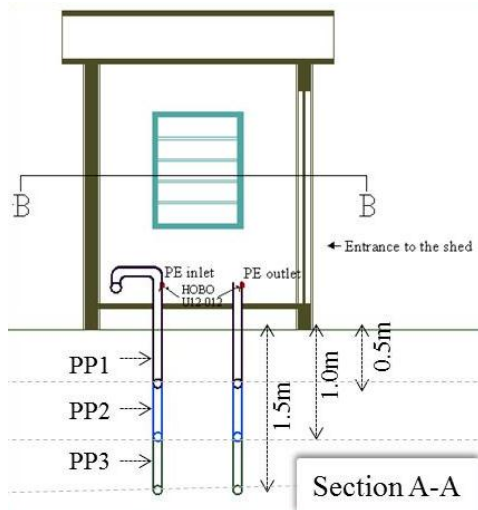


Figure 4.39: Section of the experiment set up showing cross section of the polyethylene buried pipe at 0.5m, 1.0m and 1.5m depth underground.

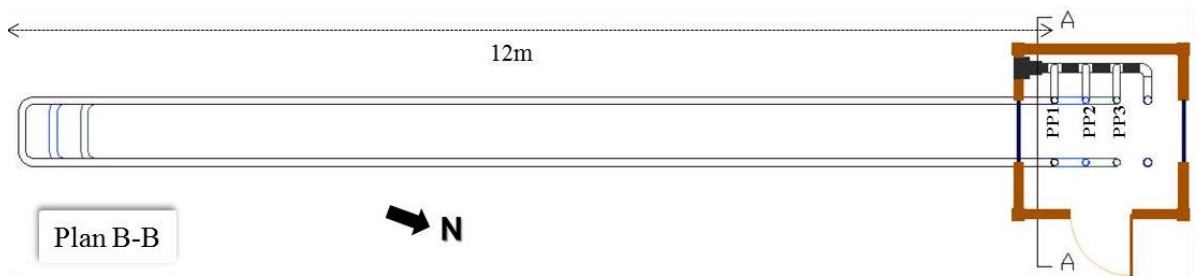


Figure 4.40: Plan of experiment set up showing experiment shed and buried Polyethylene pipes extended in South East direction for 12m long.

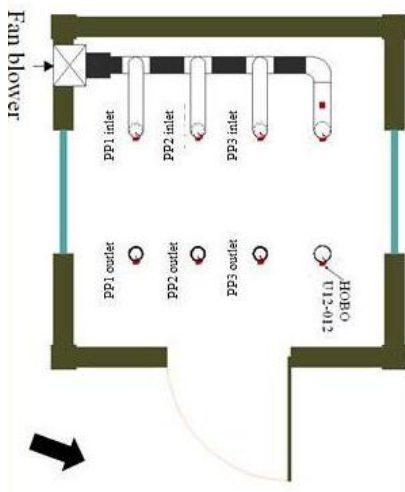


Figure 4.41: Plan of the experiment shed with example of equipments location during data recording. (PP = Polyethylene Pipe).

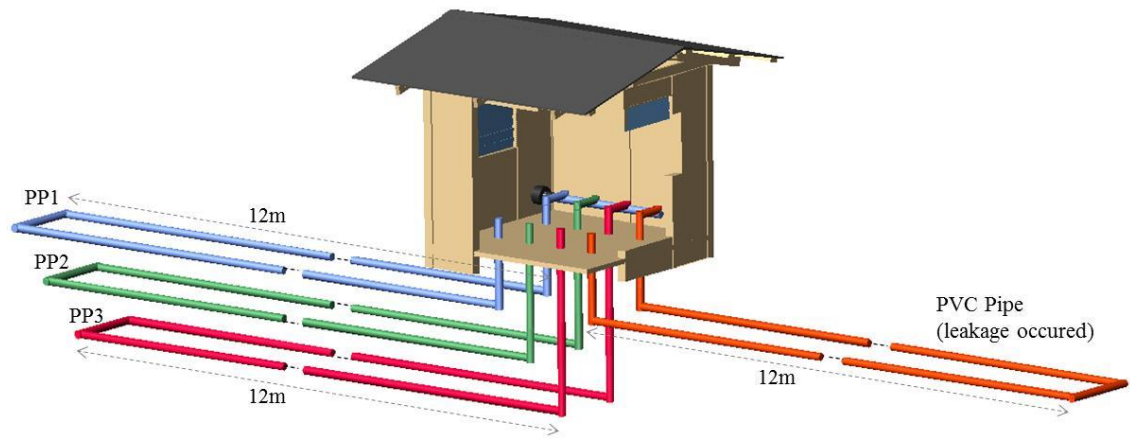


Figure 4.42: A 3d drawing of the experiment set from North showing buried pipes at 0.5m, 1.0m and 1.5m underground. (PP = Polyethylene Pipe).

Parameters of each buried pipe are determined and shown in Table 4.4 Initially PP2 was 50m long that ran 24m away from its inlet and outlet. It was then shortened to 25m long.

Table 4.4: Parameters of each buried Polyethylene pipe.

Pipes	PP1	PP2	PP3
Material	Polyethylene	Polyethylene	Polyethylene
Diameter	0.076m (3")	0.076m (3")	0.076m (3")
Length	25m	25m	25m
Buried depth	0.5m	1.0m	1.5m
Air Speed	5.6m/s	5.6m/s	5.6m/s

In the field investigation of Earth Pipe Cooling, initially three variables were kept constant, which were material, diameter, and air speed. Different effect of length was studied at 1m depth only where the original pipe length at 1m depth was 50m long, as stated before.

4.3.1 Selecting fan blower

Fan blower plays an important role in the Earth Pipe Cooling system since it provides the cooling medium, which is air through the system. This Earth Pipe Cooling

system includes buried pipe as long as 50m. For a pipe as long as 50m, significant air pressure loss could happen within the pipe, which could then reduce the air flow through the pipe. Therefore, a careful selection of a fan blower is important to ensure the fan power could overcome the pressure loss through a 50m long pipe. Therefore, it is important to identify the pressure loss of a certain pipe design prior to selecting the fan power (CIBSE Guide B, 2005)

$$P_{ef} = \frac{\Delta P_t \cdot qv}{\eta_o} \quad (\text{Equation 4.1})$$

The CIBSE Guide C, particularly the chart “flow of air in round ducts” (CIBSE 2001) was used to determine the pressure drop per unit length (Pa/m). This chart requires two of the following inputs; volume flow rate (m³/s), pipe internal diameter, (m) and air velocity (m/s). This study has used various values of two inputs; air velocity (m/s) and pipe internal diameter (m). The pressure loss data obtained were then multiplied by a correction factor for plastic duct (Table 4.5).

Table 4.5: Pressure loss in ducts of (a) neat cement or plaster, (b) spiral wound galvanised, (c) sheet aluminium and (d) plastic ducts (CIBSE Guide C, 2001)

Pressure loss from chart (Pa/m)	Correction factor for ducts of all diameters			
	(a) Plastered ducts	(b) Spiral wound ducts	(c) Aluminium ducts	(d) Plastic ducts
0.1	1.03	0.97	0.96	0.90
0.2	1.05	0.96	0.95	0.90
0.5	1.07	0.95	0.93	0.88
1.0	1.08	0.94	0.91	0.85
2.0	1.08	0.93	0.90	0.84
5.0	1.09	0.92	0.88	0.80
10.0	1.09	0.91	0.86	0.77
20.0	1.10	0.90	0.85	0.75
50.0	1.10	0.88	0.83	0.71
100.0	1.11	0.86	0.79	0.68

Table 4.6: Pressure loss, ($\Delta P \times$ correction factor from Table 4.4) per unit length (Pa/m).

Air Velocity (m/s)	Pipe diameter			
	0.076m, 3"	0.102m, 4"	0.127m, 5"	0.152m, 6"
1	0.28	0.19	0.15	0.13
2	0.94	0.68	0.51	0.41
3	2.02	1.45	1.11	0.85
4	3.36	2.35	1.76	1.45
5	4.88	3.61	2.77	2.14
10	16.50	12.32	9.24	7.04

Table 4.6 has shown that the pressure loss per unit length decreases when pipe diameter increases but increases when the air velocity increases. A 0.076m or 3” diameter pipe was chosen for use in the field investigation due to financial limit and a 100m long pipe was considered to determine the required fan power to provide adequate air flow. Therefore, referring to the values in Table 4.6, the pressure loss, ΔP of 0.076m or 3” diameter and 100m long pipe, with 5m/s air velocity is 488 Pa.

Six fan blower manufacturing companies were contacted to acquire a fan blower that would overcome 488Pa pressure loss with the above pipe/air flow configuration, which was considered to the upper limited of the pressure loss that is likely to be encountered. The configuration has a volumetric flow rate of 81.7m³/h. A manufacturing company Nicotra Fans and Blowers Manufacturing responded with 6 different models of Turbo-Aire, a multi speed centrifugal fan. A model named Fan Turbo Aire GCIL200 (Figure 4.43) was chosen, which fits the required criteria. Figure 4.44 shows the performance curve of this model. Table 4.7 lists down the fan specifications.



Figure 4.43: Fan Turbo Aire GCIL200 with uniquely designed 3 speeds external rotor motor. (The built in motor produce extra heat to the air that goes into the buried pipe inlet. This is shown in the results chapter).

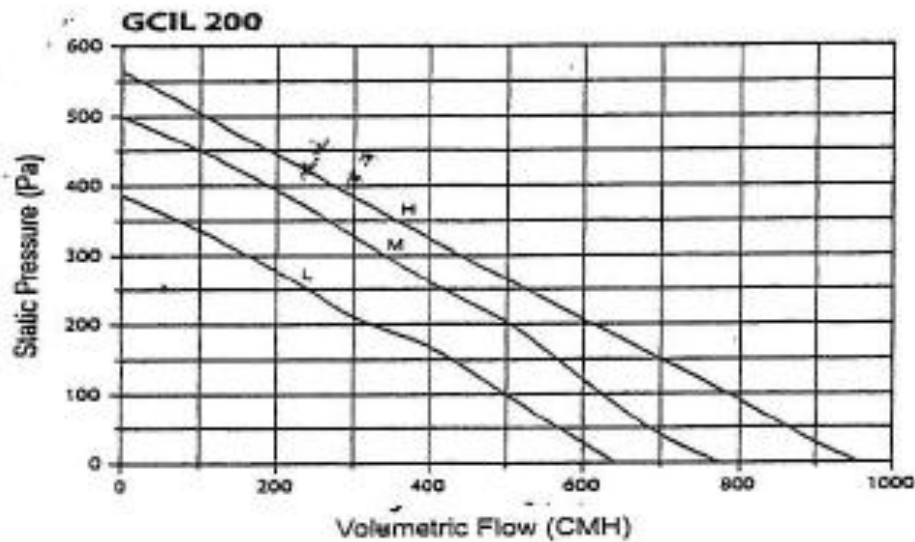


Figure 4.44: Performance curves of Fan Turbo Aire GCIL200 at Low (L), Medium (M) and High (H) fan speed (Nicotra Fans and Blowers Manufacturing (M))

Table 4.7: Specification for Fan Turbo Aire GCIL200

Impeller	Backward curve centrifugal impeller
Casing	<ol style="list-style-type: none"> 1. Rust-resistance pre-galvanised steel 2. Aerodynamically designed inlet guide vane
Motor	<ol style="list-style-type: none"> 1. 3 speeds external rotor motor 2. Moisture resistant 3. Permanently lubricated ball bearings ensuring reliable and maintenance free operation 4. Class F insulation 5. Speed controllable (optional) 6. Operate in ambient temperature range from -14° to 40°C 7. Built-in thermal protection device
Dimensions	Diameter = 0.378m Depth = 0.235m
Power	119 Watts
Performance	See Figure 4.44

4.3.2 Earth Pipe Cooling experiment in the wet season

The result from soil temperature measurement in October/November 2007 has shown that at 1m depth, soil temperature is almost stable at 28°C and it increases at 2m and below underground. Therefore, this section of field work only considered depths less than 2m underground. The first earth pipe cooling experiment aims to test each variable with different values, where the first set of soil temperature data measured in October/November 2007 used as a guideline. Table 4.8 summarizes details of each parameters used during the field work. The data collected after the broken PVC pipes were replaced by Polyethylene pipes.

Table 4.8: Details of Parameters used for field experiment in November/December 2008.

Parameters	Detail Description
Depth	0.5m, 1.0m and 1.5m
Length	25m (0.5m, 1.0m and 1.5m depth) and 50m (1.0m depth)
Pipe Diameter	Polyethylene = 7.36 cm PVC = 10.2 cm
Pipe Thickness	Polyethylene = 0.82 cm PVC = 0.20 cm
Fan Speed	5.62m/s (High), 5.15m/s (Medium) and 4.67m/s (Low)
Materials	Polyethylene Pipe (0.5m, 1.0m and 1.5m depth) and PVC Pipe (0.5m depth)

Equipments were gathered before the experiment commenced. The types of equipments were chosen with reference to the type of data needed;

- Outdoor dry bulb temperature
- Dry bulb temperature (DBT) inside the experiment shed
- Relative humidity (RH) inside the experiment shed
- Temperature at the inlet of each buried pipe
- Temperature at the outlet of each buried pipe
- Air velocity through each buried pipe

Table 4.9: Measuring equipments used that produce required data

Data	Measuring equipments
Outdoor dry bulb temperature	HOBO Pendant Temp Logger (UA-001-64)
DBT inside experiment shed	HOBO U12-012 Temp/RH/Light/Ext
RH inside experiment shed	
Temperature at inlet of each buried pipe	HOBO U12-012 Temp/RH/Light/Ext +
Temperature at outlet of each buried pipe	HOBO External Sensor TMC6-HD
Air velocity through each buried pipe	Air Flow Meter from Testo

The outdoor dry bulb temperature was measured with HOBO Pendant Temp Logger, which is the same logger as described in Section 4.2.2. It was hung just outside the experiment shed under the roof overhang Figure 4.20 that protected it from direct solar radiation. The dry bulb temperature and relative humidity inside the experiment shed was measured with HOBO U12-012 Temp/RH/Light/Ext. This equipment is also the same equipment as described in Section 4.2.2. HOBO U12-012 loggers were also used to measure the inlet and outlet of each buried pipes, with a HOBO external sensor TMC6-HD (Figure 4.45) attached to it. The external sensor was inserted into each of the pipe inlet and outlet to measure the temperatures (Figure 4.47 and Figure 4.48).



Figure 4.45: HOBO External Sensor TMC6-HD

Table 4.10: Specifications for HOBO External Sensor TMC6-HD

Range	-40° to 50°C in water or soil, -40° to 100°C in air
Accuracy with U12	±0.25°C at 20°C (see Figure 4.45)
Drift	<0.1°C per year
Resolution with U12	0.03°C at 20°C (see Figure 4.45)
Response time in air	3 minutes typical to 90% in air moving 1m/s
Response time in stirred water	1 minute typical to 90%
Housing	Stainless-steel sensor tip
Probe dimensions	0.5 cm x 2.5 cm
Length	1.8 m
Weight	37 g
Note: Sensor tip and cable immersion in fresh water up to 50°C for one year; radiation shield strongly recommended for use in sunlight	

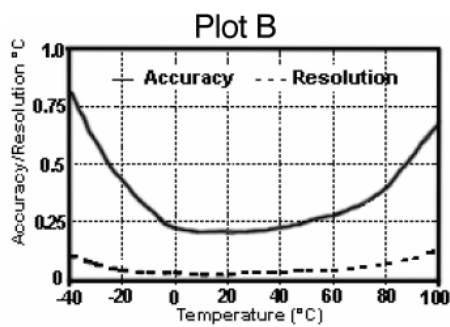


Figure 4.46: Graph of temperature accuracy and resolution for HOBO External Sensor TMC6-HD.

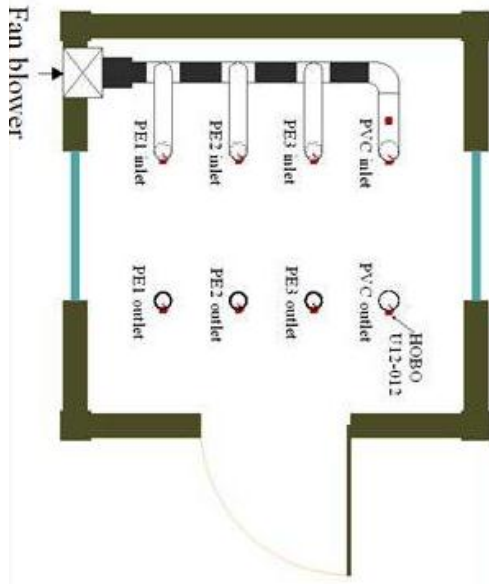


Figure 4.47: Placements of HOBO U12-012 Temp/RH/Light/Ext with attached HOBO External Sensor TMC6-HD inside the experiment shed and in each buried pipe inlet and outlet during the wet season; in plan view.

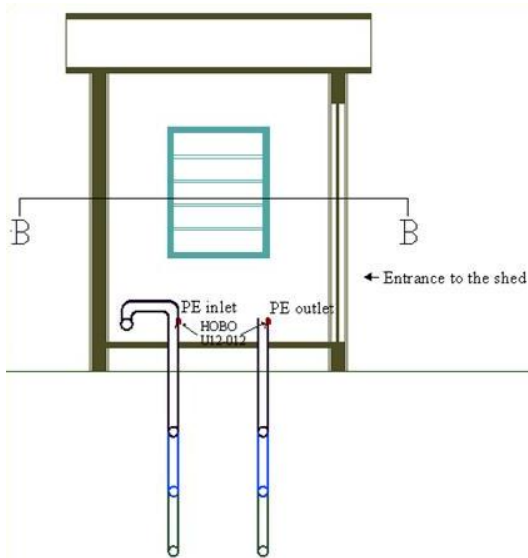


Figure 4.48: Placements of HOBO U12-012 Temp/RH/Light/Ext with attached HOBO External Sensor TMC6-HD inside the experiment shed and in each buried pipe inlet and outlet during the wet season; in section view.

The air velocity of each buried pipe was measured at various fan speed; 5.62m/s (High), 5.15m/s (Medium) and 4.67m/s (Low). These were measured with an Air Flow Meter from Testo. The fan blower operates from 10:00 am to 6:00 pm. This method was applied to find the effect of night ventilation cooling that could reduce the fan operation hours. All data were measured 24 hours daily from 22 November to 24 December 2008 at 10 minutes interval. However, each pipe temperature was measured separately to avoid interference between the pipe data.

4.3.3 Earth Pipe Cooling experiment in hot and dry season

As mentioned earlier, at the end of April and beginning of May is the beginning of hot and dry season. The graph of Kuala Lumpur weather data in Chapter 3 illustrates the annual climate condition more clearly. The Earth Pipe Cooling Experiment was repeated in April/May 2009 to capture the cooling pipe performance in hotter and dry climate. Apart from that, this experiment is intended to fill in gaps of inadequate data from the experiment in November/December 2008. Therefore, the methodology has been added and improved with a slightly different equipment arrangement.

The parameters used in this experiment were slightly different from the experiment in November/December 2008 (Table 4.8). Table 4.11 lists down the new parameters.

Table 4.11: Details of parameters used in field experiment in April/May 2009.

Parameters	Detail Description
Depth	0.5m, 1.0m and 1.5m
Length	25m
Pipe Diameter	Polyethylene = 7.36 cm PVC = 10.2 cm
Pipe Thickness	Polyethylene = 0.82 cm PVC = 0.20 cm
Fan Speed	5.6 m/s
Materials	Polyethylene Pipe and PVC Pipe

Equipments were gathered before the experiment commenced. The choice of equipments was referred to the required data from this experiment;

- Outdoor dry bulb temperature
- Outdoor Relative Humidity
- Dry bulb temperature (DBT) inside the experiment shed
- Relative humidity (RH) inside the experiment shed
- Temperature at the inlet of each buried pipe
- Relative Humidity at the inlet of each buried pipe
- Temperature at the outlet of each buried pipe
- Relative Humidity at the outlet of each buried pipe
- Air velocity through each buried pipe

Table 4.12: Measuring equipments used to produce the required data. HOBO U12-012 is the same equipment described in Section 4.2.2.

Data	Measuring equipments
Outdoor dry bulb temperature	HOBO U12-012 Temp/RH/Light/Ext
Outdoor Relative Humidity	
DBT inside experiment shed	HOBO U12-012 Temp/RH/Light/Ext
RH inside experiment shed	
Temperature at inlet of each buried pipe	HOBO U12-012 Temp/RH/Light/Ext
RH at inlet of each buried pipe	
Temperature at outlet of each buried pipe	HOBO U12-012 Temp/RH/Light/Ext
RH at outlet of each buried pipe	
Air velocity through each buried pipe	Air Flow Meter from Testo

The HOBO U12-012 that measured the outdoor dry bulb temperature and relative humidity was hung just outside the experiment shed, below the roof overhang, which protected the equipment from direct solar radiation. Meanwhile, the HOBO U12-012 that measured dry bulb temperature and relative humidity inside the experiment shed was placed away from the pipe outlets (Figure 4.50).

In this experiment, the temperature and relative humidity at pipe inlet were measured with HOBO U12-012 without HOBO external sensor TMC6-HD. The HOBO U12-012 was placed inside the pipe inlet in the middle of the air stream (Figure 4.49 and 4.50). The HOBO U12-012 that measured the temperature and relative humidity at pipe outlet was hung inside the pipe outlet (Figure 4.49 and 4.50).

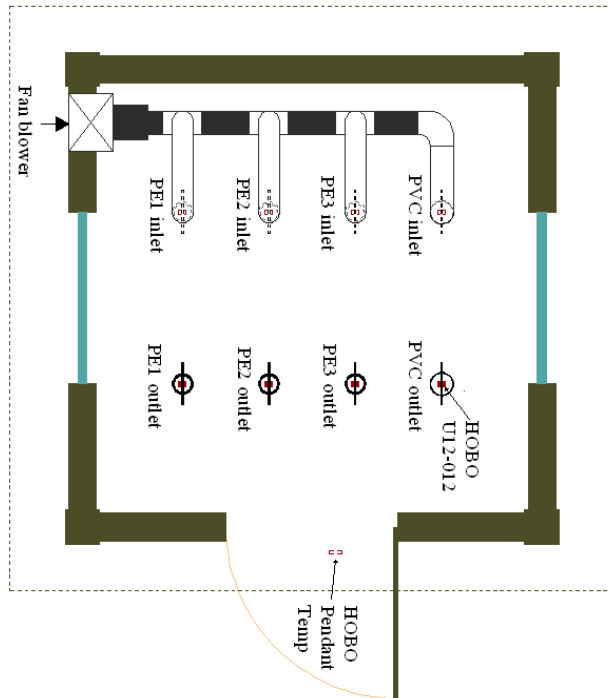


Figure 4.49: Plan view of the experiment shed showing the placements of HOBO U12-012 data loggers in each pipe inlet and outlet and HOBO Pendant Temp Datalogger outside the experiment shed.

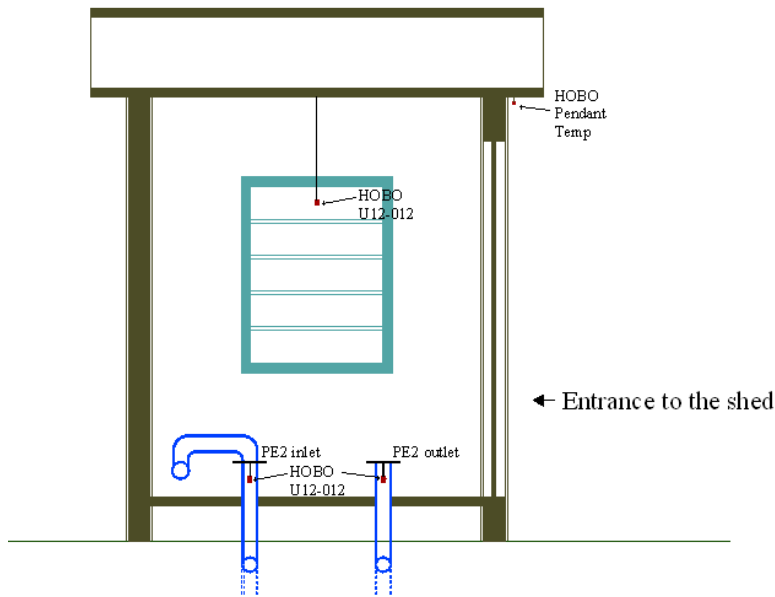


Figure 4.50: Sectional view of the experiment shed showing the placements of HOBO U12-012 data loggers in each pipe inlet and outlet, and one hung below the ceiling. Picture also shows a HOBO Pendant Temp data logger outside the experiment shed.

The fan blower was timed at two different hours; 24 hours and from 10:00 am to 6:00 pm. Similar to the previous experiment, this method was also applied to find the effect of night ventilation cooling that could reduce the fan operation hours. All data were measured throughout each day from 29 April to 16 May 2009 at 10 minutes interval. Each pipe temperature was measured separately to avoid interference between the pipe data.

4.3.4 Year-long Earth Pipe Cooling experiment

Results obtained from experiments in the wet season and the hot and dry season showed a significant (up to 2°C) difference in temperature at the buried pipe outlet between in the hot and dry season and the wet season. Therefore, a whole year data set is required to see the pattern of temperature at the buried pipe inlet and outlet throughout the different seasons in Malaysia. The downside of this is that by running the earth pipe cooling system experiment for a whole year, only one buried pipe can be used to avoid interference between pipe outlet temperatures if two or more pipes were running. The data interference could happen if two or more pipes run simultaneously

because all pipes were buried close to each other, approximately 0.5m distance with each other.

Looking at the results in the wet and hot and dry season, buried Polyethylene pipe at 1m deep provides the most temperature reduction between its outlet and inlet and therefore, the buried pipe at 1m depth was used for the extended investigation of Earth Pipe Cooling of one year. The air flow within the buried pipe was set to maximum which provides an air velocity of 5.6m/s. The pipe length was 25m and it was a 3”size Polyethylene pipe. The following variables were measured during the one year experiment;

- Outdoor dry bulb temperature (shaded by a tree)
- Outdoor dry bulb temperature (just outside the fan blower)
- Outdoor Relative Humidity
- Dry bulb temperature (DBT) inside the experiment shed
- Relative humidity (RH) inside the experiment shed
- Temperature at the inlet of each buried pipe
- Relative Humidity at the inlet of each buried pipe
- Temperature at the outlet of each buried pipe
- Relative Humidity at the outlet of each buried pipe

Throughout the year, the buried pipe inlet temperature is mostly higher than the outdoor temperature measured under a tree and away from the experiment hut. The reason behind this was because the fan blower that provides forced air flow into the buried pipe is placed with its fan exposed to solar radiation. Since the external part of the fan blower is not shaded, hot air was being extracted by the blower through the buried pipe inlet. This makes the buried pipe inlet temperature higher than the outdoor temperature measured under a tree (Figure 4.51). The air temperature at buried pipe inlet was also increased due to heat gain from built in motor in the fan blower.

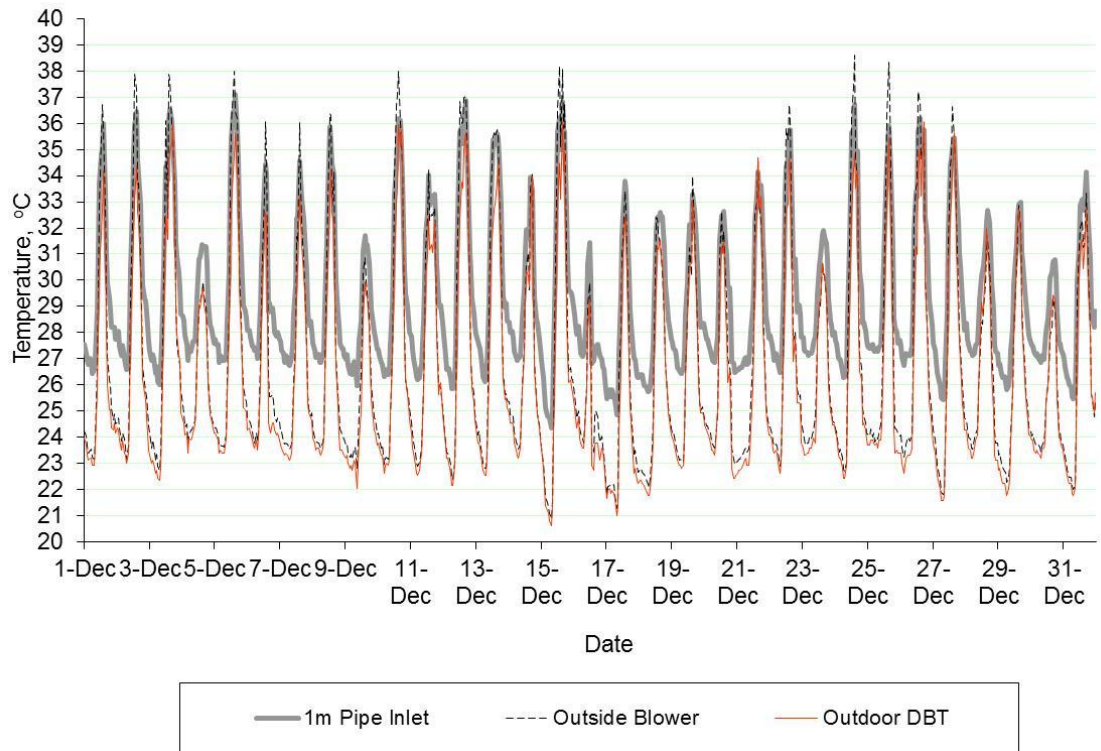


Figure 4.51: Trend of temperature at buried pipe inlet, a shaded outdoor and outdoor just outside the fan blower (Data recorded in December).

During the investigation, there has been unexpected incident where the power cable that connects the power supply to the fan blower was repeatedly cut off for at least four times. These incidents have left gaps of invalid data in April, the whole of July and August and gaps in September. However, looking at the soil temperature data in July and August, they are similar to the soil temperature in September and hence the buried pipe results in July and August were not present in the data shown and discussed in the next chapter.

Limited funds and resources for a PhD project based abroad is a major reason too for a number of limitations and gradual changes; including the absence of a proper weather station; parallel test pipes running at the same time and occurrence of invalid data caused by repetitive uncontrolled mysterious vandalism towards the test site.

CHAPTER 5 FIELD WORK RESULTS

The main factors that can be controlled by designers to make use of the Low Energy Earth Pipe Cooling system efficiently are the depth of the earth pipe buried underground, the length of the earth pipe, its diameter, the thickness of the earth pipe, its material and heat conductivity and the air flow inside the earth pipe. These have been explained in Chapter 3: Literature Review: Passive Ground Cooling. Due to the soil depth where earth pipe are buried being one of the main factors and with limited source of Malaysia soil temperature information, the research is brought together by two inter-related field works, the soil temperature measurement and the investigation of earth pipe cooling under Malaysia climate

5.1 Malaysia Soil Temperature

The Malaysia soil temperature measurement was carried out to seek the potential of applying Earth Pipe Cooling technology into Malaysia soil, before the main Earth Pipe Cooling investigation takes place. According to successful application of such cooling technology in other parts of the world, the Earth Pipes were buried at the depth between 3m to 5m underground. It was found that the soil temperature is stable and constant throughout the year around 4m underground. So far, there was very limited record of soil temperature in Malaysia and among various records of Malaysia soil temperature, the data goes as deep as 1.2m underground.

In addition to the results obtained from literature review of Malaysia soil temperature by Abdul Rahim et al. (1986) and Huat et al. (2005) another set of data on Malaysia soil temperature was obtained from Malaysia Meteorology Department. However, the data dated back from August 1977 to September 1982 and it contains the soil temperature at grass level, 0.05m, 0.10m, 0.30m and 1.20m deep underground. Furthermore, the data given was recorded in a daily basis with no information of the time of measurements. Table 5.1 below summarizes the annual maximum, minimum, average and amplitude of Malaysia soil temperature measured from January 1978 to December 1981. The data in 1977 and 1982 is not included since there are missing data at the earlier and later months of the years.

Table 5.1: Summary of Malaysia Soil Temperature in Subang Jaya, obtained from Malaysia Meteorology Department.

	Depth (m)	1978	1979	1980	1981
Maximum Temp (°C)	Grass	25.4	24.7	25.5	26.1
	0.05	34.0	33.7	33.5	33.4
	0.10	31.5	32.6	31.3	30.9
	0.30	31.0	32.0	30.3	30.7
	1.20	30.6	31.0	30.5	30.7
Minimum Temp (°C)	Grass	19.1	18.5	19.6	19.0
	0.05	26.1	26.7	26.0	26.0
	0.10	26.4	26.7	26.0	26.3
	0.30	24.5	27.0	26.8	26.9
	1.20	28.8	28.8	28.8	28.3
Average Temp (°C)	Grass	22.8	22.6	23.0	22.9
	0.05	30.3	30.4	30.2	30.2
	0.10	29.1	29.1	28.7	28.6
	0.30	29.0	29.2	28.8	28.9
	1.20	29.7	29.8	29.6	29.7
Average Amplitude	Grass	3.2	3.1	3.0	3.6
	0.05	4.0	3.5	3.0	3.8
	0.10	2.6	3.0	2.7	2.3
	0.30	3.3	2.5	1.8	1.9
	1.20	0.90	1.1	0.9	1.2

Figure 5.1 shows Malaysia soil temperature at shallow depths; from the grass surface up to 1.2m deep underground. The data from Malaysia Meteorology Department dated back in 30 years ago and they have no records of more recent years of data.

According to successful application of Earth Pipe Cooling in the temperate and hot and arid countries, the pipes were usually buried at 3 to 4 m deep underground, where the soil temperature is found to be stable, with amplitude temperature less than 0.5°C. Referring to Figure 5.1, Malaysia soil temperature fluctuation is still considered

big at 1.20m underground although Malaysia climate is hot and humid all year round. Figure 5.1 shows a soil temperature trend in year 1981 of depth up to 1.2m underground.

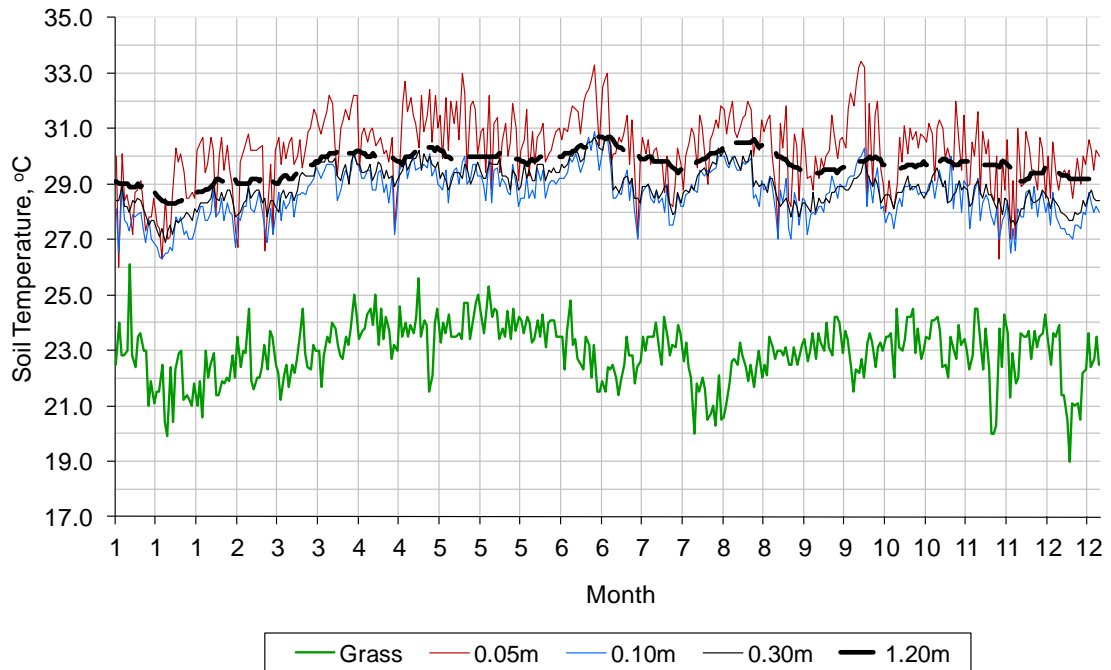


Figure 5.1: Trend of Malaysia soil temperature in 1981 from Malaysia Meteorology Department. (Grass represents data recorded on the ground surface with short grass cover).

In 1981, the figure above shows that the soil temperature becomes more stable with less annual amplitude as the measurement goes deeper underground. However, the data available from Malaysia Meteorology Department is limited to 1.2m deep underground. Earth Pipe Cooling investigation requires information on soil temperature at deeper level underground, since Earth Pipe Cooling application in other regions of the world have normally buried the Earth Pipe at 4m deep underground. Therefore, this research carried out soil temperature measurement in an experiment site, which is located in Gombak, near Kuala Lumpur, Malaysia.

Initially, the soil temperature investigation includes measurement of outdoor dry bulb temperature, soil temperature at ground level, and underground soil temperature at 1m, 2m, 3m, 4m and 5m depths. The investigation was carried out from 5 October 2007

to 14 November 2007. There was a gap of missing data from 13 to 16 October. The field work was carried out during the North East monsoon season when the weather is wet and less warm throughout Malaysia. Table 5.2 summarizes the trend of soil temperature measured during the soil temperature investigation in October and November 2007.

Table 5.2: Summary of outdoor dry bulb temperature and soil temperature measured on site at various depth underground in October and November 2007.

Depth	Maximum (°C)	Minimum (°C)	Average (°C)	Amplitude (°C)
Ambient Air DBT	35.4	21.7	26.2	6.8
Ground Level	34.9	24.4	27.8	5.2
1m deep	28.5	26.9	27.5	0.8
2m deep	29.4	27.1	28.5	1.1
3m deep	30.1	28.8	29.1	0.6
4m deep	30.3	29.1	29.4	0.6
5m deep	30.2	29.3	29.5	0.5

Table 5.2 shows that the amplitudes of soil temperatures within the two months decrease with increasing depth underground. However, soil temperature at 3m depth underground is fairly stable with amplitude similar to 5m depth soil, but with lower average soil temperature. The table also show that at 1m depth underground, the soil temperature is fairly stable with a much lower average temperature (Table 5.2).

During the investigation in October and November 2007, the outdoor dry bulb temperature ranges from 21.8°C to 35.4°C. The maximum diurnal temperature during these two months was 12.8°C, which occurred on 11 November 2007 where the ambient dry bulb temperature ranges from 22.5°C to 35.4°C (Table 5.2). Meanwhile, the minimum diurnal temperature at this period was 6.4°C where the ambient dry bulb temperature ranges from 22.5°C to 28.9°C. This occurred on 10 November and rain

started falling from 11:00 am until 5:00 p.m., which has caused the ambient dry bulb temperature to maintain below 29.0°C in the middle of the day.

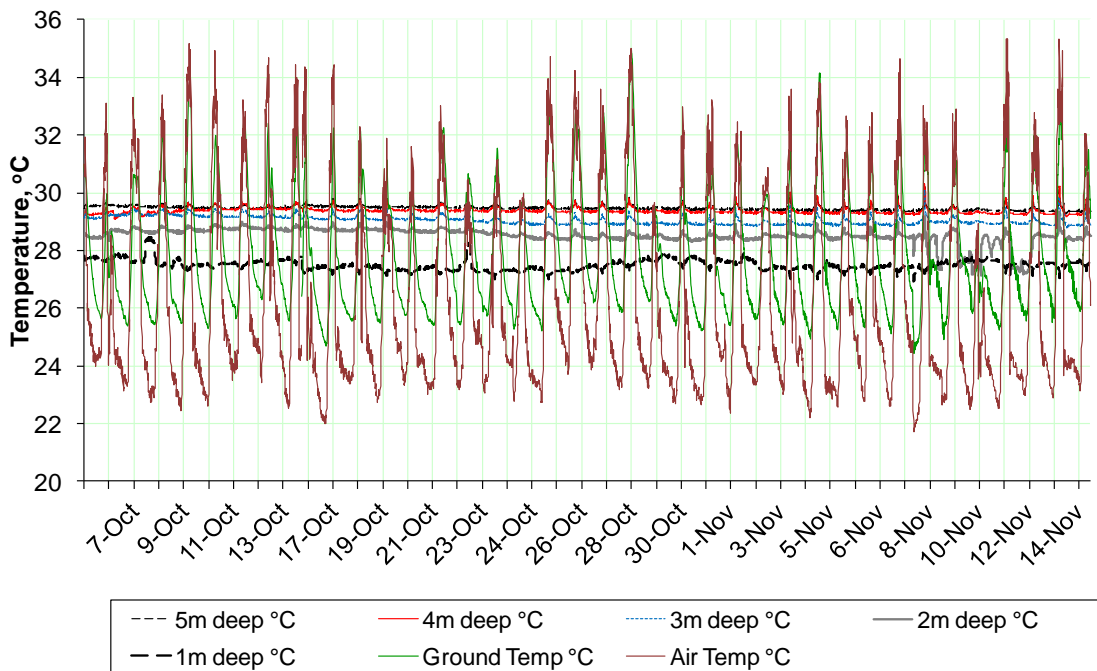


Figure 5.2: Trend of ambient air temperature and soil temperature measured on field site in Gombak, Malaysia from 5 October to 14 November 2007.

The ground temperature trend follows the outdoor DBT slightly with temperature ranges from 24.4°C to 34.9°C. At the ground level of soil, the temperature amplitude is 5.2°C and is considered quite high (Figure 5.2) although its average temperature was fairly low, which was 27.8°C. Meanwhile, the soil temperature at 1m deep underground has the lowest average temperature throughout the investigation period, which is 27.5°C and its temperature amplitude is reasonably low, which is 0.8°C. Beyond 1m deep, the average temperature increases again (Table 5.2 and Figure 5.2). The average soil temperature at 1m deep underground is 7.9°C lower than the absolute maximum ambient DBT and 5.5°C lower than the average maximum ambient DBT within the investigation period. This temperature reduction shows a potential of using the soil as a heat sink to reduce the ambient air temperature.

The above soil temperature investigation was measured during the wet season, from October to November 2007. Another soil temperature measurement was carried out during the hot and dry season, from 27 April to 16 May 2009. The second investigation was carried out after analysis of data from the first soil temperature experiment, which has shown that at 1m depth underground, the soil temperature is fairly stable and has a lower soil temperature compared to the deeper soil. Therefore, the second soil temperature experiment measures soil temperature at 0.3m, 0.5m, 0.8m and 1.0m depth below ground level and also ambient temperature. Table 5.3 summarizes the trend of soil temperature measured during the soil temperature investigation in April and May 2009.

Table 5.3: Summary of outdoor dry bulb temperature and soil temperature measured on site at various depth underground in April and May 2009.

Depth	Maximum (°C)	Minimum (°C)	Average (°C)	Amplitude (°C)
Ambient Air DBT	39.9	22.8	29.2	8.5
0.3m deep	31.8	28.8	30.1	1.5
0.5m deep	31.0	29.3	30.0	0.9
0.8m deep	30.6	29.4	29.9	0.6
1.0m deep	30.3	29.4	29.7	0.5

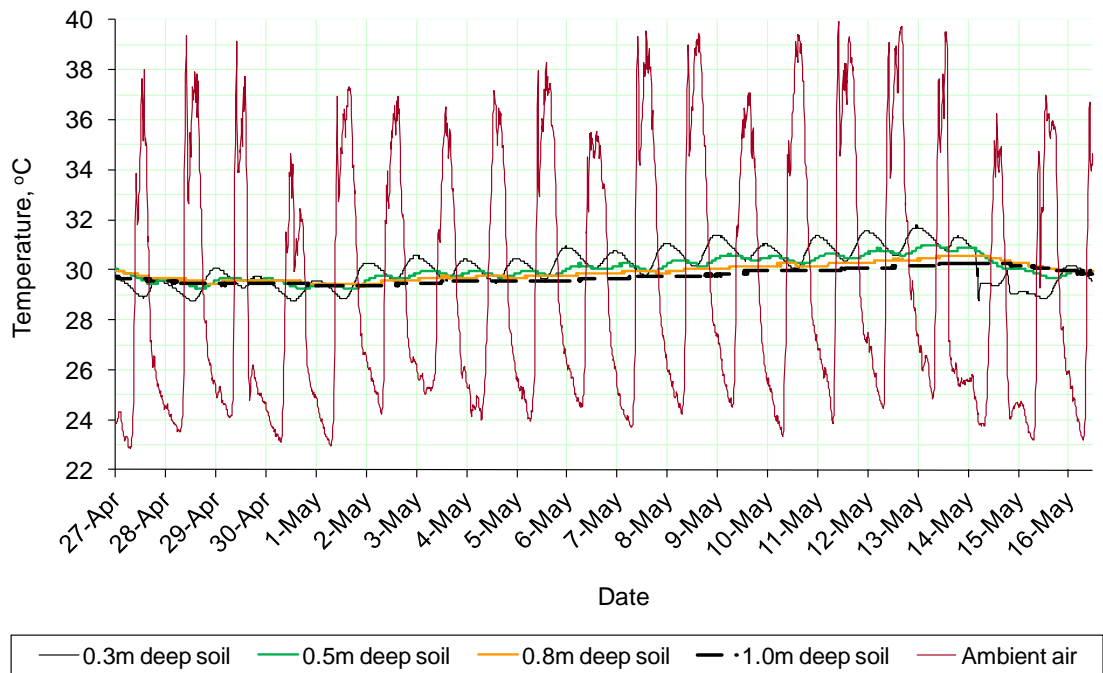


Figure 5.3: Trend of ambient air temperature and soil temperature measured on field site in Gombak, Malaysia from 27 April to 16 May 2009.

During the soil investigation in April and May, the ambient DBT ranges from 22.8°C to 39.9°C and the maximum diurnal temperature difference during the experiment period was 16.1°C which occurred on 11 May 2009, where the maximum ambient air temperature was 39.9°C and its minimum was 23.9°C (Figure 5.3). The average maximum ambient DBT during this investigation was 37.9°C, which is 4.9°C higher than the average maximum ambient DBT during the first soil temperature experiment that took place in October and November 2007. This shows there is a temperature difference of 4.9°C in average maximum ambient DBT between the hot and dry season and warm and wet season.

The graph in Figure 5.3 above shows that the increase of ambient DBT has affected the trend of soil temperature at 1m deep. Although the soil temperature amplitude maintains to be as low as 0.5°C, the average soil temperature at 1m deep was 29.7°C, which is 2.2°C higher than the average soil temperature at 1m deep underground during the wet season. The result of this investigation shows that at 1m deep underground, the soil temperature is still affected by the ambient DBT. Figure 5.3 also shows that as the soil gets nearer to the ground surface, the temperature amplitude

increases, which makes the soil temperature became less constant with more fluctuations.

Due to the rather significant differences at 1m depth soil temperature, another soil temperature measurement was carried out for the whole year. Figure 5.3 shows that, throughout the day, the soil temperature at 1.0m depth does not fluctuate significantly, comparatively to the soil temperature at 0.5m and 0.3m depth. Therefore, the next soil temperature investigation measures at 0.5m, 1.0m and 1.5m depth.

Figure 5.4 shows an hourly distribution of soil temperature at the field work site in Gombak where the data loggers were buried at 0.5m, 1.0m and 1.5m deep underground. However, there is an error in the reading of data logger buried at 1.5m in the month of January and February, which leaves a gap in the soil temperature trend (Figure 5.4).

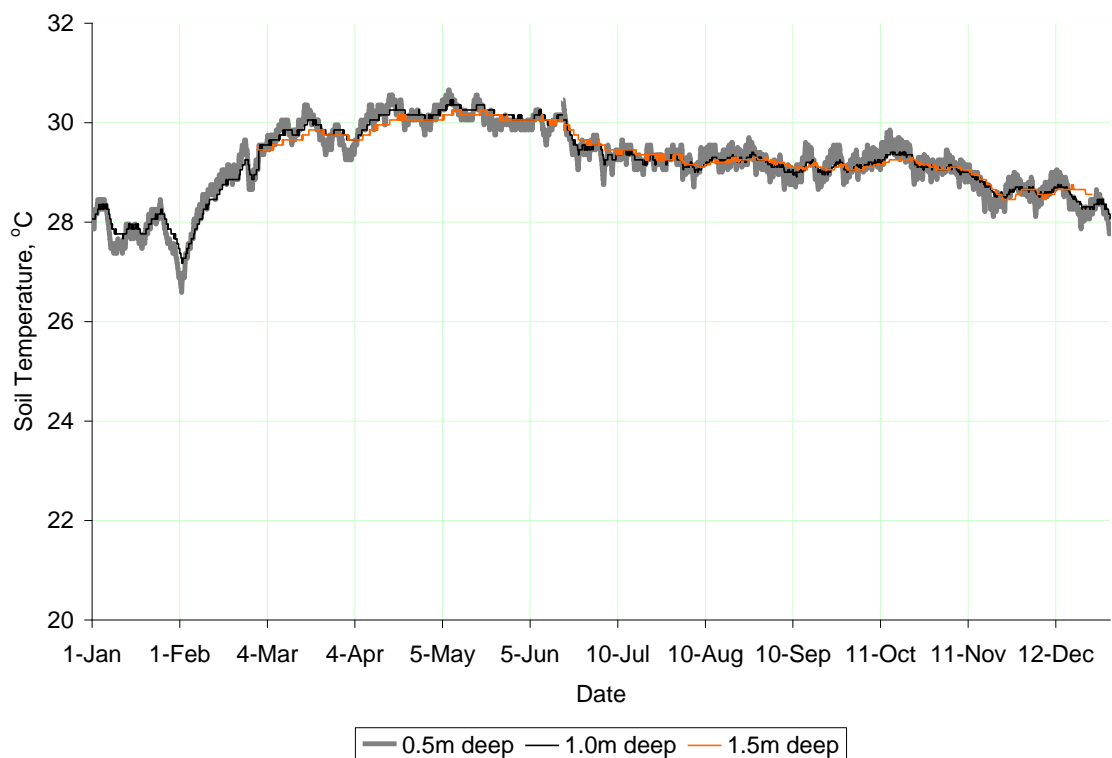


Figure 5.4: Hourly distribution of soil temperature (°C) at 0.5m, 1.0m and 1.5m depths within a year at the field work site in Gombak, Kuala Lumpur, Malaysia.

Figure 5.4 above shows the daily fluctuations of soil temperature is reduced as the depth underground increased. As mentioned in Chapter 2, Malaysia climate is hot and humid through the year but does have different season with slightly different average weather data; air temperature, relative humidity and rainfall. Between October and March the weather is warm and wet, whereas in March, April and May, the weather is usually hot and dry. The weather data explains the trend of soil temperature in Figure 5.4. The soil temperature at all depths that are successfully recorded are found to be lower in November, December, January and February while the soil temperature is higher in March, April and May.

In a year, the soil temperature at 0.5m depth ranges from 26.6°C to 30.7°C (Figure 5.5). The absolute maximum temperature occurred in the hot and dry month May while the absolute minimum temperature occurred in February. Due to the shallow depth of the measured soil, the annual amplitude is 2.05, which is considered to be large. However, the monthly amplitude ranges from 0.46 (May) to 1.53 (February) and the average monthly amplitude is 0.81.

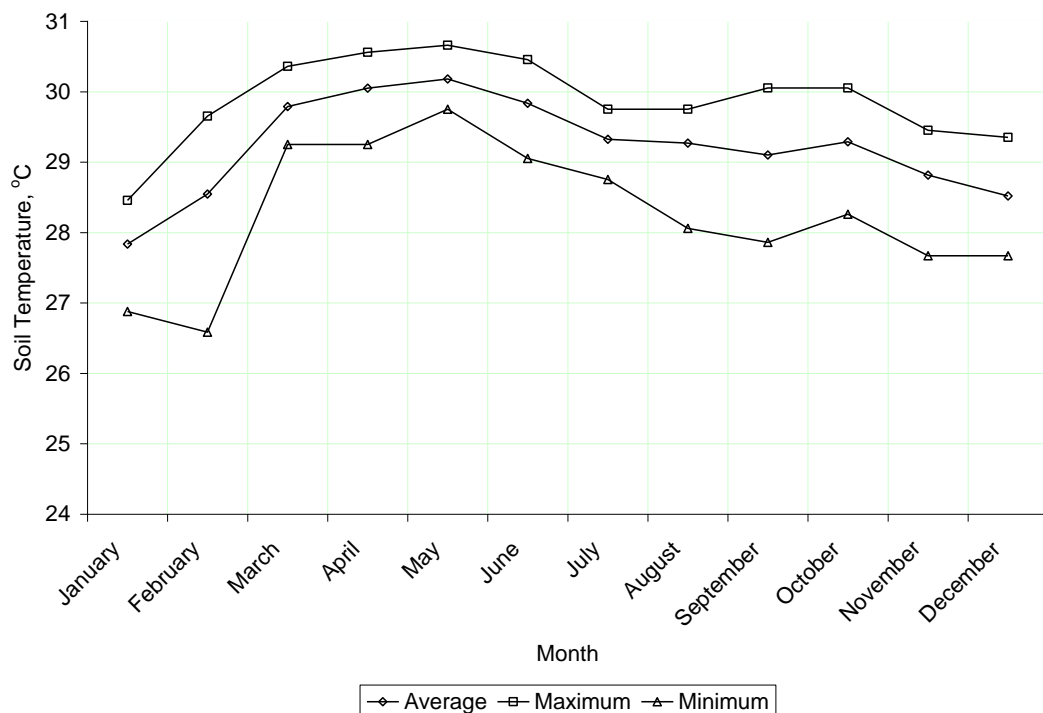


Figure 5.5: Monthly absolute maximum, absolute minimum and average soil temperature (°C) at 0.5m depths within a year at the field work site in Gombak, Kuala Lumpur, Malaysia.

Meanwhile, at 1.0m depth underground, the soil temperature ranges from 27.2°C to 30.5°C (Figure 5.6). The absolute maximum soil temperature recorded in May while the absolute minimum soil temperature is recorded in February. The annual amplitude is 1.65, which is 0.4 lower than the annual amplitude of soil temperature at 0.5m depth. On the other hand, the monthly amplitude ranges from 0.2 (in May and July) to 1.04 (February) and the monthly amplitude gives an average of 0.45 in a year. This average monthly amplitude is halved the average monthly amplitude of 0.5m depth soil temperature.

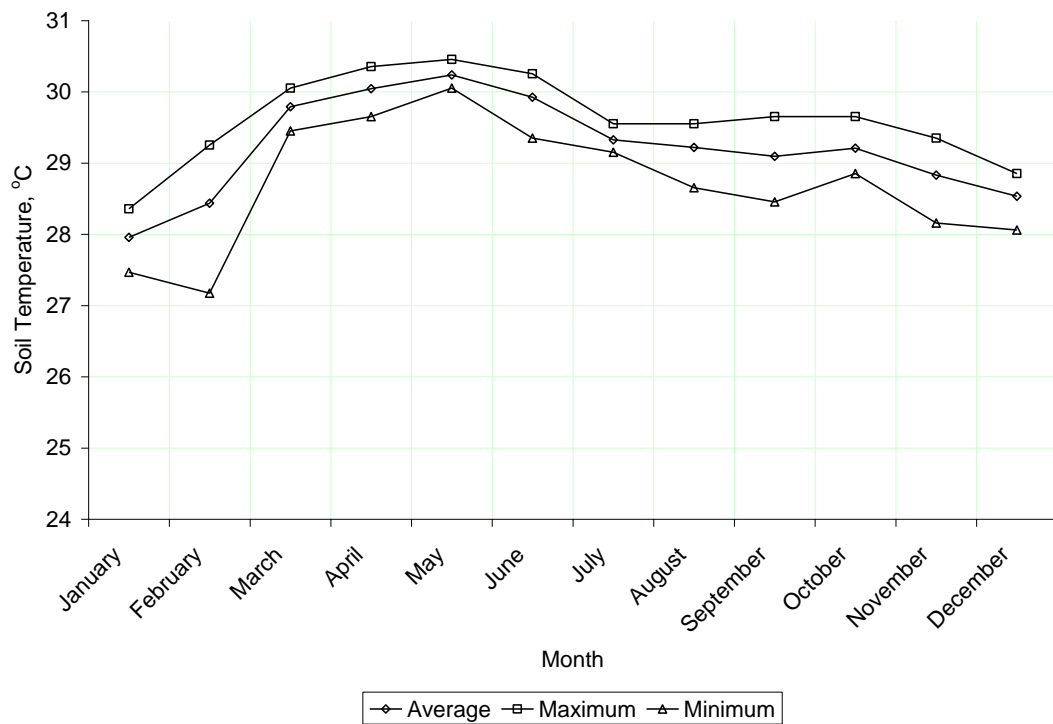


Figure 5.6: Monthly absolute maximum, absolute minimum and average soil temperature (°C) at 1.0m depths within a year at the field work site in Gombak, Kuala Lumpur, Malaysia.

At 1.5m depth underground, the valid soil temperature data is recorded from March to December due to unexpected error in the data logger throughout January and February. Therefore, the soil temperature at 1.5m depth ranges from 28.5°C to 30.3°C within a year excluding data in January and February (Figure 5.7).

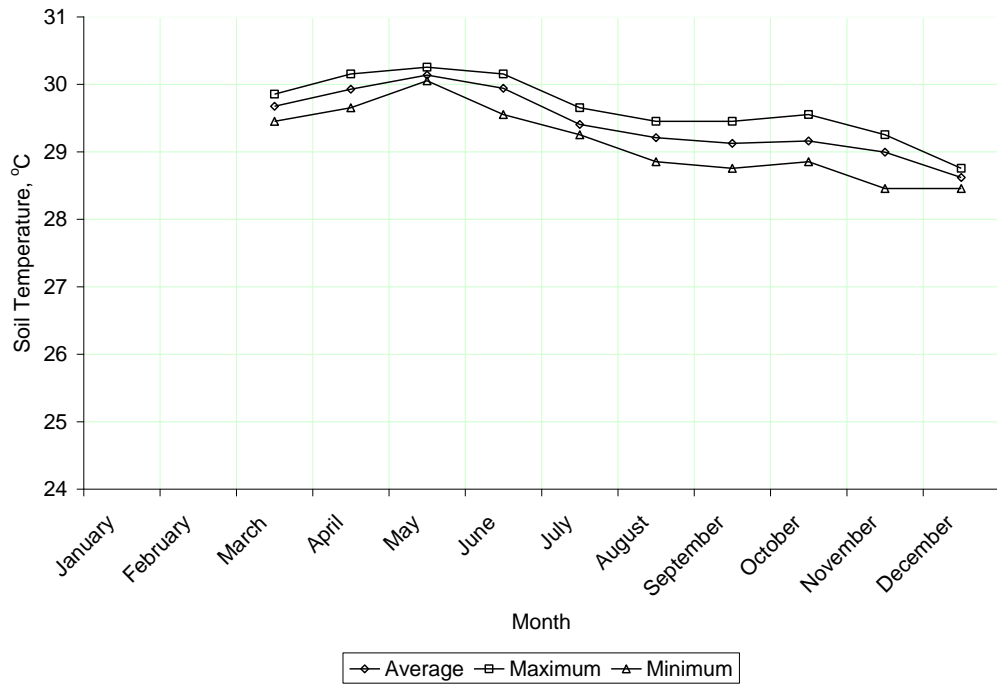


Figure 5.7: Monthly absolute maximum, absolute minimum and average soil temperature ($^{\circ}\text{C}$) at 1.5m depths within a year at the field work site in Gombak, Kuala Lumpur, Malaysia.

Because there are no data in January and February, the annual amplitude of soil temperature at this depth cannot be calculated. However, the monthly amplitude ranges from 0.10 (May) to 0.40 (November) and the average monthly amplitude (excluding January and February) is 0.26.

The monthly amplitude for all 0.5m, 1.0m and 1.5m depth soil temperature are tabulated in Table 5.4.

Table 5.4: Summary of monthly amplitude of soil temperature at 0.5m, 1.0m and 1.5m depth at the field work site.

Amp- litude	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
0.5m depth	0.79	1.53	0.56	0.65	0.46	0.70	0.50	0.85	1.10	0.90	0.89	0.84
1.0m depth	0.44	1.04	0.30	0.35	0.20	0.45	0.20	0.45	0.60	0.40	0.60	0.40
1.5m depth			0.20	0.25	0.10	0.30	0.20	0.30	0.35	0.35	0.40	0.15

It is interesting to see that although each depth varies with different monthly absolute maximum, absolute minimum and amplitude soil temperatures, their monthly averages are nearly the same (Figure 5.8). Figure 5.8 also shows that the trend curve of monthly average soil temperature at all three depths follow the trend curve of monthly average air dry bulb temperature but the soil temperature monthly averages are elevated mostly 2°C higher than the monthly average air dry bulb temperature.

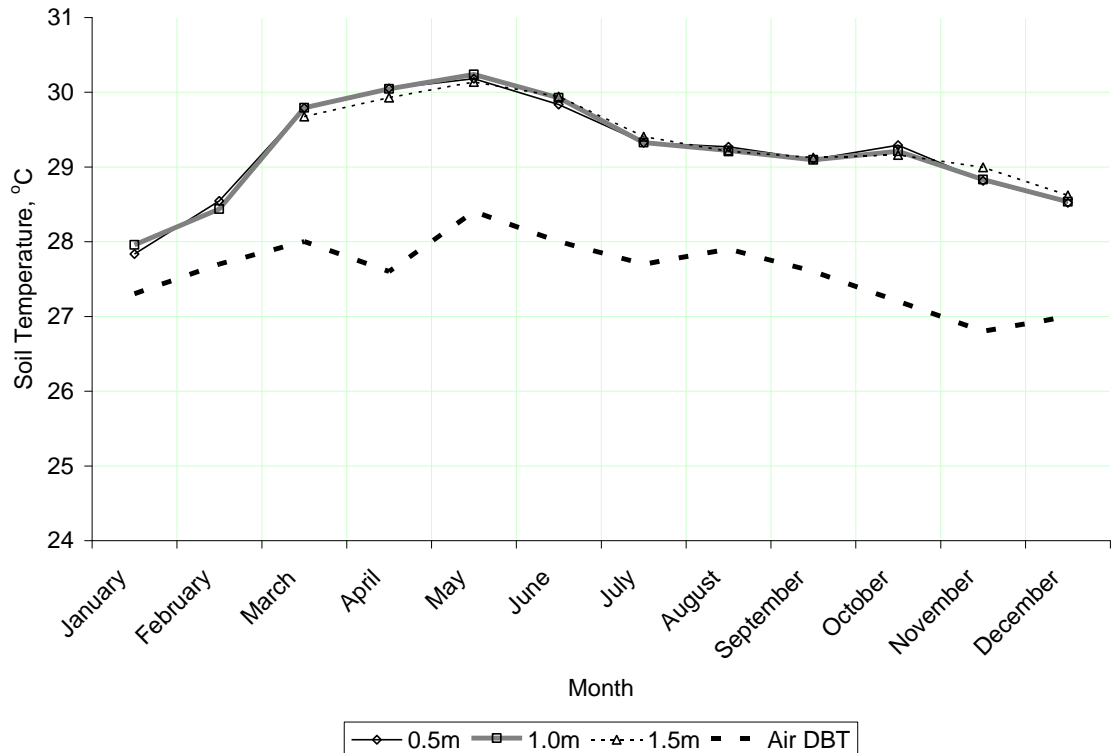


Figure 5.8: Monthly average air dry bulb temperature and soil temperature at 0.5m, 1.0m and 1.5m depths within a year at the field work site in Gombak, Kuala Lumpur, Malaysia.

An additional study of soil temperature was carried out from November to February. This investigation is carried out simultaneously while the earth pipe cooling experiment were running. It is initiated to compare the soil temperature in two different locations, at 1.0m depth. The determined location is the usual spot, which is away from the buried pipe and the other location is within 0.5m from the buried pipe. As mentioned in Chapter 3: Literature Review: Passive Ground Cooling, this investigation is carried out in response to a literature by Li et al. (2009) that reported an increase of

soil temperature within 1.0m proximity to the buried pipe for earth pipe cooling in long term due to the heat dissipation from the pipe effect. However, due to time limitation, this research only managed to compare the two soil temperatures in two locations for three months. The determined soil depth for this investigation is 1.0m because the only running earth pipe cooling at that time is buried at 1.0m depth underground.

The data logger was buried long after the earth pipe cooling system started running and therefore the soil should already be affected by the heat dissipated from the buried pipe by the time the data logger reads the soil temperature near the buried pipe. Figure 5.9 shows that the soil temperatures at two locations are very similar with maximum of 0.4°C temperature differences, which occurred in January and February. This shows that in the short term, the heat dissipated from earth pipe cooling system does not affect the soil temperature significantly. Further studies of the long term effect of heat dissipation from earth pipe cooling system to the nearby soil temperature can be carried out in the future when there is no time limitation to the research.

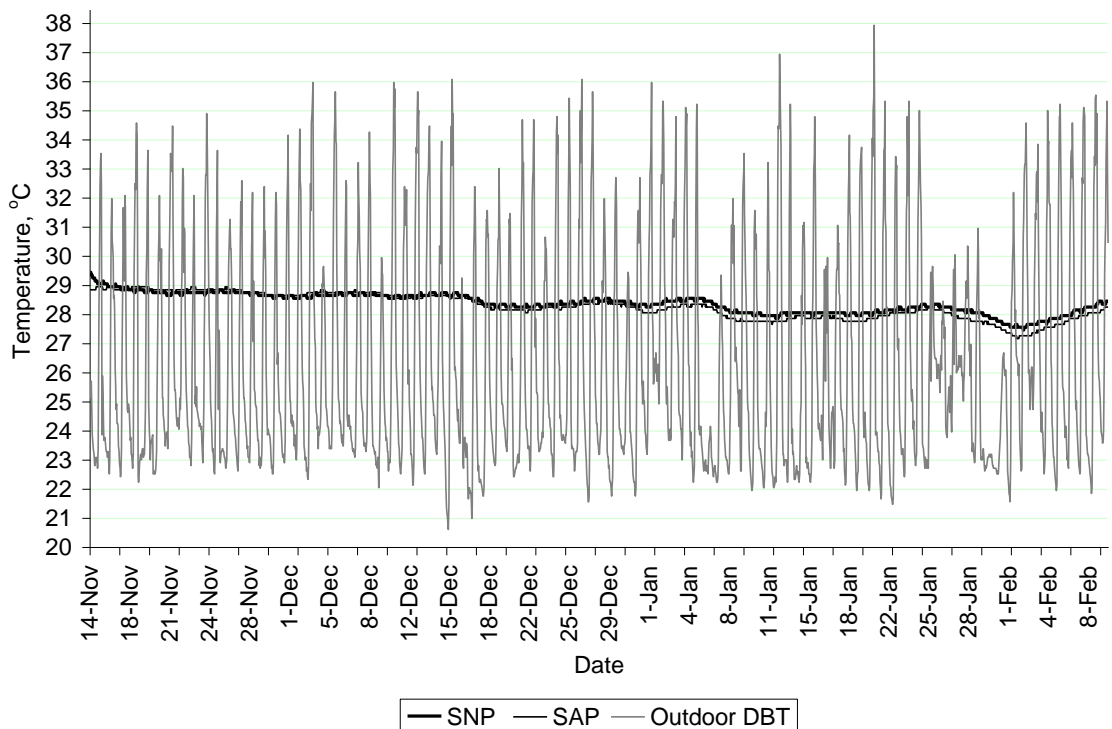


Figure 5.9: Trend of soil temperature at 1.0m depth underground in two locations; near pipe (SNP) and away from pipe (SAP) and outdoor air dry bulb temperature.

5.2 Earth Pipe Cooling Investigation in Malaysia.

The Earth Pipe Cooling investigation in Malaysia was carried out three times on the same site throughout the research year. The first set of data was recorded in November and December, during the wet season. The second set of data was recorded in April and May during the hot and dry season. The results obtained from the investigations in wet and hot season show variation in buried pipe outlet air temperature even though Malaysian climate is hot and humid throughout the year. Therefore, the third investigation recorded data for one year. The aim of these investigations was to obtain optimum design of Earth Pipe Cooling set up to be implemented in Malaysia climate. Another aim is to seek the viability of applying this technology under Malaysia climate by looking at the result of temperature drop between the buried pipe inlet and outlet.

As mentioned earlier, the parameters that could affect the performance of Earth Pipe Cooling technology apart from surrounding weather condition are the depth of pipe buried underground, the length of pipe, its diameter, the pipe material and the airflow inside the buried pipe.

5.2.1 Investigation in the Wet Season

Investigation in the wet season; November and December, comprises the inlet and outlet temperature of the 25m long Polyethylene pipes buried at 0.5m, 1.0m and 1.5m and 50m long Polyethylene pipe buried at 1.0m deep underground. The various parameters used were part of the investigation in the wet season since it is the first investigation of Earth Pipe Cooling System of this research. The parametric studies consist of the effect of pipe length, and depth of pipe buried underground. However, the parametric study has its limits because the different setup was run separately to avoid interference at the buried pipe outlet. The fan blower that provides air into the buried pipe operates daily from 10:00am to 6:00pm and the air velocity maintains at 5.6m/s.

Alongside the buried pipe inlet and outlet temperature, this investigation also records the indoor DBT in where the buried pipe inlet and outlet are located. As mentioned earlier, each data group of each Earth Pipe Cooling design were measured separately. This is to avoid interference among different Earth Pipe Cooling design data measurements since the pipes were buried fairly close to each other.

a) 25m long Polyethylene pipe buried at 0.5m depth underground

In the graph shown in Figure 5.10 below, day 1 temperatures data seem to maintain low throughout the day. The reason behind this was because it rained during the day, hence the low outdoor, indoor and buried pipe inlet temperatures. During the two days of operation, the temperature at buried pipe inlet and outlet ranges from 23.1°C to 33.9°C and from 23.3°C to 28.4°C respectively. The maximum temperature reduction between the two ends of the buried pipe was 5.9°C, which occurred at 1:00pm. At this hour, the buried pipe inlet and outlet temperatures were 33.8°C and 27.9°C respectively. The average daily maximum temperature reduction between the two ends of the buried pipe was 5.9°C, which is the same as the absolute maximum in two days, because there is no temperature reduction on day 1 due to rainfall and hence the pipe inlet temperature became lower than the pipe outlet. Indoor DBT ranges from 22.8°C to 32.2°C while the outdoor DBT ranges from 22.3°C to 37.3°C.

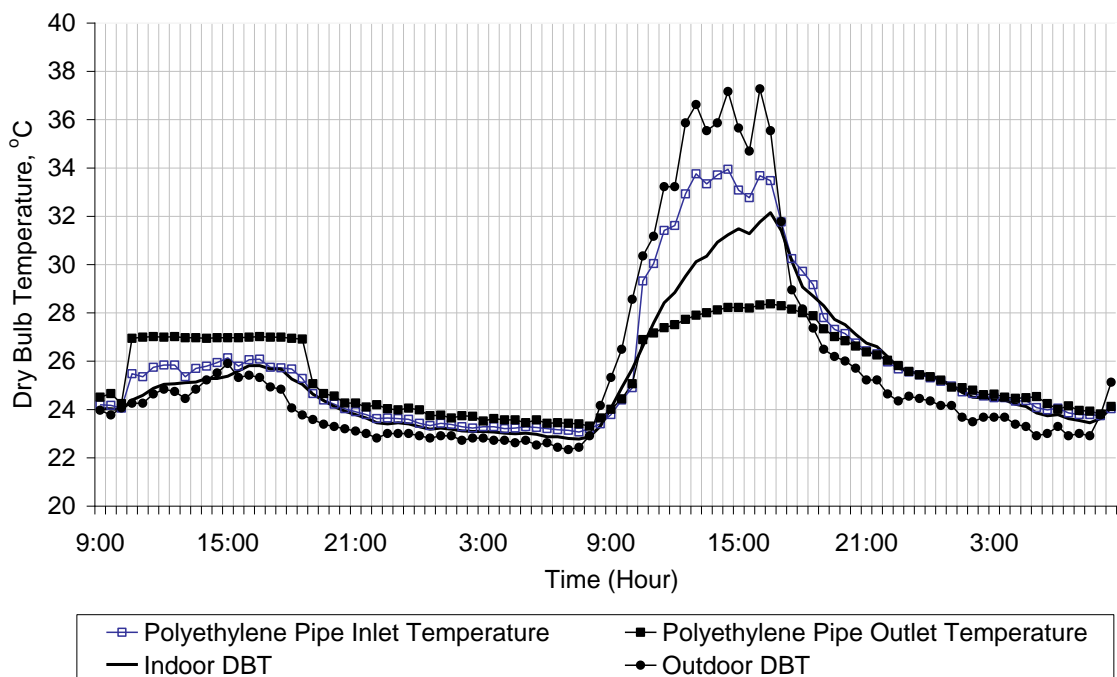


Figure 5.10: Temperature during investigation of 25m long Polyethylene pipe buried at 0.5m depth underground. Fan blower operated from 10:00 a.m. to 6:00 p.m. in November 2008.

b) 25m long Polyethylene pipe buried at 1.0m depth underground

Within the 25m long Polyethylene pipe which was buried at 1.0m depth underground, the temperatures at the inlet and outlet range from 22.8°C to 34.8°C and from 22.8°C to 29.5°C respectively. Figure 5.11 below shows there is a jump in pipe outlet temperature on day at 6:30pm. This happened because the fan blower was switched off too soon before the outdoor DBT reduced to lower than the pipe outlet temperature in the previous hours. During the time when fan blower operates, which was from 10:00am to 6:00pm, the pipe outlet temperature ranges from 26.8°C to 28.5°C. However, the maximum temperature reduction in two days of operation is 6.4°C, which occurred at 1:00pm. At this hour, the buried pipe inlet and outlet temperatures are 34.6°C and 28.2°C respectively. The average daily maximum temperature reduction within the two days of operation is 5.7°C.

The indoor DBT ranges from 22.7°C to 32.6°C while the outdoor DBT ranges from 21.9°C to 35.8°C. The two ranges of dry bulb temperature (DBT) are very similar where there is not much temperature reduction between the outdoor and indoor DBT.

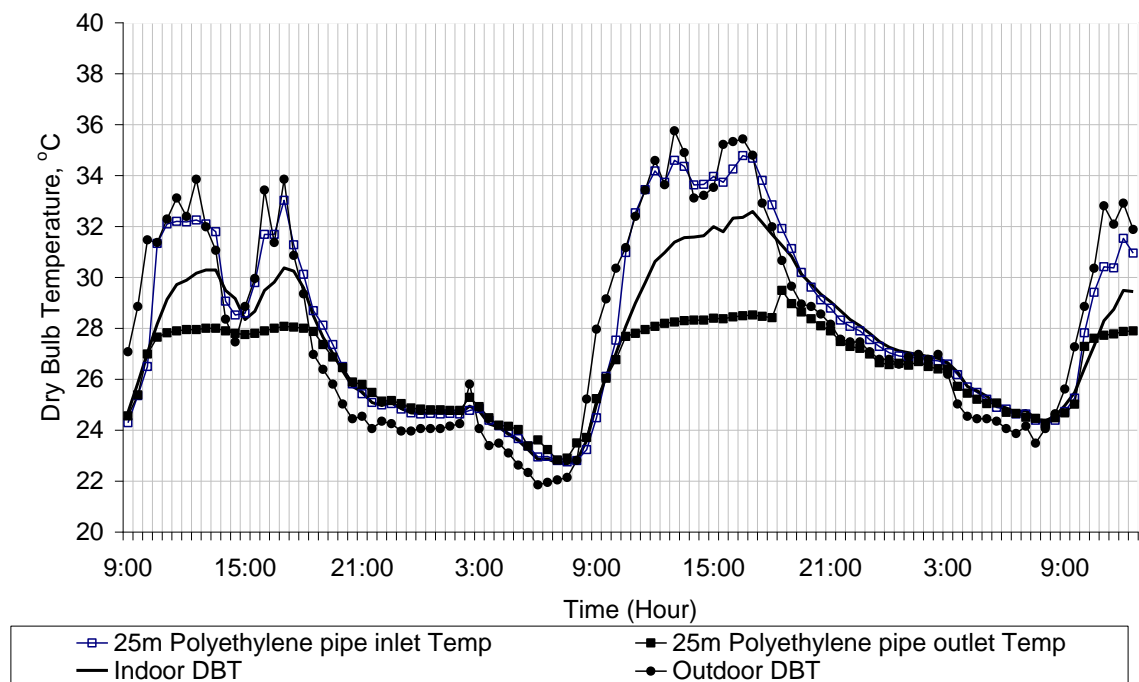


Figure 5.11: Trend of temperature during investigation of 25m long Polyethylene pipe buried at 1.0m depth underground. Fan blower operated from 10:00 a.m. to 6:00 p.m. in November 2008.

c) *25m long Polyethylene pipe buried at 1.5m depth underground*

Figure 5.12 illustrates data obtained from this investigation. The temperature at buried pipe inlet ranges from 22.7°C to 32.4°C while the buried pipe outlet temperature ranges from 22.7°C to 28.6°C. The maximum temperature reduction from the pipe inlet to outlet is 4.0°C, which occurred at 11:30am. At this hour, the buried pipe inlet and outlet temperatures were 32.3°C and 28.4°C respectively. Between the two days of experiment, the average daily maximum temperature reduction is 3.9°C. Meanwhile, the indoor DBT ranges from 22.6°C to 30.9°C while the outdoor DBT ranges from 22.0°C to 33.6°C. The data shows there is not much difference in temperature between the indoor and outdoor.

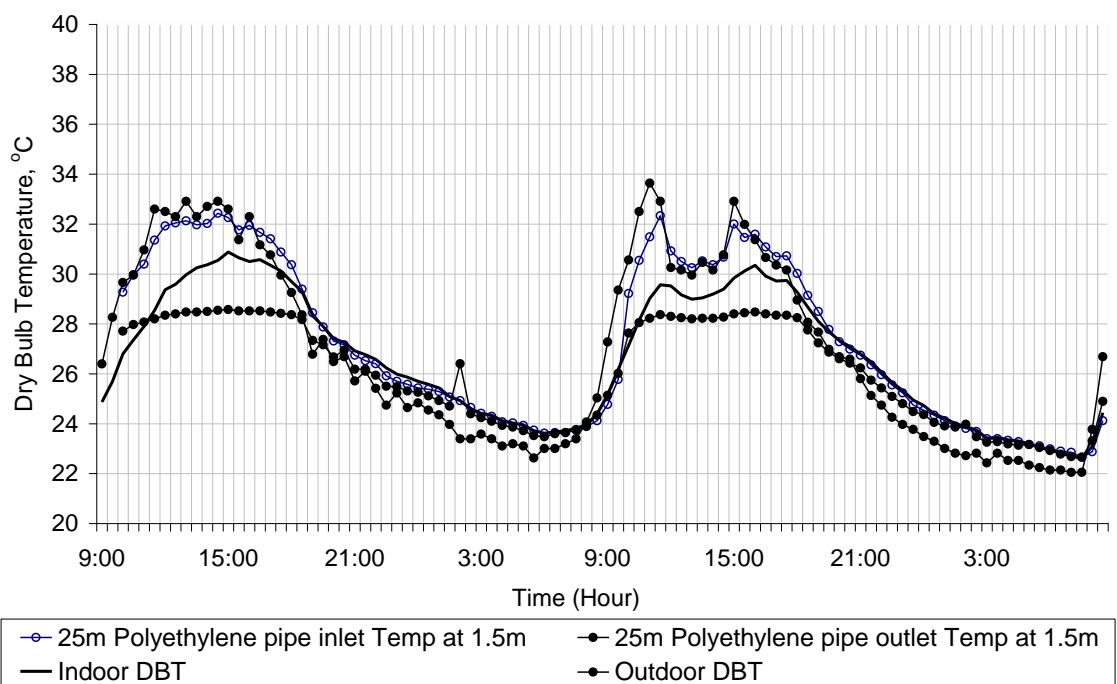


Figure 5.12: Trend of temperature during investigation of 25m long Polyethylene pipe buried at 1.5m depth underground. Fan blower operated from 10:00 a.m. to 6:00 p.m. in November 2008.

d) *50m long Polyethylene pipe buried at 1.0m depth underground*

A 50m long Polyethylene pipe is also buried at 1.0m depth underground and the temperatures at the pipe inlet and outlet ranges from 23.9°C to 35.3°C and from 23.9°C to 28.6°C respectively (Figure 5.13). The maximum temperature reduction within the two days of investigation, the maximum temperature reduction between the two ends of

the buried pipe is 6.8°C, which occurred at 3:00pm. At this hour, the buried pipe inlet temperature was 35.3°C while the outlet temperature was 28.5°C. Meanwhile, the average daily maximum temperature reduction is 6.3°C.

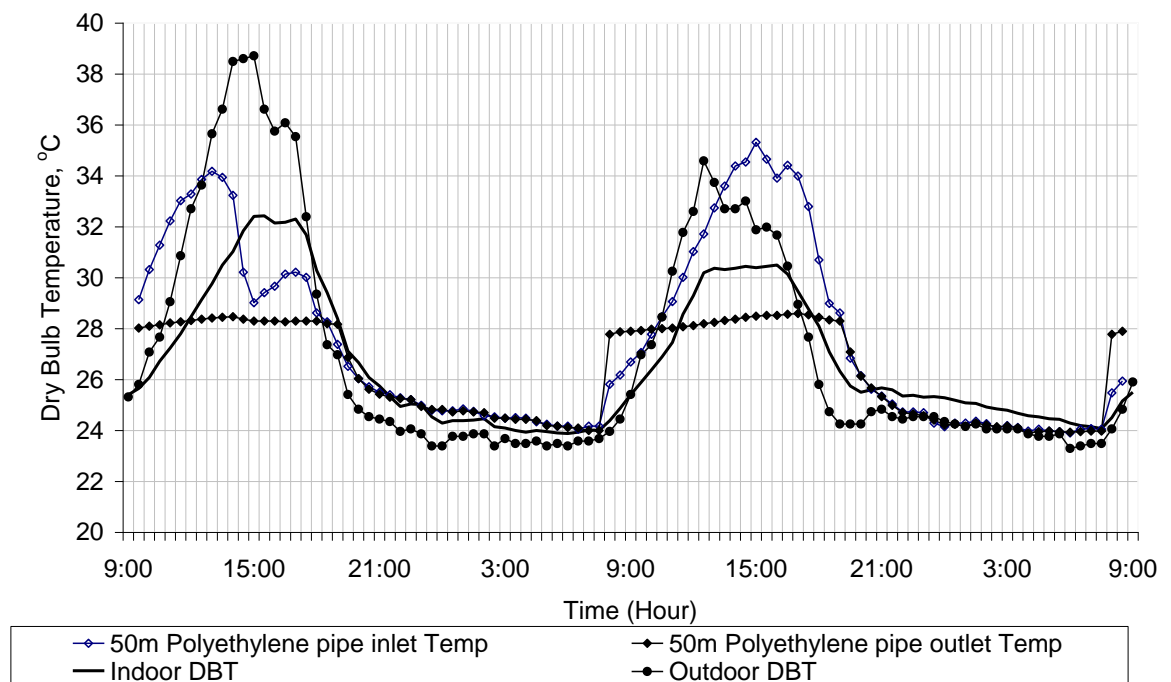


Figure 5.13: Trend of temperature during investigation of 50m long Polyethylene pipe buried at 1.0m depth underground. Fan blower operated from 10:00 a.m. to 6:00 p.m. in November 2008.

The indoor DBT in this investigation ranges from 23.9°C to 32.4°C and the outdoor DBT ranges from 23.3°C to 38.7°C. Looking at the pipe outlet temperature graph in Figure 5.13, the temperature had a sudden rise at 8:00am in all three days. This is because unlike the other investigation, the fan blower operated from 8:00am to 7:00pm. This was the first investigation carried out during the wet season and the fan blower operation time was determined according to the hour after sunrise and before sunset. The result shows that the pipe outlet temperature is higher than the inlet until approximately 10:00. The pipe outlet temperature became higher than the inlet again after 6:00pm. Therefore, the following investigations during the wet season had the fan blower operated from 10:00am to 6:00pm.

Table 5.5 summarises the result of each cases a), b), c) and d). The table includes the temperature reduction between the two ends of each buried pipe and also temperature ranges of each buried pipe.

Table 5.5: Summary of results of 24 hours obtained from investigation carried out during the wet season. TR=Temperature Reduction, OT=Outlet Temperature and IT=Inlet Temperature.

	Case a) Polyethylene pipe, 25m long, 0.5m deep	Case b) Polyethylene pipe, 25m long, 1.0m deep	Case c) Polyethylene pipe, 25m long, 1.5m deep	Case d) Polyethylene pipe, 50m long, 1.0m deep
Outdoor DBT, °C	22.3 – 37.3	21.9 – 35.8	22.0 – 33.6	23.3 – 38.7
ITRange, °C	23.1 – 33.9	22.8 – 34.8	22.7 – 32.4	23.9 – 35.3
OTRange, °C	23.3 – 28.4	22.8 – 29.5	22.7 – 28.6	23.9 – 28.6
Max TR, °C	5.9	6.4	4.0	6.8
Average daily maximum TR, °C	5.9	5.7	3.9	6.3
Indoor DBT, °C	22.8 – 32.2	22.7 – 32.6	22.6 – 30.9	23.9 – 32.4
Blower on period	10:00 to 18:00 hrs			

5.2.2 Investigation in the Dry Season

Similar to investigations in the wet season, the experiments during hot and dry season are carried out with various parameters. The experiments are carried out in four different cases, a), b), and c). In each case temperatures at the buried pipe inlet and outlet were obtained. Simultaneously, the DBT of indoor that houses the two ends of the buried pipe and outdoor were also recorded. Outdoor DBT was also recorded but the data logger was not properly shaded and produced temperature readings that are too high during the daytime in all case experiments. The various parameters differ in depths. Three Polyethylene pipes were buried separately at 0.5m, 1.0m and 1.5m deep underground. All buried pipes are 25m long and all pipe inlets are connected to a fan blower. The fan blower provides air flow through each buried pipe at 5.6m/s. The fan blower supply air into one buried pipe at a time to prevent interference among the different buried pipe designs. The fan blower was scheduled to operate daily from 10:00am to 6:00pm.

In this season, the investigations include collection data of relative humidity at the buried pipe inlet and outlet, outdoor and indoor. The purpose of this was to find the possibility of condensation that might occur within the buried pipe or in the experiment shed, which houses the two ends of the buried pipe.

a) 25m long Polyethylene pipe buried at 0.5m depth underground

The related soil temperature in this investigation is also at 0.5m deep underground. The soil temperature shown in Figure 5.14 ranges from 29.8°C to 30.3°C. The temperature at the inlet and outlet buried pipe ranges from 24.7°C to 35.2°C and from 25.3°C to 30.6°C respectively. There is temperature difference between the two ends of the buried pipe when the fan blower was operating. The maximum temperature reduction at the pipe outlet from the inlet was 4.9°C while the average daily maximum reduction was 4.2°C. The indoor DBT ranges from 25.1°C to 33.5°C. The maximum indoor DBT is 1.7°C less than the maximum temperature at the buried pipe inlet.

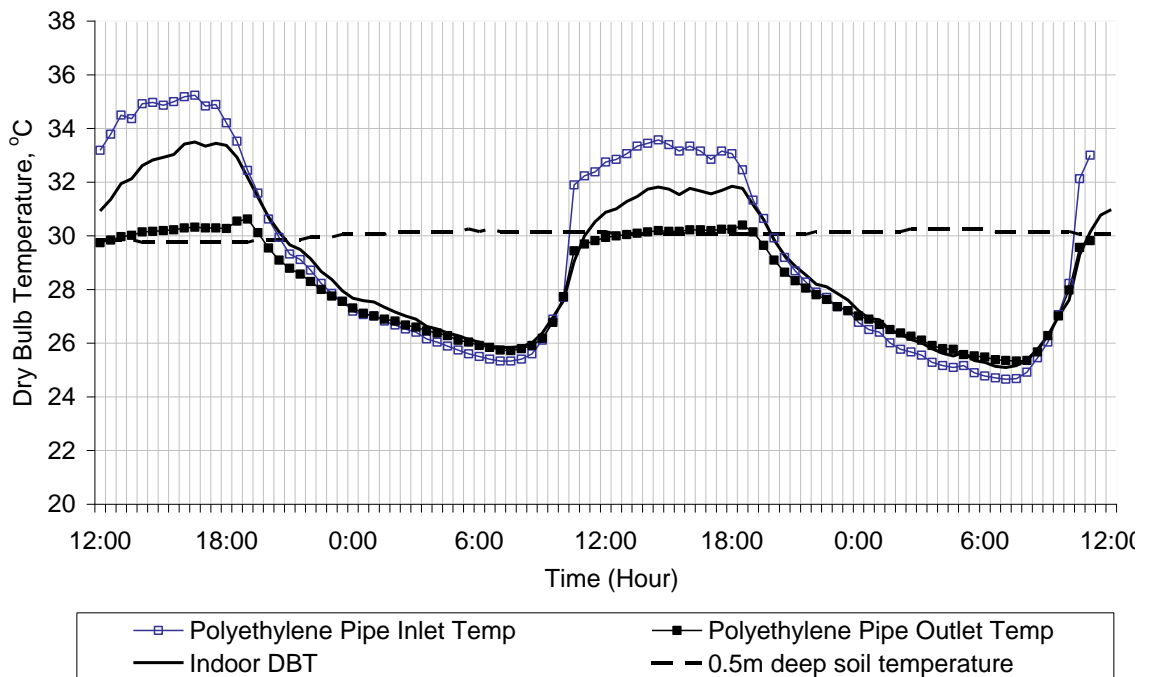


Figure 5.14: Trend of temperature from the investigation of 25m long Polyethylene pipe buried at 0.5m deep underground. Fan blower operated from 10:00 a.m. to 6:00 p.m. in May 2009.

Figure 5.15 shows that the RH at the inlet and outlet of the buried Polyethylene pipe ranges from 51.4% to 85.7% and from 63.0% to 84.5% respectively. In Polyethylene pipe buried at 0.5m deep underground, the RH at outlet is similar to the inlet RH when the fan blower stopped operating. The maximum RH rise between the two ends of the buried pipe is 16.4% where it is higher at the pipe outlet. The indoor RH ranges from 56.3% to 81.3%. Within the two days of experiment, the resulting RH did not exceed 85%.

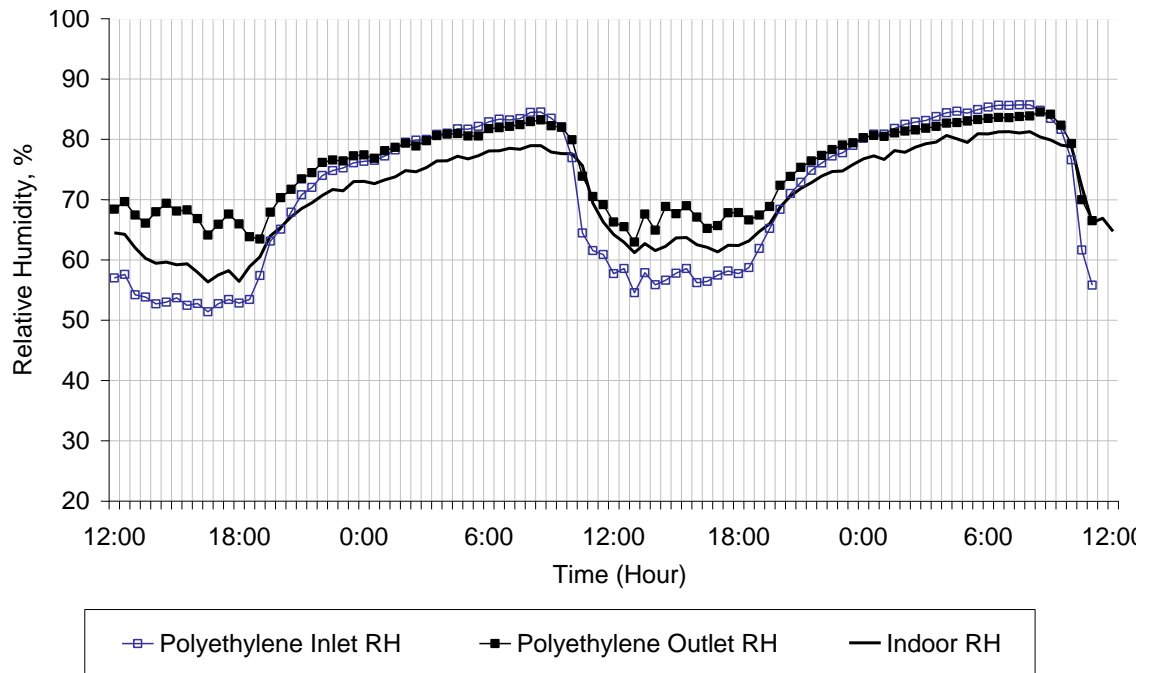


Figure 5.15: Trend of relative humidity from the investigation of 25m long Polyethylene pipe buried at 0.5m deep underground. Fan blower operated from 10:00 a.m. to 6:00 p.m. in May 2009.

b) 25m long Polyethylene pipe buried at 1.0m depth underground

At 1.0m depth underground, the soil temperature measured in two days ranges from 29.9°C to 30.0°C. The temperatures at buried pipe inlet and outlet range from 24.4°C to 37.0°C and from 24.7°C to 31.2°C respectively (Figure 5.16).

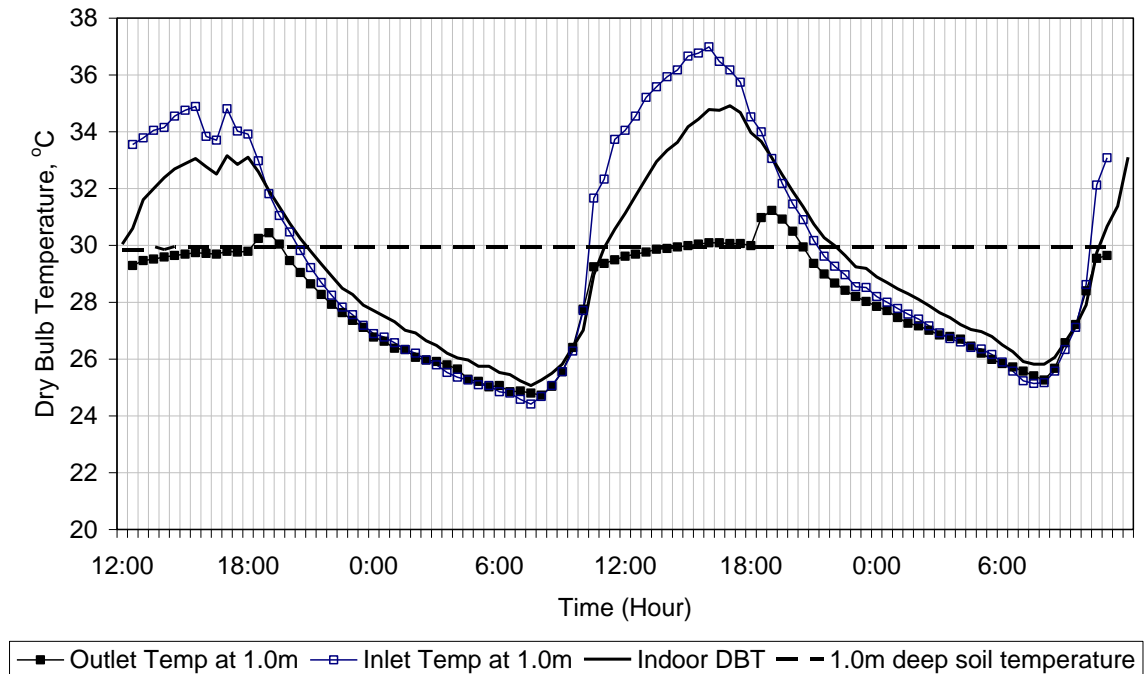


Figure 5.16: Trend of temperature from the investigation of 25m long Polyethylene pipe buried at 1.0m deep underground. Fan blower operated from 10:00 a.m. to 6:00 p.m. in May 2009.

The maximum temperature reduction occurred during the day when the fan blower was operating and the value was 6.9°C. Within the two days, the average daily maximum temperature reduction was 6.0°C. Meanwhile, the indoor DBT ranges from 25.1°C to 34.9°C. The maximum indoor DBT is 2.1°C less than the maximum temperature at the buried pipe inlet.

Similar to case a), Figure 5.17 shows that the RH in the buried pipe inlet and outlet are similar when the fan blower stopped operating. The RH at the buried pipe inlet and outlet ranges from 46.0% to 83.5% and from 60.3% to 83.2% respectively (Figure 5.17). The maximum rise in RH at the pipe outlet from the inlet was 17.3% and the resulting RH maintained below 85%. The indoor RH ranges from 53.2% to 77.5%.

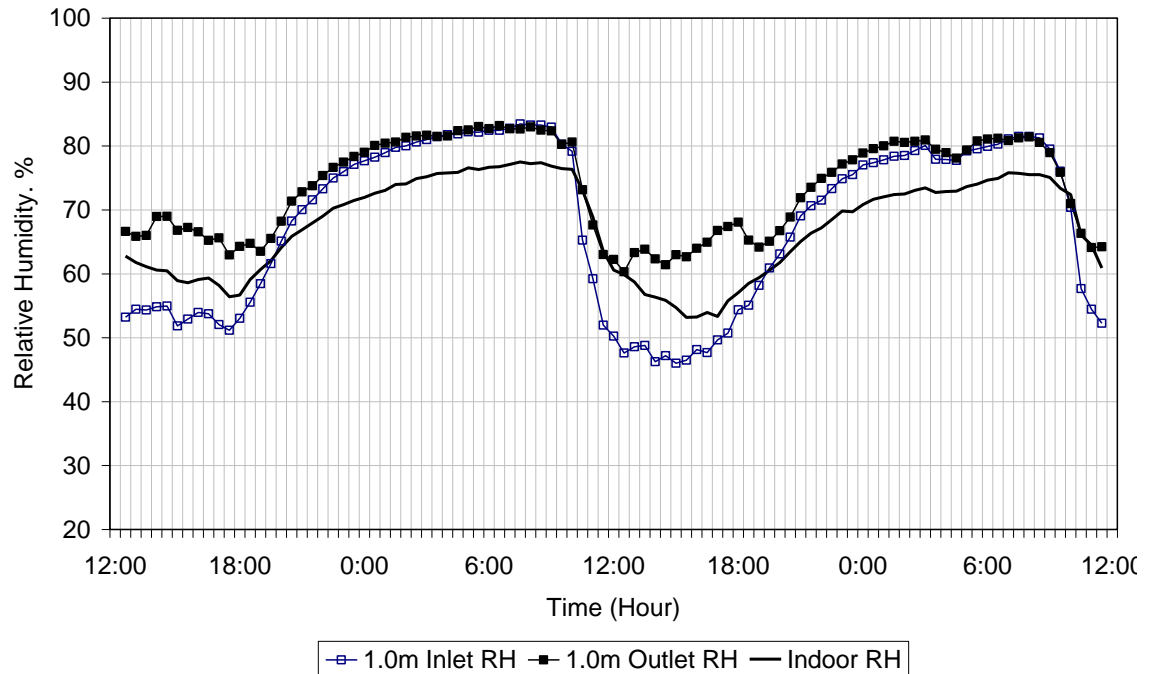


Figure 5.17: Trend of relative humidity from the investigation of 25m long Polyethylene pipe buried at 1.0m deep underground. Fan blower operated from 10:00 a.m. to 6:00 p.m. in May 2009.

c) 25m long Polyethylene pipe buried at 1.5m depth underground

In this season, the soil temperature measured was limited to 1.0m deep underground and hence there's no available soil temperature at 1.5m depth. The temperature at the buried pipe inlet and outlet ranges from 23.9°C to 36.1°C and from 23.7°C to 30.2°C respectively (Figure 5.18).

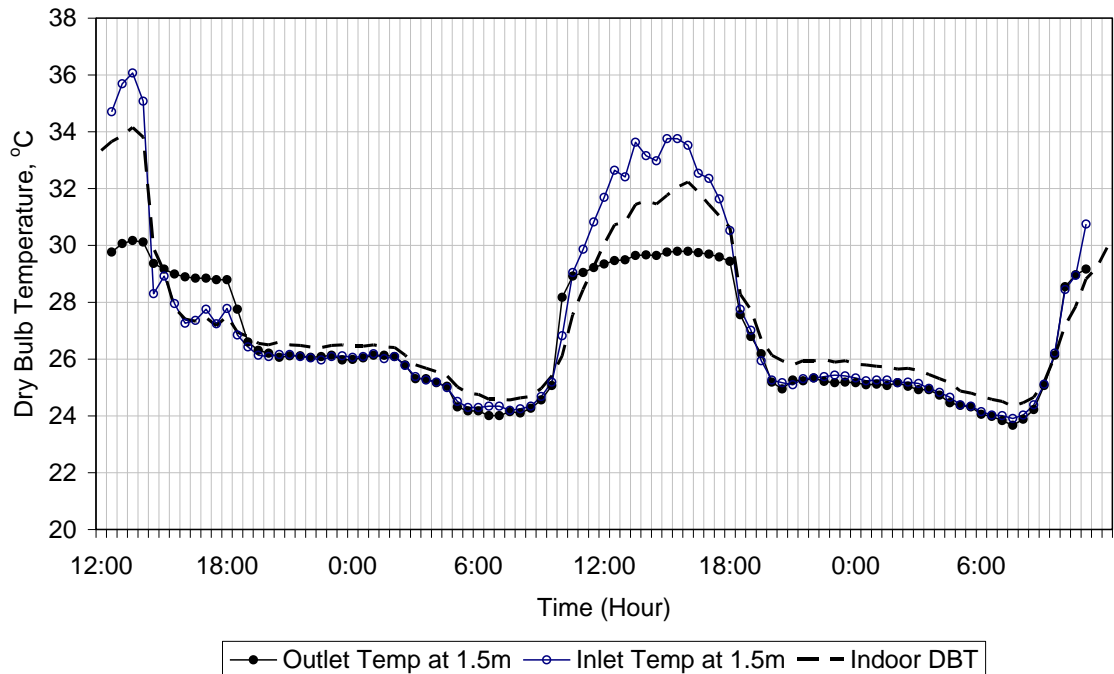


Figure 5.18: Trend of temperature from the investigation of 25m long Polyethylene pipe buried at 1.5m deep underground. Fan blower operated from 10:00 a.m. to 6:00 p.m. in May 2009.

In the evenings when the fan blower was not operating, the temperatures at pipe inlet and outlet are similar. When the fan blower operates during daytime, there was temperature reduction between the two ends of the buried pipe that developed until the maximum value of 5.9°C. Within the two days of experiment, the average daily maximum temperature reduction was 4.9°C. The indoor DBT during the experiment ranges from 24.3°C to 34.2°C. The maximum indoor DBT is 1.9°C less than the maximum temperature at the buried pipe inlet.

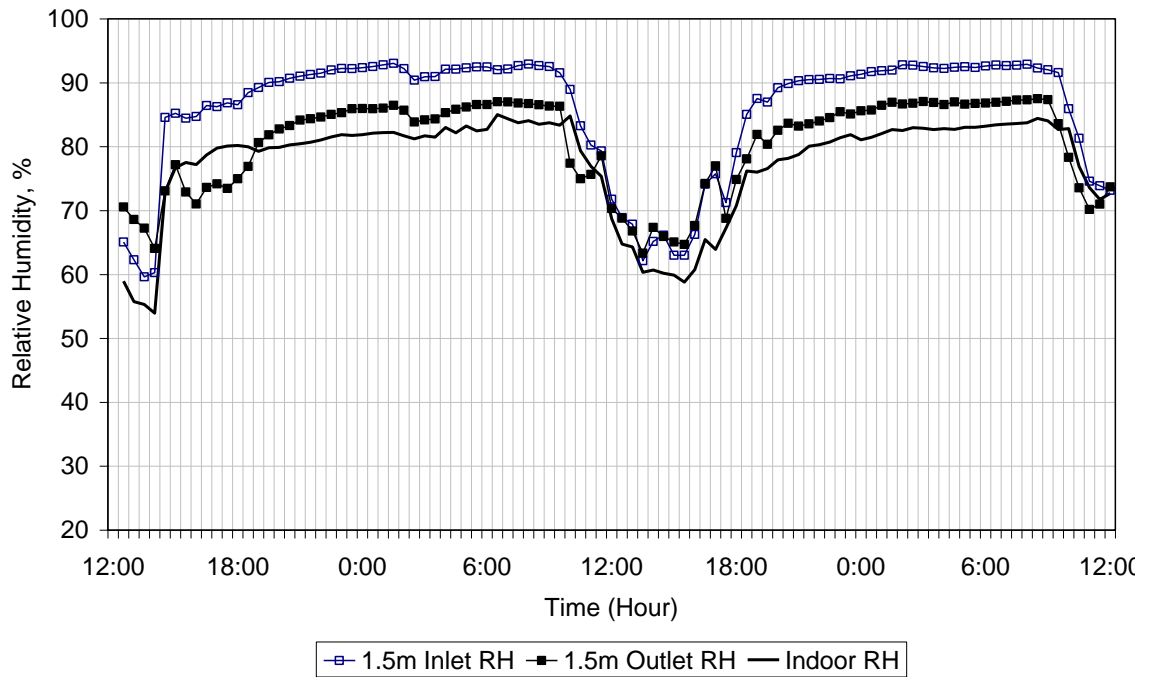


Figure 5.19: Trend of relative humidity from the investigation of 25m long Polyethylene pipe buried at 1.5m deep underground. Fan blower operated from 10:00 a.m. to 6:00 p.m. in May 2009.

In this case, the RH at the buried pipe inlet and outlet ranges from 59.6% to 93.0% and from 63.3% to 87.5% respectively (Figure 5.19). The RH trend of pipe inlet is different from the previous cases. During night time, the pipe inlet RH became significantly higher than the RH measured in the pipe outlet. The maximum rise in RH within the buried pipe is 7.6%. The indoor RH ranges from 53.9% to 85.0%. The resulting RH exceeded 85% but maintained below 90%. Even though case c) used the same experiment setup, only deeper than case a) and b), the significantly high RH at the buried pipe inlet of case a) in comparison to case a) and b), was due to rainfall that occurred in the late afternoon on day 1 of case c) investigation.

Table 5.6 summarises the result of each cases a), b), and c). The table consists of temperature and also relative humidity at the two ends of the pipe, within the relative soil and inside the experiment shed.

In comparison between summary of results in the wet season (Table 5.5) and summary of results in the hot and dry season (Table 5.6), the temperature range in hot and dry season are most of the time higher than the temperature range in the wet season.

The maximum temperature at pipe outlet in this case is at least 1.6°C more than in the wet season. The temperature at pipe outlet in the wet season did not exceed 30.0°C. Whereas, in the hot and dry season, in all buried pipes, the outlet temperature exceeded 30.0°C.

Table 5.6: Summary of results obtained from investigation carried out during the hot and dry season. TR=Temperature Reduction, OT=Outlet Temperature, IT=Inlet Temperature and RH=Relative Humidity.

	Case a) Polyethylene pipe, 25m long, 0.5m deep	Case b) Polyethylene pipe, 25m long, 1.0m deep	Case c) Polyethylene pipe, 25m long, 1.5m deep
Soil Temperature, °C	29.8 – 30.3	29.9 – 30.0	n/a
ITRange, °C	24.7 – 35.2	24.4 – 37.0	23.9 – 36.1
OTRange, °C	25.3 – 30.6	24.7 – 31.2	23.7 – 30.2
Max TR, °C	4.9	6.9	5.9
Average daily max TR, °C	4.2	6.0	4.9
Indoor DBT, °C	25.1 – 33.5	25.1 – 34.9	24.3 – 34.2
Inlet RH, %	51.4 – 85.7	46.0 – 83.5	59.6 – 93.0
Outlet RH, %	63.0 – 84.5	60.3 – 83.2	63.3 – 87.5
Max RH rise, %	16.4	17.3	7.6
Indoor RH, %	56.3 – 81.3	53.2 – 77.5	53.9 – 85.0

5.2.3 One year investigation of 1.0m depth buried pipe.

The next investigation is intended to record data from the Earth Pipe Cooling experiment for a whole year. The rationale behind this is due to the differences found in outlet temperature between the wet and hot and dry season. Initially, it was assumed that with the knowledge of Malaysia climate being warm and humid throughout the year, the Earth Pipe Cooling result would give the same trend of output temperature throughout the year. After analysing and comparing the results of experiments carried out in the wet season and the hot and dry season, the Earth Pipe Cooling output temperature does vary

and sometimes significantly. Therefore, a record of experiment data of a whole year is collected. To avoid interference between different buried pipe readings, only one buried pipe was used for the whole year investigation and the pipe buried at 1.0m depth was chosen. The fan blower provides forced air flow through the buried pipe and the air velocity is maintained at 5.6m/s continuously. The results of each month is analysed separately.

a) *January*

As mentioned in Chapter 2, January falls within the northeast monsoon season. The outdoor dry bulb temperature ranges from 21.5°C to 37.9°C (Figure 5.20) and its average is 26.1°C. Soil temperature at 1m depth underground in January ranges from 27.5°C to 28.4°C and its average is 28.0°C. The amplitude of the soil temperature at 1m depth underground is 0.4. Meanwhile, the temperature at the buried pipe inlet ranges from 25.4°C to 37.0°C and temperature found at the buried pipe outlet ranges from 27.1°C to 28.9°C. The pipe outlet range is slightly wider than the 1m depth soil temperature. The minimum temperature was 0.4°C lower and the maximum pipe outlet temperature was 0.5°C higher than the maximum soil temperature at 1m depth. The graph in Figure 5.20 shows significant temperature drop in buried pipe outlet from the outdoor DBT and buried pipe inlet. Temperature drop occurs mostly during the daytime when the ambient air temperature is higher than the soil temperature. The maximum temperature drop between the outdoor DBT and buried pipe outlet temperature is 9.4°C and its average daily maximum is 4.1°C. The temperature drop between the buried pipe inlet and outlet is 8.6°C and its average daily maximum is 5.3°C. Since the buried pipe outlet is located in an experimental shed, the indoor space temperature is also measured and it ranges from 24.4°C to 33.7°C. The indoor temperature is not significantly reduced by the earth pipe cooling system.

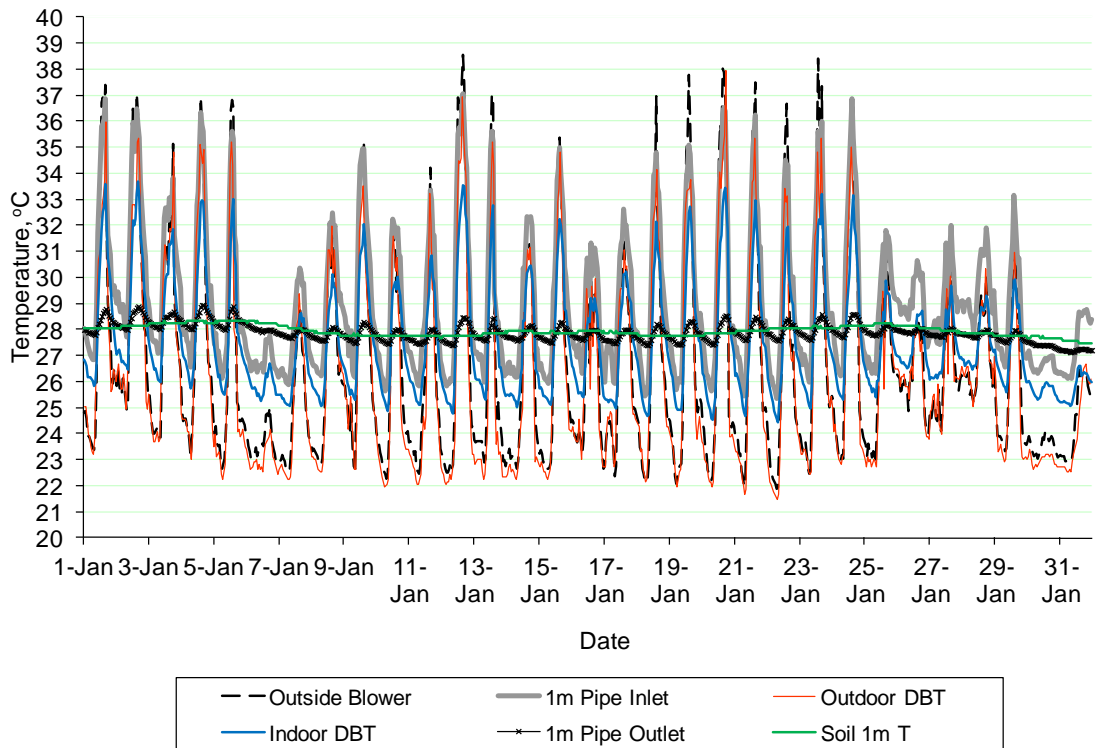


Figure 5.20: Trend of temperature in January 2011.

When temperature drops in a contained space, condensation may occur and therefore, this chapter also analyse the humidity of the cooling system and what it produces (Figure 5.21). The buried pipe inlet relative humidity ranges from 45.6% to 79.2% and its average is 68.4%. The relative humidity at the buried pipe outlet ranges from 59.7% to 79.2% and its average is 71.3%. There is no significant increase in relative humidity across the buried pipe during the night time but in the day time, there is. The maximum relative humidity increment across the pipe is 26.9% during the daytime. Even so, the maximum relative humidity is lower than 80% and therefore, no condensation was found across the buried pipe. The indoor shed relative humidity ranges from 52.9% to 83.0% and its average is 72.8%. Figure 5.21 shows that the relative humidity of the indoor shed is mostly lower than the outdoor relative humidity.

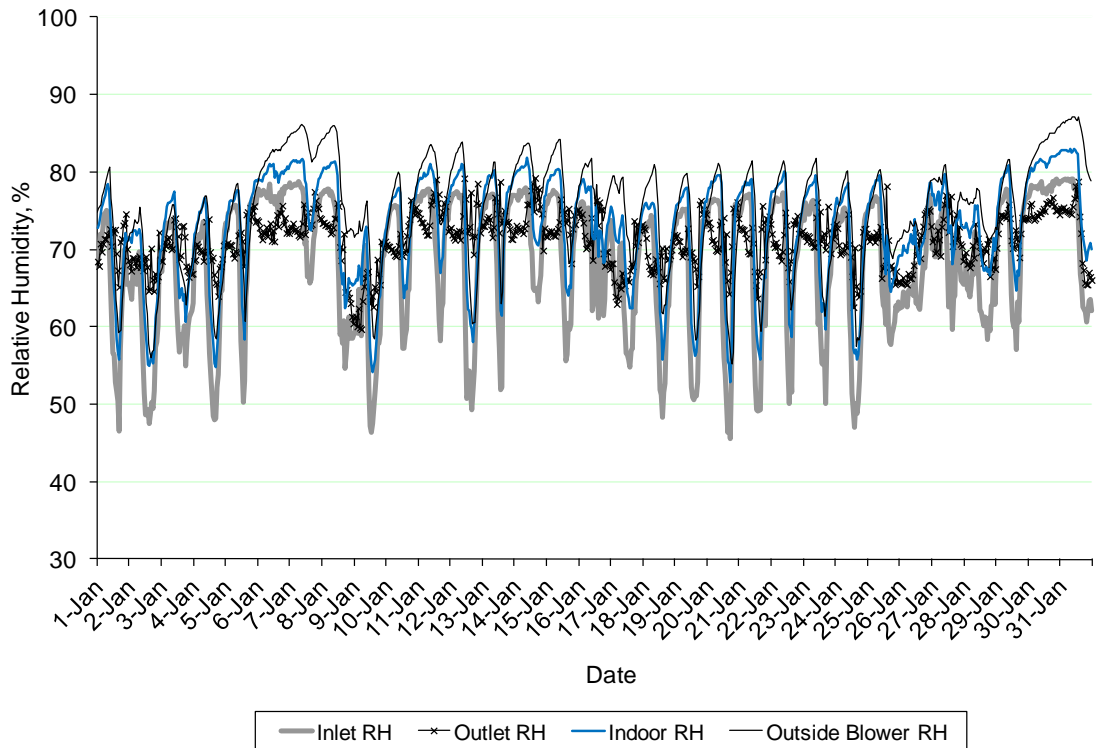


Figure 5.21: Trend of relative humidity in January 2011.

b) *February*

February also falls within the northeast monsoon season. Due to technical error, the correctly measured data was only recorded for 9 days (Figure 5.22). In February, the outdoor temperature measured under a tree and away from the experimental shed ranges from 21.6°C to 35.5°C. The temperature at the buried pipe inlet, after the fan blower, ranges from 25.1°C to 36.7°C. The pipe inlet temperature is higher than the outdoor temperature despite the air is covered. Looking at the outdoor temperature of air just outside the fan blower, it ranges from 21.6°C to 38.5°C. The non-shaded data logger that measures the air temperature outside the fan blower has a maximum temperature 3°C higher than the maximum air temperature shaded by a tree. This affected the air temperature extracted by the fan blower and hence the higher air temperature of pipe inlet than the outdoor shaded air.

The soil temperature ranges from 27.2°C to 28.3°C and its average is 27.7°C. The buried pipe outlet temperature ranges from 26.9°C to 29.0°C and its average is 27.7°C. The pipe outlet temperature average is the same as the soil temperature average

but the temperature pipe outlet temperature range is wider than the soil. In February, the maximum temperature drop given by the Earth Pipe Cooling between the buried pipe inlet and outlet is 8.1°C and its average daily maximum is 7.6°C. Meanwhile, the maximum temperature drop between the buried pipe outlet and shaded outdoor air temperature is 7.1°C and its average daily maximum is 6.4°C. Even though there were significant temperature drop at the buried pipe outlet, the indoor Dry Bulb Temperature (DBT) does not reduced significantly from the outdoor DBT. The indoor DBT of the experimental shed ranges from 24.1°C to 34.1°C. The shed was well ventilated but its timber material allows easy heat transmission from outside to inside making the indoor shed very warm. All temperatures are at its peak between 3:00 to 4:00pm and at its minimum between 6:00 to 8:00 am.

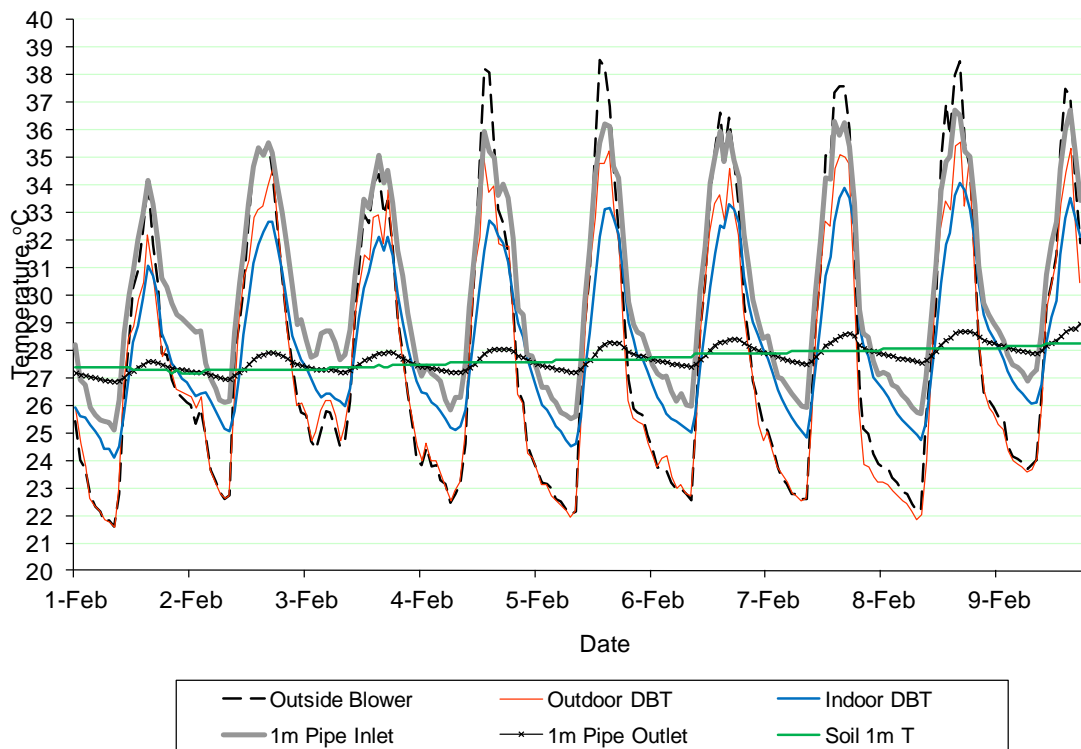


Figure 5.22: Trend of temperature in February 2011.

The relative humidity is also analysed for February data. Figure 5.23 shows the trends of relative humidity in February. The outdoor relative humidity in February ranges from 54.6% to 83.9% and the relative humidity inside the experimental shed

ranges from 51.6% to 80.2%. The maximum relative humidity at the buried pipe inlet and outlet are similar, which are 77.0% and 77.1% respectively. On the other hand, the minimum relative humidity at the buried pipe outlet and inlet varies significantly. The maximum increment of relative humidity at the pipe outlet from the pipe inlet is 24.5% and this occurred at 3:00pm when the relative humidity at the inlet was 47.2% and at the outlet was 71.7%. The outdoor, indoor and pipe inlet relative humidity peaks to its maximum between 8:00 to 9:00am and their minimum often occurred between 3:00 to 4:00pm.

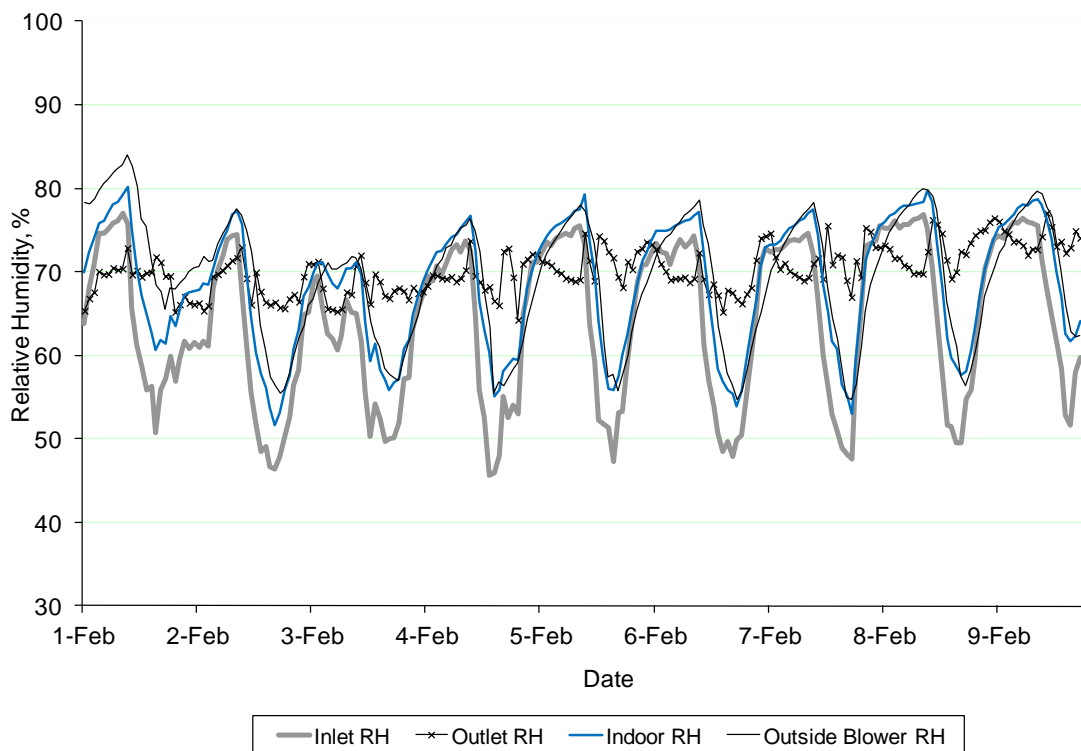


Figure 5.23: Trend of relative humidity in February 2011.

c) *March*

March is the beginning of the hot and dry season in Malaysia. The outdoor DBT are missing from the graph in Figure 5.24 because the values are not valid to be included in the analysis. The measured outdoor DBT ranges from 23.0°C to 44.3°C. The maximum outdoor DBT rises above 40°C because the datalogger was not shaded properly from the solar radiation. Therefore, the outdoor temperature data are not used

for analysis. The buried pipe inlet temperature ranges from 25.9°C to 38.1°C and the 1m deep soil temperature ranges from 29.6°C to 30.1°C. These inputs produce a buried pipe outlet temperature that ranges from 27.4°C to 33.1°C. However, referring to Figure 5.24, the curve for buried pipe outlet temperature shows that it fluctuates daily from 29.1°C to 31.0°C most of the days. The buried pipe outlet reached above 32.0°C only twice.

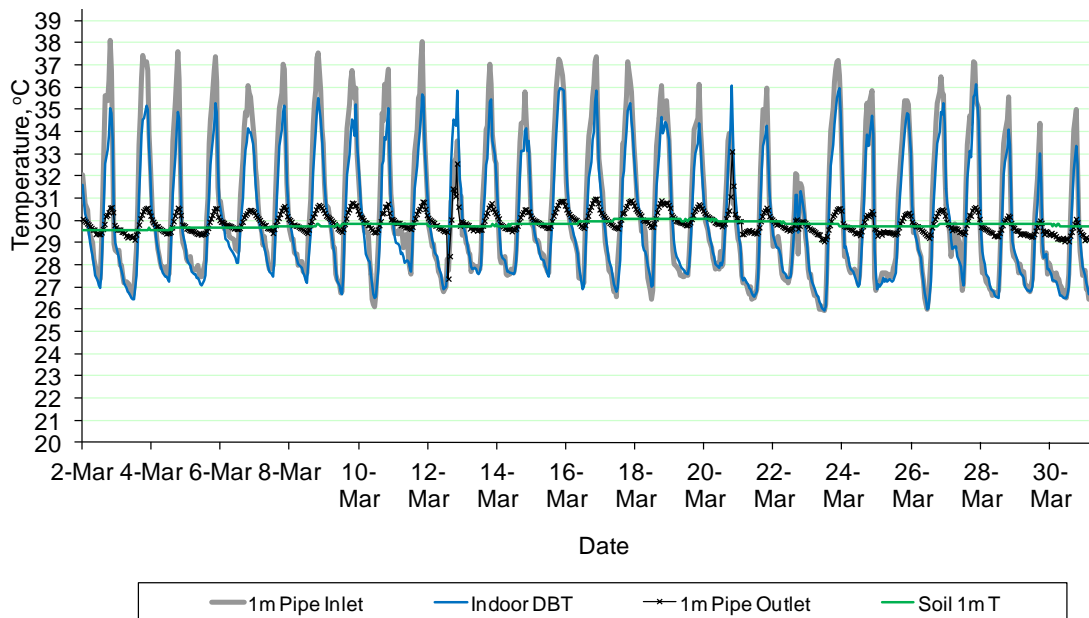


Figure 5.24: Trend of temperature in March 2010.

The maximum temperature drop between the buried pipe outlet and inlet is 7.5°C but the average daily maximum temperature drop between the buried pipe outlet and inlet is 5.7°C. Similar to the previous months, the indoor temperature did not reduce significantly and it fluctuates daily from 26.0°C to 36.1°C. In most days, all temperatures were at their minimum between 6:00 to 8:00am and the temperatures peak between 2:00 to 4:00pm.

The maximum relative humidity in March is also higher than that in February when comparing Figure 5.25 to Figure 5.23. The relative humidity at buried pipe inlet ranges from 32.9% to 81.6% and the relative humidity at buried pipe outlet ranges from 44.4% to 81.6%. The maximum relative humidity at the buried pipe outlet occurred at 3:00pm when the humidity at the pipe inlet was 62.9%. Therefore, there was a rise of 18.7% in relative humidity between the buried pipe inlet and outlet. The temperature

drop between the buried pipe inlet and out let was 5.0°C and this could have led to the increase in relative humidity at the buried pipe outlet.

Meanwhile, the relative humidity of experiment shed indoor ranges from 37.5% to 82.1%. This relative humidity range is not much different from the buried pipe inlet relative humidity and the graph shows that the relative humidity of the shed indoor follows closely to the relative humidity at the buried pipe inlet (Figure 5.25).

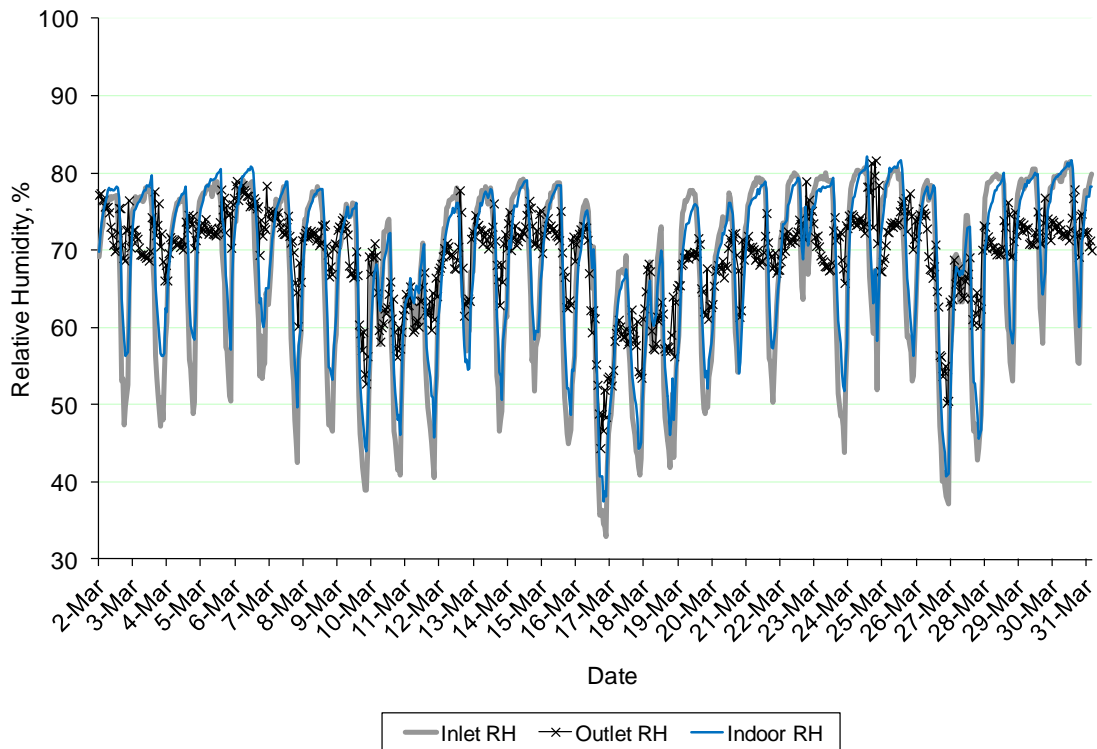


Figure 5.25: Trend of relative humidity in March 2010.

d) *April*

In April, there was an unfortunate event that the power cable has been cut off for 14 days and therefore, the data within the 14 days became invalid. In April, the outdoor DBT ranges from 23.0°C to 44.3°C. Similar to the maximum outdoor DBT in March, this maximum DBT is not accurate because the data logger was not properly shaded from the solar radiation and therefore, it was not used for analysis. However, the buried pipe inlet temperature in April ranges from 26.3°C to 36.9°C and the soil temperature at 1m depth underground ranges from 29.7°C to 30.3°C, with an average of 29.9°C. The temperature at the buried pipe outlet ranges from 28.9°C to 30.7°C and its average is 29.7°C. The maximum temperature drop between the buried pipe inlet and outlet is

6.3°C and its average daily maximum temperature drop is 5.4°C. Even though there is a significant temperature drop, the indoor DBT was not reduced significantly. The indoor DBT ranges from 26.2°C to 36.2°C, which is similar to the temperature range at the buried pipe inlet. Figure 5.26 shows that most temperatures fell to its minimum between 6:00 to 8:00am. The temperature rose to their maximum between 2:00 to 5:00pm.

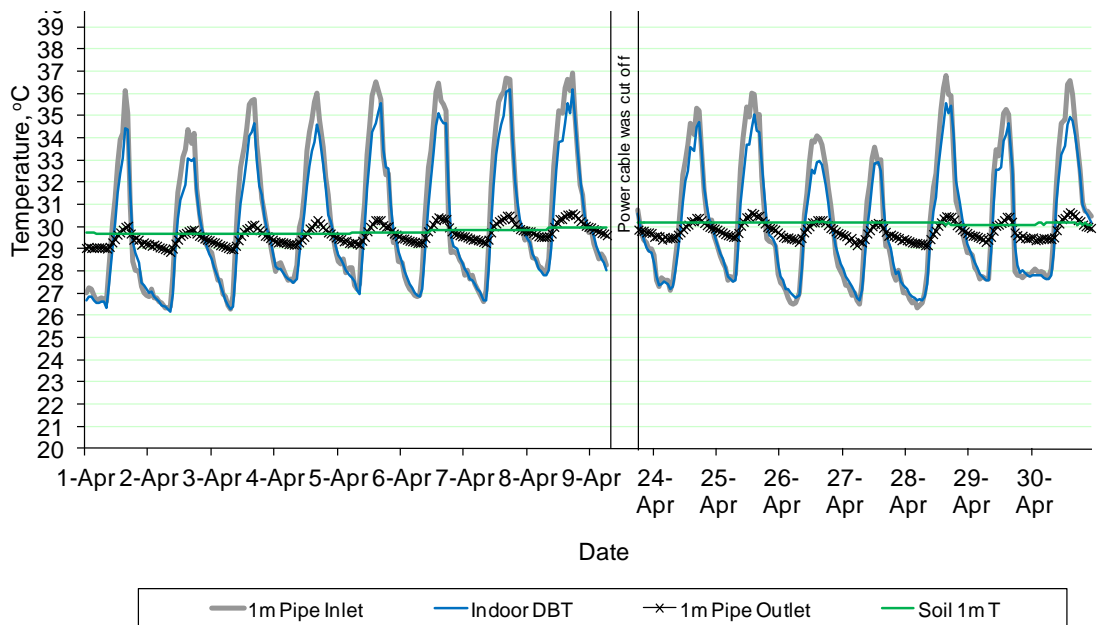


Figure 5.26: Trend of temperature in April 2010.

Relative humidity (RH) increases to its daily peak in the morning between 6:00 to 8:00am and sometimes at 9:00am (Figure 5.27). The RH reduced to its minimum mostly in the afternoon between 2:00 to 5:00pm when the temperatures reach their maximum. The RH at buried pipe inlet ranges from 43.3% to 82.1%. The RH inside the experimental shed ranges from 48.9% to 82.2% which is slightly higher than in the buried pipe inlet. However, the RH at the buried pipe outlet ranges from 60.7% to 80.9%. There has been increase between the RH of buried pipe inlet and outlet. The most increment was 23.0%, which occurred at 3:00pm. At this hour, the RH at buried pipe outlet was 77.5% and at buried pipe inlet was 54.5%. Figure 5.27 shows the RH graph of buried pipe outlet does not fluctuate evenly, unlike the pipe inlet and room RH.

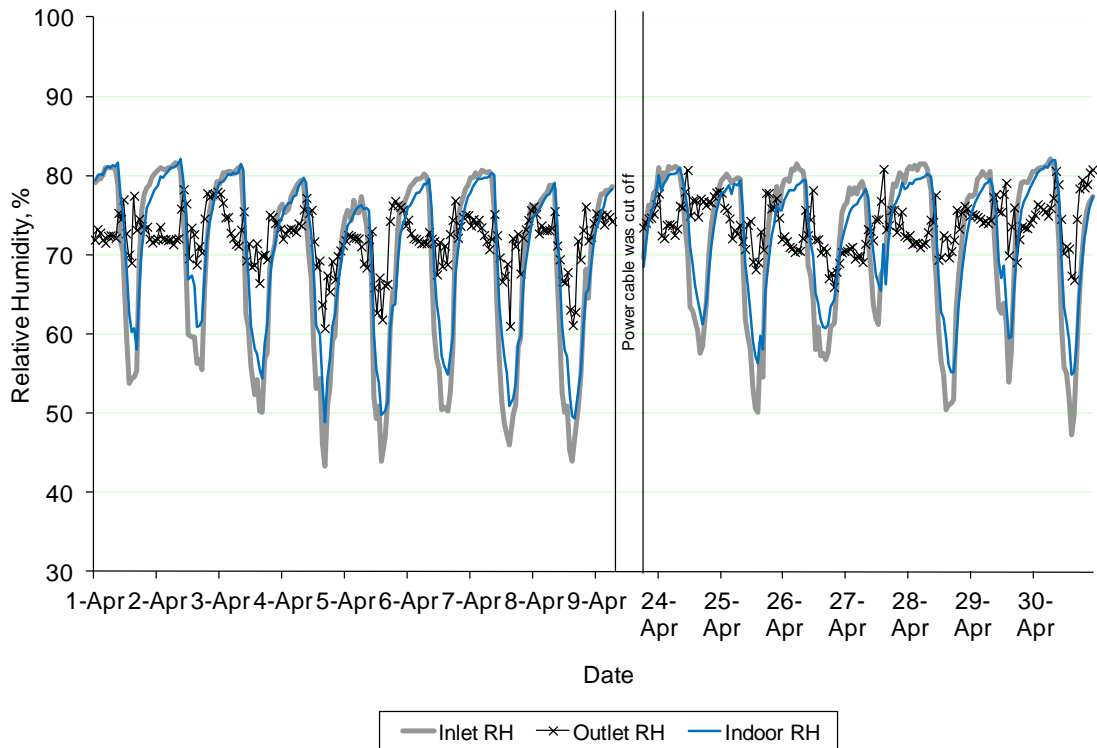


Figure 5.27: Trend of relative humidity in April 2010.

e) *May*

May is another month with hot and dry climate. Chapter 2 has shown that in May as well as March, they had the highest annual average mean daily maximum dry bulb temperature within the year 2002 to 2008 and it was 33.0°C. The month May experienced the highest annual average absolute daily maximum dry bulb temperature within the same years which was 35.1°C. Figure 5.28 illustrate the trend of temperatures in May. The outdoor DBT ranges from 23.0°C to 45.2°C. During measurement, the data logger was not properly shaded from the solar radiation, hence the very high maximum temperature that was recorded in the afternoon. Therefore, the maximum outdoor DBT was not used for analysis. The closest data available to outdoor DBT is the buried pipe inlet temperature which ranges from 25.7°C to 37.1°C. The soil temperature measured at 1m depth underground ranges from 30.1°C to 30.5°C and its average is 30.2°C. The buried pipe outlet temperature ranges from 29.0°C to 30.9°C and its average is 29.9°C. The maximum temperature drop at buried pipe outlet from the inlet is 6.4°C but the

average daily maximum temperature drop between the two ends of the pipe is 5.2°C (Figure 5.28).

Similar to previous months, as much temperature drop occurred at the buried pipe outlet from the inlet, the temperature reduction in the indoor shed compared to the pipe inlet temperature is not much. The indoor DBT ranges from 25.9°C to 36.4°C.

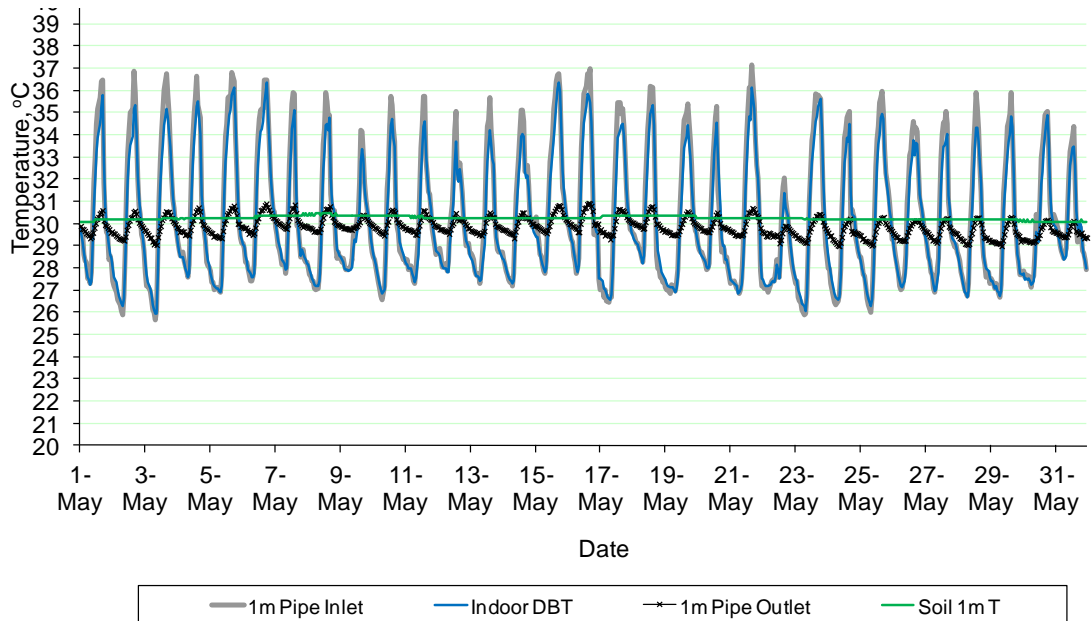


Figure 5.28: Trend of temperature in May 2010.

Looking at the relative humidity (RH) trend in May (Figure 5.29), the RH at the buried pipe inlet ranges from 42.7% to 82.1% while the RH at the pipe outlet ranges from 62.7% to 81.1%. The indoor RH ranges from 52.1% to 81.9%. Within the pipe, there has been increase in relative humidity from the inlet to the outlet. A maximum of 24.1% increase in RH is found at 4:00pm, when the RH at the pipe inlet was 50.8% and at the pipe outlet was 74.9%. During this hour, the indoor RH was 58.9%, which is not very high.

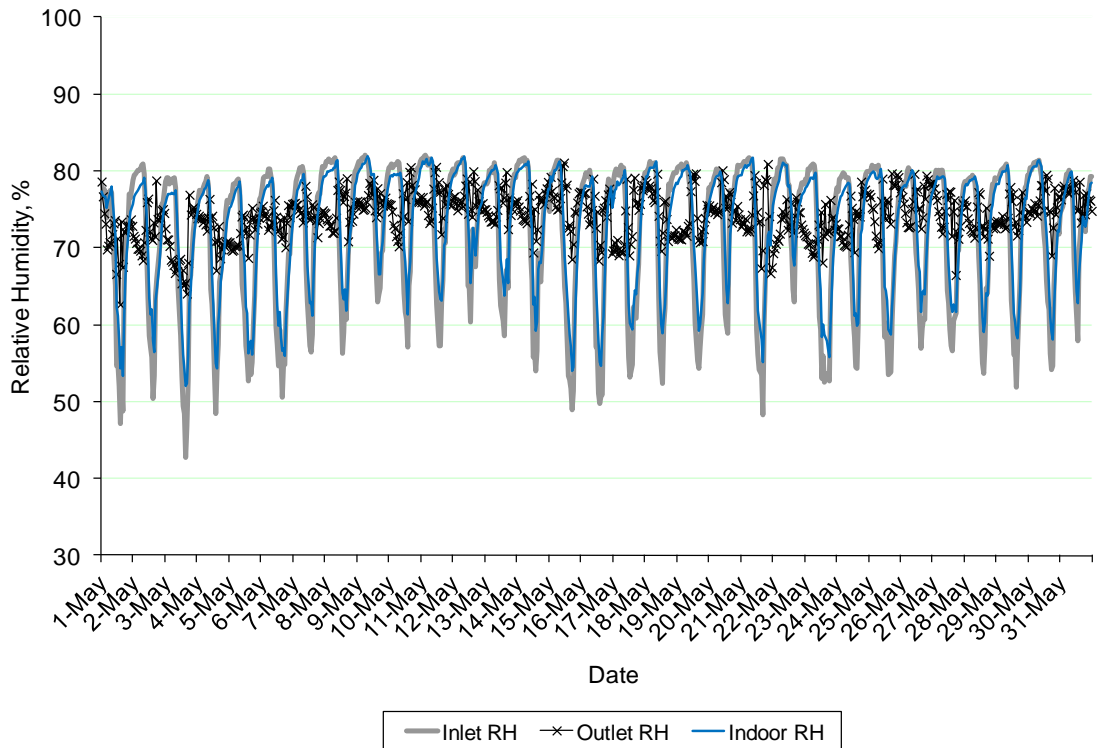


Figure 5.29: Trend of relative humidity in May 2010.

f) *June*

In June, the outdoor DBT ranges from 22.9°C to 42.3°C but same case as in May, the data logger was not properly shaded and that is the reason of the very high maximum temperature. However, the temperature at the buried pipe inlet in June ranges from 25.8°C to 36.8°C and the soil temperature at 1m depth underground in June ranges from 30.0°C to 30.3°C. The temperature found at the buried pipe outlet ranges from 28.7°C to 30.5°C (Figure 5.30). The pipe outlet temperature has slightly bigger amplitude than the soil temperature but fluctuates less when compared to the pipe inlet temperature. A maximum temperature drop found in the pipe outlet from the pipe inlet, which was 6.3°C that was recorded at 4:00pm. During this hour, the pipe inlet temperature was 36.8°C, which was the maximum inlet temperature recorded in the month, while the pipe outlet temperature was 30.5°C. The average daily maximum temperature drop is 5.0°C. Indoor DBT in June ranges from 25.8°C to 36.1°C, which is similar to the buried pipe inlet temperature.

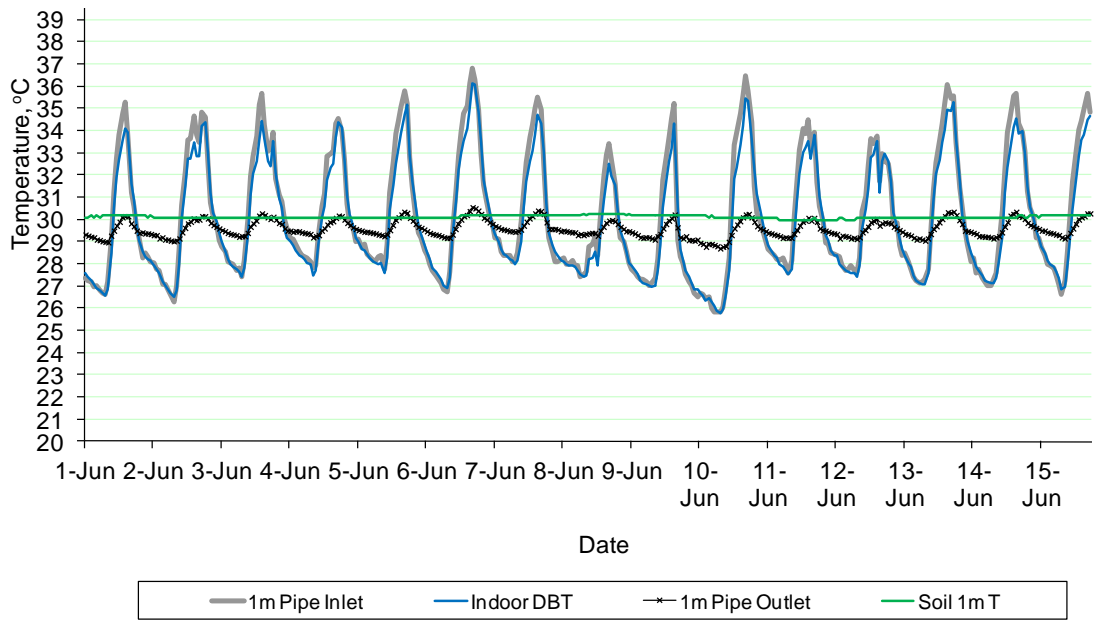


Figure 5.30: Trend of temperature in June 2010.

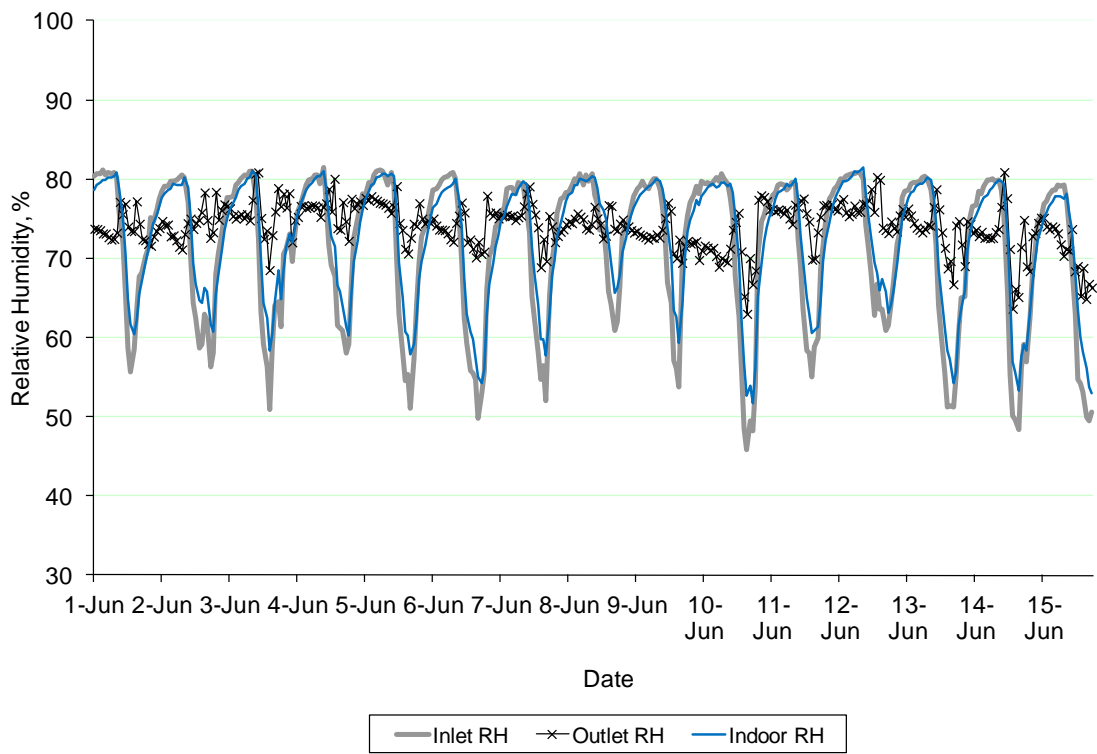


Figure 5.31: Trend of relative humidity in June

Looking at relative humidity (RH) in June (Figure 5.31), the RH at the buried pipe inlet ranges from 45.9% to 81.4% while the RH at the pipe outlet ranges from 63.0% to 80.9%. The indoor RH ranges from 51.7% to 81.4%. Similar case to the earlier months, the indoor RH is similar to the RH at the pipe inlet (Figure 5.31). While the earth pipe cooling system was running, there has been a rise in humidity between the pipe inlet and outlet. The maximum rise of RH found in the buried pipe outlet from the inlet is 22.4%, which occurred at 4:00pm. At this hour, the pipe inlet RH was 49.7% and the pipe outlet RH was 72.1%. Although there is a big rise in RH between the two ends of the buried pipe, the RH at pipe outlet maintains below 80%.

g) September

In September, the valid recorded data is only found in seven days because the power cable was cut off again for the second and third time, before September and after the 7th of September respectively. Within the seven days, the outdoor DBT ranges from 20.9°C to 34.4°C. Figure 5.32 shows that the temperature at the buried pipe inlet ranges from 25.1°C to 36.1°C while the soil temperature ranges from 29.1°C to 29.3°C. The temperature recorded at the buried pipe outlet ranges from 28.1°C to 29.5°C. The maximum temperature drop from the pipe inlet to the pipe outlet is 6.6°C while the temperature difference between the pipe outlet and outdoor DBT is 4.8°C. However, the average daily maximum temperature reduction between the two ends and between pipe outlet and outdoor DBT are 5.2°C and 3.3°C respectively. Meanwhile, the indoor DBT ranges from 24.3°C to 33.6°C. The indoor DBT is 3.4°C higher than the outdoor in the early morning, and only 0.8°C lower than the outdoor DBT during the hottest hour of the day. All temperatures peak between 2:00 to 4:00 pm and reduced to its minimum at 7:00am in most days.

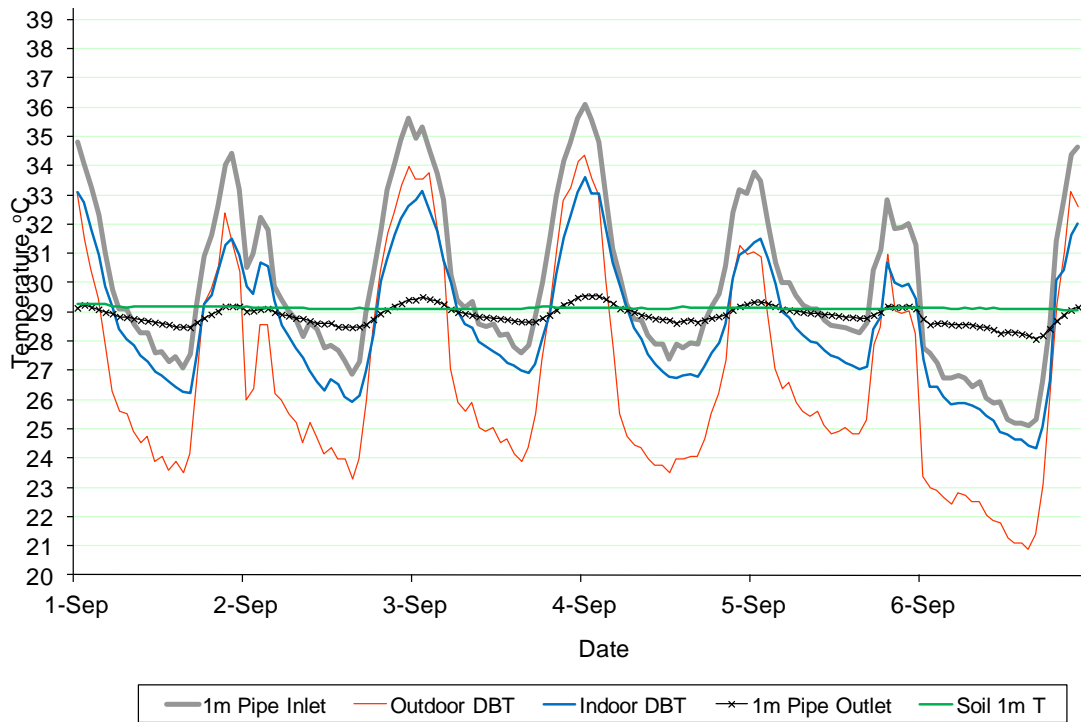


Figure 5.32: Trend of temperature in September 2010.

Within the seven days of valid data, the relative humidity at pipe inlet ranges from 46.9% to 77.7% while the RH at pipe outlet ranges from 59.5% to 80.8%. Meanwhile the RH inside the experiment shed ranges from 53.8% to 80.6% (Figure 5.33). Unlike the temperature, the RH trend fluctuates randomly day by day and there was increase in RH at the buried pipe outlet from the inlet. The maximum increase of RH was 18.1% and it occurred at 1:00pm. During this hour, the RH at pipe inlet and outlet was 54.9% and 73.0% respectively and the indoor space RH was 64.2%. Unlike in previous months, the indoor RH is higher than the RH at pipe inlet.

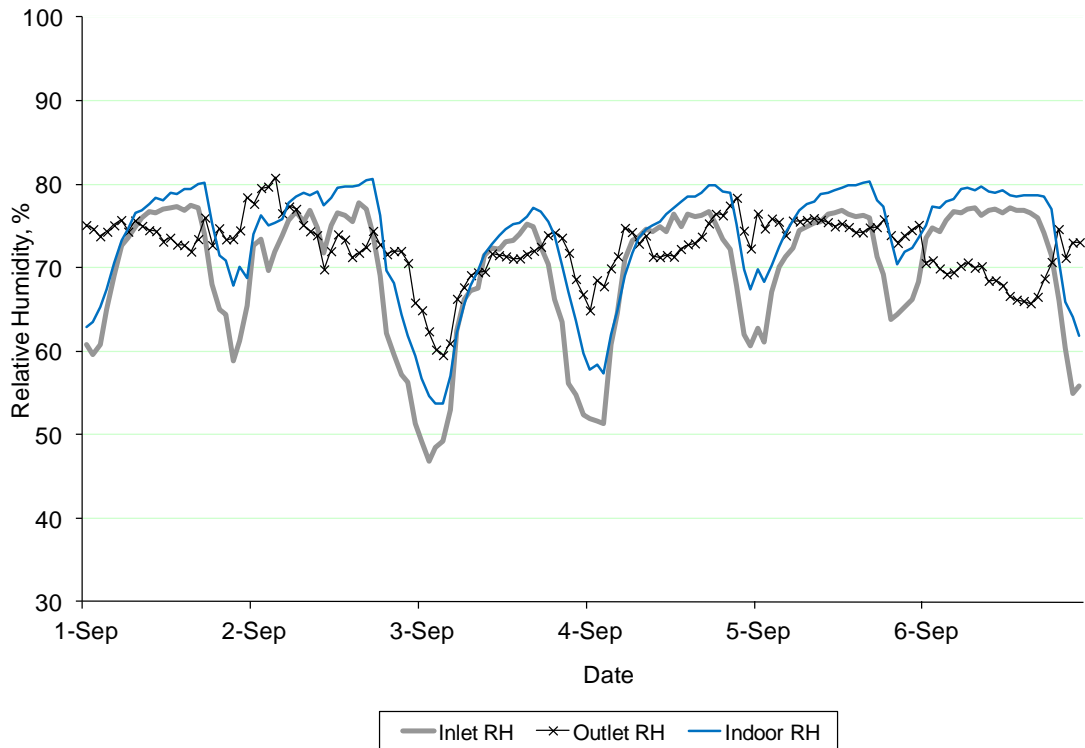


Figure 5.33: Trend of relative humidity in September 2010.

h) October

October is the beginning of Northeast Monsoon season, which lasted until March. As explained in Chapter 2, during this season, the wind is slightly stronger than in the Southwest Monsoon season but blows in North Easterly direction. A slightly cool temperature occurred during this season, which the middle of the season turns out to be the wet season with more rainfall compared to the other months.

The power cable of the fan blower was cut off in September and was completely repaired on the 26th of October. In this case, the recorded data is only valid from the 26 October until the end of October, which makes 5 full days of valid data. On site, the outdoor DBT ranges from 21.9°C to 35.5°C while the DBT inside the experiment shed ranges from 25.1°C to 33.9°C. Within the buried pipe, the DBT at the pipe inlet ranges from 25.7°C to 36.5°C and at the pipe outlet, it ranges from 28.5°C to 29.5°C (Figure 5.34). The graph below shows an almost constant soil temperature which ranges from 29.1°C to 29.2°C.

A maximum temperature reduction at the buried pipe outlet from the inlet was found to be 7.0°C while the maximum temperature reduction from between the outdoor DBT and the buried pipe outlet is 6.1°C. However, the average daily maximum temperature reduction between the pipe inlet and outlet was found to be 5.9°C. The average daily maximum temperature reduction between the outdoor DBT and pipe outlet was 3.9°C.

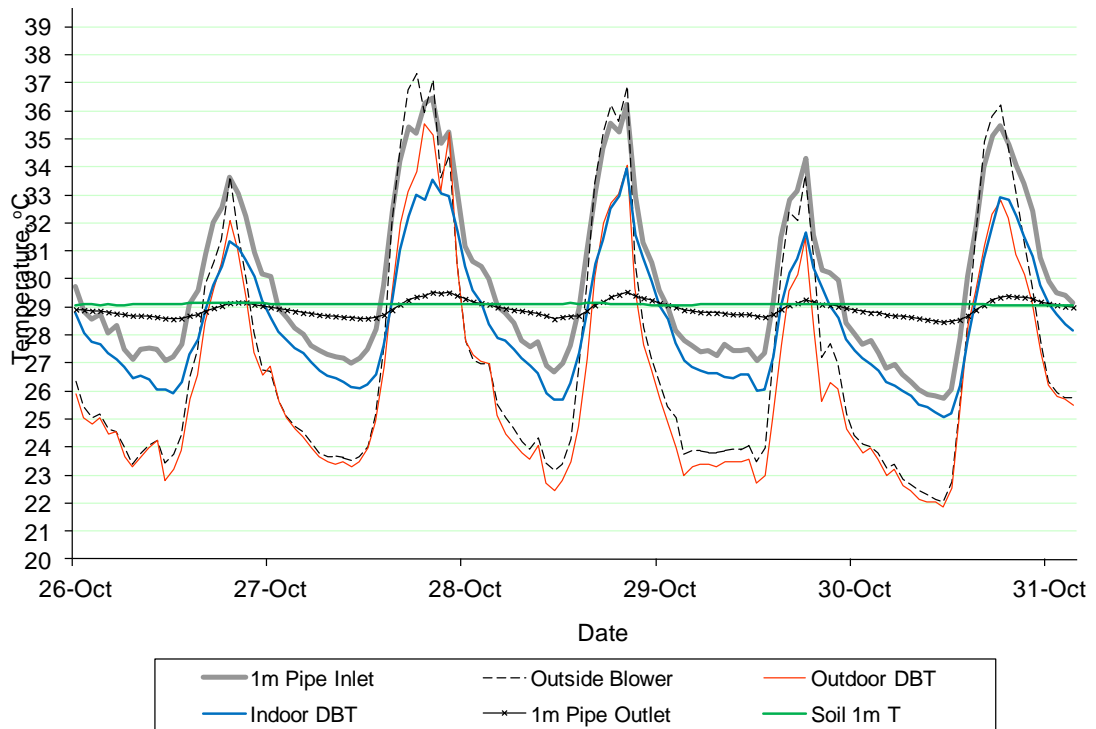


Figure 5.34: Trend of temperature in October 2010.

In October, the data recorded includes data of outdoor air temperature measured just outside the fan blower, which is the supply of air being extracted into the fan blower for the buried pipe. It can be seen in Figure 5.34 that the DBT at buried pipe inlet is higher than the outdoor DBT measured under a tree but similar to the outdoor air DBT measured just outside the fan blower. The DBT at night shows that when there is no solar radiation, the outdoor DBT in two locations; under the tree and just outside the fan blower are similar.

In terms of relative humidity (RH), the RH at buried pipe inlet and outlet ranges from 50.7% to 76.9% and 67.1% to 77.8% respectively. The indoor RH ranges from

59.5% to 79.8% while the outdoor RH just outside the blower ranges from 64.8% to 82.5% (Figure 5.35). The indoor RH was reduced from the outdoor RH and the RH at pipe inlet is lower than the indoor RH. The RH peaks between 6:00 to 9:00am and at its minimum between 3:00 to 4:00pm. The maximum RH rise within the buried pipe is 20.7%, which occurred at 4:00pm. At this hour, the RH at buried pipe inlet and outlet are 50.7% and 71.4% respectively.

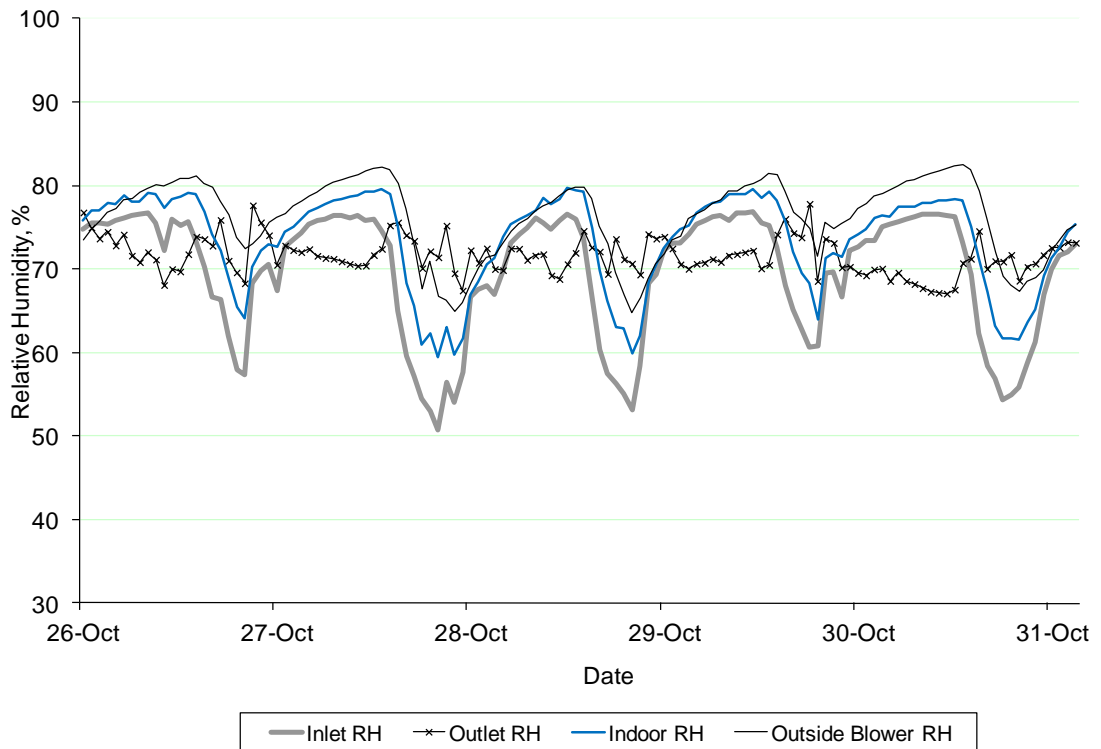


Figure 5.35: Trend of relative humidity in October 2010.

i) *November*

Figure 5.36 shows the trend of temperature in November. The outdoor DBT measured under a tree ranges from 22.2°C to 36.3°C while the outdoor DBT measured just outside the fan blower ranges from 22.4°C to 38.8°C. The DBT at the buried pipe inlet ranges from 25.8°C to 37.2°C and the soil temperature measured at 1m depth below ground ranges from 28.5°C to 29.2°C. This gives the buried pipe outlet DBT, which ranges from 28.1°C to 29.7°C. A maximum temperature reduction within the buried pipe was found to be 8.0°C and the maximum temperature reduction from the outdoor DBT to the pipe outlet was 6.6°C. However, the average daily maximum

temperature reduction within the buried pipe was 5.9°C while the same average temperature reduction between the outdoor DBT and the buried pipe outlet was 3.7°C. Although the temperature reductions are significant, the indoor DBT was not reduced very much. It ranges from 25.3°C to 34.1°C. The DBT peaks between 1:00 to 4:00pm and at reach its minimum between 6:00 to 7:00am in most days

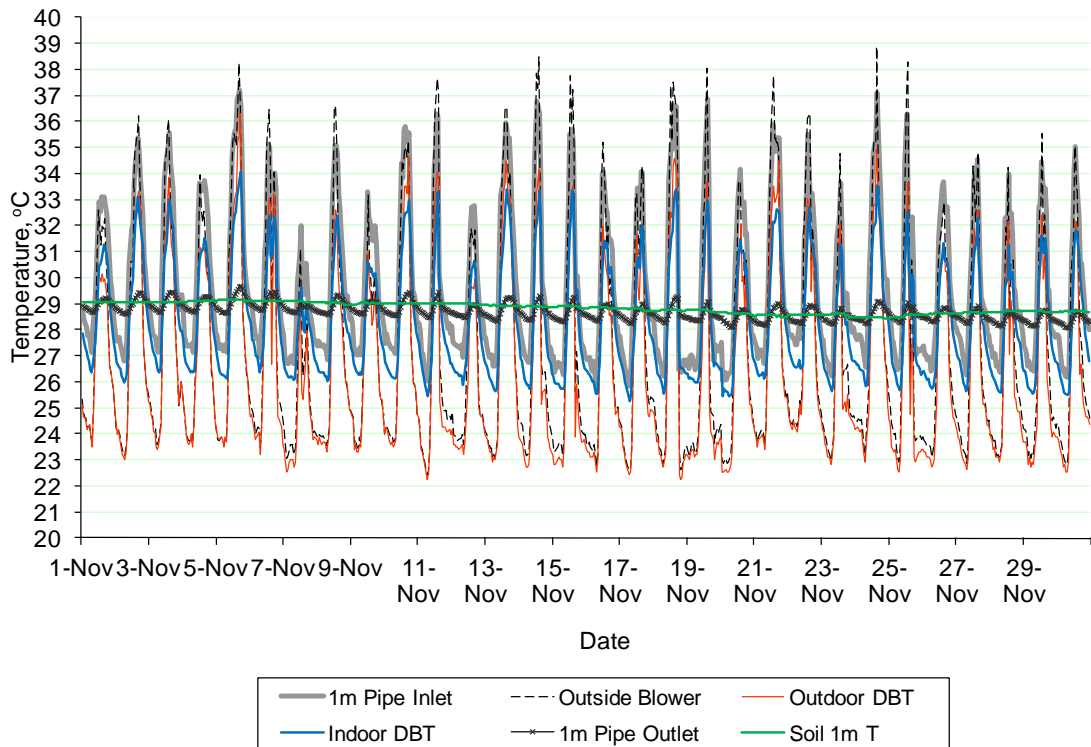


Figure 5.36: Trend of temperature in November 2010.

In terms of relative humidity (RH), the RH at buried pipe inlet and outlet ranges from 44.8% to 79.5% and from 59.6% to 81.8% respectively. The indoor RH ranges from 50.6% to 82.4% while the outdoor RH measured just outside the fan blower ranges from 58.3% to 89.6% (Figure 5.37). Similar to the RH trend in October, the indoor RH is higher than the buried pipe inlet RH.

A maximum rise in RH within the buried pipe was 24.0%, which occurred at 3:00pm. At this hour, the RH at buried pipe inlet and outlet were 55.3% and 79.3% respectively. The indoor RH at this hour was 63.9% and the RH just outside the fan blower was 76.9%. Unlike the DBT trend, the RH peaks between 8:00 to 10:00am and at its minimum between 1:00 to 4:00pm in most days.

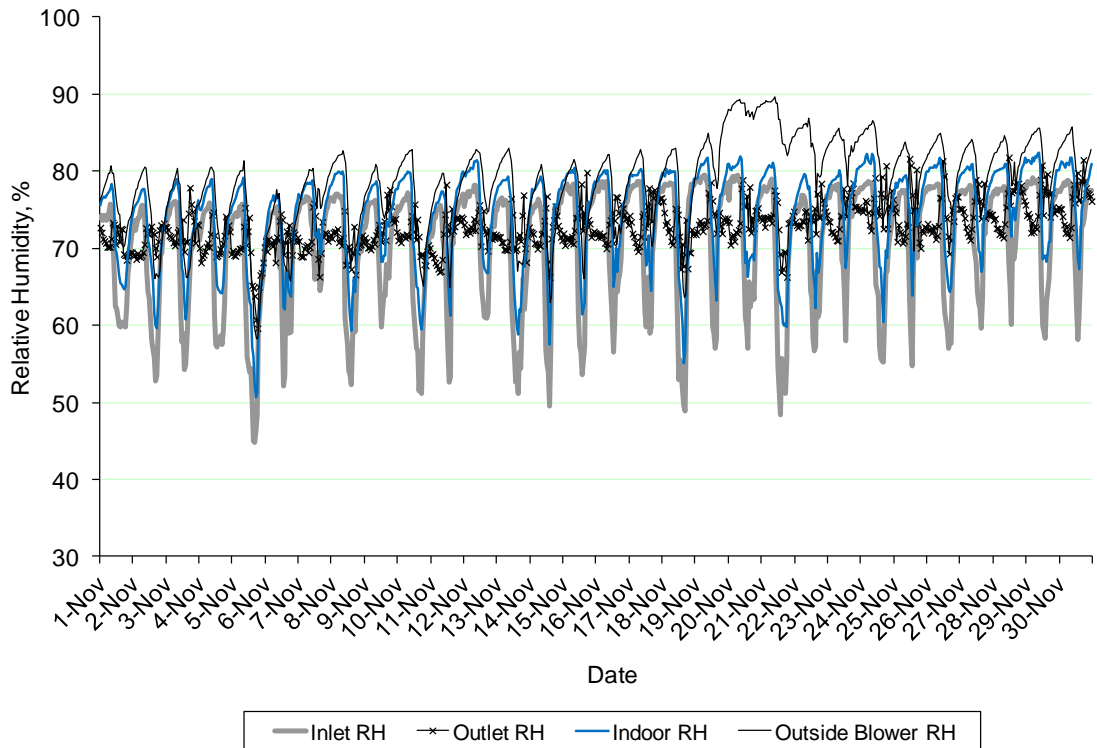


Figure 5.37: Trend of relative humidity in November 2010.

j) *December*

In December, the outdoor DBT measured under the tree ranges from 20.6°C to 36.1°C while the outdoor DBT just outside the fan blower ranges between 20.9°C to 38.6°C. The soil temperature measured at 1m depth ranges from 28.1°C to 28.8°C, which makes it almost constant throughout the month of December (Figure 5.38). The DBT at buried pipe inlet ranges from 24.4°C to 37.1°C and at the buried pipe outlet ranges from 27.7°C to 29.1°C.

A maximum temperature reduction found within the buried pipe was 8.0°C and the maximum temperature reduction at pipe outlet, compared to the outdoor DBT was 7.2°C. However, the average daily maximum temperature reduction within the buried pipe turned out to be 5.8°C and between the outdoor DBT and pipe outlet was 4.7°C. The indoor DBT ranges from 24.3°C to 33.8°C. In December, the DBT peaks between 1:00 to 4:00pm and at its minimum between 6:00 to 8:00am in most days.

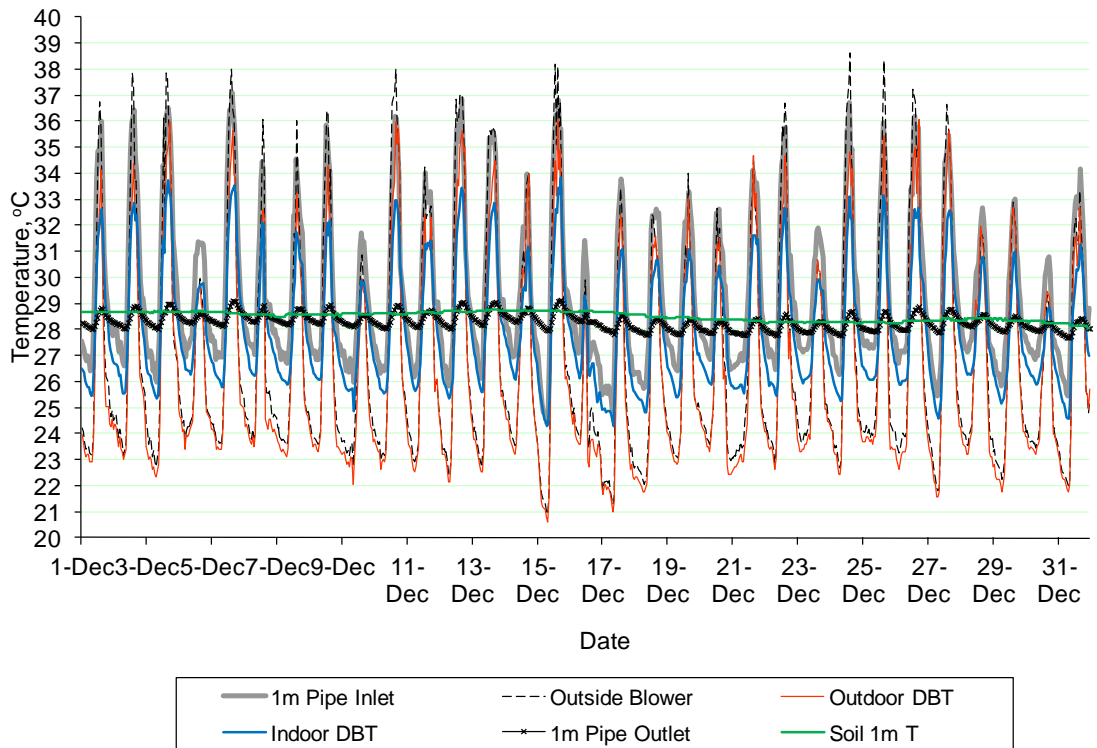


Figure 5.38: Trend of temperature in December 2010.

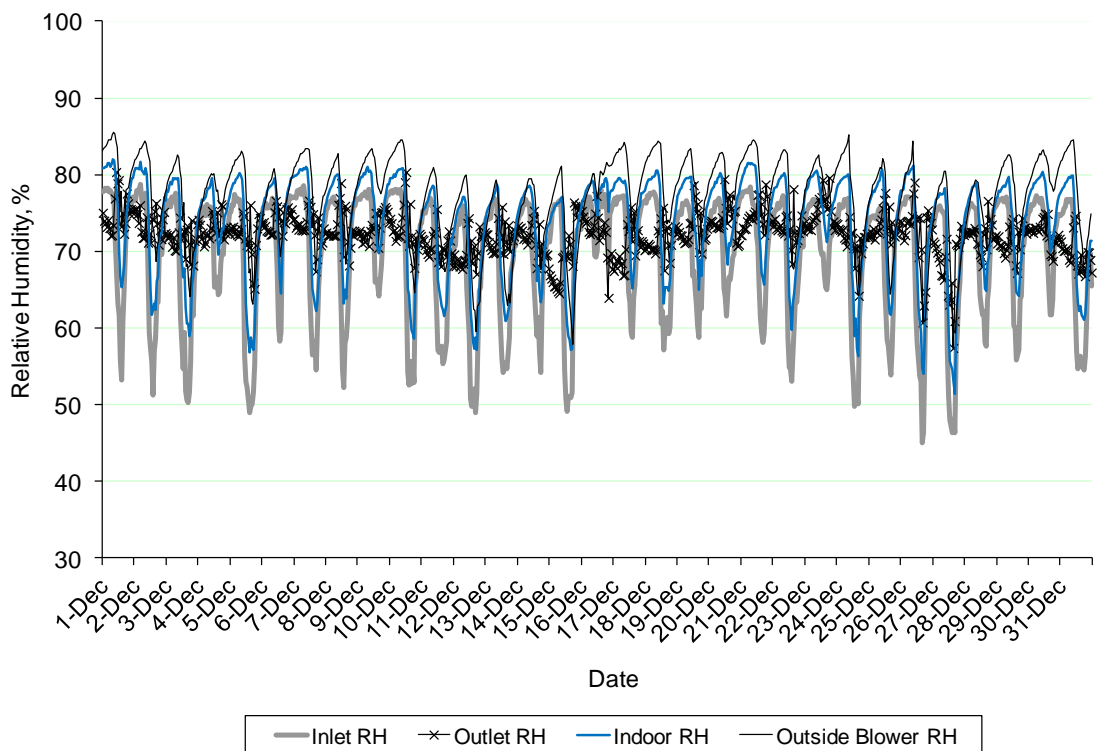


Figure 5.39: Trend of relative humidity in December 2010.

Figure 5.39 shows the trend of relative humidity (RH) in December. The RH at pipe inlet and outlet ranges from 45.1% to 78.8% and from 57.4% to 80.4% respectively. The indoor RH ranges from 51.5% to 81.9% while the RH just outside the fan blower ranges from 57.9% to 85.5%. A maximum rise in RH within the buried pipe was 26.2% that occurred at 3:00pm. At this hour the RH at pipe inlet and outlet were 49.8% and 76.1% respectively. The indoor RH at this time was 58.8% and the RH just outside the fan blower was 67.7%. The RH peaks between 8:00 to 10:00am and at its minimum between 1:00 to 4:00pm in most days.

5.2.4 Summary of Dry Bulb Temperature and Relative Humidity

Table 5.7 below summarises the performance of Earth Pipe Cooling system buried at 1m depth underground where the air supplied by a fan blower connected to one of the buried pipe.

The summary of Earth Pipe Cooling system performance with reference to Table 5.7 is analysed among the valid available data. The absolute maximum temperature reduction within the buried pipe is lowest in April and June with 6.3°C temperature drop and highest in January with 8.6°C temperature drop. Meanwhile, the average daily maximum temperature drop is lowest in June with 5.0°C and highest in February with 7.6°C. The buried pipe outlet data is then compared to the available outdoor DBT. TR2 shows that the temperature reduction between the outdoor and the buried pipe outlet is lowest in September with 4.8°C and the highest in January with 9.4°C.

Table 5.7 also shows that February provides the best result with the lowest minimum temperature at the buried pipe outlet. March has the highest maximum temperature at the pipe outlet. However, the minimum outlet temperature in March is 27.4°C, which is quite low. The average monthly outlet temperature in March and May are the highest among the months with a valid data of a whole year, which are both 29.9°C. Meanwhile, February have the lowest average air temperature at the buried pipe outlet.

Table 5.7: Summary of Earth Pipe Cooling System performance with respect to temperature. Maximum TR1=Temperature Reduction between pipe inlet and outlet. Maximum TR2=Temperature Reduction between outdoor and pipe outlet. AveMx=Average daily maximum and Ave=Average. *The outlet temperature value in a bracket is an error found which only occurred twice in the month.

Month	Jan	Feb	Mar	April	May	June	July	Aug	Sep	Oct	Nov	Dec
Unit	°C											
Max TR1	8.6	8.1	7.5	6.3	6.4	6.3	Data not available	Data not available	6.6	7.0	8.0	8.0
Max TR2	9.4	7.1	n/a	n/a	n/a	n/a			4.8	6.1	6.6	7.2
AveMx TR1	5.3	7.6	5.7	5.4	5.2	5.0			5.2	5.9	5.9	5.8
AveMx TR2	4.1	6.4	n/a	n/a	n/a	n/a			3.3	3.9	3.7	4.7
Outlet	27.1 - 28.9	26.9 - 29.0	27.4 – 30.9 (33.1)*	28.9 - 30.7	29.0 - 30.9	28.7 - 30.5			28.1 - 29.5	28.5 - 29.5	28.1 - 29.7	27.7 - 29.1
Inlet	25.4 - 37.0	25.1 - 36.7	25.9 – 38.1	26.3 - 36.9	25.7 - 37.1	25.8 - 36.8			26.5 - 36.1	25.7 - 36.5	25.8 - 37.2	24.4 - 37.1
Ave Outlet	27.6 - 28.3	27.3 - 28.3	29.4 – 30.7	29.3 - 30.3	29.4 - 30.5	29.1 - 30.2			28.6 - 29.4	28.6 - 29.4	28.4 - 29.1	28.0 - 28.7
Indoor DBT	24.4 - 33.7	24.1 - 34.1	26.0 – 36.1	26.2 - 36.2	25.9 - 36.4	25.8 - 36.1			25.8 - 33.6	25.1 - 33.9	25.3 - 34.1	24.3 - 33.8

Table 5.8 summarises the relative humidity found throughout the field investigation. It has shown that there are increments within the buried pipe. However, the most increment in RH through the buried pipe was 26.9%, which occurred in January. The maximum RH at the buried pipe outlet was found to be 81.8%, which occurred in November.

Table 5.8: Summary of Earth Pipe Cooling System performance with respect to relative humidity. *Ave=Average.

Month	Jan	Feb	Mar	April	May	June	July	Aug	Sep	Oct	Nov	Dec
Unit	%											
Max RH rise	26.9	24.5	18.7	23.0	24.1	22.4	Data not available	Data not available	18.1	20.7	24.0	26.2
Outlet	59.7	64.3	44.4	60.7	62.7	63.0			59.5	67.1	59.6	57.4
	–	–	–	–	–	–			–	–	–	–
	79.2	77.1	81.6	80.9	81.1	80.9			80.8	77.8	81.8	80.4
Inlet	45.6	51.6	32.9	43.3	42.7	45.9			46.9	50.7	44.8	45.1
	–	–	–	–	–	–			–	–	–	–
	79.2	80.2	81.6	82.1	82.1	81.4	77.7	76.9	79.5	78.8		
Ave Outlet	71.3	70.2	69.2	72.9	74.3	74.1	72.4	71.6	72.8	72.3		
Indoor RH	52.9	51.6	37.5	48.9	52.1	51.7	53.8	59.5	50.6	51.5		
	–	–	–	–	–	–	–	–	–	–		
	83.0	80.2	82.1	82.2	81.9	81.4	80.6	79.8	82.4	81.9		

5.2.5 Further field investigation on buried pipe inlet

Throughout all data obtained during the investigation of Earth Pipe Cooling, repetitive anomalies were found in the trend of dry bulb temperature at the pipe inlet particularly at night time, when there is no solar radiation. At most times, the buried pipe inlet temperature is higher than the outdoor ambient dry bulb temperature. During the night, the temperature difference between the buried pipe inlet and outdoor DBT

were more significant. These anomalies were investigated further in another experiment, which was carried out within a short time frame.

As a recap, the buried pipe inlet and outlet are located within the experiment shed so that they are secured. A fan blower is punched through a wall of the experiment shed, where the exhaust is connected to the buried pipe air inlet. The fan extracts air from outside, circulates it within the fan turbines and blows the air into the buried pipe. The distance of air travelled within the pipe from the fan blower to the location of data logger logging pipe inlet temperature is approximately 1.1m. Since the air from outside is blown through the fan into the buried pipe inlet at a speed of approximately 5.6m/s within a short distance, assumptions were made that the air temperature outside the fan should be similar to the air temperature at the buried pipe inlet. However, the results did not meet the assumption.

The fan was operating continuously for 24 hours a day and therefore, outside air flow into the buried pipe continuously. As an investigation to the anomalies found, the experiment measures all that has been measured in the previous experiment, outdoor air temperature under a tree, outdoor air temperature just outside the fan blower, indoor air temperature at 1.4m high, air temperature at the buried pipe inlet and pipe outlet. Three additional dataloggers were placed within the pipe, nearer to the fan blower. Their distances are 0.3m, 0.6m and 0.8m from the fan blower. The results given during fan operation for all measurements are illustrated in Figure 5.40.

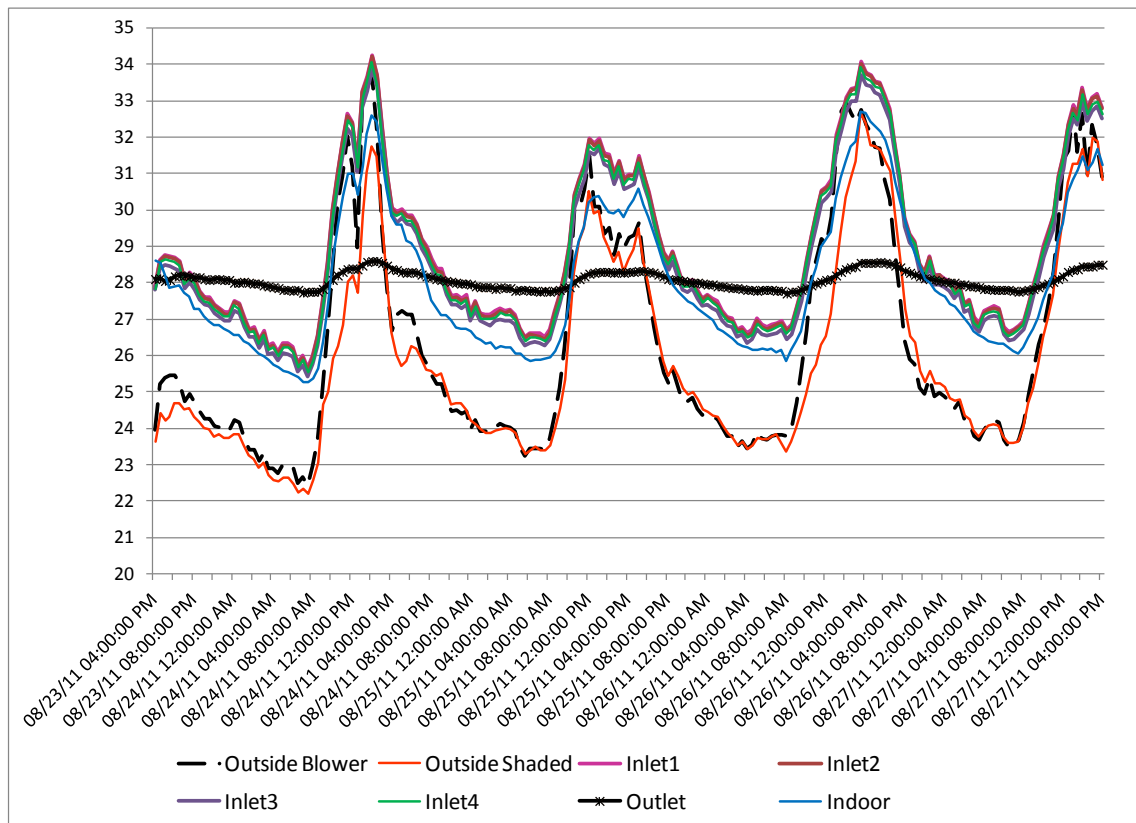


Figure 5.40: Another result showing temperature trends of field investigation of 25m Polyethylene pipe buried at 1m depth in August 2011. This time it has multiple position of buried pipe inlet.

Referring to Figure 5.40, all data of buried pipe inlets are higher than the outdoor air temperature. However, the temperature differences between the outdoor air temperature and all the four locations of pipe inlets are at different rate throughout the day. The results has shown that the air temperature between the fan blower and the point before the pipe goes underground are the same in all four locations, Inlet 1, 2, 3 and 4. The air temperature at Inlet 1 is the closest to the fan blower and it has the same temperature as Inlet 4, which is 0.8m further than Inlet 1, away from the fan blower. The same question arises again on the high temperature difference between the air outside the fan blower and the air at just 0.3m after the fan blower, particularly during night time (Figure 5.40). The result show a possibility of heat gained from the fan blower particularly at night time. The heat gain is found to be from the built in motor in the fan blower.

5.2.6 Field Investigation using PVC buried pipe

Investigation in both the wet season and hot and dry season also comprises the inlet and outlet temperature of the 25m long PVC pipe buried at 0.5m. This section presents the results obtained from field investigation using buried PVC pipe.

a) *Wet season, November*

Figure 5.41 presents data collected during the field investigation of PVC pipe. Within the 25m long PVC pipe, the temperature at the inlet and outlet ranges from 23.1°C to 33.3°C and 22.6°C to 27.0°C respectively. The maximum temperature reduction within the two days of operation is 6.6°C, which occurred at 12:30pm. At this hour, the temperatures at pipe inlet and outlet were 33.3°C and 26.8°C respectively. The average daily maximum temperature reduction within the two days is 6.4°C. Although there is a significant temperature reduction, the indoor DBT is reduced slightly, which ranges from 23.1°C to 31.6°C. Data logger that measured the outdoor DBT is not properly shaded, hence the fairly high maximum temperature during the day (Figure 5.41).

The fan blower operates from 10am to 6pm. A distinguish results were found in the PVC pipe field result in comparison to the results from Polyethylene pipe. The anomaly occurred from 6pm to 10am the next morning in both days. Referring to the buried pipe outlet temperature, it maintains at a constant level when the fan switches off at 6pm (Figure 5.41). It maintains the constant daytime temperature at most times during night time. Table 5.0 summarises the data obtained from this field investigation using PVC pipe.

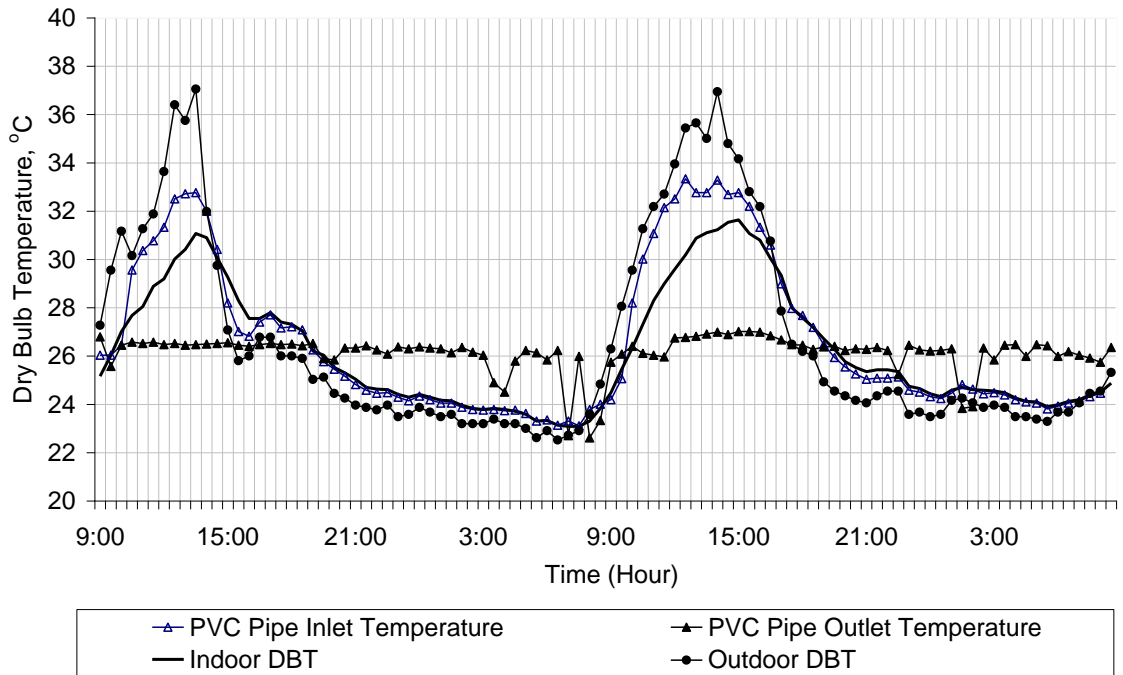


Figure 5.41: Temperature during investigation of 25m long PVC pipe buried at 0.5m depth underground in the wet season, November 2008

Table 5.9: Summary of temperature from the investigation of 25m long PVC pipe buried at 0.5m deep underground.

	PVC pipe, 25m long, 0.5m deep
Outdoor DBT, °C	22.5 – 37.1
ITRange, °C	23.1 – 33.3
OTRange, °C	22.6 – 27.0
Max TR, °C	6.6
Average daily maximum TR, °C	6.4
Indoor DBT, °C	23.1 – 31.6

b) *Hot and dry season, May*

Similar field investigation of the PVC buried pipe was repeated in the hot and dry season. The initial purpose is to test the effect of different material with different thermal conductivity, on the field investigation results.

Figure 5.42 shows the trend of air temperature of the Earth Pipe Cooling system. In this investigation, the relative soil temperature at 0.5m deep underground ranges from 30.5°C to 31.0°C. The temperature found in the buried pipe inlet ranges from 25.2°C to 37.4°C. The temperature found at the other end of the buried pipe, which is the pipe outlet ranges from 27.5°C to 30.6°C. When the fan blower operates between 10:00am and 6:00pm, there is temperature differences found between the two ends of the buried pipe and the maximum temperature difference was 6.9°C. However, the average daily maximum temperature difference was 6.7°C. Meanwhile, the indoor DBT ranges from 25.2°C to 35.7°C. The maximum indoor DBT is 1.7°C less than the maximum temperature at the pipe inlet.

The relative humidity, RH at the buried pipe inlet ranges from 44.6% to 89.7% while the RH at the outlet ranges from 68.8% to 95.6% (Figure 5.43). There is a maximum RH rise of 26.9% within the buried pipe. The maximum RH is close to 100%, which shows that it gets very humid at the buried pipe outlet. The RH is higher during the night even when the fan blower is not operating. Meanwhile, the indoor RH ranges from 44.4% to 85.0%.

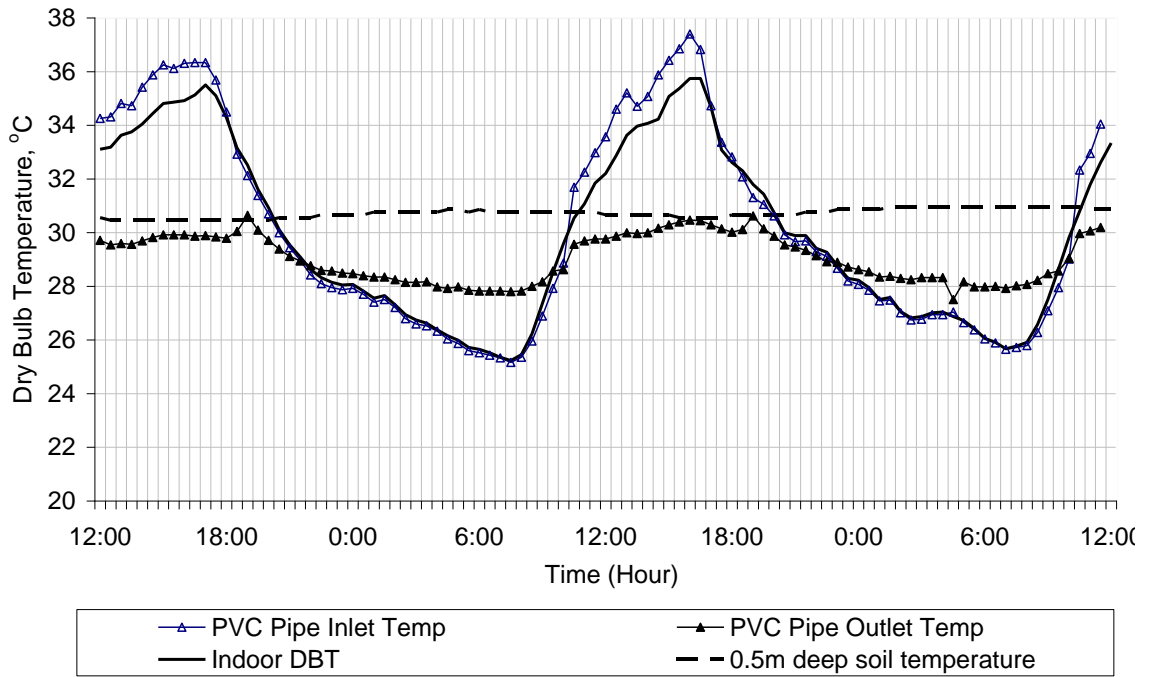


Figure 5.42: Trend of temperature from investigation of 25m long PVC pipe buried at 0.5m deep underground in the hot and dry season, May 2009.

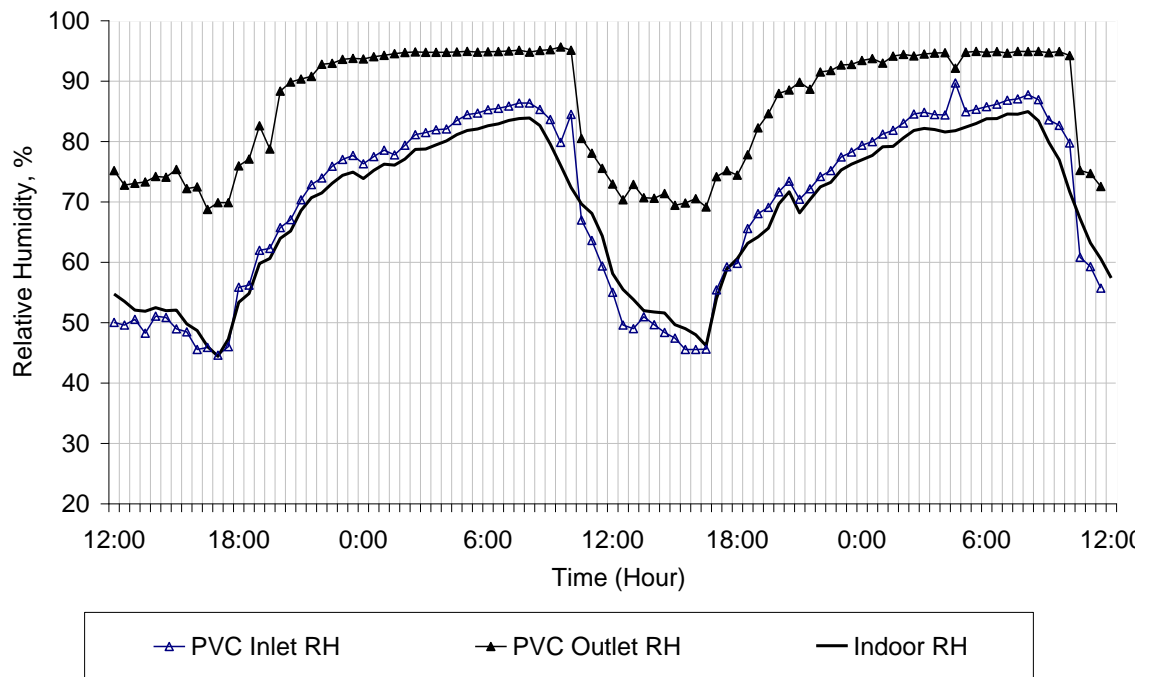


Figure 5.43: Trend of relative humidity from investigation of 25m long PVC pipe buried at 0.5m deep underground in the hot and dry season, May 2009.

Table 5.10: Summary of temperature and relative humidity during the field investigation of PVC pipe, which is 25m long and buried at 0.5m depth.

	PVC pipe, 25m long, 0.5m deep
Soil Temperature, °C	30.5 – 31.0
ITRange, °C	25.2 – 37.4
OTRange, °C	27.5 – 30.6
Max TR, °C	6.9
Average daily max TR, °C	6.7
Indoor DBT, °C	25.2 – 35.7
Inlet RH, %	44.6 – 89.7
Outlet RH, %	68.8 – 95.6
Max RH rise, %	26.9
Indoor RH, %	44.4 – 85.0

Apart from the data recorded, another discovery was found inside the outlet of PVC pipe. The datalogger that measured PVC pipe outlet temperature was found wet and a stick that holds the datalogger was found slightly covered with mould (Figure 5.44 and Figure 5.45). It was assumed that there has been condensation occurred within the buried PVC pipe that produced water particles. The reason for this could be because of the pipe thickness, which is much thinner than the thickness of Polyethylene pipe.

The assumption of condensation occurrence in the PVC pipe was confirmed by the humidity graph in Figure 5.43, where the maximum buried pipe outlet relative humidity was 95.6%.



Figure 5.44: A wet data logger taken out from the PVC pipe outlet



Figure 5.45: A stick used to hang data logger in PVC pipe outlet were found to be covered with mould.

CHAPTER 6 COMPUTATIONAL SIMULATION

Computational Simulation work was required for this research to extend the investigation beyond the constraints of field experiment, which was both temporal and financial. In this study, simulation software Energy Plus was used to complete the Earth Pipe Cooling investigation in hot and humid climate with particular reference to Malaysia. Energy Plus (Crawley, 2005) has a basic user interface which requires inputs from the user, to produce the outputs, which is the computer simulation results required. Version 1.2.2 of Energy Plus was created in April 2005. The software includes the best capabilities and features of two softwares known as DOE-2.1E and BLAST. Both DOE-2.1E and BLAST calculate or predict energy consumption in buildings. In addition to that, Energy Plus also tabulates temperatures of building in zones.

Another simulation tool called Buried Pipes, (Hollmuller P) was also introduced to predict the results of Earth Pipe Cooling system. However, when relating the result of Buried Pipe with field work, there were significant differences.

6.1 Comparison of Data Obtained from Energy Plus, Buried Pipe and Field Experiments.

Energy Plus requires inputs such as weather data, soil temperature data at various depths, design of buried pipe and building containing the buried pipe outlet, and the fan power that creates air movement into the buried pipe. Similarly, simulation tool Buried Pipe also requires inputs such as weather data, mean soil temperature of soil surrounding the buried pipe, design of the buried pipe, the depth of the buried pipe underground and thermal property of the soil.

The weather data used by Energy Plus software contains the monthly soil temperature at several depths, hourly dry bulb temperature and hourly dew point temperature, which obtained by calculating the dry bulb temperature and relative humidity. In a different case, the weather data used by Buried Pipe software requires the annual mean soil temperature at the depths of where the pipe is buried and the dry bulb temperature of the outdoor space. The latter simulation tool does not consider the humidity of the ambient air as well as it does not take into account the monthly average soil temperature.

Figure 6.1 illustrates a comparative study among data obtained from field work measurement, Energy Plus simulation and Buried Pipe simulation. Data measured in May were chosen for this comparative study when the climate was hot and dry.

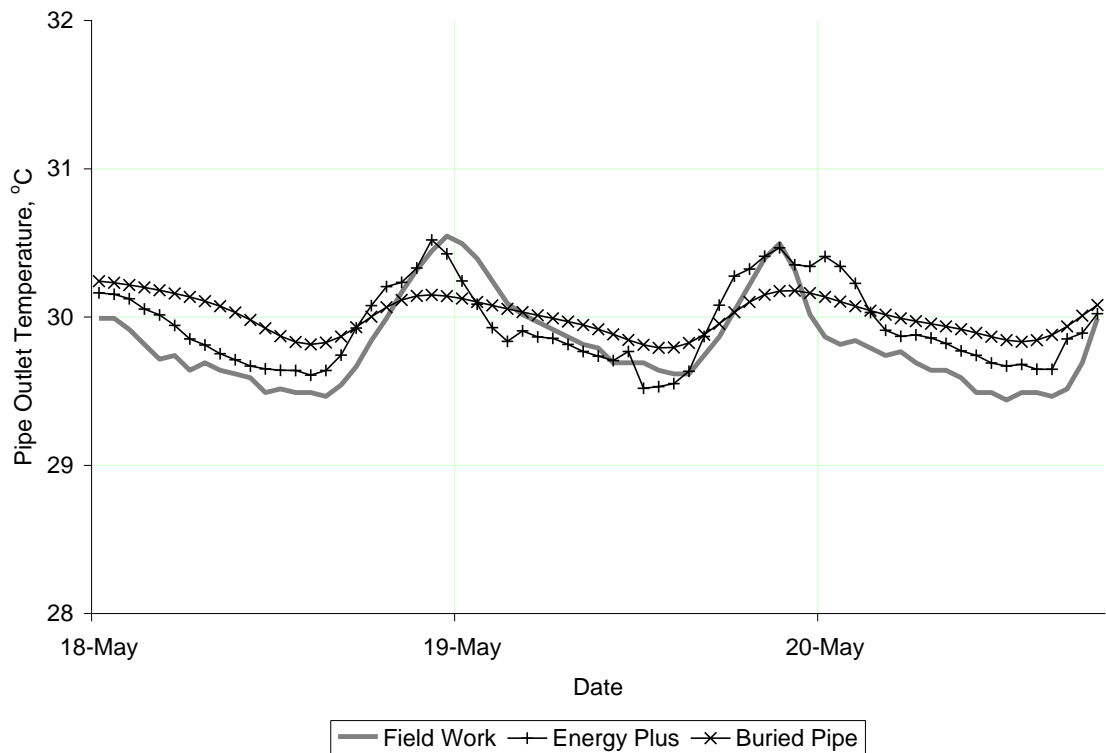


Figure 6.1: Pipe Outlet Temperature measured during field experiment and pipe outlet temperature predicted by Energy Plus and Buried Pipe simulation tools.

Figure 6.1 above shows that the data predicted by Energy Plus is similar to the data obtained from field work investigation. On the other hand, data predicted by Buried Pipe have rather significant temperature difference to the field work data. The maximum temperature difference between the field work and Buried Pipe data was 0.5°C, whereas the maximum temperature difference between the field work and Energy Plus was 0.3°C. Therefore, between these two simulation tools, Energy Plus is more suitable because it agrees more with the data obtained from field work. In the next section 6.2, Energy Plus data are compared with field work data in each month throughout a year.

6.2 Simulation Set Up in Energy Plus

As mentioned earlier, Energy Plus requires inputs such as weather data, soil temperature data at various depths, design of buried pipe and building containing the buried pipe outlet, and the fan power that creates air movement into the buried pipe. In most cases, having weather data is sufficient to predict soil temperature using external module that came with Energy Plus software. In some cases, researchers have developed the model to determine the annual mean soil surface temperature (Karti et al., 1995). There is another study, carried out by Labs (1989), where the model was developed to determine the soil temperature at various depths using annual mean and amplitude of soil surface temperature (Lee and Strand, 2008).

The input data file in Energy Plus is called the .idf file. IDF stands for Input Data File. The input data is classified in various class lists. However, only 7 class lists are applicable to the simulation related to Earth Pipe Cooling system. Within each 7 class lists, there are various numbers of input data. The first applicable class list is entitled Simulation and Parameters. Within this class list, inputs given were Energy Plus version, simulation controlled by the sizing period and weather file run periods, and the number of data in an hour. Since the data recorded in field work were hourly, the number of data in an hour was set to 1 in Energy Plus.

The second related class list is regarding the location of climate of the experiment site. This includes input of the site latitude, longitude, time zone and elevation above sea level. The input in this class list continues with the sizing period of the file. Since the comparative study between field work and Energy Plus data is carried out monthly, one Energy Plus file is dedicated to each month. Therefore, the sizing period that connects to the weather file, was set to one month. This is followed by the run period which was also set to the same month as the sizing period. This class also includes the monthly soil temperature at shallow (0.5m) and deep (3-4m) depths.

A module that calculates three parameters essential for Earth tube simulation to be successful, is available in the Energy Plus program. The three are calculated parameters are annual mean ground surface temperature, amplitude of the annual soil surface temperature variation and phase constant of the soil surface. The calculation was derived from its weather data file of the particular country.

However, in circumstances of getting it accurate, this study used real soil temperature data for all soil related inputs in the software. The soil temperature data was measured in the field experiment site throughout one whole year and these were used in Energy Plus study (Table 6.1). The shallow ground temperature inputs were soil temperature data measured at 0.5m underground whereas the deep ground temperature inputs, were data measured at 4m underground.

At 0.5m underground, the monthly average soil temperature ranges from 27.8°C to 30.2°C. However, at hourly measurements, it can drop as low as 26.6°C in February and when it experiences the wet season. It can increase as high as 30.7°C in May, when it is hot and dry season. The annual amplitude was as significant as 2.1°C because the soil temperature was measured at a shallow depth of 0.5°C below ground.

Meanwhile, at 4m underground, the annual soil temperature is more stable due to it being deeper underground and less affected by air dry bulb temperature. The hourly soil temperature at this depth ranges from 29.1°C to 30.3°C, which gives the annual amplitude of 0.6. However, soil temperature at 4m depth of soil was measured only in November and December and the monthly average 4m depth soil temperature for both months is 29.4°C. Therefore, the annual monthly average would be the same as 29.4°C, referring to the two months result and theory of soil temperature stability in literatures reviewed.

Table 6.1: Input data of Site:GroundTemperature:Shallow and Deep in Energy Plus file.

Month	Ground Temperature: Shallow (°C)	Ground Temperature: Deep (3-4m depth) (°C)
January	27.8	29.4
February	28.6	29.4
March	29.8	29.4
April	30.1	29.4
May	30.2	29.4
June	29.8	29.4
July	29.3	29.4
August	29.3	29.4
September	29.1	29.4
October	29.3	29.4
November	28.8	29.4
December	28.5	29.4

The third related class list is Schedules. This is used to determine the operation of the fan blower, whether it is operating all day or at certain hours of a day. In this study, the fan operation is set to 24 hours. The fourth related class list is Surface Construction Elements. This class list starts with inputs of all building materials used with a full set of each material's thermal properties. The thermal properties include the material's roughness, thickness, conductivity, density, specific heat, thermal absorptance, solar absorptance and visible absorptance. An additional layer of material, which is an air gap and window glazing is also included. Next input that follows is the construction of the building surface using the materials listed previously.

The fifth class list is Thermal Zones and Surfaces. In this class list, all building surfaces are given its own vertex coordinates that form the building walls, floor, roof, windows and door. All the building surfaces form the building to be measured, which in Energy Plus is called thermal zone. In this study, there is only one thermal zone since the experiment building is a single space building with centrally 2 pitched roof, two windows and one door. To get the vertex coordinates of each building surface, the building was drawn separately in another programme Google SketchUp 7 (Figure 6.2).

The Google SketchUp 7 must be installed where the Energy Plus software is already available. This enables a link between Google SketchUp 7 and Energy Plus softwares.

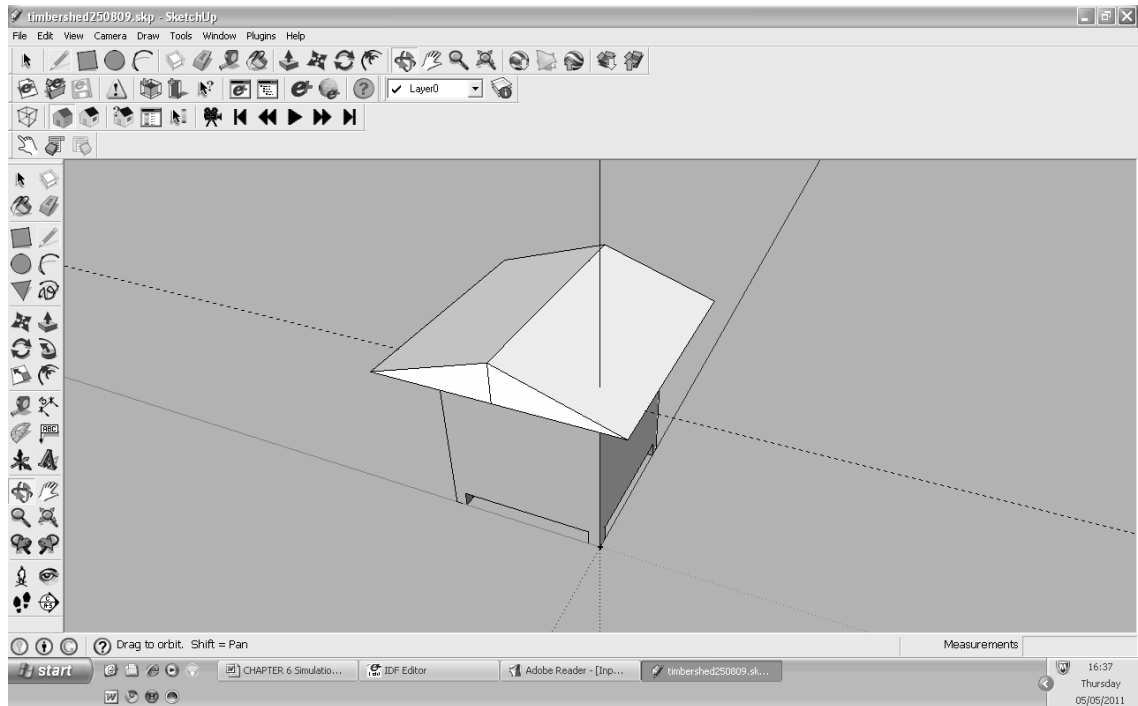


Figure 6.2: Experiment shed drawn in Google SketchUp 7(before inserting the two windows and door) to obtain vertex coordinates for each building surface for Energy Plus input.

The drawing in Google Sketchup 7 does not have to be orientated to the correct angle from North. This can be done in Energy Plus class list Thermal Zones and Surfaces. The final drawing of the experimental shed titled at the correct angle from the North sign can be viewed in a programme called Volo View Express. On the real field work site, all pipe inlets and outlets are installed within the experimental shed. In Energy Plus, there is no enquiry on the specific location where the pipe inlet and outlet are installed.

The 6th related class list is Zone Airflow, which contains the specific input of the Earth Pipe design (Table 6.2). During the real field work investigation, the pipe radius and thickness was limited to 0.0368m and 0.0082m respectively. The pipe length was 25m and the depth where the pipe was buried was 1m. The type of pipe used in the real

field work was Polyethylene pipe, which limits the pipe thermal conductivity to 0.42 W/mK. The main purpose of simulating pipe outlet data in Energy Plus software is to extend the variables further than the limit of the real field work. This was carried out to perform a parametric study of different sets of variables with respect to the pipe length, diameter, material and depth it was buried.

Table 6.2: Basic Set Up in Energy Plus file in Zone Earthtube column, under Zone Airflow Class List.

Parameters	Values
Schedule Name	Fan Blower Operates All Day (24 hours)
Design flow rate	0.0238m ³ /s, 0.0128m ³ /s, 0.0043m ³ /s
Minimum Zone Temperature when Cooling	20°C
Maximum Zone temperature when Heating	50°C
Earthtube Type	Intake
Fan pressure rise	520 Pascal
Fan Total Efficiency	0.85
Pipe Radius	Original; 0.0368m (3.5"), Parametric Study; 0.045m (4"), 0.0511m(5"), 0.0102m (1") or 0.1023m (10")
Pipe Thickness	Original; 0.0082m (3.5" pipe), Parametric Study; 0.010m (4" pipe), 0.0114m (5" pipe), 0.0023m (1" pipe) or 0.0227m (10" pipe)
Pipe Length	Original; 25m. Further parametric study; 6.3m, 12.5m and 50m
Pipe Thermal Conductivity	0.42 W/mK (Polyethylene PN 12.5), 0.19 W/mK (PVC), Clay (1.8 W/mK) or Brick (0.69 W/mK)
Pipe Depth Under Ground Surface	1m
Soil Condition	Heavy and Damp
Average Soil Surface Temperature	29.21°C (at 1m depth)
Amplitude of Soil Surface Temperature	1.642°C
Phase Constant of Soil Surface Temperature	350 days

The 7th class list is Natural Ventilation and Duct Leakage. This class list is considered because the windows of the experiment shed are always opened and there is a gap between the ceiling and the top edge of each wall. Therefore, the ventilation control was set to 24 hours.

Once all input have been recorded, the simulation was carried out using the EP-Launch programme. In this programme, the .idf file and Malaysia weather file are selected before the simulation commences.

6.3 Validation of Energy Plus using monthly experimental data

A series of graphs are illustrated below comparing the data obtained in field work with the data predicted by Energy Plus. However, there are no records of field work valid data in July and August and therefore the validation would skip these two months. There are also a few months with incomplete data recorded during the field work.

All these graphs show that the data obtained from Energy Plus simulation tool agrees very well with the data obtained from the actual field investigation. However, a slight significant difference between Energy Plus and field work data is shown in the month of February (Figure 6.4). Even so, the maximum temperature difference found in Figure 6.4 is 1.57°C.

Referring to Figure 6.3, in early January, the temperature graph shows a flat distribution of buried pipe outlet temperature. This result shows the effect of rainfall that occurred in early January (Figure 5.20 in Chapter 5). The same occurrence repeated again at the end of January. This was also due to rainfall or low ambient temperature.

Figure 6.4 shows that there is a significant gap between the field work data and Energy Plus data. In Energy Plus, the monthly average soil temperature represents the whole month of soil temperature. The field investigation soil temperature is lower than monthly average soil temperature of Energy Plus, in the early February. Field data obtained in February was limited to the first nine days of the month. It can be seen in Figure 6.4 that the field investigation data and Energy Plus data starting to merge on the 9th of February. This can predict the energy Plus and field investigation data became similar and agrees well with each other.

a) *January*

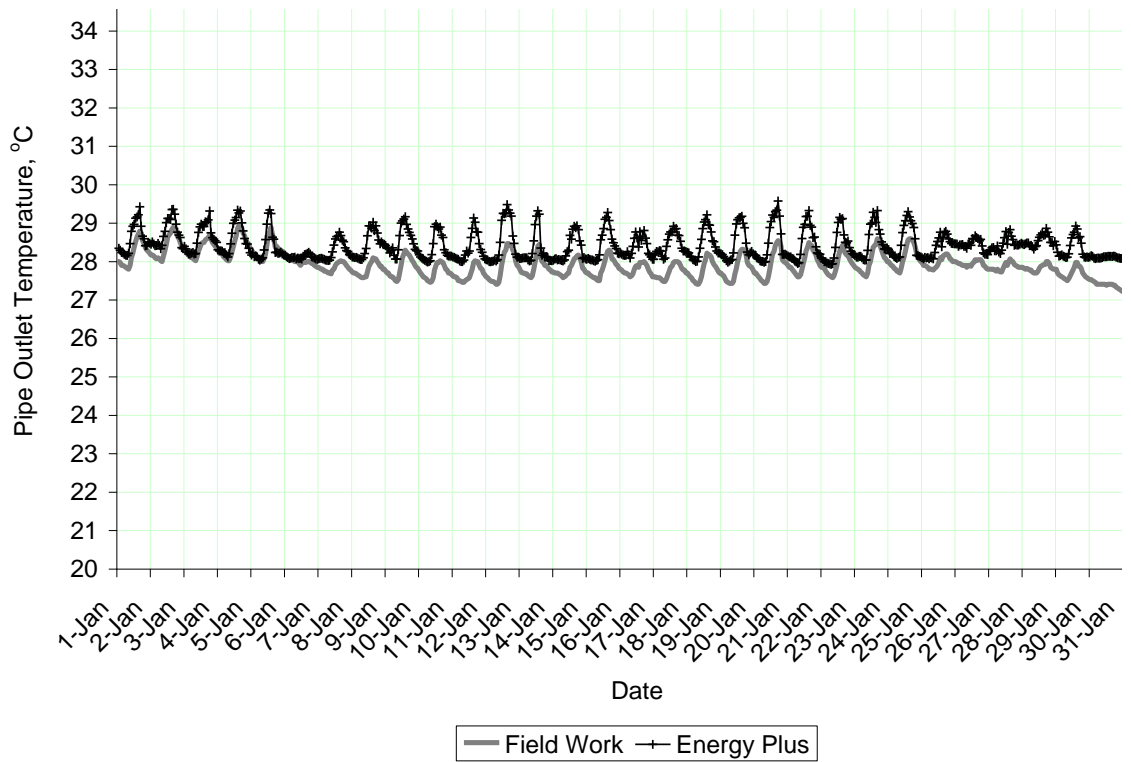


Figure 6.3: Data obtained in January from field work and Energy Plus.

b) *February*

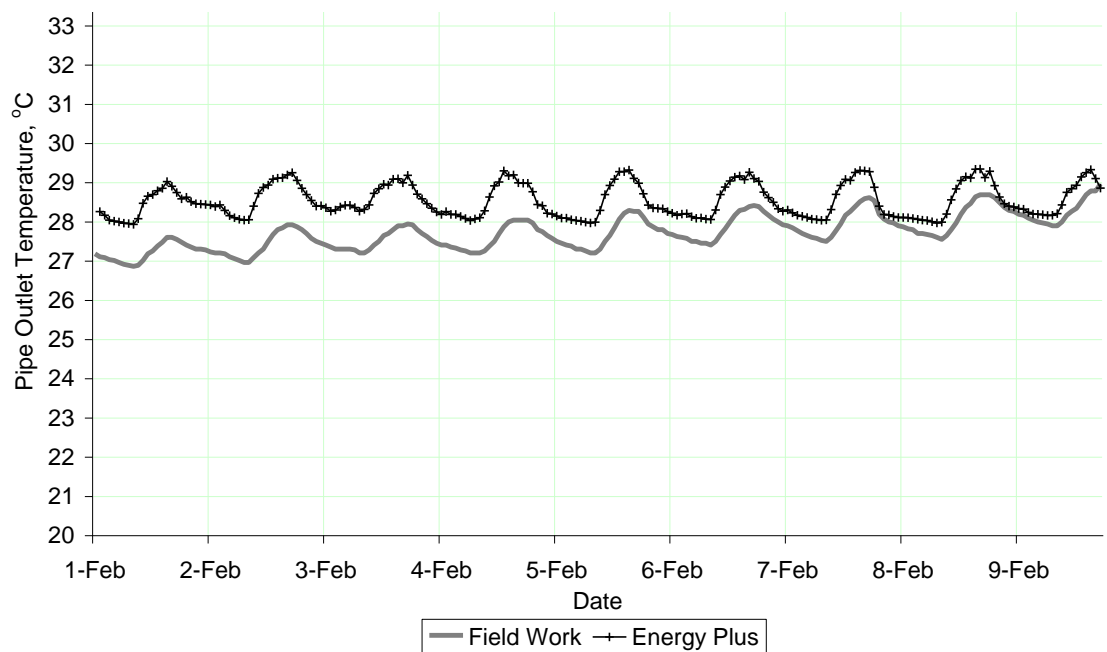


Figure 6.4: Data obtained in February from field work and Energy Plus.

In March, the Energy Plus data agrees very well with the field investigation data but the graph has been removed from this section because there is an error in field data. The original graph can be viewed at Appendix 6.1.

April data in Figure 6.5 shows similarity to February data in Figure 6.4 in terms of gap between field data and Energy Plus data in the early April. In April data, complete whole month of data were obtained. The two data trends merge into each other after the 5th of April.

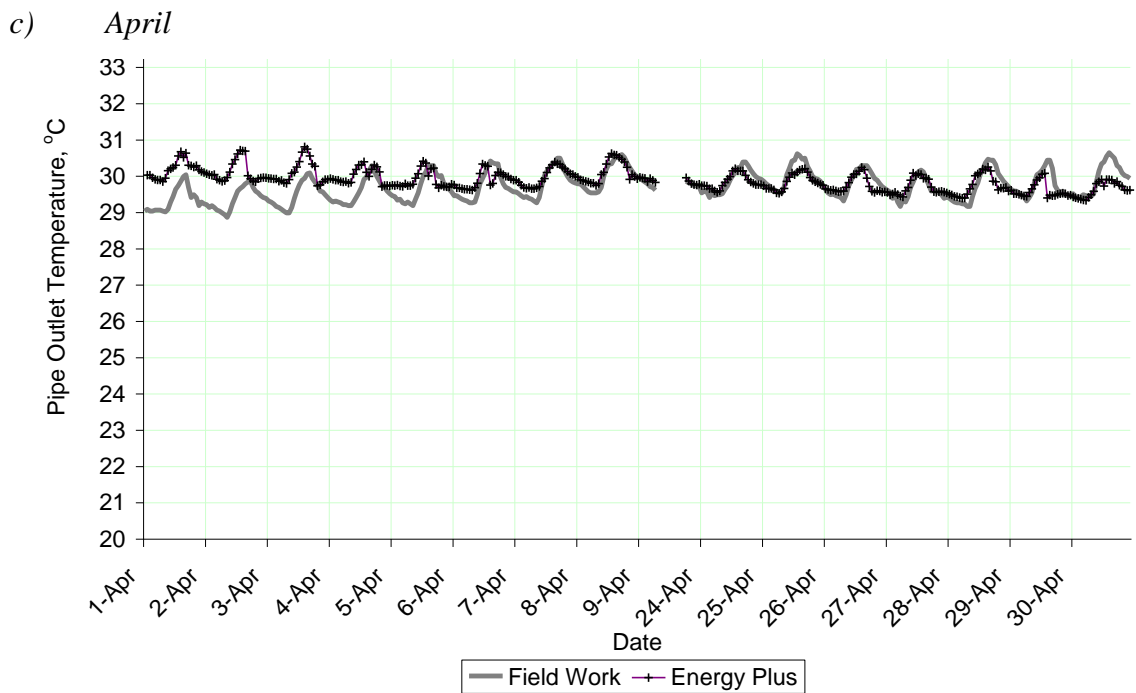


Figure 6.5: Data obtained in April from field work and Energy Plus.

d) *May*

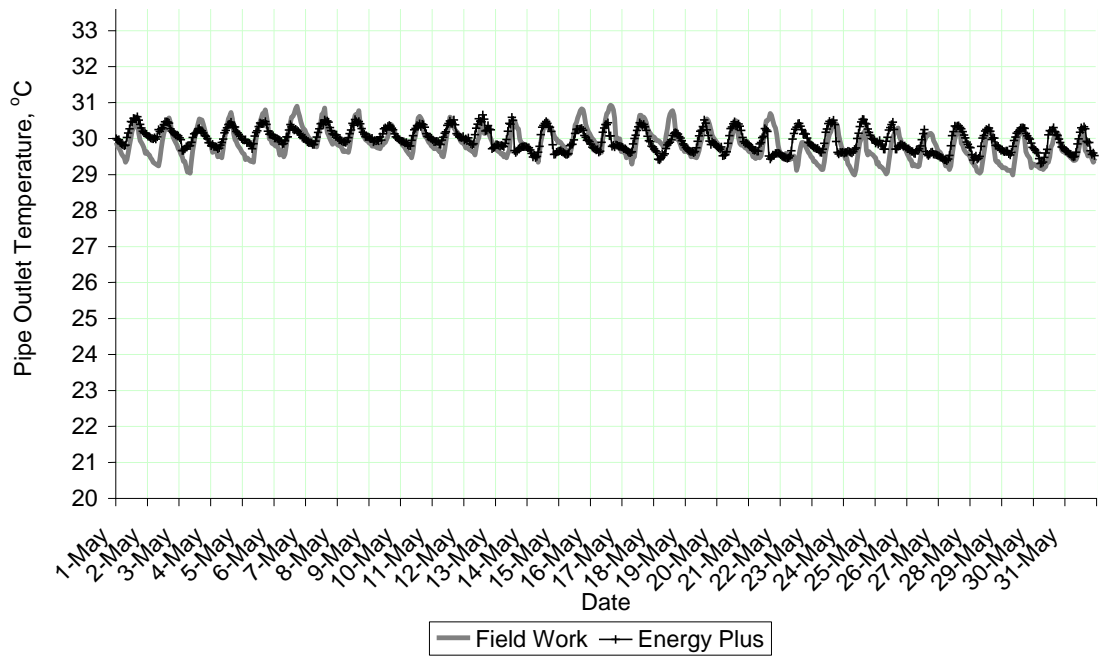


Figure 6.6: Data obtained in May from field work and Energy Plus

e) *June*

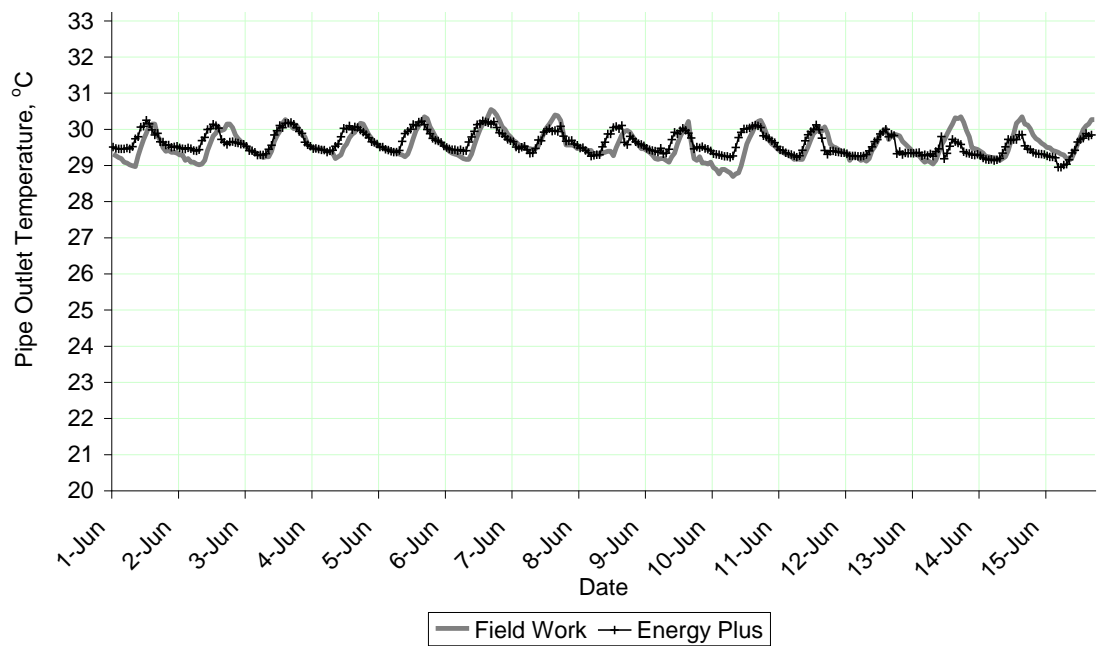


Figure 6.7: Data obtained in June from field work and Energy Plus

f) *September*

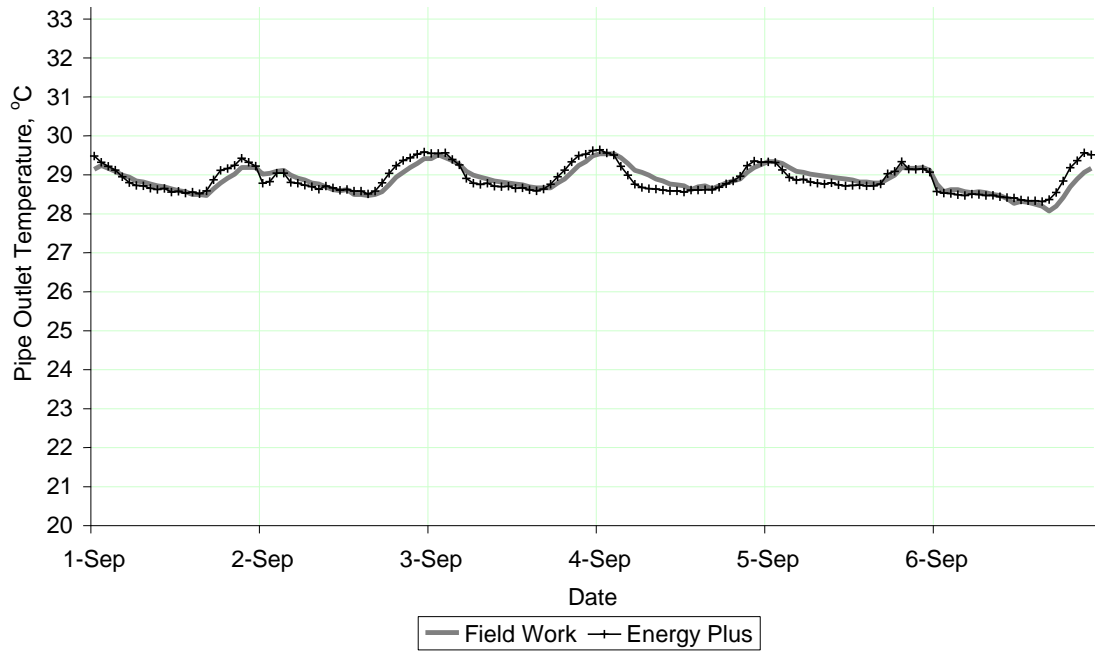


Figure 6.8: Data obtained in September from field work and Energy Plus

g) *October*

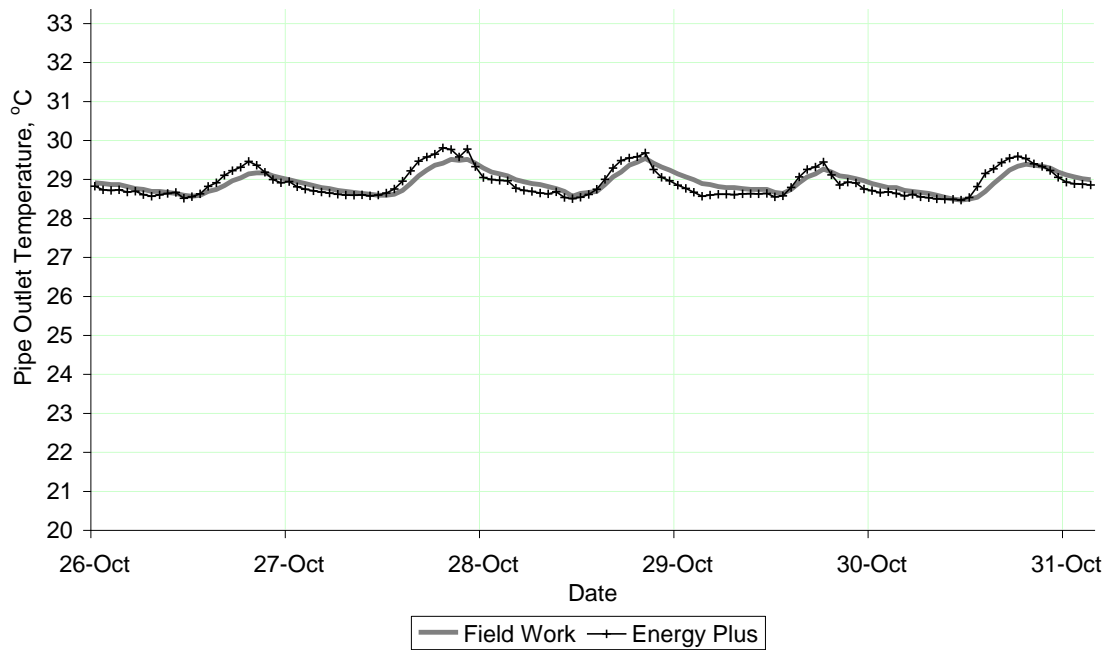


Figure 6.9: Data obtained in October from field work and Energy Plus

h) *November*

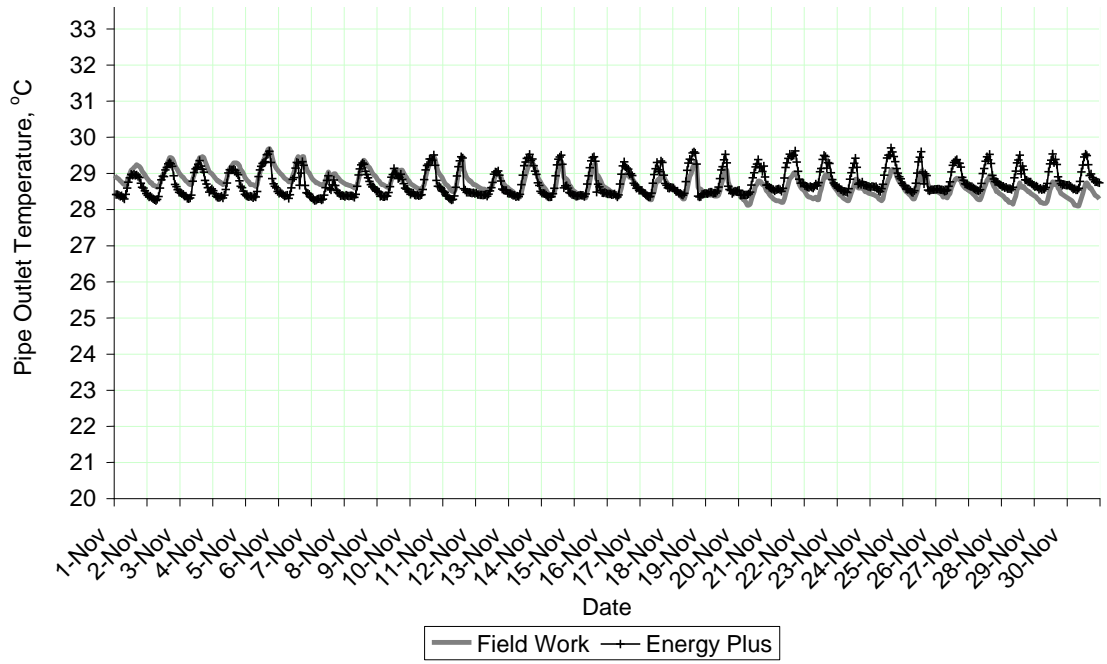


Figure 6.10: Data obtained in November from field work and Energy Plus

i) *December*

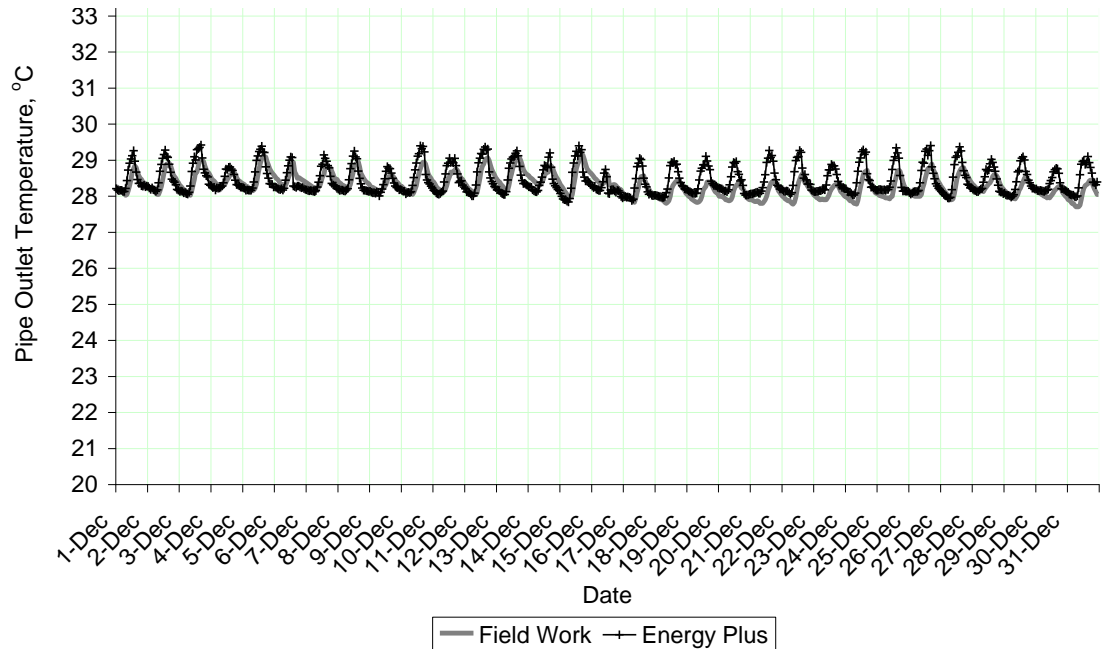


Figure 6.11: Data obtained in December from field work and Energy Plus.

6.4 Parametric Studies – Extended Investigation of Earth Pipe Cooling in Kuala Lumpur, Malaysia with Energy Plus Software.

Due to the good agreement between Energy Plus and field work data, the Earth Pipe Cooling investigation is able to expand with different set of variables. Among the many months, December is chosen for the weather and soil conditions for the parametric studies.

The first parametric study is the effect of different pipe lengths used. The study is to investigate the minimum requirement for the buried pipe length to be to achieve earth pipe cooling. In this length investigation, the other variables remain as original; $0.0238\text{m}^3/\text{s}$ air flow rate, 3” pipe (radius 0.0368m) and 1m deep underground. The result of study of different length has shown that when the length is halved or quartered, the pipe outlet temperature range increases and therefore, its amplitude changes. When the length of the earth pipe is doubled to 50m long, the pipe outlet temperature range reduced and the outlet temperature becomes more stable (Figure 6.12).

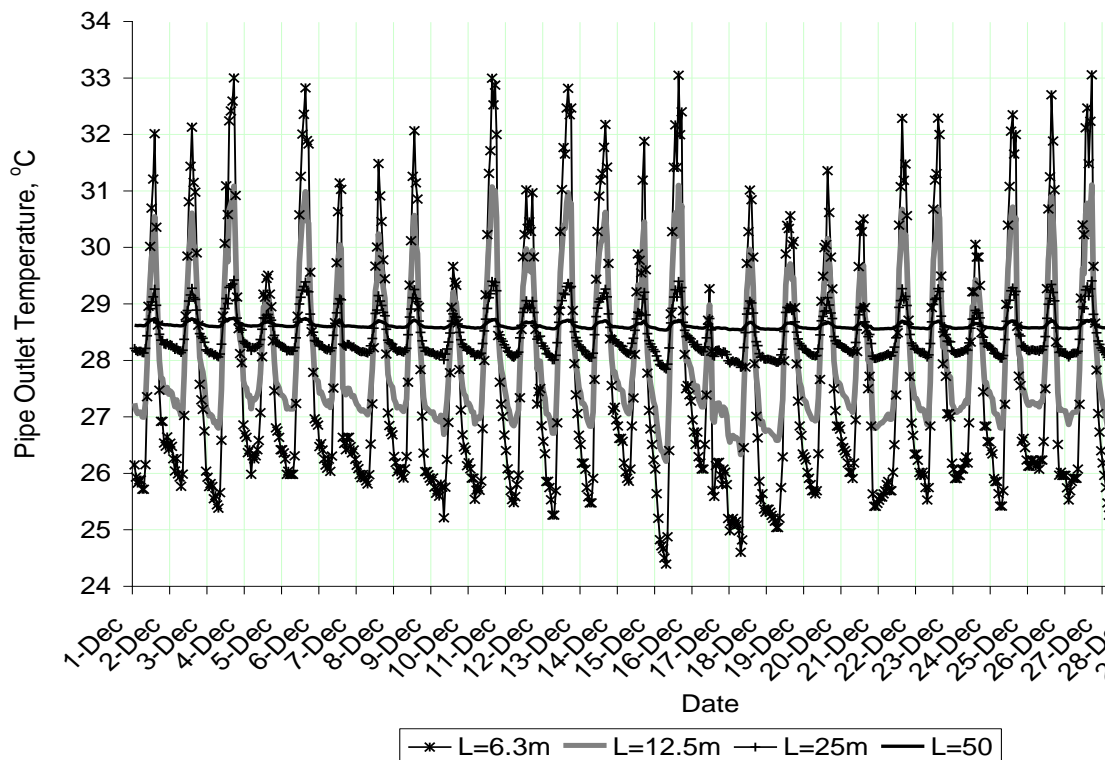


Figure 6.12: Parametric study with Energy Plus using four different pipe lengths.

This predicts that when the buried pipe is long, heat transfer process underground becomes longer since the air flow inside the buried pipe stays longer in the soil, which allow more air inside the buried pipe to transfer heat to the soil. From Figure 6.12, Energy Plus suggested 50m long Polyethylene pipe would be most efficient.

The second parametric study investigates the effect of different pipe size on the Earth Pipe Cooling performance. Each size has its own radius and thickness (Table 6.3). The other variables remain as original; 0.0238m³/s air flow rate, 25m long pipe and 1m deep underground.

Table 6.3: A list of Polyethylene pipe radius and thickness for Energy Plus parametric study on different pipe size.

Size	1"	3.5" (field work size)	4"	5"
Radius	0.0102m	0.0368m	0.045m	0.0511m
Thickness	0.0023m	0.0082m	0.010m	0.0114m

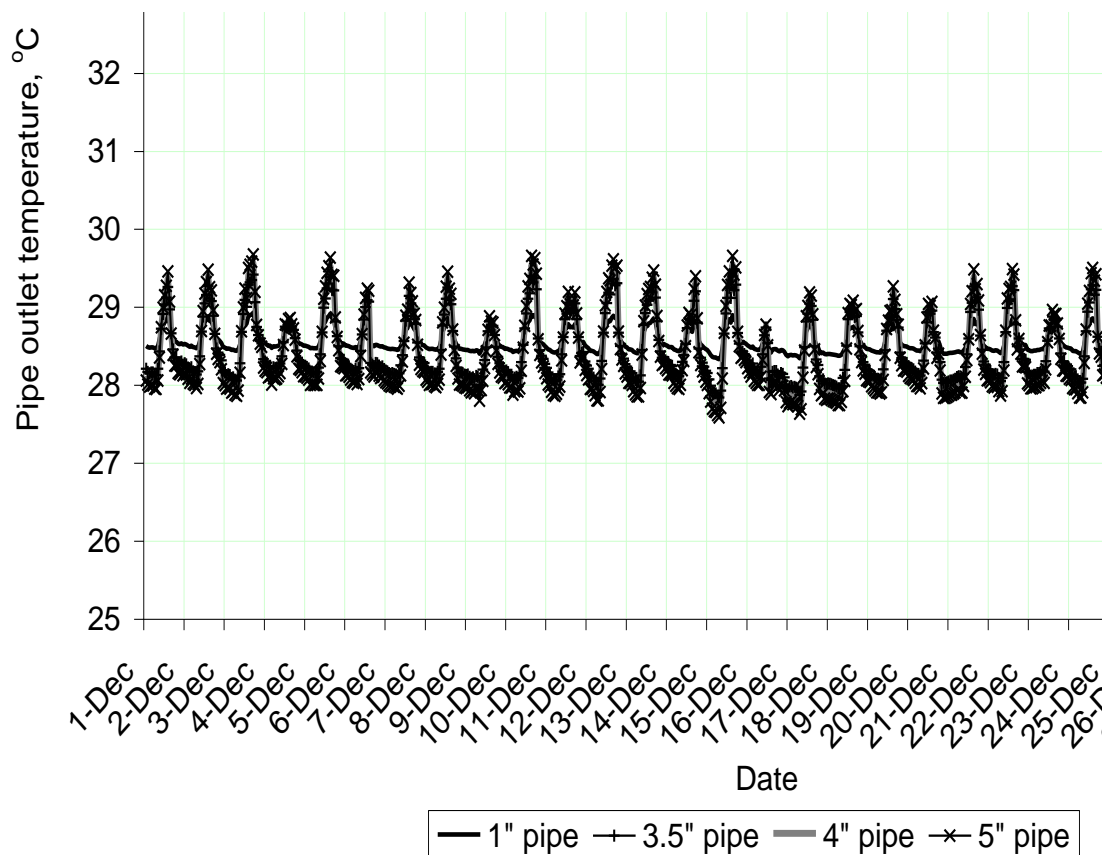


Figure 6.13: Parametric study with Energy Plus using four different pipe sizes.

Figure 6.13 shows that the increment of pipe diameter leads to an increase in pipe outlet temperature range. In 1" Polyethylene pipe, the pipe outlet temperature ranges from 28.3°C to 28.9°C. Its amplitude is only 0.30°C, which is almost the same as the amplitude of the soil temperature at the same depth; 0.35°C. In 5" Polyethylene pipe, the pipe outlet temperature ranges from 27.6°C to 29.7°C. The maximum outlet temperature is higher than that in 1" Polyethylene pipe. The graph has shown the Earth Pipe Cooling is more efficient when using a pipe with small size. The rationale behind this is when the pipe diameter is small, air in the center of the pipe gets closer to the surrounding soil, enables more efficient heat transfer and hence a closer temperature range to the surrounding soil temperature. Another obvious reason is the effect of the pipe thickness. Polyethylene pipes come in standard sizes with standard diameters and thicknesses. The smaller pipes have less thickness. Figure 6.13 shows that the thickness of the pipe reduces with the size of the pipe and 1" pipe are the thinnest pipe wall.

When the pipe wall is thin, the heat transfers between the air inside the buried pipe and the soil surrounding the pipe increases.

The third Energy Plus parametric study involves the effect of different air velocity of air and the airflow rate flowing within the buried Polyethylene pipe (Figure 6.14).

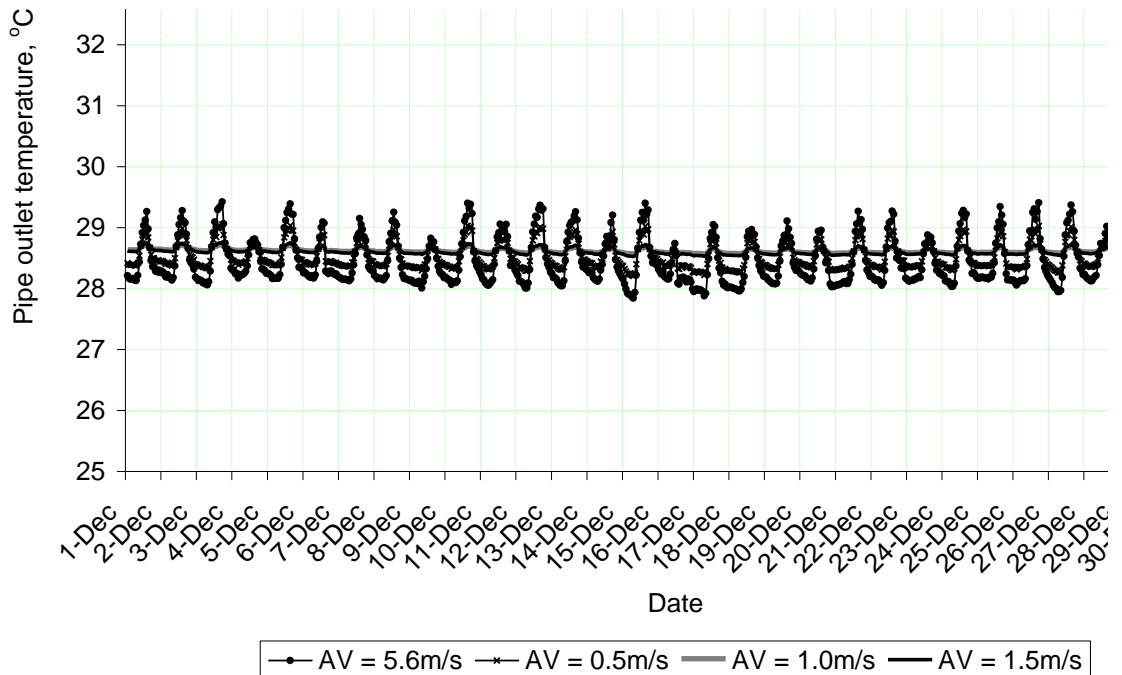


Figure 6.14: Parametric study with Energy Plus using four different air velocities (AV).

The air velocities selected for this study are 0.5m/s, 1.0m/s, 1.5m/s and 5.6m/s. The air velocity provided in the field work experiment is 5.6m/s.

When the air velocity is 0.5m/s, the pipe outlet temperature ranges from 28.2°C to 29.1°C. When the air velocity is increased to 1m/s, the pipe outlet temperature has smaller range with values from 28.6°C to 28.7°C. When the air velocity is increased to 1.5m/s, the pipe outlet temperature ranged from 28.5°C to 28.8°C. Therefore, the best air velocity is 1m/s or 1.5m/s with lower and higher velocities performing less well in this parametric study.

The fourth parametric study investigates Earth Pipe cooling system performance with various materials of buried pipe. This study looked at the materials PVC, Polyethylene, brick and clay (Figure 6.15).

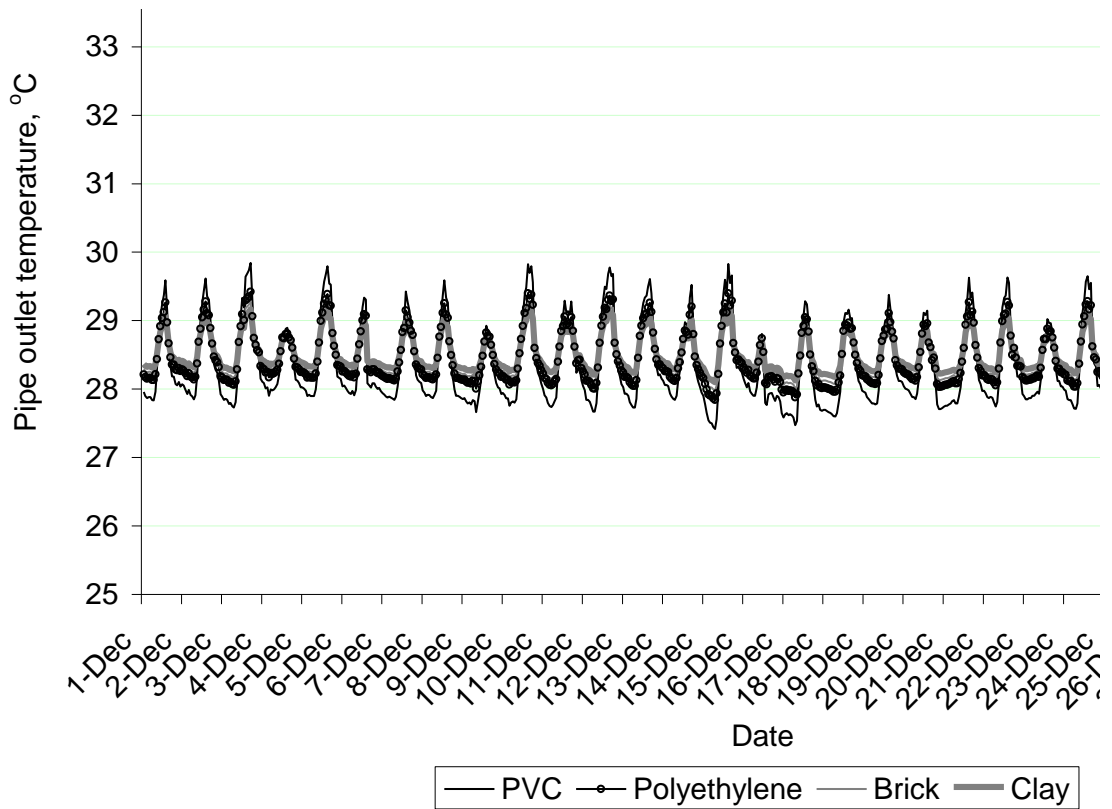


Figure 6.15: Parametric study with Energy Plus using four different materials with different thermal conductivity.

The Earth Pipe Cooling performance of different buried pipe materials relies on the thermal conductivity of the materials. Table 6.4 lists the thermal conductivities for PVC, Polyethylene, Brick and Clay.

Table 6.4: Thermal conductivities of various pipe materials.

Material	PVC	Polyethylene	Brick	Clay
Thermal Conductivity, W/mK	0.19	0.42	0.69	1.80

PVC pipe have the least thermal conductivity among the four materials used, which produce pipe outlet temperature that ranges from 27.4°C to 29.8°C. Figure 6.15

shows that the bigger the thermal conductivity is, the narrower the range of pipe outlet temperature becomes. Among the four pipe materials, clay pipes provides lower maximum outlet temperature, therefore clay is most efficient pipe material among the four pipe listed in Table 6.4.

According to all the above parametric studies, the variables that influence the performance of Earth Pipe Cooling significantly are the pipe length, radius, thickness and air velocity of the air flowing in the buried pipe; with the first being the most significant in impact. Soil temperature also influences the outcome temperature of Earth Pipe Cooling system significantly.

CHAPTER 7 THERMAL COMFORT AND ENERGY DISCUSSIONS

7.1 Thermal Comfort Performance

7.1.1 Malaysia Thermal Comfort Temperature Range in Naturally Ventilated Building

In Chapter 2, Table 2.8 listed a number of comfort range in naturally ventilated buildings in Malaysia and neighbouring countries, which have similar hot and humid climate to Malaysia. It has been stated that the neutral temperature, T_n ranges from 26.1°C to 28.9°C with an average T_n of 28.1°C. The comfort temperature ranges from 22.7°C to 31.6°C and the average upper limit of the thermal comfort temperature is 30.1°C.

This chapter analyzed data obtained for a whole year but excluding the month July and August, when the power cable to the fan blower was mysteriously cut off. In the one year investigation, one pipe design was selected to avoid data interference, which could happen if there were to be multiple earth pipe cooling system that functioned simultaneously. The system design chosen for an annual experiment was the 25m long Polyethylene pipe buried at 1.0m depth underground. The fan blower, which is connected to the buried pipe inlet and supplied air through the system at a constant air velocity of 5.6m/s, operated for 24 hours.

Table 5.7 in Chapter 5 has shown that the monthly minimum temperature produced at the buried pipe outlet ranges from 27.1°C to 29.0°C and the monthly maximum temperature at the pipe outlet ranges from 28.9°C to 30.9°C. Monthly average maximum outlet temperature is 29.9°C. Although the indoor temperature reaches beyond the studied thermal comfort zone for hot and humid building, the temperature range of air that comes out from the buried pipe outlet, falls within the studied thermal comfort zone for buildings in Malaysia at most times. Therefore, the result has shown at this stage of investigation that Earth Pipe Cooling system in buildings under Malaysia climate is most suitable for localized cooling for most efficient results.

7.1.2 Auliciems Thermal Comfort Range

Auliciems and Nicol (1981) produced an equation to find neutral temperature, T_n and comfort temperature range. Aynsley (1999) then used the equation to conduct a survey of post-occupancy response in buildings in South East Asia. The equation is described as follows.

$$T_n = 17.6 + 0.31 T_m \text{ } ^\circ\text{C}$$

(Equation 7.1)

Where T_m = the mean annual dry bulb temperature.

$$80\% \text{ acceptance comfortable Temperature range} = T_n \pm 3.5 \text{ } ^\circ\text{C}$$

(Equation 7.2)

Table 7.1 shows the monthly average dry bulb temperature within the year 2002 until 2008, which was obtained from Malaysia Meteorology Department.

Table 7.1: Monthly Average Dry Bulb Temperature from 2002 to 2008 (Malaysia Meteorology Department)

Month	Jan	Feb	March	April	May	June	July	Aug	Sep	Oct	Nov	Dec
Average DBT	27.3	27.7	28.0	27.6	28.4	28.0	27.7	27.9	27.6	27.2	26.8	27.0

Calculated from data in Table 7.1, the T_m is 27.6°C and that makes the neutral temperature T_n of Malaysia, which is predicted by Auliciems equation, to be 26.2°C . By considering 80% of occupant's acceptance, the comfort temperature range calculated with Equation 7.4 turns out to be from 22.7°C to 29.7°C .

Referring to the thermal comfort survey in naturally ventilated buildings in Table 2.8, the upper limit of thermal comfort range varies in every researchers findings and the average of the upper limit of thermal comfort range was found to be 30.1°C . This is 0.3°C higher than the upper limit of comfort temperature range calculated with Auliciem and Nicol equation.

Table 7.2 shows the temperature monthly temperature range at buried pipe outlet and inside the experiment shed. The maximum temperature at buried pipe outlet maintains within the comfort temperature range in the two months in the beginning of the year and in the four end months of the year. There are times in the four middle months; March, April, May and June that the buried pipe outlet temperature edges beyond the comfort temperature range. Note the effect of the air velocity is not taken into consideration here.

Table 7.2: The summary of Earth Pipe Cooling System performance with reference to temperature

Month	Jan	Feb	Mar	April	May	June	July	Aug	Sep	Oct	Nov	Dec
Pipe Outlet temperature, °C	27.1	26.9	27.4	28.9	29.0	28.7			28.1	28.5	28.1	27.7
	-	-	-	-	-	-	N/A	N/A	-	-	-	-
	28.9	29.0	31.0	30.7	30.9	30.5			29.5	29.5	29.7	29.1

In March, 62% of the total hours in the whole month, experienced temperature at buried pipe outlet beyond the comfort temperature range. 47% of the total hours in the whole month of April have temperature at the pipe outlet higher than the comfort temperature range. 59% of the total hours in the month May experience temperature at buried pipe outlet beyond the maximum comfort temperature calculated by the Equation 7.1. In June, 34% of the total hours in the whole month have temperature at buried pipe outlet higher than the calculated comfort temperature range. However, if the flow velocity is considered, they are mostly within comfort range, according to Khedari thermal comfort chart.

This analysis is only based on temperature without considering the effect of relative humidity and air velocity. In the next section, another analysis on the thermal comfort performance of Earth Pipe Cooling system in Malaysia, is carried out. This next analysis uses a comfort chart created by Khedari et al. (2000).

7.1.3 Khedari Thermal Comfort Chart

Khedari et al (2000) have produced a thermal comfort chart for predicting comfort of space in Thailand. Thailand being the neighboring country to Malaysia, have similar hot and humid climate and therefore, the same chart was used to analyze the thermal comfort performance of the Earth Pipe Cooling system with reference to the air temperature produced at the buried pipe outlet.

The Thailand thermal comfort chart, also known as ventilation comfort chart was developed using 183 male and 105 female college-age volunteers as the subjects. They were exposed to various thermal conditions and the purpose of investigation is to find the effect of air velocity on occupant's thermal comfort in naturally ventilated spaces. A commercial fan used to control the air velocity in the space with air velocity range from 0.2m/s to 3.0m/s. Khedari has used the the Predicted Mean Vote to determine the indoor neutral temperature. He has concluded that this developed chart could be used to design buildings in surrounding countries (Khedari et al., 2000).

Figure 7.1 shows the original thermal comfort chart. The x- and y-axis represent the dry bulb temperature and relative humidity respectively. The lines that cross the graph at various individual angles represent the limit of comfort zone according to different air velocity provided.

The comfort zone started with a triangular zone called Proposed Standard Zone (Figure 7.1). This Proposed Standard Zone is thermal comfort zone for occupants in air-conditioned space or building. For naturally ventilated buildings, the thermal comfort zone expands according to the provided air velocity.

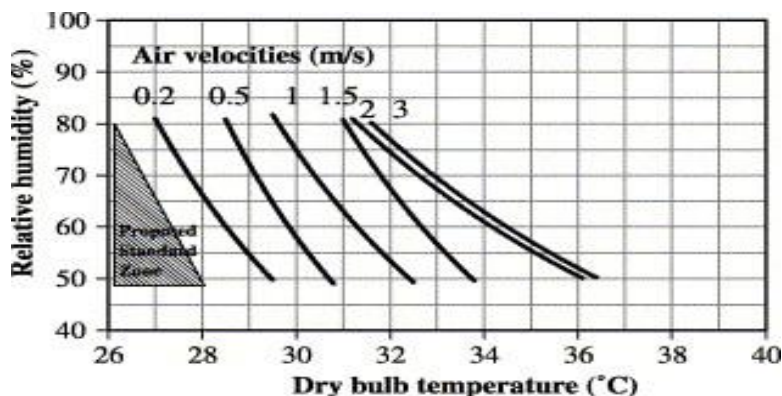


Figure 7.1: Thermal comfort chart by Khedari et al (2000).

Hourly data of the pipe outlet temperature from the Earth Pipe Cooling field investigation for each month are plotted into the Khedari thermal comfort chart to see if the buried pipe outlet temperature falls within the thermal comfort range for localized cooling from the buried pipe outlet. This analysis had to exclude the month July and August due to no valid data available for these two months.

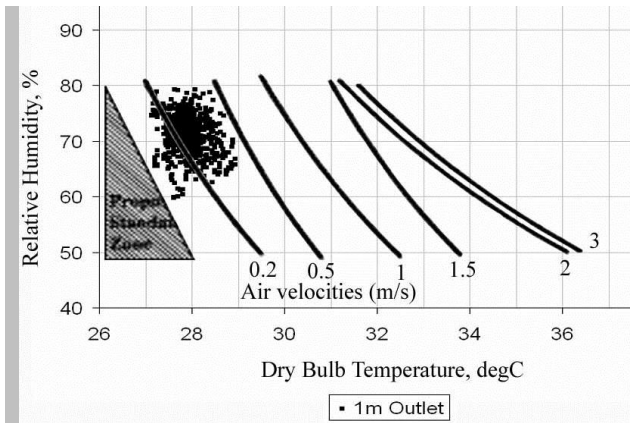


Figure 7.2: January hourly data plotted onto Khedari thermal comfort chart

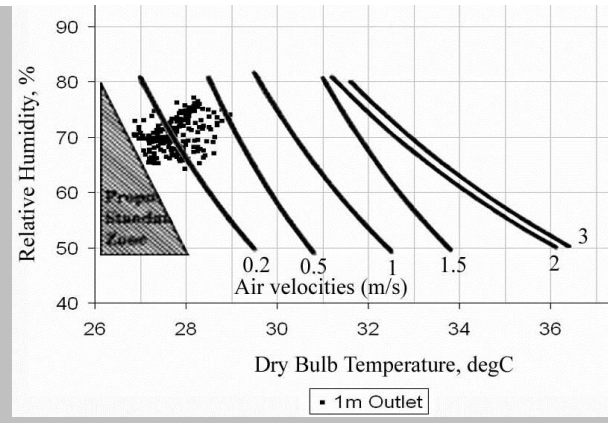


Figure 7.3: February hourly data plotted onto Khedari thermal comfort chart

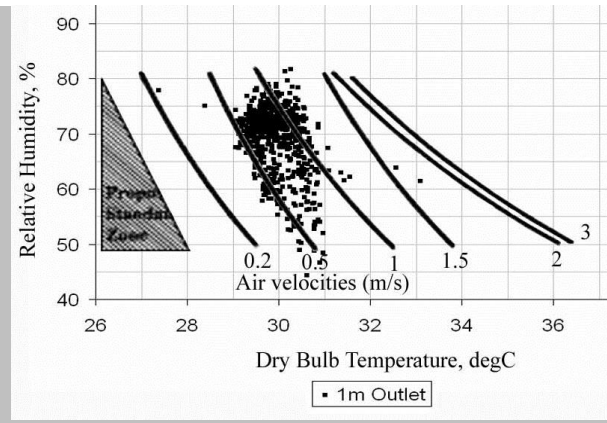


Figure 7.4: March hourly data plotted onto Khedari thermal comfort chart

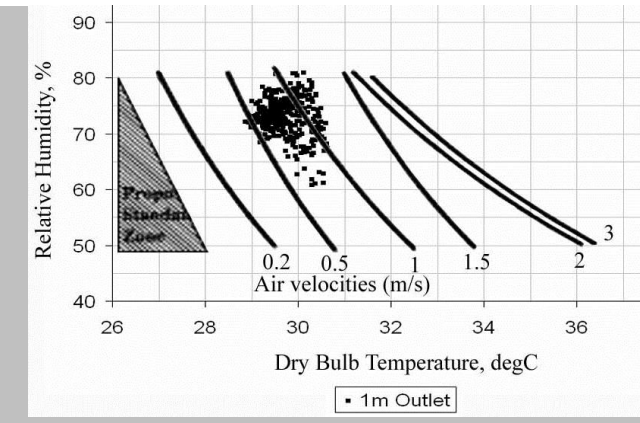


Figure 7.5: April hourly data plotted onto Khedari thermal comfort chart

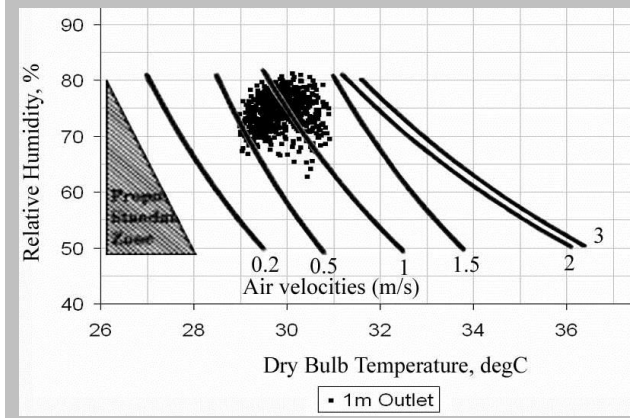


Figure 7.6: May hourly data plotted onto Khedari thermal comfort chart

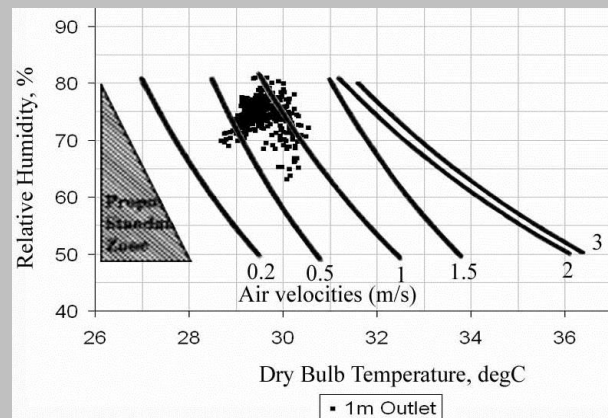


Figure 7.7: June hourly data plotted onto Khedari thermal comfort chart

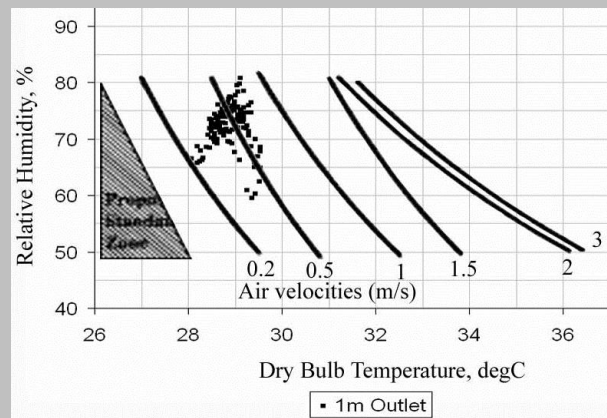


Figure 7.8: September hourly data plotted onto Khedari thermal comfort chart

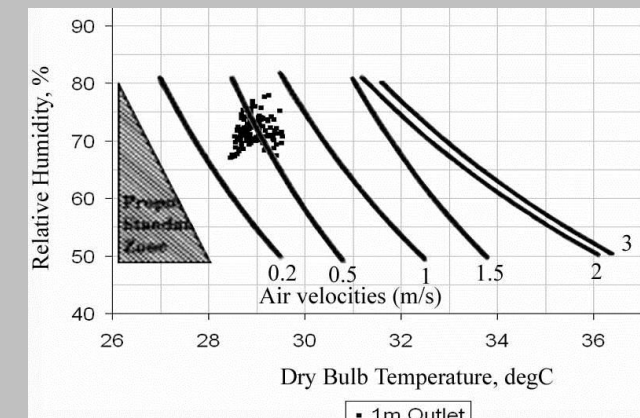


Figure 7.9: October hourly data plotted onto Khedari thermal comfort chart

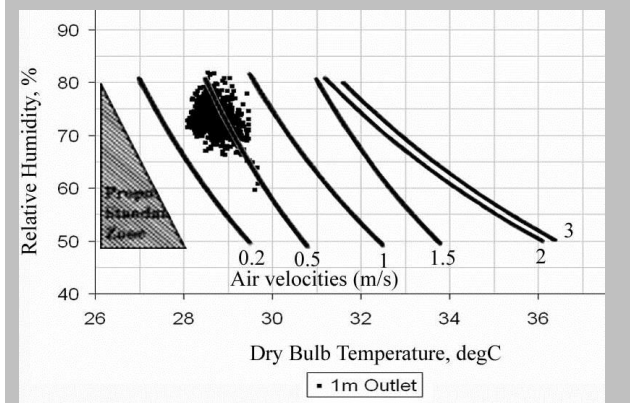


Figure 7.10: November hourly data plotted onto Khedari thermal comfort chart

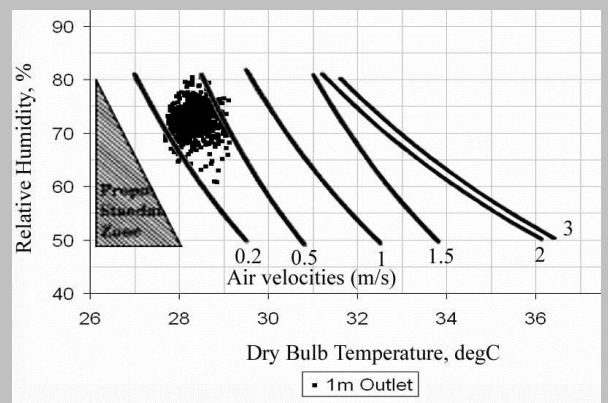


Figure 7.11: December hourly data plotted onto Khedari thermal comfort chart

a) *Beginning of the year; January and February*

In the beginning of the year, within the month January and February, the investigation of Earth Pipe Cooling system on the site produced data at the buried pipe outlet that falls within the thermal comfort zone., upon plotting them onto Khedari comfort chart, knowing the air velocity maintains at 5.6m/s. Figure 7.2 shows that in January the air that came out from the buried pipe outlet is comfortable throughout the day and can stay as comfortable even if the air velocity is reduced to 0.5m/s.

b) *Middle of the year; March, April, May and June*

Chapter 2 analyzed environmental data, which was obtained from Malaysia weather station and have stated that throughout the year 2002 until 2008, the highest absolute and mean daily maximum dry bulb temperature occurred in March, April and May. This makes the three months warmer than the rest of the year in an annual calendar. However, this section also includes graph of data recorded in June.

In these four months, the data plots in Khedari thermal comfort chart have been shifted to the right in comparison to data plots in January and February. This is because the buried pipe outlet temperature is above 30.0°C most of the time and therefore required the air velocity to be 1.5m/s to achieve thermal comfort. However, there are two plots in March that require the air velocity to be 2m/s but the extraordinary jump in temperature that has occurred only twice will be ignored as it might be an error in data recording.

Similar to March, the data plot in April shows that the air temperature at the buried pipe outlet falls within Khedari thermal comfort range (Figure 7.5). Almost half of the month, the air velocity needs to be 1.5m/s for the buried pipe outlet to produce comfortable cooled air.

Similar to data in April, the data of buried pipe outlet in May falls within Khedari comfort zone and the maximum air velocity required to achieve thermal comfort throughout the month is also 1.5m/s (Figure 7.6).

Figure 7.7 illustrates June data plots. Similar to April and May, the air temperature produced by the buried pipe outlet fall within Khedari thermal comfort range and the maximum air velocity required to maintain within the comfort zone is

1.5m/s, which according to Szokolay (2004) is draughty but not annoying. For warm and humid climate of Malaysia, draughty could be a pleasant sensation.

c) End of the year; September, October, November and December

In this season of the year, from analysis of the weather data obtained from Malaysia Meteorology Department, it was found that the last four months in a year usually experience the most rainfall particularly in October, November and December (Chapter 2).

Figure 7.8 shows the data in September. The data of the buried pipe outlet fall within the thermal comfort zone and required a maximum air velocity of 1m/s to achieve thermal comfort.

Similar to September, the data of buried pipe outlet in October falls within Khedari thermal comfort zone and the maximum air velocity required to achieve thermal comfort is also 1m/s (Figure 7.9).

Air temperatures at buried pipe outlet measured in November maintains below 30.0°C and most of the RH is below 80%. These data of buried pipe outlet falls within Khedari thermal comfort zone. Similar to September, the maximum required air velocity at the buried pipe outlet is 1m/s (Figure 7.10).

In December, the data plots have shifted slightly to the left showing a cooler air temperature at the buried pipe outlet (Figure 7.11). The data plots of buried pipe outlet fall within Khedari thermal comfort zone. Most of the time in December, the maximum air velocities required to achieve comfort is 0.5m/s and only a few times that the air velocity need to be 0.7m/s for the air coming out from the buried pipe outlet to be comfortable and cooling.

7.2 Energy Efficiency of Earth Pipe Cooling in Malaysia

As mentioned in Chapter 2, the Malaysian Standard guideline for Energy Efficiency building energy consumption is 140kWh/m²year (MEGTW, 2009) while a typical conventional building energy consumption is within the range of 200 and 300 kWh/m²year. In this research work, a fan blower called Turbo-Aire, which is a multi-speed centrifugal in-line fan, used to supply air through the buried pipe. Figure 7.12

shows the electric data of the range of available model types of Turbo-Aire and this research has chosen to use the model GCIL200.

Due to a small very small scale passive cooling investigation, the energy efficiency discussion will look upon the power requirement for a fan blower to provide a thermally comfortable pipe outlet temperature. This fan blower power is than compared with a typical room air-conditioning power and a typical domestic fan power

Among the three different speeds, the fan blower was set to high speed. At this speed, the motor power is 156 Watts. However, electrical readings of the fan blower were recorded on-site and the meter has shown that the average motor power from 6 readings is 119.4W (Table 7.3).

Model		Volt/ Phase/Hz	Motor Watts	Airflow CMH	Amps	RPM
GCIL 100	- High	240/1/50	67	260	0.22	2611
	- Medium		53	210	0.21	2341
	- Low		51	180	0.20	2095
GCIL 125	- High	240/1/50	69	345	0.28	2625
	- Medium		59	300	0.27	2322
	- Low		59	238	0.24	1952
GCIL 160	- High	240/1/50	63	465	0.27	2575
	- Medium		52	407	0.23	2263
	- Low		50	345	0.22	1932
GCIL 200	- High	240/1/50	156	960	0.67	2504
	- Medium		142	776	0.62	2108
	- Low		136	643	0.60	1730
GCIL 250	- High	240/1/50	176	1111	0.73	2450
	- Medium		158	900	0.66	2005
	- Low		149	600	0.63	1598
GCIL 315	- High	240/1/50	164	1500	0.71	2583
	- Medium		157	1150	0.67	2142
	- Low		148	955	0.63	1780

Figure 7.12: Electrical Data for different models of fan blower Turbo-Aire (Source: Turbo-Aire specification sheet)

Table 7.3: Electrical readings of the fan blower from a power meter, recorded in February. This fan blower provides air speed of 5.6m/s.

Time	Motor Watts			Volts	Hz	A
	High	Medium	Low			
Morning	124.5	120.5	113.4	243	50	0.512
Mid Day	124.5	120.7	113.4	245	50	0.514
Evening	124.5	119.8	113.4	243	50	0.510

The fan power of 119.4W has given an air velocity of 5.6m/s of air flowing through the buried pipe in the field investigation. The referred buried pipe is 25m long with 74mm diameter and 8.2mm thickness, buried at 1m deep below ground. From the analysis in Section 7.1, according to Khedari's comfort chart, the pipe outlet temperature in all months presented above falls within Khedari's thermal comfort zones with a maximum requirement of 1.5m/s air velocity. Some months requires only 0.5m/s and some only requires 1.0m/s. However, in determining the effective fan power for the fan blower that provides comfortable air at the pipe outlet, the required 1.5m/s air velocity were taken into consideration. Therefore, the air velocity can be reduced from 5.6m/s to 1.5m/s if the Earth Pipe Cooling is meant for localised cooling within personal space. The air velocity required is 3.73 times lower than provided.

The formula to calculate the effective fan power, P_{ef} is as follows (CIBSE Guide B):

$$P_{ef} = \frac{\Delta P_t qv}{\eta_o} \quad \text{(Equation 7.5)}$$

where P_{ef} = Effective fan power

ΔP_t = Pressure loss

qv = volume air flow (m^3/s)

η_o = efficiency

The pressure loss must be calculated first in order to obtain the effective fan power. The formula to calculate the pressure loss, ΔP_t of a turbulent air flow is as follows (CIBSE, Guide B):

$$\Delta P_t = f \frac{l}{D} \rho \underline{v}^2 \quad \text{(Equation 7.6)}$$

where f = constant

D = Diameter

l = pipe length

ρ = air density

v = air velocity

The air flow is classified as a turbulent flow from the calculation of the Reynolds number, Re :

$$Re = \frac{\rho v D}{\mu}$$

$$= \frac{1.2 \times 5.6 \times 0.074}{1.79 \times 10^{-5}}$$

$$= 27781$$

The current velocity v_1 of air flowing in the buried pipe is 5.6m/s. According to Khedari's thermal comfort chart, thermal comfort can be achieved at 0.5m/s, 1.0m/s or 1.5m/s depending on the weather conditions of specific months considered. The effective fan power, P_{ef1} , which is approximately 120W provides air velocity, v_1 5.6m/s. What would be the effective fan power, P_{ef2} , if the air velocity, is reduced to v_2 1.5m/s. To find this, first all variables in Equation 7.5 and 7.6 except for air velocity, v and diameter, D are considered as constant. Therefore, assuming f is a constant,

$$P_{ef} = \frac{f L \rho v^2}{D 2 \eta_o} qv$$

$$P_{ef} = \text{Constant} \times \frac{v^2}{D}$$

Assuming the flow rate remains the same,

$$P_{ef1} / P_{ef2} = (v_1/v_2)^2 (v_1/v_2)^{1/2}$$

Using the above, the effective fan power P_{ef2} is 26.9 times lower at 4.44W.

It is interesting to see in the parametric study using Energy Plus of different air velocity effect on the performance of Earth Pipe Cooling, 1.5m/s air velocity provides the best results among three other air velocities; 0.5m/s, 1m/s and 5.6m/s (Figure 6.14).

A set of electrical readings of an air-conditioner in a room located near the field work site was recorded. The air-conditioner was operating 24 hours and the temperature was set to 16°C. The room area is 40ft X 24ft. The voltage, current and Power are found to be constant throughout the day for three days. The voltage reads 235.4 V, the current is found to be 14.7 Ampere. The power of a typical air-conditioning measured in a room located near the field work site is 3.4kW. However, the power of the air-conditioning unit is not comparable to the required power for the Earth Pipe Cooling system fan

blower due to the difference in temperature and extent of cooling provided. The two rooms are not comparable also because the two rooms are very different.

CHAPTER 8 CONCLUSION

This last chapter summarises the research findings and conclusion of findings from literature, field investigation and computer simulation work. The final part of this chapter outlines potential future research on Low Energy Earth Pipe Cooling Technology for Malaysia.

8.1 Key Findings and Conclusions

This section of the chapter presents the key findings and conclusion as a product of the two field investigation, computer simulation work using Energy Plus and thermal comfort study. The four main objectives are to obtain soil temperature data at test site in Kuala Lumpur for various depths, to determine the optimum setup for buried pipe in Malaysia, to ascertain temperature reductions performance of buried pipes in Malaysia and to conduct computer simulation of the soil pipe. These four main objectives have been achieved which forms the foundation of the research findings.

8.1.1 Soil temperature investigation

Soil temperature is the main factor affecting the performance of Earth Pipe Cooling system. This research has taken that into account and managed to obtain soil temperature data of Kuala Lumpur for various depths up to 5m underground. This investigation answers questions related to the first two research objectives.

The first key finding is that soil temperature measured on the site in Kuala Lumpur is found to change little beyond the depth of 4m, which ranges from 29.3°C to 30.2°C). This finding agrees with research finding Goswami and Biseli in 1993 in Florida, which is mentioned in Chapter 3. However, this value is 2°C higher than the annual average air temperature of Kuala Lumpur, which is around 28°C. The soil temperature gets warmer as it gets deeper and nearer to the Earth core since the Earth core is the hottest part of the Earth. Beyond 4m depths, the soil temperature became stable and increases slowly as it gets deeper into the Earth core. This has been explained in chapter 3 with supporting illustrations in Figure 3.2, 3.3 and 3.4 (b).

At shallow depth above 1.5m underground, there is seasonal difference of 2°C, referring to soil temperature at 1m depth. This was found by comparing data collected in the wet season and the hot and dry season. The soil temperature amplitude increases

at the shallow depths of underground because of the environmental impact from cool ambient air temperature at night and warm ambient air temperature and solar radiation in daytime.

The seasonal different in soil temperature has led to another soil temperature investigation for one whole year at shallow depths. The annual soil temperature results confirmed the 2°C seasonal temperature differences at depth 0.5m, 1.0m and 1.5m.

1m depth underground is probably the optimum burial depth for Earth pipe Cooling system. Although the annual soil temperature fluctuates from 27.2°C to 30.5°C, the maximum temperature is similar to the maximum soil temperature at 4m depth, which is said to have a stable and constant soil temperature. However, the minimum soil temperature at 1m depth underground reduced down to 27.2°C. This reduction in soil temperature during the wet season was influenced by and benefits from the low ambient air temperature during the wet season.

Heat dissipated from the buried pipe to the soil could heat up the soil. This fact was investigated at 1m depth for three months, where one data logger was buried near the buried pipe and another one away from the buried pipe. There seem to be 0.4°C difference in temperature. Therefore, the heat dissipates from the buried pipe to the soil does not affect the soil temperature significantly in short term. Perhaps more significant results can be found in long term investigation.

8.1.2 Earth Pipe Cooling investigation

This part of conclusion provides answers to the third research objective. The results have shown significant temperature reductions at the buried pipe outlets from their inlets. At the initial stage of research one month of data was collected during the wet season, with assumption the set of data could represent the whole year performance of the Earth Pipe Cooling system. To confirm this, another investigation of Earth Pipe Cooling was carried out for one month in the hot and dry season. Both investigations measured Earth Pipe Cooling system buried at three depths underground; 0.5m, 1.0m and 1.5m.

During the wet season, maximum temperature drop through the buried pipe was found to be 6.4°C while during the hot and dry season the temperature drop was 6.9°C.

In both seasons, the maximum temperature drop occurred in the buried pipe at 1m depth underground.

The buried pipe outlet temperature during the hot and dry season was found higher than the pipe outlet temperature during the wet season. At depth 0.5m, 1.0m and 1.5m, the 25m long buried pipe outlet temperature range were 23.3°C – 28.4°C, 22.8°C – 29.5°C and 22.7°C – 28.6°C respectively during the wet season. Meanwhile, during the hot and dry season, the pipe outlet temperature at the same three depths ranges from 25.3°C – 30.6°C at 0.5m depth, from 24.7°C – 31.2°C at 1.0m depth, and from 23.7°C – 30.2°C at 1.5m depth.

Same as soil temperature investigation, the Earth Pipe Cooling Technology is investigated for one year duration due to seasonal differences. However, for a continuous annual run of investigation, only one buried pipe was used. The reason is to prevent interference between buried pipe outlet temperatures of the three buried pipes if they were to run simultaneously 24 hours for one year.

Because the maximum temperature drop occurred in 1m buried pipe in both the wet and hot and dry season, the pipe was chosen to be investigated further duration of one year. From the one year results, maximum temperature drop was found to be 8.6°C and this occurred in January. The annual average maximum temperature drop was found to be 5.7°C.

8.1.3 Validation of Energy Plus simulation tool

Due to limitations in field investigations, parametric study on the Earth Pipe Cooling Technology was explored using computer simulation programme. Initially, two programmes were explored in search for a suitable programme.

The same input data used in and obtained from field investigation were added to Energy Plus and Buried Pipe programme and sets of buried pipe outlet temperature were recorded. The results were then compared with field investigation data of the same data and input.

Referring to the comparative graph shown in Chapter 6, Energy Plus data agrees well with the field investigation with similar temperature range and amplitude. The maximum temperature difference between Energy Plus and field investigation data was 0.3°C. On the other hand, data from Buried Pipe shows less fluctuation of the buried

pipe outlet temperature with less amplitude compared to the field investigation data. The maximum difference between the two was 0.5°C. Therefore, between the two simulation tools, Energy Plus appears clearly to have agreed with the field investigation data compared to Buried Pipe. The research concludes Energy Plus to be a suitable simulation programme for further investigation.

Since the Energy Plus simulation tool has been validated and agrees well with the field work results, parametric study with extended value of variables were carried out using the simulation tool.

It was shown that the performance of the buried pipe increases with increasing pipe length. However, when the pipe length was set up beyond 50m, the buried pipe outlet temperatures remain the same, with no influence from the increasing pipe length.

The parametric study concerning effective pipe diameter shows that Earth Pipe Cooling system performs more temperature reduction within the buried pipe when using a smaller size pipe. Small pipe diameter enables more efficient heat transfer and hence closer temperature range to the surrounding soil temperature. The rationale behind this is when the pipe diameter is small, air in the centre of the pipe gets closer to the surrounding soil.

In terms of air flow, the best velocity is 1 m/s or 1.5m/s. When the air velocities are higher or lower than this range, the temperature reduction between the buried pipe inlet and outlet became less.

In conclusion, the parametric study with Energy Plus showed significant effect of pipe length, diameter and air velocity.

8.1.4 Thermal Comfort analysis

An extended analysis of the field investigation data was carried out in the form of evaluating the thermal comfort performance of the Low Energy Earth Pipe Cooling Technology. The evaluation was performed in three methods. First method is to compare the field work buried pipe outlet temperature with the Malaysia thermal comfort range for naturally ventilated building. Second method is to compare the field work data with thermal comfort temperature range obtained from Auliciems Thermal Comfort Equation. The third method is to plot the field work data on to Khedari's Thermal Comfort Chart.

The average monthly maximum temperature at the buried pipe outlet falls below the upper limit average of a collection of Malaysia thermal comfort ranges for naturally ventilated buildings, which were determined by previous researchers. The average monthly maximum temperature at the buried pipe outlet was 29.9°C, while the average maximum thermal comfort range found for naturally ventilated buildings in Malaysia was 30.1°C. However, looking at the outlet pipe temperature in each month, during the hot season; March, April, May and June, the maximum temperature were just beyond the thermal comfort range average limit. In the findings of thermal comfort range by previous researchers, the air velocity range varies and not all have recorded the related air velocity.

In comparison of the data obtained in field work with thermal comfort range obtained from Auliciem's thermal comfort range equation, in four months the buried pipe outlet temperature edges beyond the comfort temperature range. These four months are during the hot and dry season. The Auliciem's equation gave a thermal comfort range of 22.7°C to 29.7°C, which has lower maximum limit. However, this equation does not take into account the air velocity effect.

Since the air velocity effects were not taken into account systematically in the above thermal comfort range findings, this research used Khedari's Thailand Thermal Comfort Chart for evaluating the thermal comfort achievement of the buried pipe outlet temperature.

It was found that all buried pipe output measured at 1m depth pipe falls within Khedari thermal comfort zone when the air velocity is either 0.5m/s, 1.0m/s or 1.5m/s, depending on the weather conditions of specific months considered. The comfort chart has considered the dry bulb temperature, relative humidity and air velocity. Throughout the field experiment, the airflow at the buried pipe outlet has air velocity of 5.6m/s. Therefore, at the current experiment setup, the air blown at the buried pipe outlet should be comfortable for localized cooling. However, ambient temperature inside the shed that contained the pipe outlet had a higher temperature range. Therefore, at this stage, this shows that for Malaysia weather, the Earth Pipe Cooling are mostly suitable for localized cooling of personal space. However, this has shown potential for further investigation

From Khedari's thermal comfort chart, the outlet air temperature is comfortable at 1.5m/s air velocity. From the Energy Plus simulation data, the parametric study shows at the pipe outlet temperature is best at 1.0m/s or 1.5m/s rather than 0.5m/s and 5.6m/s. The effective fan power that provides 5.6m/s air velocity was 120W. The effective fan power that could provide 1.5m/s air velocity was found to be 4.5W. Therefore, the effective fan power required is 26.9 less than the effective fan power currently used to provide 5.6m/s.

In conclusions, the research findings support the research intention and established significant temperature reduction between the buried pipe inlet and outlet of the Earth Pipe Cooling system in Malaysia. Although some months edged slightly just below the upper thermal comfort range limit, the significant temperature reduction within the buried pipe can certainly help with solving the problem on escalating energy consumption in Malaysia.

8.2 Potential Future Research

As the research developed, a number of issues were recognized as having potential for further investigation in the future. Even though the research findings have fulfilled the research objectives, the application of Earth Pipe Cooling Technology have the potential to be developed further in Malaysia or other hot and humid countries. By investigating the technology further, designers would understand more about the potential of soil being the heat sink. Some of the issues are:

- The field investigation findings show similarity in average between the buried pipe outlet temperature and the relative soil temperature at most times. This demonstrates the high influence of soil temperature on the performance of Earth Pipe Cooling Technology. This suggests the treatment of the soil, having it shaded from the daytime solar radiation with either plantation or lightweight structure. According to a study by Givoni, as mentioned in Chapter 3, shaded soil has lower average temperature. Since the soil temperature affect the pipe outlet temperature, a lower soil temperature could reduce the pipe outlet temperature even more than recorded in this research finding.
- The Earth Pipe Cooling system can be coupled with Solar Photovoltaic (PV) Panels and form a hybrid sustainable technology. The fan could be connected to

Solar PV Panels in such a way and benefit from the energy collected by the Solar PV Panels from the sun. If this is applied at the same current site, it would save the trouble of finding power supply in the middle of the field. It also saves the investigation from being interrupted by having its power cable across the road being cut off.

- The current Earth Pipe Cooling should be repeated in a better insulated experiment shed. At the current field site, the experiment shed was constructed as a very basic timber structure with minimal insulation due to funding limit and time constraint. By having a better insulated shed, the effect of Earth Pipe Cooling system towards the room ambient temperature can be investigated along with a thermal comfort study of the room.
- Extending Energy+ modelling work by investigating the effects of different room designs coupled with the Earth Pipe Cooling system. The room design is to be tested in its form, size, materiality and construction.

APPENDIX

Appendix 4.1: Specification of USB TC-08 Thermocouple Data Logger

USB TC-08 Thermocouple Data Logger General Specifications	
Number of channels (per TC-08)	8
Maximum number of channels (using multiple TC-08s)	160
Conversion time	100 ms (thermocouple and cold junction compensation)
Temperature accuracy	Sum of $\pm 0.2\%$ of reading and $\pm 0.5\text{ }^{\circ}\text{C}$
Voltage accuracy	Sum of $\pm 0.2\%$ of reading and $\pm 10\text{ }\mu\text{V}$
Overload protection	$\pm 30\text{ V}$
Maximum common mode voltage	$\pm 7.5\text{ V}$
Input impedance	2 M Ω
Input range (voltage)	$\pm 70\text{ mV}$
Resolution	20 bits
Noise free resolution	16.25 bits
Thermocouple types supported	B, E, J, K, N, R, S, T
Input connectors	Miniature thermocouple

Appendix 4.2: Specification of HOBO Pendant Temperature Data Logger UA-001-64

Channels	One Internal Temperature Sensor
Data Storage Capacity	UA-001-08: Approximately 6,500 Readings/Samples UA-001-64: Approximately 52,000 Readings/Samples
Sampling Intervals	User-selectable, 1 second to 18 hours
Alarms	High and low alarm-indication LEDs with user settable levels and delay options
Temperature Range	<u>In Air</u> : -20°C to 70°C (-4°F to 158°F) <u>In Water</u> : 0°C to 50°C (32°F to 122°F)
Accuracy	0.47°C (0.85°F) at 25°C (77°F)
Resolution	0.10°C (0.18°F) at 25°C (77°F)
Response Time	<u>In Airflow of 1 m/s</u> : 10 minutes, typical to 90% <u>In Water</u> : 5 minutes, typical to 90%
Operating Range	<u>In Water/Ice</u> : -20°C to 50°C (-4°F to 122°F) <u>In Air</u> : -20°C to 70°C (-4°F to 158°F)
Time Accuracy	± 1 minute per month at 25°C (77°F)
Water Depth Rating	30 m from -20° to 20°C (100 ft from -4° to 68°F)
Battery	User Replaceable CR2032 Type Lithium Battery
Battery Life	1 Year Typical Use
Standards Compliance	CE
Dimensions	58mm x 33mm x 23 mm (2.3" x 1.3" x 0.9")

Measurement range:

Temperature: -20° to 70°C (-4° to 158°F)

RH: 5% to 95% RH

Light intensity: 1 to 3000 footcandles (lumens/ft²) typical; maximum value varies from 1500 to 4500 footcandles (lumens/ft²)

Analog channels:

0 to 2.5 Vdc (w/[CABLE-2.5-STEREO](#)); 0 to 5 Vdc (w/[CABLE-ADAP5](#)); 0 to 10 Vdc (w/[CABLE-ADAP10](#)); 4-20 mA (w/[CABLE-4-20MA](#))

Accuracy:

Temperature: ± 0.35°C from 0° to 50°C (± 0.63°F from 32° to 122°F), see Plot A

RH: ±2.5% from 10% to 90% RH (typical), to a maximum of ±3.5%, see Plot B

Light intensity: Designed for indoor measurement of relative light levels, see Plot D for light wavelength response

External input channel (see sensor manual): ± 2 mV ± 2.5% of absolute reading

Resolution:

Temperature: 0.03°C at 25°C (0.05°F at 77°F), see Plot A

RH: 0.03% RH

Sample Rate:

1 second to 18 hours, user selectable

Drift:

Temperature: 0.1°C/year (0.2°F/year)

RH: <1% per year typical; RH hysteresis 1%

Response time in airflow of 1 m/s (2.2 mph):

Temperature: 6 minutes, typical to 90%

RH: 1 minute, typical to 90%

Time accuracy: ± 1 minute per month at 25°C (77°F), see Plot C

Operating temperature:

Logging: -20° to 70°C (-4° to 158°F)

Launch/readout: 0° to 50°C (32° to 122°F), per USB specification

Battery life: 1 year typical use

Memory: 64K bytes (43,000 12-bit measurements)

Weight: 46 g (1.6 oz)

Dimensions: 58 x 74 x 22 mm (2.3 x 2.9 x 0.9 inches)

Appendix 6.1: Data obtained in March from field work and Energy Plus.

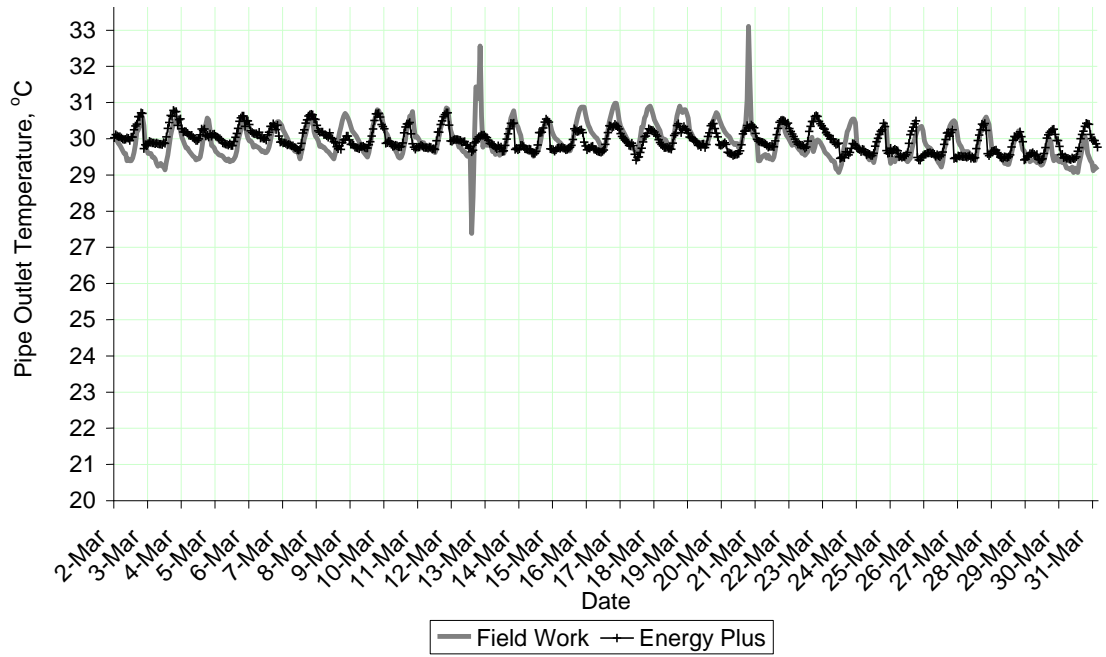


Figure Appendix 6.1: Data obtained in March from field work and Energy Plus

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