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Investigation of pipe materials and thermal conductivity of soil on the performance of ground heat exchanger operating under Malaysia climate

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Investigation of pipe materials and thermal conductivity of soil on the performance of ground heat exchanger operating under Malaysia climate

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Abstract. In nature, renewable energy is inherently free and must be implemented. The use of air conditioning and refrigerants that affect global warming is a serious issue. In building applications, renewable energy from the geothermal source, namely ground heat exchanger (GHE), has great potential. The main concept of GHE is utilizing the ground as an infinite thermal reservoir for cooling and heating to the fluid medium. In the GHE system, the air is used as a fluid medium of work. Because of the temperature difference between the air and underground temperature, the air cools in summer and gets heated in winter. In this present work, a study has been conducted to investigate the effect of pipe materials and thermal conductivity of soil on the performance of the GHE. The study acknowledges that the pipe materials do not give a significant effect on the performance of the GHE. Therefore, the lower thermal conductivity of pipe materials with low cost can be used in GHE implementation. The study also revealed that the range of thermal conductivity of soil which gives good ground heat exchanger performance is between 1.5 to 5 W/m·K. Besides, the length of the pipe was reduced from 25 to 10 meters.

Keyword: Ground Heat Exchanger, Earth to Air Heat Exchanger, GHE Performance.

1. Introduction

Geothermal technologies can result in significant energy savings, mainly related to building heating and cooling [1]. In ancient times, the idea of using the earth as a heat sink was well known. In about 3000 B.C., Iranian architects were used passive cooling through wind towers and underground tunnels [2, 3]. In the 20th century, air conditioning is widely used in tropical climates, not only for industrial production, but also for the comfort of humans. It can be efficiently achieved with vapor compression refrigerant machines. However, the accumulation of chlorofluorocarbons (CFCs) in the atmosphere released by the vapor compression refrigerant machines has reduced the ozone layer. Consequently, the world needs for reduction in the use of vapor compression refrigerant machines. The ground heat exchanger is one such suggestion that can support the reduction of the use of vapor compression refrigerant machines as shown in Figure 1. GHE is used for years in developed countries because of their higher energy efficiency than conventional heat and cooling systems. Their heat exchangers have been a common feature of the system. The use of ground-based heat exchangers is known to lead to an efficient, economical and environmentally friendly design [4]. GHE uses soil as a heat sink and air as the medium of heat transfer for the summer cooling space. When the warm air flows through the GHE pipe, heat passes from the air to the earth. As a result, at the exit of the GHE pipe, the air temperature is much lower than the ambient temperature [5]. GHE is a passive climate control technology that uses the underground soil temperature at a depth of around 2.5 to 3 meters in residential and farm buildings [3]. Previous studies have shown that GHE systems have excellent cooling and heating potential [6]. A study conducted by Gao, Li, Xu, Gang and Yan [7] showed that the use of the GHE system is an excellent solution to meet the Zero Energy Buildings (ZEB) target.

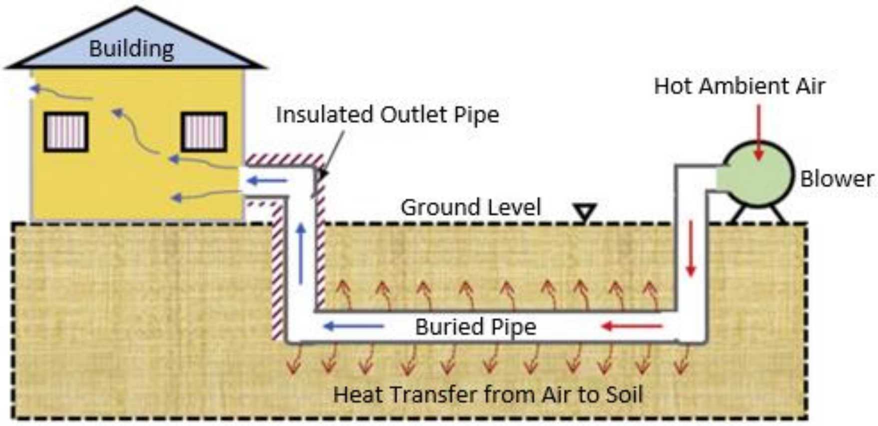

Figure 1. GHE system used for summer cooling [8].

Several researchers, such as Sodha, Sharma, Singh, Bansal and Kumar [9], have studied the use of the earth as a heat source and sink. At one of the hospitals in India, they tested a large GHE system intended to provide thermal comfort inside the entire building complex. A parametric model in which different parameters were length of pipe, radius of pipe, air velocity inside the tube and the depth of the buried pipe under the surface of the earth was presented by Mihalakakou, Santamouris, Asimakopoulos and Tselepidaki [10]. The effect of various ground surface boundary conditions on the efficiency of a single and multiple parallel earth to air heat exchanger system was investigated by Mihalakakou, Santamouris, Lewis and Asimakopoulos [11]. The conservation potential of an earth air pipe system coupled with a building without air conditioning was evaluated by Kumar, Ramesh and Kaushik [12]. A thermal model was developed by Ghosal, Tiwari, Das and Pandey [13] to investigate the performance of earth to air heat exchanger (EAHE) which is integrated with green house. The cooling capacity of the earth to air heat exchangers for domestic buildings in a desert climate was studied by Al-Ajmi, Loveday and Hanby [14]. A ground heat exchanger model based on the numerical transient bi-dimensional approach was developed by Badescu [15]. In order to evaluate the effects of the operating parameters for example the length of pipe, pipe radius, depth of ground and air flowrate on the thermal performance and air-pipe cooling capacities, Wu, Wang and Zhu [5] developed a transient and implicit model. The model based on numerical heat transfer and computational fluid dynamics and then implemented it on the CFD (computational fluid dynamics) platform, PHOENICS. A one-dimensional transient analytical model was proposed Cucumo, Cucumo, Montoro and Vulcano [16] to estimate the performance of earth to air heat exchangers, installed at different depths, used for cooling/heating buildings. Finite element numerical model for the simulation of the ground Cui, Yang and Fang [17] have developed a finite element numerical model for the simulation of ground heat exchangers in alternative modes of operation over a short period of time for ground-coupled heat pump applications.

From literature that have been done by the author, it has been found that the range of study for thermal conductivity of soil for the GHE implementation is not comprehensively covered. Since the thermal conductivity of soil and pipe materials have related to each other on the performance of the GHE. Therefore, in the present study, the effect of thermal conductivity of soil and pipe materials on the performance of the GHE will be investigated using simulation analysis. The performance analysis of the

GHE is simulated for cooling during summer only. There are five different types of pipe materials have been used in this study namely PVC, HDPE, stainless steel, aluminium, and copper with different thermal conductivity from low to high thermal conductivity. Meanwhile, the soil thermal conductivity was 0.5, 1.5, 2.5, 5.0 and 10 W/m.K.

2. Methodology

Simulation of GHE system is an interesting approach to predict and analyse the performance of the GHE based on available information and input parameters. It requires less time to analyse the performance of the system, repeatable analysis and running at various input settings. In the present work, the simulation uses the Excel software to obtain the temperature of the GHE system. Basically, the performance of GHE strongly depends on the thermal characteristics of the heat exchanger. The effect of pipe materials and soil thermal conductivity on GHE performance is analysed in the simulation. Figure 2 shows the flow chart of the methodology.

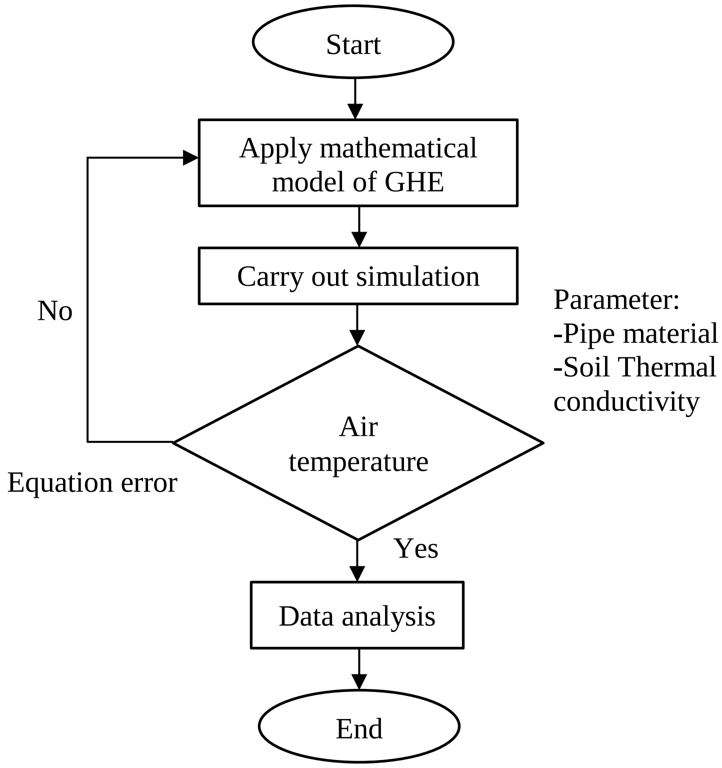

Figure 2. Flow chart.

Based on the schematic diagram in Figure 3 [18], the mathematical model of heat transfer from the air inside the GHE pipe to the surrounding ground can be analysed. The figure shows the ambient temperature of air (T_{air}) that enters the pipe. At a constant ground temperature ($T_{z,t}$), heat will be transferred to the surrounding ground as the air flows inside the pipe. In this case, several assumptions have been made that i) the heat capacity rate of the ground surrounding is infinity, or treated as a thermal reservoir, ii) the presence of a pipe in the area around the pipe does not affect the temperature profile. Therefore, the temperature in the surface is consistent in y direction, iii) the pipe has a uniform cross sectional area, iv) the air convection flow in the pipe develops hydrodynamic and thermally, and v) thermal properties of the ground around the pipe is homogeneous and its thermal conductivity has a constant value [19, 20].

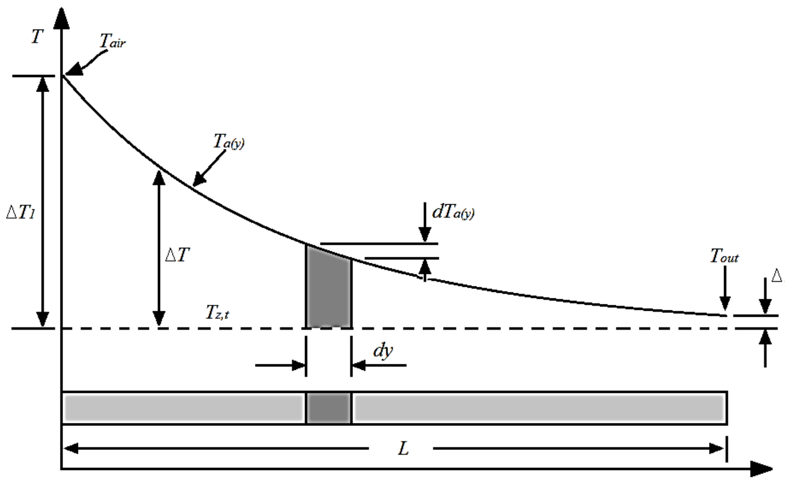

Figure 3. Schematic of heat transfer process in GHE pipe.

The hot ambient air at T_{air} enters the pipe, which will decrease at $T_{a(y)}$ with the distance of the pipe from the inlet (y) increases. At T_{out}, the hot air leaves the pipe which is slightly above ground temperature, $T_{z,t}$. Therefore, the heat transfer rate received by the ground for arbitrary length in the differential section of dy shall be expressed by Equation 1.

$$dQ = U\pi D\left[T_{air(y)} - T_{z,t}\right]dy \tag{1}$$

On the other side of the heat transfer, the heat rate transmitted by the air inside the pipe in the differential section of the dy is shown in Equation 2 [21];

$$dQ = -\dot{m}_{air}c_p\left[dT_{air(y)}\right] \tag{2}$$

The temperature change of the air is a negative quantity, which decrease the temperature as the pipe length increases and a negative sign therefore added to Equation 2, which result in positive heat transfer rate. In theory, the heat transfer within the pipe between the earth and the air is equal to the heat loss as the air flows along the pipe. Therefore, Equation 1 and Equation 2 are then equated to yield Equation 3 as follow.

$$U\pi D\left[T_{air(y)} - T_{z,t}\right]dy = -\dot{m}_{air}c_p\left[dT_{air(y)}\right] \tag{3}$$

Rearranging Equation 3 in order to solve for $T_{a(y)}$ yields;

$$\frac{dT_{air(y)}}{T_{air(y)} - T_{z,t}} = -\frac{U\pi D}{\dot{m}_{air}c_p}dy \tag{4}$$

By integrating both sides of Equation 4, for $T_{air(y)}$ from $T_{air(y)}$,0 to $T_{air(y),L}$ and for y from 0 to L. Hence;

$$\int_{T_{air(y)}=T_{air(y),0}}^{T_{air(y),L}} \frac{1}{T_{air(y)} - T_{z,t}}dT_{air(y)} = -\frac{U\pi D}{\dot{m}_{air}c_p}\int_{y=0}^{L} dy$$

$$ln\frac{T_{air(y),L} - T_{z,t}}{T_{air(y),0} - T_{z,t}} = -\frac{U\pi Dy}{\dot{m}_{air}c_p}\bigg|_{y=0}^{y=L}$$

$$T_{air(y),L} - T_{z,t} = \left(T_{air(y),0} - T_{z,t}\right)\left(e^{-UA_{sur}/\dot{m}_{air}c_p}\right)$$

$$T_{air(y),L} = T_{z,t} + \left(T_{air(y),0} - T_{z,t}\right)\left(e^{-UA_{sur}/\dot{m}_{air}c_p}\right) \tag{5}$$

Therefore, Equation 5 can be written as Equation 6 for $y = L$.

$$T_{air.out} = T_{z,t} + \left(T_{air.in} - T_{z,t}\right)\left(e^{-UA_{sur}/\dot{m}_{air}c_p}\right) \tag{6}$$

where T_{air} out is the outlet air temperature, $T_{z,t}$ is the ground temperature at depth z and time t, T_{air} in is the inlet air temperature, U is the overall heat transfer coefficient, y is the length of the pipe, $\dot{m}$ is the mass flowrate and c_p is specific heat of air. By definition;

$$NTU = \frac{UA_{sur}}{\dot{m}_{air}c_p} \tag{7}$$

Therefore Equation 6 can be written as a function of NTU as shown below;

$$T_{air.out} = T_{z,t} + \left(T_{air.in} - T_{z,t}\right)e^{-NTU} \tag{8}$$

Table 1 shows the physical and thermal parameters used in the simulation to investigate the effect of pipe materials and thermal conductivity of soil on the GHE performance. There are five pipe materials with different thermal conductivity which are polyvinyl chloride (PVC), high-density polyethylene (HDPE), stainless steel, aluminium and copper were considered in this simulation. Meanwhile, five different of thermal conductivity of soil that has been used in this simulation that is 0.5, 1.5, 2.5, 5 and 10 W/m·K for each pipe materials. Table 2 tabulates conditions of all the pipe materials and its surrounding for the input of the simulation. Simulation is conducted based on same pipe diameters for all pipe materials with 25 m length. Besides, the velocity of air, flowrate, ground temperature and air inlet temperature also set to be constant in this simulation. The thermal conductivity value of the ground is considered as homogenous [22, 23].

Table 1. Physical and thermal parameters used in simulation.

Materials	Thermal conductivity of pipe, k_p (W/m·K)	Thermal conductivity of soil, k_s (W/m·K)
PVC	0.18	0.5, 1.5, 2.5, 5.0 and 10
HDPE	0.47	0.5, 1.5, 2.5, 5.0 and 10
Stainless steel	13	0.5, 1.5, 2.5, 5.0 and 10
Pure aluminium	220	0.5, 1.5, 2.5, 5.0 and 10
Pure copper	386	0.5, 1.5, 2.5, 5.0 and 10

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Table 2. Conditions of pipe and its surrounding for the input of the simulation.

Input name	Value	Units
Outer diameter of pipe, OD	100	mm
Inner diameter, ID	101.8	mm
Pipe length, L	25	m/s
Velocity of air, V	10.73	m/s
Flowrate, ṁ	0.1	kg/s
Thermal diffusivity, α	0.046	m^2/day
Ground temperature, $T_{z,t}$	24	°C
Air inlet temperature, $T_{air.in}$	35	°C

3. Results and discussion

Analysis of the output air temperature has been conducted for all the pipe materials and five different soil thermal conductivity. In this analysis, there is two parameters variation which are pipe materials and soil thermal conductivity while, other parameters are fixed. The aim of this analysis is to investigate the effect of pipe materials and soil thermal conductivity on the performance of GHE. The output air temperature has been recorded for all pipe materials with five different soil thermal conductivity. Table 3 shows the output air temperature of the GHE for PVC pipe and five different soil thermal conductivity. The data was recorded from 0 to 25 m length of pipe with an increment of 1 m. Meanwhile, other materials of pipe are HDPE, stainless steel, aluminium, and copper were analysed the same as PVC pipe materials.

Data from the analysis for all the pipe materials have been manipulated in the form of graphs as shown in Figure 4 which represents pipe length against air temperature for five different soil thermal conductivity. From the graph, the same trend has been obtained throughout length against air temperature for all pipe materials. However, their air temperature is different for all pipe materials at the same thermal conductivity of soil. This is due to all pipe materials namely PVC, HDPE, stainless steel, aluminium and copper has different thermal conductivity which are 0.18, 0.47, 13, 220 and 386 W/m.K respectively. Regarding the thermal conductivity of soils, the variation of air temperature decreased along the length of pipe from 0 to 25 m as the thermal conductivity of soil increased for all pipe materials. The thermal conductivity of soil range from 0.5 to 1.5 W/m.K has a significant effect on the air temperature drop along the length of pipe for all pipe materials. In the meantime, the thermal conductivity of soil from range 1.5 to 10 W/m.K has no significant effect on the air temperature drop along the length of pipe for all the pipe materials as shown in Figure 4. Therefore, it can be concluded that the good range of soil thermal conductivity was between 1.5 to 10 W/m.K.

Table 3. Simulation data of GHE temperature output for PVC pipe with five different of soil thermal conductivity PVC.

Pipe length, L	**Thermal conductivity of soil, k_s**				
	0.5	1.5	2.5	5	10
	T_{out}, °C	T_{out}, °C	T_{out}, °C	T_{out}, °C	T_{out}, °C
0	35.00	35.00	35.00	35.00	35.00
1	32.90	32.04	31.77	31.54	31.41
2	31.21	29.88	29.49	29.17	29.00
3	29.84	28.29	27.88	27.55	27.37
4	28.72	27.14	26.74	26.43	26.27
5	27.82	26.29	25.94	25.67	25.53
6	27.10	25.68	25.37	25.14	25.03
7	26.51	25.23	24.97	24.78	24.69
8	26.03	24.90	24.68	24.54	24.47
9	25.64	24.65	24.48	24.37	24.32
10	25.33	24.48	24.34	24.25	24.21
11	25.08	24.35	24.24	24.17	24.14
12	24.87	24.26	24.17	24.12	24.10
13	24.71	24.19	24.12	24.08	24.07
14	24.57	24.14	24.09	24.06	24.04
15	24.46	24.10	24.06	24.04	24.03
16	24.37	24.07	24.04	24.03	24.02
17	24.30	24.05	24.03	24.02	24.01
18	24.25	24.04	24.02	24.01	24.01
19	24.20	24.03	24.02	24.01	24.01
20	24.16	24.02	24.01	24.01	24.00
22	24.11	24.01	24.01	24.00	24.00
25	24.06	24.00	24.00	24.00	24.00

Figure 5 shows a graph of the pipe length against air temperature for all pipe materials at constants thermal conductivity which is 10 W/m·K. By referring the Figure 4, HDPE pipe materials give a more significant effect compared with PVC pipe materials while, stainless steel, aluminium and copper pipe materials give a larger effect to the performance of GHE system compared with HDPE and PVC pipe materials. This variation happened due to the different of thermal conductivity of pipe materials. However, stainless steel, aluminium and copper pipe materials give almost the same performance as shown in Figure 5 even the copper pipe materials have the highest thermal conductivity compared with stainless steel and aluminium pipe materials. Therefore, this analysis can be concluded that the pipe materials does not give a significant effect on the performance of GHE system which similar with previous studies [24, 25]. The low-cost pipe materials with low thermal conductivity can be used in GHE system instead of high-cost pipe materials with high thermal conductivity. In addition, the drop of air temperature remains consistent at a range of pipe length between 10 m to 25 m for PVC pipe. Hence, the length of pipe that can be used was 10 m instead of 25 m. It can be reducing the space of pipe installation and at the same the cost of installation also can be reduced.

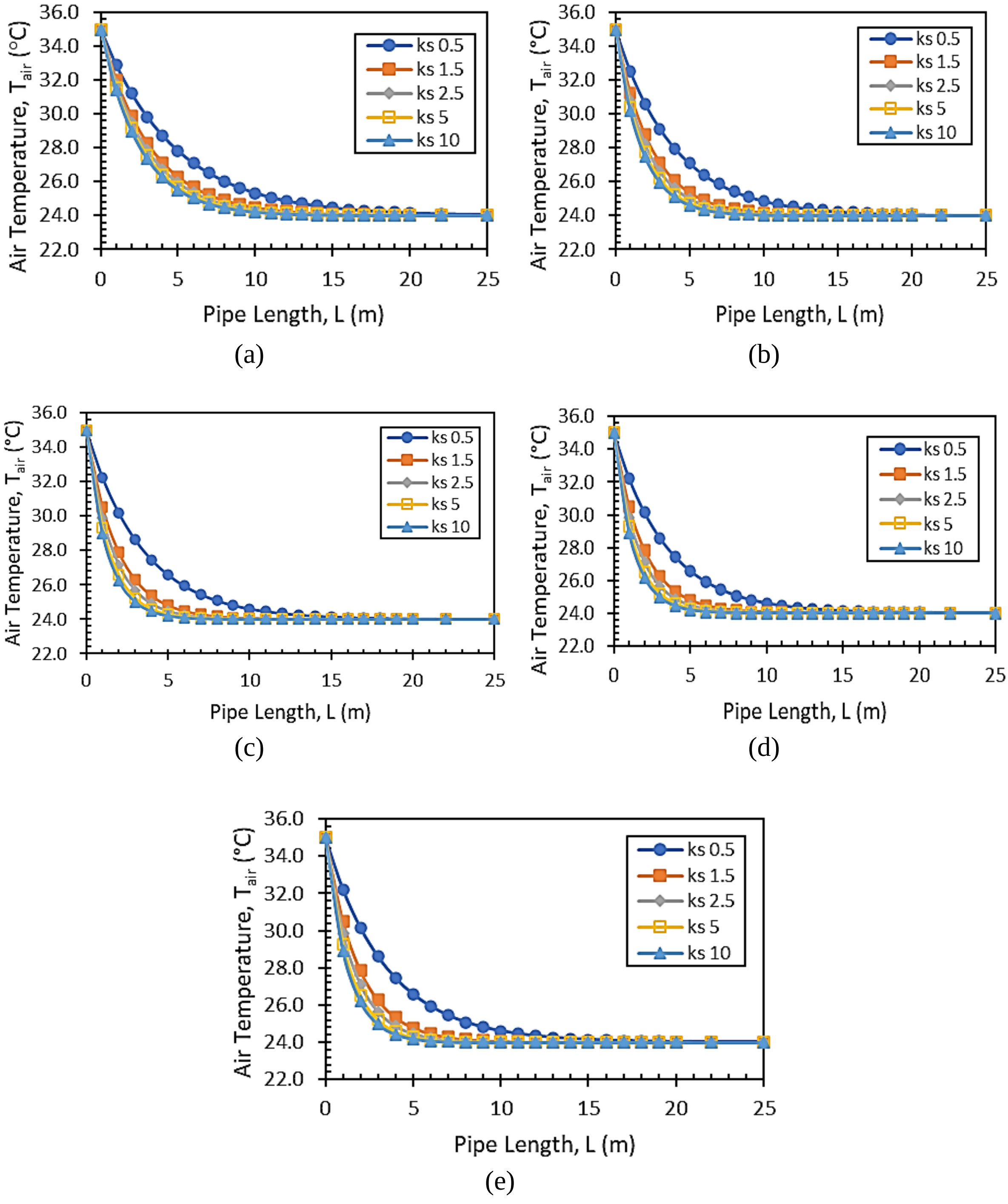

Figure 4. Pipe length against air temperature for five different of soil thermal conductivity (a) PVC, (b) HDPE, (c) Stainless steel, (d) Aluminium and (e) Copper.

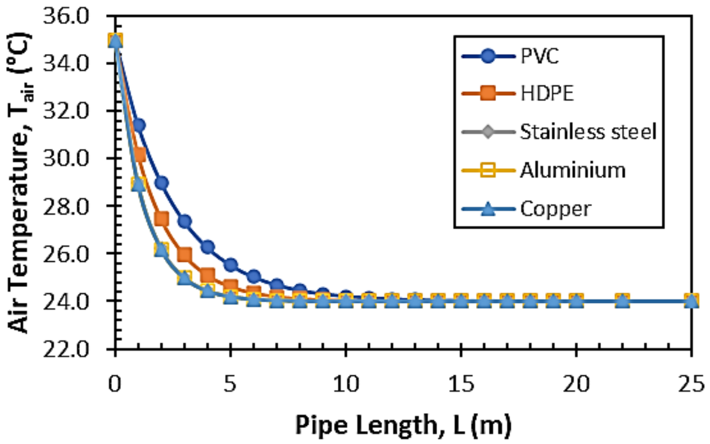

Figure 5. Pipe length against air temperature for five different materials of pipe at 10 W/m·K of soil thermal conductivity.

4. Conclusion

The influence of pipe materials and thermal conductivity of soil on the performance of the ground heat exchanger (GHE) system has been determined by a simulation study. There are five different types of pipe materials which are PVC, HDPE, stainless steel, aluminium, and copper with different thermal conductivity 0.18, 0.47, 13, 220 and 386 W/m·K respectively. Meanwhile, there are five different soil thermal conductivity that has been used in this study, which is 0.5, 1.5, 2.5, 5 and 10 W/m·K. The soil thermal conductivity from 1.5 to 10 W/m·K is a good range for the performance of GHE system. in the meantime, from this analysis the pipe materials do not give a significant effect on the performance of GHE system even the thermal conductivity of the pipe materials is lower. Therefore, it can be concluded that the low cost of pipe material can be used in GHE system instead of high-cost pipe materials. besides, the optimum length of pipe is about 10 m for PVC pipe materials at range 1.5 to 10 W/m·K of soil thermal conductivity.

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