Working parameters affecting earth-air heat exchanger (EAHE) system performance for passive cooling: A review.

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Abstract. The study on the effect of the working parameters such as pipe material, pipe length, pipe diameter, depth of burial of the pipe, air flow rate and different types of soils on the thermal performance of earth-air heat exchanger (EAHE) systems is very crucial to ensure that thermal comfort can be achieved. In the past decade, researchers have performed studies to develop numerical models for analysis of EAHE systems. Until recently, two-dimensional models replaced the numerical models in the 1990s and in recent times, more advanced analysis using three-dimensional models, specifically the Computational Fluid Dynamics (CFD) simulation in the analysis of EAHE system. This paper reviews previous models used to analyse the EAHE system and working parameters that affects the earth-air heat exchanger (EAHE) thermal performance as of February 2017. Recent findings on the parameters affecting EAHE performance are also presented and discussed. As a conclusion, with the advent of CFD methods, investigational work have geared up to modelling and simulation work as it saves time and cost. Comprehension of the EAHE working parameters and its effect on system performance is largely established. However, the study on type of soil and its characteristics on the performance of EAHEs systems are surprisingly barren. Therefore, future studies should focus on the effect of soil characteristics such as moisture content, density of soil, and type of soil on the thermal performance of EAHEs system.

Keyword: Earth-air heat exchanger, soil characteristics, thermal performance.

1 Introduction
The utilization of geothermal energy to meet the heating and cooling needs in buildings has received increasing attention during recent years, as this technology will help the global community reduce its dependence on fossil fuel. Geothermal energy is widely used for the heating and cooling of commercial and residential buildings in North America and Europe [1]. Even so, this sustainable geothermal technology has not been widely implemented in other countries, including Malaysia. Chin [2] stated that the growth for electricity use in Malaysia has risen from 3.1% in 2011 and to 3.7% in the following year. Moreover, the total number of residents with air-conditioning in Malaysia has increased exponentially, up to 16.2% in 2000 from a mere usage in 1970s as mentioned by Kubota et al., [3]. Therefore, Tang [4] proposed that there is a need to study alternative ways to provide thermal comfort in buildings, in the effort to save energy and to minimize harmful effects on the environment. One of the ways to overcome this is by introducing the earth air pipe heat exchanger (EAPHE) as a passive cooling system in Malaysia.
An earth air pipe heat exchanger (EAPHE) is a long metal or plastic pipe, which are buried a few meters deep that utilizes the ground as a heat sink for cooling or heating purposes. EAPHE as a passive cooling system works when hot air flows from a room into the EAPHE system through length of the pipe, where heat is transferred from the surrounding soil into the air, thus causing the air to be cooled and enters the room again as cooler air during the cooling period. [5] [6]

As stated above, the utilization of the geothermal energy in Malaysia has yet to be explored. In recent years, there are several studies conducted on the potential of shallow geothermal technology in Peninsular Malaysia. Noor Aziah et al., [7] have conducted a study concerning the effect of pipe materials on the EAPHE system as a passive ground cooling technology, specifically for the hot-humid climate in Malaysia. Sanusi et al., [8] have conducted a study to investigate the characteristics of Malaysian soil temperature to demonstrate the potential of applying the EAHE technology in Malaysia. Consequently, Yusof et al. [9] have recently reviewed the potential and benefit of ground heat exchanger (GHE) implementation in the Malaysian climate for cooling applications to reduce the energy used in buildings and greenhouse gas emission. Amaludin et al., [10] have conducted a study to determine the effect of moisture content on thermal conductivity, thermal resistivity and volumetric specific heat values of various cohesive soils to assess the viability of shallow geothermal energy pile system installed in the Malaysian environment.

2 Type of earth-air-heat exchanger EAHE
Most EAHE systems are either classified as an open loop or closed loop EAHE system [11]. In an open loop EAHE system, fresh ambient air is drawn through buried pipes, which is moderated to the ground temperature and supplied to the building in order to meet the building’s heating/cooling requirement. Meanwhile, for closed loop EAHE systems, warm air flows from the building through the buried pipes, and cooler air is recirculated to the building. The closed loop EAHE system is not preferred over open loop EAHE system because it does not meet the building’s fresh air requirement as stated by [6] [9]. The subsections below will explain the details of both types of the EAHE system.

2.1 Open-loop system
This type of system uses wells or surface body water as the heat exchange fluid which circulates directly through the ground heat pump (GHP) system. Once it has circulated through the system, the water returns to the ground through the well, a recharge well, or surface discharge. This option is practical only where there is an adequate supply of relatively clean water, and all local codes and regulations regarding groundwater discharge are met. This system is usually used for larger installations. Figure 1 below shows an open-loop system.
2.2 Closed-loop system

This type of system uses heat exchangers that are located underground, either in horizontal or vertical position and a heat carrier medium is circulated inside the heat exchanger within a closed loop. It transfers heat from the ground to a heat pump or vice versa. For the horizontal type ground heat exchanger, there are three types of horizontal ground which differs with the ways of which the pipes are connected, namely the series, parallel or spiral connections. Figure 2 below shows the closed loop system in an EAHE system.

![Closed-loop system in EAHE](image)

Vertical EAHE are widely used when there is a need to install sufficient heat exchange capacity under a confined surface area. Examples include when the earth is rocky and close to the surface, or where minimum disruption of the landscaping is desired. This is possible because the temperature below a depth of 15 m to 20 m remains constant over the year. In a standard borehole, which in typical applications is 50 to 150 meters deep, plastic pipes (polyethylene or polypropylene) are installed, and the space between the pipe and the hole is filled with an appropriate material to ensure good contact between the pipe and the undisturbed ground and reduce the thermal resistance.

3 Recent studies conducted on modelling of the EAHE systems

In recent decades, a lot of research has been carried out to develop analytical and numerical models to analyse EAHE systems. The performance analysis of EAHE involves the calculation of conductive heat transfer from the pipe to the groundmass, or the calculation of convective heat transfer from the circulating air to the pipe and changes in the air temperature and humidity. In order to model the EAHE systems, there are a few types of computer modelling tools that are readily available to be used. For example, EnergyPlus and TRNSYS have EAHE modules that work well; but it is not suitable for design purposes and is more suitable to be used as an analysis tool for the EAHE system. Nowadays, a lot of researchers have used computational fluid dynamics (CFD) to model and study the performance analysis of the EAHE systems. This is because CFD employs a very simple rule of discretization of the whole system in small grids and governing equations applied on these discrete elements, which are done to obtain numerical solutions concerning flow parameters, pressure distribution, and temperature gradients in less time and at reasonable cost because of reduced required experimental work [12] [13].

A lot of research papers on different design methods of EAHE systems have been published. Previous research conducted on the calculation models of EAHE systems are presented in the subsequent three subsections; namely, one-dimensional models, two-dimensional models, and three-dimensional models of EAHE systems.
3.1 One-dimensional Models of EAHE systems.
Kabashnikov et al., [14] have developed a mathematical model to calculate the soil and air temperature in a soil heat exchanger for ventilation systems. The model was based on the representation of temperature in the form of the Fourier integral. The study was carried out to analyse the effect of air flow rate, variation in length, diameter of tubes, depth of the buried pipe, and spacing between tubes on the thermal performance of the EAHE systems. Then the results of the calculation was validated against the experimental data. The developed mathematical model does not involve difficult calculations and can therefore be used for design considerations.

De Paepe and Janssens, [15] have presented a one dimensional analytical method to analyse the effect of design parameters of the heat exchanger on thermo-hydraulic performance. Parametric study for tube length, tube diameter, and number of parallel tubes of the heat exchanger on thermo-hydraulic performance have been carried out. Based on the results, it was found that both thermal performance of the heat exchanger and pressure drop increases with the increase of tube length. However, in the case of tube diameters, it was found that smaller tube diameters give better thermal performance, but also larger pressure drop. Other than that, it also found that an increase in the number of tubes in parallel gives both better thermal performance, albeit with a larger pressure drop. Based on the specific pressure drop, the correlation between thermal effectiveness and the pressure drop of the air inside the tube was made. This correlation allows a design method to be formulated, in order to find the characteristic dimensions of the EAHE system that permits optimal thermal effectiveness to be reached with an acceptable pressure loss. Therefore, the choice of characteristic dimensions are independent of the soil type and climatological conditions, which allows designers to select the EAHE configuration with the best performance.

Hollmuller, [16] had demonstrated the complete analytical solution for the heat diffusion of a cylindrical air/soil heat exchanger with adiabatic or isothermal boundary condition, submitted to a constant airflow with harmonic temperature signal at input. The analytical results were verified against the finite-difference numerical simulation model with an experimental setup.

Lee and Strand, [5] developed a new module and performed it in the EnergyPlus program for the simulation of earth tubes. A parametric analysis was conducted using the new module to study the effect of pipe radius, pipe length, pipe depth and air flow rate on the overall performance of the earth tube under various conditions during cold weather. The model was validated against the data from other theoretical and experimental studies and showed good agreement with both theoretical and experimental data. It reveals that pipe length and pipe depth appeared to affect the overall cooling rate of the earth tube, whereas pipe radius and air flow rate mostly affect earth tube inlet temperature. It was deduced that with a proper design, an earth tube can save more than 50% of the total cooling load of the earth tube, depending on the weather and soil conditions. Even so, the earth tube alone cannot replace conventional air-conditioning system in these case studies, but it can greatly help reduce the cooling load in buildings.

Cucumo et al., [17] have proposed a transient one-dimensional analytical model which can be used for the correct installation and the calculation of the performances of EAHEs buried at different depths. With acceptable theory, the model is able to calculate the length and humidity ratio at the outlet section of a buried pipe at different depths of installation and to evaluate the performance of a buried pipe of assigned length. The model was obtained by the solution of heat and mass balances for air through the buried pipe, considering a suitable temperature profile in the ground. This was achieved by two methods: the first is based on Green’s functions and the second, simplified, was based on the principle of superposition. The numerical and the experimental data showed a very satisfactory agreement with each other.

A one-dimensional numerical model has been proposed by Sehli et al., [18], to check the performance of EAHEs installed at different depths. Parametric study on the effects of Reynolds number, installation depth, and form factor on the performance of an earth-to air heat exchanger (ETHE) system were analyzed. Ratio of pipe length to pipe diameter of the EAHE systems was defined as a form factor. From the result, it is found that as the installation depth increases, the form
factor of the outlet air temperature decreases, while the increase in Reynolds number also causes the outlet air temperature to increase. The study finds that EAHE systems alone are not sufficient to create thermal comfort, but it can be used to reduce the energy demand in buildings in south Algeria, if used in combination with conventional air-conditioning systems.

De Jesus Freire et al., [19] presented a study examining the use of a heat exchanger with a multiple layer configuration and comparing it with a single layer of pipes and reporting the major performance differences. Other than that, a parametric analysis of the effect of the main input parameters on the heat exchanger was also performed and it was concluded that the heat exchanger power increases with the layers depth until 3m and the distance between layers should be kept at 1.5m to make sure the heat exchanger is more efficient. It was found that a one-dimensional discrete model can respond faster to a performance analysis of compact buried pipes systems compared to the two dimensional model and still producing results within a good accuracy.

In a one-dimensional model, the description of the pipe to derive a relation between its inlet and outlet temperature is used and therefore it is very simple to solve to obtain the design parameters. It can be concluded that 1D models are simplest to solve within a short time period, but the analysis is not able to analyze the EAHE system completely.

3.2 Two-dimensional Models of EAHE systems
Zhao et al., [20] performed a research to evaluate the thermal performance of saturated soil around coaxial ground-coupled heat exchanger (GCHE). The heat-transfer experiments were conducted based on some artificial glass microballs as porous medium. A theoretical model with Darcy’s natural convection was developed and numerical solutions were obtained by using Keller’s shooting method. There was a better correlation between experimental and numerical results, which further verified the validation of theoretical model. Based on the results, the heat transfer usually happens near the outer wall of coaxial GCHE and inclines to stabilization at far-field. It was found that, the major factors affecting heat transfer were inlet temperature, initial temperature of porous medium, and the flow rate. It was reported that there was a linear relationship between the dimensionless temperature gradient along the outer wall of GCHE and the dimensionless height.

Tittelein et al., [21] proposes a new numerical model of earth-to-air heat exchangers. The discretized model was solved using the response factors method in order to reduce computational time. Each response factor was calculated using a finite elements program which solves two-dimensional (2D) conduction problems. Based on the result, there are a few advantages of the new model, firstly the calculation time was reduced by the use of response factor. Moreover, it was precise for a short solicitation period (1-day) and a long solicitation period (1-year). Secondly, every type of soil characteristic (inhomogeneous, anisotropic etc.) and of geometry can be considered due to the response factor calculation in a 2D finite elements program (not as analytical models). Lastly, multiple pipes exchangers could be considered with their interaction by calculating more response factors.

To conclude, 2D models allow calculation of soil temperature at the surface and at different depths. The finite element programs are used in 2D models to solve two-dimensional conduction problems of EAHE systems by using finite element programs.

3.3 Three-dimensional Models of EAHE systems
To conduct the performance analysis of EAHE systems using 3D heat transfer and energy balance equations, the computational fluid dynamic (CFD) method will be used. In recent years, CFD has become a popular and a powerful method to study heat and mass transfer. The complex fluid flow and heat transfer processes involved in any heat exchanger can be solved by using CFD software that uses partial differential equations governing airflow and heat transfer.

Ramırez-Davila et al., [22] have carried out a numerical study to predict the thermal behavior of an earth-to-air heat exchanger (EAHE) for three cities in Mexico. Based on the finite volume method, a computational fluid dynamics code has been developed in order to model the EAHE systems. Simulations have been conducted for sand in the city of Ciudad Juarez, silt in the Mexico city, and
clay soil in the city of Merida. It was found in simulation results that the thermal performance of the EAHE is better in summer than in winter. For both Ciudad Juarez and Mexico City, the air temperature decreases at an average of 6.6 and 3.2 °C for summer and increases by 2.1 and 2.7 °C for winter, respectively. On the contrary, the EAHE thermal performance in winter is the highest, where the air temperature increases by 3.8 °C for Merida. Therefore, it was concluded that the use of EAHEs is acceptable for either heating or cooling of buildings in lands of extreme and medium temperatures, where the thermal inertia effect in soil is higher.

Flaga-Maryanczyka et al., [23] have demonstrated the experimental measurements and numerical simulation of a ground source heat exchanger operating at a cold weather for a passive house ventilation system. The study carried out for a passive house was located in the South of Poland. The house and its components were fitted with a data acquisition system that was running from 2011 and records 139 points at an interval of 1 minute. The calculations were performed using the CFD ANSYS FLUENT software package. Based on the experimental data on the CFD simulations done for the ground source heat exchanger that was operating for the passive house ventilation system on February, it showed a good correlation with the measured values. Moreover, the difference between measured and calculated values at the level of 1.7°C on average leads. Therefore, it was concluded that CFD tool is acceptable to be used for simulations of the ground source heat exchanger working in cold climates for the passive house ventilation system.

In conclusion, 3D models are dynamic and technically more advanced, which can provide room for all types of grid geometry to produce detailed thermal analysis of EAHE systems. However, their applicability for design is limited to the people who are able to use the calculation codes. In 3D models, finite volume method are used to solve 3D conduction equations. It is concluded that CFD is an effective tool for predicting the behavior and performance of a wide variety of heat exchangers.

4 Factors affecting the thermal performance of the EAHE systems

The energy performance of an earth air pipe (EAP) system can be mainly influenced by a few parameters such as; pipe materials, geometric dimension and design of the EAPHE and the air velocity (air flow), pipe burial depth, air temperature, soil temperature and type of soil [6]. To design an efficient system of EAHE, a study should be conducted for the parameters affecting thermal performance of EAHE. Therefore, in the last two decades, investigational work have been carried out intensively on the parameters affecting the thermal performance of the EAHE system. In the subsections below, previous studies conducted on each of the parameters were stated and discussed.

4.1 Pipe Materials

As mentioned before, one of the parameters affecting the performance of the EAPHE system is the pipe material. Recent studies have not clearly explained the major reason behind the selection of pipe materials for their respective studies. However, it can be concluded that the selections were made based on the availability of materials and cost. The materials of higher thermal conductivity have higher heat transfer rate, and therefore can reduce the buried pipe outlet temperature more efficiently. The impact of different pipe materials were analysed through a number of studies as summarized below.

Bansal et al., [24] studied the EAPHE system performance during winter in Ajmeer (Western India). The pipes were buried at a depth of 2.7 m in a flat land with dry soil. They experimented on steel and PVC pipe materials with the air velocity ranging from 2-5 m/s which flowed through 23.42 m length of 150 mm diameter pipe. The result showed that the system gives heating in the range of 4.4 - 4.8 °C. In another study, Bansal et al., [25] further analyzed the EAPHE system performance using CFD simulation during summer with similar parameters and showed that the system gives a cooling range of 8 - 12.7 °C in reduction compared to the ambient temperature. He concluded that the performance of EAPHE system is not affected by the material, therefore the cheaper material may be used to construct the pipe.
Ascione et al., [26] evaluated the energy performances achievable by using an earth-to-air heat exchanger for an air-conditioned building for both winter and summer for the Italian climate. Three different Italian climates (cities of Naples, Rome, Milan) and an air-conditioned building have been analyzed for both winter and summer. The energy requirements of these systems have been evaluated as a function of the main boundary conditions (such as the typology of soil, tube material, tube length and depth, velocity of the air crossing the tube, ventilation airflow rates, and control modes). The obtained results show that concrete, plastic or metallic materials have very similar energy performances. In fact, due to the small thickness of the tubes (5 mm in the case of PVC, 7 mm for the metallic material, 7 cm for the concrete), the different thermal conductivity values are almost negligible and does not significantly influence the heat exchange, if the right depths and lengths are used as the earth tube model.

Sanusi, et al., [27] have studied the potential of this system in the hot-humid climate in Malaysia. The study uses 3 polyethylene (PE) pipes with 76 mm in diameter and 30 m long. All three pipes were buried separately at depths of 0.5 m, 1.0 m and 1.5 m. Fan blowers were installed at each inlet of the pipes which provided air velocity at 5.6 m/s. The result showed the best reduction of temperature of up to 6.4°C during the wet season, and 6.9°C during the hot and dry season, where the pipes were buried at 1 m depth underground. Meanwhile, 30m long PVC pipes were also buried at 0.5m, 1.0m and 1.5m depth underground at the same time. However, due to the increasing weight of the soil as it goes deeper underground, the PVC pipes below 0.6m were found broken just before measurements were taken. It concluded that the PVC pipes have low durability as compared to PE pipes. Furthermore, a parametric study was carried out in EnergyPlus in comparing other pipe materials, namely PVC, PE, Brick and Clay [8].The results had shown that Clay pipes provide the lowest pipe outlet air temperature among the four pipes. This research extends the type of buried pipes for its parametric analysis on buried pipe materials.

Hatraf et al., [28] have investigated the parameters influencing the performance of earth to air heat exchanger through modeling and experimentation. They have done the calculation using a simple model the distribution of the air temperature and varied several parameters such as nature of the ground and the ground depth diameter of the duct. One of their finding was that the pipe material has no effect on the performance of the heat exchanger, which is in agreement with the findings of Bansal et. al (2010).

Aziah et al., [7] have studied the materials for the EAPHE system using computer simulation to find the best pipe material for the EAPHE system for the hot and humid climate in Malaysia. The study utilizes the EnergyPlus environmental simulation program to investigate the performances of three pipe materials system; which includes single pipe material, hybrid pipes (combination of pipe materials) and insulated hybrid pipes system (combination of pipe materials with insulation). It is found that for single pipe material polyethylene (PE), it has the maximum temperature reduction followed by steel (St), copper (Cu) and polyvinyl chloride (PVC). Through an exhaustive enumeration process, the study found that the insulated hybrid pipes system gave the best temperature reduction, which indicates a promising cooling and energy savings potentials. It also concluded that the choice of the pipe material does not have any significant consequence on the temperature reduction by the EAPHE system in hot and humid climate.

Jahkar et al., [29] have designed and simulated an earth water heat exchanger (EWHE) in transient analysis tool TRNSYS (v17.0) in Pilana, Rajashtan (India). Parametric study was conducted to analyse the effect of mass flow rate, pipe length, diameter of buried pipe and pipe material on the performance analysis of the EWHE. To conduct the performance analysis, the pipe length, pipe diameter and mass flow rate was fixed to 90m, 25mm and 0.02kg/s, respectively. Three types of material have been used to conduct the analysis such as high density polyethylene (HDPE), Galvanized Iron (GI) and steel pipe (St). Based on the result, GI and steel is at 0.2 °C and for HDPE is around 1.6 °C for the temperature difference at the outlet of the EWHE system with the same inlet conditions. This slight difference occurred because the HDPE pipes coefficient of friction is lower than the other pipes. Even though the thermal conductivity for both of GI and steel is higher than HDPE, the coefficient of friction for
HDPE is higher compared to both materials. Hence, a lower outlet temperature is observed for both, GI and steel pipes compared to HDPE pipe.

Ahmed et al., [30] developed a thermal model for the horizontal earth pipe cooling (HPEC) system using the simulation model, FLUENT 15.0 in a hot humid subtropical climate at Rockhampton, Australia. The studied mainly focused on the parameters affecting the thermal performance of the earth pipe cooling system, which are the air velocity, pipe length, pipe diameter, pipe depth and also pipe material. Materials such as PVC, polyethylene, concrete and clay have been chosen to study the effect of the pipe material on the thermal performance of HPEC. It is found that the clay PVC pipe produces higher temperature at the pipe outlet that varies from 19.5°C to 24.9°C, compared to the other material and while the clay pipe provides the lowest average pipe outlet temperature as 20.5°C.

Serageldin et al., [31] studied the thermal performance of an earth air heat exchanger (EAHE) used for heating and cooling under the Egyptian weather conditions. They have developed a mathematical model based on unsteady, one-dimensional, quasi-state for energy conservation equation, and also a three dimensional, steady and double precision Computational Fluid Dynamics (CFD) ANSYS Fluent simulation model that is established to predict the air and soil temperature. A parametric study was done to investigate the impact of different parameters such as pipe diameter, pipe material, pipe space, pipe length and flowing fluid velocity. Three different types of pipe materials were used, namely PVC, steel and copper. The outlet air temperature was 19.7 °C in PVC pipe, and 19.8 °C for both steel and copper respectively. Therefore, it is concluded that the change in outlet air temperature for various pipe material is too small and hence it is negligible.

Based on previous studies, the pipe material does not significantly affect the thermal performance of the EAHE system. However, pipe materials with higher thermal conductivity can increase the thermal performance of EAHE, but it is not reliable to use it when compared to the price of the materials which have higher thermal conductivity. This is because materials such as copper and steel are more expensive and the availability in market is quite low compared to PVC pipes, even though it has lower thermal conductivity as reported by previous researchers [24-31]. Therefore, it can be concluded that pipe material selection does not significantly affect the thermal performance of EAHE, and is therefore negligible. Types of pipe materials used in the past studies are listed in Table 1.

Table 1. List of pipe materials have been used in the past studies

| Authors                  | Type of Pipe Material used                | References |
|--------------------------|------------------------------------------|------------|
| Bansal et al.,           | PVC                                      | [24]       |
| Ascione et al.,          | PVC, Metallic, Concrete                   | [26]       |
| Sanusi et al.,           | Polyethylene (PE), PVC, Brick, Clay      | [27]       |
| Aziah et al.,            | Polyethylene (PE), Copper, PVC            | [7]        |
| Jahkar et al.,           | High Density Polyethylene (HDPE), Galvanized Iron, Steel | [29] |
| Ahmed et al.,            | PVC, PE, Concrete, Clay                   | [30]       |
| Serageldin et al.,       | PVC, Steel, Copper                        | [31]       |

4.2 Geometric dimension and design of the EAHE pipe system

Geometric dimension and design of the EAHE pipe system also plays a big role in determining the thermal performance of the system. A number of studies have been conducted by researchers on different geometric design of the EAHE system which includes; length of pipe, burial depth of the pipe, diameter of the pipe and pipe arrangements.

Ghosal and Tiwari, [32] have developed a thermal model to analyse the potential of using thermal energy of the ground for greenhouse heating and cooling, where the earth to air heat exchanger (EAHE) system was integrated with the greenhouse located in the premises of IIT, Delhi, India. Experiments were conducted extensively throughout 2003, and the developed model was validated
against typical clear and sunny day experiments. Parametric studies were carried out to study the effects of buried pipe length, pipe diameter, mass flow rate of air, depth of ground and types of soil on the greenhouse air temperatures. Based on the results, the effect of the length of buried EAHE pipes, the increase of the length of buried pipes from 30m to 50m directly impacted the temperature changes of the air inside the greenhouse; where an increase in the winter period and a decrease during the summer period were observed. This is mainly because the longer pipe length allows a longer time for the thermal heat exchange between the air and the ground to take place. Meanwhile, for the effects of diameter of buried pipe of the EAHE, an increase in diameter results in lower and higher greenhouse air temperatures in the winter and summer, respectively. This is caused by the decrease in the heat transfer of heat from earth or lower convective heat transfer coefficient due to increase of pipe surface and slower air flow.

Maerefat and Haghighi, [33] have proposed and studied a passive solar system comprising of solar chimneys and earth to air heat exchangers (EAHEs). In this study, it was shown that the optimum diameter for cooling pipes is 0.5m (with the lowest number of solar chimney) and the EAHE was needed to achieve the cooling demand required. It also reveals that the pipe length of more than 20m should be used in the EAHE system to provide a better thermal comfort condition.

Pohstiri et al., [34] have developed a mathematical model based on energy conservation equations and solved by iterative method to study the capability of the solar chimney and earth air heat exchanger system to meet the thermal needs of individuals and also the dependence of the system performance on environmental and geometrical issues. Based on the results, EAHE pipe lengths of less than 35m should be used to provide a better thermal comfort condition. Other than that, the result of the effect of EAHE pipe diameter on system performance reveals that the increase of the EAHE diameter up to 0.5m does not increase the room air temperature.

Misra et al., [35] developed a transient and implicit numerical model based on coupled simultaneous heat transfer and turbulent flow, to conduct the study on the effect on time duration of continuous operation, thermal conductivities of soil pipe diameter and flow velocity on thermal performance of earth air tunnel heat exchanger (EATHE) system. Three different pipe diameters were chosen; 0.10m, 0.15m, and 0.20m and the air flow velocity was kept constant to investigate the effect on transient performance of EATHE system to work in long continuous operation. Based on the result, thermal performance of EATHE system with larger pipe diameter had dropped faster after 24h of continuous operation especially the pipe length which are 20m or less from the inlet. Other than that, pipes with smaller diameter and pipe length are beyond 30m experiencing less deterioration in thermal performance.

Jahkar et al., [29] have designed and simulated an earth water heat exchanger (EWHE) in transient analysis tool TRNSYS (v17.0) in Pilana, Rajasthan (India). Parametric study was carried out to analyse the effect of mass flow rate, pipe length, diameter of buried pipe and pipe material on the performance analysis of the EWHE. To study the effect of variation of length, the mass flow rate of 0.02 kg/s with diameter of 25mm for HDPE pipe was set to be constant. By varying the length of the pipe from 50 m to 90 m, the result was obtained. It was found that the increase in length caused an increase in the temperature drop. When the pipe length was at 90 m and the fluid temperature inlet at 90°C, the outlet temperature recorded was 31.9 °C. The effect of variation in pipe diameter ranging from 25 mm to 50 mm of HDPE pipe at the same flow rate of 0.02 kg/s and 90 m length was recorded. It reveals that the increase of the pipe diameter caused the outlet temperature to decrease gradually over a period of time. After 10 hours of operation, the outlet temperature differences were 31.80 °C for 50 mm and 36.16 °C for 25 mm. In another study, Jahkar et al., [36] presented a model of earth air pipe heat exchanger that was generated using TRYNSS 17 simulation tool and was validated using experimental investigation in an experimental set up in Ajmer, India. The experiment was done during winter season, where the system was examined for the effect of different inlet flow velocities, pipe length and depth of burial on the outlet air temperatures of the EAHE systems. The effect of pipe length with respect to changes in flow velocities has been conducted. It was found that about 82–85%
of the total increase in the temperature of air along the EAHE pipe is achieved at a length of 34m from the inlet.

Ahmed et al., [37] have developed a thermal model to compare the earth pipe cooling performance between two different piping systems for a hot and humid subtropical climatic zone in Queensland, Australia using ANSYS Fluent. Vertical earth piping cooling VEPC system and horizontal earth piping cooling HEPC systems were laid in the ground in order to compare the cooling performance as shown in Figure 3. The developed model was validated at the pipe inlet and different points of the room with the measured data. The inlet air velocity and air temperature was set at the pipe inlet to predict their effect on the room temperature. The simulation result shows that the minimum temperature reductions of approximately 1.82 °C and 1.02 °C in the modelled room of vertical and horizontal earth pipe cooling system, respectively. Based on the results, the vertical earth pipe cooling system is better than the horizontal earth pipe cooling system even though there was no large temperature reductions found for both systems.

![Figure 3](image)

Figure 3. (a) - Vertical earth piping cooling VEPC system, (b) - Horizontal earth piping cooling HEPC systems

Gan [38] has developed models of coupled heat and moisture transfer in soil and simulation of the thermal performance of an earth air heat exchanger for building ventilation, considering the dynamics variations of climatic, load and soil conditions. The dynamic interactions between soil, ambient environments and heat exchanger have been analysed. Other than that, the effect of the heat exchanger length on thermal performance are also investigated. It has been found that the heat transfer rate decreases along the heat exchanger and the rate of decrease is non-linear. Thus, the heat transfer rate and temperature rise of supply air per unit length decrease with increasing length of the heat exchanger for preheating.

According to the recent studies conducted, the increasing depth of burial of the EAHE pipes making the outlet air temperatures of EAHE systems to increase in winter and decrease in summer. Whereas for the pipe diameter, it shows that an increase in diameter resulted in lower thermal performance in the EAHE systems. The result is caused by the decrease in the heat transfer of heat from earth or lower convective heat transfer coefficient due to increase of pipe surface and slower air
flow. For the effect of pipe length on the thermal performance of EAHE system, each of the recent study has different optimum lengths. However, the increase of pipe length does increase the thermal performance of EAHE system until certain length of the pipe, which causes the thermal performance of EAHE system to decrease.

4.3 Air flow

Air flow or volume flow rate of air is one of the parameter which affects the thermal performance of EAHE system. In this subsection, previous studies focussed on the air flow rate is reviewed.

Ghosal and Tiwari, [32] have developed a thermal model to analyse the potential of using thermal energy of the ground for greenhouse heating and cooling, where the earth to air heat exchanger (EAHE) system was integrated with the greenhouse located in the premises of IIT, Delhi, India. Parametric studies were carried out to study the effects of buried pipe length, pipe diameter, mass flow rate of air, depth of ground and types of soil on the greenhouse air temperatures. It is found that for the effects of mass flow rate of flowing air in EAHE, the increase in mass flow rate leads to the decrease and increase of the greenhouses air temperature in the winter and summer, respectively. This may be caused by the air that has a shorter time in contact with the soil, causing lower thermal exchange rate between soil and air.

Misra et al., [35] developed a transient and implicit numerical model based on coupled simultaneous heat transfer and turbulent flow to conduct the study on the effect on time duration of continuous operation, thermal conductivities of soil pipe diameter and flow velocity on thermal performance of earth air tunnel heat exchanger EATHE system. Three different velocities were chosen; 2.0m/s, 5.0m/s, and 8.0m/s and the pipe diameter was kept at 0.1m for all different flow velocities to investigate the effect on transient performance of EATHE system to work in long continuous operation. From the result, the increase in flow velocity cause the thermal performance of EATHE system to deteriorate. This is because when the flow velocity increases, the amount of heat is transferred to the soil from air per unit time also increases. Later, this causes more heat to be accumulated in the soil layers in the immediate vicinity of pipe surface for soil with less thermal conductivity. It is concluded that increasing the flow velocity has a detrimental effect on the thermal performance of EATHE system.

Jahkar et al., [29] have designed and simulated an earth water heat exchanger EWHE in transient analysis tool TRNSYS (v17.0) in Pilana, Rajashtan (India). Parametric studies were done to analyse the effect of mass flow rate, pipe length, diameter of buried pipe and pipe material on the performance analysis of the EWHE. To study the effect of mass flow rate on the performance of EHWE, the length of pipe and pipe diameter have been fixed to 90m and 25mm, respectively. Five values of mass flow rate have been used in the analysis; 0.008 kg/s, 0.02kg/s, 0.03kg/s, 0.04kg/s and 0.05kg/s. It is found that with an increase in mass flow rate, the outlet temperature of EHWE increases. It is noticed that the highest temperature drop occurred when the mass flow rate is set at 0.008 kg/s. In another study, Jahkar et al., [36] have presented a model of earth air pipe heat exchanger that was generated using TRNSYS 17 simulation tool, and was validated using experimental investigation on an experimental set up in Ajmer, India. The experiment was done during winter season, where the system was examined for the effect of different inlet flow velocities, pipe length and depth of burial on the outlet air temperatures of the EAHE systems. There are three different air velocity used; 2.5m/s, 3.5m/s and 5.0m/s to study the effect of air flow velocity on the EAHE outlet temperature and it reveals that, with the increase in air velocity, EAHE outlet temperature decreases. This is mainly because the convective heat transfer coefficient have increased by 2.3 times. Moreover, the increase of air velocity reduces the time to which the air remains in contact with the ground by a factor of 2.5. It is concluded that, the velocity at 5m/s has the best increase in EAHE outlet temperature compared to velocity at 2.5m/s and 3.5m/s.

Based on the recent studies conducted on the effect of air flow velocity in EAHE systems, it is found that the increase of air velocity leads to the decreasing thermal performance of the EAHE
system. This is caused by the shortened time in contact between air and the ground, therefore the heat from the air has not enough time to achieve thermal equilibrium with the ground. Therefore, the later effect was dominant and causing the thermal performance of EAHE to decrease at a higher flow rate compared to lower flow rate.

4.4 Site characteristic
Research work on EAHE system comes from various location around the world. Each site offers different climate condition which affects the EAHE performance and suitable applications. A list of research papers published in different locations are summarized in Table 2.

| Authors         | Weather types         | Location               | Type of ground heat exchanger                        | Application                          | References |
|-----------------|-----------------------|------------------------|-----------------------------------------------------|--------------------------------------|------------|
| Bansal et al.   | Winter                | Ajmer, India           | Earth air pipe heat exchanger (EAPHE)                | Passive heating                      | [24]       |
| Jahkar et al.   | Winter                | Ajmer, India           | Earth water heat exchanger (EHWE)                   | Passive heating                      | [36]       |
| Jahkar et al.   | Winter and summer     | Pilana, Rajhastan, India | Earth water heat exchanger (EHWE)                   | Passive cooling and heating          | [39]       |
| Ghosal and Tiwari. |                      | Premises ITT, Delhi, India | EAHE                                                                                   | Passive cooling and heating          | [32]       |
| Ahmed et al.    | hot and humid subtropical | Queensland, Australia | Horizontal earth pipe cooling (HEPC) and Vertical earth pipe cooling (VEPC) | Passive cooling system               | [37]       |
| Ahmed et al.    | hot and humid subtropical | Rockhampton, Australia | Horizontal earth pipe cooling (HEPC)                | Passive cooling                      | [30]       |
| Aziah et al.    | Hot and humid         | Malaysia                | EAHE                                                                                   | Passive cooling system               | [7]        |
| Sanusi et al.   | Hot and humid         | Malaysia                | EAHE                                                                                   | Passive cooling system               | [27]       |
| Ascionne et al. | Winter and summer     | cities of Naples, Rome, Milan (Italy) | EAHE                                                                                   | Passive cooling and heating          | [26]       |
Based on Table 2, it can be concluded that researchers in India have investigated the EAHE system based on the weather/climate of its location compared to any other country. It also can be deduced that the EAHE system can be implemented to provide thermal comfort either in hot or cold weather using the EAHE passive cooling system. Even though there are a limited number studies conducted on different locations with different weather conditions, there is still no studies conducted in Malaysia, particularly in Sabah. Therefore, there is a need to assess the performance of EAHE system in the Sabah weather condition to determine its viability as a thermal comfort mechanism.

4.5 Soil characteristic
Ahmed et al., [30] conducted an experimental study of thermal and moisture behaviours of dry and wet soils heated by buried capillary plaits. A prototype, which is similar to an agricultural tunnel greenhouse was used to carry out the experiment. There are three different operational conditions of the capillary plaits: heating at 70°C, heating at 40°C and without heating in summer, in order to understand the greenhouse climate effect on soil behaviour. It is revealed that, in unsaturated moist soils the transport of heat is complicated by the fact that heat and mass transfer is a coupled process. It was found that the surface temperature amplitude was higher in wet soil compared to dry soil during the daily soil temperature variation. Even though thermal diffusivity, calculated according to the phase delay method between 0 and 20 cm, in wet soil was higher than in dry soil, the wet soil surface temperature was higher during daytime. The formation of a superficial thin dry soil layer will thermally insulate the soil, causing both the surface heat flux to fall and the surface temperature to rise.

Ghosal and Tiwari, [32] have developed a thermal model to analyse the potential of using thermal energy of the ground for greenhouse heating and cooling, where the earth to air heat exchanger (EAHE) system was integrated with the greenhouse located in the premises of IIT, Delhi, India. Parametric studies were carried out to study the effects of buried pipe length, pipe diameter, mass flow rate of air, depth of ground and types of soil on the greenhouse air temperatures. With the same operational parameters of the EAHE experiment (length of buried pipe 39 m, diameter 0.06 m, mass flow rate 0.027 kg/s and depth 1 m), the experiments were conducted to analyze the effect of the types of soils on the greenhouse air temperatures. Based on the result of the effect of different soil types on the greenhouse air temperatures, it was seen that both of the greenhouse air temperatures are highest either in winter or summer day especially in sandy soil followed by sandy loam, gravelly sand and silt loam. The higher thermal conductivity of sandy soil followed by sandy loam, gravelly sand and silt loam soil are responsible for the higher temperatures of greenhouse air temperature.

Bansal et al., [40] have conducted study on the effect of thermal conductivity of soil on thermal performance of earth air tunnel heat exchanger under transient operating conditions in predominantly hot and dry climate of Ajmer (India) using experimental and computational fluid dynamics modeling with FLUENT software. From the result, maximum air temperature drop obtained under steady state operation of EATHE for pipe length 100 m is 18.4 °C, 18.7 °C and 18.4 °C for soil thermal conductivity of 0.52, 2.0 and 4.0 Wm⁻¹ K⁻¹ respectively. However, the maximum air temperature drop under transient conditions for 24 h of operation varies between 18.3°C and 14.0 °C, 18.3 °C and 17.2 °C and 18.6 °C and 18.0 °C for soil thermal conductivity of 0.52, 2.0 and 4.0 Wm⁻¹ K⁻¹ respectively. This is due to higher soil thermal conductivity results into better thermal performance of EATHE system under transient conditions, even after longer period of operation. It is deduced that for better
thermal performance of EATHE, the soil placed in the immediate vicinity of the EATHE pipe should have higher thermal conductivity. On the other hand, while optimizing the thermal performance of EATHE, the thermal conductivity of soil, duration of continuous operation of EATHE and length of pipe should be taken into account so as to confirm that the EATHE would be able to give a steady thermal performance for longer duration of operation.

Gan [38] has developed models of coupled heat and moisture transfer in soil and simulation of the thermal performance of an earth air heat exchanger for building ventilation, considering the dynamics variations of climatic, load and soil conditions. The dynamic interactions between soil, ambient environments and heat exchanger have been analyzed. It has been found that the direct thermal and moisture interaction between heat exchanger, soil and atmosphere have a significant impact on the heat transfer through the heat exchanger.

Studies done by the above researchers shows that thermal conductivity of soil generally affect the outlet air temperature of EAHE system. As reported by Bansal et al., [40], the thermal conductivity of soil increases the thermal performance of EAHE system increases. Moreover, Ghosal and Tiwari, [32] also reported the higher thermal conductivity of sandy soil followed by sandy loam, gravelly sand and silt loam soil are the reason for the higher temperatures of the greenhouses air temperature. More study on soil properties should be conducted since soil characteristic is very unique. Below is the summary of soil properties that have been used in past studies conducted by the researchers, as shown in Table 3.

| Authors            | Soil Properties                              | References |
|--------------------|----------------------------------------------|------------|
| Ahmed et al.,      | Wet and Dry Soil                             | [30]       |
| Ghosal and Tiwari  | Sandy loam, Gravelly sand, Silt loam         | [32]       |
| Bansal et al.,     | Varies the soil thermal conductivity of 0.52, 2.0, 4.0 Wm⁻¹k⁻¹ | [39]       |

5 Conclusion
This paper has reviewed the recent discoveries related to EAHE and factors affecting it performance. The method to assess the performance of EAHE is first discussed. Research trends show that with the advancement of computational technology, investigational work have evolved from lengthy experimental investigation to computer powered simulation work. This is expected as computational method matures and produces more reliable data, thus reducing cost and time.

Reviews of published research work on parameters affecting EAHE performance have shown that the performance are governed by four parameters, namely the pipe dimension, pipe material, depth, air velocity and soil properties. Interestingly, pipe material does not have a significant impact on the thermal performance of the EAHE system. Whereas for the effect of the depth of pipe installation, it can be deduced that, as the depth of the EAHEs pipe installation increases, the thermal performance of EAHE system also increases. However, an increase in diameter of the EAHEs pipes have resulted in a lower performance in the EAHE systems. For the effect of pipe length on the thermal performance of EAHE system, each of the recent studies has different optimum lengths with varying results. Nevertheless, the researchers have found that the increase of pipe length does increase the thermal performance of EAHE system until an optimum length of the pipe is achieved and subsequently causing the thermal performance of EAHE system to decrease. For the effect of air velocity on the thermal performance, it can be deduced that the increase of air velocity leads to the decreasing thermal performance of the EAHE system.

Several EAHE performance assessments were done in different parts of the world. This trend shows that the EAHE system can be used to provide thermal comfort in various seasons. According to
recent studies, the effect of soil characteristics on the thermal performance shows that as the thermal conductivity of soil increases; the thermal performance of EAHE system also increases. However, thus far there are no investigations conducted in East Malaysia. Therefore, a study on EAHE performance in East Malaysia region is highly sought as different types of soil have unique properties in different parts of the world. To implement an efficient EAHE system in Malaysia especially in East Malaysia (Sabah), both of these opportunities should be pursued to gain a profound understanding of EAHE system performance and its potential use in the Island of Borneo.

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