3-Dimensional Numerical Modelling to Assess Geothermal Piles Efficiency in Tropical Countries

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Abstract. Nowadays, climate changes caused by intense and continuous greenhouse gases emission is one of the most curtail issues that facing the human beings. Throughout the years, researchers have tried to find other reliable sources available to control the exhaustion of coal, gases, and oil. Geothermal energy is one of these alternatives that have been investigated and considered as one of the most promising renewable and clean energy sources. Tropical climate countries such as Malaysia could benefit from this technology due to its high cooling demand throughout the year. Geothermal piles for instance, are one of the methods that can be used to extract geothermal energy by employing the piles as a heat transfer bodes. Therefore, this paper presents numerical simulations as an early attempt to realise the potential of adopting geothermal piles catered to Malaysia’s soil condition and pile standards for low-rise construction. A pipe with a U-tube shape was simulated at three different inner diameters (14, 19, and 26) under two inlet dischargers (0.009 m$^3$/s, 0.050 m$^3$/s). The U-tube was placed inside concrete square pile with dimensions of 1.5 m width, 1.5 m length and 10 m height. The simulation was conducted under two soil conditions namely, (i) dry soil, and (ii) soil effected by groundwater. The performance of the geothermal pile was measured by the amount of temperature reduction in the pipe outlet after heat exchange has been done. The results obtained showed that geothermal piles with lower flow discharge (0.009 m$^3$/s) operation produced more temperature reduction in the pipe outlet. Without the presence of groundwater, the 26 cm diameter recorded the highest temperature reduction, with pipe outlet temperature of 29.89 °C equivalent to a 1.0 % reduction. Similarly, with the groundwater effect, the same pipe diameter recorded the highest temperature reduction, with pipe outlet temperature of 28.43 °C equivalent to a 1.57 % reduction. Based on the numerical modelling results it can be said that combination of 26 cm pipe diameter, at 0.009 m$^3$/s flow rate, and the advection effect of groundwater temperature has produced an optimum condition for the geothermal piles in cooling system.

1. Introduction
Global warming caused by the emissions of greenhouse gases from different sources around the globe has become a critical issue nowadays [1]. Hence, throughout the years, people have tried to find other reliable sources available to control the exhaustion of coal, gases, and oil. Renewable energy sources such as solar, wind, biomass, and hydroelectric energy are among the most common that has been explored by mankind to generate power whilst minimalizing carbon emission to the atmosphere [2]. Currently, the term "Geothermal" is known to be economically and environmentally optimal for...
electricity production [3]. Based on Lund and Toth (2021) [4], a total of 88 countries have directly utilized geothermal energy in works to decrease the emission of greenhouse gases and reducing the cost. The versatility of geothermal energy can be incorporated into numerous fields ranging from space heating and cooling, agricultural crop drying, to bathing and swimming purposes [5],[6].

Geothermal piles technology is one of the techniques that can be used to extract geothermal energy from the shallow soil layers for heating and cooling purposes [7]. Geothermal piles provide a dual purpose of supporting the load generated by the structure above the ground and act as a heat sink or heat source depending on varying seasons [8]. A typical geothermal heat pump (GHP) system consists of a primary unit known as the ground heat exchange system (GHE) (i.e., geothermal piles), a heat pump unit where the geothermal energy extracted shall be pressurized according to its heating or cooling system, and a secondary unit or ventilation system which distributes the desired temperature into the surrounding area as shown in Figure 1 [7]. Countries experiencing four seasons are taking advantage of this technology by providing energy for their heating system during the winter, as well as generating energy for their cooling system during summer. On the other hand, tropical countries with only one session such as Malaysia could benefit from the cooling system function [9].

In the implementation of geothermal piles, there are various parameters to be considered to ensure the system’s efficiency. The first parameter to be considered is the pile length. Pile length is typically associated with the amount of load placed on the foundation. If geothermal piles were to be utilized, pile length is essential to obtain the constant temperature of the earth. Most studies have proven that the optimum pile length should be at least 4 m deep or more to achieve a constant and reliable underground temperature to be utilized for the heat transfer [10-12]. This is because the soil temperature nearer to the surface is highly dependent on the surrounding and ambient temperature. The next parameter to be focused on is the design concept of the energy loops in the geothermal piles. According to Sani et al. (2019) [7], there are various layouts of pipe networks that could be applied to the geothermal piles. The shape and sizes of the energy loops determine the heat transfer rate of the water from or to the ground. The most shape tested is the U-shaped because of its construction feasibility. Further, the material of the energy loops is considered as one of the main parameters that play the main role in the amount of heat that could be transferred from the soil layers. A numerical study has been conducted by Bezyan et al. (2015) [13], the efficiency of heat transfer with various shapes, namely the U-shape, W-shape, and spiral-shape. All initial parameters such as pile length and initial temperature are kept constants for all configurations, which are 5 m and 35 °C, respectively. The results of the simulation obtained that the most efficient heat transfer rate comes from the spiral-shaped energy loops, with a pitch size of 0.04 m. It is proven to drop the initial temperature by approximately 7 °C. A spiral-shaped loop has a higher contact surface area compared to the other two shapes, which is why the heat transfer is the highest when utilizing this shape.
Nowadays, phase change materials PCM commonly used on the interior or exterior walls of the building application to optimize the energy consumption during heating and cooling periods. It was found out that using PCM inside the walls increased not only the charging and discharging capacity but also the storage efficiency of the walls [14]. PCM could absorb, store, and release an amount of energy during the phase transition without any significant temperature change, due to its internal molecular energy change. This feature made the PCM an attractive element for energy storage systems, especially thermal energy storage systems [15]. Therefore, implementing the PCM in the geothermal pile's system will enhance its efficiency leading to the most optimized system. PCM can be categorized into three groups based on their phase change state, namely solid-solid, solid-liquid, and liquid–gas [11]. According to Akeiber et. al. (2016) [15], the most suitable PCM material for thermal energy storage systems is the solid-liquid PCM. This is because of the small volume change during melting and solidification, large phase change enthalpy, and large varieties of the melting temperature. Currently, PCM’s are available in markets with more than thousand types, making the choice among them more difficult. However, there are specific characteristics for PCM to be used in building applications [16],[17].

Previously, several studies have been conducted to assess the geothermal piles efficiency under various pipe configurations, shapes, and combinations [18-21]. Most studies utilised the U-tube configuration as it is conventional and easier to manufacture and assembled in the pile. Aligned with the different pipe configurations, there are also two ways to connect the pipe network inside the pile to enhance the heat exchange, namely, the serial and parallel connection. Parallel connection or using the connection of more than one pipe is not only complicated to assemble, but also could promote pipe-to-pipe thermal interaction. This could hinder the heat exchange and provide smaller change in temperature reduction between the inlet and the outlet. Due to its complexity in design, the serial or single pipe connection is more desirable.

In this paper, 3-dimensional numerical modelling was conducted to assess the geothermal piles efficiency in tropical countries. A high-density polyethylene (HDPE) tube (pipe) with U shape was simulated in three different inner diameters including 14, 19, and 26 cm. Besides, the effects of groundwater existence were simulated and investigated. This paper first describes the material properties, model component and arrangement in a 3-D form. Next, a detailed description of the numerical modelling setup is presented which includes the mesh blocks arrangement and sizing, initial conditions, and boundary conditions. Later, main findings and results are presented and discussed. Finally, some conclusions are presented regarding the outcomes at the end of this paper.

2. Methodology

In this paper, the efficiency of extracting geothermal energy in tropical countries was investigated numerically. A commercialized computational fluid dynamics (CFD) software called FLOW-3D was used to conduct the numerical runs. The FLOW-3D is a general purpose CFD software that employs the basics of finite volume method in performing the numerical modelling [22-24]. It employs specially developed numerical techniques to solve the equations of motion for fluids to obtain transient, three-dimensional solutions to multi-scale, multi-physics flow problems. Finite difference and finite volume methods form the core of the numerical approach in FLOW-3D [25]. Three high-density polyethylene (HDPE) U-tube with inner diameter of 14 cm, 19 cm, and 26 cm were tested under two different flow discharges including (i) 0.009 m³/s and 0.05 m³/s. The percentage of area covered by the U-tube size in the pile were denoted as approximately 2.8, 3.3, and 4.3 % for 14, 19 and 26 cm diameter, respectively. Figure 2 illustrates the general configuration of the geothermal pile tested in this study. The model consists of four main elements, namely (i) soil with square cross section with dimensions of 6 m x 6 m and a height of 10.5 m, (ii) concrete square pile with dimensions of 1.5 m x 1.5 m x 10 m, (iii) HDPE U-tube, (iv) and the fluid as water. Note that the soil model was four times the size of the concrete pile to guarantee full heat transfer encircling the geothermal pile. For simplicity of the numerical simulation, the soil was deemed homogenous and defined as the heat source with a constant volumetric energy total amount of 140 W, having a constant temperature of 30 °C. Other components including concrete pile and HDPE were considered as full heat transfer models.
Figure 2. General configuration of the geothermal pile and its components.

Effects of the groundwater was investigated by applying a water depth with a total height of 1.5 m as shown in Figure 3. The effects of groundwater on the geothermal energy extracted from the piles was tested at flow discharge of 0.009 m$^3$/s only (based on the outcomes tested earlier to identity the most optimized inlet discharge). The groundwater temperature was assumed to be constant with a value of 20 °C.

Figure 3. Model configuration with groundwater effects.

2.1. Material characteristics and specifications
As previously mentioned, the geothermal pile tested in this study consists of four main components. In numerical modelling, inserting the accurate characteristics of these components is one of the main parameters controlling the outputs. Therefore, a detailed descriptions of these components’ characteristics are provided in this section. Tables 1 summarizes the main properties of HDPE U-tube, concrete pile, soil, and fluid.

Table 1. Material properties specifications.

| Materials          | HDPE  | Concrete | Clay soil | Water  |
|--------------------|-------|----------|-----------|--------|
| Density (kg/m$^3$) | 1100  | 2500     | 2660      | 1000   |
| Thermal Conductivity (W/M. K) | 0.42  | 1.8      | 2.015     | 0.597  |
| Specific heat (J/kg. K)       | 1465  | 837      | 2899      | 4182   |

2.2. Meshing
To capture all model component accurately a special mesh was generated in this study. A total of 4 mesh blocks were developed including one containing mesh block (no. 1) and three nested mesh blocks (no.
2, 3, and 4) with a total cells number of 1,292,551 as shown in Figure 4. Mesh block 1 was designed to capture the whole model with cell size of 0.08 m, while mesh block 2 was used to capture the U-tube and fluid domain with cell size of 0.02 m. Mesh blocks 3 and 4 were developed to define the inlet and outlet boundaries. Table 2 shows a summary of the mesh blocks properties used in this study.

| Mesh block no. | Cell size (m) | Number of cells | Captured domain          |
|----------------|--------------|-----------------|--------------------------|
| 1              | 0.08         | 714,375         | Whole model              |
| 2              | 0.02         | 571,520         | U-tube and fluid         |
| 3              | 0.02         | 3,328           | Inlet                    |
| 4              | 0.02         | 3,328           | Outlet                   |

Before conducting the numerical simulation, mesh quality was checked using Fractional Area/Volume Obstacle Representation (FAVOR) solver. The FAVOR solver is a unique tool which can be used to check the mesh quality and confirm whether the geometry was accurately captured [26]. Based on the FAVOR solver outcomes, it was found out that the selected cell sizes can capture all model geometries perfectly.

2.3. Initial and boundary conditions
In this analysis, soil and concrete pile temperature were defined with a value of 24 °C as initial condition. On the other hand, the fluid domain was set at temperature of 30 °C. Figure 5 and Table 3 provide a detailed description of the boundary conditions being used. To simplify the numerical simulation, mesh block 1 boundary conditions were defined with atmospheric pressure and 0 fluid fraction. Furthermore, to insulate the soil sides from outer environments, the sides boundary conditions were assigned with constant temperature equal to 24 °C.
3. Results and discussion

3.1. Variation of water temperatures at U-tube outlet

Figures 6a and 6b show the temperature changes with time at the outlet point of the U-tube for flow discharges of 0.009 m$^3$/s and 0.05 m$^3$/s, respectively. It was found out that the temperature values decreased gradually with time for all pipe diameters until reaching steady-state condition. Furthermore, it was observed that the U-tube with diameter of 26 cm was the most efficient when compared with other U-tube sizes (14 cm and 19 cm) for both flow discharges. This was due to the difference in terms of the area size that in contact with the heat source, at which pipe with diameter of 26 cm had the largest surface area.
reduction as compared to 0.050 m³/s. This observation matched the expectations, at which lower flow velocity inside the tube gave the opportunity to the injected water to become colder. The pipes tested under 0.009 m³/s flow discharge produced a temperature reduction of 0.3, 0.8, and 1.0 % for diameters of 14, 19, and 26 cm, respectively. On the other hand, the pipes tested under 0.05 m³/s flow discharge generated a temperature reduction of 0.1, 0.3, and 0.4 % for diameters of 14, 19, and 26 cm, respectively. It was observed that there was constant decrease in temperature for all pipe diameters.

Finally, it could be debated that slower flow rate allowed more heat transfer to occur between the U-tube, the pile, and the soil domains. On other words, there was a longer time for the water to transfer the heat coming from the water in the U-tube to the pile, then transferring the heat absorbed by the pile to the soil which carried a colder temperature, denoted as 24 °C. Similarly, the process was vice versa from the perspective of the soil. Temperature variations along the whole U-tube.

### Table 4. Temperature variations measured in the pipe outlet.

| Pipe inner diameter (cm) | Inlet water discharge (m³/s) | Inlet water temperature (°C) | Outlet water temperature (°C) | Temperature reduction (°C) |
|-------------------------|-----------------------------|-----------------------------|-------------------------------|--------------------------|
| 14                      | 0.009                       | 30                          | 29.90                         | 0.10                     |
| 19                      | 0.009                       | 30                          | 29.75                         | 0.25                     |
| 26                      | 0.009                       | 30                          | 29.71                         | 0.29                     |
| 14                      | 0.050                       | 30                          | 29.97                         | 0.03                     |
| 19                      | 0.050                       | 30                          | 29.91                         | 0.09                     |
| 26                      | 0.050                       | 30                          | 29.89                         | 0.11                     |

3.2. Variation of water temperature throughout the U-tube

Figures 7a-7c and 8d-8f illustrate the temperature changes through the whole U-tube length at the end of the numerical simulation (steady-state condition) at inlet flow rate of 0.009 m³/s and 0.05 m³/s, respectively. It can be observed that the water temperature at the inlets was the same and the maximum for all pipe diameters with a value of 30 °C. The water temperature decreased gradually at the locations after the inlet point to reach to the minimum value at the outlet point. Based on Figure 7, it can be seen that the water temperatures at the outlet points at flow discharge of 0.009 m³/s were lower when compared with those tubes with flow discharge of 0.05 m³/s.

3.3. Groundwater effects

Based on the results discussed in Sections 3.1 and 3.2, it was concluded that the lower flow discharge and higher pipe diameter were preferable and more efficient when compared with others. However, to deduce that the geothermal pile was assessed with both design and operational parameters to obtain the optimum configuration, all the pipes’ diameters were further assessed with the groundwater flow effect at flow discharge of 0.009 m³/s. The methodology of the simulation was like the previous models, but with an additional heat transfer coming from the colder soil temperature, which was affected by the groundwater, as previously explained in Section 2. Based on the results, it was observed that the pipe outlet temperature was reduced further with an addition of the soil affected by groundwater as expected. The pipes tested produced a temperature difference of 0.6, 3.6, 5.2 % for 14, 19, and 26 cm pipe, respectively. It was proven to be ultimately higher compared to the normal soil condition. In terms of pipe diameter, the 26 cm generated the highest temperature reduction out of the three pipes tested. Table 5 and Figure 8 summarize the results obtained from the modelling of the three U-tube sizes under the effects of the groundwater.
Comparing to the previous studies, most of the geothermal pile operations in cooling system were tested with soils having lower temperature than the ones obtained from Malaysia. This was inevitable because tropical climates were usually hot and humid, thus, having a constant soil temperature based on its average ambient temperature throughout the year. With the aid of groundwater flow in recharge zones
as tested by Yasukawa et al (2009), the soil temperature could decrease even further than the normal condition without the groundwater surrounding the soil. Hence, it could be judged that the performance of geothermal piles in cooling system increases with reducing soil temperature.

4. Conclusions
In this paper, the efficiency of geothermal piles in tropical countries was assessed through 3D computational fluid dynamics. Different pipe inner diameters (14 cm, 19 cm, 26 cm) were tested at two flow discharge rates (0.009 m$^3$/s and 0.05 m$^3$/s) under the effects of dry and wet soil conditions. The performance of the geothermal pile was measured based on the temperature reduction between the pipe inlet and pipe outlet. It was found out that the pipe diameter and flow rate played a main rule in terms of temperature difference and heat transfer rate. It was observed that the extracted geothermal energy increased with the decrement of the flow rate and increment of the pipe diameter. Pipe with diameter of 26 cm recorded the highest temperature reduction measured in the pipe outlet. The pipe inlet temperature denoted as 30°C was reduced to 29.71°C, which was equivalent to 1.0% temperature reduction. Besides, the soil moisture content had a significant effect on the temperature different between the inlet and outlet, at which the soil mixed with groundwater performed better when compared with dry soil. Finally, the results gathered and analysed has deduced that the combination of 26 cm pipe diameter, at 0.009 m$^3$/s flow rate, and the advection effect of groundwater temperature has produced an optimum condition for the geothermal piles in cooling system.

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