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Numerical Simulation of a Ground Heat Exchanger in Pile Foundation

Nasim Ahmed[1], *Ali Akbor Topu*[2,*], *Ashik Chawdhury*[3]
[1,2,3]Department of Mechanical Engineering, Khulna University of Engineering & Technology, Khulna-9203, BANGLADESH

ABSTRACT

In this work, the thermal performance of a vertical double-tube ground-coupled heat exchanger in a pile foundation has been investigated numerically in the cooling mode of operation suitable for the weather of Bangladesh. Pile foundation expedites the use of enormous stable energy of soil which provides a suitable temperature of 25 degrees under a depth of 7 or 8 meters persistent all over the world. The heat transfer rate of concrete is higher than soil thus pile foundation is suitable for harnessing ground energy. Therefore, pile foundation is compatible with every condition and in every place. A model that is axisymmetric in two dimensions was analyzed by using ANSYS Fluent. The rate of heat transfer, outlet temperature, and pressure drop was listed and briefly described for different models. For investigating the performance, 24 hours of continuous operation was considered. The temperature almost stabilizes at a depth of eight meters, according to the Kasuda Equation. Therefore, three different borehole length models of 10m, 15m, and 20m are compared at different flow rates for optimum performance. A velocity inlet-type boundary condition is applied in the inlet section and a constant pressure outlet is used in the outlet section. The operating pressure is set to 1 atm, and the temperature is considered 293.15K. The flow rates have been selected between 2 lit/min to 100 lit/min to measure the correlation between the heat transfer rate with the pressure drop. The heat transfer rate increases with the increase of the water flow rate, but the higher the flow rate, the higher the pressure drop. Higher pressure drop increases the pumping cost. Heat transfer and pressure drop are optimum for flow rates of 2 liters per minute to 5 liters per minute. The temperature difference between the inlet and outlet was increased when the borehole length was increased. In the design of the ground-coupled heat exchanger (GCHE), the heat exchange rate and pressure drop are crucial factors. Therefore, the result of this analysis can give constructive information for designing the ground-coupled heat exchanger (GCHE).

Keywords: Geothermal Energy, Double Tube Ground Heat Exchanger, Numerical Simulation, Heat Transfer rate.

1. Introduction

A particular type of heat exchanger in a pile foundation exchanges heat with both the concrete and the underground soil. Regardless of the winter or summer season the soil's temperature is essentially constant. In the summer, soil temperatures are lower than those of the atmosphere, whereas in the winter, soil temperatures are higher than those of the atmosphere. In the summer, a ground couple heat exchanger dissipates heat, and in the winter, it extracts heat.

The ground source heat pump (GSHP) systems are more environmentally friendly and have higher levels of efficiency. Ground source heat pump systems have become more appealing in residential and commercial buildings worldwide in recent years. The ground is used as a sink, a source of domestic hot water, and to heat or cool spaces. The ground is warmer than the atmosphere in the winter and cooler in the summer. The temperature of the ground becomes nearly constant after a certain depth. A pipe buried in the ground is the foundation of a ground-coupled heat exchanger (GCHE). Either vertical boreholes or horizontal trenches can be used to bury the heat exchanger. It is installed in a building or industry's underground.

The price of the equipment and the cost of installation are crucial factors in economic consideration. GSHP systems, despite having a greater initial cost, are the most energy-efficient heating and cooling technology since they use 25% to 50% less electricity [1] than other conventional heating and cooling systems. Worldwide, 35% of energy is utilized for HVAC and water heating in the single-building sector [2]. GCHE is primarily utilized for HVAC and other heating and cooling purposes, including ground coupled heat pumps, cooling ice, industrial usage, agricultural drying, green house heating, room heating, aquaculture pond and raceway heating, etc. [3]. Systems with ground-coupled heat pumps can also be combined with refrigeration, evaporative cooling, solar PV, etc. for cooling or heating purposes [2].

The overall installed capacity for geothermal use reported to the end of 2009 is 48,483 MWh, a rise of 72% from 2005 to 2010 at an annual compound rate of 11.4%. The overall annul energy consumption is 423,968 TJ (117,778 GWh), and between 2005 and 2010, it increased by 55%, or 9.2% annually [4].

When compared to other heating and cooling systems, ground-coupled heat pumps (GCHP) are the most effective. According to the US Environmental Protection Agency, this system is described as an energy star [5].

High energy efficiency and superior environmental performance are features of GCHE systems. The year-round clean, effective, and energy-saving heating and cooling is provided by ground coupled heat pumps (GCHPs), which cooperate with the environment. GCHPs

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* Corresponding author. Tel.: +88-01741623105
E-mail addresses: aatopu@gmail.com

save natural resources by using less energy than other heating and cooling systems. These are a crucial technological advancement for lowering emissions of harmful gases like carbon dioxide (CO2), sulfur dioxide (SO2), and nitrogen oxides (NOx).

When heat pumps are powered by renewable or hydroelectric energy, for example, emissions are reduced more than when electricity is produced by coal, oil, or natural gas power plants. The GCHP technology may cut CO2 emissions in both residential and commercial buildings by 15 to 77 percent. Compared to air-to-air heat pumps and other systems, GCHP is more efficient [6].

There have been numerous studies conducted in the topic of ground-coupled heat exchangers (GCHE) by researchers from around the globe. Ozudogru et al. [7] conducted an analysis of a 3D vertical GCHE model. For the examination of the geothermal down-hole heat exchanger, a novel numerical methodology has been introduced. This model aids in the proper utilization of geothermal reservoirs with low enthalpy [8]. Rui et al. [9] conducted research on how well a geothermal heat exchanger performed when groundwater advection and heat conduction were linked. Additionally, numerous numerical and simulation models have been developed. [10].

Environmental factors, soil temperature and characteristics, pressure drop, flow rate, heat exchanger length and diameter, among others, have a significant impact on the performance and cost-effectiveness of a GCHE installation. Ali et al [11]. The double tube heat exchanger was numerically improved based on pressure drop.

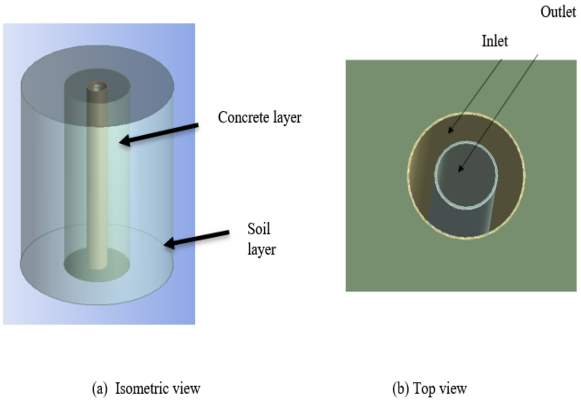
The usage of ground-coupled heat exchangers is widespread throughout the world. Geothermal district heating capacity has been growing in China at a rate of roughly 10% yearly. Geothermal heat pumps have been installed more frequently over the previous 15 years in the United States, with an estimated 100,000 to 120,000 equivalent 12 kWt units added in 2009. According to current estimates, there are at least one million installed units, mostly in midwestern and eastern states. [4].

There are no statistics that indicate Bangladesh is adopting ground coupled heat exchangers (GCHE) in comparison to other countries. A GCHE-based heat pump has a high COP and uses less energy. Use of a ground-coupled heat pump could result in significant energy savings in Bangladesh.
Consequently, the performance of ground-coupled heat exchangers is examined in the Bangladeshi environment.

2. Double Tube VGHE’s Simulation Modelling

2.1 Physical Model Configuration

The double-tube vertical heat exchanger consists of an inlet tube and an outlet tube. This double tube is set in a pile foundation on the ground. Concrete has a higher heat conductivity than soil. The outlet tube is set in the inner portion of the inlet tube. The outer pipe should be hard enough to resist the pressure when set in underground. The thermal conductivity of the outer pipe should be high and the inner pipe should be low. The thermal conductivity of concrete is more than soil. So, heat transfer may be high in the pile foundation. Fig.1shows the isometric view of a ground-coupled double tube heat exchanger in the pile foundation and soil layer.



(a) Isometric view (b) Top view

Fig.1 Isometric view (a) and Top view (b) between concrete & soil layer.

2.2 Physical properties of models

Table 1 Properties of materials used in the analysis

Materials	Density(kg/m3)	Specific heat(J/kg-k)	Thermal conductivity(W/m-k)
Copper (inlet tube)	8978	381	387.6
Polyvinyl chloride (outlet tube)	1300	900	.14
Slit	2038.74	1415.46	1.67
Concrete	2400	955	2.5

Table 2. Geometric description of GCHE models.

Model	Outer tube diameter (mm)	Inner tube diameter (mm)	Outer tube thickness (mm)	Inner tube thickness (mm)	Outer tube length (m)	Inner tube length (m)
M-1	130	40	5	5	10	9.9
M-2	130	40	5	5	15	14.9
M-3	130	40	5	5	20	19.9

2.3 Numerical Method for Optimization

To analyze the vertical GCHE, numerical simulations were run using ANSYS FLUENT, a commercial CFD program. 18.1. The governing equations are given below:

For 2D axisymmetric geometries, the continuity equation is given by:

$$\frac{\partial p}{\partial t}+\frac{\partial}{\partial x}(pv_x)+\frac{\partial}{\partial r}(pv_r)+\frac{pv_r}{r}=0 \qquad (1)$$

Where, Vx is axial velocity, Vr is radial velocity, ρ is density, t is time, x is axial coordinate, and r is radial coordinate

Equations (2) and (3) provide the axial and radial momentum conservation equations of 2D axisymmetric configurations

$$\frac{\partial}{\partial t}(pv_x)+\frac{1}{r}\frac{\partial}{\partial x}(rpv_xv_x)+\frac{1}{r}\frac{\partial}{\partial r}(rpv_rv_x)=-\frac{\partial p}{\partial x}+$$
$$\frac{1}{r}\frac{\partial}{\partial x}\left[r\mu(2\frac{\partial v_x}{\partial x}-\frac{2}{3}(V.v))\right]+\frac{1}{r}\frac{\partial}{\partial r}\left[r\mu\left(\frac{\partial v_x}{\partial x}+\frac{\partial v_r}{\partial x}\right)\right] \qquad (2)$$

$$\frac{\partial}{\partial t}(pv_r)+\frac{1}{r}\frac{\partial}{\partial x}(rpv_xv_r)+\frac{1}{r}\frac{\partial}{\partial r}(rpv_rv_r)=-\frac{\partial p}{\partial x}+$$
$$\frac{1}{r}\frac{\partial}{\partial r}\left[r\mu(2\frac{\partial v_r}{\partial r}-\frac{2}{3}(\nabla.v))\right]+\frac{1}{r}\frac{\partial}{\partial x}\left[r\mu(\frac{\partial v_r}{\partial x}+\frac{\partial v_x}{\partial r})\right]-2\mu\frac{v_r}{r^2}+\frac{2}{3}\frac{\mu}{r}(\nabla.v) \qquad (3)$$

Where pressure is represented by P, and viscosity is by μ,

$$\nabla.\mathrm{v}=\frac{\partial v_x}{\partial x}+\frac{\partial v_r}{\partial r}+\frac{V_r}{r} \qquad (4)$$

The energy equation is given by

$$\frac{\partial(ph)}{\partial t}-\frac{\partial p}{\partial t}\nabla.(\mathrm{pvh}=\nabla\left[\left(\mu+\frac{\mu_t}{Q_t}\right)\nabla\mathrm{h}\right] \qquad (5)$$

Where Qt is constant, t is the turbulence viscosity, and h is the enthalpy.

In the ground soil region, the energy transport equation given by

$$P_sC_p\frac{\partial T}{\partial t}=\nabla.(\mathrm{k}\nabla\mathrm{T}) \qquad (6)$$

Where P_s is the density of soil, Cp is the specific heat of soil, k is soil thermal conductivity, and T is temperature.

2.4 Numerical Simulation Procedure

In this analysis, ANSYS FLUENT has been used. First, the axisymmetric model is designed by the Design Modeler (DM). The model is shown in Fig. 2 with its concrete & soil layer and its symmetric axis. To get a more accurate result, the mesh should be done properly. For this purpose, Face meshing and edge sizing functions are used to get the appropriate mesh. Fine relevance center and high smoothing are also used. To get an accurate mesh, the face split function was also used. The mesh around and inside the GCHE tubes was densified by employing the bios mesh function in order to lower the overall mesh count and produce an accurate result, while gradually increasing the mesh size away from the GCHE tube. Fig.3 shows the mesh and densified area.

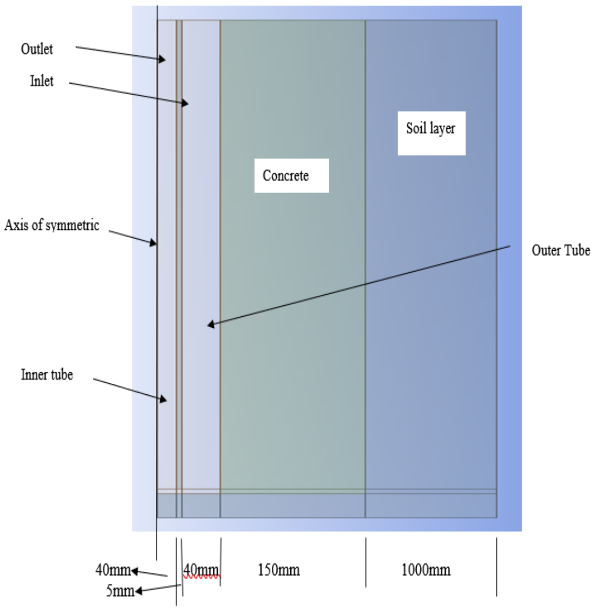


Fig. 2 2D axisymmetric model.

Double precision applied on Fluent set-up launcher. Pressure-Based, Absolute velocity formulation, transient time step, and axisymmetric solver have been applied. The gravitational acceleration effect is also considered. Energy equation and K-epsilon, standard, scalable wall function model are applied to solve the problem.

Velocity inlet type boundary condition applied in inlet section and constant pressure-outlet used in the outlet section. Operating pressure set into 1 atm pressure and operating temperature set into 293.15K.

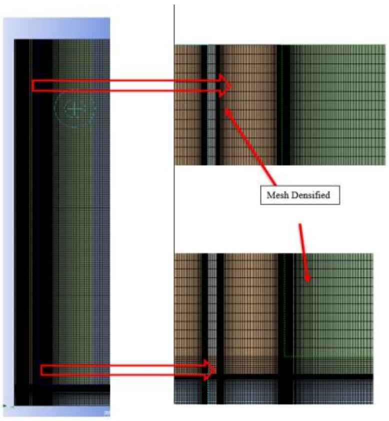


Fig. 3 Mesh of double tube GCHE.

2.5 Boundary and Initial Conditions

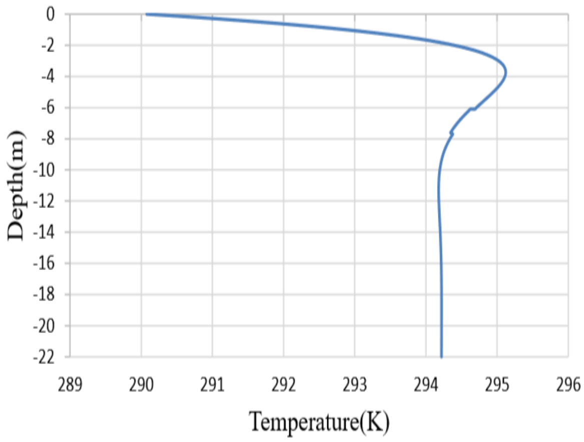
Input water temperature was adjusted at 308.15K, and the inlet flow rates of 1 lit/min, 2 lit/min, 3 lit/min, 4, 5, 6, 8, 10, 15, 30, 40, 60, 80, and 100 lit/min were taken into consideration. A constant uniform temperature of 293.15K was set on the upper surface. No heat flux was considered at the side wall from the center line and a bottom surface heat flux of 65 mW/m^2 was applied [13].

The ground temperature was calculated by Kasuda equation [14] on November 28, 2017, at Khulna University of Engineering &Technology, Khulna.

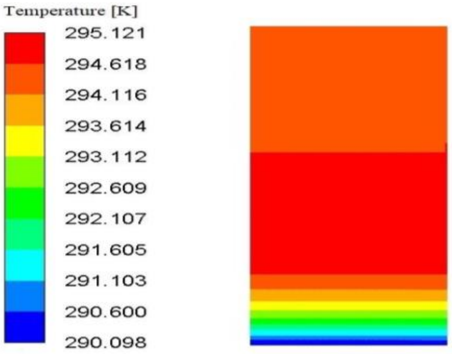
Kasuda [14] discovered that the relationship between the ground's temperature and the season and its depth underneath the surface may be characterized by the below relationship:

$$T = T_{\mathrm{mean}} - T_{\mathrm{amp}} \times \exp\left(-z \times \sqrt{\frac{\pi}{365 \times \alpha}}\right) \times \mathrm{Cos}\left(\frac{2\pi}{365} \times \left[t_{year} - t_{shift} - \frac{z}{2} \times \sqrt{\frac{\pi}{365 \times \alpha}}\right]\right)$$

Where:
T = Temperature
T_{mean}= Mean surface temperature (average air temperature)
T_{amp}= Amplitude of surface temperature (maximum air temperature minus minimum air temperature)
Z = Depth below the surface, α = Thermal diffusivity of the ground (soil)
t_{year} = current time (day), t_{shift}= day of the year of the minimum surface temperature



(a) Ground temperature profile.



(b) Temperature contour.

Fig.4 Initial condition for simulation models (a) ground temperature profile; (b) temperature contour

2.6 Mesh Elements Independence Test

To perform the mesh element independence test, a flow rate of 1 lit/min and an inlet temperature of 308.15K was considered. After 24h operation outlet temperature is shown in Table 3

Table 3 Outlet temperature after 24h operation

Model (Borehole length)	Number of Elements	Outlet Temperature(K)
M-1(10m)	36250	302.9728
	142800	**302.9619**
	202800	302.9678
M-2(15m)	135000	301.9611
	205200	**302.1732**
	261300	302.1601

M-2(20m)	108750	301.3492
	200850	301.427
	356850	**301.426**

The result shows that, with the increasing number of elements, outlet temperature will little change. In this study, **142800** elements were selected for M-1, **205200** elements were selected for M-2, and **356850** elements were selected for the M-3 model.

2.7 Model validation

In the present study, the model M-3 validated with the experimental result was done by Jalaluddin et al. at Saga University, Japan, and the numerical result of Jalaluddin et al.[12]. And the model M-3 is also validated with the numerical result of Ali et al. [11].

Table 4 Numerical and experimental results.

Flow rate(lit/min)	Present simulation (Ps) average heat transfer rate (W/m)	Experimental [12] (Ep)average heat transfer rate (W/m)	Hasan Ali et al. [11] simulation Average heat transfer rate (W/m)
2 lit/min	37.06	36.9	37.7
4 lit/min	50.82	47.414	51.7
8 lit/min	56.20	53.663	55.3

The average heat transfer rate of the present simulation compares with experimental and numerical simulations in Table 4. The present result shows a similar trend with experimental and numerical analysis. This comparison confirms good agreement of simulation model results with previous authentic results.

3. Result and Discussion

Pressure drop and average heat transfer rate of unit borehole length were considered for the performance test of a double tube vertical GCHE in the foundation pile. For every model 1 lit/min, 2 lit/min, 3 lit/min, 4, 5, 6, 8, 10, 15, 30, 40, 60, 80, and, 100 lit/min flow rates and 308.15K temperature were considered.

3.1 Outlet Temperature

When increasing the flow rate outlet temperature was increased. After starting the operation its outlet temperature gradually increased and approached the set value. For Model M-1, M-2, M-3, average outlet temperatures are shown in Fig.5. Outlet temperature increases rapidly from 1 to 20 lit/min then it becomes steady after 30 lit/min flow rate. Fig.6 illustrates the outlet temperature for different flow rates over a 24 hours continuous flow.

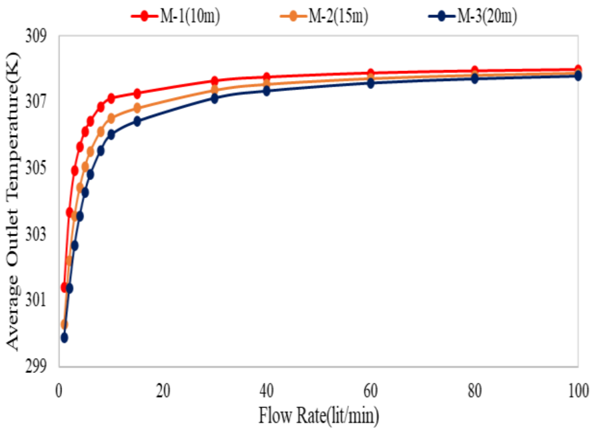


Fig.5 Model M-1, M-2, M-3 average outlet temperature for different flow rates.

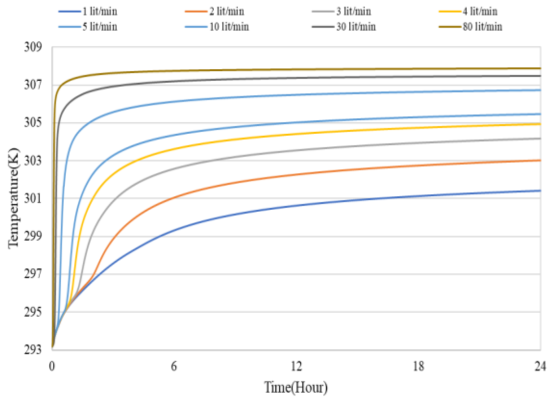


Fig.6 Outlet temperature at difference time of day for difference flow rates and 308.15K inlet temperature.

3.2 Heat Transfer Rate

The rate of heat exchange shows the GCHE's thermal efficiency. The heat exchange rate can be measured by

$$Q = m C_p \Delta T$$

where ΔT is the temperature difference between the water's entrance and output(K), Cp is the specific heat (J/kg K), and m is the mass flow rate (kg/s).

Following is the formula for the heat transfer rate per meter of borehole depth:

$$q = \frac{Q}{L}$$

where L stands for the borehole's length. Analysis of the average heat transfer rate using three conditions, such as borehole lengths of 10 m, 15 m, and 20 m was done over a continuous time of 24 hours.

Numerical simulation of a ground-coupled heat exchanger in pile foundation for models M-1, M-2, and M-3 for different flow rates. when increasing the flow rate, the average heat transfer rate also increases.

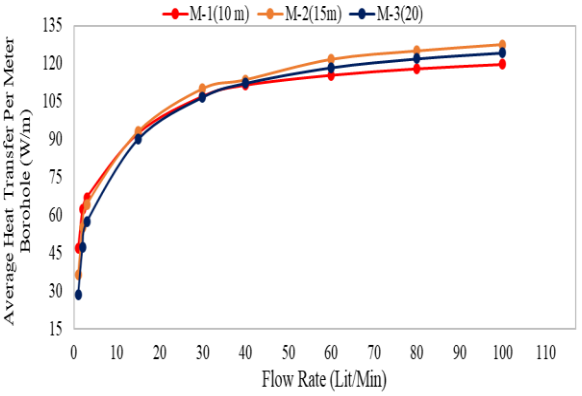


Fig.7 Model M-1, M-2, and M-3 average Heat transfer rate for different flow rates.

3.3 Pressure Drop

Pressure drop is also an important parameter for measuring the performance of GCHE. It can be calculated by the formula given below:

$$\Delta P = f_s \left(\frac{L}{D_H}\right) \times \left(\frac{\rho V^2}{2}\right)$$

where V is the fluid velocity (m/s), fs is the friction factor, ΔP is the pressure drop (Pa), D_H is the hydraulic diameter of the tube (m), L is the tube length (m), ρ is the density of the fluid (kg/m3).

For laminar flow, the Hagen-Poiseuille equation is used to measure the friction factor

$$f_s = \frac{64}{Re}$$

Blasius equation for turbulent flow:

$$f_s = \frac{0.316}{Re^{0.25}}$$

Again, there is a pressure drop created during the entering of water from the inlet tube to the outlet tube can be measured by

$$\Delta P_c = \frac{\rho(V_{0-}V_i)^2}{2}$$

where Vi is the velocity in the inlet tube and Vo is the velocity in the outlet tube.

The total pressure drop through the GHE is calculated by:

$$\Delta P_{total} = \Delta P_{inlet\ tube} + \Delta P_{outlet\ tube} + \Delta P_c$$

The total pressure drop between the inlet and outlet is a very important factor because a higher pressure drop increases the pumping cost. Fig. 8 illustrates the relationship between the total pressure and the flow rates.

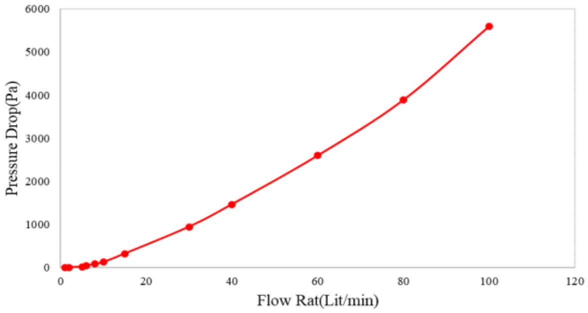


Fig.8 Total pressure drop at difference flow rates

Fig. 9 and Fig. 10 shows the pressure drop for different flow rate. Pressure drop is slightly high for 1 lit/min to 10 lit/min but is high for 10 lit/min and 40 lit/min flow rate. High-pressure drop increases pumping cost and required more power. So, 10 Lit/min to 40 lit/min flow rate should not be chosen. Flow rate between 1-10 lit/min is called laminar and for above 15 lit/min flow, it is called turbulent. Turbulent flow is not economical. So, the flow region should be laminar.

For 2-5 lit/min flow rate, heat transfer is quite sufficient and pressure drop is also in a reasonable range. On the basis of performance, it is suitable to choose a flow rate between 2 lit/min to 5 lit/min.

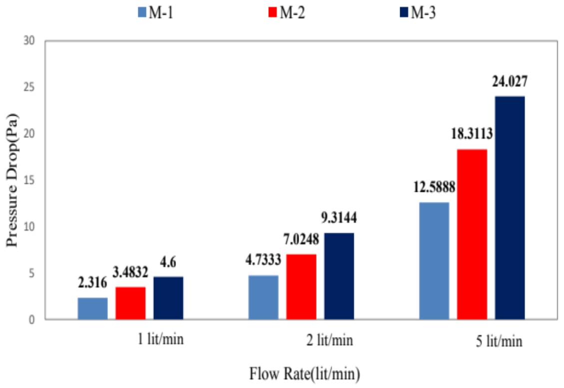


Fig.9 Model M-1, M-2, M-3 Total pressure drop for 1lit/min, 2 lit/min and 5 lit/min flow rate respectively

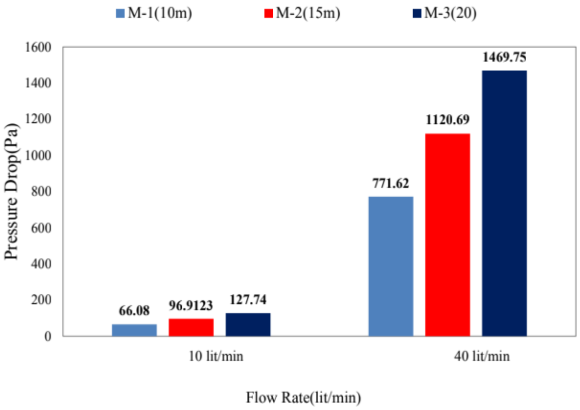


Fig.10 Model M-1, M-2, M-3 Total pressure drop for 10 lit/min and 40 lit/min flow rate respectively.

3.3 Optimization Evaluation

For 2lit/min average outlet temperatures were 304.9066K, 303.7427K, 303.0213K and the average heat transfer rate per meter borehole were 62.44(W/m), 55.3163(W/m), 47.34(W/m) and pressure drop were 4.733(pa), 7.024(pa), 9.3144(pa) respectively for model M-1(10m), M-2(15m), M-3(20m). Model M-2 outlet temperature and pressure drop have been moderately low. For 5 lit/min, its pressure drop is high with compare to the 2 lit/min flow rate. So M3 model should be selected with a 2 lit/ min to 5lit/min flow rate. For more economical running it's should below 5 lit/min flow rate.

4. Conclusion

Three axisymmetric models of vertical double tube GCHE in pile foundations have been studied. Firstly, the Ground-coupled heat exchanger was validated with the experimental result and numerical simulation result. The numerical findings align fairly well with the experimental outcomes. The initial and boundary conditions, soil's thermal characteristics, and other unknowable factors contributed to the slight difference between the experimental result and the numerical simulation result. Transient 24 hours continuous operation has been selected for the cooling mode in this study. The performance of vertical double tube GCHE in pile foundation has been analyzed on the basis of outlet temperature, pressure drop, and average heat transfer rate per unit borehole length. From the consequences of this examination, the accompanying ends are drawn:

- Pressure drop and average heat transfer are higher in double tube VGHE in pile foundation. It gives better performance than normal double-tube GCHE.
- Pressure drops are high for a 5 lit/min to 100 lit/min flow rate. High-pressure drop increases the pumping cost. Flow rates 1-10 lit/min are said laminar region because pressure drop is low in this flow region.
- Considering heat transfer rate and pressure drop 2 lit/min to 5 lit/min is an economical condition.

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NOMENCLATURE

c_p : Specific heat at constant pressure, kJ・kg^{-1}・K^{-1}
h : specific enthalpy, kJ・kg^{-1}
k : Thermal conductivity
Q : Heat transfer rate
q : Heat transfer rate per meter borehole length
COP: Coefficient of Performance