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Effect of Grout Thermal Conductivity and Leg-spacing on the Borehole Length of U-tube Ground Heat Exchanger

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ABSTRACT

This study explores the effects of grout thermal conductivity and leg spacing between a single U tube pipe on the borehole length of a ground-coupled heat exchanger, which is required to dissipate heat from a 1-ton air conditioner to the ground under the climatic conditions of Bangladesh. The result obtained from the zeroth-order multipole approach has been compared with first-order multipole, and Liao *et al.* methods to predict borehole length. Additionally, the impact of flow rate and inner pipe diameter on the pressure drop of U tube pipe has been evaluated here. Python-based simulations have been conducted to analyze them. The results demonstrate that increasing grout thermal conductivity significantly reduces borehole length—up to 31%—by minimizing grout thermal resistance. However, at higher conductivities, borehole length approaches an asymptotic behavior as other factors, such as ground thermal conductivity, dominate. Comparisons revealed that zeroth-order and first-order methods yield almost identical results, while minor deviations (<6%) occur with the Liao *et al.* method in the low-conductivity regime due to differing heat transfer assumptions. It has been investigated that larger leg spacings were shown to reduce thermal interference between U-tube legs, thereby shortening borehole lengths. The study also highlights that smaller pipe diameters lead to higher pressure drops, necessitating lower flow rates to minimize frictional resistance and higher pumping costs. However, ensuring sufficient flow rates to maintain turbulent flow is recommended for effective heat transfer. These findings underscore the importance of optimizing grout conductivity, leg spacing, and flow conditions to enhance borehole heat exchanger efficiency. The results provide a robust foundation for further research and practical applications in sustainable Ground Heat Exchanger (GHE) technologies over conventional air-cooling systems.

Keywords: Ground Coupled Heat Exchanger, U-tube Heat Exchanger, Grout Materials, Python Simulation.

1. Introduction:

Air source/sink HVAC systems have become a critical environmental concern due to their high energy consumption and contribution to global warming, especially in hot urban climates where air conditioning condensers account for up to 60% of greenhouse gas emissions [1]. As an alternative, ground coupled heat pump (GCHP) systems offer an eco-friendly solution with lower energy consumption, longer lifespans, and superior performance compared to conventional air conditioning. The ground maintains a consistent temperature all year round—warmer than the atmosphere in winter and cooler in summer at relatively shallow depths [2]. GCHP uses this stable ground temperature for efficient winter heating and summer cooling. A key component of these systems is the ground heat exchanger (GHE), which plays a critical role in determining overall performance, as well as installation and operating costs. In a GHE, heat is transferred via a heat carrier fluid circulating through a pipe into the borehole. For example, in cooling mode, the warm fluid absorbs heat from the indoor environment, which is then transferred into the surrounding cooler soil through conductive heat flow shown in Fig.1 [3]. The efficiency of this process is heavily influenced by the borehole's thermal resistance. A higher thermal resistance reduces the heat transfer rate between the fluid and the earth, necessitating a longer borehole and increasing drilling and piping costs [4]. Minimizing borehole thermal resistance is therefore, a critical design goal. This can be achieved by improving the thermal conductivity of the grout (the material filling the borehole) and reducing thermal interference between the pipes within the borehole. There are usually three types of GHEs used: coiled, vertical, and horizontal. The efficiency of the BHE is nearly proportional to the thermal conductivity of the grout in all varieties [5]. So, researchers are interested in investigating new grout materials with high thermal conductivity incorporating water saturation and additives like mixture of concrete, clay, lime, graphite, fly ash, sand, etc. with conventional cementitious and bentonite materials [6]. For example, Jobmann *et al.* [7] investigated that 14% water and 15% graphite with pure bentonite could increase thermal conductivity by 3 W/ m. K. On the other hand, bentonite with 30% graphite could increase thermal conductivity by 3.5 [3]. Thermal conductivity became 5 W/m. K when only 5% graphite was used [8]. Delaleux *et al.* [8] claimed that Bentonite with 95% graphite could enhance thermal conductivity up to 11.5 W/ m.K, potentially leading to critical increases in the grout viscosity and cost. Allan *et al.* [9] demonstrated that incorporating fillers such as alumina grit, steel grit, silica sand, and silicon carbide with cement could enhance thermal conductivity from 1.7 W/m· K to 3.3 W/m· K.

Pressure drop is another important factor when considering overall system performance. Ali *et al.* [10] investigated pressure drop for different inlet and outlet diameters and

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flow rates of double (coaxial) tube pipe. They investigated that a double tube is more effective for laminar flow.

Jalaluddin and Miyara *et al.* [11] evaluated the thermal performance and pressure drop of the spiral-tube GHE numerically. Qi *et al.* [12] evaluated U-tube GHE configurations using CFD simulations, finding that series setups resulted in 20-36% higher pressure losses compared to parallel configurations. Besides, conventional triple-helix GHEs can achieve up to 147 times lower pressure losses than traditional helix GHEs [13].

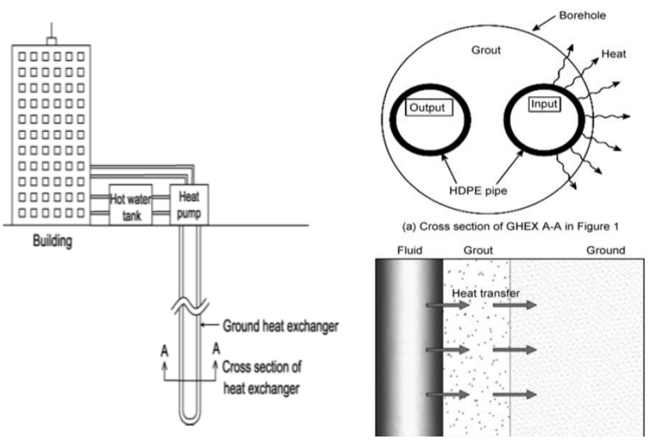


Fig.1 Closed loop vertical U-tube GHE and its heat transfer mechanism at cooling mode [3].

GCHP holds excellent potential for Bangladesh, particularly in urban areas and large commercial buildings with substantial cooling demands from its geographic point of view. Several research studies have been conducted to investigate the performance of GHE in Bangladesh's climate. Ahmed *et al.* [14] investigated the thermal performance of a vertical coaxial ground-coupled heat exchanger in a pile foundation using ANSYS fluent. Ahammad *et al.* [15] performed an experimental analysis of heat transfer rate for different flow rates of a vertical double-tube ground-coupled heat exchanger with no grout. The thermal performance of a U-tube Ground Heat Exchanger with a concrete foundation pile between U-legs was demonstrated by Lubaba *et al.* [16]. However, no significant work has been found to examine the impact of grout materials and heat exchanger dimensions on borehole length in the climate of Bangladesh. The current research study presents how the thermal conductivity of grout material and the spacing of single U-tube legs impact the borehole length required to release heat from a 1-ton residential air conditioner into the ground for the climate of Bangladesh. An optimum range for grout conductivity and U-tube leg spacing have been investigated to find suitable borehole length through Python simulation. Additionally, the impact of flow rate and inner pipe diameter on pressure drop are discussed here.

2. Methodology

Zeng *et al*. [17] stated that the heat transfer process in GHE can be analyzed in two separate regions: (1) Ground soil outside the borehole, where the heat conduction of soil needs to be treated as a transient process. (2) Inside the borehole including the grout material to fill the borehole, U-tubes, and the circulating fluid inside the pipes, the heat transfer approximately becomes a steady-state process after a few hours of operation [15], shown in Fig.2(a). Since the borehole depth is much larger than its diameter, so the borehole is considered as a one-dimensional infinite line source where heat is transferred radially [18]. To keep the problem analytically manageable, some simplifications are assumed to analyze heat transfer inside the borehole. They are:

(a) The ground outside the borehole is homogeneous and involving all the thermal properties are independent of temperature.
(b) Initial condition of the ground is equal to undistributed ground temperature i.e $T(r,t)= T(r,o)=T_g$
(c) In the far field ground temperature is considered constant as before starting the operation.
(d) Thermal short-circuiting among U-tube legs has been considered in this paper.
(e) The impacts at the soil surface, groundwater, and bottom of the U-tube are ignored.

There are several methods to solve borehole resistance for borehole length calculation. Hellström *et al.* [19] proposed 1st order multiple method as

$$R_b' = \frac{1}{4\pi k_g}\left[\beta + ln\left(\frac{\theta_2}{2\theta_1(1-\theta_1^4)^{\sigma}}\right) - \frac{\theta_3^2\left(1-\frac{4\sigma\theta_1^4}{1-\theta_1^4}\right)^2}{\frac{1+\beta}{1-\beta}+\theta_3^2\left(1+\frac{16\sigma\theta_1^4}{(1-\theta_1^4)^2}\right)}\right]$$

Liao *et al*. [20] presented another expression to determine the borehole resistance, which is related to ground conductivity,

$$R_b' = \frac{1}{2\pi k_g}\left[(-0.185\theta_1 + 0.0663)\ln\left(\frac{k_s}{k_g}\right) + (0.545\ln\theta_2 - 0.335\ln\theta_1 - 0.353)\right] + R_p'/2$$

Where $\theta_1 = \frac{s}{2r_b}$, $\theta_2 = \frac{r_b}{r_o}$, $\sigma = \frac{k_g - k_s}{k_g + k_s}$. $\theta_3 = \frac{r_o}{s} = \frac{1}{2\theta_1\theta_2}$, $\beta = 2\pi k_g R_p'$

In this paper zeroth order multipole approach has been used to investigate borehole resistance because of its simplicity and accuracy [17,21- 23]. Then the obtained result has been compared with other approaches. For zeroth order multipole method, total borehole thermal resistance per unit length of a single U-tube pipe,

$$R_b' = \frac{1}{4\pi k_p}\left[ln\frac{r_b}{r_o} + ln\frac{r_b}{s} + \frac{k_g - k_s}{k_g + k_s}ln\left(\frac{r_b^4}{r_b^4 - (0.5s)^4}\right)\right] + \frac{R_p'}{2}$$

Pipe resistance, $R_p' = \frac{1}{2\pi k_p}ln\frac{r_o}{r_i} + \frac{1}{2\pi r_i h_f}$

Heat transfer coefficient of fluid, $h_{\text{conv}} = \frac{Nu \cdot k_f}{d_i}$, In laminar flow, Nusselt number, Nu is 4.36 for uniform heat fluxan 3.66 for uniform wall temperature. For fully developed turbulent flow:

$$Nu = 0.023Re^{0.8}Pr^{0.3}, \quad (0.7 < Pr < 160;\ Re > 10^4)$$

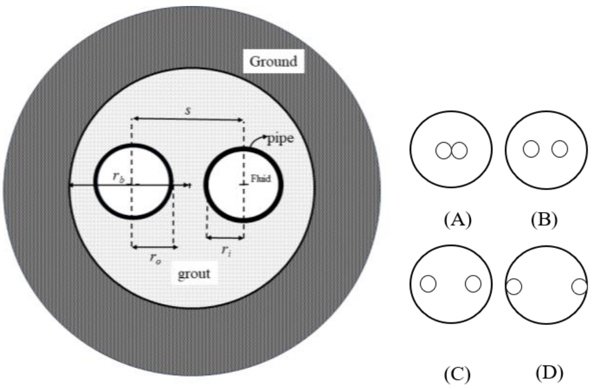
Soil resistance over time, $R_g' = \frac{1}{4\pi k_s}E_1\left(\frac{r_b^2\rho_s c_s}{4k_s t}\right)$

Borehole length, $H = \dfrac{Q(R_b' + R_g')}{\Delta T_f}$

Calculation of pressure drop inside the pipe:

$$\Delta P = f \cdot \frac{(2*H)}{d_i} \cdot \frac{\rho_f v_e^2}{2}$$

In laminar flow in the tube: $f \cong 64/Re$. *Blasius* formulation for turbulent flow in the tube: $f \cong 0.3164Re^{-0.25}$.



(a) (b)

Fig.2 (a). Schematic diagram of borehole thermal resistance and **2(b).** Different configurations of spacing between legs.

For the analysis, Python 3.11.10 has been used with input values for design conditions and material properties described in Table 1. Here, the cooling load of GHE was set at 3520 W (equivalent to a condenser load of a 1-ton residential air-conditioning system), which lasted 8 hours per day from March to October during hot weather in Bangladesh considering 10 years simulation period. Water has been used as the working fluid, with an average temperature of 35.5°C. A single U-tube pipe has been used for the simulation as a heat exchanger and thermally enhanced HDPE pipe with nano-carbon instead of typical HDPE pipe [24]. The spacing configuration between the two legs of the U tube has been shown in Fig.2(b) with values 0.032m(A), 0.064m(B), 0.096m(C), and 0.1204 m(D). The simulations have been conducted using an undisturbed ground temperature of 20.5°C [25]. In areas of the Ganges Delta, soil conductivity is 2.45 W/m. K has been taken in this paper [26]. Soil density and heat capacity values have been taken from [27]. Several grout conductivity samples have been collected from various literatures [3-5,7-9,22,28-30] described in Table.2.

NumPy, SciPy, Panda, and Matplotlib libraries have been used in this paper. After inputting the parameters described in Table.1, convective heat transfer, pipe thermal resistance, borehole, and soil thermal resistance have been calculated using the above equations. Then, the required borehole length has been calculated, summing up the total thermal resistance. After that calculations have been performed iteratively for multiple grout conductivities and pipe spacings to observe their effects on borehole length on the plot.

For different flow rates (e.g. 1.8 L/min to 72 L/min) varying with pipe inner diameters shown in Table.3 [31] (i.e.25.9 mm, 27.4 mm, 29.5 mm, and 32.85 mm), pressure drop has been calculated from the above equation. All constants of fluid properties, borehole length, pipe diameters, and flow rate range have been defined. Iteration has been performed over pipe diameters to compute pressure drops for a range of flow rates using fluid velocity, Reynolds number, and Darcy-Weisbach equation. Then a series of graphs have been plotted showing the relationship between flow rate and pressure drop for each pipe's internal diameter.

Table 1. Values of different input parameters.

Parameters		Values
Cooling load	Q	3520 W
Fluid flow rate	V	6 L/min
Fluid density	ρ_f	1000 Kgm^{-3}
Fluid specific heat	c_p	4186 Jkg^{-1} K^{-1}
Fluid thermal conductivity	k_f	0.6 Wm^{-1} K^{-1}
Dynamic viscosity	μ	0.001 Pa. s
Average fluid temperature	T_f	35.5 °C
Soil density	ρ_s	2100 kg m^{-3}
Soil specific heat	c_s	1459 J kg^{-1} K^{-1}
soil thermal conductivity	k_s	2.45Wm^{-1} K^{-1}
Soil temperature	T_g	20.5 °C
Borehole diameter	D_b	0.1524 m (6 in)
HDPE thermal conductivity	k_p	0.7 Wm^{-1} K^{-1}
Outer diameter of U-tube pipe	d_o	0.032m
Inner diameter of pipe	d_i	0.027m
U-tube leg Distance (center to center)	s	0.032, 0.064, 0.096,0.1204 m

Table 2. Thermal conductivity of grout material.

Grout material	Thermal Conductivity (W/m. K)	Grout material	Thermal Conductivity (W/m. K)
20%Bentonite	0.73	Cement -sand	1.70
Cement Mortar	0.78,0.84,0.95	Al cement detritus	2.04
Pure bentonite	0.69	Cement Portland sand shavings	2.20
Cement +sand (S/C=0.5)	1.28	Al cement sand shavings	2.789
Concrete 2100 kg/m³	1.04	30% Bentonite	0.74
20%pulverized fuel ash+ fine sand, mixed ground glass	1.15,1.39	Homemade admixture,5%natural graphite	2.30
30% Bentonite - 30% Quartzite	1.30	Home-made admix-ture, Synthetic graphite 150 mm 5%	2.50
30% Bentonite - 40% Quartzite	1.47	Cement, silica sand and graphite	2.65
60% Quartzite -Flowable Fill (Cement+ Fly Ash + Sand)	1.85	20%pulverized fuel ash+ fluorspar, coarse sand,	2.88,2.47
Concrete (50% Quartz Sand)	1.90	Sand+3.5% Aluminum shavings	3.62
Homemade admixture, Graphite 0%	1.50	Sand+0.5% Aluminum shavings,	3.752
Sand+0.5% Aluminum shavings	3.27	30% graphite + bentonite	3.50
15% graphite +bentonite	3.0	5% graphite + bentonite	5.0

Table 3. Pipe Specification [31].

SDR	Internal Diameter (mm)	Pressure Rating (bar)
SDR9	25.9	13.8
SDR11	27.4	11.0
SDR17	29.5	6.9
SDR 9	32.85	13.8

3. Results and Discussions:

3.1 Impact of grout conductivity and spacing on borehole length

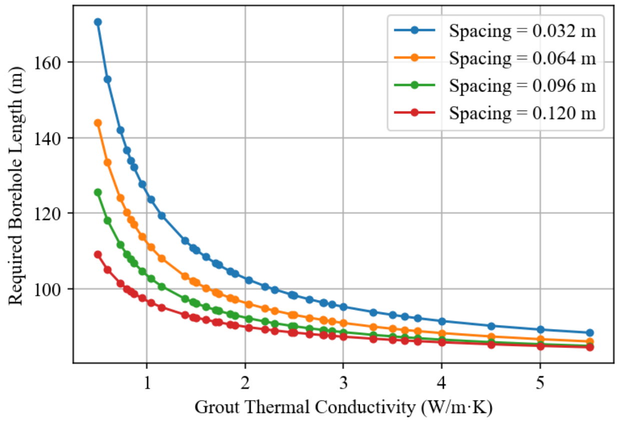


Fig.3 Variations of borehole length with grout thermal conductivity for various spacings.

The variations of borehole length with the grout thermal conductivity (W/m. K) are shown in Fig. 3 for several leg-spacing values. The borehole length (m) is a critical parameter in GSHP design and each curve corresponds to a specific pipe spacing value. As grout thermal conductivity increases, the borehole length decreases significantly. This is due to minimizing the thermal resistance in the grout. This result has been validated by Treviño *et al.* [32], who performed four thermal response tests (TRT) in a similar geological area and each borehole is filled with a different grout mix. They demonstrated the reduction of the thermal resistance of grout mixture with increasing thermal conductivity of grout. However, at higher grout conductivities (>2.5 W/m. K), the borehole length approaches asymptotic behavior, which means a reduction of borehole length is not significant, though the curves are steeper at lower grout conductivities. For instance, the length of the borehole decreased up to 31% when the cement-sand (1.7 W/m. K) was used in the GHX in place of neat cement (0.84 W/m. K). Allan *et al.* [28] also obtained the same result. But when the conductivity increases from 3.0 W/m. K to 5.5 W/m. K, change of borehole length is highest 7% only. Because with the increase of additive mixture in grout materials, viscosity increases and beyond a certain point, increasing thermal conductivity of grout has little effect on total resistance due to ground resistance becomes the bottleneck. The curve also represents smaller spacing values (e.g., 0.032 m) has longer borehole length for a given grout conductivity. This occurs because reduced spacing increases thermal interference between the pipes, reducing borehole length. Larger spacings (e.g., 0.1204 m) reduce thermal interference, requiring shorter borehole lengths, even at lower grout conductivities. There is interesting information we can observe from Fig.5 that with the increase of grout thermal conductivity (>3.5 W/m. K), the effect of tube leg spacing ($2d_o<s$)on borehole length becomes minor. It means at that condition length didn't change significantly. Under the current conditions of dissipating heat to the ground for a 1-ton air conditioner in the Bangladeshi climate and geology, selecting grout with a thermal conductivity of 2.8-3.3 W/m·K and a spacing of 0.096 meters can shorten the borehole length to 85.75 meters, without causing thermal interference, grout viscosity issues, or increasing costs.

3.2 Compare the result with other methods:

A comparative analysis of borehole length as a function of grout thermal conductivity has been presented in Fig.4. The results from the current study, computed using the zeroth-order multiple method, are compared against those derived from the first-order multiple method [19] and Liao *et al.* [20]. As illustrated in Fig. 4, the zeroth-order and first-order multipole methods yield nearly identical results across all grout conductivity levels. However, slight deviations less than 6%—are observed in comparison with the Liao *et al.* [20] method in the low-conductivity regime. The probable reason can be because of their assumptions about heat transfer might handle the inefficiency of low-conductivity grout differently. Notably, as grout conductivity increases, the deviations diminish, and all methods converge. This convergence occurs because, at higher grout conductivities, heat transfer is predominantly governed by factors other than grout properties, such as the thermal resistance of the surrounding soil or the pipe configuration. These findings align with conclusions drawn by Desmedt *et al.* [33] and Javed *et al.* [34], further supporting the validity of the numerical analysis presented in this study.

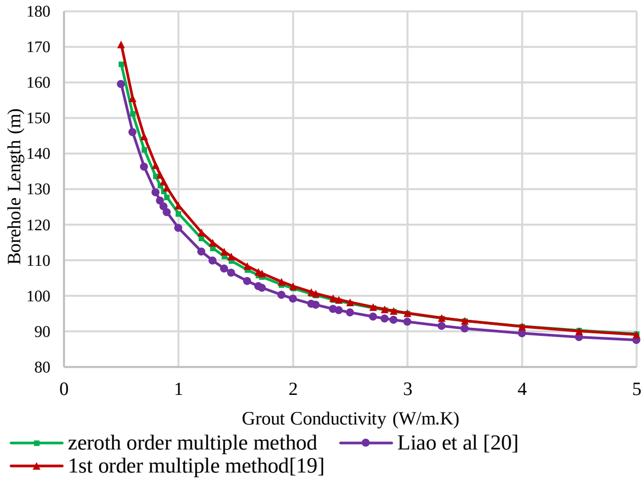


Fig.4 Comparison of methods for 32 mm pipe diameter and 32mm leg spacing.

3.3 Pressure drop for different pipe diameters and flow rates

In Fig.5**,** the horizontal axis represents the flow rate, measured in cubic meters per second (m^3/s), and the vertical axis shows the pressure drop per unit length, measured in Pascals per meter (Pa/m), which reflects the resistance to flow in the pipe. The four curves represent the performance of the U-tube heat exchanger with pipes of different diameters. From the graph, it can be observed that smaller diameters have higher pressure drop due to greater frictional resistance, which requires more pumping work to overcome, but it enhances turbulence and heat transfer rates due to higher flow velocities. At low flow rates, the pressure drop is minimal for all diameters. On the other hand, at higher flow rates, pressure drop becomes a dominant factor, especially for smaller diameters (e.g., 25.9 mm). This would increase the energy demand for circulating the fluid, impacting operational efficiency. Table. 4 shows the critical laminar flow pressure drop. It illustrates that though the pressure drop in a laminar flow rate is minimal, it is recommended to run pump above the critical laminar flow threshold to ensure sufficient turbulent flow to increase the inlet and outlet pipe temperature so that it can work efficiently in all ground conditions. Banks *et al.* [35] recommended operating ground loops at a pressure of 2-3 bar. Be careful pressure rating of pipe can't be exceeded and minimize pumping costs varying with different pipe diameters.

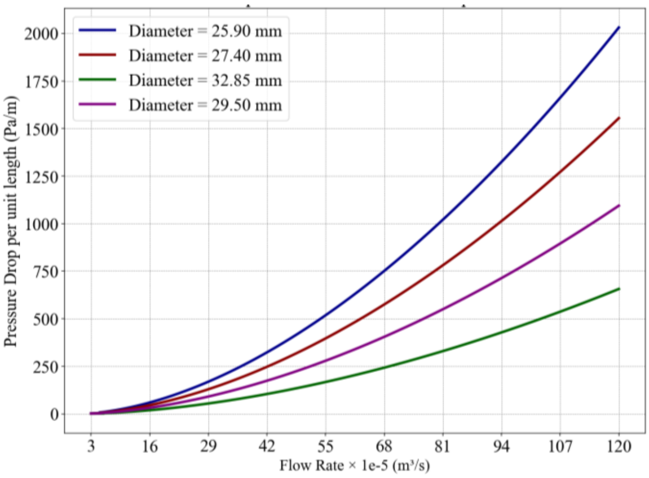


Fig.5 Pressure drop per unit length and flow rate variation for different pipe inner diameters.

Table 4. Pressure drops per unit length at critical laminar flow rate.

Pipe inner diameter(mm)	Critical laminar flow rate (L/min)	Pressure drops per unit length (Pa/m)
25.9	2.80717	4.236
27.4	2.9697	3.5778
29.5	3.1973	2.86689
32.85	3.5604	2.0762

4. Conclusion

This study investigated the effects of grout thermal conductivity and single U-tube leg spacing on borehole length for dissipating heat from a 1-ton residential air conditioner to the ground under the climate conditions of Bangladesh using Python simulations. Additionally, different borehole resistance methods were compared to calculate borehole length, and the influence of pressure drop on flow rate and inner pipe diameter was analyzed.

The key findings reveal that

a) Increasing the grout's thermal conductivity significantly reduces borehole length—up to 31%—by minimizing the grout's thermal resistance. However, at higher conductivities, the borehole length approaches an asymptotic behavior.

b) Zeroth-order and first-order methods produce nearly identical results across all conductivity levels, with slight deviations (<6%) observed in the low-conductivity regime when compared to the Liao *et al.* [20] method. The deviation is due to different assumptions about heat transfer might handle the inefficiency of low-conductivity grout.

c) Larger leg spacings (e.g., 0.1204 m) reduce thermal interference between the U-tube legs, resulting in shorter borehole lengths.

d) Choosing grout of thermal conductivity is 2.8- 3.3 W/m. K and 0.096 m spacing can shorten borehole length to 85.75 meters in such conditions to avoid higher viscosity of grout and cost.

e) Smaller inner pipe diameters lead to higher pressure drops due to increased frictional resistance, necessitating lower flow rates to minimize energy losses.

f) Flow rates must be kept more than critical flow rates to ensure turbulent flow for effective heat transfer.

These insights emphasize the critical importance of optimizing grout conductivity, leg spacing, and flow conditions to enhance the efficiency and performance of borehole heat exchangers. Future research could explore long-term operational impacts considering different soil layers, groundwater, temperature variation per depth of ground, and seasonal influence on near-surface of the ground, alternative materials, and cost analyses to further refine the design and applicability of such systems in varied climatic conditions.

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NOMENCLATURE

$T(r,t)$	: Temperature distribution
T_g	: Undisturbed ground temperature
R'_b	: Steady-state borehole thermal resistance per unit length (m KW^{-1})
R'_p	: Pipe thermal resistance per unit length (m KW^{-1})
ΔT_f	: Change in fluid temperature of heat carrier fluid
k_g, k_p, k_s	: Thermal conductivity of grout, pipe and soil respectively ($Wm^{-1} K^{-1}$)
$\theta_1, \theta_2, \theta_3, \sigma$	: Dimensionless parameters
c_p, c_s	: Specific heat of soil (J $kg^{-1} K^{-1}$)