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Thermal Performance Analysis of Coaxial Borehole Heat Exchangers Under Variable Design Parameters

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ABSTRACT

Geothermal energy plays a vital role in the energy transition due to its low environmental impact and sustainable nature. In shallow geothermal applications, borehole heat exchangers (BHEs), which facilitate heat exchange with the ground, are among the most critical components that directly influence system efficiency. Professionally designed BHE systems enhance the usability of low-temperature geothermal resources and contribute to the reduction of carbon emissions. BHEs are classified into U-tube, coaxial (concentric), and spiral (helical) types. While U-tube systems offer advantages in terms of low cost and ease of installation, coaxial systems provide higher heat transfer efficiency. Spiral designs are suitable for compact installations in limited spaces. This study investigates the energy capacity of coaxial borehole heat exchangers composed of two concentric pipes. Under conditions of 30 °C inlet fluid temperature and a constant bedrock temperature of 12.2 °C, various configurations with different pipe lengths, geometries, materials (aluminum, stainless steel and PVC), and flow rates (500, 1000, 1500, and 2000 L/h) were modeled using Engineering Equation Solver (EES) software. The analysis revealed that aluminum and stainless-steel materials provide significantly higher thermal capacity compared to PVC, and that the increase in depth and flow rate directly improves system performance. Reducing the inner tube diameter has also increased BHE thermal capacity by creating a larger annular area for heat transfer.

1 INTRODUCTION

Global warming and air pollution caused by fossil fuel consumption necessitate the reshaping of energy policies around the world. Building heating and cooling systems constitute the largest energy consumption sector worldwide (Fang et al. (2018)). In this context, geothermal energy, which is a sustainable, low-carbon dioxide, abundant, and reliable energy source, has become an important focus of interest in recent years (Cui et al. (2024), Lund and Toth (2021)). Ground-source heat pump (GSHP) systems have been met with increasing interest in recent years in terms of energy efficiency and environmental sustainability, and they have become widespread as an effective alternative, especially in building cooling and heating. As of 2023, the installed capacity of GSHP systems reached 77,547 MWt worldwide, with annual energy utilization of 599,981 TJ/year; These values represent 71.6% of the total geothermal installed capacity and 59.2% of the annual geothermal energy use (Lund and Toth (2021)). BHEs, which are the heart of ground source heat pump systems, are critical components that transfer heat between the soil or rock environment and the working fluid, and perform the function of extracting heat underground or storing heat underground. BHE finds wide application in mountainous areas where the use of alternative systems is difficult due to snow load and climatic conditions, in city centers where surface area is limited, in meeting the heating and cooling needs of residential and commercial buildings in integrated systems with complementary technologies such as air source heat pumps, solar collectors, cooling towers. BHEs enable the removal of excess heat from the building underground during the summer months and the recovery of stored thermal energy underground for heating purposes during the winter months. The thermal efficiency of BHEs directly affects the performance of the entire GSHP system and plays a fundamental role in determining the Coefficient of Performance (COP) of the heat pump (Brown et al. (2024)). Each degree of temperature difference in the fluid flowing from the well can cause a 2-3% change in the performance coefficient of the heat pump (Yang et al. (2010)). Therefore, it is of paramount importance to develop cost-effective, easy-to-install, and thermally efficient BHE designs that are characterized by low temperature differences between the heat carrier fluid and the surrounding rock.

BHEs can be classified into various categories based on their depth and configuration. In the Depth-Based classification, systems typically used at depths up to 200 meters are called "Shallow (S)", those operating in the depth range of 200-1500 meters are called "Medium-Shallow (MS)", and those operating at depths of 1500-4000 meters and above are called "Deep (D)" BHEs. Shallow BHE is widely preferred in conventional GSHP

applications. While MS-BHEs offer higher heat exchange capacity and better stability against heat imbalances than shallow systems, drilling technology in this depth range is highly mature and has a high success rate (Guo et al. (2016)). Deep BHE offers significant heat extraction capacities by leveraging high geothermal gradients. Studies have shown that the heat exchange rate increases from 235 kW to 1,061 kW when the depth increases from 2,000 meters to 4,000 meters (Xia et al. (2023).

There are two main categories in configuration-based classification, U-Tube and Coaxial Tube. U-Tube BHEs are the most commonly used type of BHE and consist of two equal cylindrical tubes that go down the well through which the heat carrier fluid passes and joined at the bottom**.** The simplest and most economical configuration is Single U-Tube, which uses a single pipe. A Double U-tube configuration is also available, providing better hydraulic performance and heat transfer capacity by using four tubes.

U-Tube BHEs are low cost, readily available in the market and offer easy installation; however, uncontrolled positioning of pipes in the well can lead to problems such as improper placement of channels relative to the well wall, thermal shunt flow, and high pipe resistance. In addition, the bentonite filling process, which is mandatory in most countries, both increases the cost and can limit thermal conductivity.

Another variety in configuration-based classification is Coaxial Tube BHEs (CBHEs). CBHE systems, consisting of a central inner tube and outer ring channel, have come to the fore as an alternative design in recent years. The working fluid descends down the inner tube and the fluid returning from here exchanges heat with the surrounding formation as it moves upward in the outer annular region. The major advantage of the coaxial design is that it exhibits lower thermal resistance due to the outer pipe (tube) being in close contact with the well wall, and the heat transfer surface area is large. In addition, the thermal short circuit effect can be significantly reduced by isolating the inner pipe in some models. CBHEs offer higher heat extraction rates, especially in medium-shallow and deep geothermal applications. Lower pressure drops due to better hydraulic properties and the use of laminar flow. However, these systems have a higher initial investment cost than U-pipe systems and are not as widespread in the market.

The thermal efficiency of BHE systems is influenced by many design and environmental parameters. Many scientific studies have been conducted on this subject.

In the study conducted by Acuña and Palm (2010), a new coaxial BHE was designed with a 189-meter-deep central inner tube and annular tube in direct contact with the surrounding rock; distributed thermal response testing (DTRT) was performed using fiber optic cables and fluid temperature measurements were taken every 10 meters and compared to conventional U-tube BHEs. The researchers directly measured the well wall temperature with fiber optic technology; They found that the coaxial system is simple to install, with 50% of the heat being transferred as it passes through the central pipe. In addition, it was stated that the heat exchange in the U-pipe system took place mostly in the downward direction (75%) and thermal shunt effects were seen in the upper parts. The findings show that the well wall temperature profile follows the flow almost perfectly (with a difference of only 0.4°C); the heat transfer performance through the tube is extremely effective; It showed that thermal short-circuit flow occurs especially in the upper 40 meters, and that this system can allow the use of water instead of antifreeze solutions even in cold countries. In future studies, it is aimed to reduce the resistance of the well by testing inner pipe alternatives. The researchers emphasized that the new coaxial design offers significant advantages in terms of both ease of installation and the ability to use environmentally friendly fluids such as water.

Gao et al. (2025) investigated the heat transfer coefficients, fluid temperature profiles, and thermal resistance values of single-U-tube, double-U-tube, and coaxial tube BHEs for geothermal energy utilization at medium-shallow depths; They have developed a quasi-3D heat transfer model and have been validated by field experiments. The findings show that MSBHEs offer much higher heat transfer capacity per well than traditional shallow systems and can meet both cooling and heating modes; It has shown that initial investment costs can be significantly reduced by minimizing the total well length with optimum depth calculations. The researchers stated that these results constitute an important reference in terms of increasing the energy efficiency of heat pump systems and optimizing well designs, and that coaxial structures can be a suitable alternative to U-pipe systems in shallow geothermal applications.

In the study conducted by Song et al. (2018), in order to evaluate the heat extraction performance of deep coaxial BHEs, a steady-state heat transfer model was developed, and a numerical solution was performed using the

finite difference method (FDM) with a fully implicit scheme. The researchers studied the dynamic behavior of the reservoir temperature field; They have optimized the effects of critical parameters such as flow rate, thermal insulation length, cementing length, and reservoir conditions on heat extraction performance. The model has been validated by experimental data, and the results have shown that determining the optimum flow rate, deeper wells are beneficial for heat extraction, and significant temperature gradients are generated around the well. According to the results, the heat extraction rate increases linearly with the depth of the well, but above a certain depth (about 3000 m) the heat transfer efficiency reaches saturation. Furthermore, although a high flow rate increase initially increases heat extraction, after a certain point it reduces system efficiency due to hydraulic losses and pumping power requirements. Notably, adequate thermal isolation and appropriate flow rate are highlighted as critical for the system's long-term sustainability. These findings provide important design criteria for sustainability analysis and well spacing determination of geothermal systems.

The study conducted by Luo et al. (2013) investigated the thermal efficiency of well heat exchangers (BHEs) with three different borehole diameters (121 mm, 165 mm and 180 mm) installed in the ground source heat pump (GSHP) system of an office building in Nuremberg, Germany; thermal and hydraulic properties of the soil were measured with thermal response tests (TRT) and pumping tests, and daily and seasonal thermal change rates were calculated by monitoring the operating data of the GSHP system in 2009. The researchers analyzed the effects of different drilling diameters on daily and seasonal performance; They examined the effects of environmental temperature and underground well temperature on thermal performance. The results showed that increasing the well diameter increased both the daily and seasonal heat exchange rate, in particular, the 180 mm well provided a 7.1% higher yield in seasonal cooling performance than the 121 mm well, and this increase was found to be more pronounced at low subsurface temperatures. The study highlights that well diameter is an important parameter, especially for long-term system design, and that correct sizing can significantly improve thermal efficiency.

In the study conducted by Wang et al. (2024), a new finite volumes model (FVM) was developed to understand the heat transfer mechanisms of deep BHE and to determine the spatiotemporal distribution of heat flux in the well wall; The parameters affecting thermal performance were systematically analyzed with a different handling of the well wall boundary conditions. The researchers assessed the validity of the equivalent thermal conductivity assumption for layered floor structures; They examined the effects of thermal conductivity difference between different soil layers, well depth and time on heat flux. According to the results obtained, the heat flux is higher in the upper parts and shifts downwards over time, indicating that the lower regions begin to be affected more as the circulation time increases; Furthermore, convective effects remain limited due to the reservoir's low permeability, causing conduction to play a dominant role, which can lead to misjudgment of the system if this heterogeneous heat flux is not considered during the design phase. The findings revealed that the homogeneous-environment assumption is invalid when the thermal conductivity difference between the soil layers is greater than 2.0 W/m·K, and that well depth, geothermal temperature gradient and soil thermal conductivity are the most critical parameters determining system performance; With the developed model, a simple formula has been proposed that can predict the spatiotemporal distribution of heat flux in the well wall.

In the study conducted by Xia et al. (2023), Levelized Cost of Energy (LCOE) analysis was conducted using a thermo-economic model and a rapid heat extraction estimation algorithm to optimize the design parameters of deep coaxial well heat exchangers (BHE); the effect of well depth, flow rate and pipe diameter ratio on thermo-economic performance was investigated with the finite volumes method (FVM) and response surface method (RSM). The researchers developed a comprehensive economic model that included both CAPEX and operating costs over the 25-year life cycle; They found that when the depth varied between 2,000-4,000 m, the heat exchange rate increased from 235 kW to 1,061 kW. The findings showed that as a result of multi-factor optimization, the lowest LCOE value ($7.84/GJ) was obtained with a depth of 3912.8 m, a flow rate of 34.32 m^3/h and a pipe diameter ratio of 0.64; this optimization provides a 22-63% improvement over univariate analysis and reveals the importance of using LCOE as a balanced evaluation tool in system design, as well as the thermo-economic advantage of deep BHE heating systems over conventional energy sources.

Yildirim et al. (2019) studied the feasibility of using downhole heat exchangers (DHE) for power generation in geothermal wells with high temperature gradients but insufficient flowrates; thermodynamic model based on the ε-NTU method and economic model (net present value (NPV), simple payback time (SPT), and electricity generation cost (EPC)) were developed using Engineering Equation Solver software, with over 300 parametric

simulations analyzing effects of insulation, temperature gradient, well depth, geometry, mass flowrate, and six working fluids (R134a, R22, R125, R245fa, n-Pentane, n-Butane). The results show that DHE systems can be a viable option for geothermal power generation, particularly when key design and operational parameters are optimized. R134a performed best, producing 2511 kW at 64 kg/s mass flowrate in a 2500 m deep well with electricity generation cost of $46/MWh and payback period of 2.25 years, demonstrating that DHE systems are a feasible alternative for power generation in wells with extremely low geothermal flowrates.

This study focuses the coaxial borehole heat exchangers composed of two concentric pipes. A model was developed in the EES program for coaxial BHE (CBHE) using a existing well consisting of two intertwined axial pipes with a depth of 200 m and the water temperatures taken from this well. The heat capacity of the various configurations was calculated with different pipe lengths, diameters, materials, and flow rates with under conditions of a constant inlet fluid and grout temperature. The influence of design parameters was evaluated through numerical simulations with thermodynamic analyses.

2 SYSTEM DESCRIPTION

The study is used an existing well and CBHE as a reference scenario. The depth of the existing well is 200m. The schematic representation of the studied CBHE is shown in Figure 1.

The water used as a heat carrier fluid in the system moves from the space between the outer pipe and the well wall to the depths of the well, cools down by transferring its heat to the surrounding hot rocks in summer, and heats up by absorbing heat from hot rocks in winter, and then rises to the surface again through the inner pipe.

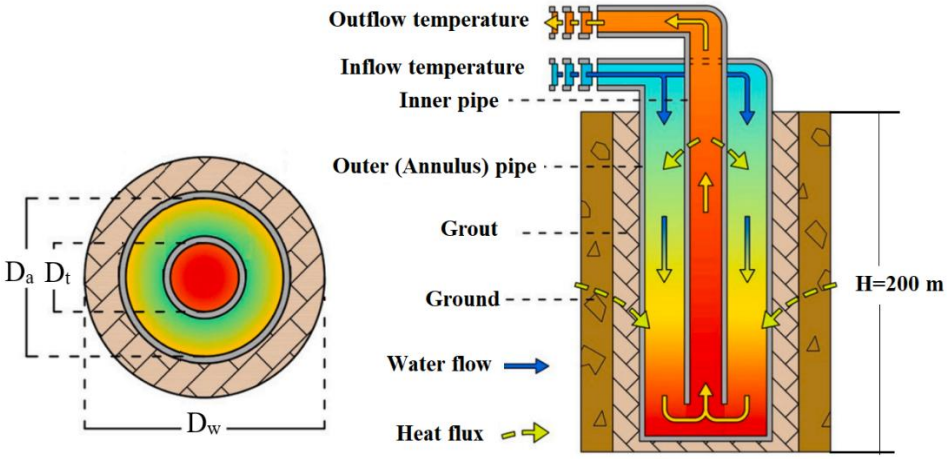


Figure 1. The schematic of the CBHE

In the existing CBHE design, aluminum pipe with an outer diameter of 70 mm (wall thickness of 5 mm) was used as the outer straight, and a composite pipe with an outer diameter of 40 mm (wall thickness of 6.7 mm) was used as the inner pipe. The diameter of the well is 74 mm; the depth is 200 meters. The features of the existing system are summarized in Table 1.

Table 1. The technical data of the existing CBHE.

Parameters	Symbol	Value	Unit
Inner pipe inner diameter	D_t	26.6	mm
Inner pipe wall thickness	t_{ib}	6.7	mm
Outer pipe inner diameter	D_a	60	mm
Outer pipe wall thickness	t_{db}	5	mm
Inner pipe heat conduction coefficient	k_{ib}	1.1	(W/mK)
Outer pipe heat conduction coefficient	k_{db}	200	(W/mK)
Grout heat conduction coefficient	k_g	2.35	(W/mK)
Ground temperature	T_g	16	(°C)
Ground temperature gradient	dT_g	0.1	(°C/100m)

3 METHODOLOGY

To determine the thermal capacity of the well and calculate the outflow temperature of the circulated water, a theoretical calculation was made by writing a code using EES (Engineering Equation Software). The technical data used within the scope of the project are presented in Table 1.

To calculate the heat transfer from the well, which consists of two coaxial pipes, thermal resistances must be determined. For this purpose, the well system was first divided into 4 meters long compartments. The temperature where the grout (cement) comes into contact with the soil on the outer wall of the well is considered as the ground temperature and the thermal resistance between the cement slit and the flow flowing through the aluminum pipe is written. ε-Fluid output was calculated for each cell using the NTU method. In the second stage, thermal resistors are written for the fluids flowing through the outer pipe and inner pipe. The main equations used in theoretical calculations are given below (Bergman et al. (2002)).

The heat transfer rate for the annulus:

$$\dot{q} = \dot{m}(h_o - h_i) \tag{1}$$

where the rate of mass flow ṁ into the control volume must be equal to the rate of mass flow out of the control volume, ho and hi represent the outlet and inlet enthalpies of the fluid stream which are function of temperature.

Log mean temperature difference (ΔT_m) is used for heat transfer analysis of heat exchangers. Heat transfer rate from hot stream to cold stream is calculated using Equation 2.

$$\dot{q} = U.A.\Delta T_m \tag{2}$$

where *A* is the total heat transfer area (m^2), *U* is overall heat transfer coefficient (W/m^2K).

The overall heat transfer coefficient of the annulus region (outer pipe) are calculated from

$$U_{op} = \frac{1}{\frac{1}{h_f} + \frac{D_a}{k_{op}} ln \frac{D_{a,o}}{D_a} + \frac{D_a}{k_{grout}} ln \frac{D_w}{D_{a,o}}} \tag{3}$$

Working fluid flows in the annulus and inner pipe by forced convection. Turbulent forced convection correlations for single phase fluids represent a significant class of heat transfer solutions for heat exchanger analyses. Depending on the roughness of the pipe inlet and pipe surface, fully developed laminar flow will be obtained up to Re ≤ 2300 if the pipe length L is longer than the hydrodynamic entry region L_{her}; however, if $L < L_{her}$, developing laminar flow would exist over the entire pipe length. The Nusselt number for laminar flow, fully developed with a constant surface temperature is 3.66 for Pr ≥ 6.

If $10^4 < Re < 5 \times 10^6$ and $0.5 < Pr < 2000$, the Nusselt number for turbulent fully developed flow becomes as Equation 4.

$$Nu = \frac{(f/8)(Re - 1000)Pr}{1 + 12.7(f/8)^{1/2}(Pr^{2/3} - 1)} \tag{4}$$

where f is the friction coefficient that can be obtained from the Moody chart that provided by EES software database or by Equation 5.

$$f = (1.58 \ln Re - 3.28)^{-2} \tag{5}$$

Then, convective heat transfer coefficient hf can be determined using Equation 6.

$$h_f = \frac{Nu.k}{D_h} \tag{6}$$

where k is thermal conductivity of working fluid and D_h is the hydraulic diameter of control volume.

For turbulent free convection flow on a vertical plate (Grz >109)

$$Nu_L = 0.0295(Ra_L)^{2/5} \frac{Pr^{1/15}}{(1 + 0.494\, Pr^{2/3})^{2/5}} \tag{7}$$

Ra_L is the local Rayleigh number which is defined as:

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$$Ra_L = Gr_L.Pr \tag{8}$$

where,

$$Gr_L = \frac{g\beta(T_w - T_{ave})L^3}{v} \tag{9}$$

The number of transfer units (NTU) is based on the concept of heat exchanger effectiveness, can be used for BHE analysis and calculated by Equation 10.

$$NTU = \frac{UA}{C_{min}} \tag{10}$$

Effectiveness (ε) of the BHE for counter and parallel flow can be calculated using NTU by Equation 11 and 12, respectively.

$$\varepsilon = \frac{1-exp[-(1-C^*)NTU]}{1-C^*\,exp[-(1-C^*)NTU]} \quad \text{for counter flow} \tag{11}$$

$$\varepsilon = \frac{1-exp[-(1+C^*)NTU]}{1+C^*} \quad \text{for parallel flow} \tag{12}$$

where C* is capacity ratio that is calculated by Equation 13.

$$C^* = \frac{C_{min}}{C_{max}} \tag{13}$$

where C_{min} and C_{max} are the smaller and larger of the two magnitudes of C_h and C_c, respectively, and C*≤ 1.

The heat exchanger effectiveness can be calculated using Equation 14.

$$\varepsilon = \frac{\dot{q}}{\dot{q}_{max}} \tag{14}$$

where $\dot{q}_{max}$ is maximum heat transfer rate that can be calculated using Equation 15.

$$\dot{q}_{max} = C_{min}(T_w - T_i) \tag{15}$$

Knowing ε and $\dot{q}$max, the actual heat transfer rate $\dot{q}$ and exit temperature (T_o) of control volume can be calculated using Equation 14 and 16, respectively.

$$T_o = T_i + \frac{\dot{q}}{C_{min}} \tag{16}$$

The pressure drop of a vertical cylinder pipe can be identified by three components; hydrostatic pressure drop (due to gravity), frictional pressure drop and kinetic pressure drop (Massoud (2005)). Kinetic pressure losses are minimal for most of the applications, therefore can be neglected. In the study, kinetic pressure losses at the inlet and exit of BHE are neglected.

Pressure drop in the main channel for a vertical cylinder due to gravity and frictional losses can be determined by Equation 17.

$$\Delta P = \rho.g.L + \frac{(f.\rho.L.u^2)}{2D_h} \tag{17}$$

At the bottom of the BHE, a kinetic pressure drop occurs due to a change in the flow area. Hence, pressure drop at the bottom of the BHE is calculated by Equation 18

$$\Delta P = \rho.g.L + \frac{(f.\rho.L.u^2)}{2D_h} + \frac{\rho(\Delta V)^2}{2} \tag{18}$$

Pressure output (Po) along the heat exchanger (L) can be determined by Equation 19.

$$P_o = P_i - \Delta P \tag{19}$$

4 RESULTS AND DISCUSSION

In the results section firstly the validation of the model is given. Then the studied scenarios to see the effect of the depth of the well, material of the outer pipe and the geometry of the BHE is introduced. In the last part the comparison of the scenarios is presented with the obtained results.

4.1 Validation

In the existing BHE, tests were conducted on 23 June 2023 by circulating mains water with a flow rate of 1000 L/h. In the tests, water inflow and outflow temperatures and outside air temperature were measured in 1-minute periods. These measurement data were used in the validation of the developed model. The comparison of the model results and measured data is shown in Figure 2. While the daily average measurement value of the water outflow temperature was 16.98°C, it was calculated as 16.83 °C in the EES model. In other words, with a difference of 0.875%, the model results are in agreement with the measurement results.

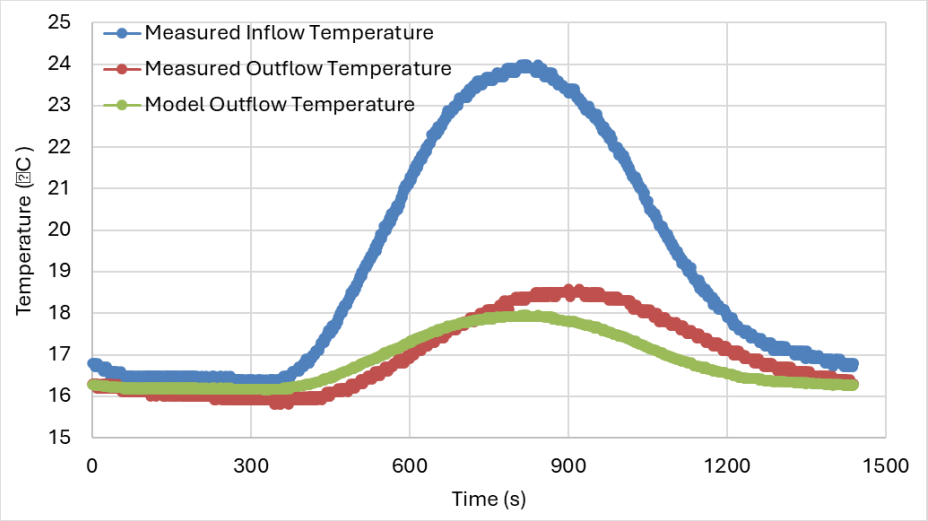


Figure 2. Validation results from the measured and calculated water outflow temperatures.

The developed EES model is also validated with the literature (Beier et al. (2014)). The results are shown in Figure 3. As can be seen from Figure 3, in the sample taken from the literature, the inlet temperature of water into the outer pipe is 17.8°C, while the exit temperature from the inner pipe is approximately 15°C. In the results obtained from the code developed with EES, an inlet temperature of 17.7°C and an outlet temperature of 14.8°C were obtained. The temperature difference, which was 2.8°C in the example in the literature, was calculated as 2.9°C with the developed code. It is thought that the very small difference is due to the fact that the rock temperature cannot be taken exactly the same.

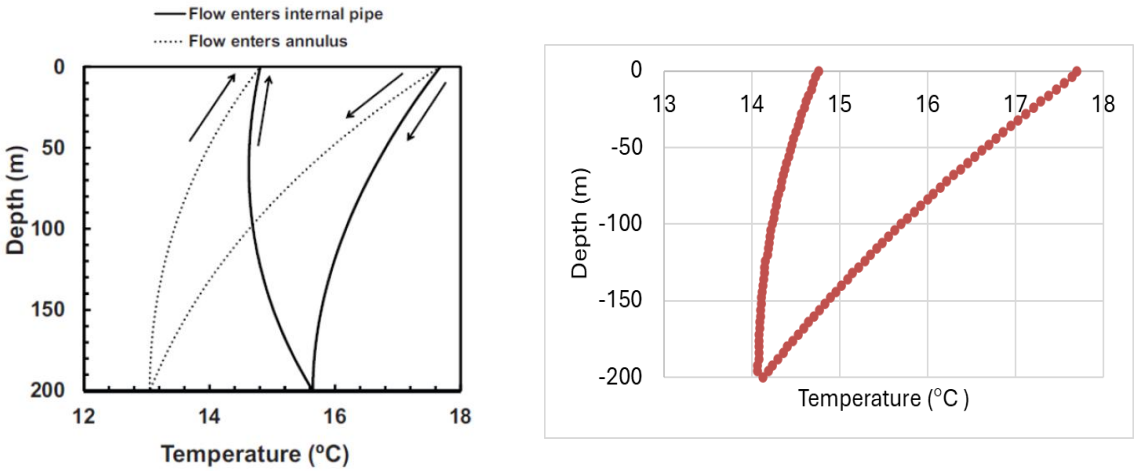


Figure 3. Validation results (a) Case study taken from the literature (Beier et al. (2014)) (b) Result obtained with the code developed in EES.

4.2 Studied Scenarios

In this study, 8 different scenarios were studied as summarized in Table 2 in order to see the effect of the material of the outer tube (Aluminum, stainless steel and PVC) used in downhole heat exchangers, well depth (100 m and

150 m), and the diameter of the inner pipe (50 mm and 40 mm) on performance. In the scenarios, composite pipe with a thermal conductivity of 1.10 W/mK was used in the inner tube. These pipe diameters have been selected according to the accessible and widespread use feature in the market. In addition, in order to see the effect of water flow rate, CBHE thermal capacity was calculated for each scenario by the water outflow temperature at 4 different flow rates (500, 1000, 1500 and 2000 L/h).

Table 2: Technical properties of the studied scenarios

SCENARIO	OUTER PIPE						INNER PIPE		
	Material	Outer Diameter (mm)	Inner Diameter (mm)	Pipe Thickness (mm)	Pipe Length (m)	Heat Conduction Coefficient (W/mK)	Outer Diameter (mm)	Inner Diameter (mm)	Pipe Thickness (mm)
S-1	Aluminum	90	75	7.5	100	200	50	33.4	8.3
S-2	Stainless Steel	90	86	2.0	100	16.2	50	33.4	8.3
S-3	PVC	90	81.4	4.3	100	0.19	50	33.4	8.3
S-4	Aluminum	90	75	7.5	150	200	50	33.4	8.3
S-5	Stainless Steel	90	86	2.0	150	200	50	33.4	8.3
S-6	PVC	90	81.4	4.3	150	0.19	50	33.4	8.3
S-7	Aluminum	90	75	7.5	100	200	40	26.6	6.7
S-8	Aluminum	90	75	7.5	150	200	40	26.6	6.7

4.3 Comparison of the Scenarios

The water outflow temperature from the CBHE and the CBHE thermal capacities were calculated with assuming a water inflow temperature of 30°C and a ground temperature of 12.2°C for the 8 CBHE models whose technical specifications are given in Table 2. The calculations were repeated for 4 different water flow rates (500, 1000, 1500 and 2000 L/h) and the results are summarized in Table 3.

Table 3: The water outflow temperature from the BHE and the BHE thermal capacities of the considered scenarios.

Flow rate	500 L/h		1000 L/h		1500 L/h		2000 L/h	
Scenario #	Outflow Temp. (°C)	Heat Capacity (kW)	Outflow Temp. (°C)	Heat Capacity (kW)	Outflow Temp. (°C)	Heat Capacity (kW)	Outflow Temp. (°C)	Heat Capacity (kW)
S-1	15.4	8.46	16.8	15.33	18.4	20.23	19.8	23.72
S-2	15.4	8.48	16.8	15.28	18.5	20.08	19.9	23.49
S-3	22.7	4.22	25.0	5.78	26.3	6.52	27.0	6.95
S-4	15.2	8.60	15.8	16.45	16.8	23.00	17.9	28.20
S-5	15.6	8.39	16.4	15.76	17.7	21.52	18.9	25.89
S-6	21.7	4.85	23.7	7.31	25.0	8.65	25.9	9.47
S-7	15.2	8.60	16.6	15.52	18.3	20.39	19.7	23.85
S-8	14.9	8.77	15.5	16.8	16.6	23.40	17.7	28.58

The first 3 scenarios were conducted to see the effect of the outer tube material on CBHE performance (Figure 4-a). Aluminum (S-1), Stainless steel (S-2), and PVC (S-3), materials are chosen. As it can be seen from Figure 4-a, the results obtained show that CBHE with stainless steel and aluminum pipe have almost the same thermal capacity. On the other hand, it is seen that PVC pipe significantly restricts heat transfer with the ground due to its low thermal conductivity coefficient and therefore has a much lower CBHE thermal capacity than other materials.

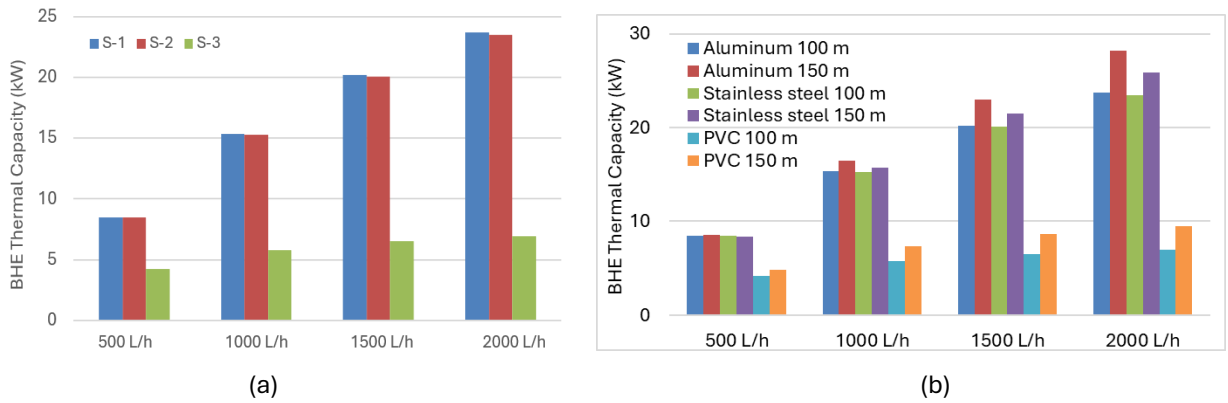


Figure 4. (a) Effect of the outer pipe material, (b) Effect of the BHE depth on the BHE thermal performance.

Figure 4-b shows the effect of well depth on CBHE thermal capacity. As it can be seen from the figure, thermal capacities increase with depth. The increase in CBHE systems with aluminum outer pipes is greater than in the system with stainless steel. This shows that aluminum is a better alternative for CBHE in terms of thermal capacity.

The effect of the inner pipe diameter was studied with Scenario 7 and 8 and comparison with the Scenario 1 and 4 is shown in Figure 5. It is seen that the decrease in the inner tube diameter increases the thermal capacity of CBHE. On the other hand, the increase in water flow rate also increases the thermal capacity of CBHE.

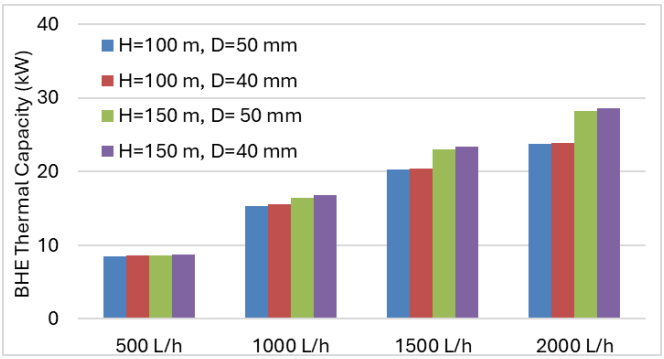


Figure 5. Effect of the inner pipe diameter.

5 CONCLUSIONS

A detailed examination was conducted on the energy capacity of coaxial borehole heat exchangers (CBHE) with two concentric tubes in this study. Based on an existing well 200 meters deep, a comprehensive thermodynamic model was developed using Engineering Equation Solver (EES) software. The model has been validated by both actual well measurement data and case studies from the literature, demonstrating a high level of accuracy with a margin of error of 0.875%. Within the scope of the study, parametric analyzes were carried out on 8 different scenarios under 30°C inlet temperature and 12.2°C constant ground temperature conditions. In these scenarios, the effects of outer pipe material (aluminum, stainless steel, and PVC), well depth (100 m and 150 m), inner pipe diameter (40 mm and 50 mm), and water flow rate (500, 1000, 1500, and 2000 L/h) on BHE thermal performance were evaluated using numerical simulations and thermodynamic calculations. The main findings obtained as a result of the analyzes are as follows:

- The outer pipe material has a significant impact: aluminum and stainless-steel exhibit similar thermal performance, while PVC negatively impacts system performance due to its low thermal conductivity.
- As the depth of the well increases, the thermal capacity of BHE increases, and this increase is especially pronounced in aluminum pipes.
- Reducing the inner tube diameter (from 50 mm to 40 mm) increases thermal capacity; hence, geometric design is of paramount importance.
- Increasing the operating flow rate (500 L/h → 2000 L/h) increases thermal capacity and results in a decrease in outlet temperatures in all configurations.

In conclusion, this study lays a solid foundation for the design optimization of coaxial BHEs and contributes to improving the efficiency of ground source heat pump systems. In the light of the findings of this study, the following suggestions can be made for future research: Life cycle and economic analyses (LCOE, NPV) should be integrated to evaluate the long-term performance of the system. It is proposed to study system behavior in different geological formations, soil (ground) thermal properties and climatic zones. Additionally, it is possible to improve system efficiency through optimization of thermal isolation parameters, comparison of hybrid system configurations, and detailed analysis of pump power requirements. Finally, the development of 3D heat transfer models in heterogeneous soil (ground) layers will contribute to obtaining more realistic design parameters.

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