Analysis of Enhanced Heat Transfer Characteristics of Geothermal Coaxial and Finned Borehole Heat Exchanger

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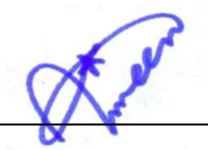
Student Signature: 

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LIST OF SYMBOLS, ABBREVIATIONS AND ACRONYMS

GSHP	Ground Source Heat Pump
SIMPLEC	Semi-Implicit Method for Pressure Equations-Consistent
LSCB	Least Squares Cell Based Method
BHE	Borehole Heat Exchanger
COP	Coefficient of Performance
GHE	Ground Heat Exchanger
ACWT	Average Circulating Water Temperature
Al_2O_3	Aluminum Oxide
RANS	Reynold Averaged Navier-Stokes
TRT	Thermal Response Test
MECC	Multi-External Chamber Coaxial
HDPE	High Density Polyethylene
PVC	Polyvinyl Chloride
PP	Polypropylene
PU	Polyurethane
W/m	Watts per meter
°C	Degree Celsius
L/min	Litres per minute

ABSTRACT

Geothermal energy has been recognized as a reliable and continuous resource of renewable energy. In the past, numerous investigations have been conducted to increase the thermal performance of the coaxial borehole heat exchangers. Previous research efforts have focused on parametric studies, incorporated the use of vortex generators and multiple external chambers. While the effect of fins on various configurations, such as U-tube, spiral tubes and horizontal type heat exchangers have been studied, there is a lack of research on their impact on geothermal coaxial borehole heat exchangers. In this study the effect of longitudinal fins on coaxial borehole heat exchanger (CBHE) was evaluated using CFD software. Transient simulations were performed for the period of 24 hours for cooling operation at different flow rates i.e 4L/min and 8L/min. Fin lengths of 5mm, 10mm, 15mm and 20mm were evaluated to determine optimum fin length. At optimum fin length of 15mm, it was observed that heat transfer rate per unit length was increased by 18% at 4L/min and 22% in case of 8L/min flow rate which indicates the increase in CBHE efficiency. This research establishes a foundation for future investigations of finned ground heat exchangers which can contribute towards a sustainable and efficient energy solution.

Keywords: Geothermal, Finned coaxial borehole, Thermal performance, Geothermal energy.

CHAPTER 1: INTRODUCTION

1.1 Background

Global warming is a crucial issue for the whole world, and its key cause is due to the use of fossil fuels. Residential houses and commercial buildings consume almost 15 to 30 percent of the world's total energy consumption [1]. One of the replacements to fossil fuels is to consume renewable energy resources to reduce carbon emissions. Geothermal energy can be employed as a solution to reduce this global issue [2].

It is considered that solar radiation is the primary energy source on the Earth. It also served as the source of numerous global energy resources, including solar, wind energy, petrochemical, and the most significant of which are geothermal systems and earth energy systems. In the ground almost 50 percent of the sun's thermal energy is absorbed in the ground. It can be utilized as an abundant source of renewable energy readily available through the year. Thermal energy from the sun is stored under the ground surface. The ground is utilized as an insulation between earth below and the ambient air. It provides a steady ground temperature that is not dependent on the ground air temperatures. It is also independent of seasonal variations.

1.2 Ground Source Heat Pump Systems

One of the clean energy technologies that offers great financial viability, energy efficiency and natural protection for the environment is the ground source heat pump systems. [3]. They can be operated because of constant ground temperature for the efficient functioning of heating and cooling process for the commercial and residential buildings [4]. The key function of GSHP system is to transfer heat to and from earth to distribution systems of the building. GSHPs are mainly composed of heating & cooling distribution system, heat pump machine and earth connection (GHE).

Through the application of work, the purpose of heat pump is to transmit heat from a cold source to a hot reservoir by utilizing energy. The distribution system provides heating and cooling to the buildings using air ducts or hydronic piping (hot water) distribution systems. GHE consists of various loops of pipes, and these are buried under the ground. It exchanges heat by passing fluid through them with the help of a pump. As a result of temperature gradient between the circulating heat carrier fluid and the ground, heat is exchanged with the assistance of heat carrier fluid due to which its temperature increases or decreases depending on the temperature gradient.

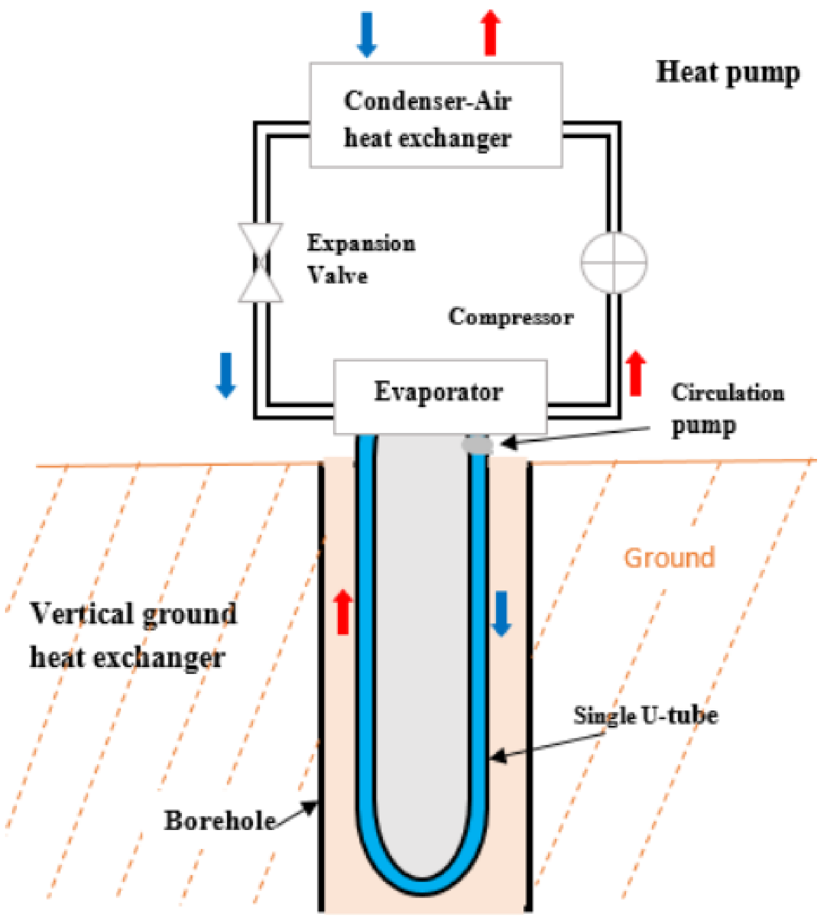

Figure 1.1: GSHPs (in heating-dominated climate) [1]

Below a certain depth from ground, the soil temperatures are significantly greater than that of ambient air temperatures in the winter season. During summer the soil temperature is significantly lower than the ambient air temperatures. Based on this ground temperature gradient from the ambient air, heat can be eliminated in the ground during summer and heat can be retrieved from the ground a ground heat exchanger is utilized. Figure 1.2 shows the underground temperature variations for different depths and were determined at energy pile test site [4].

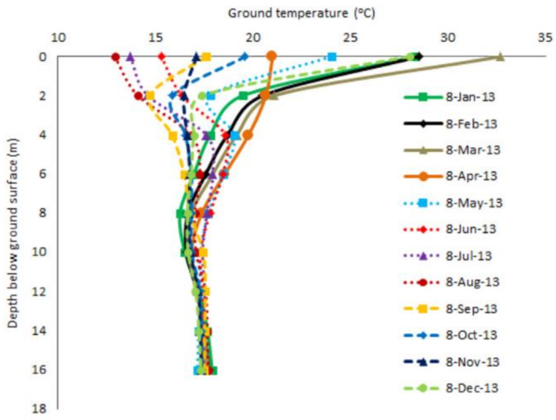

Figure 1.2: Variation of underground temperature with depth for year 2013 [4].

1.3 Types of GHE

There are two main classifications for ground heat exchangers (GHEs): Closed loop GHE and Open loop GHE systems.

1.3.1 Open Loop GHE

In an open loop GHE, GSHP continuously pumps water from water bodies such as wells and rivers. Through injection wells this fluid can be passed back to the environment. Figure 1.3 shows 2D graphical representation of an open loop ground heat exchanger [1].

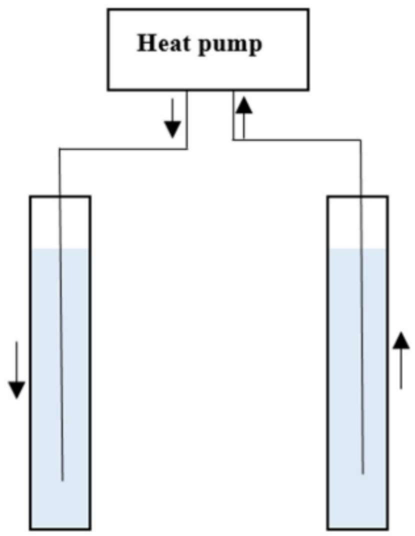

Figure 1.3: 2D Graphical representation of open loop ground heat exchanger [1].

1.3.2 Closed Loop GHE

Heat carrier fluid, such as water or a combination of antifreeze and glycol, may pass through the pipes of closed loop GHE and then returns back to the heat pump in order to transmit heat. Figure 1.4 shows 2D schematic representation of vertical closed loop GHE.

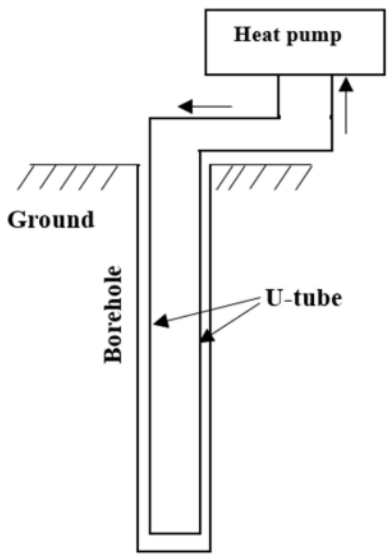

Figure 1.4: 2D Schematic illustration of vertical closed loop GHE [1].

1.3.3 Horizontal and Vertical GHE

Horizontal ground heat exchangers (HGHEs) are mainly considered as closed loop systems that are coupled to the heat pump. These heat exchangers are installed in 1-2m deep trenches, the thermal performance is relatively smaller when compared with vertical GHE. It requires a large amount of area for its installation but cost for installing these systems are much lesser as assessed to VGHE [1]. A horizontal ground heat exchanger piping system in the ground is shown in Figure 1.5 [3].

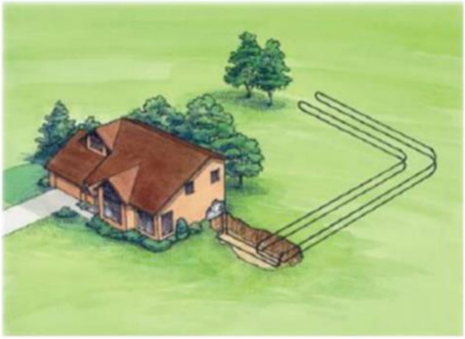

Figure 1.5: 3D View for Horizontal Ground Heat Exchanger [3].

Vertical Ground Heat Exchangers (VGHEs) are installed when the area is restricted, or the ground surface is rocky. These can also be known as borehole heat exchangers (BHEs). Installation costs for (VGHE) is higher but its performance is stable [5]. A vertical ground heat exchanger is shown in Figure 1.6 [3].

Figure 1.6: 3D View for Vertical Ground Heat Exchanger [3].

1.3.4 Types of VGHE Based on Geometric Configurations

Depending upon the geometric configurations, VGHEs can be classified into U-tube, Double U-tube, Multi-tubes Coaxial tubes, triple U-tube, W-shaped tube, or helical shaped tubes. The extremely widespread used configuration is a single U-tube. Because of limitation of heat transferral area, single U-tube configuration's performance is limited. To increase the contact surface area of pipes to the ground, one core solution is to increase the depth for the borehole or expanding the number of boreholes in the ground. Enhancing the overall depth of the boreholes will cause an increasing installation costs as well as pumping power required to pump fluid. Increasing number of boreholes requires sufficient available area [5].

1.4 Design Aspects Affecting the Performance of Ground Heat Exchangers

1.4.1 Backfill and Grouting Materials

For VGHEs grouting materials are crucial in improving heat transmission process. Backfill materials were introduced in order to increase heat transfer. Mixtures of bentonite and cement together are considered as two main components. Earlier the grouts were composed of bentonite, cement and water in ratio of (1:1:2) respectively and it has the thermal conductivity of (0.7 to 0.8) $Wm^{-1}K^{-1}$. With the advancement of technology, enhancement of mechanical and thermal properties of soil can be improved by additional materials. Enhancement of local soil can also be done by adding fillers in the soil [5].

Phase change materials (PCM) have the ability and can also be employed to enhance the thermal properties of grouting. With the ability of latent heat thermal storage capacity, PCM can decrease surrounding soil connected around BHE for temperature variations. When GSHP is working in cooling mode the PCM melts and with the latent heat storing capacity it keeps approximately steady temperature of surrounding soil of BHE. Organic phase change material (PCM) paraffin is widely used. PCM must possess a high thermal conductivity and latent heat, and besides that its ability to be non-corrosive has significance importance.

1.4.2 Pipe Materials

For improved performance of GHE systems in terms of installation and operational costs, pipe materials and grouting both are considered as an important parameter. Piping material can be divided into two categories: metals and thermoplastics. Metal pipes must be resistant to corrosion and stress corrosion to avoid cracking and to ensure long-life span. A cathodic protection should be present to ensure corrosion of the underground pipes. Galvanization or external coating may improve the life of the metal pipes. Stainless steel, aluminium, copper, nickel and titanium alloys provide corrosion prevention but they can cause increase in installation cost [6].

Thermoplastics have lower thermal conductivities than the metals or alloys, but they have corrosion resistant ability and have lower prices and readily available. Most used plastic pipes are made up of high-density-Polyethylene (HDPE) followed by polyvinylchloride (PVC). polyurethane (PU), Polypropylene (PP), and polybutylene (PB) can also be used. To increase the thermal properties of plastic pipes a secondary material can also be used having high thermal conductivity and is combined with polymer matrix [6].

1.4.3 Working Fluids

Because of the low price and relatively improved thermal properties, water is most universally used heat carrier in borehole ground heat exchanger [7]. Water starts to freeze when temperature drops to 0°C. To avoid that problem water-glycol mixtures can be used to drop the freezing point of water. Propylene glycol can be preferred over ethylene glycol because of its lower toxicity [8].

Researchers have worked on adding nanoparticles to the base fluids to enhance the thermal properties of heat carrier fluid. Thermal conductivity, viscosity, density and specific heat alters the choice of nanofluids. For heating mode, 6 different nanoparticles alongside with different volumetric concentration with base fluid (water) were analysed. It was concluded that the temperature gradient between pipe inlet and outlet of the borehole was increased. Pressure drop and GHE length was reduced in a single U-tube vertical GHE [7].

1.5 Motivation

With the increase in energy demands, fossil fuels are decreasing continuously. Geothermal energy has been recognized as a clean source of energy and is renewable. Understanding and enhancement of thermal performance of coaxial borehole heat exchanger with longitudinal fins is the focus of this research. Longitudinal fins extend down the length of the borehole heat exchanger from top to bottom. Contact surface area with the surrounding soil or rocks can be increased by applying longitudinal fins on the outer pipe of coaxial borehole. This increase in surface area allows for the efficient heat transfer phenomena between heat carrier fluid flowing in the pipes of the heat exchanger and the subsurface environment.

1.6 Research Aim

This study targets to investigate transient thermal performance of coaxial borehole heat exchangers using longitudinal fins. Longitudinal fins of rectangular cross section were incorporated to a simple coaxial borehole heat exchanger. The width of the fin used in this study was 3mm and lengths of the fins used were 5mm, 10mm, 15mm and 20mm. Furthermore, this study aims to enhance the coaxial borehole performance by varying the fin lengths.

1.7 Research Gap and Objectives

Various studies have been performed using different types of fins in different geometric configurations on geothermal heat exchangers. According to literature review, the influence of longitudinal fins on performance of coaxial borehole ground heat exchangers is not investigated. Objectives of this study includes:

1. Develop a numerical 3D computational fluid dynamics (CFD) model for finned and simple CBHE.
2. Validate the model using experimental data from past research.
3. To determine the finned coaxial borehole heat exchanger's thermal performance at different flow rates.
4. To assess how fin length affects the coaxial borehole heat exchanger's thermal performance.

CHAPTER 2: LITERATURE REVIEW

The amount of energy consumed worldwide is expected to increase by almost 56% between the year 2010 and 2040. Reliance on fossils fuels is linked to the environmental impacts like global warming. Approximately 50 percent of the total energy has been consumed by space heating and air conditioning [9]. It is beneficial for the environment to utilize renewable resources such as geothermal energy. It will reduce the reliance on usage of fossil fuels and have provided a potential opportunity to utilize it in space heating and cooling systems.

Vertical ground heat exchangers were studied in terms of their performance were reviewed by Eswiasi, A., & Mukhopadhyaya, P. [1]. It was found out that with the change in pipe configurations and grouting materials borehole thermal resistance was decreased within a range of 9% to 52%. It was found out that increase in surface area of pipe can have a considerable impact on improving overall efficiency of ground heat exchangers.

A GHE that includes (3×3) energy piles in the soil were prepared. Xu, B., et al. used CFD software to simulate heat transfer process and utilized FEM. In the space cooling configuration mode heat transfer rates gradually decreased and finally stabilized at around $60Wm^{-1}$ for system running up to one month. Heat removal from and injection into ground or surrounding soil can be kept balanced during spring and autumn season and it can result in the recovery of soil temperature.[10]

CFD simulations were carried out by Xu, B., et al. to simulate and evaluate heat transfer process. A 3-U type pile foundation ground heat exchanger was developed. Results indicated that the property that had a great influence on the performance of ground heat exchanger was pipe's thermal property such as thermal conductivity as compared to soil. [10]

A significant factor that has a great impact on the performance of is its ability to exchange heat with the soil. A common U-type pipe arrangement that was filled with ground-water BHE was studied with the help of a 3D & steady state CFD model. In a study by Gustafsson, A. M., et al. a 3m long borehole GHE with a single U-pipe configuration enclosed in the bedrock was modeled, a steady temperature boundary was applied on the outer bedrock, and it was considered at a lower constant temperature. It was concluded that, convective heat flow for borehole must be incorporated and actual injection heat transfer rates should also be measured to calculate the thermal resistance. [11]

Wu et al. studied both experimental and numerical methods on GSHP systems under UK climate environment [12]. The experimental setup for slinky coupled ground source heat was taken into consideration. The properties of the soil at the site were integrated into a (CFD) model. The study focused on assessing the performance linked with thermal exchange rate of slinky heat exchangers in the horizontal GHE system by varying the coil diameters and distances between slinky intervals, using validated 3D model over a two-month simulation process. The findings indicated a decline in the Coefficient of Performance (COP) over time, with an average COP of 2.5. Increasing the coil diameter has proved the increased thermal heat transfer rate.

Jalaluddin et al. has conducted an experimental investigation on various types of (GHEs) integrated into a steel pile foundation [13]. Ground temperatures were measured to analyze temperature distribution with depth. Results indicated that coaxial (pipe inside pipe) GHE has a greater efficiency as compared to Multi-tube and single U-tube GHE.

Jalaluddin and Miyara conducted numerical investigations on various types of ground source heat exchangers to examine their performance under different operating modes, including short-term operation, discontinuous operation with 6- and 12-hour cycles, and continuous operation over a full day. The results demonstrated that each operating mode exhibited distinct characteristics in terms of heat exchange rates [14].

Liu et al. proposed a new design aimed at addressing the shortcomings of existing GHEs [15]. The design features included a single outlet pipe and three (multiple) inlet pipes. To assess its thermal performance, experimental measurements were conducted on double U, single-U and three inlets type ground heat exchangers. The results revealed that the ACWT of the 3I-type was 3.7 degree Celsius lower than the single-U type and 1 degree Celsius lower than the double-U type. Furthermore, numerical simulations indicated that 3 inlet pipe type GHE was 17.1% and 11.6%

higher than that of the single U-type pipe and double-U type respectively under different operating conditions.

Ground heat exchangers are typically the expensive component of GSHP systems. However, their expense can be reduced by shortening the borehole length using suitable materials. Raymond et al. conducted design calculations that suggested a coaxial pipe configuration could offer significant advantages over a single U-type pipe configuration, potentially reducing the required borehole length for the system [16].

Chen et al. developed a 3D, unsteady numerical model for vertical ground heat exchangers (GHEs) using the Finite-Volume Method [17]. The study examined over 101 cases, varying factors such as thermal conductivity, inlet flow rate, porosity of the soil, borehole depth, Darcys velocity, and volumetric heat capacity. The validation for prediction equations was carried out with the help of experimentation conducted in China.

Han and Yu conducted a sensitivity analysis on a vertical GSHPs to develop design and operation strategies aimed at improving performance. The model, which incorporates fluid, grouting backfill material, and pipe, was validated by comparison with an operational ground heat exchanger (GHE). The analysis revealed that the coefficient of performance (COP) was higher during intermittent operation compared to continuous operation [18].

High initial costs are a significant barrier to the widespread adoption of Ground Source Heat Pump Systems. To address this, nanofluids can be used to improve heat transfer between the fluid and grouting. Narei et al. studied the impact of Al_2O_3/water nanofluid to reduce borehole depth. The results indicated that using Al_2O_3/water nanofluid could decrease borehole length by 1.3%. Further analysis revealed that grouting materials have greater potential for reducing borehole length compared to heat transfer fluids and tubes [19].

Pei and Zhang conducted a CFD analysis on ground source heat pumps (GSHPs) operating in both continuous and intermittent modes over a 7-day period, using single-well, single-U, and double-U heat exchangers. The study found that energy extraction was 36.44 kWh greater in intermittent operation compared to continuous operation [20].

Daneshipour and Rafee numerically modeled a coaxial borehole heat exchanger to investigate the effects of Copper Oxide & water and Aluminum Oxide and Water nanofluids. They used Reynolds-Averaged Navier-Stokes (RANS) equations to solve and with the SST k-ω turbulence model to simulate the flow and applied correlations to account for the physical properties of the nanofluids. The results indicated that there is an optimal diameter ratio that minimizes pressure loss. While CuO-water nanofluid achieved higher heat extraction compared to Al_2O_3-water nanofluid, it also resulted in greater pressure loss and higher pumping power requirements [21].

The configuration of pipes plays a crucial role in designing ground heat exchangers (GHEs), yet there has been limited research on how pipe shape affects performance. Kong et al. conducted a CFD simulation using the k-ε RNG model to explore this issue. Their study revealed that U-tubes with various petal configurations enhanced turbulent heat diffusion but also increased the pressure loss coefficient. They found that smooth U-tubes were more efficient across different velocities compared to the petal-shaped variants [22].

Kim et al. investigated the horizontal spiral-coil GHE, with a focus on the geometric factors of the spiral coil. They conducted a Thermal Response Test (TRT) to validate their numerical analysis performed with COMSOL Multiphysics. The study considered various factors impacting thermal performance, including depth of installation, ground’s thermal conductivity, and fluid velocity. The results indicated that the pitch of the spiral coil does not influence thermal performance as long as it exceeds 0.6 meters [23].

Atwany et al. conducted an experimental study to assess the performance of a ground heat exchanger (GHE) in Sharjah, UAE. For seven months, they evaluated the ground temperature distribution at a depth of 10m for two boreholes. They found that the temperature of the ground was approximately 32 Degrees Celsius, which was 5 Degree Celsius more than the average annual ambient temperature. In a separate evaluation, they tested a 300m long plastic pipe with a 0.03m diameter, buried horizontally 2.5m below the ground surface. The study revealed that the effectiveness of the GHE decreased over time and with increased mass flow rates [24].

Li et al. created a three-dimensional numerical model for a multi-external chamber coaxial (MECC) borehole heat exchanger (BHE) and compared its performance with that of a standard double U-tube (2U) BHE. The model was validated through field experiments. They studied the impact of various operating parameters and conducted a sensitivity analysis, while incorporating the effects of ground water. The results showed that the maximum and average heat transfer rates of the multi-external-chamber coaxial BHE increased by 65.3% and 10.32%, respectively, compared to the 2U BHE [25].

A significant issue with ground source heat pumps (GSHPs) is the long-term high temperature variation in the ground due to heat accumulation or depletion. To address this, Sedaghat et al. proposed an open-loop horizontal ground to air heat exchanger (GAHE) system, which was installed between horizontal ground-water heat exchangers (GWHEs). When the ground is warmer than the ambient air then the ambient air can take away the heat accumulated in the ground. The results demonstrated that the coefficient of performance (COP) of the system could be improved by 20.2% with the implementation of the heat recovery system [26].

The coaxial borehole heat exchanger benefits from enhanced heat transfer characteristics due to the geometric features of its concentric tube-in-tube configuration. Lee et al. conducted a series of parametric studies to optimize the energy efficiency of these systems. Both increase in circulating fluid and the thermal conductivity of the grout improves the performance of a CBHE [27].

Coaxial borehole heat exchangers are commonly used but often have low heat transfer efficiency. To enhance their thermal performance, Sun et al. proposed the use of vortex generators in their study. These vortex generators enhance the turbulent kinetic energy of the fluid flow within the coaxial heat exchanger, improving the mixing properties of the fluid. The results showed that incorporating vortex generators increased the performance enhancement coefficient (PEC) by 1.1 times, and also led to increases in extraction temperatures and heating power by 24.06 percent and 11.93 percent, respectively [28].

Fins are commonly employed to improve heat transfer in various energy systems, including geothermal borehole heat exchangers (GHEs). Longitudinal fins were introduced inside the U-tube heat exchanger enhancing heat transfer. A three-dimensional numerical model was developed by Bouhacina et al. for the finned heat exchanger and compared it with a simple U-tube model. The results demonstrated that adding longitudinal fins increased heat transfer by up to 7% and facilitated quicker temperature recovery, presenting a promising approach to enhancing the performance of GSHP systems [29].

Jamshidi and Mosaffa studied a finned conical coil tube GHE under the environmental conditions of Tehran, Iran. They explored its potential by varying geometric parameters and operational requirements, including coil pitch, coil diameter, and the conical angle of the helical tube, at a burial depth of 3 meters. Soil data were sourced from the Synoptic Meteorological Station. The Taguchi algorithm was employed to determine the optimal geometric parameters, such as cone angle, length-to-width ratio of the fins, number of fins, and Reynolds number. The results indicated that the incorporation of nanofluids enhanced the system's performance [30].

Saeidi et al. investigated a new spiral-type GHE equipped with aluminum fins. They found that the fins helped secure the spiral heat exchanger firmly in the ground and improved the heat transfer rate by 31%. This enhancement was attributed to the increased surface area and the high thermal conductivity of the fins [31].

Although different research studies have been done in the past with the application of fins in different configurations of geothermal ground heat exchangers. There was no study done in the past with addition of longitudinal fins in coaxial borehole heat exchanger. The addition of longitudinal fins will provide an improved contact surface area of borehole pipe with surrounding soil. The effect of longitudinal fins with different fin lengths will be studied to evaluate heat transfer rate of coaxial borehole heat exchanger. The optimum fin length will be evaluated for maximum efficiency of coaxial borehole heat exchanger.

CHAPTER 3: NUMERICAL MODELING

3.1 Problem Definition

A three-dimensional numerical model of a coaxial borehole heat exchanger with a depth of 20 meters was built in the current study. The model validation was carried out using experimental data from past research work carried out at Saga University, Japan [13]. Longitudinal fins were introduced in the model to investigate the performance of enhanced coaxial borehole heat exchanger. This model was used to find out the effect of fins on heat exchange rate in coaxial borehole heat exchanger. Different flow rates 4 & 8 Litres per minute were used to observe the thermally enhanced CBHE.

3.2 Governing Equations

The governing equations for ground heat exchanger include conservation of mass and momentum that are shown in Equation 3.1& 3.2 respectively.

$$\nabla . \vec{V} = 0 \tag{3.1}$$

$$\rho \left(\frac{\partial v}{\partial t} + v . \Delta v \right) = -\nabla p + \mu \nabla^2 v + F \tag{3.2}$$

Where ρ represents the fluid density, $\frac{\delta v}{\delta t}$ represents the rate of change of velocity with time, $v . \nabla v$ represents convective term representing change in velocity due to fluid motion, $\mu . \nabla^2 v$ represents the diffusion of momentum due to viscosity, ∇p represents the Pressure gradient and F represents the body forces e.g. gravity.

Energy conservation equation inside the heat exchanger and in solid domain are shown in Equation 3.3 & 3.4 respectively.

$$\rho c_p \left(\frac{\partial T}{\partial t} + v . \nabla T \right) = k \nabla^2 T + \acute{q} \tag{3.3}$$

$$\rho_g c_{p,g} \frac{\partial T_g}{\partial t} = k_g \nabla^2 T_g \tag{3.4}$$

Where ρ_g represents the ground density, c_p represents the specific heat capacity at constant pressure $c_{p,g}$ represents specific heat capacity of the ground $\frac{\partial T}{\partial t}$ represents rate of change of ground temperature w.r.t time $k\nabla^2 T$ represents heat diffusion due to thermal conductivity k and $\acute{q}$ represents the internal heat generation per unit volume.

3.3 Assumptions

A transient 3D numerical model was developed on following assumptions:

1. The physical properties of ground and heat transferring fluid are constant.
2. Velocity profile was considered uniform at inlet.
3. Impact of moisture or ground water on thermal conductivity of soil was excluded.
4. The surrounding soil was modeled up to a radius of 5m to include ground temperature fluctuations during operation.

3.4 3D Geometry

A full-scale 3D geometry was modelled using CAD Software. 3D geometry includes outer pipe, inner pipe, surrounding soil and fluid domain. In order to reduce the computation time only a quarter portion of coaxial borehole heat exchanger was created. Later, finned coaxial borehole geometry was created. The full-scale 3D model was imported in CFD software. Surrounding soil, Inlet pipe and outlet pipes were set as a solid domain and as a fluid for the heat transferring fluid. Geometrical dimensions for present study were based on the previous experimental research performed by [13] and are represented in Table 3.1.

Table 3.1: Geometric parameters of 3D model

Depth of borehole	2000mm
Inlet pipe (Outer Diameter, d_o)	139.8mm
Inlet pipe (Inner Diameter, d_i)	129.8mm
Outlet pipe (Outer Diameter, d_o)	48mm
Outlet pipe (Inner Diameter, d_i)	40mm

Figure 3.1 as shown below represents isometric view of 3D model from Top representing surrounding soil, inlet pipe, outlet pipe, fluid inlet and outlet.

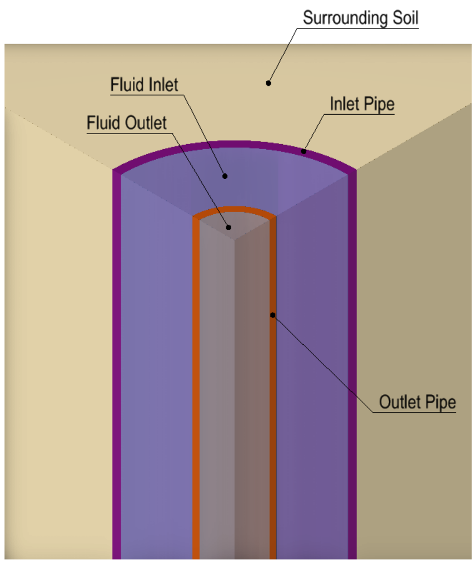

Figure 3.1: Isometric view of 3D model from Top.

In Figure 3.2 as shown below, Front view represents total depth of coaxial borehole heat exchanger. Detail A & B representing upper and lower portion of the coaxial borehole used in the current research work.

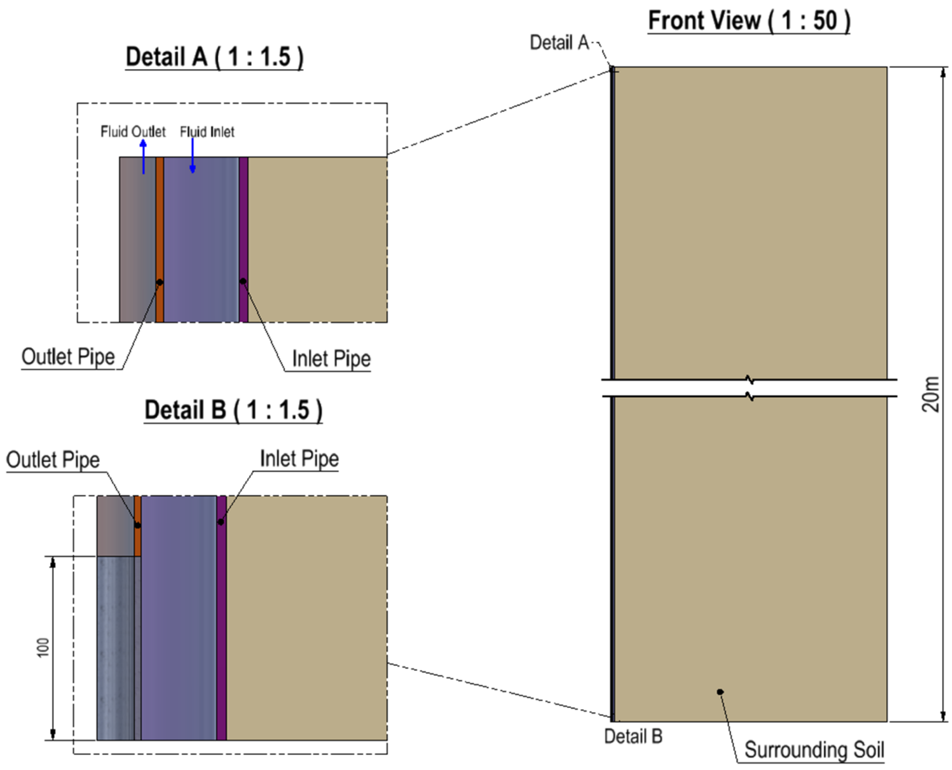

Figure 3.2: Details of 3D model used in simulation.

In Figure 3.3 as shown below, Top View represents the symmetry boundaries and radial dimension for surrounding soil. Detail C represents the geometric dimensions for inlet and outlet pipes.

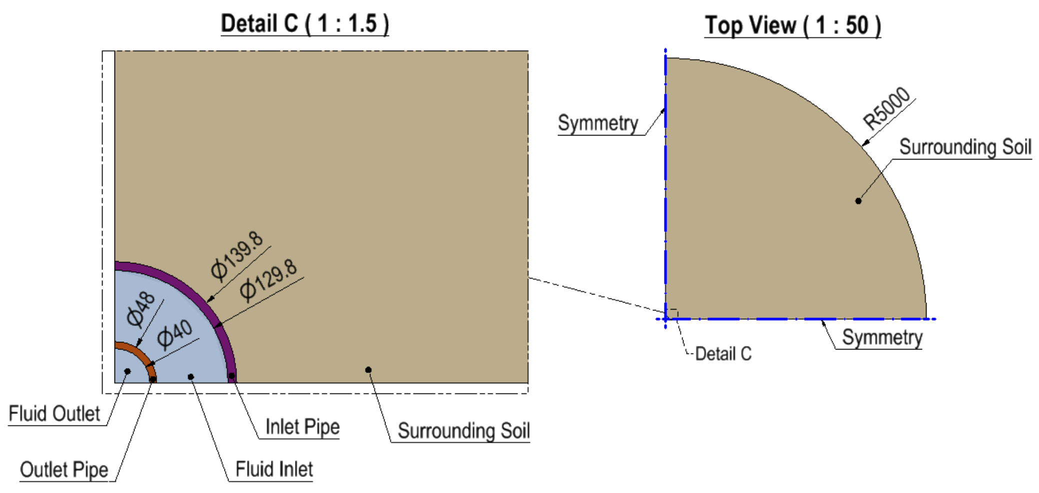

Figure 3.3: Pipes & Surrounding soil measurements used in simulation.

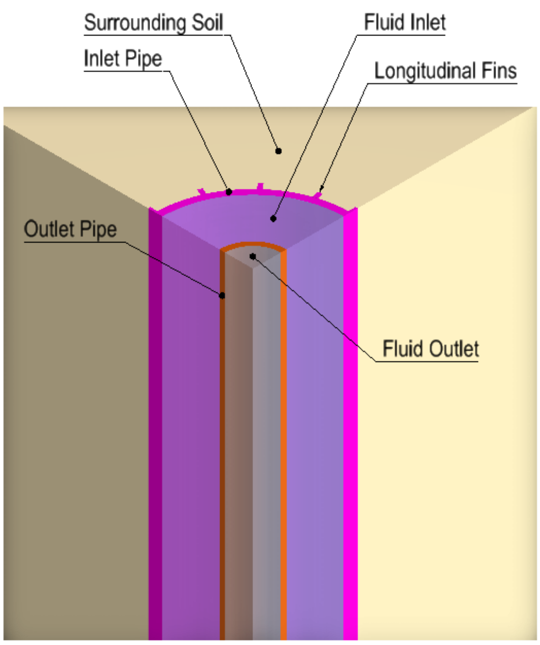

Figure 3.4: Top Isometric view of finned coaxial borehole heat exchanger

Figure 3.4 represents top isometric view of coaxial borehole integrated with fins.

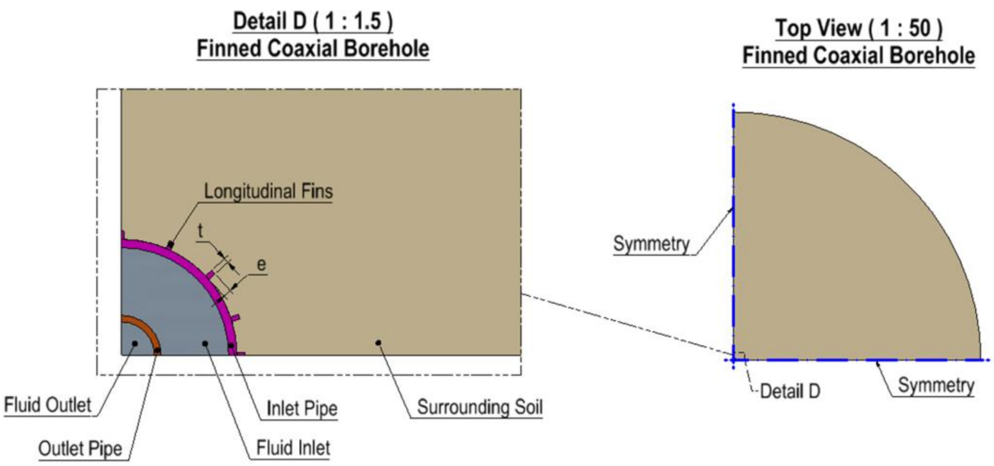

Figure 3.5: Top view and Detail D for finned coaxial borehole heat exchanger.

In Figure 3.5, Top view represents the surrounding soil diameter used in the simulations for finned coaxial borehole heat exchanger. Detail D represents longitudinal fins attached to the inlet pipe are connected to the surrounding soil to enhance heat transfer from fluid to ground. These fins are extruded from top of the heat exchanger to the bottom upto 20m depth.

3.5 Thermophysical Properties

Thermophysical properties of materials employed in simulations are given in Table 3.2. The inlet pipe material used was stainless steel to increase thermal conductivity. The outlet pipe material was considered as polyvinyl chloride to reduce the thermal interference between the fluid of inlet pipe and outlet pipe.

Table 3.2: Thermophysical properties of materials

Domain	**Material**	**Density (kg/m^3)**	**Specific Heat (J/kgK)**	**Thermal Conductivity (W/mK)**
Inlet Pipe	Stainless Steel	7817	460	13.8
Outlet Pipe	PVC	1380	960	0.15
Soil	Silica sand	1700	1800	1.2
Fluid	Water	998.2	4184	0.6

3.6 Boundary Conditions

A constant temperature of 14.5°C was applied on the ground top surface and far field boundary of soil. A constant flow rate 4L/min & 8L/min with fluid temperature 26.85°C was applied at the fluid inlet. At the outlet the gauge pressure was specified with a value of zero. Symmetry boundary conditions were imposed on the symmetric boundaries of quarter 3D model.

3.7 Solution Methods and Initialization

Pressure based solver was employed for low-speed incompressible flows based on previous research. The SIMPLEC (Semi-Implicit Method for Pressure Equations-Consistent) algorithm was used and is a frequently used method to solve Navier-Stokes equation. The "Least Squares Cell Based" method was used for determining the gradients. Spatial discretization for pressure, momentum and energy was built on "Second Order Upwind" scheme. Continuity, x-velocity, y-velocity, z-velocity and energy equations were set to the convergence criterion of 10^{-4}. The standard initialization method was used, and it was computed from fluid inlet. Initial

Temperature for surrounding soil was considered as 17.85°C and the fluid initial temperature was considered as 26.85°C before starting the solution.

3.8 Mesh Independence Study

To verify that proposed simulations were independent of mesh size and to minimize additional computational time and power requirements, a mesh independence study was performed. Four types of hexahedral meshes were created using meshing software. Boundary and initial conditions were applied in the model. The average orthogonal quality for mesh was 0.99 and the average skewness was between 0 and 0.1. Figure 3.6 shows generated mesh used in the current research simulations.

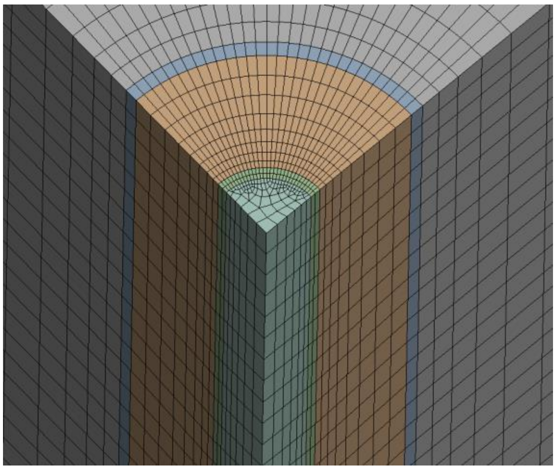

Figure 3.6: Isometric view of generated mesh used in simulations.

Average outlet fluid temperature was considered in the mesh independent study. Table 3.3 shows the outlet fluid temperatures for different mesh sizes. Mesh type 3 was used for the proposed simulations as it is independent of mesh size.

Table 3.3: Outlet temperatures for different mesh types

Mesh No.	No. of nodes	Inlet Temp (°C)	Outlet Temp (°C)	%age Difference
1.	3.5×10^6	26.85	24.786	-
2.	4.5×10^6	26.85	25.483	2.7
3.	6.0×10^6	26.85	25.585	0.3
4.	7.5×10^6	26.85	25.587	0.007

3.9 Model Validation

The model was validated using experimental results to ensure the correct simulation of the physical model. The research was carried out at Saga University, Japan. Inlet and outlet temperatures from the ground heat exchangers were measured to calculate the heat exchange rate. Fluid outlet temperatures data was measured for the period of 24 hours during the experiment [13]. The inlet flow rate was 4L/min for the validation study. Inlet fluid temperature was considered as 26.85°C. Ground temperature was 17.85°C and ground top surface temperature was 14.5°C. Figure 3.7 below shows the agreement between experimental results and CFD simulation results for outlet temperatures of simple coaxial borehole heat exchanger. Slight differences between experimental results and CFD simulation results were because soil properties are anisotropic, that are changing with temperature variation. But in simulation constant soil properties were assumed for simplification. Also in simulation, the initial temperature of the fluid was applied as 26.85°C but in experiment the initial temperature was not 26.85°C.

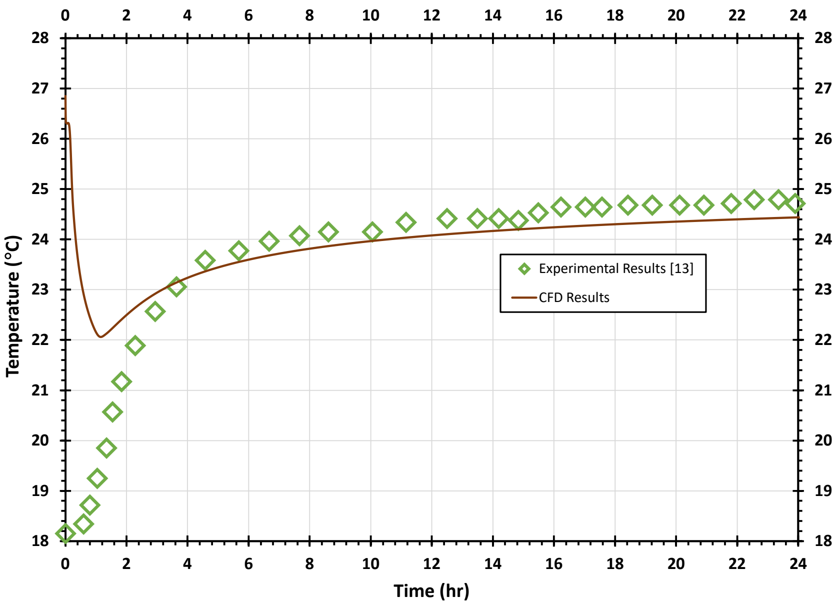

Figure 3.7: Comparison between Experimental results [13] and CFD results for fluid outlet temperatures of simple CBHE at flow rate of 4L/min

CHAPTER 4: RESULTS AND DISCUSSIONS

This current study is based on the transient analysis of geothermal coaxial borehole heat exchanger. A 3D numerical model was built and was validated from experimental results as discussed in Section 3.9. Coaxial borehole heat exchangers are very efficient because of their high thermal contact with the surrounding soil. The heat exchanging process with the surrounding soil starts when the fluid in the pipes flow under the ground.

As the GSHP systems run continuously, the ground temperature also increases or decreases with time depending upon the mode of operation. During cooling mode, ground temperature increases with the increase in time and heat gets accumulated in the surrounding soil. In this study an enhanced coaxial borehole heat exchanger was modeled in which longitudinal fins were attached to the outer side of inlet pipe and were in contact with the surrounding soil. Flow rates of 4L/min and 8L/min were applied to the inlet pipe to evaluate its effect on the thermal performance of CBHE. Parametric studies on fin lengths were also performed at different flow rates to evaluate heat exchange rate per unit length (W/m) on heat exchanger.

4.1 Temperature Variations

In this section, the impact of simple and finned coaxial borehole heat exchanger will be analyzed on the surrounding soil during continuous operation mode for 24h.

4.1.1 Longitudinal Temperature Variation

During the cooling mode, soil temperature variations at (R=150mm) along the depth were analysed at t = 8h, 12h, 16h, 20h and 24h. Initial soil temperature was considered as 17.85°C at initial time step. Soil temperature increases with time as the coaxial borehole heat exchanger runs. Longitudinal Ground temperature for simple coaxial borehole heat exchanger at flow rate of 4L/min and 8L/min are shown in Figure 4.1 and Figure 4.2.

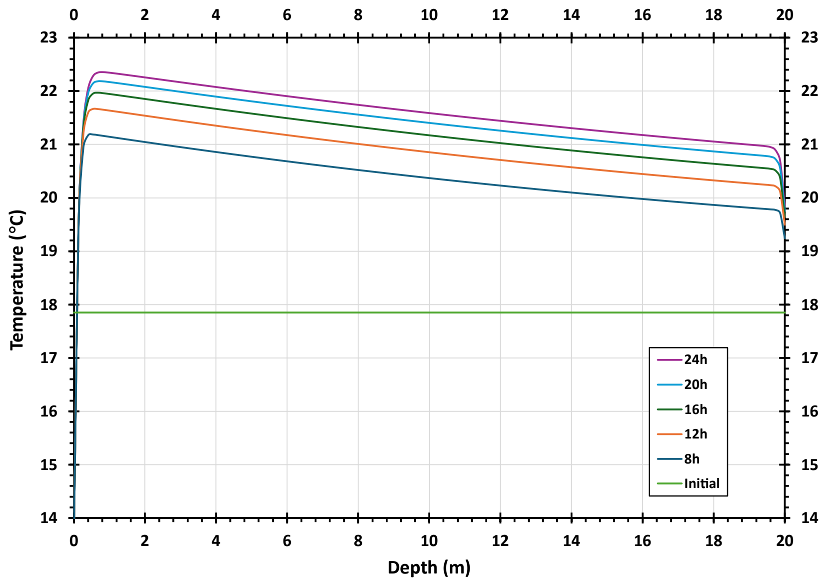

Figure 4.1: Longitudinal Ground Temperature at R = 150mm for Simple Coaxial Borehole Heat Exchanger at inlet flow rate of 4L/min

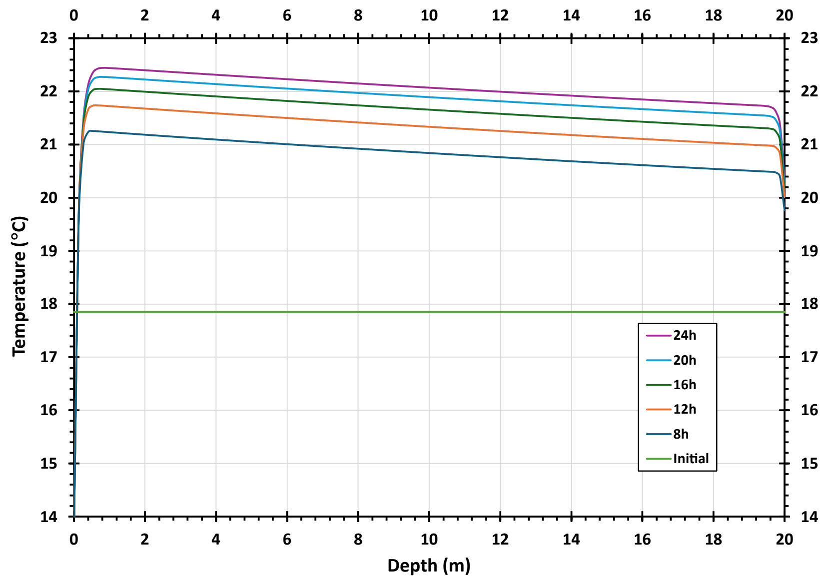

Figure 4.2: Longitudinal Ground Temperature at R = 150mm for Simple Coaxial Borehole Heat Exchanger at inlet flow rate of 8L/min

Figure 4.1 and Figure 4.2 shows for simple coaxial borehole heat exchanger at 4L/min & 8L/min flow rate, average temperature of soil was increased by 3.677°C and 4.132°C respectively at the end of 24 hours operation. The average soil temperature was increased by 20.1% and 23.15% respectively as compared to initial ground temperature 17.85°C.

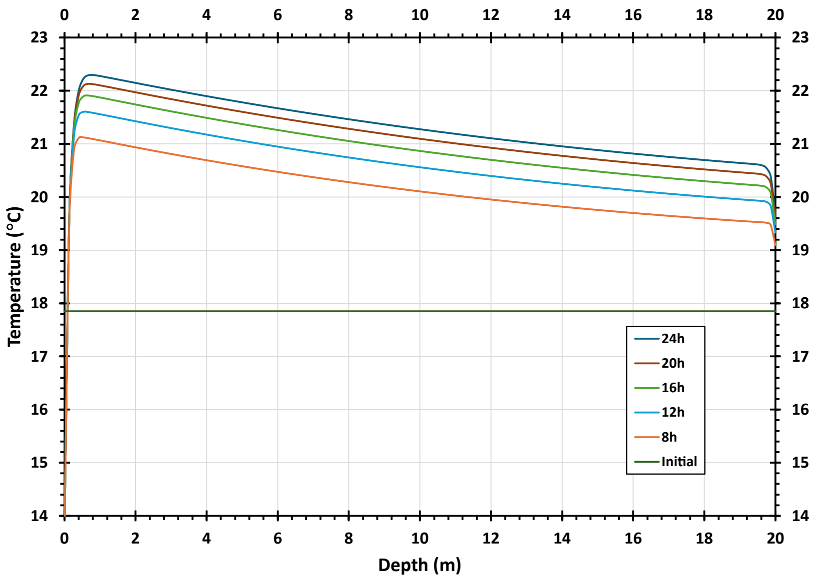

Figure 4.3: Longitudinal Ground Temperature at R = 150mm for Finned Coaxial BHE (Fin Length = 5mm) at inlet flow rate of 4L/min

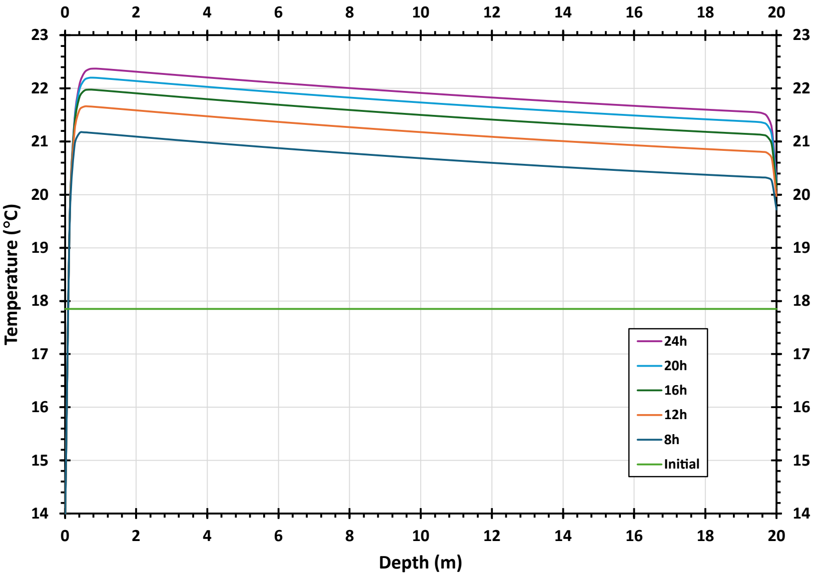

Figure 4.4: Longitudinal Ground Temperature at R = 150mm for Finned Coaxial BHE (Fin Length = 5mm) at inlet flow rate of 8L/min

Figure 4.3 and Figure 4.4 shows for finned coaxial borehole heat exchanger (fin length = 5mm) at 4L/min & 8L/min flow rate, average temperature of soil was increased by 3.408°C and 3.992°C respectively at the end of 24 hours operation. The average soil temperature was increased by 19.10% and 22.36% respectively as compared to initial ground temperature 17.85°C.

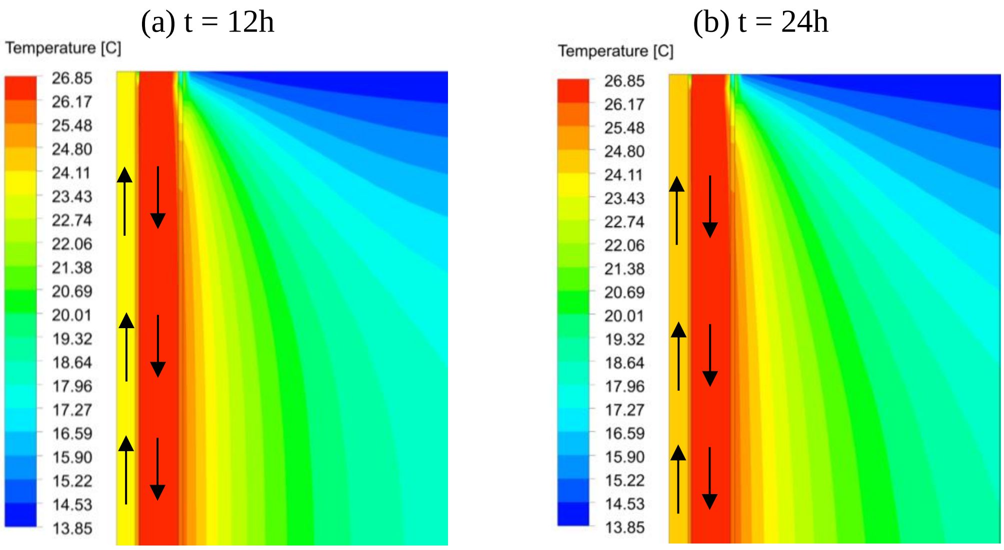

Figure 4.5: Longitudinal Temperature Distribution up to (0.5m from top) for Simple CBHE at inlet flow rate of 4L/min (a) t = 12h (b) t = 24h

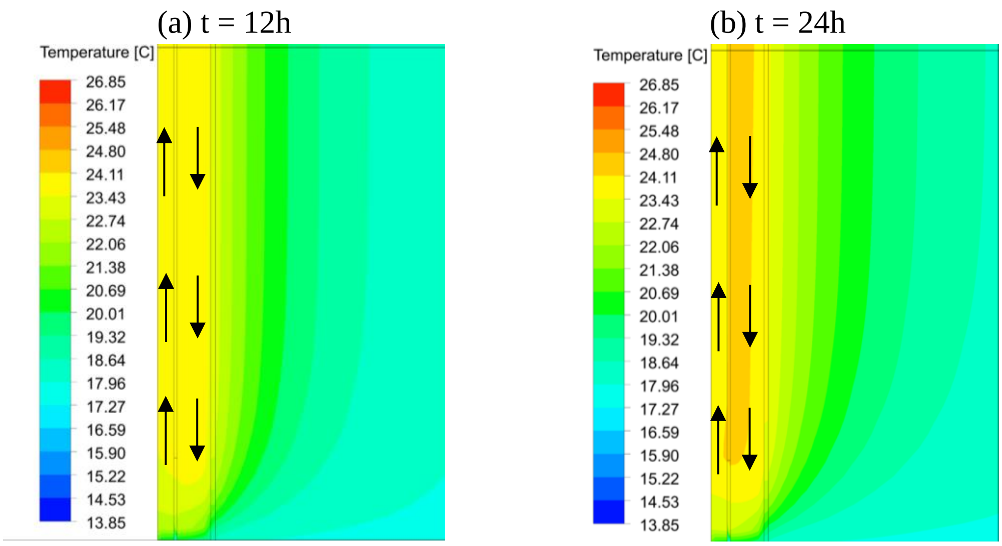

Figure 4.6: Longitudinal Temperature Distribution up to (0.5m from bottom) for Simple CBHE at inlet flow rate of 4L/min (a) t = 12h (b) t = 24h

Figure 4.5 shows longitudinal temperature distribution for depth of (0 – 0.5m) from top for simple coaxial borehole heat exchanger (flow rate = 4L/min) at t = 12h and t = 24h respectively. At 4L/min & t = 12h, temperature gradient between inlet and outlet fluid is 3.0°C and as the time passed at t = 24h it is reduced to 2.4°C. Soil temperature near inlet pipe also increased because of heat accumulation in it. Figure 4.6 shows longitudinal temperature distribution for depth of (19.5 – 20m) from bottom for simple CBHE (flow rate = 4L/min) at t = 12h and 24h respectively. It shows an increase in fluid temperature when it reaches the bottom to enter the outlet pipe.

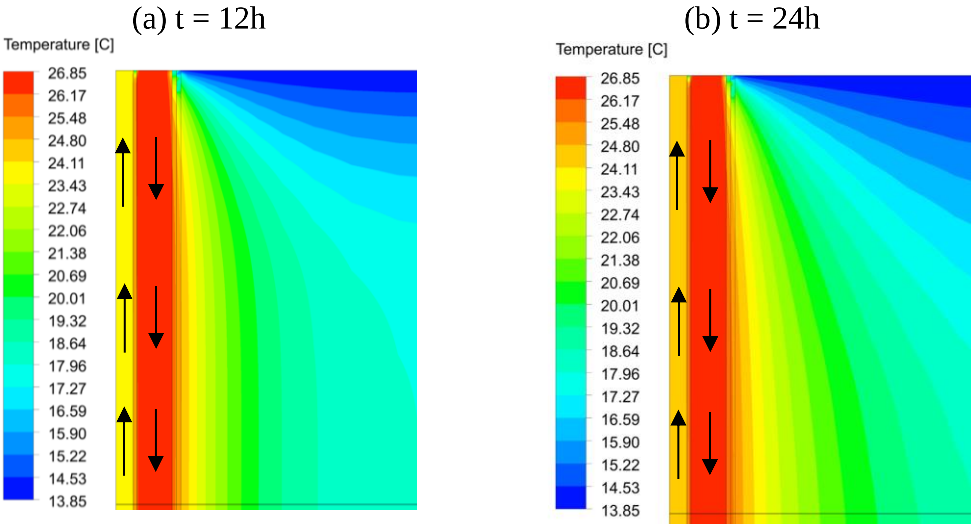

Figure 4.7: Longitudinal Temperature Distribution up to (0.5m from top) for Finned CBHE (Fin Length = 5mm) at inlet flow rate of 4L/min (a) t = 12h (b) t = 24h

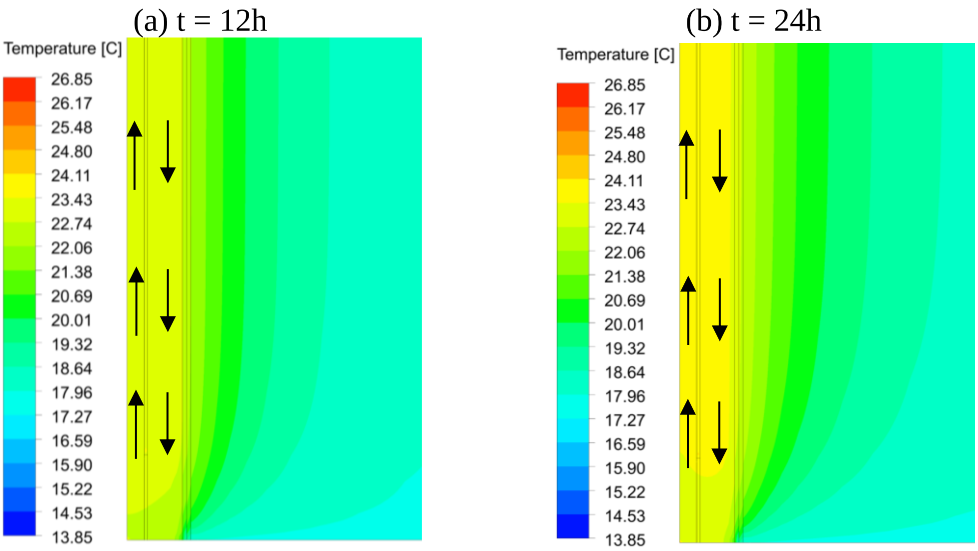

Figure 4.8: Longitudinal Temperature Distribution up to (0.5m from bottom) for Finned CBHE (Fin Length = 5mm) at inlet flow rate of 4L/min (a) t = 12h (b) t = 24h

Figure 4.7 shows longitudinal temperature distribution for depth of (0 – 0.5m) from top for finned coaxial borehole heat exchanger (flow rate = 4L/min) at t = 12h and t = 24h respectively. At 4L/min & t = 12h, temperature gradient between inlet and outlet fluid is 3.2°C and as the time passed at t = 24h it is reduced to 2.5°C. Figure 4.8 shows longitudinal temperature distribution for depth of (19.5 – 20m) from bottom for finned CBHE (flow rate = 4L/min) at t = 12h and 24h respectively.

4.1.2 Radial Temperature Variations

During the cooling mode, at depth = 10m soil temperature variations along the radius were analysed at t = 8h, 12h, 16h, 20h and 24h for simple and finned coaxial borehole heat exchangers. Initial soil temperature was considered as 17.85°C at initial time step. Soil temperature increases with time as the heat exchanger runs for 24h.

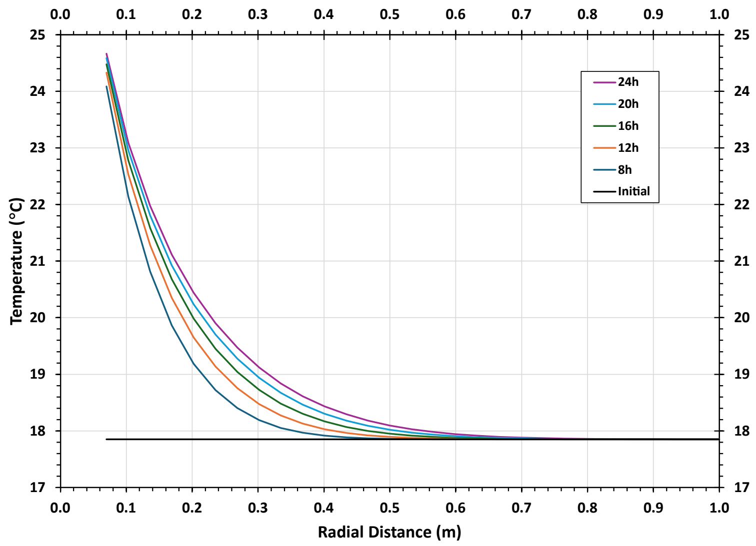

Figure 4.9: Radial Temperature Change of Ground at (Z = 10m) for Simple CBHE at inlet flow rate of 4L/min

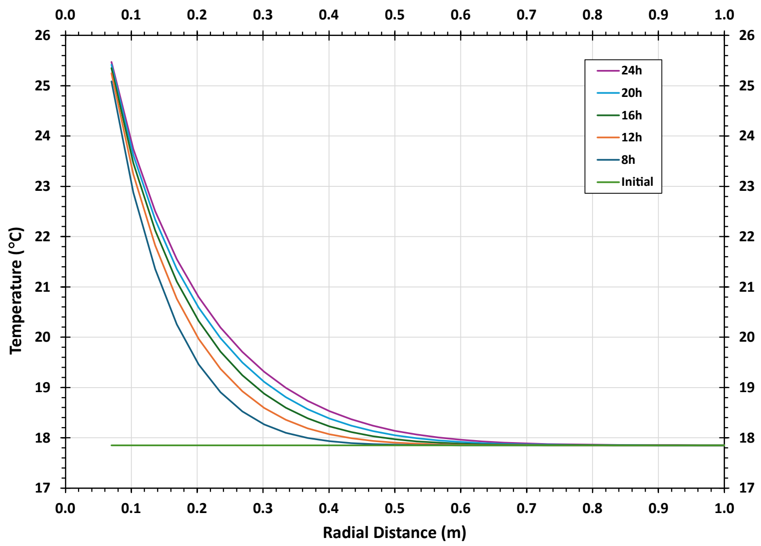

Figure 4.10: Radial Temperature Change of Ground at (Z = 10m) for Simple CBHE at inlet flow rate of 8L/min

Figure 4.9 and Figure 4.10 shows radial temperature distribution of surrounding soil for simple coaxial borehole heat exchangers at depth of 10m. Radial ground temperature changes significantly from 0.05m to 0.5m radial distance as the system runs for 24h. Temperature at contact between inlet pipe and surrounding soil was changed from 24°C to 24.8°C for flow rate of 4L/min. At 8L/min it was changed from 25°C to 25.6°C.

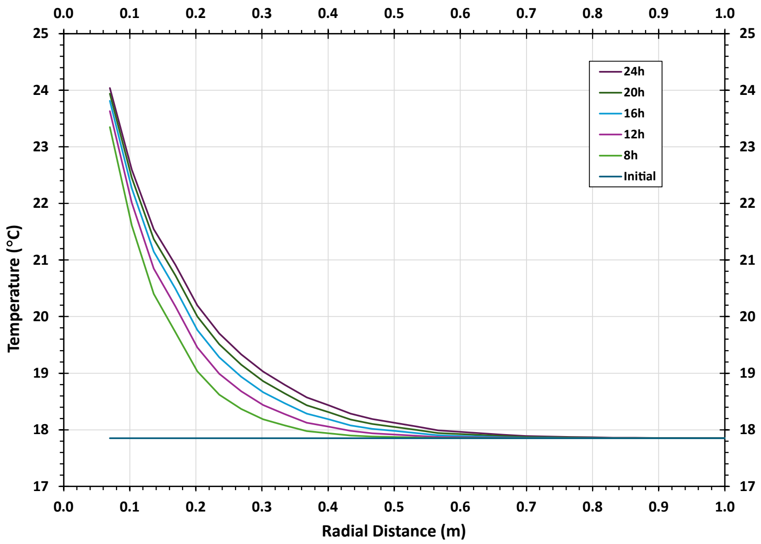

Figure 4.11: Radial Temperature Change of Ground at (Z = 10m) for Finned CBHE (Fin Length = 5mm) at inlet flow rate of 4L/min

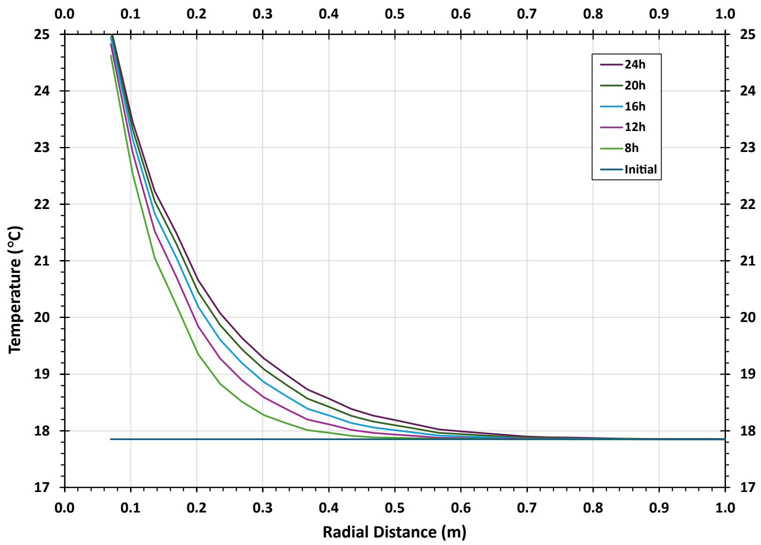

Figure 4.12: Radial Temperature Change of Ground at (Z = 10m) for Finned CBHE (Fin Length = 5mm) at inlet flow rate of 8L/min

Figure 4.11 and Figure 4.12 shows radial soil temperature distribution for finned coaxial borehole heat exchanger at flow rate of 4L/min and 8L/min. Radial ground temperature is increased more for 8L/min as compared to 4L/min.

(a) t = 12h (b) t = 24h

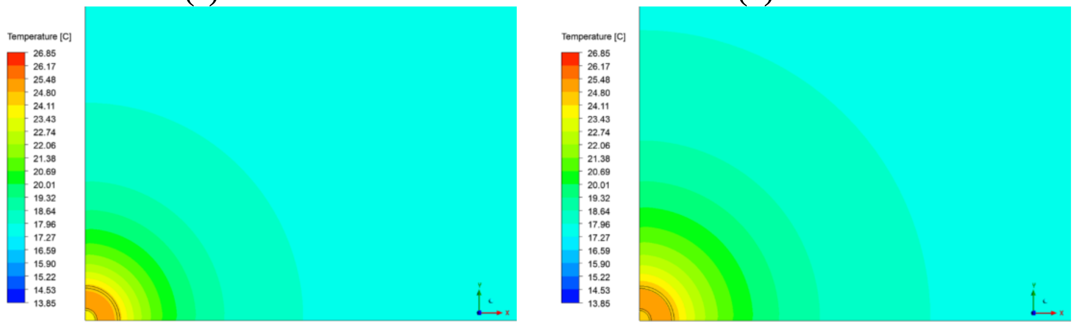

Figure 4.13: Radial Temperature Distribution at depth = 10m for Simple CBHE at inlet flow rate of 4L/min (a) t = 12h and (b) t = 24h

(a) t = 12h (b) t = 24h

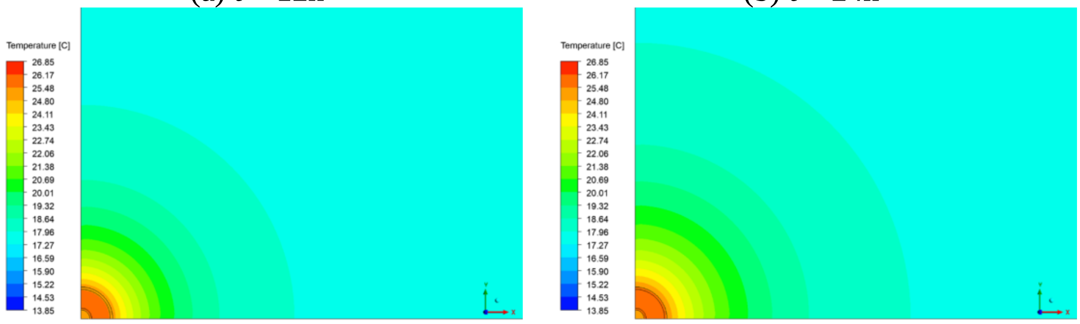

Figure 4.14: Radial Temperature Distribution at depth = 10m for Simple CBHE at inlet flow rate of 8L/min (a) t = 12h and (b) t = 24h

(a) t = 12h (b) t = 24h

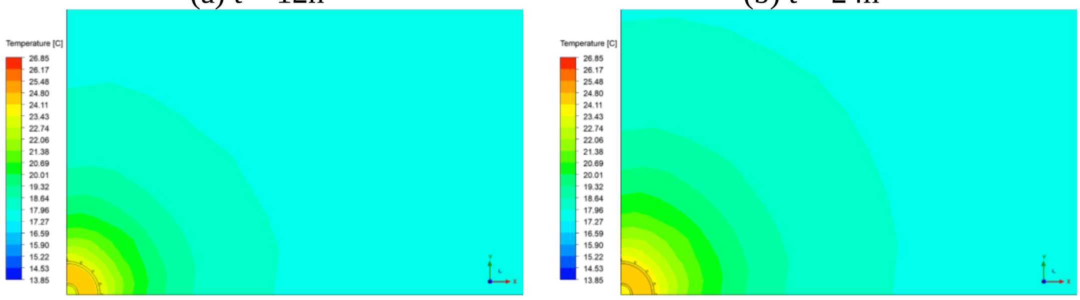

Figure 4.15: Radial Temperature Distribution at depth = 10m for finned CBHE (Fin Length = 5mm) at inlet flow rate of 4L/min (a) t = 12h and (b) t = 24h

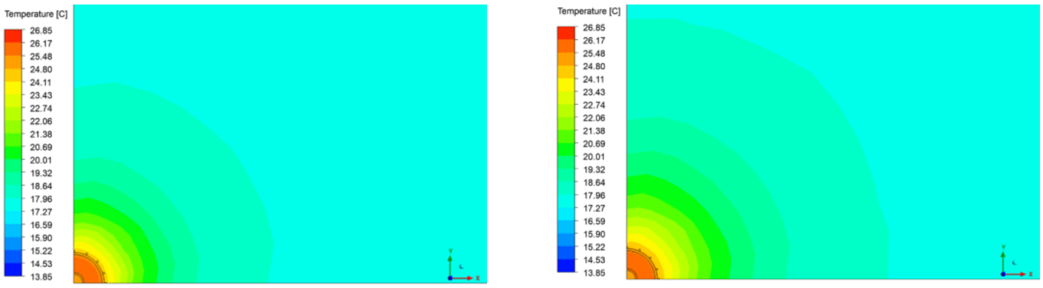

Figure 4.16: Radial Temperature Distribution at depth = 10m for finned CBHE (Fin Length = 5mm) at inlet flow rate of 8L/min (a) t = 12h and (b) t = 24h

Figure 4.13 and Figure 4.14 represents radial temperature variations for simple coaxial borehole heat exchanger at flow rate of 4L/min and 8L/min respectively. At flow rate of 8L/min fluid temperature change is smaller as compared to 4L/min. At 4L/min and t = 12h, fluid temperature change is significant as compared to 8L/min.

Figure 4.15 and Figure 4.16 represents radial temperature variations for finned coaxial borehole heat exchangers at flow rate of 4L/min and 8L/min respectively. Temperature gradient between the inlet and outlet of fluid in finned borehole is more as compared to simple coaxial borehole heat exchanger.

4.1.3 Fluid Temperature Variation with depth

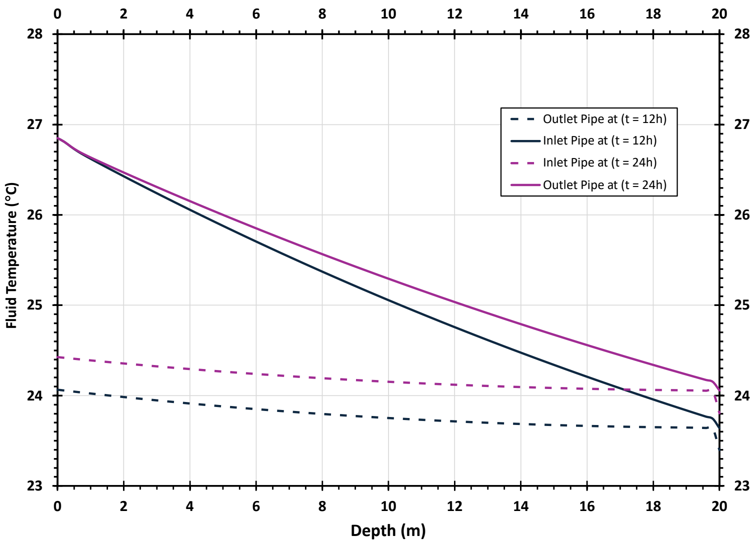

Figure 4.17: Average Temperature Variation in Simple CBHE at inlet flow rate of 4L/min.

Figure 4.17 shows average temperature variation in Simple CBHE for inlet flow rate of 4L/min. At t = 12h and t = 24h, the average temperature difference between inlet and outlet is 2.785°C and 2.425°C respectively.

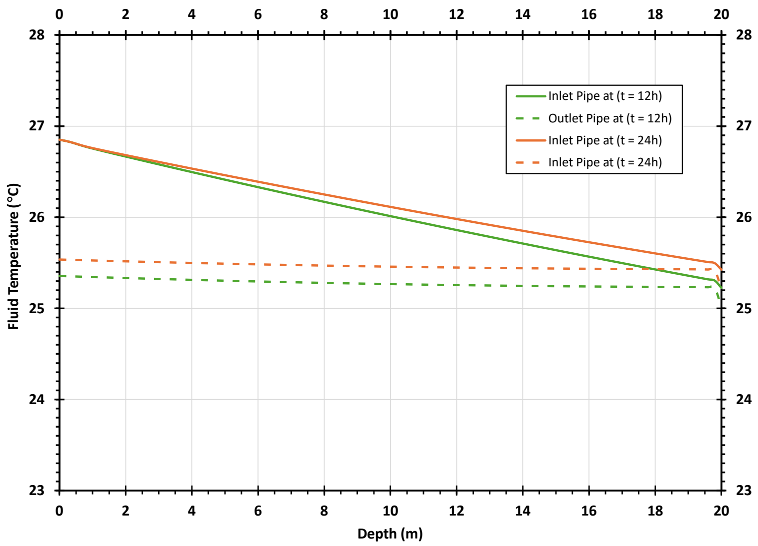

Figure 4.18: Average Temperature Variation in Simple CBHE at inlet flow rate of 8L/min.

Figure 4.18 shows average temperature variation in Simple CBHE for inlet flow rate of 8L/min. At t = 12h and t = 24h, the average temperature change between inlet and outlet is 1.495°C and 1.314°C respectively.

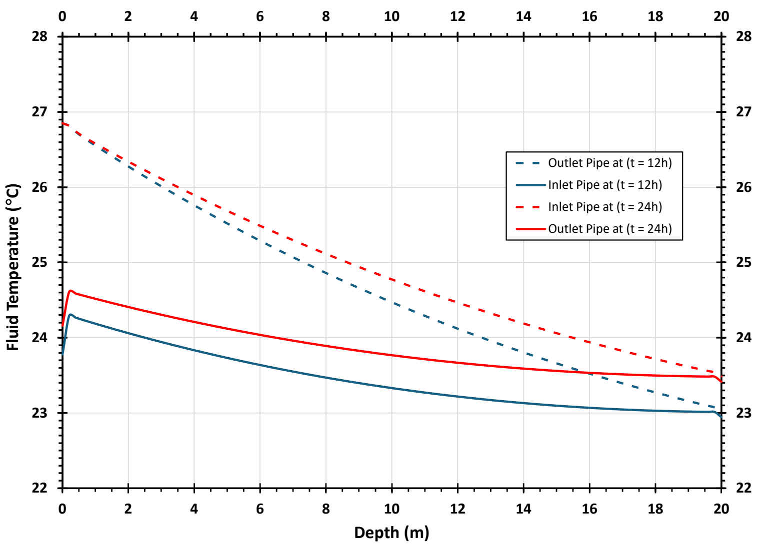

Figure 4.19: Average Temperature Variation in Finned CBHE (Fin Length = 5mm) at inlet flow rate of 4L/min.

Figure **4.19** indicates for finned coaxial borehole heat exchanger with fin length 5mm at inlet flow rate of 4L/min, temperature variation between fluid inlet and outlet temperatures at t = 12h and t = 24h are 3°C and 2.689°C respectively.

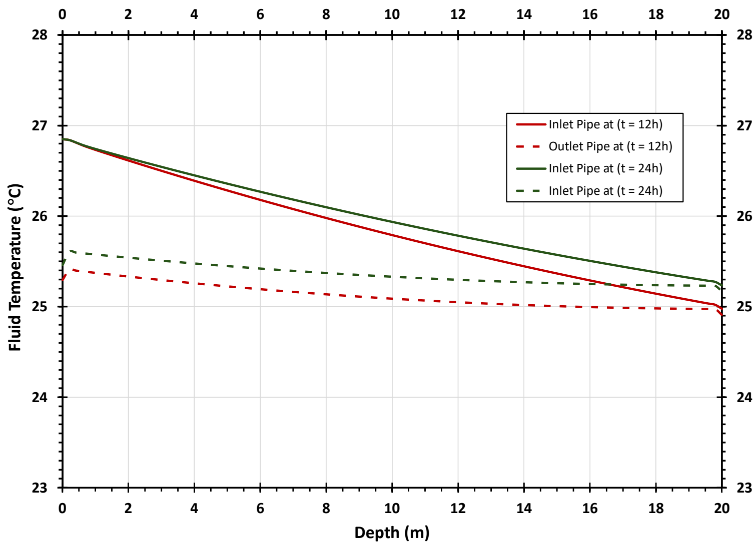

Figure 4.20: Average Temperature Variation in Finned CBHE (Fin Length = 5mm) at inlet flow rate of 8L/min.

Figure 4.20 it is observed that for finned coaxial borehole heat exchanger with fin length 5mm at inlet flow rate of 8L/min, difference variation fluid inlet and outlet temperatures at t = 12h and t = 24h are 1.555°C and 1.391°C respectively.

4.2 Analysis of CBHE at different fin lengths

Various simulations were performed considering different fin lengths (5mm, 10mm and 15mm) at flow rates of 4L/min and 8L/min. Average fluid outlet temperatures and heat exchange rates per unit length were calculated. Width (t) and no. of fins were considered constant in the simulations.

4.2.1 Average Fluid Temperatures at Outlet

Simulations were performed for simple and finned coaxial borehole heat exchangers with increasing fin lengths and were compared. During cooling mode, fluid enters at a constant temperature of 26.85°C and after exchanging heat with pipes that are connected to surrounding soil. Temperature decreases significantly after system establishing equilibrium. As the time increases, temperature difference between inlet and outlet decreases as a result of increase in surrounding soil temperature.

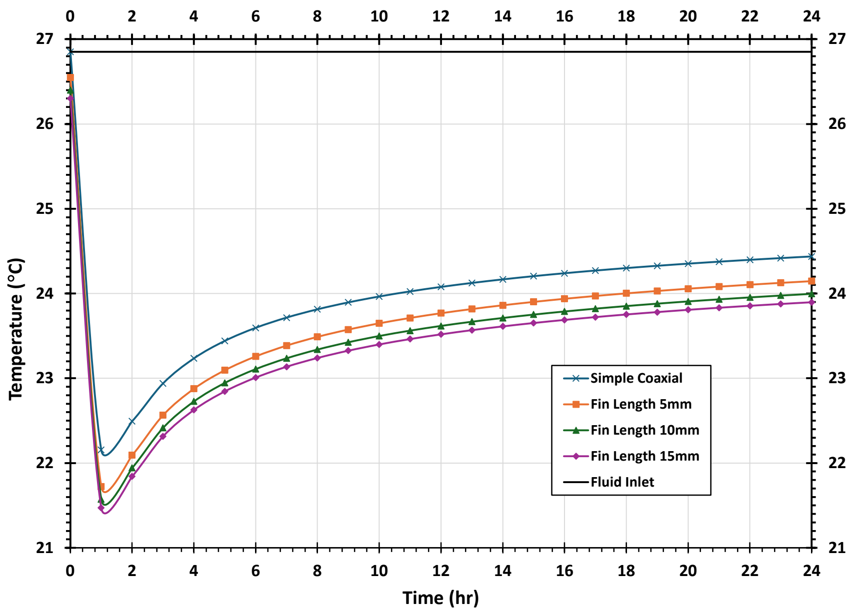

Figure 4.21: Average Fluid Temperature at Outlet for simple and finned CBHE at flow rate of 4L/min.

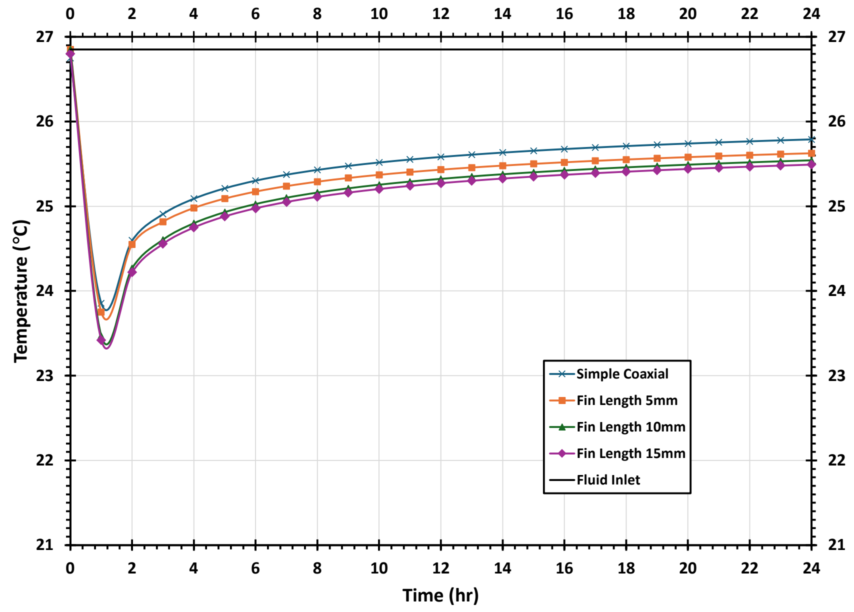

Figure 4.22: Average Fluid Temperature at Outlet for simple and finned CBHE at flow rate of 8L/min.

Figure 4.21 and Figure 4.22 shows average fluid temperatures at outlet for simple and finned coaxial borehole with fin lengths (5mm, 10mm and 15mm). Simulation was performed for 24 hours. It can be observed that the fluid temperatures at the outlet decrease as the fin length increases. Temperature difference between is significant for finned coaxial boreholes with fin length 5mm as compared to simple coaxial. At 8L/min temperature change between inlet and outlet is smaller as compared to 4L/min. At lower flow rates the ΔT will be larger.

4.2.2 Temperature Difference between inlet and outlet vs time

Figure 4.23 and Figure 4.24 represents fluid's temperature difference between inlet and outlet for 4L/min and 8L/min flow rates. At 4L/min flow rate, Average temperature difference for 24h in simple coaxial borehole was 2.86°C and for finned coaxial borehole with fin length 5mm was 3.18°C. For borehole with 10mm and 15mm fin length the average temperature difference was 3.32°C and 3.42°C respectively. At 8L/min flow rate, Average temperature difference for 24h in simple coaxial borehole was 1.36°C and for finned coaxial borehole with fin length 5mm was 1.48°C. For borehole with 10mm and 15mm fin length the average temperature difference was 1.62°C and 1.66°C respectively.

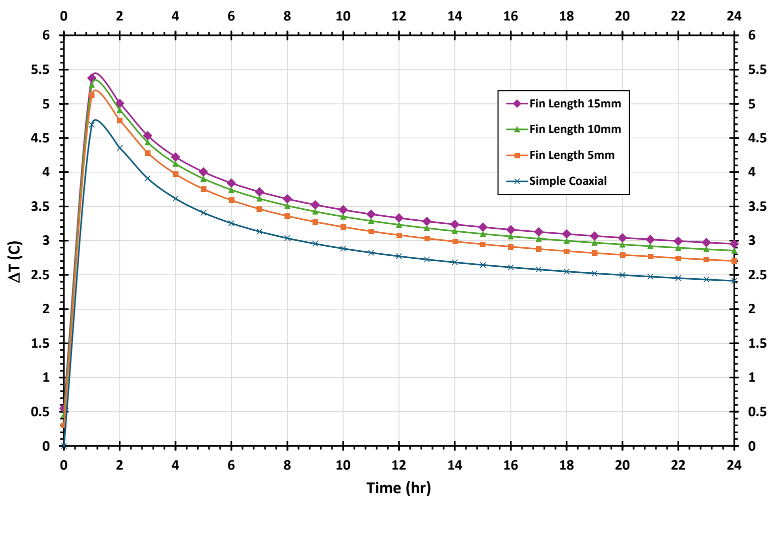

Figure 4.23: Temperature difference (ΔT) b/w inlet and outlet vs Time for simple and finned coaxial borehole at inlet flow rate of 4L/min.

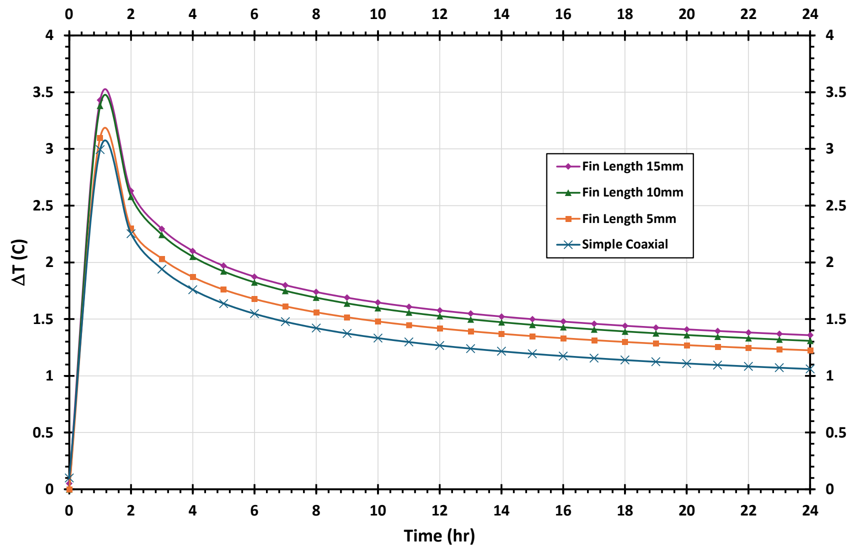

Figure 4.24: Temperature difference (ΔT) b/w inlet and outlet vs Time for simple and finned coaxial borehole at inlet flow rate of 8L/min.

4.2.3 Heat Exchange Rate per unit length vs Time

Figure 4.25 shows heat exchange rate per unit length for simple and finned CBHE at inlet flow rate of 4L/min.

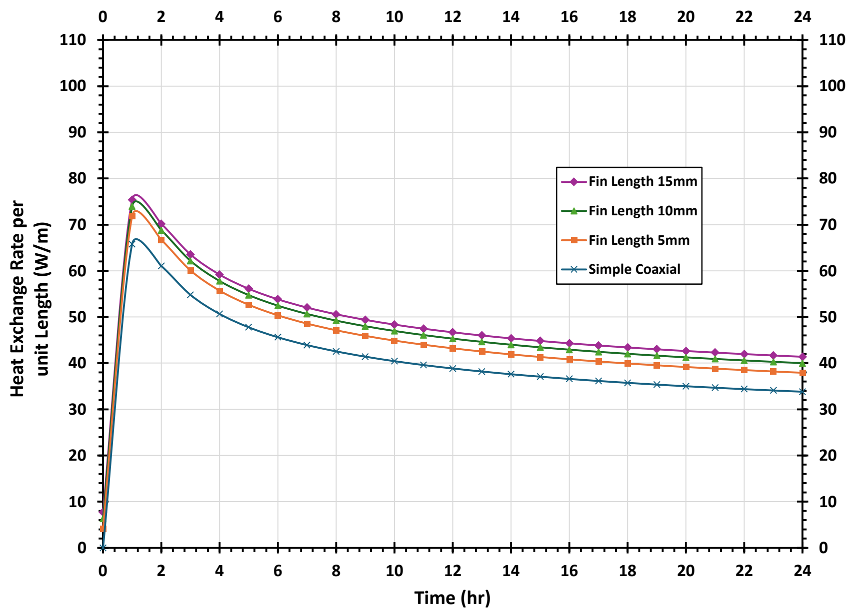

Figure 4.25: Heat Exchange Rate per unit length vs time for simple and finned coaxial borehole at inlet flow rate of 4L/min.

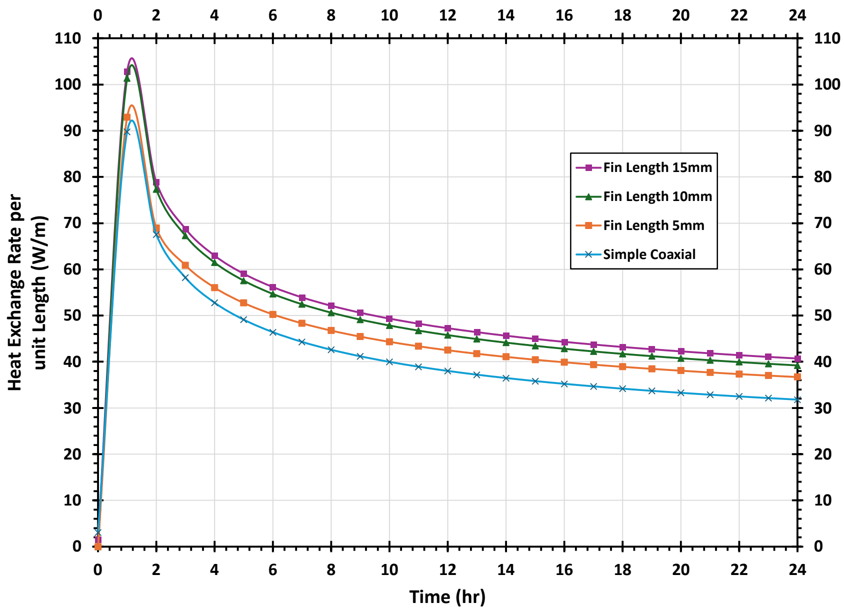

Figure 4.26: Heat Exchange Rate per unit length vs time for simple and finned coaxial borehole at inlet flow rate of 8L/min.

Figure 4.26 represents heat exchange rate per unit length for simple and finned coaxial boreholes at inlet flow rate of 8L/min. At 4L/min flow rate, Average heat exchange rate per unit length for 24h in simple coaxial borehole was 40W/m and for finned coaxial borehole with fin length 5mm was 44.5W/m. For borehole with 10mm and 15mm fin length it was 46.6W/m and 48.05W/m respectively.

At 8L/min flow rate, Average heat exchange rate per unit length for 24h in simple coaxial borehole was 42W/m and for finned coaxial borehole with fin length 5mm was 46W/m. For borehole with 10mm and 15mm fin length the average heat exchange rate per unit length was 48W/m as and 50W/m respectively.

4.2.4 Optimum Fin Length

Optimum fin length was calculated by evaluating average heat exchange rate per unit length for different fin lengths i.e (5mm, 10mm, 15mm and 20mm). Flow rate considered for calculating optimum fin length was 8L/min. With the increase in fin length up to certain length increases the average heat exchange rate per unit length for 24hr period.

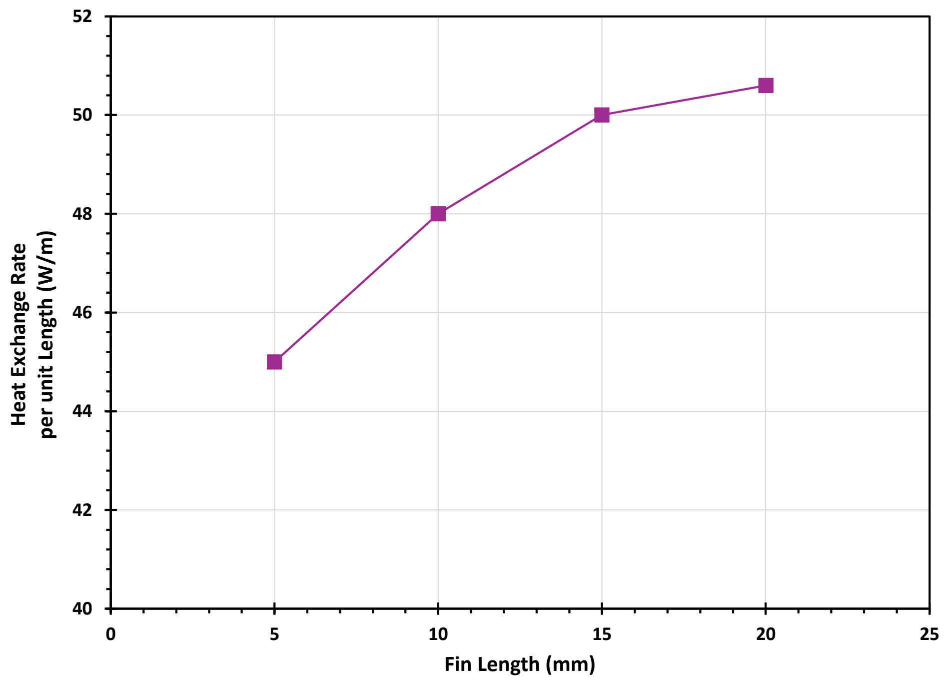

Figure 4.27: Average Heat Exchange Rate per unit Length vs Fin Length at inlet flow rate of 8L/min

Figure 4.27 shows average heat exchange rate per unit length for different fin lengths. At fin length of 15mm, average heat exchange rate per unit length was 50W/m and at fin length of 20mm, it was increased to 50.6W/m. It shows that optimum fin length is 15mm for finned coaxial borehole heat exchanger. With 20mm fin length average heat exchange rate was increased by 0.6W/m which was very small as compared to increase in fin cost for CBHE.

4.3 Overall Comparison between Simple and Finned CBHE

4.3.1 Comparison between Longitudinal and Radial Ground Temperatures at optimum fin length

At optimum fin length (15mm) the average and maximum longitudinal temperatures at R = 150mm for simple and finned coaxial borehole ground heat exchanger for inlet flow rate of 4L/min & 8L/min are shown in Table 4.1 & Table 4.2 respectively.

Table 4.1: Average and Maximum Longitudinal Ground Temperatures at Optimum Fin Length (15mm) & 4L/min Flow rate

	Simple Coaxial		**Finned Coaxial**	
Time	**Average Longitudinal Temperature (°C)**	**Maximum Longitudinal Temperature (°C)**	**Average Longitudinal Temperature (°C)**	**Maximum Longitudinal Temperature (°C)**
Initial	17.85	17.85	17.85	17.85
8h	20.35	21.18	20.51	21.40
12h	20.81	21.66	20.98	21.87
16h	21.12	21.97	21.30	22.17
20h	21.35	22.18	21.52	22.39
24h	21.52	22.35	21.70	22.55

At the end of 24hr operation and 4L/min flow rate the average longitudinal ground temperature was increased by 20% in case of simple coaxial and 21.6% in finned coaxial borehole. The maximum longitudinal ground temperature at the end of 24hr operation was increased by 25% in the case of simple coaxial and 27% in case of finned coaxial borehole heat exchanger.

Table 4.2: Average and Maximum Longitudinal Ground Temperatures at Optimum Fin Length (15mm) & 8L/min Flow rate

	Simple Coaxial		**Finned Coaxial**	
Time	**Average Longitudinal Temperature (°C)**	**Maximum Longitudinal Temperature (°C)**	**Average Longitudinal Temperature (°C)**	**Maximum Longitudinal Temperature (°C)**
Initial	17.85	17.85	17.85	17.85
8h	20.78	21.27	20.99	21.49
12h	21.27	21.74	21.47	21.96
16h	21.58	22.04	21.78	22.27
20h	21.80	22.27	22.01	22.49
24h	21.98	22.44	22.18	22.65

At the end of 24hr operation and 8L/min flow the average longitudinal ground temperature was increased by 23% in case of simple coaxial and 24.25% in case of finned coaxial borehole. The maximum longitudinal ground temperature was increased by 25.7% in case of simple coaxial and 27% in case of finned coaxial borehole ground heat exchanger.

At optimum fin length (15mm) the average and maximum radial temperatures at Z = 10m for simple and finned coaxial borehole ground heat exchanger for inlet flow rate of 4L/min & 8L/min are shown in Table 4.3 and Table 4.4 respectively.

Table 4.3: Average and Maximum Radial Ground Temperatures at Optimum Fin Length (15mm) & 4L/min Flow rate

	Simple Coaxial		**Finned Coaxial**	
Time	**Average Radial Temperature (°C)**	**Maximum Radial Temperature (°C)**	**Average Radial Temperature (°C)**	**Maximum Radial Temperature (°C)**
Initial	17.85	17.85	17.85	17.85
8h	18.75	24.08	18.80	23.99
12h	18.93	24.33	18.99	24.24
16h	19.08	24.48	19.15	24.40
20h	19.21	24.58	19.25	24.51
24h	19.32	24.66	19.40	24.60

Table 4.4: Average and Maximum Radial Ground Temperatures at Optimum Fin Length (15mm) & 8L/min Flow rate

	Simple Coaxial		**Finned Coaxial**	
Time	**Average Radial Temperature (°C)**	**Maximum Radial Temperature (°C)**	**Average Radial Temperature (°C)**	**Maximum Radial Temperature (°C)**
Initial	17.85	17.85	17.85	17.85
8h	18.92	25.08	18.97	24.98
12h	19.11	25.25	19.18	25.16
16h	19.27	25.35	19.34	25.27
20h	19.40	25.42	19.48	25.34
24h	19.51	25.47	19.60	25.40

At the end of 24hr operation and 4L/min flow rate the average radial ground temperature b/w 0.07m & 0.73m was increased by 8% in case of simple coaxial and 9% in finned coaxial borehole. The maximum radial ground temperature occurred near inlet pipe and at the end of 24hr operation was increased by 38% in the case of simple coaxial and 37% in case of finned coaxial borehole heat exchanger.

At the end of 24hr operation and 8L/min flow rate the average radial ground temperature b/w 0.07m & 0.73m was increased by 9.3% in case of simple coaxial and 9.8% in finned coaxial borehole. The maximum radial ground temperature occurred near inlet pipe and at the end of 24hr operation was increased by 43.8% in the case of simple coaxial and 42% in case of finned coaxial borehole heat exchanger.

4.3.2 Comparison between Average and Minimum Fluid Temperatures at different fin lengths

The average & minimum fluid outlet temperatures for period of 24hr are shown in Table 4.5. With the increase in fin length the average fluid outlet temperatures decreased which indicates and increase in heat exchange rate per unit length. At 4L/min and optimum fin length (15mm) the average and minimum outlet fluid temperatures decreased by 0.48°C & 0.67°C respectively as compared to simple coaxial borehole. At 8L/min and optimum fin length (15mm) the average and minimum outlet fluid temperatures decreased by 0.3°C & 0.48°C respectively as compared to simple coaxial borehole.

Table 4.5: Average & Minimum Fluid Outlet Temperatures for period of 24hr

	4L/min		**8L/min**	
Type / Fin Length	**Average Fluid Outlet Temperature (0 – 24h)**	**Minimum Fluid Outlet Temperature (0 – 24h)**	**Average Fluid Outlet Temperature (0 – 24h)**	**Minimum Fluid Outlet Temperature (0 – 24h)**
Simple	23.9°C	22.15°C	25.48°C	23.85°C
5mm	23.67°C	21.72°C	25.30°C	23.75°C
10mm	23.52°C	21.57°C	25.20°C	23.46°C
15mm	23.42°C	21.47°C	25.18°C	23.41°C

4.3.1 Comparison between Average and Maximum Heat Exchange Rates at different fin lengths

The average and maximum heat exchange rates for the period of 24hr are given in Table 4.6. At 4L/min flow rate the average heat exchange rate per unit length increased by 18% as compared to simple CBHE. At 8L/min flow rate average heat exchange rate per unit length increased by 22% as compared to simple coaxial borehole ground heat exchanger. At average for 20m borehole depth the heat exchange rate increased from 800W to 950W at 4L/min flow rate and 820W to 1000W at 8L/min flow rate.

Table 4.6: Comparison between average and maximum heat exchange rates at different fin lengths

	4L/min		**8L/min**	
Type / Fin Length	**Average Heat Exchange Rate per unit length (0 – 24h)**	**Maximum Heat Exchange Rate per unit length (0 – 24h)**	**Average Heat Exchange Rate per unit length (0 – 24h)**	**Maximum Heat Exchange Rate per unit length (0 – 24h)**
Simple	40W/m	65.8W/m	41W/m	90W/m
5mm	44W/m	71W/m	45W/m	92W/m
10mm	46W/m	74W/m	48W/m	101W/m
15mm	47.5W/m	75.3W/m	50W/m	103W/m

4.4 Discussion

Addition of longitudinal fins improves the heat exchange rate of coaxial borehole heat exchangers. With the increase in fin length up to optimum fin length increases the efficiency of the ground heat exchanger. Increasing the length beyond optimum fin length will increase the initial costs of installation for ground heat exchanger. It can be observed from optimization study that coaxial borehole heat exchanger performance is increased when the fin length was increased up to 15mm length. Beyond 15mm the performance of CBHE was reduced because of increased thermal resistance. Longer fins will create more resistance to heat flow and can increase the cost of the system.

CHAPTER 5: CONCLUSIONS AND FUTURE RECOMMENDATION

5.1 Conclusion

In this study, heat transfer characteristics of finned CBHE have been studied. Different flow rates i.e 4L/min and 8L/min were applied at the inlet of CBHE. CFD Simulations were performed to evaluate the feasibility of using finned CBHE.

3D model for CBHE with and without fins was discussed in detail. The model validation study was also discussed for simple coaxial borehole heat exchanger, which shows us the accuracy of results. All the simulations were carried out for the time period of 24 hours because of the computational resources. Moreover, simulations were carried out for the cooling mode. Although, the ground heat exchangers can work continuously for several months.

Results for simple and finned coaxial borehole heat exchangers have been discussed in detail. At 4L/min the fluid's temperature difference between inlet and outlet was more than at 8L/min. As the time passed, the radial ground temperatures also increased up to 0.7m for 24 hours. This radial ground temperature can be used to model multi coaxial borehole heat exchangers. The minimum distance between two coaxial borehole heat exchangers can be determined for different running times of the system.

Fluid temperature variations along the longitudinal direction of the pipes were also evaluated. It was found out that as the fluid passed through the inlet pipe it exchanges heat with the ground. Thermal loss between inlet fluid and outlet fluid can also be observed. Thermal loss can be avoided if insulation was used at the outlet pipe.

At 4L/min flow rate & inlet temperature of 26.85°C the average outlet temperature at the end of 24hr operation for simple coaxial borehole was 23.9°C. At optimum fin length (15mm) the outlet temperature was reduced to 23.42°C. The minimum fluid outlet temperature was 22.15°C in case of simple coaxial borehole and reduced to 21.47°C at optimum fin length for finned CBHE.

At 8L/min flow rate & inlet temperature of 26.85°C the outlet temperature at the end of 24hr operation for simple coaxial was 25.48°C. At optimum fin length (15mm) the outlet temperature was reduced to 25.18°C. The minimum fluid outlet temperature was 23.85°C in case of simple coaxial borehole and reduced to 23.41°C at optimum fin length for finned coaxial borehole heat exchanger.

The average HER per unit length at the flow rate of 4L/min and period of 24hr were increased from 40W/m to 47.5W/m when the fin length was 15mm. At 8L/min this increase in heat exchange rate is observed from 41W/m to 40W/m. Considering the 20m borehole length the overall heat exchange rate increased from 800W to 950W at 4L/min flow rate and 820W to 1000W at 8L/min flow rate.

Optimum fin length was evaluated using different fin lengths i.e 5mm, 10mm, 15mm & 20mm. It was observed that up to 15mm fin length the variation in temperature between inlet and outlet is significant. It can be concluded that at 8L/min with fin length of 15mm the efficiency of the system was increased up to 22% for the system. At 4L/min flow rate and fin length 15mm the efficiency of the system was increased by 18%. Increase in efficiency of the BHE can significantly reduce the borehole depth and the initial cost for installation.

This study provides an investigation about finned coaxial borehole heat exchanger. Results indicate that increase in fin length initially leads to enhancement in heat transfer due to increased surface area and temperature gradient. Above a certain optimum length heat transfer rate decrease. These findings can contribute towards design optimization and practical implications for energy efficient borehole heat exchangers.

5.2 Future Recommendations

In this study, we have discussed details in achieving efficient coaxial borehole ground heat exchanger. There is a lot of potential in this research area. For future work some of the recommendations are proposed:

- In the current study, rectangular fins were used. Different fin shapes can also be studied for future research.

- The current study was based on the cooling configuration, for heating configuration the system can also be studied.
- Different pipe materials can also be studied for optimum heat exchange rate.
- Experimental studies can also be performed for finned coaxial boreholes.
- Studies can also be performed for multi-coaxial borehole heat exchangers.

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