A Numerical Simulation-Based Analysis of Heat Transfer Performance for Underground U-Type Heat Exchanger in the Scope of KC05.21/16-20 Project

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Abstract. In this paper, a ground heat source cooling system based on a novel underground heat exchanger is proposed for cooling of a Base Transceiver Station (BTS) in the scope of KC05.21/16-20 project entitled “Research, design and manufacture geothermal cooling systems for Base Transceiver Station”. Compared to traditional underground heat exchanger, the perforated borehole tube is used to improve the heat transfer efficiency by favorizing the interaction between ground water flow and hot water flow in U-type tube. Since the heat transfer from the cooling water and the infinity soil, which is impacted by the soil structure and the groundwater accumulated in the void space, is complicated, the analytical computation is not suitable. The Computational Fluid Dynamics (CFD) model of underground U-type heat exchanger was developed to benchmarking the heat transfer efficiency. The influence of flow configurations and of U-type tube length on the heat load and overall thermal resistance were investigated.

1. Introduction
Over the last decade, the shallow geothermal energy sources have been widely applied in the moderate temperature heating and cooling systems as an attractive and sustainable energy source. The application of the shallow geothermal energy sources in heating and cooling has been reviewed and summarize in [1-3]. Especially, geothermal sources have been surveyed and evaluated with great potential in our country (Vietnam) because of its specific geographical location and tropical monsoon climate zone. The research on technology design and fabrication of geothermal cooling systems have high feasibility and significant savings in energy consumption for cooling industrial manufacturing areas. For example, the electronic equipment and components need to be cooled insides the large number of Base Transceiver Station (BTS) of telecommunications corporations in our country. To save most of the electrical power consumed at these BTS comparing with using other forms of energy, the paper aims to develop a ground heat source cooling system for BTS. This is a part of our research project funded by the State (code: KC05.21/16-20), which is led by the authors at Hanoi University of Science and Technology, Vietnam [4, 5].
In fact, the geothermal source air cooling and heating systems can be classified in three categories: open-loop, close-loop and a closed-loop system coupling with compressor air conditioner/heat pump. In these systems, the overall heat transfer efficiency is mainly controlled by the heat transfer efficiency of underground heat exchangers due to the high values of heat transfer resistance. Therefore, the heat transfer resistance between the fluid flow in the heat exchangers and the surrounding soil layer is an essential required data of system design procedure. This heat transfer process has been recently studied by both numerical simulations and experiments. In the experimental work of Go, Lee, Yoon, et al. [6], the inlet and outlet temperature difference and heat load of horizontal spiral-coil-loop heat exchanger have been measured. The numerical simulations of heat transfer process, economic analysis have been performed in [6] by coupling the underground heat exchanger with a heat pump. Javadi, Ajarostaghi, Pourfallah, et al. [7] have performed CFD simulations of vertical single U-shape tube ground heat exchangers with different various configurations in transient state. This work indicated that the thermal performance of ground heat exchangers could be enhanced by using a novel configuration with triple helix heat exchanger. Another CFD simulation of horizontal ground heat exchangers made by High-Density Polyethylene (HDPE) and Composite has been introduced in [8]. The numerical results showed that positioning of return pipe in vertical orientation was crucial and composite pipe coating restricts its performance identical of that in HDPE pipe. In addition to these cited works up to here, other experimental and numerical studies on the heat transfer efficiency of underground heat exchanger can be found in literature, such as [9-13]. In the cited works, the soil is considered as a solid layer; therefore, the impacts of ground water on the heat transfer are not accounted for. In our case study, a close-loop cooling system using an underground U-type heat exchanger constructed inside a perforated borehole tube is proposed for cooling a base transceiver station. The heat transfer performance of the heat exchanger is characterized by Computational Fluid Dynamics (CFD) simulations. The impact of flow configuration and geometrical properties on the heat transfer efficiency is also analyzed and assessed. The paper is structured as follows: The CFD model realization in the scope of KC05.21/16-20 project is adapted and implemented in the second section. The third section presents the details of obtained simulation results and discussions. Conclusions and future works are reported in the final section.

2. CFD model realization in the Scope of KC05.21/16-20 Project

2.1. Overview of physical system design

In this study, a cooling system based on a vertical underground heat exchanger using close water loop is proposed for cooling a BTS. The cooling system is comprised of U-type underground heat exchanger, a pump, connection tube and a Fan-Coil Unit (FCU) as shown in Fig. 1. The heat load of BTS station is mainly due to the thermally power dissipation of electric devices and battery. To prolongate the service life of this system, the station temperature should not exceed 36°C. In this work, the station temperature of 34°C is chosen for system design. A FCU with a capacity of 2kW is installed in BTS room. The liquid water with temperature of 27°C (T_{inlet}) enters the FCU and is heated by BTS heat load to 30°C (T_{outlet}) before releasing with a mass flow rate of 0.159 kg/s (\dot{M}_{water}). The high temperature water flows into the underground heat exchanger and is cooled by transferring the thermal energy to the surrounding soil.
Traditionally, the underground heat exchanger is comprised of a U-type steel tube inserting inside a borehole. At the outer of borehole, an outer tube is installed to strengthen the stability of the heat exchanger. However, since the close outer tube prevent the interaction between ground water and U-type tube, the heat transfer efficiency is restrained. In this work, the perforated outer tube has been used instead of close outer tube. We will performed the CFD simulations for the flow configurations as shown in Fig. 2. Here, Case 0 corresponds to the U-type tube in non-perforated borehole; Case 1 and Case 2 respectively correspond to U-type tubes in perforated borehole, which are perpendicular and parallel to the ground water flow.

The main geometrical parameters of the underground heat exchanger are summarized as follows:

- Pipe diameter d = 0.02m,
- U-shaped tube exchanger’s length L = 6.0m,
- Diameter of computational soil domain D = 1.2m,
- Diameter of borehole D’= 0.2m.

With the designed heat load of 2kW and these dimensional and thermal properties, a water mass flow rate of 0.0955kg/s can be estimated. Thus, the water velocity of 0.5m/s inside the U-type tube is used in the simulations. The thermo-physical properties of water, porous soil and steel, which are used in the simulations, are presented in Table I.
Table 1. Physical parameters of used materials.

| Parameters               | Soil  | Water | Steel |
|--------------------------|-------|-------|-------|
| Density \( \rho \) [kg/m\(^3\)] | 1700  | 998   | 8030  |
| Specific heat \( C_p \) [J/kg.K] | 1800  | 4182  | 502   |
| Thermal conductivity \( k \) [W/mK] | 1.2   | 0.6   | 16.27 |
| Kinematic viscosity \( \nu \) [m\(^2\)/s] | -     | 0.8×10\(^{-6}\) | -     |
| Porosity                 | 0.4   | -     | -     |
| Permeability [m/s]       | 10\(^{-5}\) | -     | -     |

2.2. Implementation of CFD model

In present design and construction of engineering systems, there were many applications that have used the CFD simulation approach by using open-source or commercial software tools to make them more effective for optimizing the system design [14-19]. In this study, the computational domain of the heat exchanger and surrounding soil is built by using DesignModeller tool of ANSYS software [20]. To reduce the computational cost of simulations, the thermal resistances of water tube walls is neglected. The geometry file is imported in Mesh tool of ANSYS software, and is discretized by unstructured mesh. The mesh size is varied to investigate the impact of mesh on the simulation results. It is obtained that when the number of elements exceed 3 million, the simulation results become mesh-independent. In this work, a mesh with the number of elements varying from 3 million to 6 million, depending on U-type tube lengths, which have been chosen to be used in the simulations. One steady state simulation takes around 2 hours to 3 hours in a PC with CPU Core i7-8700K and 16 GB of RAM. The geometry and the mesh of this heat exchanger is respectively presented in Fig. 3 and Fig. 4. The generated mesh is imported in Fluent tool of ANSYS software, the soil material is considered as a porous material. The inlet ground water velocity of 0.02m/s and temperature of 23°C are set in the model. The outer soil surface temperature is set as constant with a value of 23°C (\( T_{soil} \)), based on the experimental data obtained at Hanoi City. The residuals of energy and continuity reach \( 10^{-4} \) and other residuals are smaller than \( 10^{-6} \) when the calculation is stopped, and the results are extracted.

3. Results and discussion

The typical temperature distribution in water, sand and soil space is presented in Fig. 5. Based on the temperature distribution, the outlet temperature \( T_{outlet} \) of water is determined. The heat load \( Q \) of heat exchanger and the total thermal resistance \( R \), including working fluid, pipe, and surrounding soil during the operation, are determined as

\[
Q = M_{water} C_{p,l} (T_{inlet} - T_{outlet})
\]

\[
R = \frac{L}{Q} \left( \frac{T_{inlet} + T_{outlet}}{2} - T_{soil} \right)
\]

In Eq. (1), \( C_{p,l} \) denotes specific heat capacity of liquid water. The impact of flow configurations and U-type tube lengths on the heat load, total thermal resistance will be next presented.
Figure 3. The mesh of computational domain of underground heat exchanger and surrounding solid: outer (a) and symmetrical-slice (b) views.

Figure 4. The geometry of underground heat exchanger.

Figure 5. Temperature distribution at the symmetrical face of the domains in case 0, case 1 and case 2 for a U-tube length of 2m.
To design a heat exchanger with a heat load of 2kW, the impact of the U-type tube length on the heat transfer efficiency needs to be investigated. The exchanger length is varied from 2.0m to 6.0m in the CFD simulations whereas other parameters is unchanged. The evolution of temperature difference over U-shape tube length is shown as Fig. 6 for three implemented cases. Naturally, a longer tube leads to a large heat transfer area and the resident time of water in the heat exchanger is prolonged. It results in a higher amount thermal energy transferred and larger values of temperature difference (cf. Fig. 6). Additionally, the heat load of the heat exchanger and heat transfer coefficient are computed by using Eqs. (1) and (2) and the obtained results is reported in Table 2.

The results indicate that ground water flow through the perforated borehole tube significantly enhanced the heat transfer efficiency. As can be seen, the heat capacity of the exchanger with the proposed design increases from 550% to 830%, when the U-type tube length varies from 2.0m to 6.0m, respectively, compared to the transitional configuration. Additionally, the parallel configuration may provide a higher heat capacity compared to the perpendicular configuration since the ground water can easily interact with the U-type tube. Furthermore, the impact of U-type tube length on the heat capacity can be described by using exponential correlations as

\[ Q = Q_m \left[ 1 - \exp\left( -0.0568 \times L \right) \right] \]

\[ Q = Q_m \left[ 1 - \exp\left( -0.0696 \times L \right) \right] \]

Where \( Q_m = \dot{M}_{water} c_{p,w} (T_{inlet} - T_{out}) \). From these correlations, a heat capacity of 2kW can be reach with U-type tube length of 17.51m and of 14.72m with the perpendicular and parallel flow configurations, respectively.

![Figure 6](image_url)

**Figure 6.** Influence of U-shape tube length on the temperature difference between inlet and outlet water.
4. Conclusions and future work
In this study, a CFD model of underground U-type heat exchanger, which is used for cooling BTS, was developed. By performing a sensitivity analysis, the impacts of geometrical parameters on the heat transfer performance are investigated. The total thermal resistance of the exchanger, which is mandatory of heat exchanger design, was implemented. Based on the computational results, U-type tube length of 17.51m and of 14.72m with the perpendicular and parallel flow configurations were proposed to manufacture the underground U-type heat exchanger with capacity of 2kW for cooling the BTS.

In the future, the CFD simulations will be performed for various ground heat exchanger configurations. Then, we will describe the steps taken to transition from theory to practice and the results of actual tests performed with 3 BTS having different heat capacities, in Thai Binh Province, Vietnam, in the Spring of 2020.

5. References
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