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Heat Transfer Perfomance Of Underground U-Type Heat Exchanger: A CFD Model-Based Analysis

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ABSTRACT: In this work, a ground heat source cooling system is proposed for cooling of a base transceiver station (BTS), instead of traditional air conditioner with compressor. This cooling system is comprised of a vertical underground heat exchanger, a fan coil unit and a circulating pump. Liquid water enters the fan coil unit to be heated up by adsorbing the heat load of BTS and flows into the underground heat exchanger. In the underground heat exchanger, water released the thermal energy to the surrounding soil. To design the underground heat exchanger, the heat transfer coefficient between water and soil is required as an essential input. In this work, a CFD model of underground U-type heat exchanger has been developed. The influence of computational domain size, mesh resolution on the numerical results are checked. Based on the temperature distribution along the water tube, the heat load and overall thermal resistance are determined. The impact of tube diameter, vertical tube length, water inlet temperature and velocity, soil thermal conductivity on the overall thermal resistance are investigated.

INTRODUCTION

Generally, temperature of Earth increases gradually while moving from surface to center of the Earth, due to gigantic heat source of the Earth’s core. As a rule of thumb, when the depth increases every 100 meters, the temperature grows up 2-3 ℃. But the aforementioned tendency is not be true with the soil layer located near the surface since this soil layer is influenced by annual temperature oscillation at the surface, not by the heat source of the Earth's core. Since the temperature oscillation becomes damping with the increase of thermal permeation distance, the temperature of the soil layer with a depth of several dozens of meters, named as shallow soil layer or subsurface layer, becomes stable around the mean temperature of the climate at the Earth’s surface. This tendency can be seen in the experimental data measured in Hanoi City by Institute of Geological Sciences - Vietnam Academy of Science and Technology in frame of Vietnamese national research project KC08.16/11-15 which is reported in Fig. 1 [1]. It implies that the temperature of the subsurface is lower than the ambient air temperature in summer and higher in winter. Based on this feature, this subsurface layer can be applied as a heat capacitor for moderating indoor temperatures.

In recent years, with emerging technological advancement in design, construction and computer control, coupled with the energy shortage, fossil fuel depletion, and strict environmental regulations, the shallow geothermal energy sources became attractively a sustainable energy source which enhances energy saving capacity in moderate temperature heating and cooling systems. The application of the shallow geothermal energy sources in heating and cooling has been reviewed and summarize in [2–5].

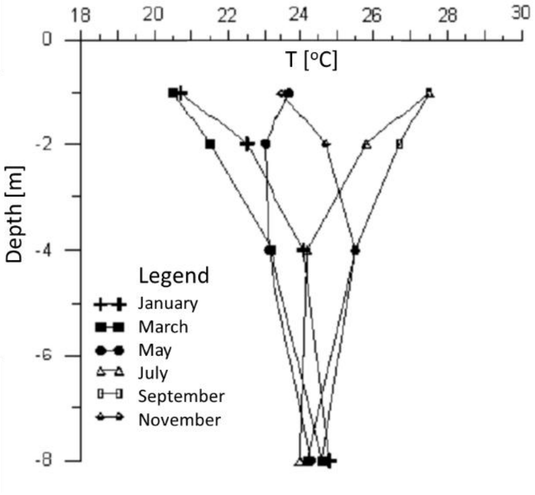


Figure 1. Temperature evolution in subsurface soil layer at different times in Hanoi [1].

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 recently has been studied by both experimental, analytical and numerical studies. In the experimental work of Go et al. [6-7], 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 [7] by coupling the underground heat exchanger with a heat pump. Javadi et al. [8-9] 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 can be enhanced by using a novel configuration with triple helix heat exchanger. Another CFD simulation of horizontal ground heat exchangers made by HDPE and Composite was performed in Selamat et al. [10]. The numerical results showed that positioning of return pipe in vertical orientation is 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 [11-20].

In this work, a close-loop cooling system using an underground U-type heat exchanger is proposed for cooling a base transceiver station. The heat transfer performance of the heat exchanger is characterized by CFD simulations. The impact of operating condition, geometrical and material properties on the heat transfer efficiency is analyzed.

MODEL DESCRIPTIONS

System design

This cooling system is comprised of a vertical underground heat exchanger, a fan coil unit and a circulating pump as sketched in Fig. 2. Since BTS is a machine-using environment, the temperature requirement is not as strict as for humans, a temperature of 36 ^{c}o. is proposed for BTS space. To maintain this temperature, an FCU with a capacity of 2 kW is installed in BTS room. The liquid water with temperature of 25 ^{o}C enters the FCU, absorb the heat load of BTS space and releases with temperature of 30 ^{o}C. The high temperature water flows into the underground heat exchanger and is cooled by releasing thermal energy to the surrounding soil.

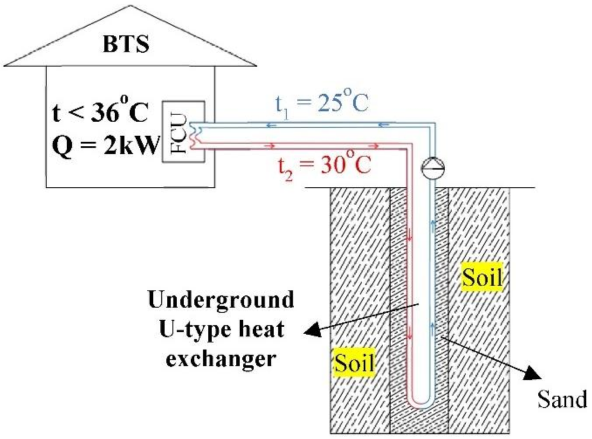


Figure 2. Cooling system for BTS station air conditioning.

The underground heat exchanger is comprised of a U-type steel tube, an outer pipe made by HDPE. The void space between the U-type tube and outer pipe are filled by sand. The heat exchanger is installed in a borehole as presented in Fig. 2. The dimensional properties of the heat exchanger are listed as following whereas the thermo-physical properties of materials are presented in Table 1. Noted that the heat exchanger with these geometrical properties is used as a benchmarking case in sensitivity analysis.

- Pipe diameter d = 20mm
- U-shape tube exchanger's height = 6 m
- Diameter of computational soil domain D = 1.2m
- Diameter of borehole D'= 0.2m

With the designed heat load of 2 kW and these dimensional and thermal properties, a water mass flow rate of 0.0955 kg/s can be estimated.

Table 1. Physical parameters of materials [17,18]

Material	Density ρ, kg/m^3	Specific heat C_p, J/kg.K	Thermal conductivity k, W/mK	Kinematic viscosity υ, m2/s
Soil	1700	1800	1.2	-
Sand	2210	750	1.4	-
Water	998	4182	0.6	0.8×10^{-6}

CFD model

The geometry of the heat exchanger and surrounding soil is created in Design Modeller tool of Ansys Fluent 19.0 software. To reduce the computational cost of simulations, the thermal resistances of tube and pipe walls are neglected. The geometry file is imported in Mesh tool 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 2 million, the simulation results change slightly when the number of mesh elements increases. In this work, a mesh with 3 160 496 elements has been chosen to be used in simulations in this work. One steady state simulation takes around 4 hours in a PC with CPU Core i7-8700k and 16 GB RAM. The geometry and the mesh of this heat exchanger is presented in Figs. 3 and 4, respectively.

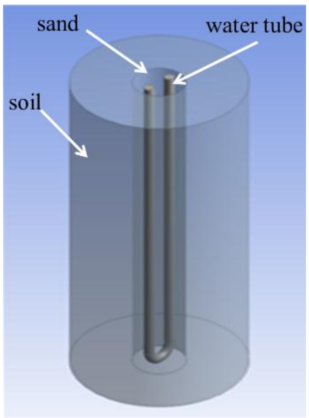
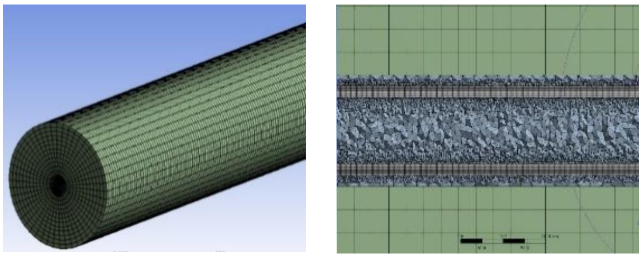


Figure 3. The geometry of underground heat exchanger.



(a) (b)

Figure 4. The mesh of computational domain of underground heat exchanger and surrounding solid: outer (a) and symmetrical-slice (b) views.

The generated mesh is imported in Fluent software, the solid phase is set for sand and soil layer whereas the fluid phase is set for tube space with standard turbulent model k- ε for water flow. The outer soil surface temperature is set as constant with a value of 23 °C, based on the experimental data obtained at Hanoi City. The simulation converges when the residual of energy and continuity reach 10^{-4} and other residuals are smaller than 10^{-6}.

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 of water is determined. Based on the inlet and outlet temperature, the heat load is determined. The heat load of heat exchanger and the equivalent heat transfer coefficient *k* is computed as

$$Q = \dot{M}_{water} c_{p,l} \left(T_{inlet} - T_{outlet}\right) \tag{1}$$

$$k = \frac{Q}{2\pi dL \dfrac{T_{inlet} - T_{outlet}}{\ln\left(\dfrac{T_{inlet} - T_{soil}}{T_{oulet} - T_{soil}}\right)}} \tag{2}$$

In the next section, the impact of computational domain size, the U-type tube inner diameter and length on the heat load, heat transfer coefficient and pressure drop are presented.

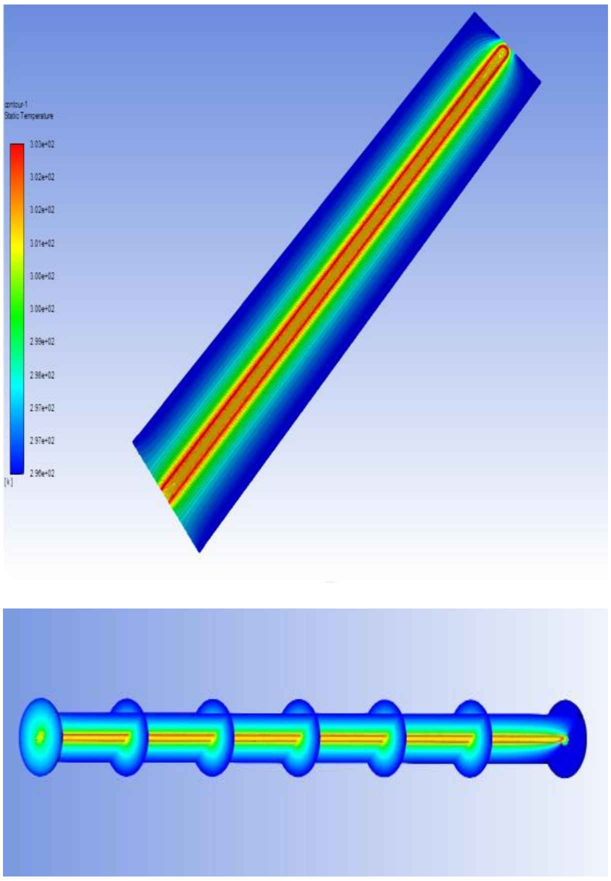


Figure 5. Temperature field at the symmetrical face and vertical slices of the domains.

Impact of computational domain size on the transport characteristic of underground heat exchanger

Indeed, the soil layer surrounding heat exchanger is a semi-infinite space, however the heat transfer process takes place only in a thermal penetrative distance. Thus, it is not necessary to simulate a wide soil layer since the temperature gradient at the soil layer far from the U-shape tube become negligible. In this work, the impact of soil layer diameter on the simulated thermal performance is illustrated. The simulations are performed with different soil diameter varying from 400 mm to 1800 mm and the simulated temperature difference between inlet and outlet water is plotted in Fig. 6. The temperature difference deduces 0.50 K to 0.31 K with soil layer diameter of 400 mm and 1200 mm. respectively. It can be explained that when the diameter of the soil layer increases the transport distance from the U-shape tube and the isothermal soil surface becomes larger resulting a smaller heat flux from the U-shape tube to soil. However, when the soil layer diameter increases from 1000 mm to 1200 mm, the temperature difference drops slightly from 0.32 K to 0.31 K. It implies that the soil layer diameter of 1200 mm can be used as thermal penetrative distance in CFD simulation which is used in the rest of this paper.

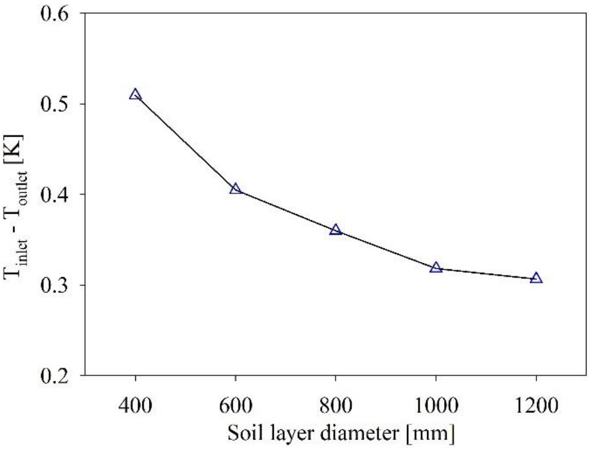


Figure 6. Influence of soil layer diameter on the temperature difference between inlet and outlet water. The connecting line is aid of eye.

Impact of U-shape tube diameter on the transport characteristic of underground heat exchanger

The CFD simulations are performed with different U-shape tube diameters in range from 10 mm to 40 mm whereas other parameters remain unchanged. The obtained results are presented in Fig. 7. Since a constant value of the mass flow rate of water in the system used in simulations, a large tube leads to smaller water velocity. Therefore, a longer residence time of water in the system can be obtained with a large tube, it results in a higher temperature difference between inlet and outlet water. It is also noted that the low velocity reduces the heat transfer coefficient between water flows and the tube wall. However, the prominent heat transfer resistance of the system is the conductive heat transfer resistance of soil and sand layer, the impact of U-shape tube diameter on the overall heat transfer coefficient is insignificant. The temperature rather increases linearly with the increasing of tube diameter in Fig. 7. Although a large U-shape tube can help to increase the heat transfer performance, the economic cost of the system is significant increases. As a compromise between heat transfer performance and manufacturing price of the underground heat exchanger, the tube diameter d = 20 mm has been selected.

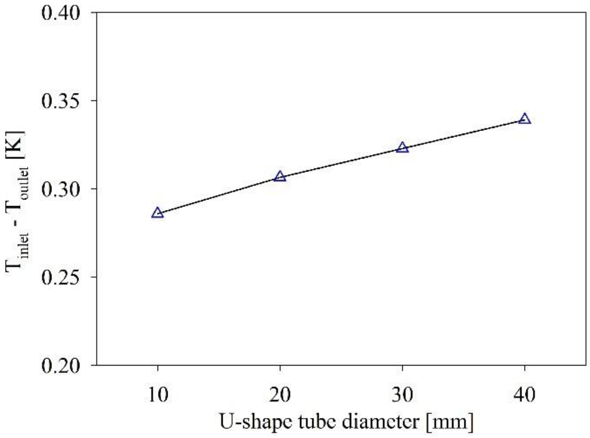


Figure 7. Influence of U-shape tube diameter on the temperature difference between inlet and outlet water. The connecting line is aid of eye.

Impact of U-shape tube height on the transport characteristic of underground heat exchanger

To design a heat exchanger with a heat load of 2 kW, the impact of the U-shape tube height on the heat transfer efficiency needs to be investigated. The exchanger height is varied from 3000 mm to 12000 mm in the CFD simulations whereas other parameters is unchanged. The evolution of temperature difference over U-shape tube height is presented in Fig. 8. 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 a larger values of temperature difference (c.f. Fig. 8). 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.

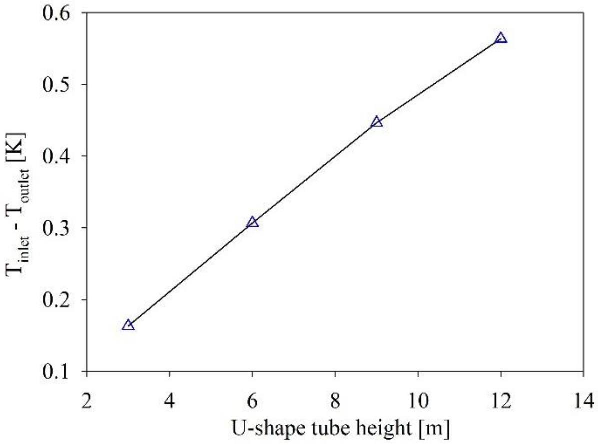


Figure 8. Influence of U-shape tube height on the temperature difference between inlet and outlet water. The connecting line is aid of eye.

Table 2. The impact of U-shape tube height on the heat load and heat transfer coefficient of the heat exchanger.

H, m	ΔT, K	Δp, Pa	Q, W	k, W/m^{2}K
3	0.1632	512.5	65.2	24.9
6	0.3067	1000.2	122.6	23.8
9	0.4463	1492.2	178.4	23.3
12	0.5756	2041.8	230.1	22.8

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 with the current configuration of underground heat exchanger, the design heat capacity of 2 kW cannot be reached. To solve the shortage of heat load, two methods for heat transfer enhancement are proposed. In the first method, the heat transfer coefficient *k* is improved by using Magnesium Oxide (MgO) to fill the borehole, instead of sand. The second method is the used the helical ground heat exchangers as in Fig. 9. Due to an expensive computational cost of CFD simulations for helical ground heat exchanger geometry, the CFD simulations are performed for the first method with filling material of MgO in the frame of this work.

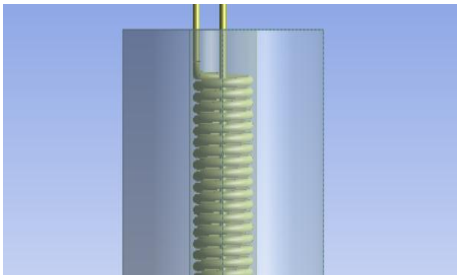


Figure 9. Underground heat exchanger with helical water tube.

Enhancement of heat transfer performance by using MgO as filling material

The MgO powder with thermal conductivity 45 W/mK is used in the CFD simulations, instead of sand. The numerical results are presented in Fig. 10 and Table 3.

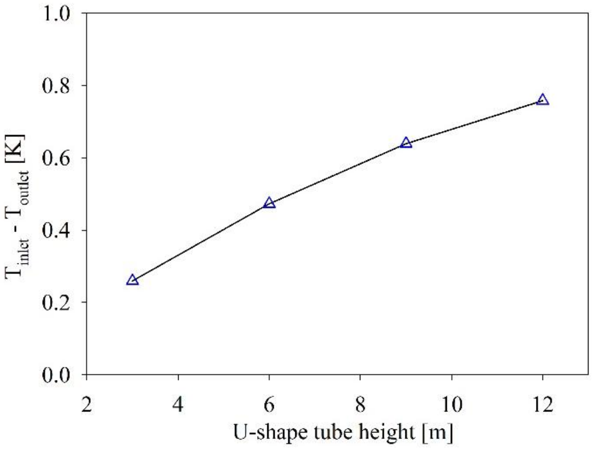


Figure 10. Influence of U-shape tube height on the temperature difference between inlet and outlet water with MgO servicing as filling material. The connecting line is aid of eye.

As can be seen, the temperature difference obtained with MgO is higher, approximately 60%, compared to simulation results with sand. The heat transfer coefficient of the heat exchanger varies from 55 W/m^{2}K to 40 W/m^{2}K when the tube height increases from 3 m to 12 m, respectively. This results practically favor MgO as filling material in the underground heat exchanger.

CONCLUSION

In this work, a CFD model of underground U-type heat exchanger used for BTS station cooling was developed. By performing a sensitivity analysis, the impact of geometrical and operating parameters on the heat transfer performance. The equivalent heat transfer coefficient between water and soil, which is mandatory of heat exchanger design, was computed. Additionally, it indicates that MgO can be to fill the borehole of ground heat exchanger to enhance the heat transfer performance. In the future, the CFD simulation shall be performed for helical ground heat exchangers. The simulation results need to be confirmed by the experiments.

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