2-бөлім **Раздел 2** **Section 2**

Механика **Механика** **Mechanics**

IRSTI 30.17.35, 44.31.41, 27.35.25 DOI: https://doi.org/10.26577/JMMCS.2022.v115.i3.07

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STUDY OF BOREHOLE HEAT EXCHANGER HEAT TRANSFER ENHANCEMENT PARAMETERS

This paper discusses the study of parameters for improving the heat transfer of a borehole heat exchanger for a ground source heat pump application. The study of efficiency parameters was carried out based on an experimental prototype of a ground source heat pump developed by the authors. A mathematical model has been developed for calculating the efficiency of a ground heat exchanger based on three-dimensional equations of heat and mass transfer in a porous medium. The numerical solution was carried out using the COMSOL Multiphysics software. The numerical calculation algorithm was verified by comparison with experimental data from the created prototype. Calculations were made of the efficiency of a borehole heat exchanger with various geometric configurations of the pipes in the well. With an increase in the tube diameter, the heat transfer increases. With a tube diameter of 40 mm, the thermal efficiency of the heat exchanger was 42.4 W/m in the heat charging mode, which is 24% more with a diameter of 20 mm. With increasing well depth, the heat transfer efficiency increases. The influence of the thermal conductivity coefficients of the pipe material, grout material and various types of ground on the heat transfer efficiency was also studied. It was shown that with an increase in the thermal conductivity coefficients of grout and ground, the heat flux increases, but above 6.0 W/m K, the heat flux practically does not change. When the coefficient of thermal conductivity of the pipe material is higher than 1.0 W/m K, the heat fluxes almost do not change. In general, materials containing plastics are used for piping of ground heat exchangers, the thermal conductivity coefficients of which vary between 0.24-0.42 W/m K.

Key words: borehole heat exchanger, ground source heat pump, thermal efficiency, heat and mass transfer in porous media, thermal conductivity, heat exchanger geometry, mathematical model, numerical solver.

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Жерасты ұңғымалы жылу алмастырғыштың жылу беруін жақсарту параметрлерін зерттеу

Бұл жұмыста жер жылу сорғысында пайдалану үшін жерасты ұңғымалы жылу алмастырғышының жылу беруін жақсарту параметрлерін зерттеу қарастырылады. Тиімділік параметрлерін зерттеу авторлар әзірлеген жер жылу сорғысының тәжірибелік прототипі негізінде жүргізілді. Кеуекті ортадағы жылу мен масса алмасудың үш өлшемді теңдеулері негізінде жерасты жылу алмастырғыш өнімділігін есептеудің математикалық моделі жасалды. Сандық шешім COMSOL Multiphysics бағдарламалық жасақтамасы арқылы жүзеге асырылды. Сандық есептеу алгоритмі жасалған прототиптің тәжірибелік деректерімен салыстыру арқылы тексерілді. ұңғымадағы құбыршалардың әртүрлі геометриялық конфигурациялары бар жерасты ұңғымалы жылу алмастырғышының өнімділгі есептеулері жүргізілді. Құбыршаның диаметрі ұлғайан сайын жылу беру артады.

Құбырша диаметрі 40 мм, жылу алмастырғыштың жылу өнімділігі жылу айдау режимінде 42,4 Вт/м құрады, бұл диаметрі 20 мм болғандағы жағдайға қарағанда 24 % артық. Ұңғыманың тереңдігі артқан сайын жылу беру тиімділігі артады. Құбырша материалының, грут материалының және әр түрлі жерасты материалдар (топырақ) түрлерінің жылу өткізгіштік коэффициенттерінің жылу беру өнімділігіне әсері зерттелді. Жерасты бетон мен топырақ жылу өткізгіштік коэффициенттерінің жоғарылауымен жылу ағыны артады, алайда 6,0 Вт/м К-ден жоғары жылу ағыны айтарлықтай өзгермейді. Құбырша материалының жылу өткізгіштік коэффициенті 1,0 Вт/м К жоғары болғанда, жылу ағындары айтарлықтай өзгермейді. Жалпы, жылу өткізгіштік коэффициенттері 0,24-0,42 Вт/м К аралығында өзгеретін жерасты жылу алмастырғыштардың түтіктері үшін қңрамында пластмасса бар материалдар қолданылады.

Түйін сөздер: жерасты ұңғымалы жылуалмастрығыш, жер жылу сорғысы, жылу өнімділігі, кеуекті ортадағы жылу және масса тасымалы, жылуөткізгіштік, жылуалмастырғыш геометриясы, математикалық модель, сандық шешім.

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Исследование параметров улучшения теплопередачи скважинного грунтового теплообменника

В данной работе рассматривается исследование параметров улучшения теплопередачи скважинного теплообменника для применения в грунтовом тепловом насосе. Исследование параметров эффективности проведено на основе разработанного авторами экспериментального прототипа грунтового теплового насоса. Разработана математическая модель расчета эффективности грунтового теплообменника на основе трехмерных уравнений тепломассопереноса в пористой среде. Численное решение было осуществлено на ПО COMSOL Multiphysics. Численный алгоритм расчета был верифицирован путем сравнения с экспериментальными данными из созданного прототипа. Проведены расчеты эффективности грунтового скважинного теплообменника с различными геометрическими конфигурациями расположения трубок в скважине. С увеличением диаметра трубки теплообмен увеличивается. При диаметре трубки 40 мм тепловая эффективность теплообменника составила 42,4 W/m в режиме закачки тепла, что на 24 % больше при диаметре 20 мм. С увеличением глубины скважины увеличивается эффективность теплопередачи. Исследовано влияние коэффициентов теплопроводности материала трубки, материала грута и различных типов грунта на эффективность теплообмена. С увеличением коэффициентов теплопроводности грута и грунта, увеличивается тепловой поток, однако выше 6,0 Вт/м К тепловой поток практически не меняется. При коэффициенте теплопроводности материала трубки выше 1,0 Вт/м К тепловые потоки практически не меняются. В основном для трубок грунтовых теплообменников используются материалы, содержащие пластик, коэффициенты теплопроводности которых варьируются между 0,24-0,42 Вт/м К.

Ключевые слова: грунтовый скважинный теплообменник, грунтовый тепловой насос, тепловая производительность, тепломассоперенос в пористой среде, теплопроводность, геометрия теплообменников, математическая модель, численный решатель.

1 Introduction

A heat pump system is more efficient when connected to a ground heat exchanger (GHE) than a conventional air source heat exchanger based heat pump. This is because the ground has a relatively more stable temperature and is generally warmer in winter and cooler in summer than the fluctuating ambient air temperatures. As a result, GHE as part of a ground source heat pump (GSHP) system is a critical element that determines its overall performance. GHEs are mainly classified as either horizontal or vertical according to their configurations. Vertical downhole GHEs, which also the so-called borehole heat exchangers (BHE), are more widely used comparing to other GHEs. Since BHEs can provide high heat transfer capacity on a limited surface area [1] and less influenced by ambient air temperature. On the other hand, when there is enough land and digging trenches is not difficult [2], horizontal GHE could be economically attractive since vertically well drilling is avoided. For climate conditions with a predominance of the heating season, horizontal GHEs are less suitable, because the influence of atmospheric air on such heat exchangers is significant. From this point of view, BHEs are more versatile. The most used BHEs are single U-shaped (one loop per well) and double U-shaped (two loops per well) heat pipes, which are used as part of a heat pump for heating and cooling [3].

Three main models for predicting the BHE heat transfer efficiency are widely available in the literature: analytical, numerical, and semi-analytical models. Compared to numerical models, analytical models are easier to implement. However, for simulations with small time intervals, discrete numerical models are most suitable. This is applicable for example for hourly energy analysis and optimal control of the GSHP depending on the local meteorological and hydrogeological conditions. Also, with the help of a computational tool, it is possible, for example, to simulate complex physical processes of heat and mass transfer in a porous medium. On the other hand, such calculations require large computational resources, especially for time variable year-round modeling and BHE life cycle modeling [4].

Analytical approaches include the line-source (LS) model [5] and the cylindrical-source (CS) model [6]. In general, the LS and CS models give a rough estimate of the actual heat transfer in the BHE; they are easy to implement and provide quick solutions. However, these models are limited to only radial conductive heat transfer and neglect heat transfer in the other coordinate direction. In addition, the BHE internal thermal resistance and heat capacity are neglected, which restricted wellbore thermal resistance prediction in short-term time interval. As a result, these models later improved by various researchers, for example in [7] non-uniform heat flow in a well was considered. As another approach, in [8] to estimate borehole wall temperature g-function dimensionless temperature response coefficient was proposed. The g-function provides the response of a single BHE to a single thermal step to predict the long-term performance of the GSHP. In [9] a more accurate two-dimensional soil heat transfer model, which is called a finite line-source (FLS) model was developed. As an improvement of basic analytical models, two-dimensional analytical (semi-analytical) models have been developed. Although they are still not suitable as a numerical simulation tool. For example, in [10] a robust two-dimensional analytical model considering U-shaped BHEs thermal interactions have been developed. In [10] by combining analytical and numerical approaches borehole thermal energy storage simulation model have been developed. Combination of analytical and numerical models for the double U-shaped BHE inner and outer regions have been studied in [11]. However, the BHE internal heat capacity was not considered, so the model cannot be applied to predict non-stationary heat transfer inside the BHE. In the recent decade, there have been research works on the study of heat transfer in single and double U-shaped GHEs. Few studies have been devoted to the study of heat transfer for more complex BHE geometries that consider the influence of thermal properties of the ground, heat exchanger material, grout, and other BHE parameters.

In [12] a detailed overview of the design aspects of various GHEs with an emphasis on improving performance and overall manufacturing costs. According to this research the most important factors influencing the GHE design are pipes geometrical configuration, GHE location, the wellbore and pipes length and diameter, pipe connections (serial or parallel), ground and grout properties, experimental methodology and mathematical modeling tool. In [13] the CFD tool was used to study the effect of linear spacing on the BHEs thermal performance with a shallow wellbore. It was reported that the temperature drop is the smallest at a small pitch and the maximum at the largest pitch of the shank. The authors also shoed that with increasing liner spacing the improvement in thermal performance decreases significantly. However, in their study, there is no effect of wellbore spacing on BHE performance with a large well depth, as well as a combined increase in the thermal conductivity of the cement slurry with other parameters. A simple analytical model for calculation of the average fluid temperature and hence improving the BHE thermal resistance estimation accuracy for a single U-shaped heat exchanger-based wellbore was proposed in [14]. The authors investigated the effect of well depth and volumetric flow rate on the estimation of RMS distribution between well thermal resistivity and efficient well thermal resistivity. Additionally, the relative deviation between the two resistances for the specific flow rate was estimated. However, a comprehensive sensitivity analysis regarding the combined effects of wellbore spacing, cement slurry thermal conductivity, well depth, wellbore and pipe diameters on the wellbore thermal resistance estimate has not been performed. As discussed above, most of the factors affecting BHE performance have been investigated. However, most of these research papers are not detailed as they deal with the influence of only one or a few parameters. A comprehensive analysis of all major influencing parameters along with a comparative performance analysis of single and double U-shaped BHEs using the same simulation model is lacking in the literature. A detailed analysis of the influencing factors, combined with a comparison of the thermal performance of single- and double-pipe BHEs in terms of thermal efficiency, heat transfer per unit wellbore depth, and wellbore thermal resistance under various conditions, is missing from the previous reports.

Therefore, in this research, a numerical analysis of the thermal performance of BHEs was carried out based on a verified mathematical and numerical model of heat transfer. The combined effect of borehole diameter, borehole depth, pipe diameter, grout/ground/pipe material thermal conductivity on the thermal performance of BHE was studied, including with various geometric configurations of the piping arrangement. Geometric configurations include single U-shaped, double U-shaped and spiral types of heat exchangers. The analysis was carried out and conclusions were drawn on the influence of these parameters on the efficiency of heat transfer between BHE and the surrounding ground both heat charging and discharging modes.

2 Physical formulation

Heat flow in a geothermal system includes heat conduction and convection occurring in well heat exchangers and the surrounding soil mass. Thermal conductivity in the soil mass occurs as a result of the transfer of thermal energy due to temperature gradients between the bottom layers of the earth, air and borehole heat exchangers. Thermal convection occurs as a result of diffusion and advection of heat due to the flow of groundwater. Temperatures and temperature gradients in geothermal systems are relatively low, on the order of 5-30°C. In the presence of groundwater, the soil mass is considered as a saturated two-phase porous material consisting of solid particles and water. Dry soil is considered as a single-phase material.

The borehole heat exchanger is one of the most important components of a ground source heat pump system. Due to the complex nature of heat transfer in BHE, an efficient thermal design that meets the required requirements is a challenge. When designing a BHE, thermal performance is an important parameter that determines the effective transfer of heat between the ground and the system. Moreover, the thermal performance of the BHE also determines the operational efficiency and operating costs of the system integrated in the BHE. In this regard, a comprehensive study of BHE is needed, especially from the point of view of the complex impact of factors affecting its thermal performance. In addition to the thermal performance of the BHE, the wellbore thermal resistance, which is an important parameter in the design and analysis of BHE heat transfer, will also be analyzed for the single U-tube BHE; and a comparative analysis will be carried out between different types of BHE in terms of heat transfer, efficiency and thermal resistance of the wellbore. The thermal performance of a BHE is influenced by various factors: geometric, thermal, geological and operational parameters. This article will discuss the combined effect of the main parameters that affect the performance of a BHE single U-tube heat exchanger.

In this work, a new model was described for simulating downhole heat exchangers consisting of a single U-tube. In the first part, the theory of building a finite element of a downhole heat exchanger was presented. The work begins with the definition of the general equation for the balance of flow and heat transfer within each element of the heat exchanger. The generated numerical model is for single U exchangers. It can also be adapted for two- or multi-pipe BHEs as shown in the results of this article. The downhole heat exchanger is modeled as a one-dimensional finite element with many degrees of freedom. It is necessary to take into account the heat exchange between the individual sections of the heat exchanger. To obtain a more accurate model, the division of the region into three subregions was introduced. The first area is the pipe, which we model as a line, the second area is the cement, which we model as a solid, and the third, the soil, which we model as a solid with porosity.

3 General equations

The nonisothermal pipe flow is used to compute the temperature, velocity, and pressure fields in pipes and channels of different shapes. It approximates the pipe flow profile by 1D assumptions in curve segments, or lines. These lines drawn in 3D and represent simplifications of hollow tubes.

The heat equation to model nonisothermal pipe flow:

$$\frac{\partial \rho_f}{\partial t} + \nabla(\rho_f u) = 0,, \tag{1}$$

$$\rho_f \frac{\partial u}{\partial t} = -\nabla p - \frac{1}{2} f_D \frac{\rho_f}{d_h} |u| u + F, \tag{2}$$

where ρ_f - density of fluid (kg/m^3),u$-velocity(m/s)$,p$-pressure(Pa)$,f$_D$ - Darcy friction factor, F - volume force (H), d_h - parametric value (m).

The heat equation to model nonisothermal pipe heat transfer:

$$\rho_f c_{p,f} \frac{\partial T_f}{\partial t} + \rho_f c_{p,f} u \nabla T_f = \nabla(k_f \nabla T_f) + \frac{1}{2} f_D \frac{\rho}{d_h} |u| u^2 + Q_w, \tag{3}$$

where $c_{p,f}$ - specific heat capacity of fluid (J/(kg K)), k_f - thermal conductivity of fluid (W/(m K)), T_f - temperature of fluid (K), Q_w - wall heat source (J).

In this work the wall heat transfer node to set up heat exchange across the pipe wall was used for define the external temperature and the nature of the heat transfer.

$$Q_w = (hZ)_{eff}(T_{ext} - T_f), \tag{4}$$

where $(hZ)_{eff}$ is an effective value of the heat transfer coefficient h (W/(m^2 K)) times the wall perimeter Z (m) of the pipe. T_{ext} (K) the external temperature outside of the pipe. Q_{wall} appears as a source term in the pipe heat transfer equation.

$$(hZ)_{eff} = \frac{2\pi}{\frac{1}{r_0 h_{int}} + \frac{1}{r_N h_{ext}} + \Sigma(\frac{ln(\frac{r_n}{r_n-1})}{k_{wall,n}})}, \tag{5}$$

where r_n is the outer radius of wall (m), r_0 - inner radius (m), Z - is the outer perimeter of wall (m), h_{int} and h_{ext} are the film heat transfer coefficients on the inside and outside of the tube, respectively $(W/(m^2K))$.

The heat transfer in solids is used to model heat transfer in solids by conduction, convection, and radiation. The temperature equation defined in solid domains corresponds to the differential form of the Fourier's law that may contain additional contributions like heat sources.

The heat equation to model heat transfer in solids:

$$\rho_s c_{p,s} \frac{\partial T_s}{\partial t} + \rho_s c_{p,s} u \nabla T_s = \nabla(k_s \nabla T_s), \tag{6}$$

where ρ_s - density of solid (kg/m^3),c$_{p,s}$ - specific heat capacity of solid (J/(kg K)), k_s - thermal conductivity of solid (W/(m K)), T_s - temperature of solid (K), u - velocity (m/s).

The heat transfer in porous media is used to model heat transfer by conduction, convection, and radiation in porous media. The temperature equation defined in porous media domains corresponds to the convection-diffusion equation with thermodynamic properties averaging models to account for both solid matrix and fluid properties. This equation is valid when the temperatures into the porous matrix and the fluid are in equilibrium. The heat equation to model heat transfer in porous media:

$$(\rho c_p)_{eff} \frac{\partial T_p}{\partial t} + (\rho c_p)_{eff} u \nabla T_p = \nabla(k_{eff} \nabla T_p), \tag{7}$$

$$(\rho c_p)_{eff} = \theta \rho_s c_{p,s} + (1-\theta)\rho_f c_{p,f}, \tag{8}$$

$$k_{eff} = \theta k_s + (1-\theta) k_f, \tag{9}$$

where T_p - temperature of porous media (K), θ - porosity, ρ_s - density of solid (kg/m^3),c$_{p,s}$ - specific heat capacity of solid (J/(kg K)), k_s - thermal conductivity of solid (W/(m K)), $c_{p,f}$ - specific heat capacity of fluid (J/(kg K)), k_f - thermal conductivity of fluid (W/(m K)), ρ_f - density of fluid (kg/m^3).

3.1 Initial and boundary condition

Two modes of operation are considered: ground charging and discharging. Ground charging is understood as heat transfer to the ground, where the working fluid inlet temperature is set as 45 °C. Ground discharging is understood as heat transfer from the ground, i.e., heat extraction. In discharging mode working fluid inlet temperature is set as 5 °C.

As an initial condition for the ground temperature constant undisturbed soil temperature is assumed. The undisturbed soil temperature is equal to 15 °C for both charging and discharging cases.

At the boundaries of the computational domain constant temperature is assumed because there is no influence of temperature boundary condition on the BHE temperature distribution.

4 Results and discussion

The numerical implementation of the indicated mathematical model with the corresponding initial and boundary conditions was carried out on the COMSOL Multiphysics software. To verify this numerical tool, a comparison was made with the experimental data of the thermal response test [15]. Figure 1 shows this comparison. According to Figure 1, the comparison was carried out according to the working fluid temperature T_{out}. The relative error does not exceed 2-3%, which indicates a very good agreement between the results.

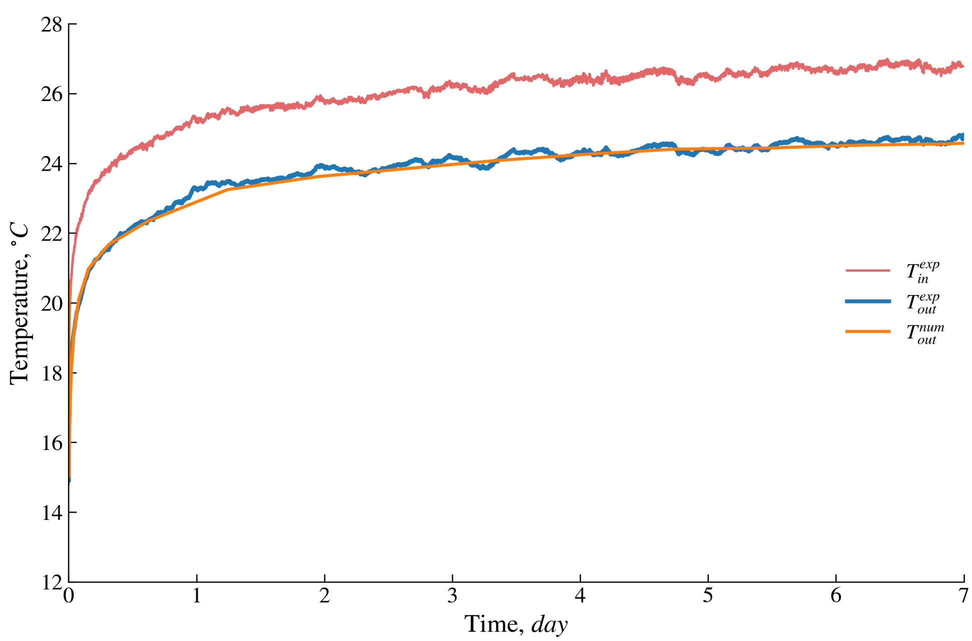

Figure 1: Verification of the numerical calculation algorithm

To study the efficiency of various heat exchanger configurations, 4 types were selected: (1) single U - shaped (U), (2) - double U-shaped cross (dU-x), (3) - double U-shaped parallel (dU-u), and (4) spiral (Spiral). Figure 2 shows these geometrical configurations. These configurations have been proposed to increase BHE thermal efficiency. Of course, the most common is the single U-configuration, whereas more complex versions are costly and laborious to install. However, with the use of more complex configurations, it is possible to save on the depth of drilling a well.

Wellbore depth is one of the important BHE geometrical parameters that affects the total amount of heat supplied (in cooling mode) and removed (in heating mode) to/from the well. Hence, it is very important to investigate its impact on BHE performance. In order to obtain the result of thermal performance in response to a change in well depth, the input parameters of the numerical model, which were fixed, are specified as: distance between inlet and outlet pipes within one BHE, $X_c = 0.05$ m, well radius $r_b = 0.017$ m, soil thermal conductivity $k_s = 1.2$ W/m.K, working fluid inlet temperature $T_{f,in} = 45$ °C , 5 °C for charging and discharging modes, flow rate $\dot{m}= 0.6\ m^3/h$, pipe thermal conductivity $k_p = 0.4$ W/m.K. Figure 3 illustrates the effect of well depth on the overall heat transfer rate and thermal efficiency of the BHE. With the increasing well depth, the heat transfer per unit length of the well tends to decrease, while thermal efficiency improves significantly. The deeper the well depth, the smaller the temperature difference between the working fluid and the surrounding soil, and this leads to a decrease in the heat transfer rate per unit depth of the well. The increase in thermal performance may be since as the well depth increases, more heat enters the well (in cooling mode); consequently, the outlet liquid temperature decreases. This, in turn, increases the difference between the inlet and outlet temperature of the working fluid, which leads to an increase in the thermal efficiency of the BHE. However, with a deep depth of the well, it is not economically feasible. This is due to an increase in drilling cost (which depends on geological conditions) and installation cost, as well as the cost of materials. As a result, when designing with a large well depth, a trade-off must be found between thermal performance and total cost. In addition, a BHE with a large well depth requires more pump power to circulate the working fluid and therefore requires more electricity consumption, which again leads to increased costs.

Pipe diameter is another factor to consider when investigating the impact of pipe parameters on BHE performance. The effect of pipe diameter on BHE thermal performance is briefly discussed here. Conventional pipe outer diameters (from 15 mm to 40 mm) were taken to evaluate the effect of pipe diameter on heat transfer rate, thermal efficiency and thermal resistance of the wellbore. The effect of pipe diameter on the overall heat transfer coefficient per unit depth of the well and the thermal efficiency of the BHE is shown in Figure 4. Heat transfer rates and efficiency increase with larger BHE pipe diameters, especially in high thermal conductivity grounds. BHE with pipe diameter 40 mm has the highest heat transfer rate and thermal efficiency than BHE with pipe diameter 25 mm and 32 mm. The average heat transfer coefficient per unit of well depth and thermal efficiency of BHE with 40 mm pipe is 42.4 W/m (charging mode), which is higher than that of BHE with 25 mm pipe diameter. Thus, according to Figure 4, BHEs with a larger diameter pipe are more efficient and improve the transfer of more heat. This can be explained by a change in the heat transfer area of the BHE with a well configuration and a change in the pipe diameter. Therefore, convective heat transfer improves as the heat exchange surface area increases.

BHE consists of a U-shaped pipe, grout material, and, accordingly, the BHE surrounding ground. Since pipe and grout materials are considered solid, the influence of their thermal conductivity coefficient on the BHE thermal efficiency should be considered. Since surrounding ground is a porous medium with predominantly conductive heat transfer

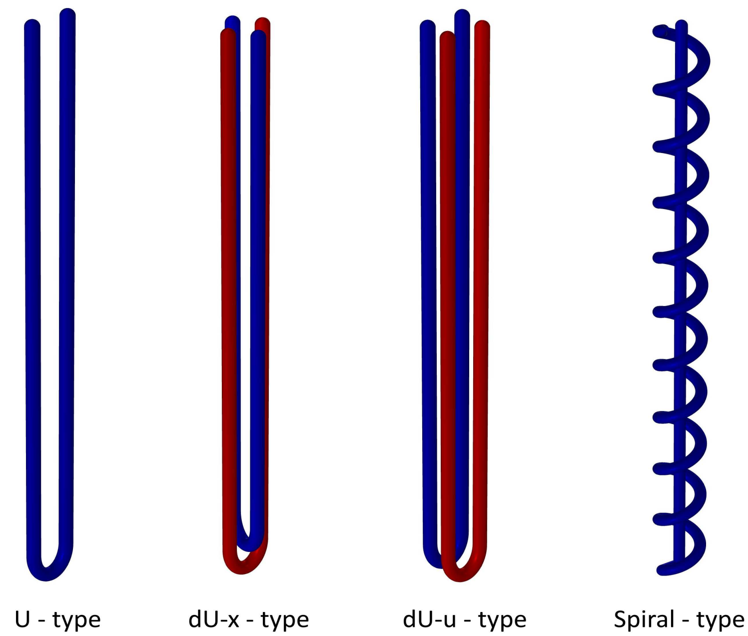

Figure 2: BHE geometrical configurations

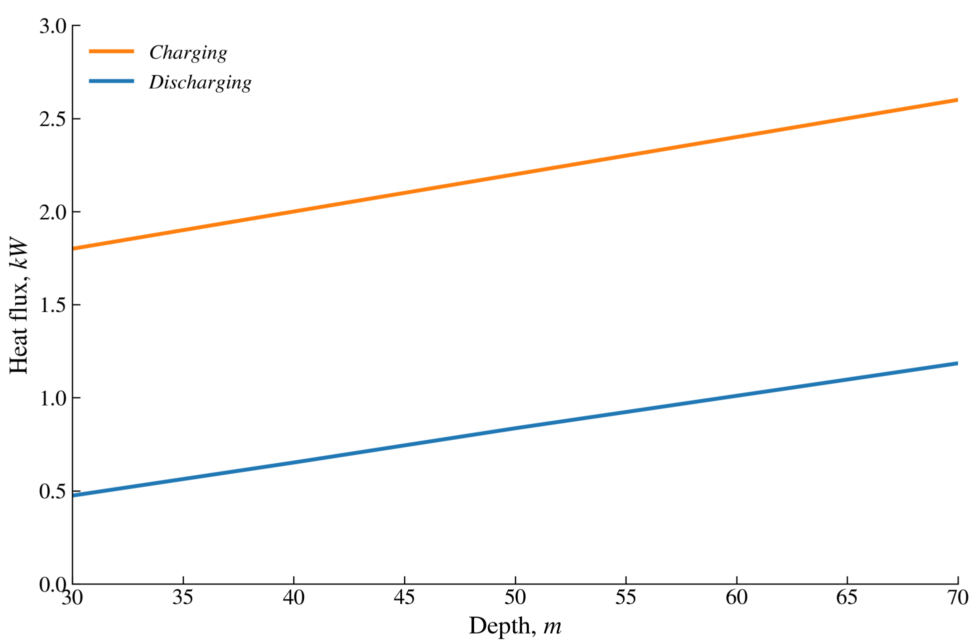

Figure 3: Influence of well depth on heat fluxes in BHE

mechanism, then influence of the ground thermal conductivity is also interesting to test. Since the surrounding ground is a porous medium with a predominantly conductive heat transfer mechanism, the influence of the ground's thermal conductivity is also interesting to test. Figure 5 shows the influence of mentioned thermal conductivity coefficients on the BHE

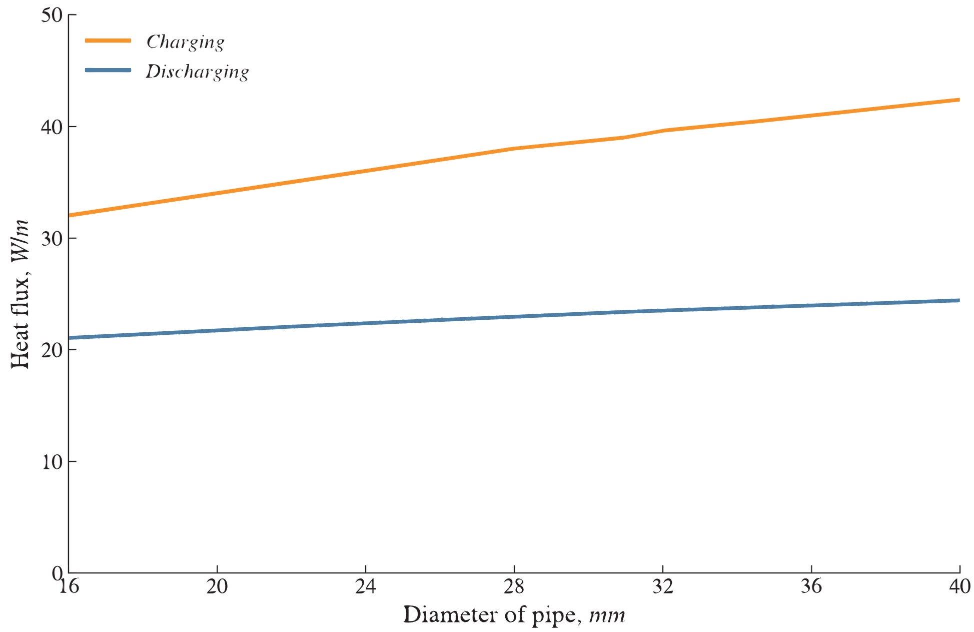

Figure 4: Influence of pipe diameter on heat fluxes in BHE

heat fluxes. A high-density polyethylene (HDPE), polyvinyl chloride (PVC), polyethylene, polyamide, steel, and copper are some of the common piping materials. Grout material is the cement slurry, which is in the ratio of 70% - water, 24% - cement, and 6% - bentonite. Underground materials could be unconsolidated ground type (clay/silt, sand, gravel/stones, till/loam), sedimentary rocks (clay/silt stones, limestones, dolomitic rocks, etc.), magmatic and metamorphic rocks (basalt, granite, quartzite, etc.). According to Figure 5, with the piping material's thermal conductivity above 1.2 W/m K, there is no change in heat flux. It is known that the HDPE, PVC, and polyethylene thermal conductivity is less than 1.0 W/m K, and because of the flexibility, durability, service life, and the piping material cost they are the most used in BHE. According to Figure 5, the influence of the thermal conductivity coefficients of the grout and ground material is almost the same. This means that with an increase in the thermal conductivity, heat fluxes increase, but above 6.0 W/m K this change is insignificant.

Additionally, calculations were carried out on the effect of the well diameter on the thermal efficiency of BHE. With an increase in the borehole diameter from 100 mm to 200 mm, the BHEs heat transfer increased by 5.5 W/m; on the other hand, the corresponding thermal efficiency is somewhat reduced by 3.7 % for BHE. The result shows that as the well diameter increases, more heat can be injected into the well as the heat transfer area increases. However, the improvement in thermal performance with borehole diameter is not as significant as the change in thermal performance with parameters such as borehole depth, inlet fluid temperature, and soil thermal conductivity. However, from an economic standpoint, a BHE with a larger borehole diameter may have a higher capital cost and therefore may not be feasible compared to a BHE with a smaller borehole diameter.

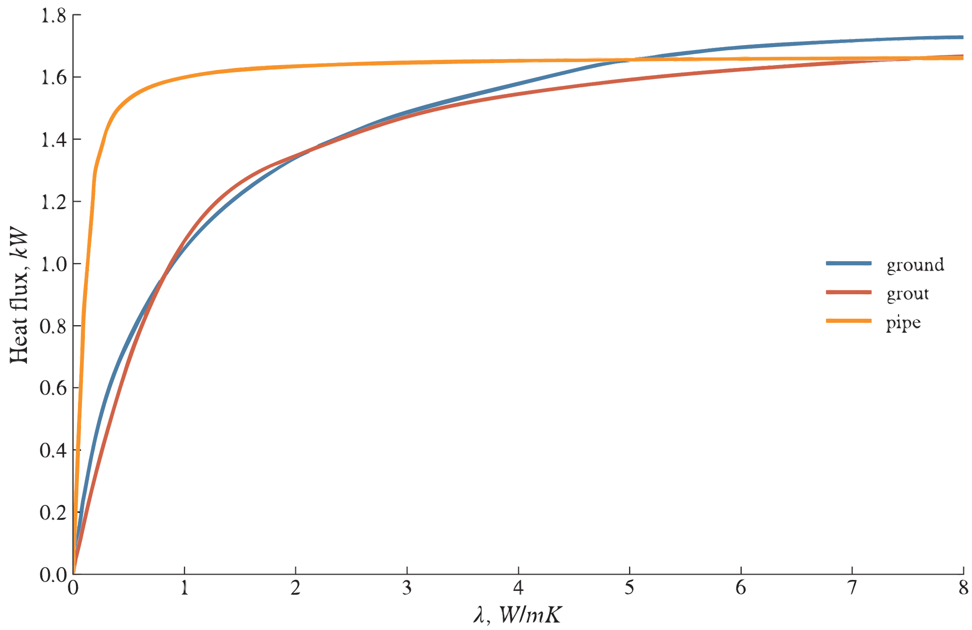

Figure 5: Influence of different thermal conductivity coefficients on heat fluxes in BHE

5 Conclusion

This paper discusses the study of parameters for improving the heat transfer of a borehole heat exchanger for a ground source heat pump application. The study of efficiency parameters was carried out based on an experimental prototype of a ground source heat pump developed by the authors. A mathematical model has been developed for calculating the efficiency of a ground heat exchanger based on three-dimensional equations of heat and mass transfer in a porous medium. The numerical solution was carried out using the COMSOL Multiphysics software. The numerical calculation algorithm was verified by comparison with experimental data from the created prototype. Calculations were made of the efficiency of a downhole heat exchanger with various geometric configurations of the pipes in the well. The study of the influence of the tube diameter on the heat transfer efficiency showed that with an increase in the tube diameter, the heat transfer increases. With a tube diameter of 40 mm, the thermal efficiency of the heat exchanger was 42.4 W/m in the heat charging mode, which is 24% more with a diameter of 20 mm. It has also been shown that with increasing well depth, the heat transfer efficiency increases. However, it is not possible to excessively increase the depth of the well and the diameter of the pipe for economic reasons. The influence of the thermal conductivity coefficients of the pipe material, grout material and various types of ground on the heat transfer efficiency was also studied. It was shown that with an increase in the thermal conductivity coefficients of grout and ground, the heat flux increases, but above 6.0 W/m K, the heat flux practically does not change. When the coefficient of thermal conductivity of the pipe material is higher than 1.0 W/m K, the heat fluxes almost do not change. In general, materials containing plastics are used for piping of ground heat exchangers, the thermal conductivity coefficients of which vary between 0.24-0.42 W/m K.

6 Acknowledgement

This research is funded by the Science Committee of the Ministry of Education and Science of the Republic of Kazakhstan Grant No. AP08857319 "Study of heat transfer enhancement mechanisms of vertical type borehole heat exchanger to ensure high heat pump performance". Postdoctoral Research Programme, Al-Farabi Kazakh National University, Almaty, Kazakhstan.

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