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Optimizing performance of U-pipe ground borehole heat exchangers by varying the pipe diameter

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Abstract

The U-pipe ground borehole heat exchanger (GBHE) is widely used to provide/reject heat from the ground heat pump working in a heating/cooling mode. While looping through the heat exchanger in the descending and ascending pipes, the working fluid exchanges heat with the ground surrounding the borehole. In deep GBHEs the time of thermal interaction between the ground and the pipes is long enough for the fluid temperature to reach a plateau at some distance before the heat exchanger outlet. Along the remaining section of the ascending pipe no effective heat transfer takes place; however, pressure drop increasing exploitation costs still occurs.
For better understanding of the temperature distribution in U-pipe GBHEs, an analytical study determining the location at which the plateau is reached has been performed. Results indicate that in U-pipes with depth greater than 100 m heat is effectively transferred across approximately 75% of the total pipe length. To reduce the pressure loss attributed to the remaining thermally inactive part of the heat exchanger, a new U-pipe GBHE with the ascending pipe diameter greater that the one of the descending pipe has been proposed in this paper. A numerical simulation has been conducted to investigate the impact of such geometry on the U-pipe thermal and hydraulic performance. Results have shown that U-pipes with increased diameter of the ascending pipe do not diminish heat transfer in the heat exchanger, and that they yield substantial reduction in pressure drop. Consequently, an increased GBHE viability is provided.

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Keywords: Ground borehole heat exchangers; U-pipe; numerical simulation;

1. Introduction

Striving towards diversification of energy sources and CO2 emission reduction has led to the development of geothermal heat pump systems coupled with heat exchangers that are buried in the ground either in horizontal or vertical configuration. The latter configuration is preferred due to less land area required for the installation and less performance dependence on the ambient air temperature variation. However, its installation cost is higher because of borehole drilling. Therefore, efforts have been made to increase the efficiency of ground borehole heat exchangers (GBHEs) so that they need less borehole depth to provide the required heating/cooling capacity.

Fig. 1 shows the most common type of GBHE - a U-pipe. Here the working fluid exchanges heat with the ground while looping through the descending and ascending pipes (legs) of the heat exchanger that are connected

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at the borehole bottom with a U-bend section. The space between the pipes and the borehole wall is filled with grouting material.

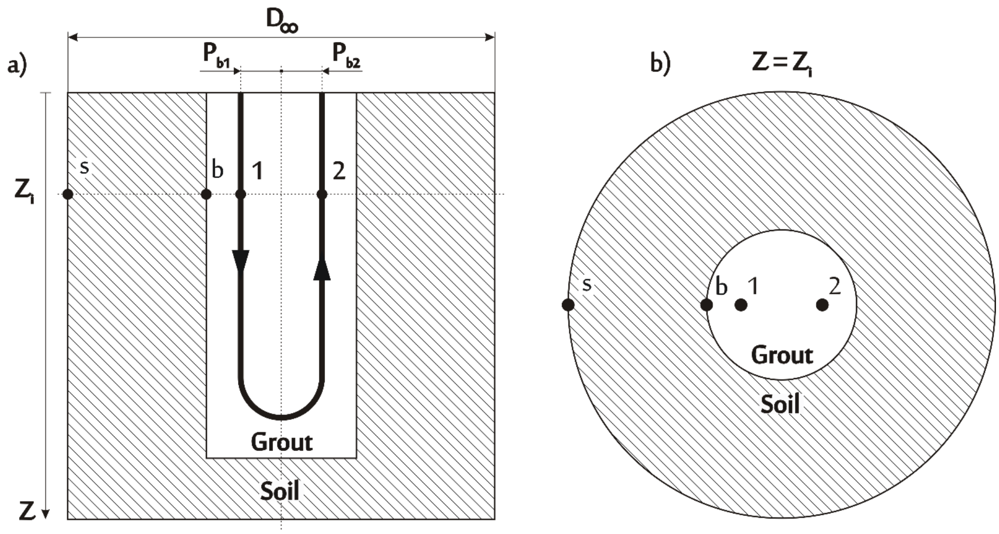

Fig. 1. A longitudinal section (a) and a cross-section (b) of a U-pipe GBHE (s – far-field boundary of the undisturbed soil temperature, b - borehole wall; 1 - descending pipe; 2 - ascending pipe).

To assess U-pipe efficiency in terms of its thermal and flow parameters, several analytical models have been developed. One of the most recognized models of steady-state U-pipe operation is the one proposed by Zeng et al. [1]. The authors assumed that the temperature raise occurring along the borehole depth is only due to radial heat transfer through the borehole wall and described it with two partial differential equations – one for each pipe. Those equations take the following form:

$$\begin{cases} \dot{m}_f c_{P,f} \dfrac{dT_{f,1}}{dz} = \dfrac{T_b - T_{f,1}}{R_{b1}} + \dfrac{T_{f,2} - T_{f,1}}{R_{12}} \\ -\dot{m}_f c_{P,f} \dfrac{dT_{f,2}}{dz} = \dfrac{T_b - T_{f,2}}{R_{b2}} - \dfrac{T_{f,2} - T_{f,1}}{R_{12}} \end{cases} \tag{1}$$

This fundamental form of heat balance equations is employed in many works focusing on mathematical modeling of U-pipe thermal performance [2, 3, 4, 5].

Apart from steady-state modeling, research efforts have been made to develop tools for simulation of transient short-time U-pipe operation [6, 7, 8]. Bandyopadhyay et al. [6] obtained Laplace domain solutions for calculation of the working fluid and borehole wall temperatures. Bauer et al. [7] proposed a numerical model to solve both transient and steady-state parts of heat balance equations for fluid, grout and soil regions of the U-pipe GBHE by means of explicit finite difference method. Zarella et al. [8] developed a numerical model which makes use of the analogy between thermal and electrical circuits and employs lumped system analysis to describe heat transfer phenomena occurring within the GBHE.

Zeng et al. [1] calculated thermal resistances accounting for heat flows between the pipes and the borehole wall (R_{b1}, R_{b2}) and between the U-pipe legs (R_{12}) under the assumptions of identical diameters of the descending and ascending pipes and their axially-symmetrical location within the borehole by the method proposed by Hellström [2]. Beier et al. [4] abandoned the above-mentioned assumptions concerning heat exchanger geometry and developed a model with arbitrarily chosen pipe diameters and their locations in the borehole. The authors employed the shape-factor method for determination of the pipe-to-pipe thermal resistance (R_{12}), and they used their experimental data to determine the pipe-to-borehole-wall resistances (R_{b1}, R_{b2}). The shape-factor method was also used in [5] to study the impact of pipe-to-pipe heat flow (otherwise called thermal shunting) on U-pipe thermal performance.

Where no experimental data is available, numerical techniques are used to determine thermal resistance describing heat transfer between the U-pipe legs [9] or the overall (effective) borehole thermal resistance describing the total amount of heat exchanged between the borehole wall and the working fluid [10]. The latter is defined as:

$$R_{eff} = \frac{\overline{T}_b - \overline{T}_f}{q} \tag{2}$$

Results of those simulations [9, 10] showed that the most beneficial pipe arrangement involves spreading the pipes apart in the borehole so that a good thermal contact between the borehole wall and the pipes is provided and the thermal shunting is restricted.

Based on those results new U-pipe geometries have been introduced [11, 12, 13]. Acuna [11] studied a U-pipe geometry with U-pipe legs kept close to the borehole wall and apart from each other by means of spacers that were placed between the pipes. Analyses performed by Dehkordi et al. [12] showed that the overall borehole thermal resistance is more affected by the distance between the pipe and the borehole wall than the one between the pipes. Therefore, they proposed a tight borehole heat exchanger geometry where the pipes were embedded in a borehole of such a small diameter that they adjoined both the borehole wall and each other. They reported that under studied conditions such geometry has the overall thermal resistance of 0.09 Km/W, whereas a traditional U-pipe GBHE analyzed in their paper had 0.06 Km/W.

By a different approach Focaccia and Tinti [13] proposed a heat exchanger where U-pipe legs are placed inside a infiltration-proof sleeve that is filled with a brine. The presence of fluid-type filling induces natural convection in the space between the sleeve and the pipes and overall borehole thermal resistance reduction. The space between the sleeve and the borehole wall is sealed with a traditional solid-type grouting material. Their study showed that the usage of the proposed heat exchanger resulted in 4% fall in the overall borehole thermal resistance compared to a typical U-pipe GBHE.

Analyzing U-pipe fluid temperature profiles shows that in long heat exchangers (with the depth of more than 100 m) the profiles may exhibit a plateau i.e. within some section of the up-going pipe close to the heat exchanger outlet, the fluid temperature remains nearly constant [4, 7]. Along this part of GBHE no effective heat transfer between the ground and working fluid takes place, but the pressure drop associated with fluid flow still occurs.

This paper focuses on the development of a more efficient GBHE geometry that is intended for heat exchangers with the depth of more than 100 m. For that reason, a new U-pipe geometry has been proposed where the diameter of the ascending pipe is greater than the diameter of the descending one. To investigate the effectiveness of the modified U-pipe GBHE in comparison with the typical geometry, numerical simulations have been performed using the OpenFoam software. The simulations covered working fluid temperature and pressure drop distributions of both the traditional and modified geometries.

Nomenclature

c_P	heat capacity (J/kgK)
CTR	cumulative temperature raise (-)
D	diameter (m)
H	borehole depth (m)
k	thermal conductivity (W/mK)
$\dot{m}$	mass flow rate (kg/s)
L	heat exchanger length (m)
x	spacing between the pipe and borehole axis (m)
Δp	pressure drop per unit length (Pa/m)
q	heat flux density per unit depth (W/m)
Q	total heat power of the heat exchanger (W)
R	thermal resistance (mK/W)
Re	Reynolds number (-)
t / T	temperature (°C/K)

Greek symbols

∞	far-field boundary

Subscripts

1	fluid in the descending pipe
2	fluid in the ascending pipe
b	borehole wall
eff	effective (overall)
f	working fluid
g	grout
p	pipe
s	soil

2. Investigation of fluid temperature and pressure drop distribution in a U-pipe GBHE

Discussion in this paper is restricted to a U-pipe GBHE steady-state operation in a heat extraction mode. It is assumed that all the thermo-physical properties of the fluid, grout and the ground surrounding are constant, and the ground and grout heat capacities are neglected. The far-field undisturbed soil temperature is also assumed to be constant along the borehole depth. Thermal resistance of the pipe material is neglected.

Calculations were performed with the reference to a U-pipe GBHE with typical geometry and thermal and flow parameters. To tie the discussion down to more universal format, the working fluid was water with all the thermo-physical properties evaluated at its temperature at the heat exchanger inlet. Full description of the analysed heat exchanger is presented in Table 1.

Table 1. Description of the analysed U-pipe GBHE.

Parameter	Value
Far-field boundary D_∞	2 m
Borehole diameter D_b	0.152 m
Pipe diameter D_p	0.034 m
Spacing between the pipe and borehole symmetry axes $x_{b1} = x_{b2}$	0.04 m
Borehole depth H	200 m
Soil thermal conductivity k_s	2.0 W/mK
Undisturbed soil temperature t_s	14 °C
Grout thermal conductivity k_g	2.0 W/mK
Working fluid mass flow rate $\dot{m}_f$	0.45 kg/s
Working fluid heat capacity $c_{P,f}$	4210 J/kgK
Working fluid initial temperature $t_{f,1}(z=0)$	3 °C

To investigate thermal performance of the analysed heat exchanger, the set of equations given by Eq. (1) needs to be solved. Calculations require providing thermal resistance between the U-pipe legs R_{12} and the resistances between the borehole wall and the fluid in each pipe R_{b1}, R_{b2} as input. Lamarche et al. in their study on methods for borehole thermal resistance assessment [14] concluded that the most recognized method for determination of the pipe-to-pipe and borehole-wall-to-pipe thermal resistances is the multipole method first introduced by Bennet et al. [15]. This method can be used for U-pipe with various position and diameter. Hellström in his work [2] used this method to derive explicit formulas for calculation of thermal resistances of a U-pipe with axially-symmetric pipes location and equal pipe diameters. As no explicit formula for calculation of the pipe-to-pipe thermal resistance in U-pipes with pipes of non-equal diameters is available, we have decided to simulate the steady-state operation of all the heat exchangers by means of the chtMultiRegionFoam solver which is a part of OpenFoam, the CFD open-source software. Simulations are performed for three diameters of the ascending pipe: D_{p2} = 0.034 m, D_{p2} = 0.044 m and D_{p2} = 0.055 m. Diameter of the descending pipe and the borehole depth remain constant during all the simulations - D_{p1} = 0.034 m and H = 3.5 m respectively.

Solution domain is divided into three regions: the soil, the grout and the pipes with the fluid. Li et al. in their paper [10] showed that choosing grout material with thermal conductivity equal to the ground thermal conductivity is a good trade-off between enhanced ground-to-pipe and pipe-to-pipe heat transfer processes. Smaller value of the grout thermal conductivity compared to the one of ground reduces the pipe-to-pipe heat flow, but it also diminishes the ground-to-pipe heat transfer. Greater than ground's value of the grout thermal conductivity promotes not only the ground-to-pipe heat flow, but also extensive pipe-to-pipe heat transfer, which yields no improvement in U-pipe overall thermal performance. Taking their conclusions into consideration, we have chosen the grout thermal conductivity to be equal to the ground thermal conductivity.

Due to the symmetry of the problem, only one half of the domain constitutes an input to the solver. Grid independence was achieved for a mesh with 203000 cells. Mesh longitudinal and transverse sections for the case with D_{p2} = 0.055 m are depicted in Fig. 2 and 3. All the other geometric dimensions and thermal properties of ground, soil or fluid region are listed in Table 1.

Soil temperature at the far-field boundary (equal to the undisturbed ground temperature) was set to T_∞ = 300 K. This temperature is higher than a typical undisturbed ground temperature to obtain noticeable fluid temperature raise across the solution domain which depth is limited to save the computational time. As thermal resistance depends only on geometry and material properties, setting higher than typical ground temperature does not influence the component thermal resistances of the analyzed U-pipes.

Calculating component thermal resistances for the U-pipe with varying pipe diameter (between the pipes, and between each pipe and the borehole wall) - R_{12}, R_{b1}, R_{b2} - requires solving equations similar to Eq. (1) with the values of T_b and T_f taken from the simulations. Lamarche et al. [14] pointed out that better accuracy of the so-calculated resistances is obtained when two distinct borehole wall temperatures are used for calculations – averages taken at the semi circumferences of the borehole wall corresponding to each U-pipe leg. Then Eq. (1) can be rewritten as:

$$\begin{cases} q_{f,1} = \dfrac{T_{b,1}-T_{f,1}}{R_{b1}} + \dfrac{T_{f,2}-T_{f,1}}{R_{12}} \\ q_{f,2} = \dfrac{T_{b,2}-T_{f,2}}{R_{b2}} - \dfrac{T_{f,2}-T_{f,1}}{R_{12}} \end{cases} \tag{3}$$

To calculate component thermal resistances for each simulated case, partial differential equations from Eq. (3) are replaced with finite difference equations written for two arbitrarily chosen borehole depths z_1 and z_2. As a result, two sets of equations are obtained – one for each borehole depth. Adding sides of each set of equations yields the following set which allows determination of R_{b1}, R_{b2}:

$$\begin{cases} \left(q_{f,1} - q_{f,2} = \dfrac{T_{b,1}-T_{f,1}}{R_{b1}} + \dfrac{T_{b,2}-T_{f,2}}{R_{b2}} \right)_{z1} \\ \left(q_{f,1} - q_{f,2} = \dfrac{T_{b,1}-T_{f,1}}{R_{b1}} + \dfrac{T_{b,2}-T_{f,2}}{R_{b2}} \right)_{z2} \end{cases} \tag{4}$$

Rewriting Eq. (3) for z_1 and subtracting sides of the so-obtained set of equations provides a formula for determination of thermal resistance between the pipes R_{12}:

$$R_{12} = \left(\frac{2\left(T_{f,2}-T_{f,1}\right)}{q_{f,1} + q_{f,2} - \dfrac{T_{b,1}-T_{f,1}}{R_{b1}} + \dfrac{T_{b,2}-T_{f,2}}{R_{b2}}} \right)_{z1} \tag{5}$$

During calculations, z_1 and z_2 were set to 0.5 and 1.75 m respectively, and dz was chosen to be 0.1 m.

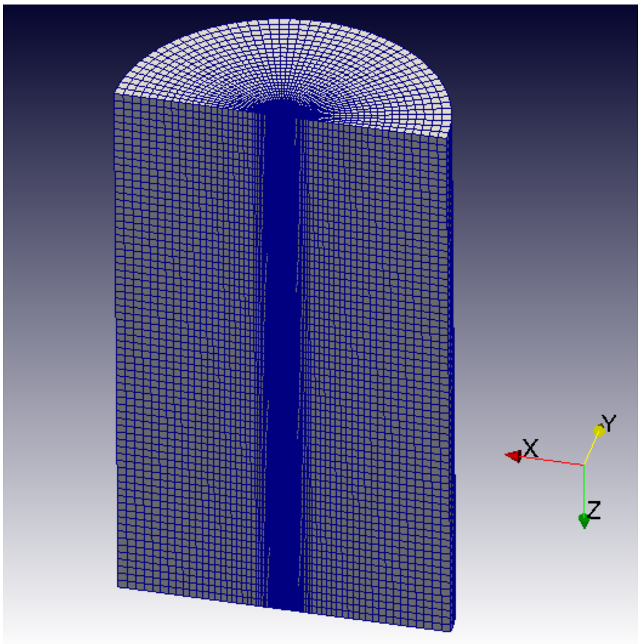

Fig. 2. Computational mesh for the case with D_{p2} = 0.055 m. A longitudinal section.

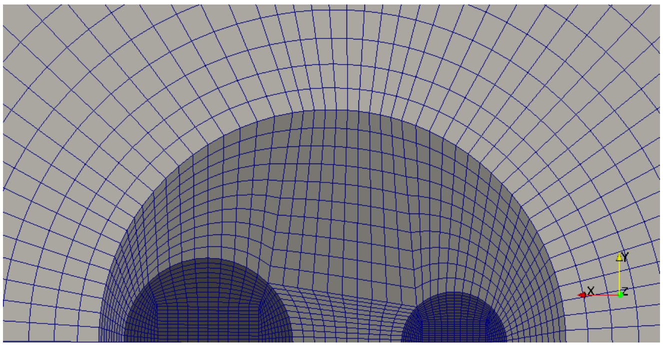

Fig. 3. Computational mesh for the case with D_{p2} = 0.055 m. A transverse section.

Hellström in his work [2] assumed that the heat flux per unit length of each U-pipe leg is constant along the borehole depth but its value may be different for each pipe. Therefore, for each of the analyzed geometries heat flux of the descending/ ascending pipe was also taken constant along pipe length and equal to an average of the heat fluxes per unit length calculated at z_1 and z_2:

$$\left(q_{f,i}\right)_{z1} = \left(q_{f,i}\right)_{z2} = \frac{\left(\dot{m}_f c_{P,f} \dfrac{dT_{f,i}}{dz}\right)_{z1} + \left(\dot{m}_f c_{P,f} \dfrac{dT_{f,i}}{dz}\right)_{z2}}{2} \tag{6}$$

Apart from fluid temperature change and pressure drop, the most popular metric by which various GBHE geometries are compared is to calculate their effective thermal resistance R_{eff} which is given by Eq. (2). As fluid temperature profiles along the borehole axis are usually non-symmetrical, average difference between borehole wall and fluid temperatures required for determination of R_{eff} was calculated as a logarithmic mean:

$$\bar{t}_f = \frac{\left[t_b - t_{f,1}(z=0)\right] + \left[t_b - t_{f,2}(z=0)\right]}{\ln \frac{\left[t_b - t_{f,2}(z=0)\right]}{\left[t_b - t_{f,1}(z=0)\right]}} \tag{7}$$

And the heat flux density per unit depth of the heat exchanger was determined by the following formula:

$$q = \frac{Q}{H} = \frac{\dot{m}_f c_{P,f} \left[t_{f,2}(z=0) - t_{f,1}(z=0)\right]}{H} \tag{8}$$

3. Results and discussion

Values of the component thermal resistances, effective thermal resistance and pressure drop per unit length of each analyzed geometry calculated by means of numerical simulation are listed in Table 2. Values of the Reynolds number for each pipe of a given geometry are also given in Table 2.

Table 2. Values of the component thermal resistances for U-pipes with identical and varying pipe diameter.

Pipe geometry	Re_{p1}; Re_{p2}	R_{b1}, mK/W	R_{b2}, mK/W	R_{12}, mK/W	R_{eff}, mK/W	Δp, Pa/m
$D_{p1} = D_{p2} = 0.034$ m	10 314; 10 314	0.119	0.113	0.077	0.058	118.14
$D_{p1} = 0.034$ m; $D_{p2} = 0.044$ m	10 314; 7 971	0.132	0.094	0.071	0.051	77.62
$D_{p1} = 0.034$ m; $D_{p2} = 0.055$ m	10 314; 6 331	0.156	0.076	0.022	0.047	65.72

Results show that increasing the diameter of the ascending pipe causes the pipe-to-pipe thermal resistance to fall (due to smaller distance between the pipe walls), reduces the pipe-to-borehole-wall thermal resistance for the ascending pipe but increases the pipe-to-borehole-wall thermal resistance for the descending pipe. For the ascending pipe smaller value of R_{b2} can be explained by increased heat transfer area resulting from greater pipe diameter. Increasing the up-going pipe diameter results in greater heat flux exchanged between the pipes (thermal shunting). As on average the total heat flux reaching the descending pipe falls with increasing the ascending pipe diameter, the amount of heat exchanged between the borehole wall and the down-going pipe also falls. At the same time, temperature difference between the borehole wall and the down-going fluid remains nearly constant, so the pipe-to-borehole-wall thermal resistance increases. As for the overall thermal resistance, it becomes lower with rising the ascending pipe diameter, which suggests that in general the U-pipe with varying pipe diameter is more efficient that its typical version. We will see later in this section that the last conclusion may be misleading. Unit pressure drop also falls with greater diameter of the ascending pipe because of smaller fluid velocity and reduced friction factor in this pipe.

To calculate temperature profiles of the analyzed heat exchangers with the depth of 100 m, Eq. (3) needs to be solved for each simulated geometry. As the undisturbed ground temperature was set to a higher than a typical value during numerical simulations, the numerically obtained borehole wall temperatures cannot be used for solving Eq. (3). Therefore, the following modified version is used:

$$\begin{cases} \dot{m}_f c_{P,f} \dfrac{dT_{f,1}}{dz} = \dfrac{T_\infty - T_{f,1}}{R_s + R_{b1}} + \dfrac{T_{f,2} - T_{f,1}}{R_{12}} \\ -\dot{m}_f c_{P,f} \dfrac{dT_{f,2}}{dz} = \dfrac{T_\infty - T_{f,2}}{R_s + R_{b2}} - \dfrac{T_{f,2} - T_{f,1}}{R_{12}} \end{cases} \tag{9}$$

where thermal resistance of the soil R_s is given by the formula for heat conduction through a cylindrical wall:

$$R_s = \frac{\ln\left(D_\infty / D_b\right)}{2\pi k_s} \tag{10}$$

The resulting value is $R_s = 0.205$ mK/W. The component thermal resistances – R_{b1}, R_{b2}, R_{12} – were set equal to those listed in Table 2. Eq. (9) was solved by means of the ODEINT function which is a part of the Python-based SciPy package.

To assess thermal performance of the analyzed U-pipe geometries, we calculated a cumulative temperature raise CTR along heat exchanger by the following equation:

$$CTR(l) = \frac{T_{f,2}(l) - T_{f,1}(l=0)}{T_f^{\max} - T_{f,1}(l=0)} \tag{11}$$

Pressure drop and temperature distributions of traditional U-pipe and U-pipes with varying pipe diameter are presented in Fig. 4 and 5. Borehole depth is 100 m. Fluid temperature at the outlet of the traditional GBHE is 5.92 °C which corresponds to total heat power of 5487 W, whereas heat exchangers with D_{p2} = 0.044 m and D_{p2} = 0.055 m yield 5.93 °C and 5.58 °C which translates into 5510 and 4848 W of heat power, respectively. The shape of temperature profile and resulting drop in thermal performance observed for GBHE with D_{p2} = 0.055 m is due to intensive thermal shunting between the U-pipe legs and lower borehole wall temperature induced by close proximity of the ascending pipe to the borehole wall. Comparing obtained total heat powers to the overall thermal resistances listed in Table 2 indicates that smaller effective thermal resistance R_{eff} does not always translate into greater fluid temperature raise and greater total heat power of the heat exchanger. The overall thermal resistance provides information on how much heat is exchanged per unit temperature change between the fluid and the borehole wall, but it gives no data on how great temperature change is obtained provided given geometry. As for the pressure drop, its value drops substantially from 23.6 kPa for the typical geometry to 15.5 and 13.1 kPa for U-pipes with D_{p2} = 0.044 m and D_{p2} = 0.055 m respectively, which yields a reduction of 34% and 44% compared to the typical GBHE.

CTR distributions are presented in Fig. 6. For a typical U-pipe fluid temperature plateau with *CTR* = 0.98 is reached at *l* = 145 m, which indicates that effective heat transfer occurs along approx. 72.5% of the heat exchanger length. The remaining 27.5% of pipe length remains thermally inactive due to thermal shunting, but the pressure drop along this pipe section still occurs, which increases exploitation costs. Similar temperature evolution (i.e. temperature plateau in returning pipe) was reported in [4, 7]. Increasing diameter of the ascending pipe to 0.044 m causes no significant changes in *CTR* distribution, whereas for D_{p2} = 0.055 m *CTR* equal to 0.98 is reached at *l* = 110 m, and the thermally inactive section, where intensive thermal shunting takes place, becomes extended to 45%.

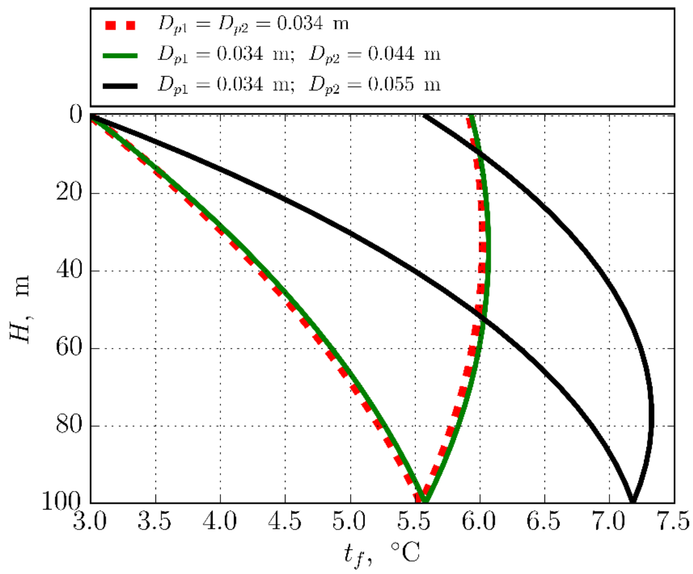

Fig. 4. Temperature profiles as a function of depth of the analyzed U-pipe GBHEs.

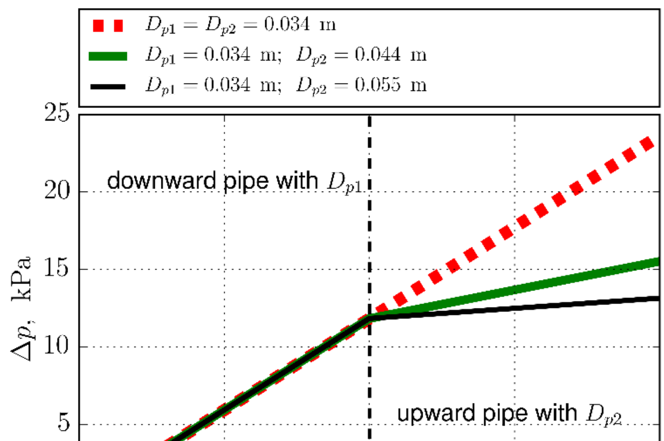

Fig. 5. Pressure distribution along the length of the analyzed U-pipe GBHEs.

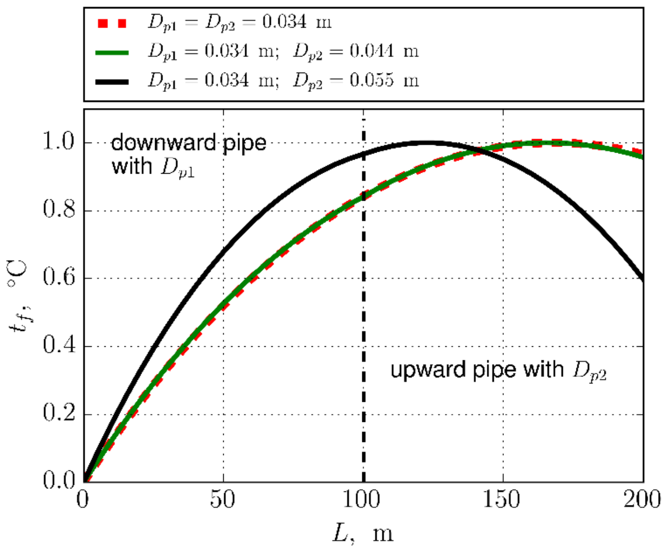

Fig. 6. CTR distribution along the length of the analyzed U-pipe GBHEs.

Taking pressure drop into account (see Table 2 and Fig. 7), the best performance improvement is achieved for U-pipe with D_{p1} = 0.034 m and D_{p2} = 0.044 m with no loss in fluid temperature change and 34% reduction of pressure drop compared to the typical geometry. Increasing diameter of the ascending pipe further to D_{p2} = 0.055 m yields reduction of 44% in pressure drop and loss of approx. 6% in temperature change compared to the typical heat exchanger.

4. Conclusions

In this paper we proposed a new U-pipe ground borehole heat exchanger geometry with the diameter of the ascending pipe greater than the diameter of the descending one intended for heat exchangers with the depth of more than 100 m. The new geometry yields reduction of pressure drop occurring along U-pipe legs without significant change in GBHE thermal performance.

We performed 3D numerical analyses of three U-pipe geometries:

- traditional with descending and ascending pipe diameter of 0.034 m;
- with the diameters of 0.034 m and 0.044 m for descending and ascending pipes, respectively;
- with the diameters of 0.034 m and 0.055 m for descending and ascending pipes, respectively.

Analysis of temperature profiles showed that for traditional U-pipe with the depth of 100 m fluid temperature reaches a plateau at about half the distance between the borehole bottom and heat exchanger outlet. The remaining part of the ascending pipe is thermally inactive, which means that no effective heat transfer occurs along this pipe section, although pressure drop still takes place. The observed plateau in fluid temperature profile of a traditional U-pipe has been also reported in [4, 7]. The temperature evolution is a function of GBHE geometry, material properties of grout, ground or fluid and flow regime. Therefore, further investigation is needed to fully understand the conditions under which the temperature plateau occurs.

Introducing new geometry with the diameter of 0.044 m for the ascending pipe yields substantial performance improvement with no loss associated with fluid temperature change and sufficient pressure drop reduction of 34% while compared with the traditional heat exchanger. Further raise in ascending pipe diameter to 0.055 m causes 6% loss in fluid temperature change and 44% reduction of pressure drop in comparison with the traditional U-pipe. Moreover, for the latter geometry maximum fluid temperature change is observed after reaching 55% of GBHE length. Along the remaining 45% excessive thermal shunting takes place, which reduces the temperature of fluid leaving the heat exchanger.

The obtained results indicate that U-pipes with varying pipe diameter can provide substantial improvement in hydraulic performance without loss in thermal performance when compared with typical geometry. However, choosing the right diameter of the ascending pipe requires careful prior analysis, otherwise an undue thermal shunting between U-pipe legs may occur, which, in turn, worsens thermal performance of the heat exchanger.

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