Excerpt from the Proceedings of the COMSOL Conference 2009 Milan

Local Conduction Heat Transfer in U-pipe Borehole Heat Exchangers

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Abstract: The most common way to exchange heat with the bedrock in Ground Source Heat Pump (GSHP) applications is circulating a fluid through a U-formed closed loop in vertical boreholes drilled several tenths of meters into the ground. The quality of the heat exchange depends on the flow conditions along the channels, the pipe properties, and the relative position of the flow channels to each other and to the rock wall. One of the ways to measure the performance of such heat exchangers is determining and evaluating a thermal resistance that accounts for all these factors, the borehole thermal resistance.

This study presents and compares the results of eight cross sectional U-pipe Borehole Heat Exchanger configurations, modeled with the software COMSOL Multi-physics. Values from recent experimental temperature measurements and calculated heat transfer coefficients are used as boundary conditions.

The two dimensional problem is solved with steady state heat transfer equations, and the net heat exchanged with the ground is obtained. The borehole thermal resistance is subsequently calculated and a quantitative comparison among all cases is presented. Isothermal lines and heat flow directions illustrate the results, pointing out how opportune the use of certain U-pipe BHE configurations is.

Keywords: Borehole heat exchanger, ground source heat pump, thermal shunt flow, borehole thermal resistance.

1. Introduction

Thermal energy from the ground is being used to efficiently heat and cool buildings of different sizes in Europe and North-America, harnessed by means of Borehole Heat Exchangers (BHE) installed in vertical boreholes that are drilled several meters into the ground. Nowadays, almost all BHEs consist of a closed U-pipe, two single cylindrical pipes made of polyethylene through which a heat carrier fluid is circulated and thereby exchanging heat with the ground. These pipes are attached at the borehole bottom in U-form. Such a BHE has been successful in the market due to its easiness to install and its relative low cost. There are approximately 360 000 such systems installed in Sweden today, and a small improvement on their thermal performance could have a considerable influence on the Swedish energy system. A one degree Celsius change of the out coming fluid from a BHE could give a 2-3% increase to the heat pump system efficiency. It is therefore of interest to evaluate how U-pipe channels could perform in the most efficient way. Other BHE types of BHE are obviously also important, but they are not considered in this paper.

One of the first studies in U-pipe BHE was carried out by Claesson et al [1], where the heat flows between the pipes and the outer rock were computed by an equation system based on a Fourier expansion around each pipe and the outer circle. The work by Hellström [3] presents a 3D temperature field around a U-pipe and very useful values of borehole thermal resistance for a single U-pipe as a function of borehole filling material for three different pipe positions in the borehole. Analytical solutions of the fluid temperature profiles and borehole thermal resistance for different BHE configurations were considered by Zeng et al[12]. A recent FEM analysis presented by Esen et al [4], shows the two-dimensional temperature distribution at three depths of U-pipe BHEs, indicating that thermal shunt flow takes place between channels and that it becomes larger with deeper boreholes.

This study represents the first COMSOL Multi-physics results of a research project that aims at achieving more effective heat exchange with the ground. The study uses advanced temperature measurement equipment in order to depict the real temperature profiles along the borehole depths, and intends (among other goals) to validate models with the field measurements.

Several BHEs are tested, including the common U-pipe, and the use of spacers, i.e. a device used to ensure the separation of the channels along the depth and guarantee their proximity to the borehole wall.

The tested spacer dimensions are 53 mm and 78 mm (center to center separation between pipes), installed in boreholes of 140 mm in diameters. The U-pipe tubes have an external diameter of 40 mm and a wall thickness of 2.4 mm. Figure 1 is a picture of the BHE equipped with the 38 mm spacers. It can be observed that the pipes are not in direct contact with the borehole perimeter, nor with each other. The first experimental works by Acuña et al [5] and Ten [6] illustrate that 13 mm spacers might not make a difference as compared to the common U-pipe.

***Figure* 1**. U-pipe BHE with 38 mm spacers

2. Methodology

The present study intends to compare the above mentioned spacers by using the software COMSOL Multi-physics. The common U-pipe without spacers is also included, being the pipes located in four hypothetical positions that may occur when installing such systems. The pipe position variation along the depth has been experimentally identified by Acuña et al [7], showing the importance of the position for the performance of the BHE.

As was previously mentioned, one of the indicators used to compare BHE thermal performance is the borehole thermal resistance, introduced by Hellström [2] and denominated as R_b, being the result of dividing the temperature difference between the borehole wall and the average fluid temperature T_f [K] by the total net heat flow [W/m] rejected or absorbed from or to the BHE channels, as expressed in equation 1.

$$R_b = \frac{\Delta T}{q'} = \frac{T_f - T_{bhw}}{q'} \qquad \text{eq. 1}$$

Given the undisturbed ground temperature T_{rock}, and a 140 mm borehole with two PE 40x2,4mm tubes having temperatures T_1 and T_2 (both higher than T_{rock}), there exist two independent temperature differences between the fluid and the undisturbed rock, and two independent heat flows. The total net heat flow *q’* to the outer circle is the algebraic sum of the ones corresponding to each pipe.

R_b associates all the different parts that normally are involved in BHE heat transfer analysis, i.e. the arrangement of the BHE flow channels, the convective heat transfer in the ducts, and the thermal properties of the BHEs as well as the filling material (a typical borehole in Sweden is naturally filled with groundwater and this material is thus used as a sub-domain in this study).

In groundwater filled boreholes, it is common to expect a certain degree of natural convection between the BHE pipes and the borehole wall, resulting in a lower R_b values. This phenomenon has been neglected here and it is left as a next step. This has, however, partially been studied by Gustafsson [13] using a three dimensional CFD model where groundwater movement was induced. An equivalent radius model was also used and validated.

COMSOL Multi-physics has been used in this paper in order to quantify the heat flow from the U-pipe channels to the rock at different pipe positions. These flows are then used to calculate the fluid to ground thermal resistance (total resistance from T_f to T_{rock}), and subsequently subtracting the thermal resistance corresponding to the surrounding rock in order to obtain R_b for each of the cases. This type of problem can be easily solved with an equations system. However, as demonstrated in [7], the channels position inside the borehole changes along the depth, giving importance to doing quantitative studies on the effect of these changes.

Neither the borehole wall nor the rock temperatures in the vicinity of the borehole vary in a symmetrical way. It is therefore of importance to use an outer ring located sufficiently far away from the borehole (1 meter in diameter was chosen in this case) as a boundary condition, instead of setting the borehole wall temperature to be constant.

The thermal properties of the PEH pipes were taken from [9] and the ones corresponding to the rock (granite) are based on [10], except the thermal conductivity that was obtained from [7].

The COMSOL sub-domain characteristics and the boundary conditions are presented in Table 1 and Table 2, respectively. They are based on carefully performed thermal response test measurements. Average temperature values for both pipes are taken from 100 meters depth and set as boundary conditions for the models, among others. These measurements were taken with optical fiber cables installed in a real test installation.

Table 1. Thermal properties of the sub-domains

Rock	
Density [kg/m^3]	2700
Cp [J/kg K]	830
Thermal conductivity [W/m K]	3.1
Polyethylene pipes PEH	
Density [kg/m^3]	950
Cp [J/kg K]	2000
Thermal conductivity [W/m K]	0.4
Groundwater	
Density [kg/m^3]	1000
Cp [J/kg K]	4200
Thermal conductivity [W/m K]	0.56

The convective heat transfer in the ducts is modeled by introducing a previously calculated heat transfer coefficient as a boundary condition at the internal wall of the pipes. The volumetric flow rate is 0.5 liters per second, a typical rate in a Swedish application. The determination of these coefficients is based on thermal properties from [11] of an ethanol aqueous solution (16% in weight) at the measured temperatures.

Table 2. Boundary conditions

Heat transfer coefficient upwards [W/m^{2}K]	1162
Heat transfer coefficient downwards [W/m^{2}K]	1242
Temperature upwards [K]	287,05
Temperature downwards [K]	289,64
Undisturbed ground temperature [K]	281,74

3. Results and discussion

Figures 2-9 illustrate the result of all eight cross section simulations (pipes apart; two possible arrangements of pipes together aside; pipes together centered in the borehole; and two for each of the spacer dimensions, centered and aside). Each figure shows the BHE channels placed at the different positions as well as isothermal lines and heat flow direction arrows. All figures use the same temperature scale. The heat flow arrows are only plotted in order to illustrate the direction of the heat flows. The arrow size should not be compared among figures. The exact values of the total net heat flow resulting from the COMSOL calculations are given in table 3 for each configuration.

Table 3. Total heat flow for all models [W/m]

Pipes apart	30,20
Pipes aside together	23,10
Pipes together - aside 2	25,23
Pipes together - centered	18,30
13 mm spacers - centered	19,81
13 mm spacers - aside	26,46
38 mm spacers - centered	24,14
38 mm spacers - aside	28,92

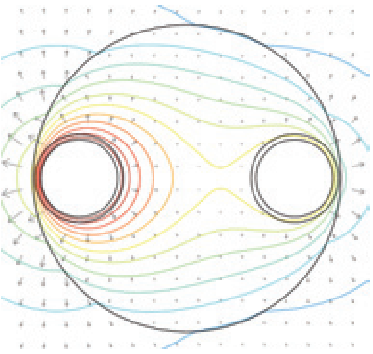


***Figure* 2.** Pipes apart

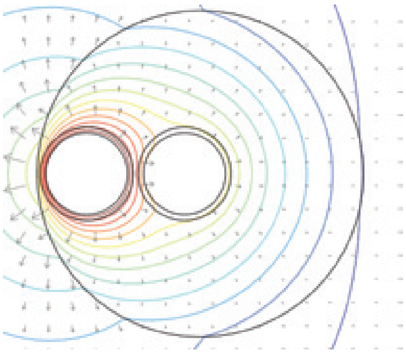


***Figure* 3.** Pipes aside together

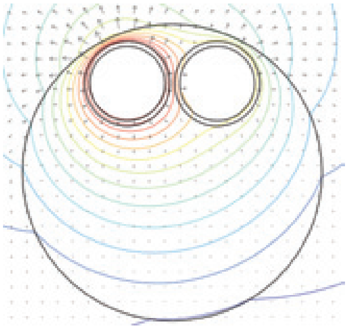


***Figure* 4.** Pipes together aside - 2

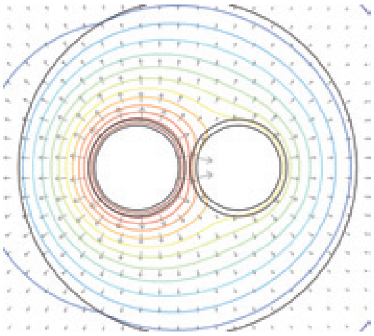


***Figure* 5.** Pipes together centered

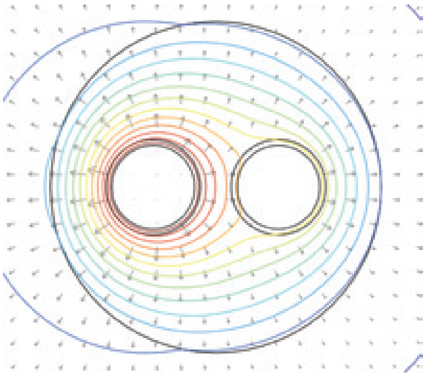


***Figure* 6.** 13 mm spacers - centered

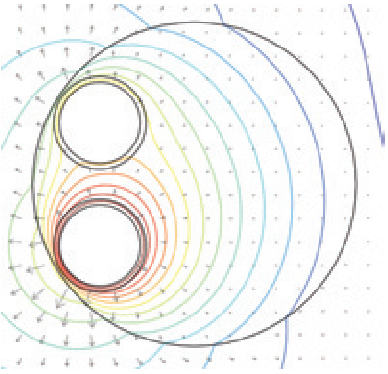


***Figure* 7.** 13 mm spacers - aside

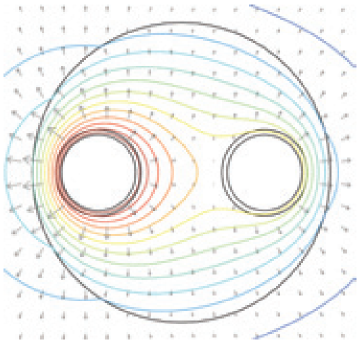


***Figure* 8.** 38 mm spacers - centered

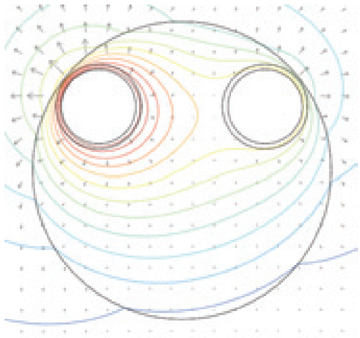
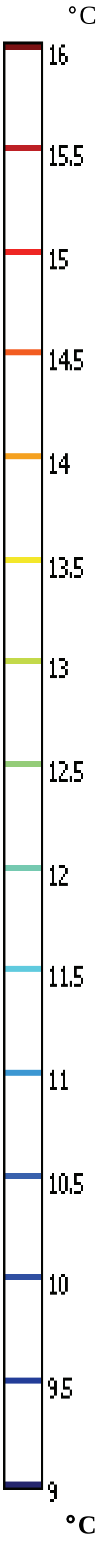


***Figure* 9.** 38 mm spacers - aside



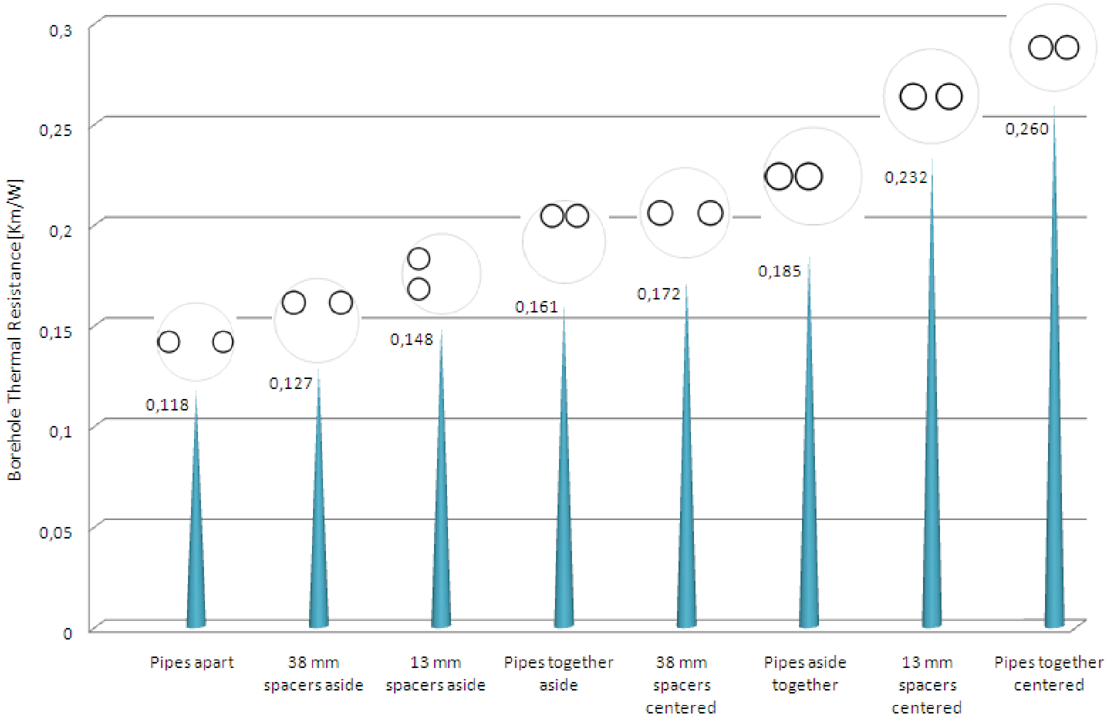


***Figure* 10**. Comparison of R_b for all the pipe positions

Figure 2 represents the case where the pipes are almost in direct contact with the borehole wall. This is almost impossible to achieve in practice, unless a system is activated to separate the pipes once the BHE is into the borehole, a solution that has been tested in USA and presented in [8].

Figures 3 to 5 are probably the closest to a real installation, with the arrangement in figure 5 presumable the least probable. This is due to the fact that both BHE pipes are normally delivered together in a roll in such a way that they can be inserted into the borehole in parallel. It is clear from table 3 that these configurations do not offer the best heat transfer performance. On the other hand, it can be noticed that the highest heat flows take place for separated pipes (pipes apart) or for 38 mm spacers laying aside. These two solutions are probably intuitive, although their quantification makes them useful.

Figures 6 and 7 illustrate the solution after modeling the 13 mm spacers in two different positions, centered and aside. It is possible to appreciate that, still with this distance, there is certain thermal influence between channels, visible at the warmer isothermal lines that go into the colder pipes, i.e. transferring heat to it. This phenomenon is even more obvious in the previous three figures (Fig 2-5). In contrast, Figure 2 demonstrates that total separation of the pipes partially eliminates their thermal contact.

Figures 8 and 9 correspond to the solution of the 38 mm spacers in the centered and side position, respectively. The illustration is similar to the shorter version of spacers, but the shape of the isotherms in the surrounding of the pipes significantly change. The higher temperatures (14.5 to 16 K) are concentrated on the surroundings of the warmer pipe.

It is relevant to put special interest on the borehole wall temperature for each model. The isothermal lines illustrate how the borehole wall temperature varies along the borehole perimeter, changing sometimes up to 4 degrees along the borehole periphery.

Finally, a useful illustration is presented in Figure 10, where the R_b results are plotted for each of the pipe positions. The resistance values are within the range 0.118-0.260 K m/W. The lowest value corresponds to the configuration when the pipes are apart from each other, and the largest to when the pipes are together in the center. This figure demonstrates that the use of spacers does not necessarily mean an improvement of the heat transfer performance.

4. Conclusions

Eight cross sectional U-pipe BHE configurations modeled and calculated with the software COMSOL Multi-physics were presented and compared. The boundary conditions were based on recent experimental temperature measurements and calculated heat transfer coefficients. The two-dimensional problem was solved with the steady state heat transfer equation. The borehole thermal resistance is calculated in order to quantitatively compare the thermal performance of all presented cases. Isothermal lines and heat flow directions illustrate how heat is transferred between the rock and the pipes as well as the thermal shunt flow occurring between channels.

The best U-pipe BHE configuration corresponds to when the pipes are completely apart from each other, with a borehole thermal resistance of 0,118 Km/W. However, this pipe arrangement is hard to achieve. The 38 mm spacers may give a good thermal performance if located aside, i.e. next to the borehole wall. This arrangement is very likely to occur in real installations and has an R_b value equal to 0.127 K m/W, about 10% lower than the separated pipes case. The same pipe location when using 13 mm spacers would as well be within the best three configurations, having an R_b of 0.148 Km/W.

Using 13mm and 38 mm spacers may not always be profitable. The spaced pipes may end up in certain positions that would decrease the thermal performance of the BHE, being even worse than certain non-spaced configurations. Therefore, the use of spacers does not necessarily mean an improvement of the heat transfer performance.

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