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A Novel Coaxial Borehole Heat Exchanger: Description and First Distributed Thermal Response Test Measurements

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ABSTRACT

The thermal performance of a Borehole Heat Exchanger plays a significant role when defining the quality of heat exchange with the ground in Ground Source Heat Pumps. Different designs have been discussed and increased interest on innovation within this field has taken place during the last years. This paper presents the first measurement results from a 189 meters deep novel coaxial Borehole Heat Exchanger, consisting of an inner central pipe and an annular channel in direct contact with the surrounding bedrock. The measurements were taken during a distributed thermal response test using fiber optic cables installed in the energy well. Fluid temperature every ten meters along the borehole depth are presented and compared with similar measurements from a common U-pipe heat exchanger. A unique measurement of the borehole wall temperature in the coaxial collector illustrates how effective the heat transfer performance is through the annular channel.

1. INTRODUCTION

The most common method to exchange heat with the ground in Ground Source Heat Pump installations is by means of U-pipe Borehole Heat Exchangers (BHE) installed into energy wells, boreholes.

The U-pipe consists of two equal cylindrical pipes joint together at the bottom and through which a heat carrier fluid travels down an up while exchanging thermal energy with the ground. In northern countries, it is common to use an antifreeze solution such as water + ethanol as working fluid in order to ensure the appropriate operation of the system during cold days. The thermo physical properties of these fluids are well known from Melinder (2007).

An important issue in the design of BHEs is to identify effective methods so that heat can be injected or extracted into/from the ground without unnecessary temperature differences between the secondary fluid and the surrounding bedrock, i.e. the BHE must be thermally efficient. One Celsius degree higher or lower temperature flowing from the borehole may represent 2-3% change in the Coefficient of Performance of the Heat Pump. This is based on a calculation for a Swedish family house where distribution temperatures vary within the range 40-60°C depending on the type of system, and the heat carrier fluid temperatures oscillate around 0°C. Detailed equations for this type of calculation can be found in Granryd et al. (2005). It is therefore of great relevance to design cost effective BHE characterized by moderate temperature differences between the secondary fluid and the surrounding ground, and not least, it should be easy to install and of course relatively inexpensive in order to have rapid access to the market.

The heat transfer between the circulating fluid and the surrounding rock depends on the flow conditions inside the BHE flow channels, the thermal properties of the pipes, and on the borehole filling material (groundwater or backfill materials). The thermal resistances associated with these different parts are normally added together into a so called borehole thermal resistance R_b introduced by Hellström (1991), and mathematically expressed as shown in (1).

$$R_b = \frac{T_f - T_w}{q'} \qquad (1)$$

where *q'* is the heat injection or extraction rate over a certain borehole length (W/m), T_f the mean fluid temperature (average between downwards and upwards) and T_w the borehole wall temperature, at a particular depth. Since the goal is to have an effective heat exchange with the ground, it is obviously desirable to have as low R_b.

The value for R_b strongly depends on the BHE geometry since it defines the channel position with respect to each other and to the borehole wall and hence how near to the rock the secondary fluid is circulating. Since the fluid must travel down and upwards, it is also of preference to avoid thermal shunt flow, i.e. thermal contact between channels. This occurs especially at low volumetric flow rates. More turbulent flow within the pipes contributes on solving this problem and not least on eliminating the temperature gradient of the inner fluid.

Figure 1 illustrates a cross section of a U-pipe BHE. Measurements from such a collector are presented later in this paper. U-pipe BHE do not have the lowest R_b that we could expect, mainly due to the low thermal conductivity of the pipes, thermal shunt flow between channels, and undesirable channel placement inside the borehole relative to the borehole wall. Moreover, the relatively low thermal conductivity of the water (in groundwater filled boreholes) plays of course an important role.

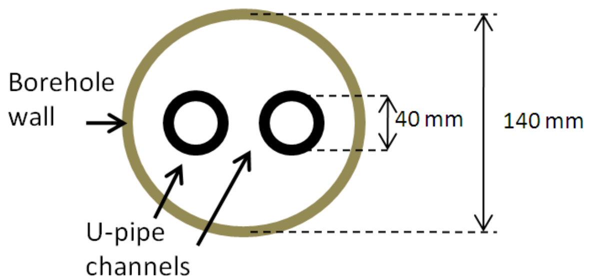

Figure 1: Cross section of U-pipe BHE

The effect of the pipe thickness becomes less important with increased amount of channels. This fact has promoted the use of double U-pipes, not least for their slightly better hydraulic performance. Although a better pipe material would contribute to a lower R_b, the asymptotic character of the tubes contribution to the total thermal resistance shows that it is not necessary to use a material with exceptionally high thermal conductivity. The pipe positions and the filling material also play an important role. It is common in Sweden to use groundwater filled boreholes whilst in some central European countries and USA other filling materials are used, such as bentonite, cement or quartz sand. This is many times mandatory by law and not only for thermal improvement reasons.

Hellström (1998) presents a very illustrative figure showing the R_b value for a single U-pipe as a function of filling material thermal conductivity for three different pipe positions in the borehole. Furthermore, the work by Bose et al. (2002) shows the results from five thermal response tests (TRTs) in U-pipe BHEs, where bentonite and a thermally enhanced grout were used as backfill materials instead of just groundwater. Bose et al. (2002) include the use of a patented spacer, clips, for separating the pipes from each other (i.e. avoid thermal shunt flow) and place them as close as possible to the borehole wall. Using clips together with thermally enhanced grout resulted on 30% borehole length reduction possibilities. The clips guaranteed good separation between the pipes and therefore their proximity to the borehole wall. On the other hand, the experimental work by Ten (2008) and Acuña et al. (2008a) illustrate that the use of relatively small spacers (13 mm distance between PE40x2.4mm pipes in a 140 mm borehole) does not make a difference as compared to the U-pipe without spacers.

In groundwater filled boreholes, it is common to expect a certain degree of natural convection outside U-pipe BHEs, resulting in a lower R_b value especially during thermal response tests. If ignoring this phenomena, a simple steady-state heat conduction analysis of this BHE carried out in a borehole with diameter 140 mm indicate that R_b varies between 0.11 – 0.26 Km/W for the best and worst pipe positioning, respectively (using PE 40x2.4mm pipes). Thermal Response Testing of U-pipes normally results in values between 0.06-0.08 Km/W depending on how much the natural convection takes place during the test and on the borehole dimensions. Hellström et al. (2000) compared R_b at different temperature levels and heat rates for U-pipe BHEs, among others. The results show values between 0.053 and 0.08 Km/W, indicating the influence of free convection heat transfer. This range for R_b is in good accordance with the tests carried out by Gehlin (2002). The R_b decreasing effect due to free convection is expected to increase with higher groundwater temperatures. Moreover, a very detailed study carried out by Acuña et al. (2009) identified the R_b variations along the borehole depth, with an average value of 0.061 Km/W, calculated from R_b values for twelve sections along the borehole, differing within the range 0.054 – 0.068 Km/W.

U-pipe BHEs are relatively inexpensive and very easy to install, resulting on its total dominance in the GSHP market for many years. On the other hand, coaxial BHE might have a unique advantage if they are appropriately designed: their closer contact between the external channel(s) and the borehole wall, and low thermal contact between channels.

A large variety of BHEs have been tested in different countries during the last two decades. A complete report was presented by Hellström (2002). Particularly, development of coaxial BHEs have been presented by Platell (2006), who presents an interesting idea consisting of one central insulated pipe and several outer pipes. Platell shows a list of different models illustrating its thermal advantages and not least their good hydraulic characteristic, i.e. lower pressure drop thanks to the use of laminar flow. A first prototype was tested and presented by Hellström et al. (2000), resulting on thermal resistances between 0.009 - 0.028 Km/W. The prototype consisted on 62 thin pipes (diameter of 3.8 mm and thickness of 0.65 mm) arranged close to the borehole wall in a special laboratory installation. The diameter of the laboratory borehole was 104 mm. Similar designs have been suggested in Switzerland.

Another attractive prototype has been released by the company Mateve Oy from Finland, and it is at the moment being tested both in Finland and Sweden. The collector consists of one central channel and five outer channels with trapezoidal cross section. Several installations have already been done and the first measurements show very high heat extraction rates in the outer channels with the fluid flowing in any of the two possible directions. More details as well as simulation results from this BHE are found at the work by Andersson (2008).

Furthermore, a coaxial annular BHE was demonstrated during the EU project GROUNDHIT by EWS (2006). The collector consisted of one PE63x5.3 mm outer pipe with an inner channel with dimensions PE40x3.7mm. Installation and assembling methods were as well tested and presented.

Additionally, Hellström (2002) describes the experiments with an open annular coaxial BHE where the fluid travels in absolutely direct contact with the rock in the annular channel, i.e. an open groundwater system. Some operating conditions resulted in R_b values of circa 0.01 Km/W, drastically lower than the one corresponding to U-pipes.

The work presented in this paper shows measurements from two borehole installations located in the city of Stockholm, Sweden. The first one is a U-pipe (see Figure 1), and the second a novel coaxial BHE. A cross section showing the channel dimensions and a longitudinal view of the novel coaxial BHE are presented in Figure 2 and Figure 3, respectively. More details are described in the next section.

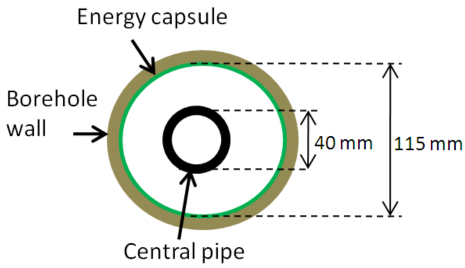

Figure 2: Cross section of the annular coaxial BHE

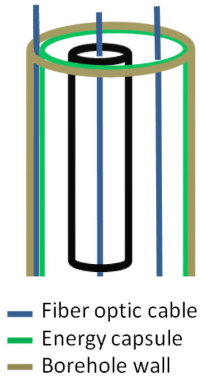

Figure 3. Longitudinal sketch of the coaxial BHE

The idea with this special coaxial BHE design is to bring the secondary fluid as close as possible to the borehole wall by almost direct contact between the annulus (energy capsule) and rock. The annulus consists of a channel externally delimited by a thin hose, the energy capsule, developed by PEMTEC AB, illustrated with the green color in Figures 2 and 3. A contact thermal resistance between the energy capsule and the borehole wall could be considered when identifying the value for R_b in this BHE. This can be calculated using equation (2).

$$R_{contact} = \frac{1}{2\pi\lambda_{gap}} \ln\left(\frac{r_e + \delta_{gap}}{r_e}\right) \tag{2}$$

being r_e the external radius of the energy capsule, δ_{gap} the width of the gap, and λ_{gap} the thermal conductivity of the material filling the gap.

The installation of this coaxial BHE has allowed installing a fiber optic cable between the energy capsule and the rock, thereby making possible to measure the borehole wall temperature. A slightly higher pressure in the inner part of the capsule tightens the fiber against the borehole wall. The location of this fiber optic cable is illustrated in Figure 3, together with a second cable located inside the flow channels for measuring the circulating fluid temperature.

Measurements with fiber optics in the groundwater side of the U-pipe BHE have been previously presented in Acuña et al. (2008a) and (2008b), showing a wide spread of tempeature measurment values due to the unkown exact location of the cable in the borehole. This problem has been solved to a large extent with the coaxial BHE installation, thanks to the fiber that has been tightened against the borehole wall, giving an array of controlled measurement points and a significant amount of valuable information.

The performance of BHEs has for many years been evaluated by the so called Thermal Response Test (TRT), first presented by Mogensen (1983) and widely studied by Gehlin (2002). Mogensen found that it was possible to determine the borehole thermal resistance besides the rock's thermal conductivity of the ground during a TRT.

A TRT test consists of applying (and logging) a constant cooling or heating power to a BHE while logging the fluid inlet and outlet temperature as well as the volumetric flow rate. The test should be relatively long in order to achieve the appropriate conditions that allow evaluating the BHE performance in a correct way. Testing BHEs during short term heat pump cycles and rapid temperature changes might be difficult due to the fact that capacitive properties may influence the results. During the Thermal Response Tests carried out in this study, a constant heat injection rate is supplied during at least 48 hours to both BHEs making distributed temperature measurements with the optical fiber cables.

The distributed temperature measurement technique consists of sending laser pulses through the optical fiber cables, and analyzing the Raman scattering of the backscattered light which is a function of the temperature. The position of the temperature measurement regions is identified by the readout equipment with the light velocity and the delay time. Temperature measurements of this type in BHEs were first presented by Fujii et al. (2006) and Acuña et al. (2009).

A Distributed Thermal Response Test (DTRT) is carried out in this study in a U-pipe and the novel coaxial BHE, measuring temperatures every 10 meters along the energy well during a standard thermal response test. The measurements are, as mentioned before, taken in the heat carrier fluid side along the downward and upward channels, accompanied by a pioneering measurement of the borehole wall temperature during the coaxial BHE test.

2. THE BOREHOLE INSTALLATIONS

The first installation is a U-pipe BHE consisting of a 257 meter long collector of the type PE 80 40x2.4 mm installed into a 260 m deep water filled borehole (groundwater level was 5.5 m) with a diameter equal to 140 mm. The circulating fluid is an aqueous solution of 16 % weight concentration ethanol.

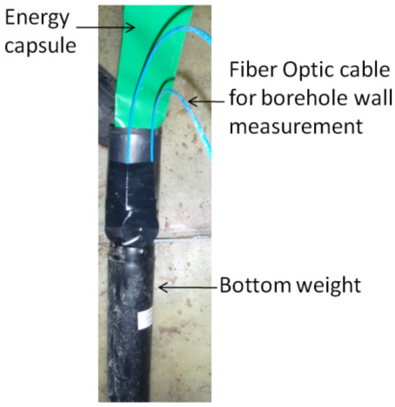

Figure 4. Bottom part of energy capsule with external fiber optic cable

Figure 5. Energy capsule already installed and before water filling. The external fiber cable is taken out through a trace opened in the steel casing

Figure 6. Central pipe, internal bottom weight and fiber cable

The second installation consists of a 189 meter long collector consisting of a central pipe inserted into the so called energy capsule. The latter consists of a thin hose (0.4 mm thick) that is sent into the borehole and subsequently filled with water. The borehole diameter is 115 mm and the energy capsule 114 mm. Once the energy capsule is filled with water, it seals the borehole from the surrounding rock and groundwater. The energy capsule can also be used in energy wells for protecting the groundwater in restricted areas by installing the common U-pipes into it. Figure 4, Figure 5 and Figure 6 show photographs taken during the installation of this BHE.

Figure 4 shows the first moment of the test installation. The energy capsule and fiber optic cables are first installed into the borehole with the help of a bottom weight. This process took approximately 20 minutes. Figure 5 shows the energy well after this moment was completed, where it is observed that the energy capsule is still flat, meaning that it has not yet been filled with water. The duration of the water filling process depends on the borehole dimensions and the injection flow rate.

Once the energy capsule is filled with water, the installation of the central channel constitutes the next step. The channel is, in this case, a typical polyethylene tube for GSHP installations of the type PE 40x2.4 mm. Figure 6 presents the channel together with a bottom weight. The latter is used to facilitate the pipe installation.

The novel coaxial BHE consists, in other words, of a cylindrical central channel and an annular external channel in almost direct contact with the borehole wall. The cross section of the collector illustrated in Figure 2 shows that there are no means of ensuring a concentric central channel. Therefore, a high degree of eccentricity is expected. Visualizations with an underwater camera confirm that the pipe is not centered.

Since low temperature differences between the borehole wall and the circulating fluid are expected, the initial idea is to use water as a circulating fluid, instead of an antifreeze aqueous solution, offering significant advantages from the hydraulic, thermal and environmental point of view. There is, however, a risk for fluid freezing in cold places where the undisturbed ground temperature is close to the water freezing point conditions.

The installation procedure was simple. The capsule and the central pipe were easily inserted as rapid as when inserting common U-pipe BHEs, although the fiber optic cables made the work relatively more especial. In other words, the installation process of such BHEs does not have any complications. An exception could be wells with high groundwater flow or cracks, which may set hurdles when water filling the energy capsule.

Experiences from coaxial BHE designs described in the introduction point out complications during the installation process due to buoyancy forces and stiffness when rolling them out from the delivery package, a problem that practically disappears in this particular novel design. However, such problems may arise if the central pipe is to have better insulation characteristics.

4. INSTRUMENTATION AND EXPERIMENTS

The two borehole test installations have been carefully measured using Distributed Temperature measurements. The optical fiber cables are of type 50/125, with two graded index multimode fibers coated with a thin stainless tube. Only one fiber is used during these measurements. The temperature readout equipment is of type HALO-DTS supplied by Hydroresearch AB (instrument located at the lower right corner in Figure 8). The fiber cable diameter is 3.8 mm.

This instrumentation was used for measuring the fluid temperature every 10 m along the BHEs length (both downward and upwards flow) with a measurement interval of 5 minutes. As mentioned and illustrated before, the borehole wall temperature is as well measured in the coaxial case.

In order to guarantee the quality of the temperature measurements, a calibration process was carried out by rolling together about 40 meters of cable that are located before and after the borehole loop, and subsequently inserting them into an ice-bath, as illustrated in Figure 7.

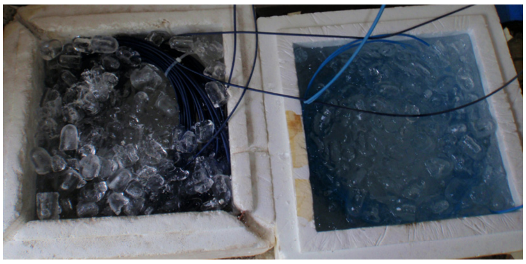

Figure 7. Fiber optic cables in ice-bath during calibration

The ice-bath arrangement was also insulated on the top. The water freezing point was used as a reference in order to adjust slope losses and offsets from the fiber measurements.

A thermal response test apparatus built at KTH was used for testing the BHEs. The fluid circulation and heat injection were applied by connecting the TRT apparatus to the borehole channels. This device consists of a circulation pump of the type Magna 25-100 from Grundfos, an inductive flow and energy meter of the type HGS9-R6 from Brunata, a STAD flow regulation valve, and an electric heater with adjustable heating power. Figure 8 shows a photo of the TRT apparatus to the left of the picture.

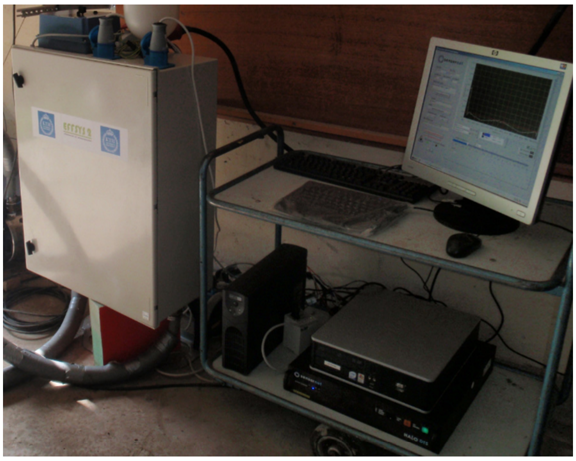

Figure 8. The thermal response test equipment and the HALO instrument

Both BHEs were tested with similar injection and volumetric flow rates. In the coaxial case, the flow travels downwards through the central pipe and comes back through the annulus. The total duration of the heat injection processes were 48 and 56 hours for the U-pipe and the coaxial BHE, respectively.

5. RESULTS FROM THE FIRST MEASUREMENTS

The average of all measurement points along both energy wells during undisturbed ground conditions were 9.10 °C and 8.45 °C in the U-pipe and the coaxial BHE installation, respectively. Both installations are located in the city of Stockholm, Sweden. The age of the houses built in these areas is expected to have an insulation effect, causing higher temperatures at depths where the heat pulse have had time to travel through since the moment when the houses were built. The temperatures at 180 meters depth are about the same in both wells.

The average temperature profile along the borehole depth in the U-pipe and coaxial BHE during the whole heat injection period are illustrated in Figure 9 and Figure 10, respectively. The fluids were circulated without interruption during 48 and 56 hours (respectively) while supplying constant heat.

It is observed in Figure 9 that the fluid was injected into the U-pipe with a temperature of about 18°C, reaching a value of about 14.8°C at the bottom and leaving the BHE with circa 13.7°C, a temperature change of about 3°C on the way down and 1°C on the way up, indicating that most of the heat (about 75% of the total heat injection) in the borehole is exchanged when the fluid is traveling down. The shape of the upwards flow temperature curve during the last 80 meters is almost vertical, representing an almost useless section of the BHE from the heat transfer point of view due to the thermal shunt flow between channels. This behavior could become even worse at lower volumetric flow rates, resulting in thermal short circuiting problems.

The measurements corresponding to the coaxial BHE are presented in Figure 10, also illustrating the borehole wall temperature. The injection temperature is about 15.5°C. The temperature at the bottom is 14°C and the outlet temperature is 12.6°C. A significant portion (about 50%) of the heat is transferred when the fluid travels through the central pipe and the rest through the annular channel. Additionally, it is clearly observed how the borehole wall temperature profile follows almost perfectly the shape of the annular flow, differing by about 0.4°C.

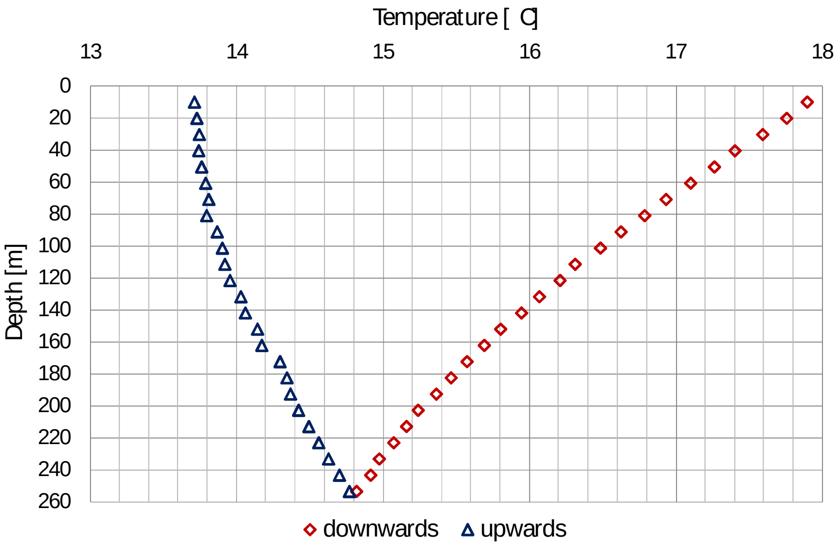

Figure 9. Average temperature profile in U-pipe BHE . The measurements were taken every five minutes during 48 hours of constant heat injection.

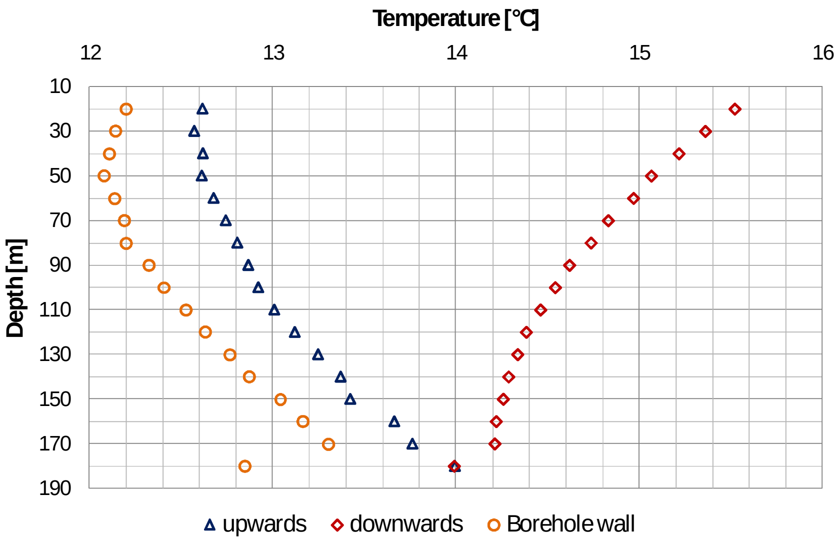

Figure 10. Average temperature profiles in coaxial BHE. The measurements were taken every five minutes during 56 hours of constant heat injection.

A slight asymptotic tendency is observed at the last 40 meters of the upward flow, meaning that significant thermal shunt flow starts to take place. A higher borehole thermal resistance is expected to result in the higher sections of the BHE and lower values close to the bottom of the borehole.

The calculation of R_b along the borehole length is straightforward from the figure after calculating the specific heat injection. This will be done and carefully confirmed with a complete Distributed Thermal Response Test analysis in the continuation of this study. The contribution of the gap resistance could probably emerge due to the fact that the BHE worked almost as an open system with slightly low pressure difference between the inner and outer part of the capsule. The groundwater level outside the energy capsule is 3 m under the ground surface and a three meters water column above this level was kept constant in the inner part during the test in order to try guaranteeing the cylindrical from of the capsule, i.e. its attachment to the borehole wall.

The low temperature difference between the annular channel temperature and the borehole wall points at several potentials for improvements of this BHE design, as for example insulating or increasing the thickness of the central pipe. Insulating only several meters would also be of help.

CONCLUSIONS

Distributed temperature measurements in a U-pipe BHE and a Coaxial BHE were carried out during Thermal Response Test with similar heat injection rates. The measurements were done using fiber optic cables that measured the circulating fluid temperature every 10 meters during circa 2 days.

U-pipe BHEs have several constrains. The exact position of the tubes can not be controlled in most of the installation cases, resulting in thermal contact between the channels and high borehole resistance (R_b) values. Moreover, they require being backfilled with grouting materials in many countries, making the installation process more complicated (grouting the boreholes could also limit to the utilization of the coaxial collector).

The measurements from the U-pipe BHE indicate that about 75% of the total heat is exchanged when the fluid is traveling down. The shape of the upwards flow temperature curve during the last 80 meters is almost vertical, representing the thermal shunt flow between channels and indicating that BHE section is almost useless from heat transfer point of view and. This behavior could become even worst at lower volumetric flow rates, resulting in thermal short circuiting problems.

The interest for designing cost effective BHEs characterized by moderate temperature differences between the secondary fluid and the surrounding ground, and easiness during installation have resulted in the development of a novel coaxial Borehole Heat Exchanger, consisting of an inner central pipe and an annular channel in direct contact with the surrounding bedrock. The idea with this novel collector is of course to lower the R_b as much as possible, which already seems to be feasible with the presented alternative.

The installation procedure was simple. The capsule and the central pipe were easily inserted as rapid as when inserting common U-pipe BHEs.

The first measurements from the coaxial BHE show that about 50% of the heat is transferred when the fluid travels through the central pipe. The high temperature difference between the down and upward flows negatively affects the average fluid temperature T_f, especially at lower depths. This will result in an increased borehole resistance value for this particular case. Thermal shunt flow takes place especially at the 40 higher most meters of the BHE.

Another advantage of this BHE is that it might be possible to use water as a secondary fluid even in colder countries where antifreeze solutions are used, resulting in significant advantages from the thermal, hydraulic and environmental point of view.

A unique measurement of the borehole wall temperature in the coaxial collector illustrates how effective the heat transfer performance is through the annular channel. The measurement is also done using DTS technology with an optic fiber tightened between the rock and the annular channel. It is clearly observed how the borehole wall temperature profile follows almost perfectly the shape of the annular flow, differing by about 0.4°C.

Future work will consist on testing different central pipe alternatives in order to decrease the R_b value, as well as studying different solutions for the eccentricity problem. The calculation of R_b along the borehole length will be done and carefully confirmed with a complete Distributed Thermal Response Test analysis in the continuation of this study.

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