COMPREHENSIVE SUMMARY OF BOREHOLE HEAT EXCHANGER RESEARCH AT KTH

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ABSTRACT

A research project that aims at presenting recommendations for improving the COP of ground source heat pump systems by 10-20% through better design of Borehole Heat Exchangers (BHE) is described in this paper. Experiments are carried out with temperature measurements taken in different BHE types during heat pump operation conditions as well as during the thermal response tests. It is also expected to point out methods for having natural fluid circulation in the BHE, i.e. demonstrating that the heat carrier fluid can naturally circulate thanks to temperature induced density differences along the borehole depth, and thereby avoiding the use of electricity consuming pumps. A brief background presenting the most relevant work regarding BHE research around the world is first presented, followed by a comprehensive description of the current research at KTH. Some new measurements and obtained results are presented as an estimation of to what extent the project results have been achieved is discussed. An analysis on how the project results could allow reducing the borehole depth keeping today’s Coefficient of Performance is presented.

1. BACKGROUND

The bedrock is an attractive energy source that keeps a near constant temperature over the year regardless of ambient temperature variations. Its reliability and high efficiency has encouraged a rapid growth of the bedrock coupled heat pump systems use during the last two decades. However, the performance of these systems is still vulnerable to improvements if better Borehole Heat Exchangers (BHE) designs are used and if circulation pumps are eliminated. Today, U-pipe BHEs consisting of two equal plastic pipes brazed together at the borehole bottom, dominate the market. This design is economic and easy to install, but its thermal performance is relatively poor, i.e. it does not guarantee a low temperature difference between the surrounding ground and the heat carrier fluid.

A research project at the Royal Institute of Technology (KTH), aims at presenting recommendations to decreasing the temperature difference between the refrigerant evaporation temperature and the bedrock by three degrees, i.e. this would contribute to a 6-9% increase of the COP of the heat pump system. Moreover, the project intends to demonstrate the use of thermosyphon loop BHEs as a way to eliminate the need of circulation pumps, implying a possible increase of overall COP by about 5-10%. The latter involves demonstrating that the heat carrier fluid can naturally circulate thanks to temperature induced density differences along the borehole depth. A disadvantage of these systems is that they only can work in one thermal flow direction, i.e. the heat is always absorbed from the ground and released at the borehole top. This eliminates any possibilities of using them for cooling applications.

The performance of the U-pipe BHE has been widely studied for several years, both theoretically and experimentally. Hellström (1998) presented how its thermal performance changes as a function of the filling material thermal conductivity for three different pipe positions in the borehole. Moreover, Hellström et al. (2000) shows a performance comparison at different temperature levels and heat rates. The results show values between 0.053 and 0.08 K m/W, indicating the influence of free convection heat transfer in the groundwater. Bose et al. (2002) showed results from five thermal response tests with the use of spacers and different grout materials, pointing out a 30% borehole length reduction possibility when using spacers and thermally enhanced grout. Particularly, a coaxial design has been studied by Platell (2006), who presents interesting ideas consisting of one central insulated pipe and several outer pipes that offer thermal and hydrodynamic advantages. The first prototype consisted of 62 thin pipes (inner diameter 3.8 mm and wall thickness 0.65 mm) arranged close to the borehole wall in a special laboratory installation. The diameter of the laboratory borehole was 104 mm. This was tested by Hellström et al. (2000). The result was significant possible improvement in thermal performance.
Investigations in self-circulation borehole heat exchangers have been concentrated on CO₂ as heat carrier fluid. Rieberer et al. (2002) were pioneers initiating investigation of CO₂ heat pipe prototypes. The temperature levels measured at different depths confirmed good operation of several probes of 50-65 m deep and 15 mm in diameter. Later, Rieberer et al. (2004) presented details about mass flow rates, the refrigerant superheat temperature differences in the heat pump, different BHE probe heads (heat pump evaporator), and discussions about the amount of probes to be inserted in a single borehole. Riberer et al. (2005) shows results from two 65 m deep self circulating BHEs, having a heat extraction rate of 58 W/m per borehole and it identifies the probe heads as the bottleneck of these systems, since they must guarantee a small pressure drop and good heat transfer at operating conditions. Another design consisting of a corrugated stainless steel heat pipe for counter current liquid-vapor was presented by Kruse and Russmann (2005). Experiments results were compared to a typical brine system in a 18 m deep borehole. It resulted in smaller temperature differences between the CO2 and the heat pump refrigerant than for the brine solution. Different heat pipe diameters (from 6 to 25 mm) CO2 charges were tested in order to investigate how these influence the performance. The filling ratio was found to be directly related to the specific heat flux under which the thermosyphon will work. The requirement of higher filling rates for achieving higher heat flux was evident. Three years later, Kruse and Peters (2008) present tests from 50 m and 100 m deep boreholes where the temperature values along the depth varied between -1.5 °C and -3 °C. Furthermore, Ochsner (2008) presents his experiences with a 40 mm flexible high-grade steel corrugated heat pipe system with the same working principle as the ones presented above. The depth of the BHE is 100 m and it can be installed both as single or double tube. The proposed double tube arrangement is in fact a coaxial design, where the liquid phase falls down through a central pipe and the vapor flows upwards through an annular channel, i.e. between the central pipe and the inner wall of the external pipe. Heat extraction rates of about 50 W/m are mentioned.

2. RESEARCH ON BOREHOLE HEAT EXCHANGERS AT KTH

3.1 Description

Since 2007, as part of the EFFSYS2 research program (www.effsys2.se) financed by the Swedish Energy Agency, KTH has started a collaboration with the industry in order to test borehole heat exchangers, point out improvement possibilities, and promote the development of more efficient designs. The tests are particularly special thanks to the use of new and advanced temperature measurement techniques: thermocouples are locally inserted through the pipes at different depths for a direct measurement of the heat carrier fluid temperature, and fiber optic cables are installed along the test boreholes for measuring temperatures of the heat carrier fluid, the groundwater, and even of the borehole wall to some extent. Details about how the boreholes were instrumented are presented in Acuña (2008). The pressure drop and the flow rates are measured in all the BHEs in order to evaluate their hydrodynamic performance.

Figure 1 is a photograph of a research borehole where some cables coming from the inner and outer side of the collector pipes can be seen. These are part of the equipment that allows measuring the borehole temperature along its depth. The blue cables are fiber optic that can be used to measure up to every one meter along the boreholes, and the orange ones are thermocouple cables coming from local points. All the research boreholes are instrumented, at least, with one of these two temperature measurement technique.

Previous to testing the BHEs, some of the test boreholes have been characterized regarding the groundwater flow, their deviation from the vertical direction, the thermal conductivity of the ground. This, in order to be able to correlate the characterization results to the performance evaluation of the BHEs. Details about the characterization methods and results are presented in Acuña et al. (2008a).
3.1 Undisturbed Conditions
The first measurement that is usually carried out at each borehole is under undisturbed ground conditions. The undisturbed ground temperature profile may help to understand the shape of the temperature vs. depth curve for a certain borehole heat exchanger in operation. If the borehole has not been in operation earlier, it allows determining the true undisturbed ground temperature profile at each site. Measurements in boreholes that are not in operation can furthermore be of significant help when calibrating the temperature measurement equipment. Figure 2 illustrates measurements under undisturbed ground conditions at (a) 260 m, (b) 220 m, and (c) 190 m deep borehole, respectively. They have been with different instruments at different times of the year and with different measurement integration times.

![Figure 2. Undisturbed ground temperature profile at different measurement locations](image)

All three boreholes presented in Figure 2 are water filled and are geographically located in Stockholm, Sweden; with an average of all installations of about 8.3°C, slightly higher than the normal yearly ambient average temperature for this region as of SMHI (2010). The borehole in Figure 2 (b) has been in operation before the measurements were taken, meaning that the true undisturbed ground temperature levels are somewhat higher than the ones illustrated in the figure. Two insulation factors may explain the higher ground temperature as compared to ambient air mean: the effect of snow layers during some year periods, and the construction of buildings that cause a warming effect over the upper part of the ground. The latter factor is specially evidenced in Figure 2(a) and Figure 2(c) where the minimum borehole temperature is found at about 110 m depth. How deep under the ground surface this minimum point is found is proportional to how long time has passed between the urbanization of the area and the temperature measurement. The area where the borehole in Figure 2(b) is drilled has certainly been populated significantly later than the other two.

3.2. The Borehole Heat Exchangers
Figure 3 shows some of the heat exchanger designs that are being tested: (a) a three pipe 40x3.7mm collector consisting of three equal pipes out of which two are connected in parallel, (b) a coaxial BHE consisting of one central and five peripheral flow channels (the five external channels are connected in parallel), (c) a U-pipe 40x2.4mm with spacers for separating the U-pipe channels, i.e. placing them away from each other and close to the rock wall, (d) an annular coaxial collector composed of one central pipe and an outer annular shaped channel, (e) a U-pipe 40x2.4mm with insulated upper part of the upward flow channel (for studying to what extent this decreases the thermal contact between the pipes), and (f) U-pipe 40x2.4mm with inner fins. All six designs are made with polyethylene (plastic) pipes and the fluid circulation is achieved thanks to the use of a circulation pump. Moreover, the last two designs (g) and (h), are two thermosyphon loops made of copper. In these, the heat carrier circulation does not demand a circulation pump.
To find the optimum BHE design, measurements are evaluated considering that the heat transfer between the heat carrier fluid and the surrounding rock depends on several factors: the arrangement of the heat transfer in the flow channels, possible free convection heat transfer in the borehole (if the well is water filled), the thermal properties of the pipes, and the borehole filling material. The thermal resistances associated with these different parts are traditionally added together into a single term often called the borehole thermal resistance. For a given working condition, each BHE has a borehole thermal resistance that characterizes it. The design with the lowest borehole thermal resistance will deliver the highest temperature to the heat pump for a given heat extraction rate and borehole wall temperature. It is, therefore, desirable to have as low resistance as possible in order to have the lowest temperature difference between the fluid and the ground.

The BHE performance evaluations are normally based on heat pump operation conditions and thermal response tests (TRT), but also to a minor extent on numerical analyses and simulations. Examples of the latter are the local steady-state heat conduction analysis presented in Acuña et al. (2009b) and Acuña et al. (2010b), where the local thermal resistance between the fluid temperature and the borehole wall was estimated for the BHE illustrated in Figure 3(b), and (c), as compared to a U-pipe design. The simulations were done for a 140 mm water filled borehole, resulting in thermal resistance variations between 0.11–0.26 K m/W depending on the pipes’ positions in the borehole. The coaxial design - Figure 3(b) - may have a similar performance as the U-pipe. In addition, as expected for all the cases, the thermal performance improved as the flow channels are closer to the borehole wall and separated from each other. However, although spacers help on separating the pipes, they may often not imply an improvement.

3.3 Heat Pump Operation

Measurements during heat pump operation have also confirmed that some of the tested spacers do not improve the heat exchange with the ground in boreholes. The experimental work by Ten (2008) and Acuña et al. (2008b) show that the use of spacers for 13 mm separation between PE40x2.4mm pipes in a 140 mm borehole does not result on performance improvement as compared to U-pipe without spacers. Acuña et al. (2008b) also present the first results from the designs in Figure 3(a) and Figure 3(f). The U-pipe with fins shows a slight improvement in thermal and hydrodynamic performance whilst the 3-pipe collector performance is relatively worst than for U-pipes. Testing BHEs during heat operation is probably not the best way to compare BHEs’ thermal performance. Though, if heat pump cycles are long enough to allow the fluid temperature profile to develop along the BHE for a certain flow rate, the temperature distribution the specific heat extraction rate per meter along the BHE can be observed.

Figure 4, an example of temperature measurements carried out with thermocouples at different points along a 260 m deep U-pipe BHE, shows that a temperature drop occurs in all the thermocouples following the flow direction as the heat pump starts operating. The heat pump takes heat from the borehole and the temperatures increase as the fluid travels along the BHE: the first thermocouple, at 15 m depth on the downward flow, is the earliest point to register the heat pump start up. Conversely, the last thermocouple at 15 m depth on the upward flow, notices the heat pump about 1/5 of hour after. For this case, the total temperature change is of
about 3.6°C, an increase of three degrees on the way down and of one degree on the way up. The heat distribution in the borehole (equivalent to the temperature difference between measurement points) varies according to how fast the fluid is traveling. The duration of each heat pump cycle will vary according to the outdoor temperature and the building energy demand. The fluid temperature at all points in Figure 4 is higher than the ambient temperature for this measurement period. When the outside temperatures are lower, the heat pump operation periods are longer.

Figure 5 is a measurement taken with fiber optics in a 220 m deep U-pipe BHE with spacers at an instant during heat pump operation. At this time point, the fluid temperature differences along the BHE were relatively constant, meaning that this temperature vs. depth profile would be maintained, at least for a relatively short period of time. A linear regression was done for each pipe in order to generate a trend line, which equations are also shown in the figure. The downward flow changes its temperature with 0.013 K/m and the upward flow with 0.007 K/m, meaning that the heat extraction rate is almost twice as high along the downward channel. The total temperature change between inlet and outlet temperature is of 4.5K, 3K change on the way down and 1.5K on the way up. Whether this relationship should be linear or curved may depend on the borehole depth, the ground temperature profile, and the flow rate at which the heat carrier fluid is circulated. How this profile may change at different flow rates was partially presented by Madani et al. (2010) together with an analysis of the heat pump system. Higher the flow rates result in the less thermal contact (thermal shunt flow) between U-pipe channels, meaning that the slopes (the relation °C/m) of the downward and upward flow tend to be more similar as the flow is increased. The thermal contact also depends on the relative position of the pipes to each other and to the borehole wall.

3.4 Thermal Response Test (TRT)
A TRT consists of applying a constant cooling or heating power to the heat carrier fluid while logging its inlet and outlet temperatures, flow rate, and applied power, during two main phases: pre-circulation of the fluid, and a heat extraction or injection phase. A calculation of the thermal response of the BHE is used, together with the measurements, for determining the borehole thermal resistance and the thermal conductivity of the surrounding ground. One innovation that KTH’s research brings to the widely known thermal response test praxis is the possibility of using distributed temperature measurements along the borehole during a TRT, i.e. Distributed Thermal Response Test (DTRT). Figure 6 shows temperature measurements at different depths during a DTRT carried out on a U-pipe BHE during this project. Four main phases are distinguished. In a chronological order, the first 65 hours represent temperatures under undisturbed ground conditions, i.e. the borehole is at its undisturbed level and the temperatures are kept constant at any depth that is long enough from the ground surface. During the subsequent 24 hours (pre-circulation phase), the temperature along the whole borehole becomes almost constant due to no more than the circulation of the fluid. Next, about two days of heat injection into the borehole during which the fluid is constantly heated and circulated. The heat injection period allows the determination of the borehole thermal resistance and the rock thermal conductivity at different depths along the well.
The final twenty hours show how the temperatures at different depths along the borehole tend to go back to their undisturbed conditions after the heat injection period is finished. Here, the radial temperature gradients in the borehole are very small, making it also possible to determine the ground thermal conductivity variations along the depth.

As presented in Acuña et al. (2009a), this temperature measurements have allowed determining variations in rock thermal conductivity in the range of 2.6 - 3.6 W/mK and in borehole thermal resistance between 0.054 - 0.078 K m/W along a U-pipe BHE.

DTRTs have also been carried out at the two of the new coaxial BHE designs presented in Figure 3. The results in Acuña et al. (2010a) show that the annular design shown in Figure 3(d) can reach low temperature differences (about 0.5 K) between the heat carrier fluid and the borehole wall. The measurement to some extent of the borehole wall is possible since the annular channel is installed so that it is in contact with the borehole wall allowing a fiber optic cable to be installed between the rock and the wall of the annular channel. Moreover, the work by Acuña et al. (2010b) studies a 250 m long prototype of the coaxial design with five peripheral channels shown in Figure 3(b). The results show a thermal performance similar to that of U-pipe BHE and the thermal shunt flow that occurs in this pipe.

3.3. Experiences with thermosyphon BHE loops

As it was explained in section 1, most of the work carried out until today regarding self circulating probes correspond to solutions implying counter current flow between the liquid and gas phases of the fluid. Counter current flow systems may decrease the circulation possibilities by slowing down the liquid phase of the fluid, preventing the liquid to reach the bottom of the BHE. Eliminating this risk by using thermosyphon loops where both fluid phases move in the same direction along the BHE channels is a possible solution.

Two different thermosyphon loops, a helix and a U-pipe loop, have been partially tested at KTH during this project. These two designs can be observed in Figure 3(g) and Figure 3(h). The tests have been carried out using CO₂ as heat carrier fluid. The former consisted of a straight insulated down pipe and a helical riser. The idea with this design is to locate the circulating CO₂ as close as possible to the rock walls in the borehole in order to reduce the borehole thermal resistance. The second loop consists of a 22 mm insulated down pipe brazed at the bottom to a 28 mm riser tube. The study of the helix loop is presented in Rudorf (2008) and Brulles (2008), who showed with experiments and calculations that insufficient natural circulation was achieved with this design. Deficiencies of the central pipe insulation, too high pressure drop, and dry out of the fluid along the helical pipe are some of the hypotheses for the malfunctioning of the system. In the experiments, only the borehole water temperature (and not the CO₂ temperature along the helical pipe) was measured, which added some uncertainty to the measurements.

The first results from the U-pipe loop are presented in Acuña et al. (2010c), who show an operating system during several heat pump cycles. Relatively constant temperatures along the groundwater-riser interface indicate that phase change conditions occur along the whole tube, starting at the bottom of the borehole. This is illustrated in Figure 7 where the measurement at zero “0” minutes shows the temperature profile before the heat pump started, followed by three measurements at different times after the heat pump began to operate. The change in temperature profile that occurs at the moment of the startup and the decrease in temperature levels due to heat extraction from the borehole are evident.
The temperature change at the bottom is of about 1.4 K whilst almost insignificant at the top. The lower temperature levels measured at the lower part of the BHE during operation may indicate that the heat transferred per meter borehole is higher in this region, where the bedrock is in fact warmer. The total temperature difference from bottom to top of the BHE is about 0.6 K. This may have to do with several issues.

The pressure difference between the evaporation and condensation ends of the riser may be relatively small in spite of the gravitational pressure difference (about 60 m CO₂ column). If the down pipe is filled with liquid, the saturation temperature at the inlet of the riser should be about 6 K higher than at the outlet. However, some evaporation may start to take place at the down pipe, originating an extra pressure drop that will be reflected on the temperature levels. An estimation of the saturation pressure at the borehole bottom results on about 540 kPa higher than at the top of the borehole (an approximate gradient of 9 kPa/m). The CO₂ saturation temperature at the bottom would result from summing the pressure at the borehole top with this difference, but also minus the pressure drop due to friction along the down pipe. If the down pipe insulation is ideal, the liquid will be sub-cooled some degrees according to the resulting pressures at 60 m depth.

**CONCLUSIONS**

As part of the EFFSYS2 research program financed by the Swedish Energy Agency, KTH has started a strong collaboration with the industry in order to point out improvement possibilities for borehole heat exchanger design. The tests are characterized by the use of distributed temperature measurements of the heat carrier fluid, groundwater, and even the borehole wall temperature to some extent. Some BHEs that are being tested were briefly presented in this paper.

The undisturbed ground temperature profile at three research boreholes located in the city of Stockholm show an average temperature of about 8.3°C, slightly higher than the ambient normal yearly average. The effect of snow layers during some periods of the year and the time has passed since the specific areas were urbanized partially explain the relatively warmer upper part of the ground in all the boreholes.

Distributed measurements in U-pipe BHEs during heat pump operation show typical temperature distribution in boreholes. As an example, a linear regression was done for each pipe in order to generate a trend line. The downward flow increases its temperature with 0.013 K/m while the upward flow with 0.007K/m, meaning that the heat extraction rate is almost twice as high along the downward channel. Whether this relation is linear or not depends mainly of the borehole depth and the flow rate at which the heat carrier fluid is circulated. Higher the flow rates result in the less thermal contact between BHE flow channels. The thermal contact also depends on the relative position of the pipes to each other and to the borehole wall, as demonstrated with local heat conduction steady state analysis carried out for the U-pipe (with and without spacers) and the coaxial BHE prototype with five peripheral channels. The latter design was also tested with a TRT in a 250 m long borehole, resulting in similar overall thermal performance to that of U-pipe BHE and significantly lower pressure drop.

A Distributed Thermal Response Test carried out along a U-pipe BHE determined variations in rock thermal conductivity between 2.60-3.62 W/mK and in borehole thermal resistance between 0.054-0.078 K m/W. The first results from such a test in the annular design show that low temperature differences are reached between the heat carrier fluid and the borehole wall. The measurement of the borehole wall, to some extent, is possible since the annular channel is installed so that it is in contact with the rock, allowing a fiber optic cable to be sandwiched between by the borehole wall and the annular channel.
Results from the U-pipe thermosyphon BHE loop show an operating system with relatively constant temperatures along the groundwater-riser interface during heat pump operation, indicating that phase change conditions occur along the whole tube starting at the bottom of the borehole.

Positive indications for lowering the temperature difference between the rock and the evaporator by 3 K and for eliminating the need of circulation pumps with thermosyphon BHEs have been obtained during the first two years of the research at KTH. More efficient heat exchange would allow reducing the borehole depth by keeping today’s Coefficient of Performance, automatically reducing installation costs. Increasing the COP by keeping the current borehole depths is also an alternative. The use of U-pipe thermosyphon loops for eliminating the need of circulation pumps would cause a further improvement of the overall COP.

REFERENCES

23. SMHI (2010), Swedish Meteorological and Hydrological Survey (http://www.smhi.se)