

# DISTRIBUTED TEMPERATURE MEASUREMENTS ON A U-PIPE THERMOSYPHON BOREHOLE HEAT EXCHANGER WITH CO<sub>2</sub>

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## ABSTRACT

In thermosyphon Borehole Heat Exchangers, a heat carrier fluid circulates while exchanging heat with the ground without the need of a circulation pump, representing an attractive alternative when compared to other more conventional systems. Normally, the fluid is at liquid-vapor saturation conditions and circulation is maintained by density differences between the two phases as the fluid absorbs energy from the ground. This paper presents some experimental experiences from a 65 meter deep thermosyphon borehole heat exchanger loop using Carbon Dioxide as heat carrier fluid, instrumented with a fiber optic cable for distributed temperature measurements along the borehole depth. The heat exchanger consists of an insulated copper tube through which the liquid CO<sub>2</sub> flows downwards, and a copper tube acting as a riser. The results show temperatures every two meters along the riser, illustrating the heat transfer process in the loop during several heat pump cycles.

## 1. INTRODUCTION

The operation costs for running electrically driven pumps in Borehole Heat Exchangers can be eliminated if thermosyphon technology is used. Thermosyphons can be used as a method of passive heat exchange based on natural circulation of a fluid maintained by density differences which allow the fluid to flow over considerable distances. In Ground Source Heat Pump Applications, the operation of such systems has normally been based on counter current flow conditions consisting of liquid fluid flowing down through a channel as it absorbs heat from the ground and, at some point, evaporating. As this happens, the vapor rises through the same channel due to buoyancy until it comes to the cooled surfaces of an evaporator located at the top of the borehole, where it condenses and releases heat. This heat is transferred to the refrigerant in the heat pump evaporator. 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.

In order for this type of systems to operate properly, it is obviously necessary to use a heat carrier able to change phase at the required operating conditions. Carbon Dioxide (CO<sub>2</sub>) is one of the most feasible fluids for this application, having a high volumetric heat capacity leading to small volumetric flow rates and small pressure loss. High heat extraction rates in groundwater filled borehole heat exchangers may, in the long run, lead to lower rock temperatures, freezing problems in the borehole groundwater, and to lower CO<sub>2</sub> saturation temperatures. From the environmental point of view, CO<sub>2</sub> has zero ozone depletion potential, a GWP equal to 1, it is non-explosive, non flammable, non toxic, and non-reactive.

Since most of processes in thermosyphon BHEs occur in saturation state, the pressure levels in the CO<sub>2</sub> loops are determined by the borehole (or rock) temperature levels. Although CO<sub>2</sub> has low critical temperature (31.1°C), there is no risk to fall into this region. Normal rock temperatures in countries with heating demand imply CO<sub>2</sub> operating pressures of about 30-45 bar. In case of leakage, no

environmental effects are caused in the groundwater side and, on the building side, since CO<sub>2</sub> also is odorless and colorless, the installation of CO<sub>2</sub> concentration meters is recommended in order to detect any harmful increase on the gas concentration levels. The use of appropriate BHE materials and welding techniques is also important. Materials that tolerate these pressure levels may sometimes not be appropriate from the corrosion point of view, e.g. for long term contact with groundwater.

The first investigations in CO<sub>2</sub> borehole heat exchangers were done by Rieberer et al. (2002). Several heat pipe prototypes 50-65 m deep and 15 mm in diameter were tested. The first tests resulted in undesired CO<sub>2</sub> superheat at the head of the borehole. Later, a second prototype was built in which good fluid circulation was achieved and the superheat was acceptable. The temperature levels measured at different depths confirmed good operation of the system during the heat pump cycle. Moreover, 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. Rieberer et al. (2005) mention that the number of known commercial heat pump installations using natural circulation BHEs was about 100 between 2001 and 2005. The latter study shows results from two 65 m deep self circulating BHEs, having a heat extraction rate of 58 W/m per borehole. Moreover, it identifies the probe heads as the bottleneck of these systems. Probe heads must guarantee a small pressure drop and good heat transfer at operating conditions. Different models are presented and a vertical pipe solution is recommended as compared to pot, serpentine, and spiral geometries. Later, Rieberer (2005) adds results from a computer model showing simulated saturation temperatures in the probe heads at different CO<sub>2</sub> filling concentrations, as well as the temperature increase due to the pressure change along the borehole.

Another design consisting of a counter current liquid-vapor BHE was presented by Kruse and Russmann (2005). The BHE consists of a corrugated stainless steel heat pipe. It was experimentally investigated and the results were compared to a typical brine system in a 18 m deep borehole. It resulted in smaller temperature differences between the CO<sub>2</sub> and the heat pump refrigerant than for the brine solution. Moreover, this work shows results from a 7 meter long CO<sub>2</sub> heat pipe laboratory setup inserted into a simulated water filled borehole of 60 mm in diameter with constant water temperature. Different heat pipe diameters (from 6 to 25 mm) were tested in order to investigate the performance at different heat fluxes. The rig has 15 thermocouples along the pipe separated 0.5 m from each other. An important phenomenon pointed out by Kruse and Russmann (2005) is the flooding of the heat pipe, that occurs when the vapour flowing upwards prevents that the liquid reaches the lower part of the pipe, being evident from the tests with the 6 mm and the 25 mm heat pipe. The CO<sub>2</sub> charge was varied in order to find the optimum necessary amount that avoids flooding, i.e. the minimum charge to guarantee a liquid film along the whole heat pipe BHE length. 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 from their last tests with the 25 mm pipe.

Three years later, Kruse and Peters (2008) mention that a dozen of the corrugated steel heat pipe systems have been commercially installed in Germany and Austria. Moreover, tests from 50 m and 100 m deep boreholes are presented. The latter have seven temperature measurement points along the collector. The temperature values along the depth varied between -1.5 °C and -3 °C. This was simultaneously tested and compared to a brine BHE system of the same depth installed at the same place, ten meters away. Two different evaporator heat exchangers were tested: a plate type for the brine system and a shell and coil type evaporator for condensing the CO<sub>2</sub> at the borehole top. No details are given about what type of brine BHE nor what volumetric flow rate was used. The inlet CO<sub>2</sub> temperature to the evaporator was -3.9 °C while for a brine it was 1.9 °C. However, the evaporating temperature for the latter was lower.

Ochner (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. The installation of this BHE is done with an unwinding device, similar to common polyethylene pipe installations. A remark is written in the paper about appropriate borehole filling that must be done between the BHE and the borehole rock wall, pointing out that a deficient filling could cause deformation of the BHE at pressures of 40 to 42 bar. This pressure levels are in fact likely to occur.

As seen above, most of the work carried out until today with the exception of the coaxial design presented by Oschner (2008), correspond to heat pipe solutions implying counter current flow between the liquid and gas phases of the fluid. This may decrease the circulation possibilities by slowing down the liquid phase of the fluid, preventing the liquid to reach the bottom of the heat pipe. This risk can be eliminated by the use of thermosyphon loops where both fluid phases move along in the same direction, only hindered by the friction with the tube walls and the gravitational force, instead of in counter current flow. Certainly, the pressure drop limitations may limit the capacity and this should be avoided. Details about heat transfer and pressure drop in thermosyphon loops have been presented by Khodabandeh R. (2004) for a different application.

This paper presents the first experiences from some CO<sub>2</sub> thermosyphon loop Borehole Heat Exchangers installed in Sweden, and in particular one corresponding to a U-pipe loop. The tests are evaluated with distributed temperature measurements every two meters along the borehole with fiber optic cables. The loops have two components, an insulated down comer and a riser. Both pipes are made of copper and they are designed so that liquid CO<sub>2</sub> travels downwards towards the warmest section of the borehole due to gravity, where it starts to evaporate. Subsequently, the vapor flows upwards through the riser, absorbing heat on its way and reaching the heat pump evaporator located at the top of the borehole, where it condenses and runs back through the downcomer.

## 2. DESCRIPTION OF THE TEST INSTALLATIONS

Both attempts for the thermosyphon Borehole Heat Exchanger loop presented in this paper have been carried out in the same 70 m deep groundwater filled borehole. The average undisturbed ground temperature is about 8°C. The borehole diameter is 115 mm and the groundwater level oscillates around 7 meters under the ground surface level. The heat pump coupled to this BHE is of the type Vary Scroll Optimal 6-10 and uses R404A as a refrigerant.

The first loop consisted of a straight insulated downcomer and a helical riser as the one shown in Figure 1. The idea with this design is to locate the circulating CO<sub>2</sub> as close as possible to the rock walls of the borehole in order to reduce the borehole thermal resistance.

The second loop consists of a 22 mm insulated downcomer brazed at the bottom to a 28 mm riser tube, as illustrated in Figure 2.

Installing the former design was difficult, given that several helical sections were brazed together as the BHE was inserted into the borehole. On the other hand, the installation of the U-pipe was simple since both, the downcomer and the riser pipe, were rolled out simultaneously as they were inserted into the borehole. Only two brazing points were necessary in each tube.

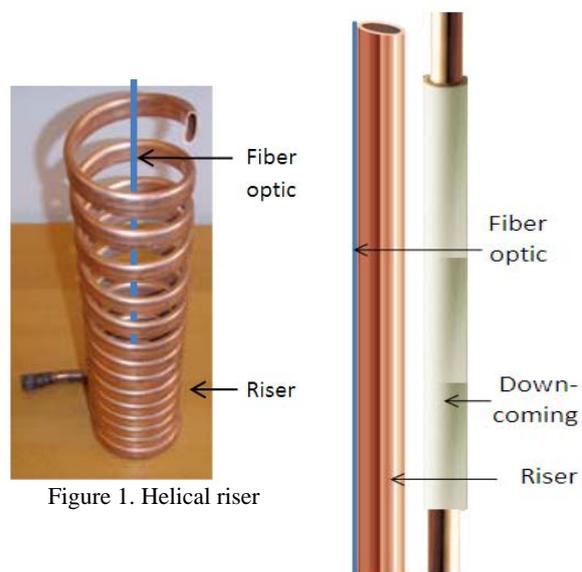


Figure 1. Helical riser

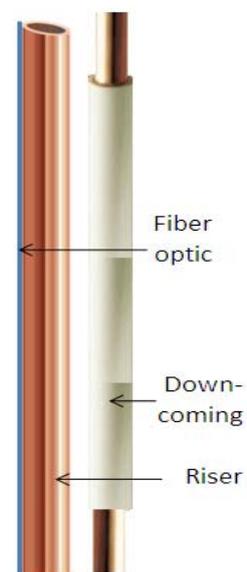


Figure 2. U-pipe Thermosyphon BHE

The idea with both solutions is that the liquid CO<sub>2</sub> travels down towards the warmest section of the borehole through the insulated pipe due to gravity, and starts to evaporate at the bottom so that the fluid flows upwards as a mixture of vapor and liquid through the riser. A separator, where the saturated liquid and vapor coexist has been connected between the down comer tube and the evaporator in order to guarantee that only liquid is fed to this pipe, as illustrated in Figure 3. Both designs were instrumented with Distributed Temperature Sensing (DTS) for measuring the temperatures along the borehole length.

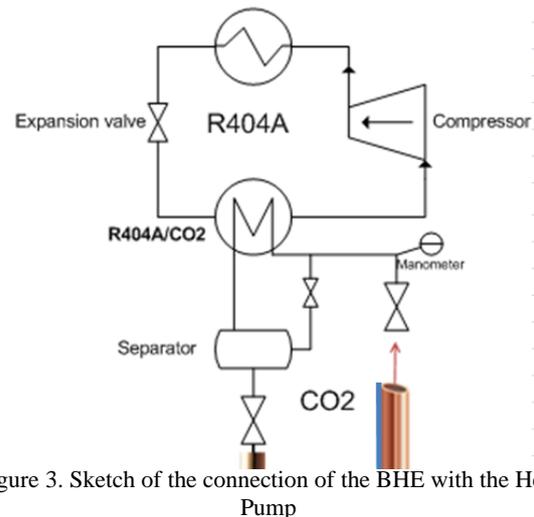


Figure 3. Sketch of the connection of the BHE with the Heat Pump

DTS technology is based on laser pulses sent through the fiber optic cables, followed by a subsequent analysis of the backscattered light which is a function of the temperature (Raman scattering). The readout equipment is of the type HALOn Sensornet and it is capable of integrating and converting these signals into average temperatures for every two meters along the cables. The accuracy depends on integration time and measuring length interval, among other factors. Several experiences using this technology in borehole heat exchangers have been published by Acuña et al. (2008) and Acuña et al. (2009).

In this case, measurements have been taken with an integration time of five minutes and a repetition time of ten minutes. Since the position of the fiber optic cable inside the borehole may vary somewhat, especially in the helical type BHE where the cable hangs freely in the middle of the helix as illustrated in Figure 1, there will be some scatter in the temperature data. For the U-pipe installation, the cable position was more carefully controlled, as the cable was attached with tape every thirty centimeters along the whole riser. Nevertheless, it is important to keep in mind that the measurements were not done directly on the CO<sub>2</sub> but at the groundwater-riser interface.

### 3. RESULTS AND DISCUSSION

#### 3.1. The helical pipe

As previously mentioned, the idea with the helical tube was to geometrically locate the circulating CO<sub>2</sub> as close as possible to the borehole rock in order to reduce the borehole thermal resistance. Both experimental (Rudorf, 2008) and theoretical studies (Brulles, 2008) demonstrated that insufficient free convection was achieved with this design. The experimental tests could not determine the CO<sub>2</sub> temperature in the BHE due to the unknown exact location of the fiber optic cable. However, between 15 and 40 meters depth in the borehole, the temperatures registered were lower than in the rest of the borehole. It is suspected that good circulation of the CO<sub>2</sub> could not be maintained because of too large pressure drop in the circuit. Probably the CO<sub>2</sub> started evaporating in the downcomer, and the vapor went back up through this pipe. The conclusion of the theoretical study pointed at deficiencies of the central pipe insulation and of dry out of the fluid along the helical pipe. A margin of helical tube diameters within which the system would work was suggested considering the pressure drop along the collector. A change in the helix angle was as well recommended.

#### 3.2. The U-pipe

The U-pipe thermosyphon design has been operating for more than one year and several measurements have been taken with the distributed temperature sensing equipment. Figure 4 gives a detailed picture of continuous temperature measurements along the BHE riser (taken with the fiber optic cable shown in Figure 2) during heat pump operation periods. The temperatures are represented by different colors while the horizontal and vertical axes stand for the time and borehole depth,

respectively. Four complete heat pump cycles are observed, represented by the sequence of high and low temperatures along the whole borehole depth. The constant low temperatures along the riser during the periods when the heat pump is running, illustrated by the blue color, indicate that evaporation occur along the whole riser starting at the bottom of the borehole. This shows that the CO<sub>2</sub> charge is appropriate for this operating condition, as the whole length of the riser is utilized. The vapor generation rate at these operating conditions is about 0.0185 kg/s. This BHE was filled in such a way that the liquid level when the heat pump was not operating, was in the separator tank. In this way, the risk of starving the evaporator was minimized. Overcharging the system is not harmful for the system operation, as compared to the case of low filling where the risk for dry out along the riser is increased. Dry out conditions will also decrease the evaporation temperature. If the CO<sub>2</sub> charge is low, the liquid may also evaporate before reaching the borehole bottom, especially in the absence of an appropriate insulation of the downcomer.

Another point illustrated in Figure 4 is the heat recovery of the borehole when the heat pump is turned off. The temperatures along the borehole depth slowly increase and reach values between 2.5 to 3 °C between heat pump start up moments. Figure 5 represents the temperatures at an specific instant during one of the heat extraction periods from the borehole illustrated in Figure 4. The location of the optical fiber cable is once again shown here in order to remind the reader about the fact that the temperatures are measured at the groundwater-riser wall interface, meaning that lower temperatures may indicate higher heat extraction rates at certain sections. It can be observed that the total temperature difference from bottom to top of the BHE is about 0.6 °C, i.e. the temperatures along the riser vary between 0.4 °C and 1 °C during operating conditions, giving an average change of about 0.01 °C per meter borehole.

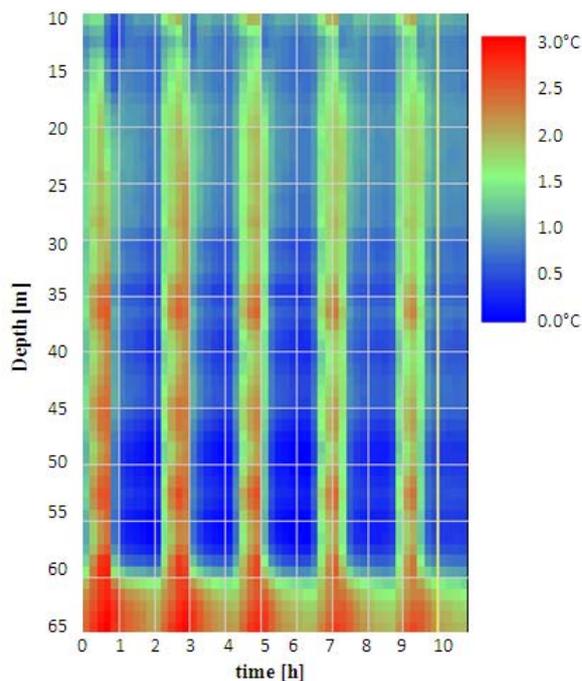


Figure 4. Temperature levels along the riser during several heat pump cycles

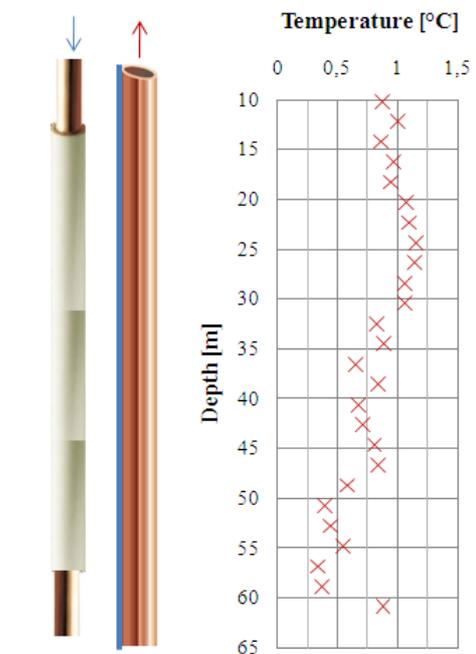


Figure 5. Temperature profile along the riser at one instant during heat pump operation

Along the riser, where boiling occurs, higher saturation pressure and temperature at deeper locations may be expected. Carbon Dioxide, being a high pressure fluid, has a moderate saturation temperature increase with increasing pressure (the relation is approximately 1 bar/K), as compared to other fluids. This means that 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 CO<sub>2</sub> column). If the downcomer is filled with liquid, the saturation temperature at the inlet of the riser should be about 6 Kelvin higher than at the outlet. However, this difference is not evident in Figure 5, where only a slight decrease in temperature with depth is observed. This may have to do with several issues. The

lower temperature levels measured at the bottom 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. Some evaporation may start to take place at the downcomer, originating an extra pressure drop that will be reflected on the temperature levels. Since the fluid is fed through the downcomer, an estimation of the saturation pressure at the borehole bottom results on about 5.4 bar higher than at the top of the borehole (an approximate gradient of 0.09 bar/m). The CO<sub>2</sub> saturation temperature at the bottom would thus result from summing the pressure at the borehole top with this difference, but also minus the pressure drop due to friction along the downcomer. If the downcomer insulation is ideal, the liquid will be sub-cooled some degrees according to the resulting pressures at 60 m depth.

The CO<sub>2</sub> condensation temperature at the heat pump evaporator will be close to the temperature shown at 10 meters depth. A temperature change will as well occur at the top of the borehole due to a slight lower pressure, as compared to the one corresponding to the temperature shown at this depth. Superheating of the R404A in the evaporator should be limited to a minimum in order to guarantee good heat transfer conditions in this heat exchanger.

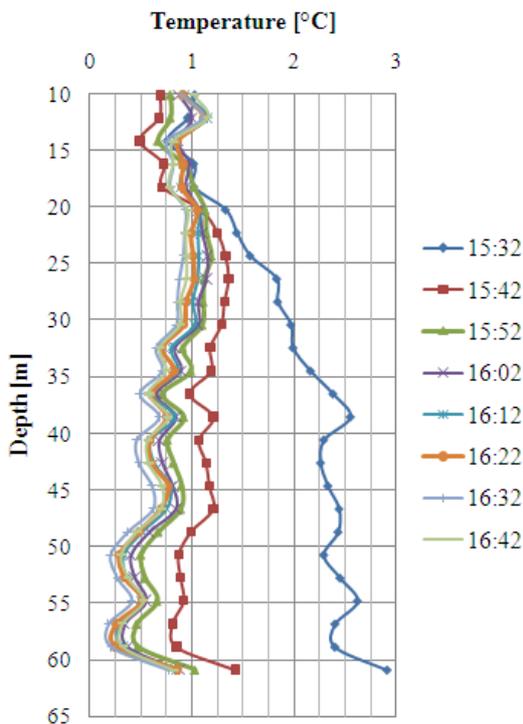


Figure 6. Temperature profile along the riser every ten minutes during heat pump operation

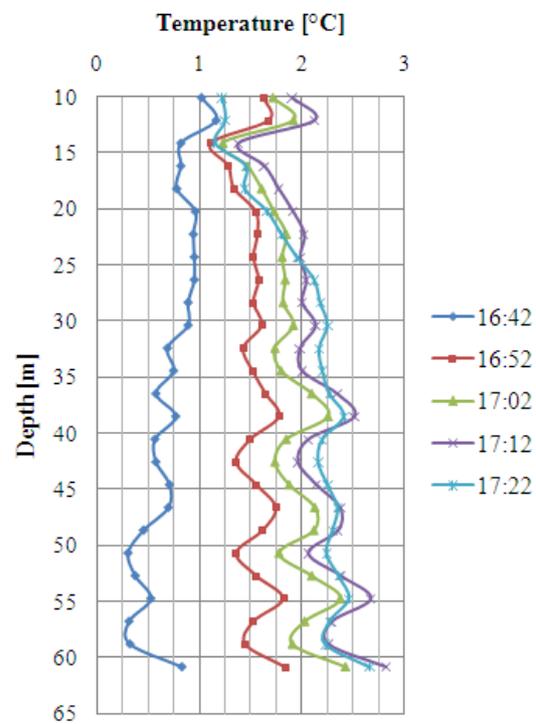


Figure 7. Temperature profile along the riser every ten minutes during borehole recovery

Figure 6 and Figure 7 present temperature vs. depth charts showing the temperature profile along the riser during a typical heat pump cycle. The different lines stand for temperature values every ten minutes, although their values have been integrated for five minute periods. Figure 6 corresponds to the heat pump start up moment and operation time until the moment when it turns off. The difference between the first ten minute lines illustrates the significant change in temperature profile that occurs at the moment of the start up. Subsequently, the decrease in temperature levels due to heat extraction from the borehole is evident as the time passes. It can be observed that the temperature change taking place during the first ten minutes increases with depth, i.e. the change at the bottom is of about 1.4 degrees at the same time as almost insignificant at the top. This reinforces the above mentioned hypothesis that high heat extraction takes place in this section.

Additionally, the relative shape of the temperature profile curves in the borehole axial direction is constant when the heat pump is running, meaning that the boiling conditions are the same at every moment in spite of that the temperature levels tend to decrease with time. This behavior along the borehole has been stable during several days of operation.

Figure 7 shows the temperature values directly after the heat pump is turned off, illustrating how the temperature levels along the depth slowly increase as the borehole recovers from a heat extraction period. Comparing the shape of the curves from Figure 6 and Figure 7, it can be stated that the temperatures along the riser have a tendency to be more constant (vertical) when the heat pump is in operation, while tending to vary with depth and adopt an undisturbed profile as the heat pump resting mode becomes longer.

A typical heat extraction rate in the heat pump evaporator for these working conditions was also measured, being about 4.3 kW, meaning that the average heat extraction rate from the borehole is 71 W/m. It is worth mentioning that this heat extraction rate is high when compared to common pump dependent secondary fluid solutions that extract about 30 W/m (with common U-pipe 40x2.4 mm collectors and flow rates of about 0.5 l/s).

#### 4. CONCLUSIONS

Attempts for a thermosyphon Borehole Heat Exchanger loop using CO<sub>2</sub> in a 70 m deep groundwater filled borehole are presented in this paper, including a properly operating loop that consists of a 22 mm insulated pipe brazed together at the bottom with a 28 mm riser tube that has been demonstrated.

Experimental and theoretical studies of a loop consisting of a straight insulated pipe and a helical riser demonstrated that insufficient natural circulation was achieved with this design. The idea with the helical riser was to locate the circulating CO<sub>2</sub> as close as possible to the rock wall. In the tests, the borehole water temperature was measured, but not the CO<sub>2</sub> temperature in the BHE. 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.

Continuous temperature measurements along the riser of the U-pipe thermosyphon BHE have been shown for several heat pump operation periods. Considerably constant temperatures along the riser indicate that phase change conditions occur along the whole tube, starting at the bottom of the borehole. The total temperature change from bottom to top of the BHE riser is about 0.6 °C, with an average of about 0.01 °C per meter borehole. The CO<sub>2</sub> condensation temperature is approximately 0°C, and the thermal power given to the R404A in the evaporator is about 4.3 kW, corresponding to a CO<sub>2</sub> vapor generation rate of 0.0185 kg/s. The average heat extraction rate from the borehole is 71 W/m, being significantly higher than for typical pump dependent secondary fluid solutions which are designed for extracting about 30 W/m.

Temperature curves along the riser during typical heat pump cycles give details about the significant change in temperature profile that occurs at the moment of the heat pump start up and during the borehole operating heat recovery period. The decrease in temperature levels due to heat extraction from the borehole as the time passes are as well presented. Lower temperatures at the bottom of the BHE during operation may indicate that the heat transferred per meter borehole is higher in this region.

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