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Experimental Investigation of Innovative and Conventional Shallow Borehole Heat Exchangers

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ABSTRACT

The objective of this work is to analyze the performance of gas injecting geothermal borehole heat exchangers (GI-BHX). GI-BHX are capable to create an artificial groundwater flow along the heat exchanger and increase the heat transfer rate. Beside this benefit by increasing the gas injection rate, the performance of a GI-BHX changes within minutes and allows geothermal systems to be used for transient and peak load applications. The artificial groundwater flow is created by a density difference of the gas-water mixture along the heat exchanger and the surrounding groundwater.

The results of a first demonstrator showed that the heat transfer rate of GI-BHX can be increased up to a factor of 5 for peak loads and a factor of 2 for steady state conditions. In addition, these changes in performance are highly dynamical connected to the gas injection rate and allows such systems to react within minutes to changing demands. For further investigations a big test field was constructed with 7 GI-BHX and 5 ordinary borehole heat exchangers (BHX). The GI-BHX were built with varying geometries and heat exchanger to improve the understanding of the system and determine optimal operation points and methods experimental. The different types of GI-BHX are compared and the influence of several GI-BHX to each other and also to BHX is tested. It is shown that the GI-BHX having a high potential to improve the heat transfer rate and to reduce the total number of geothermal heat exchangers necessary as well as the drilling depth of systems if crucial.

1. INTRODUCTION

The shallow geothermal energy is limited to the first few hundred meters below ground surface. Within this depth the temperature is at least 10°C and increases about 3°C each 100 m approximately. This approach is valid for most parts in north und middle Europe. The predictable temperature gives the possibility to heat or cool buildings with thermal energy from the soil. There are two common systems to use the geothermal energy, with close and open systems.

The closed system transfers the energy with the soil just by conduction in case of no ground water flow. Due to the fact that conduction is a very weak procedure, the efficiency and the energy output is limited. If there is a groundwater flow the dominating heat transfer method is convection, which is much faster and capable of transferring more energy. This increases the energy output of a geothermal heat exchanger (Ma and Grabe, 2009a). An open system is using a forced convection in the groundwater due to the two wells, one as suction well and the other one as injection well. The suction well is normally located in an upstream direction to avoid an influence among each other. Beside the major advantage of forced convection in the open system, the authorities have really strict rules for building and operating an open system so that the dominating systems are the closed ones (VDI 4640 Part 1).

Closed-loop geothermal systems having major issues to cover peak loads. For conventional systems the transferred energy from or into the soil is barely affected by the flow rate. This is valid for stationary and transient operation points. For transient operation points a sudden change of the mass flow rate is considered. The limiting factor of the heat transfer problem is not the convective heat transfer in the pipe. It is the transfer between the soil and the heat transfer fluid inside the pipe. The significant effect of a varying flow rate is just the increase of mean temperature difference between soil and heat transfer fluid. Due to the required temperature difference in terms of technical applications this effect is limited. The major thermodynamic process in the ground is heat conduction. It is usually a slow mechanism of energy transfer. Therefore, closed loop geothermal system are mainly used for stationary or semi stationary applications. Required dynamic behavior is often achieved by huge storage tanks of the geothermal system. Especially for the purpose of geothermal assisted air conditioning, the capacity of conventional geothermal systems can be exceeded during peak loads. Despite the depth of the system the velocity of the groundwater the biggest influence of the transferred amount of energy of geothermal systems has. The convective flow along the heat exchanger increases the efficiency of a geothermal system significantly. Therefore, the performance of such systems can be significantly beneficial against heat exchangers at locations without groundwater flow. To counteract this drawback an artificial groundwater flow along the heat exchanger can be enforced for the near field of the system. For this purpose the principal of air sparging technology is used. It is a common method for decontamination of water saturated soils which uses an artificial groundwater flow to strip pollutants from the groundwater. This technique allows to provide highly dynamic and powerful geothermal systems at locations with no natural groundwater flow.

Ma and Grabe (2009b) introduced a new method to couple a forced convection with a closed system in case of no natural groundwater flow. The idea is to combine a borehole heat exchanger with a groundwater circulation technology. In this patented system the artificial ground water circulation is induced by an air sparging well. The driving force of this method is a difference in density of the surrounding water compared to the water air mixture inside the well. Ma and Grabe (2009b) numerically showed that this method can lead to a significant increase of efficiency and energy output. To prove and validated the numerical calculation a demonstrator and a test field was built to measure the heat transfer rate and behavior of GI-BHX in situ.

2. GAS INJECTION BOREHOLE HEAT EXCHANGER

Based on an ordinary double-U pipe BHX a gas injecting borehole heat exchanger (GI-BHX) is integrated in a well. The well is built with filter pipes about the whole depth of the water depth and is protected against silting up by a layer of filter gravel around the filter pipe. Above the water table solid pipes are used. Different to an ordinary BHX the borehole is not filled with grouting material. It is filled with groundwater like a well. Together with the heat exchanger pipes another tube is installed inside the well which will conduct the gas to the bottom of the well. The upper end of the GI-BHX is built like a well head. Figure 1 shows the schematic layout of the GI-BHX.

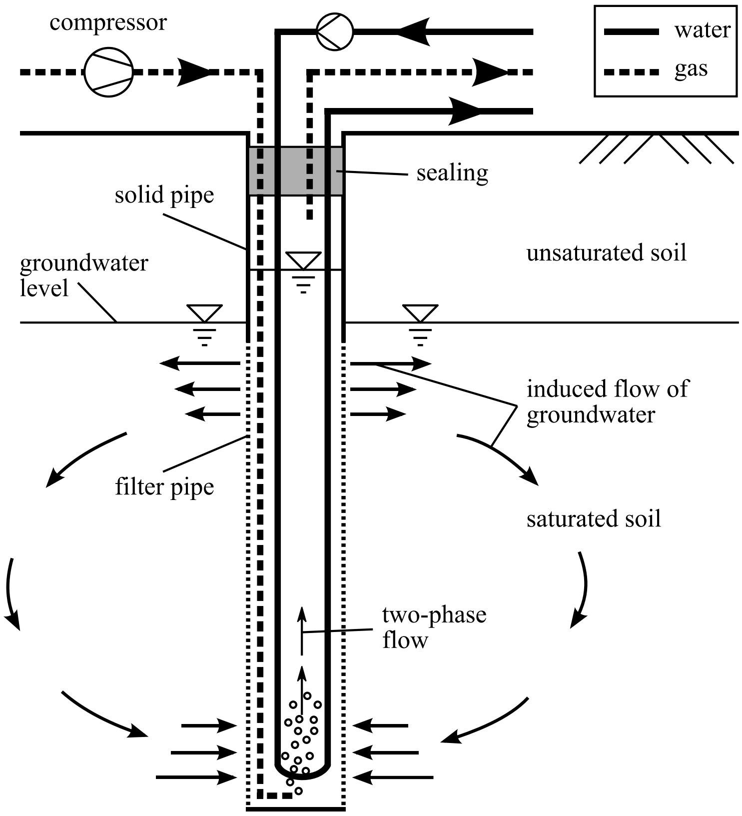

Figure 1: Layout and operating principal of the GI-BHX (Ma and Grabe 2009a).

In operation, preferably air is pumped with help of an air compressor through the air pipe to the lowest point of the GI-BHX. The air rises in the well and a mixture of water and air develops. This mixture has a lower density compared to the surrounding groundwater. To compensate the density difference, the water air mixture rises inside the well. Comparing the water pressures inside the well to the ones outside of the well shows that a higher pressure occurs in the upper part and a lower pressure in the lower part (see Figure 2). The resulting pressure difference is the driving force for an outflow in the upper part and an inflow in the lower part of the well. This leads to a circulating flow of groundwater along the GI-BHX with the following advantages:

- The upwards groundwater flow inside the well causes a convective energy transfer between the heat exchanger pipes and the groundwater.
- The groundwater flow improves the energy transfer between the groundwater and the soil in the near field of the GI-BHX.
- The soil volume which interacts with the GI-BHX is much bigger and therefore the capacity of the system is increased.

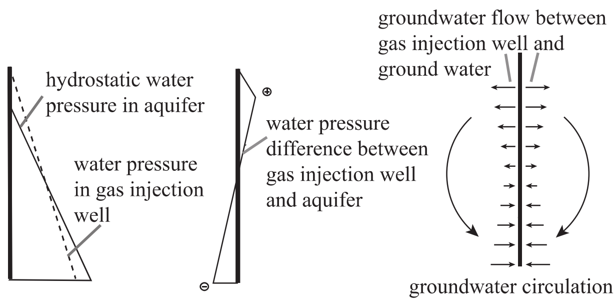

Figure 2: Water pressure and pressure difference between GI-BHX and groundwater (left and center), artificial ground water flow (right).

Numerical investigations about a GI-BHX by Ma and Grabe (2009b) show that a significant improvement of heat exchange can be achieved. The efficiency is mainly depending on the water permeability of the soil and the injected air flow rate. Theoretically, an increase up to 1600 % is possible (Ma and Grabe 2009b).

2.1 First Demonstrator

To investigate the potential of the GI-BHX, a demonstrator was built on a test field in Hamburg, Germany for the first time. The experimental setup consisted of the GI-BHX itself, three boreholes with four pore water pressure and temperature sensors each and a small container which contain required technical installation. For the location several criteria had to be taken into account. These included a soil volume as homogeneous as possible, no natural groundwater flow and a good permeability of the soil. The soil structure and the configuration of the boreholes are shown in Figure 3. The GI-BHX had a drilling depth of 21 m and an active heat exchanger length of 19 m. The borehole had a diameter of 324 mm and was filled with a clay plug and filter sand. Inside, a filter pipe with a diameter of 150 mm was installed which contained the heat exchanger tubes. It was built as a double U-tube 32 mm PE heat exchanger that was centered in the well with spacers.

Due to the high concentration of iron and manganese in the groundwater in the north of Germany, it was not possible to operate the GI-BHX with air. The induced oxygen would cause a chemical reaction with the iron and manganese which would clog the well and the filter would not be able to work any longer. The reduction of the permeability of the gravel around the well would cause a complete failure of the artificial groundwater flow. Therefore, a nitrogen generator was used for the tests. This guaranteed a long lasting operation without any problems concerning iron and manganese clogging. The aim of the investigation was to determine the potential of the technique as well as its properties. At location with less iron and manganese in the groundwater it is easily applicable to use a normal air compressor.

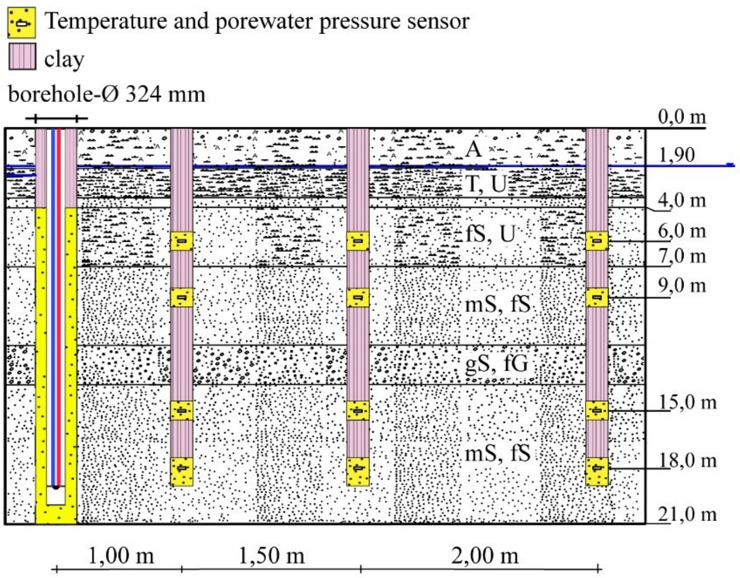

Figure 3: Soil structure and setup of the demonstrator.

To determine the temperature and pressure distribution in the near field of the heat exchanger three boreholes were drilled and equipped with four pore water and temperature sensors each. The position of the sensors was chosen to get information as detailed as possible about the pressure and temperature changes in the soil and the groundwater.

To investigate the energy transfer of the GI-BHX in the ground a compact temperature control unit was constructed which was capable of providing a constant temperature for the inlet of the GI-BHX. To keep the system simple it was just possible to heat the transfer fluid. This mode simulated summer operation. The investigation of winter mode with cooling the heat transfer fluid inside the heat exchanger pipes was furthermore not allowed due to regulation by the authorities to use no anti-freeze because of the missing grouting material around the double U-tube heat exchanger. The measurement equipment for the heat exchanger itself contained a temperature sensor in the inlet and outlet as well as a volume flow sensor. The cycle was driven by a high efficient pump. The air injection system was controlled by a temperature, pressure und volume flow sensor.

2.2 Measurement Results from Demonstrator

To evaluate the performance of the GI-BHX without air injection was investigated first in terms of providing a benchmark. Subsequently, experiments were carried out with different air injection rates. All measurements were done with a constant flow rate of the borehole heat exchanger of 17 l/min and a constant inlet temperature of approximately 20°C.

Figure 4 shows the results of the first test without air injection for a period of 24 days. At the beginning it was possible to transfer 800 W into the soil. Within the first six days a stationary operation point was reached. The BI-BHX was capable of a heat transfer rate of 600 W continuously. The energy transfer into the groundwater is just done by natural heat convection and conduction.

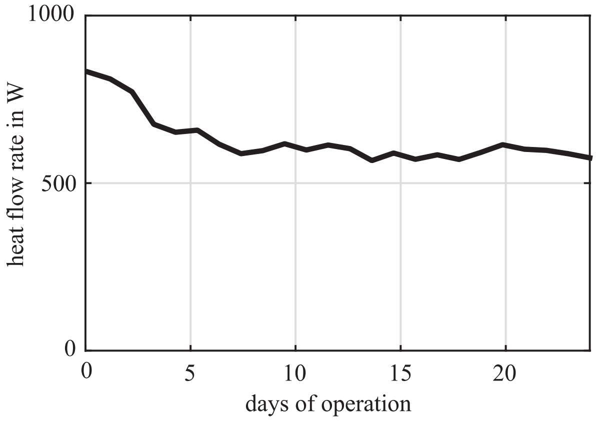

Figure 4: Heat flow rate of GI-BHX without gas injection at fixed operation point.

Figure 5 shows the results of the first test with gas injection. The injection rate was set to 20 l/min. A significant increase of the heat transfer is recognizable. The start value of 3,500 W decreased within 15 days to a value of 1,500 W. The slightly enhanced air injection rate within the first four days is caused by an error of the air supply controller and should not have a considerable influence. The performance drop between day 13 and day 15 can not be explained. However, the results show that gas injection technology increased the performance of the borehole heat exchanger by a factor of 2.5 over 30 days and even about a factor of 5 for a short time. After 33 days of operation the gas injection rate was increased to 30 l/min. The performance raised directly from the moment the air injection rate was changed. The heat transfer improved up to 2,500W. For the investigated period the output drops until 2,000 W. The results of this tests are showing a surprising behavior of the GI-BHX. Ordinary BHX are having a very weak dynamic response to peak loads or load changes. The investigated GI-BHX responded within a few minutes to the changing gas injection rate and showed a significant change of performance. That allows an application of this system for transient and dynamically changing conditions.

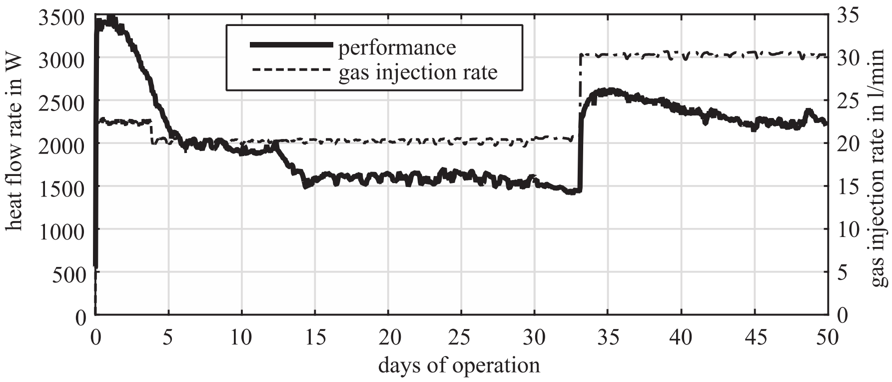

Figure 5: Heat flow rate of GI-BHX for varying gas injection rates.

Beside the prove of function with help of comparing the heat transfer rates and varying the air injection rates it was also possible to show the effect of groundwater flow using pore water pressure sensors. The pressure difference between the closes to the fares sensor are shown in Figure 6 for the upper und lowest sensor row. The distance between the sensors in one row is 3.5 m. To clarify the figure the gas injection rate is also plotted. It is obvious that the pore pressure increases in the upper sensor row and decreases in the lower one for starting or increasing the air injection. The pressure change for the upper row is higher than for the lower one due to the clay layer above which reduces the water volume to interact with. These results confirm the theoretical expectation of the mechanism of gas injection.

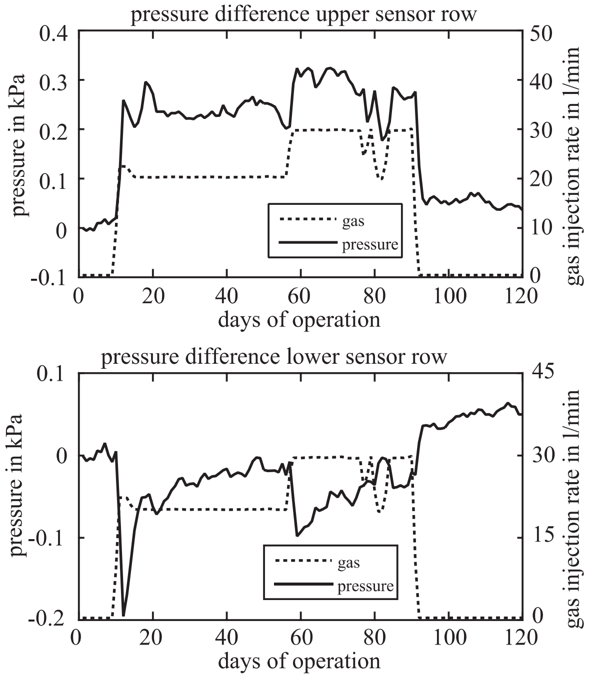

Figure 6: Change of Pore water pressure depending on gas injection rate.

2.2 Conclusion of Demonstrator Tests

The first test of a GI-BHX showed that the system is capable of increasing the heat transfer significantly by a factor of 2 to 5 compared to operation without gas injection. Furthermore, the dynamic behavior of a GI-BHX was discovered that allows a geothermal system to adapt the performance to the demand. This offers more applications and the usage with fluctuating energy demands.

3. EXPERIMENTAL STUDY

In the following the test facility for the gas injection test field is described and experimental data are presented. Based on the very promising results of the demonstrator a large scale test field was built to investigate the behavior, geometry and parameters of a GI-BHX setups in detail.

The scope of this paper is not to analyze the efficiency of the system regarding the gas injection. This will be done in future papers. The quantification of energy demand for the gas injection for GI-BHX in a test field like presented is not trivial and therefore needs further investigation. The purpose of this paper is to show results and present the behavior and thermal performance of GI-BHX and compare the different types.

3.1 Test Facility

A new test field with several GI-BHX was built in the east of Hamburg approximately 15 km away for the main campus of Hamburg University of Technology. Due to lack of space, it was not possible to build the field on the campus or even integrate it into the campus infrastructure. On the site seven GI-BHX and five BHX has been built. The GI-BHX having a length of the heat exchanger of 28 m and the BHX having a length of 29 m and are backfilled with thermal improved grouting material. The seven GI-BHX are divided in four types (A, B, C, D). Type A and B are equipped with double U-tube heat exchangers with a pipe diameter of 32 mm, type C and D are equipped with coaxial heat exchangers with an outer diameter of 63 mm. Type A and C are installed with filter pipes for the whole length of groundwater level, whereas type B and D are only having filter pipes in the first and last 4 m of length. This should investigate the effect of channeling the artificial groundwater flow in the well and increasing the flow velocity. The BHX are named as type E. Due to the remote location it is necessary to provide heating and cooling devices for the geothermal field because no consumers, heat sources or heat sinks are present. To supply the heat exchangers the hydraulic, pneumatic and measurement equipment is installed in three 20ft. and one 10ft. container. In Figure 7 on the left a satellite image of the test field is shown with the location of the different types of geothermal heat exchangers as well as the 4 containers in the upper left corner, on the right side type A and D of the GI-BHX are shown with the different installation of filter pipes and heat exchanger types.

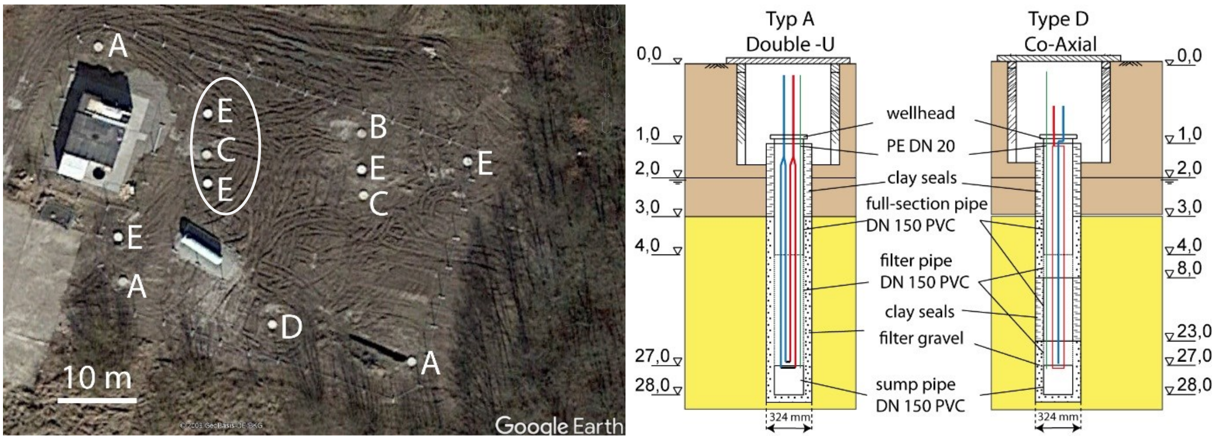

Figure 7: Satellite image of test field (left) (by Google Earth), GI-BHX type A and D (right).

For the test field the following soil structure is given. For the first 2 m a mixture of artificial infill with demolition waste and native soil is present. From 2 m to 3.5 m a layer of clay is followed by a layer of fine sands up to 11 m. From 11 m to 30 m medium sands and gravel are existent. At approximately 2 m the groundwater level is present. There is no significant natural groundwater flow at the location.

For a wide variance of experiments on the test field heating and cooling devices were installed. To provide hot and cold water for the whole year and to simulate any possible operation point for cooling demand a 40 kW chiller was integrated in the system that supplies a 2000 l cold water storage tank. For the hot water supply a 35 kW condensing combi boiler was installed that uses liquid gas. The hot water system is also includes a 2000 l hot water tank. The cold water tank can be cooled down to 2 °C and the hot water tank can be heated up to 45 °C. Each geothermal heat exchanger is connected with the help of mixing valves for (GI-)BHX hydraulic circuit to the hot and cold storage and is capable to set any temperature between the possible ranges given by the tanks. The volume flow of each heat exchanger is controlled by its own pump and measured by a volume flow sensor. To quantify the temperature difference between the inlet and outlet flow as precise as possible the temperature sensors are located directly in the inlet and outlet point of the GI-(BHX) to avoid any influence of the feed pipes or weather changes. Based on the temperature difference and the volume flow the heat transfer between the heat exchanger and the soil can be determine and evaluated.

For the gas supply of the GI-BHX a nitrogen generator was installed. This was necessary due to the high iron and manganese concentration in the groundwater at the drilling location and is beneficial for research purposes. The system is capable to provide 150 l/min of nitrogen with a purity of 99.5 %. Using nitrogen for gas injection ensures that no clogging occurs.

Some impressions of the installation are shown in Figure 8.

Figure 8: Hydraulic system, nitrogen supply, storage tanks.

3.2 Performance Investigation of the Geothermal System

To observe the performance of the different types of GI-BHX, several sensors are used at each site. Table 1 gives an overview of relevant measurement devices and corresponding measurement uncertainties to evaluate the performance of the geothermal system. The heat flow rate for all heat exchangers is calculated as given in Eq. (1), with $\dot{Q}$ as heat transfer rate, ρ the density of the heat transfer fluid, c_p the specific heat capacity, $\dot{V}$ the volume flow rate of the heat transfer fluid, ϑ_{in} the inlet and ϑ_{out} the outlet temperature.

$$\dot{Q} = \rho \cdot \dot{V} \cdot c_p \cdot (\vartheta_{in} - \vartheta_{out}) \qquad (1)$$

Table 1: Measurement devices and corresponding measurement uncertainties.

Measured value		Sensor type / measuring principle	Measurement uncertainty
Water temperature	ϑ	PT1000 (accuracy class W0.1)	$\pm 1/3 \cdot (0.3 + 0.005 \cdot \vartheta)$℃
Volume flow (water)	$\dot{V}$	Electromagnetic flow meter	$\pm 0.5\%$ of reading $\pm$ 2 mm/s

3.3 Measurment Results

Experimental results presented in this section are based on measurement data from first tests of the geothermal testing field for GI-BHX. The different types of GI-BHX are investigated and characteristics in operation and reaction are described.

3.3.1 Comparison of Type A, B, C and D

To analyze and evaluate the behavior of the different GI-BHX types for the first time a benchmark test has been done. The control settings for all BHX was the same. The inlet temperature was set to 20 °C and the flow rate was 16 l/min. For the gas injection phase a gas volume flow of 10 l/min was chosen. For steady state condition the GI-BHX were operated for several days without gas injection to mark the reference value (no gas). After gas injection started (peak value) it took 11 days that all systems settle to steady state. As shown in Figure 9 the four types of GI-BHX show very different behavior. For the first stage with no gas injection types A and B show a higher performance then types C and D. After switching on the gas injection the heat flow rate of all types increases significantly. Type A and B shows an increase of heat transfer by a factor of 2.8. The types C and D are capable of increasing the heat transfer with a factor of approximately 2. Over time a steady state condition developed with decreased heat flow rate compared to the peak case. For GI-BHX type A heat transfer is increased by a factor of 1.8 compared to no gas injection and is therefore the most powerful GI-BHX in this comparison. Type C still is able to keep the heat transfer 1.6 times higher than without gas injection. Type B and D are almost equal with a factor of 1.4.

Comparing the results of this test it is shown that a double U-pipe heat exchanger like installed in type A and B has a much higher performance compared to a coaxial heat exchanger. The explanation for this fact is the surface area of the system. It is twice as large for the double U-pipe heat exchanger as for the coaxial one. This ratio is also evident in the experimental results. The values are almost exactly twice as high for these types. Comparing the GI-BHX with the filter line over the whole length with the ones which just having the filter pipes in the upper and lower region for this test the differences are negligible. The type A and C with the longer filter line are showing slightly higher heat transfer rates but further investigations are necessary to have convenient results.

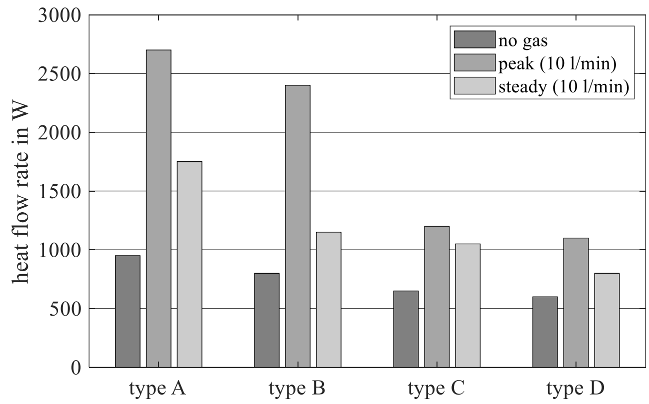

Figure 9: Heat flow rate of different GI-BHX for different boundary conditions.

3.3.2 Comparison of GI-BHX type A and B with different gas injection rates (full filter pipe to section filter pipe)

To investigate the influence of the length of filter line and the impact of varying gas injection rates the GI-BHX type A and B are compared. Both heat exchangers were provided with the same inlet temperature and inlet volume flow as well as the same gas injection rate. The water inlet temperature was 22 °C and the flow rate was 16 l/min. The test was separated in 4 stages, each lasted for 7 days with constant parameters. For each stage the gas injection rate was raised from 0 l/min to 15 l/min with 5 l/min steps. The results are shown in Figure 10.

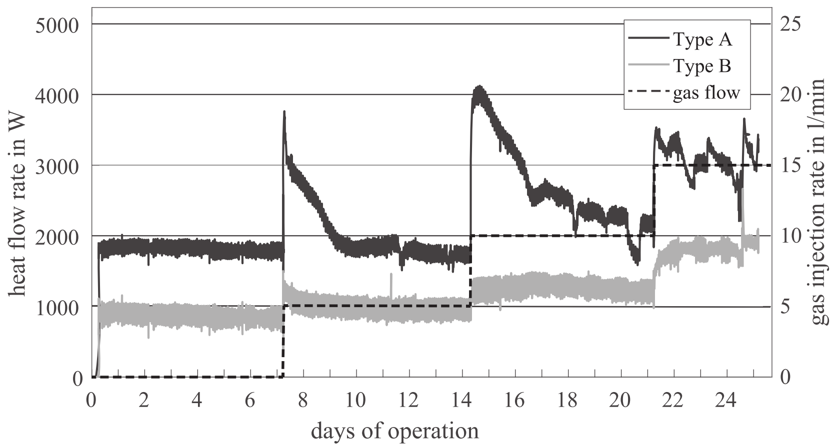

Figure 10: Heat transfer rate of type A and B GI-BHX by varying gas injection rate.

The heat transfer rate for stage 1 without gas injection shows a significant difference between the two GI-BHX. The performance of type A is twice as high. The initial value for type A is 1800 W and for type B 900 W. Starting with gas injection in stage 2 with a flow rate of 5 l/min heat transfer rate of type A rises for 2 days up to 3000 W and settled than back to the previous level. The influence on the type B GI-BHX is very low in terms of peak load performance but shows a slightly higher steady state performance over the investigated period of 1000 W. Increasing the gas injection rate to 10 l/min the type A is capable of improving the heat transfer to a peak load of 4000 W which decreased within 7 days to 2200 W. The type B GI-BHX shows no peak load characteristics but enhanced the performance to 1200 W. For the last stage 4 with a gas injection rate of 15 l/min the heat transfer rate of type A can increased again to a peak load of 3400 W and settled to 3000 W over time. For the type B it is the biggest improvement of performance to a value of 1800 W.

Comparing the results of this experiment it is shown that the type A GI-BHX has much higher performance values and shows a far better dynamic reaction to the change of the gas injection flow whereas the type B system seems to show not a real peak load behavior und needs a minimum gas injection rate of approximately 15 l/min to overcome some flow resistant to benefit from the artificial groundwater flow. Also the type A shows an almost stable output with the highest gas flow rate. The fluctuations in the heat transfer rate of type A were caused by some control trouble with the gas injection of this system but should not affect the overall performance. To sum up this experiment an increase of the gas flow rate leads to a significant increase of heat transfer rate of GI-BHX type A and can be repeated while further increasing the gas flow rate. For the type B system the overall performance is much lower and shows not the expected channeling effect of the reduced filter line to even increase the heat transfer rate.

3.3.3 Influence of GI-BHX to BHX in the near field

While planning the layout of the test field the position of each BHX or GI-BHX was considered with a number of experiments taken into account. Therefore, a configuration was planned to investigate the influence of a GI-BHX on surrounding BHX. It is marked in Figure 7 with the white ellipse. A GI-BHX is between two BHX which have a distance of 3 m and 5 m to the GI-BHX. The influence of the artificial groundwater flow should be measured on the performance of the BHX. The results of this experiment are shown in Figure 11. To achieve this setting after a certain time the gas injection of the GI-BHX was activated without any thermal load to the GI-BHX. This should analyze the pure influence of the groundwater to the closed BHX systems. To have a reference the BHX far away from this set up in the upper right corner of the test field was controlled the same way like the BHX in this experiment. To eliminate any transient or fluctuation influence all 3 BHX were operated for 3 weeks with fixed settings of an inlet temperature of 25 °C and a volume flow of 20 l/min. All geothermal systems behave the same and settle from a heat transfer rate of 2300 W in the beginning to a value of 1400 W after 3 weeks. After this prove that all BHX showing same results, the experiment for investigation of the influence of artificial groundwater flow to surrounding BHX started with a gas flow rate of 17 l/min. For the investigated period of 2.5 weeks with gas injection no influence on the BHX can be identified. Thus, the induced groundwater flow is not effecting the heat exchangers. This could be caused by a very slow groundwater flow or that the groundwater current is not spreading that far in the surrounded soil. Further investigations will be done on the long term behavior of the groundwater flow to close BHX system.

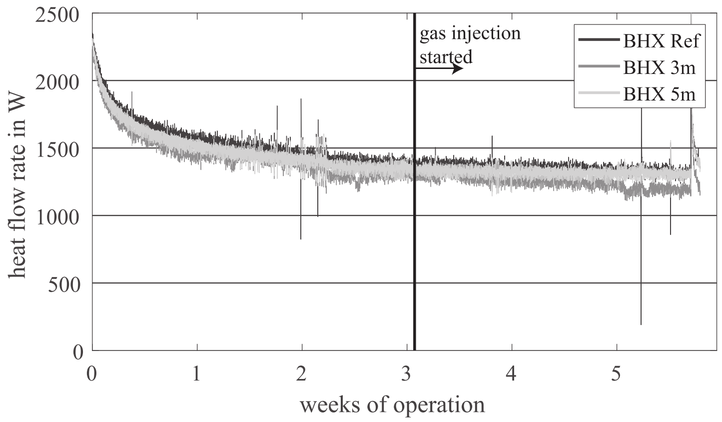

Figure 11: Influence of artificial groundwater flow on nearby BHX.

4. CONCLUSION

The presented experimental study shows a possible way to improve the performance of BHX and offers a possibility to add a dynamic behavior to closed-loop geothermal systems. The main results can be summarized as follows.

- It is possible to create an artificial groundwater flow along a geothermal heat exchanger by gas injection.
- The performance of a borehole heat-exchanger can be increased significantly by using gas injection technique up to a factor of 2 to 5. This avoids drilling very deep or reducing the total number of boreholes.
- By adding gas injection into a geothermal system a dynamic behavior and a further control value is added to the system. This enhanced the number of possible applications.
- Further investigations have to be done to evaluate the energy demand for the gas injection and further experimental test are required to determine the influence of GI-BHX to BHX and their long term performance

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