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GeoFit: Experimental investigations and numerical validation of shallow spiral collectors as a basis for development of a design tool for geothermal retrofitting of existing buildings

Stephan Kling[1], Edith Haslinger[1], Michael Lauermann[1], Henk Witte[2], Christoph Reichl[1], Alexander Steurer[1], Constantin Dörr[1], Dragisa Pantelic[1], Robin Friedrich[1]

1: AIT Austrian Institute of Technology. Giefinggasse 4, 1210 Vienna, Austria. Corresponding author: stephan.kling@ait.ac.at

2: Groenholland Geo-energysystems BV, Valschermkade 26, 1059CD Amsterdam, The Netherlands.

stephan.kling@ait.ac.at

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ABSTRACT

The H2020 GEOFIT (grant no. 792210) project will implement and demonstrate easy-to-install and economical geothermal systems in combination with heat pumps for energy-efficient building retrofits at five pilot sites across Europe - a historic building (ITA), a school (ESP), an indoor swimming pool (IRL), an office building (FRA) and a single-family house (IRL) (GEOFIT,2018).

Heat pump tests and experimental laboratory tests with shallow geothermal heat collector types are carried out in climate chambers at the AIT. Material data of different soil types are determined in the thermophysics laboratory. Furthermore, CFD simulations of the conducted experiments are calculated with ANSYS Fluent. All this provides data and know-how for the development of a design tool for ground collector configurations such as helices and slinky loops, which are particularly relevant for building retrofits in GEOFIT.

Experimental work focused on near-surface spiral geothermal heat exchanger configurations that can be installed at a maximum depth of five metres. Real-scale experiments were carried out for vertically oriented spiral collectors (helix) in real soil. One objective was to develop a measurement concept in the laboratory environment to create the framework for a reliable database. This database is used as a basis for the further development or new development of engineering design tools.

Distributed resistance temperature sensors and a fibre-optic temperature measurement system (DTS) were used. The moisture content of the soil was recorded using soil moisture sensors. A heat flow was conditioned by means of a helix shaped electric heating cable in a 1m³ cuboid soil container. The measurements were carried out in a climate chamber at a defined constant temperature of 10 °C. The evaluation of the transient response behaviour is spatially resolved. This results in coordinate-related temperature points, which describe temperature gradients in all axes of the container over time.

Three different types of soil were investigated. The temperature behaviour of humus soil, sand and a mixture of these was investigated experimentally in smaller experiments and the material data such as heat capacity, thermal conductivity and density were determined thermophysically in the laboratory. Based on this data, a CFD model was developed which can be used to modify the geometry parameters of the helix.

1. INTRODUCTION

This Within the EU program “Horizon 2020”, the project “GEOFIT” was started in May 2018. GEOFIT is an international project about geothermal retrofitting of buildings, cofounded by the EU Commission in the framework of LCE-17-2017—“Easier to install and more efficient geothermal systems for retrofitting buildings”. Geothermal systems have been considered some of the most efficient and renewable technologies to attain sustainability goals for existing buildings. In this line, the H2020-project GEOFIT does not only consider the main geothermal concepts, such as heat exchangers and ground source heat pumps, but also their integration with heating and cooling components. When undertaking building retrofitting, low-intervention and non-invasive techniques are commonly re-quired. The limited space available, and the risk of building instabilities and structural damages due to drilling or geological limitations demand specific types of HEX configurations, in general with low-depth drilling. GEOFIT will optimize a novel generation of vertical and horizontal closed-loop systems, aimed to be installed at a low depth maximum of five meters. These systems will be optimized by the project team and integrated with other enhanced geothermal system components like the heat pump, allowing flexibility in the installation procedure. Horizontal closed-loop heat exchangers will be used, suitable for the use of trenchless drilling approaches performed by a comprehensive drilling plan (CDP). This allows the installation of horizontal heat exchangers with minimum disturbance, smaller diameters, and the ability to make use of the limited geothermal potentials associated with existing buildings and infrastructure.

The main type of ground source heat pump systems (GSHP) in Europe uses vertical borehole heat exchangers (BHE). The installation depths of these types range be-tween 100 and 300m, where the undisturbed ground temperature offers a robust heat source for heat pumps for up to 50 years and longer. Currently, this is a proven technology, used for more than 30 years in hundreds of thousands of systems worldwide (Sanner, 2003).

Between 2006 and 2018, approx. 100,000 GSHP systems were installed annually throughout Europe. Although the annual number is stable, the average capacity is increasing. Applications are becoming more commercial and industrial (Nowak and Westring 2019).

GSHP systems use earth-coupled, ground-source, and water-source heat ex-changer types. These types are either used in open- or closed-loop concepts. Closed-loop GSHP systems consist of one or more heat pumps, a ground heat ex-changer, circulation pumps and a heating or cooling system to distribute the energy where it is needed. In this paper, only closed-loop systems and near-surface GHEX types up to 5 m depth are discussed. Figure 1 shows the shares of installed GHEX types from the years 2010–2018. The statistics show only borehole GHEX; therefore, horizontal flat collectors are excluded. Only 13% are the spiral GHEX type.

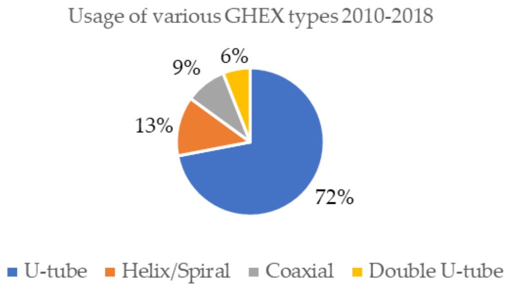

Figure 1: Usage of various GHEX types, numbers adapted from Javadi et al 2019

Design tools and software for GHEX, such as Earth Energy Designer EED, Ground Loop Heat Exchanger Design Software GHLEPRO, GLD, etc., exist for planning geo-thermal systems and design of vertical borehole heat exchanger types. Earth basket and slinky type GHEX are not common or not fully parameterizable in these tools regarding all thermodynamic parameters. To assist in develop such a design tool for slinky and earth basket HEX, experimental data describing the thermal characteristics are investigated in this paper.

In recent years there have been several investigations and studies on the thermal behavior of spiral GHEX. This includes numerical, experimental, analytical, and optimizing methods. As shown in Figure 2, 50% of all studies were performed numerically with simulation software. All methods consider geometry, material, operating fluid, and installation depth in the soil. The aim of this paper is to create the basis for a method to dimension vertical spiral collectors more precisely for design purposes. The difference to the previous studies found during this research is that no hydraulic collector model with optional heat pump is used, but an electric heating cable. In addition, the material properties of the soil types are analyzed in more detail. The combination provides a more rapid and accurate simulation by means of CFD.

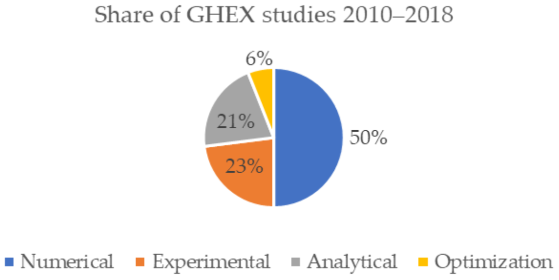

Figure 2: Share of GHEX studies by type, numbers adapted from Javadi et al 2019

In this paper, only vertical spiral GHEX (helix) are discussed and this type was used in the laboratory experiments.

2. MATERIALS AND METHODS

For the creation of an experimental database, vertical and horizontal helix and also slinky-loop geometries in combination of three different soil types were discussed. This paper comprises the work on one of these variants, namely vertical helix, sand, soil, and heat injection mode. Within these basic variants, the geometry like loop pitch, diameter, as well as different soil temperatures were supposed to be tested. The use of an electric heating cable facilitates the control of energy input. Electrical energy can be controlled more precisely and faster than hydraulic piping system. Based on the data acquired with these measurements, CFD simulations are to be developed. Since experimental tests are time-consuming and cost-intensive, validated CFD simulations offer a wide range of variations in terms of material parameters and geometries.

2.1 Materials

The experiment was designed to be set up in a 1.1 m3 HD-PE container (L × W × H 1130 × 725 × 1350 mm), which was situated in a climatic chamber (Figure 3). Constant soil parameters can be realised as boundary conditions via the climate chamber controlling. A HD-PE plastic grid net with a mesh size of 30 × 25 mm and a total height of 1200 mm acts as a support structure for the geometry of the heating cable (not depicted). To measure temperature gradients in all axes (XYZ) and to determine the moisture content of the soil, a measuring setup based on PT1000 sensors, FDR-based moisture sensors, and a DTS system was designed. Due to symmetry, only one quarter, shown in pink in Figure 3, was monitored. To reduce the influence of the sensors on the soil concerning thermal conductivity, a DTS system (Sensortran 5100A) was used. Such systems are often used for vertical boreholes and in the oil industry for monitoring piping networks. DTS systems provide a temperature profile along a fiber-optic cable. This has the advantage of a higher density of data points and not having to install individual sensors, including supply lines.

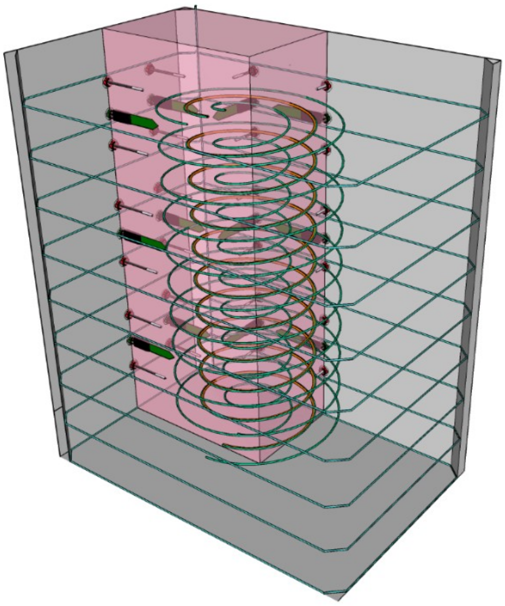

Figure 3: 3D rendering of the experiment setup container

Figure 4 shows a more detailed view of the arrangement of the helix (orange) and the fibre optic cables in green in the inner and outer area which were installed parallel to the helix in order to measure the temperature gradient.

Figure 5 shows the physical structure and part of the container. The iron rods and the wooden construction stabilised the container during the filling process in order to maintain the geometry. These were removed at the end of the construction.

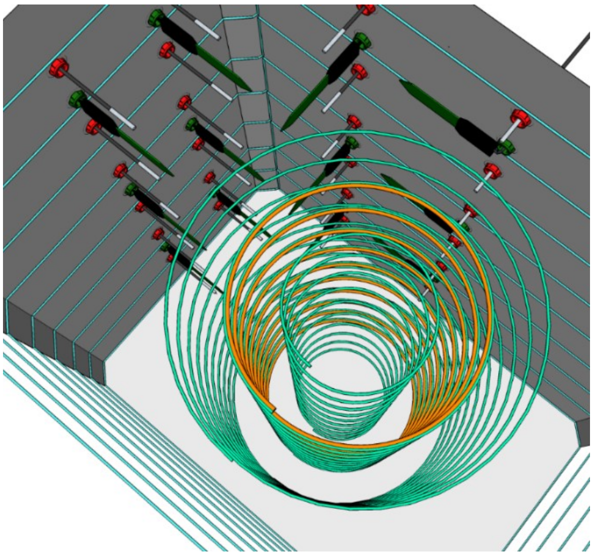

Figure 4: Isometric top view of the rendering

Figure 5: Physical model of the experiment

2.2 Methods

A central system based on LabView was developed for control and data acquisition (Figure 6). There, all signals of the sensors except the DTS can be processed and analog in- and outputs can be controlled. PT1000 and SMT100 moisture sensors were used to monitor the data inside of a quarter of the container. A DTS fiber-optic cable was mounted next to the heating cable, in two different soil layers parallel in- and out-side to the helix and next to the container inner surface to define a boundary condition. Raw data of all sensors and temperature and moisture values were logged. The heating cable was regulated by a digital SCR voltage controller. For monitoring and measuring the electric parameters as voltage, current, and power an Agilent 34970A connected to LabView was used.

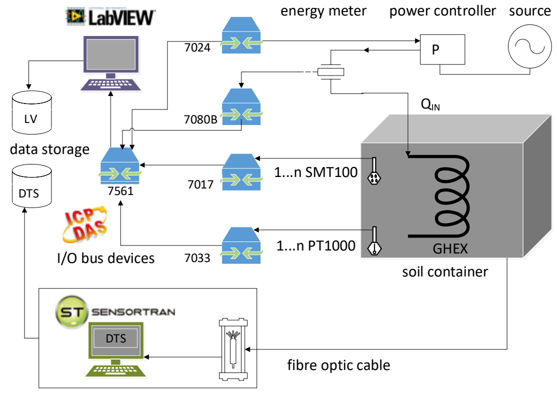

Figure 6: Data acquisition scheme

Figure 7 depicts the defined coordinate system inside the container related to the DTS fiber-optic cable. The datapoint resolution per meter of fiber-optic cable is 2 (2/m). To double the amount of data points to 4/m, the fiber-optic cable was installed bi-directionally. This results on a data point every 0.25 m.

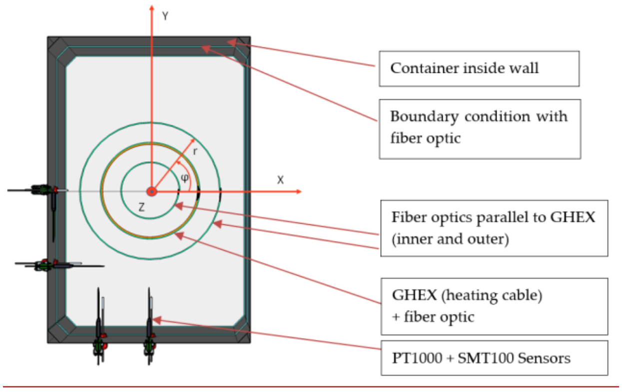

Figure 7: Coordinate system of the container

This results in the following Cartesian data points as shown in Figure 8. “Basket” refers to the respective support grid structures where the DTS cable is installed in the same pitch level as the heating cable. The innermost basket (blue) has the smallest number of data points. The basket with the heating cable (middle basket) is shown in orange, and the outer basket, shown in green, has the largest diameter.

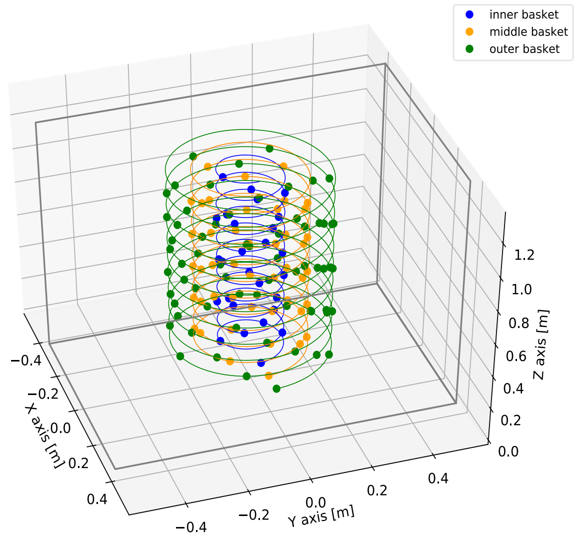

Figure 8: DTS data points in container

3. RESULTS

The following results show a comparison of dry sand and untreated soil with the same helix geometries. A specific heating power of the spiral collector (helix) of 10 W/m were used in each case. In combination with determined material data, these provided the basis for the development of CFD simulations that are not discussed in this paper.

The results are based on the following experiment settings:

<u>Geometry of helix:</u>
h = 1 m, d = 0.35 m, p = 0.1 m
<u>Specific heating rate:</u>
10 W/m–113.1 W total
<u>Soil type:</u>
Sand (Figure 9) and soil (Figure 10); untreated H2O content
<u>Ambient temperature:</u>
10 °C as starting condition

Figure 9 and Figure 10 show the comparison between sand and soil for a measurement duration of 140 h. The aim was to achieve a quasi-stationary state in the climate chamber in order to later model the CFD calculations in a stationary state also. Due to the duration of the measurement, this was a challenge and proved to be impossible. The three colored curves represent the bidirectional DTS sensor lines per basket. In correlation to Figure 9, blue represents the inner basket (d = 0.2 m), orange the helix heating cable (d = 0.35 m), and green the outer basket (d = 0.5 m). The y-axis depicts the height in the container and the x-axis the temperature of all DTS data points. Additionally, the temperature curves from the start time in 24 h steps to the end time of 140 h are shown. The DTS points of the boundary condition (inside container wall) are not shown, as these represent the temperature of 10 °C approximately constantly over the entire measurement.

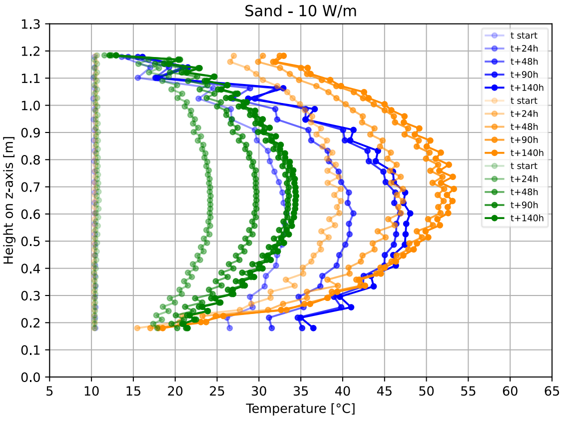

Figure 9: Temporal evolution of Temperature in Sand

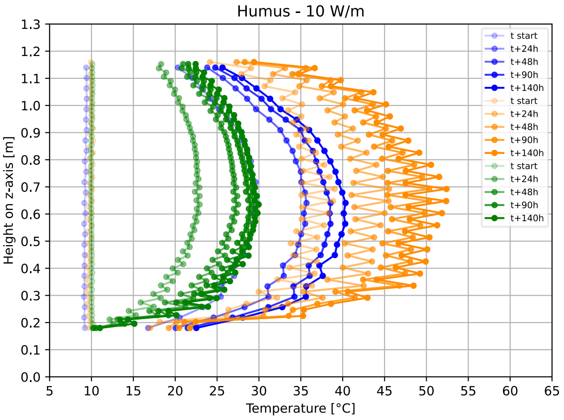

Figure 10: Temporal evolution of Temperature soil/humus

Figure 11 and 12 show all temperature data points (DTS + PT100) in the form of a scatterplot at time t = 140 h. As expected, the temperature distribution reached its maximum in the center. On the left (Figure 13a) the experiment with dry sand is shown, on the right (Figure 13b) the one with untreated soil. Due to the lower heat conductivity properties of the dry sand, temperatures in the center are slightly higher than in the moist soil.

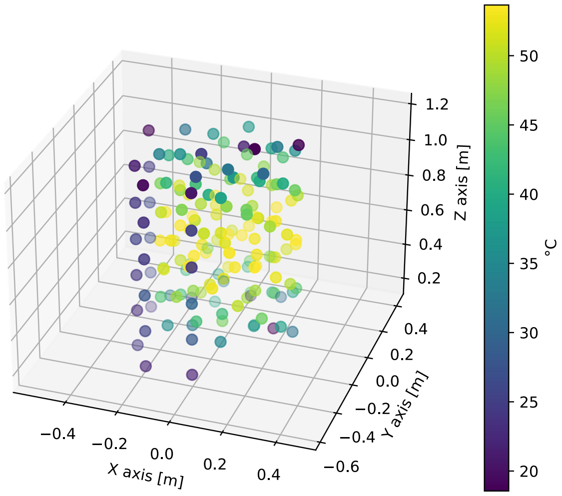

Figure 11: Scatter plot sand

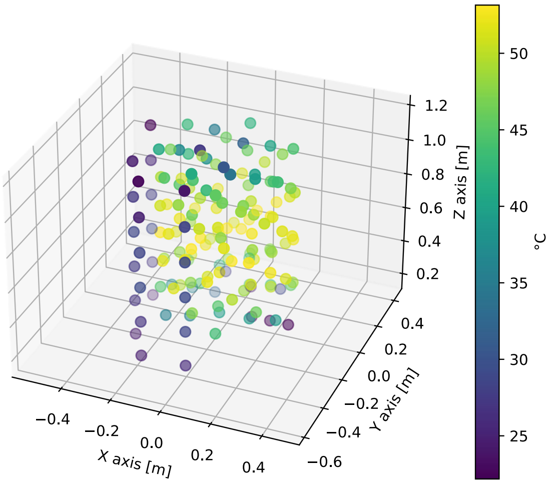

Figure 12: Scatter plot soil/humus

The humidity sensors (SMT100) did not provide any useful data during the experiments, as the values fluctuated strongly over the entire series of measurements, most likely due to a calibration error. To determine the moisture content of the soil, which has a significant influence on the material data and thus the results, material samples were taken in situ at various positions before and after the experiment. These were then measured using the mass thermogravimetry method.

Parallel to the experimental measurements, a CFD model was developed. The geometry and properties of the heating cable were defined exactly according to the physical test setup. The geometry model, from which the simulation mesh is created, was developed in form of a parameter construction in ANSYS Workbench ©. Thus, changes in the geometry can be made efficiently later to study the behaviour of different helix pitches, helix diameters, and box geometries in detail. Figure 13 and Figure 14shows the result of a transient simulation at start and end time during the injection of energy into the system.

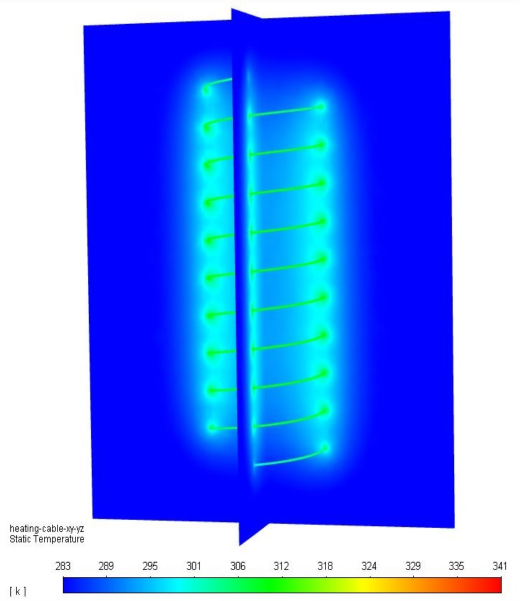

Figure 13: CFD simulation at t_start

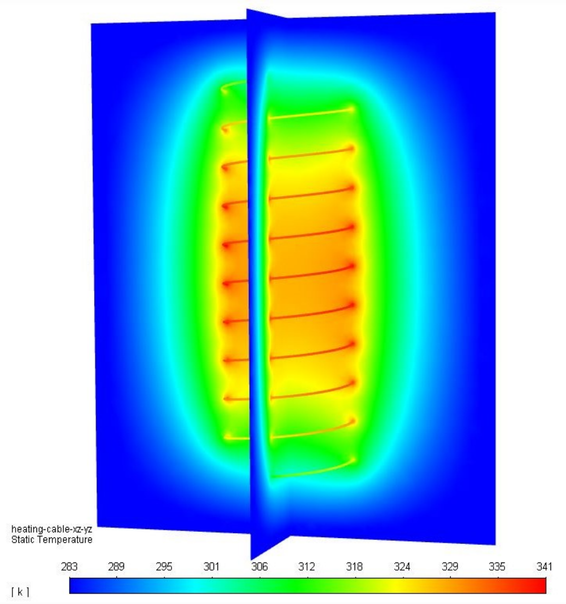

Figure 14: CFD simulation at t_140h

3. SUMMARY AND CONCLUSION

In order to characterize shallow GHEX, experimental tests were carried out in a laboratory environment. The aim was the measurement of a vertical helix (spiral) GHEX in a container of 1 m³ filled with sand and soil. The implementation was realized by developing a measurement concept. This concept includes the measurement of temperature and moisture content of the sediment in different layers to record all temperature gradients over a certain time. In addition, a data evaluation script was programmed, which stores all data in a database and allows a detailed numerical and graphical evaluation at any time of the measurements. To simulate constant boundary conditions or undisturbed soil, the tests were carried out in a climatic chamber at constant environmental parameters. A total of seven measurements were carried out. Only three of them resulted in usable data sets due to technical problems on the power controller and the DTS system. Two of them are shown in this paper.

A combination of experimental results and CFD simulations will be used to characterize various complex geometries of GHEX (Witte et al 2022). The results can be used for the improvement or new development of an engineering tool for the design and dimensioning of spiral GHEX in combination with the heat pump system, since only a few practical and reliable calculation exist to date. The design of a new engineering tool for spiral GHEX will help to increase the share of these collector types, which are especially suitable for geothermal retrofitting.

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