

Geothermal Energy Used in Buildings Heating and Cooling

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ABSTRACT

Globally buildings are responsible for approximately 40% of the total world annual energy consumption. Most of this energy is for the provision of lighting, heating, cooling and air conditioning. An increase in awareness of the environmental impact of CO₂, NO_x and CFCs emissions triggered a renewed interest in environmentally friendly cooling and heating technologies. Under the 1997 Protocol, governments agreed to phase out chemicals used as refrigerants that have the potential to destroy stratospheric ozone. It was therefore considered desirable to reduce energy consumption in order to decrease the rate of depletion of world energy reserves as well as the pollution to the environment. One way of reducing building energy consumption is to design buildings, which are more efficient in their use of energy for heating, lighting, cooling and ventilation. Passive measures, particularly natural or hybrid ventilation rather than air-conditioning, can dramatically reduce primary energy consumption. Therefore, promoting innovative renewable energy applications including the ground source energy may contribute to preservation of the ecosystem by reducing emissions at local and global levels. This will also contribute to the amelioration of environmental conditions by replacing conventional fuels with renewable energies that produce no air pollution or the Greenhouse Gases (GHGs). An approach is needed to integrate renewable energies in a way to achieve high building performance standards. However, because renewable energy sources are stochastic and geographically diffuse, their ability to match demand is determined by the adoption of one of the following two approaches: The utilisation of a capture area greater than that occupied by the community to be supplied, or the reduction of the community's energy demands to a level commensurate with the locally available renewable resources. Ground Source Heat Pump (GSHP) systems (also referred to as geothermal heat pump systems, earth-energy systems and GeoExchange systems) have received considerable attention in recent decades as an alternative energy source for residential and commercial space heating and cooling applications. The GSHP applications are one of three categories of geothermal energy resources as defined by ASHRAE and include high-temperature (>150° C) for electric power production, intermediate temperature (<150° C) for direct-use applications and GSHP applications generally (<32° C). The GSHP applications are distinguished from the others by the fact that they operate at relatively low temperatures.

Keywords: Renewable energy technology; Ground source heat pump; Built environment

INTRODUCTION

In recent years, Ground Source Heat Pumps (GSHPs) have been used increasingly for space heating and air-conditioning of buildings and for the purpose of energy saving and emission reduction. In these systems, Borehole Heat Exchangers (BHEs) are usually used to exchange heat with the underground

environment. It is accepted that heat conduction is the predominant mechanism for heat transfer of the BHEs in most saturated fine-grained soils. Previous studies have shown that backfill materials have a certain influence on the thermal performance of the BHEs. Generally, the increase in the thermal conductivity of backfill materials is helpful to reduce the thermal resistance between the BHEs and the surrounding soils, which

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was expected to be a major approach to shortening the required length of the BHEs for the GSHP applications.

Thermally enhanced backfill materials, therefore, have been paid much attention by researchers and designers during the past decade. For example, Allan tested the mean thermal conductivity of sand-cement grouts in the saturated state, ranging from 2.49 W/m K at laboratory to 2.19 W/m K in field tests. By adding ballast material into bentonite, Engelhardt and Finsterle obtained a high thermal conductivity of 2.3 to 2.6 W/m K, leading to an increase in heat conduction. Compared the effects of sandstone and cement backfills on the thermal performances of two vertical BHEs in a cold climate region. Developed a super absorption polymer mixed with the original soil as backfilled material of the BHEs. Compared the thermal performance of the BHEs with saturated medium-coarse sand and fine sand as backfill materials, where a 6-10% enhancement on heat transfer was obtained. More recently, due to a good water absorbing and swelling property of bentonite crystals, sand-bentonite mixtures are used frequently as a backfill material for vertical boreholes in many GSHP applications. However, selection of backfill materials for geothermal boreholes is a complex function of thermal, regulatory, and economic considerations. There are still some problems to be solved, such as the effect of the mixed ratio, saturation, grain sizes and other factors on the thermal conductivity of sand-bentonite mixtures, which finally may influence the thermal performance of the BHEs.

The objective of this communication was to quantitatively analyse the effects of sand-bentonite backfill materials on the thermal performance of the BHEs. Thermal needle probe tests were conducted at laboratory to measure the thermal conductivity of sand-bentonite mixtures in order to seek for an optimal mixed ratio. Based on microscopic observations, the mechanism of bentonite affecting heat conduction between the sand grains was analysed. Further, field tests were carried out to compare the thermal performance of two BHEs with an optimal sand-bentonite mixture and a common medium-coarse sand mixture as backfill materials, respectively. The present study can provide helpful guides for the design of the GSHP systems [1].

Experimental study

This study is an introduction to the energy problem and the possible saving that can be achieved through improving building performance and the use of ground energy sources. The relevance and importance of the study is discussed in the communication, which, also, highlights the objectives of the study, and the scope of the theme.

Laboratory experiments

In this study, Thermal Probe Tests (TPTs) were performed to measure the thermal conductivity of sand-bentonite backfill materials. TPT is a typical laboratory unsteady analysis method, in which the thermal conductivity of porous media is obtained by the temperature increase of an infinite constant linear heat source within an infinite object. Proposed an analytical representation for this problem.

A long stainless steel pipe with the outer diameter of 2.0 mm was used as a thermal needle probe. The enamel-insulated constantan wires with the diameter of 0.1 mm and the resistance of 35 to 40 ohm were used as a linear heat source and heated electrically by a WYJ-15 type DC power meter with a constant voltage output ranging from 5 to 10 V. The wires were carefully installed into the probe. At the same time, a copper constantan temperature sensor with $\pm 0.1^\circ\text{C}$ accuracy was installed at the half length of the probe. Before the installation, the sensor was calibrated carefully. Finally, in order to reduce the response time, the probe was filled with the silicone grease with metal powers. Usually, the aspect ratio (length: diameter) of needle probes should be higher than 55 to obtain idealised conditions of an infinite linear heat source which is required to fulfill the thermal probe theoretical assumptions. The deviation from this assumption can be compensated by using the factor η . In the present work, the commercial glycerol with a purity of over 99% was used as a standard sample (0.286 W/m K at 20°C) to calibrate the TPT results. After calibration, the maximum test error was about $\pm 2\%$. Prior to the TPTs, the probe was inserted vertically into a sample. After 5 min, a constant heating power was applied. Simultaneously, an Agilent 34970 a type data acquisition recorder was used to record the variations of the needle probe temperature during the tests. The heating time for each test was about five to eight minutes [2].

Two types of sand, i.e., fine sand (0.1-0.3 mm) and coarse sand (0.5-0.8 mm), were chosen by the screen size for the preparation of matrix samples. Commercially available sodium bentonite with 86% montmorillonite was used as the additive, and its average ratio of water absorption was 300% (after 2h). After measurement, the dry density of sand and bentonite were 1580 kg/m^3 and 1460 kg/m^3 , respectively. It shows the micrographs of dry sand and bentonite, which were obtained by a SIGE300-type optical microscope. It can be seen that the average diameter of bentonite powders was by far smaller than that of sand. Therefore, once tiny bentonite powders are mixed fully with fine or coarse sand, they will be able to take up the pores surrounded by those relatively large sand grains, thereby influencing the heat conduction capability of the whole mixture.

For the preparation of sand-bentonite mixtures, both sand and bentonite were placed into a dry box at 105°C . After drying for 12 h, the samples were cooled down to the room temperature. Then, sand and bentonite were fully mixed according to different ratios of dry weight. Further, pure water with a certain mass was added into the sand-bentonite mixtures, mixed fully to reach a required saturation and then moved into different sealed metal cylinders with the diameter of 110 mm and the height of 240 mm. After 2 h, the cylinders were uncovered to conduct the TPTs at room temperature.

Field tests

For the GSHP applications, the heat transfer rate of a BHE as a function of depth can be calculated by the measured inlet and outlet fluid temperature and the flow rate through the BHE. It can be expressed, It shows the experimental setup testing the thermal performance of a BHE. The setup mainly consisted of a heat/cold source system, a measuring system, and a vertical

BHE. The heat/cold source system was able to keep a relatively constant temperature inside a 40 L insulated water tank, thus guaranteeing a stable inlet fluid temperature to the BHE. The water tank was made of stainless steel plates. The stainless steel plates were 2 mm thick, and the polyurethane insulation layer surrounding them was 30 mm thick. The heating was provided by an adjustable electric water heater, while the cooling was obtained by means of a typical R22 refrigeration cycle consisting of a Daikin-JT95 type rotor compressor, a fin condenser, an expansion valve, and a coil evaporator. The condenser was cooled by an axial air-cooling fan. The maximum heating and cooling output was 12 kW and 9 kW, respectively. In addition, an advanced Proportional-Integral-Derivative (PID) temperature controller was mounted on the operation panel. The operation temperature for the water tank ranged from 5° to 40° C, with the accuracy of $\pm 0.5^\circ$ C. A 90 W Wiley-RS25 type circulating pump was used to keep the flow circuit. Its maximum flow rate and the hydraulic head were 2.5 m/h and 6 m, respectively [3].

The measuring system included two Pt1000-type temperature sensors with $\pm 0.1^\circ$ C accuracy, a GPR-II type electromagnetic flow meter with ± 0.001 m³/h accuracy. Before the installation, all temperature sensors were calibrated by an XLR-1 type constant-temperature bath with $\pm 0.01^\circ$ C accuracy.

For comparison, the thermal performance of two double U-shaped BHEs with different backfill materials was tested in shows a part of view of field tests. The BHEs were made of high-density polyethylene materials. The depth and diameter of both boreholes were 105 m and 200 mm, respectively. The distance between two boreholes was 15 m. For backfill materials, one borehole was grouted by unsized sand containing a little of clay, and another by the sand-bentonite mixture. The mixed ratio of the latter was determined by the results of laboratory measurements, which will be discussed in the following sections. In addition, all exposed pipes were insulated effectively using black polyethylene foam materials with a thickness of 20 mm, in order to reduce the undesired loss of heat or cold. Other more details on the experimental setup can be seen in our previous studies. Data collection was once every 10 minutes, and the test period extended from 10 September to 30 September 2010.

It shows the laboratory results of the thermal conductivity of sand-bentonite mixtures with different mixed ratios under the saturation of 80%. It can be seen that the thermal conductivity of sand-bentonite mixtures first increases with increasing percentage of bentonite by dry mass, then reaches a peak at a certain percentage range, beyond which the thermal conductivity decreases. In detail, the optimal percentage of bentonite by dry mass as

backfill materials of the BHEs was 10% for the fine sand-bentonite mixture and 12% for the coarse sand-bentonite mixture, and the corresponding thermal conductivity was 2.15 W/m K and 2.37 W/m K, which were 36.1% and 26.7% higher than that of fine sand and coarse sand at the same saturation, respectively. Note that when the percentage of bentonite exceeded 15%, the thermal conductivity decreased gradually and finally reached the value of about 0.75 W/m K, which was in good agreement with the thermal conductivity of saturated bentonite. Therefore, the measurement results of the TPTs in

this study were reliable. During the experiments, we also found that, as the saturations of sand-bentonite mixtures were over 80%, they were no longer be compacted because little compressible air remain and only low compressible water was left.

It should be noted that ASHRAE also recommended the thermal conductivity ranges of three types of sand-bentonite mixtures as follows: i) 2.08 to 2.42 W/m K for 10 wt. % bentonite and 90 wt. % sand, ii) 1.00 to 1.10 W/m K for 15 wt. % bentonite and 85 wt. % sand, iii) 1.47 to 1.64 W/m K for 20 wt. % bentonite and 80 wt. % sand. By contrast with the measurement results in this study, it is clear that there was a good agreement for the first and third situation, exception for the second case that was not confirmed in our study. So the present laboratory measurements (Figure 1) [4].



Figure 1: A part of view of field tests of the thermal performance of the BHEs Results and Discussion.

From the point of view of microscopic observations, the enhancement mechanism of bentonite on the thermal conductivity of sand-bentonite mixtures can be explained as follows: when bentonite is added into sand, it will absorb water and swell quickly due to the hydrophilicity of montmorillonite mineral crystals, and finally become a sticky paste taking up those local or whole pores surrounding the sand grains. Thus, heat conduction between the solid grains is enhanced greatly by a higher thermal conductivity of bentonite, e.g., 0.75 W/m K at saturations of over 75 to 80%, than that of water (0.6 W/m K at 20° C). On the other hand, with continually increasing percentage of bentonite, the amount of sand tends to decrease and most sand grains are surrounded by the bentonite paste with a lower thermal conductivity than that of quartz (7.7 W/m K) and other minerals (2-3 W/m K depending on the quartz content of the total sand solids), thereby resulting in a weakening of heat conduction between the solid grains. Henceforth, for sand-bentonite mixtures used as a backfill material of geothermal boreholes, there exists an optimal percentage of bentonite by dry mass, i.e., 10-12%, as shown in the shadow region. If the requirements on the thermal performance of the BHEs are not very strict, an extended range of 8-12% wt. bentonite is acceptable, too. Further, the mixture of 90% wt. medium and coarse sand and 10% wt. bentonite was determined in the field tests as an optimal backfill material to compare the thermal performance of the BHE. Firstly, in order

to obtain the natural ground temperature, the BHE was operating under the condition without heating or cooling, only driven by the circulating pump. As the inlet and outlet fluid temperature reached a steady state after 12 h. According to the recommendation by the International Energy Agency (IEA), the natural ground temperature is usually treated as the average fluid temperature at the above steady state. In the present study, this temperature was calculated as 17.3° C after 16 h measurement. In addition, it should be noted that the natural ground temperature has a seasonal effect, which is mainly caused by the seasonal variations of the ground temperature at the shallow zone reaching a depth of about 2-20 m. If so, the heat transfer performance of the BHE may be affected to a certain extent. Considering the test period in this study was not very long, however, the above seasonal effect was neglected [5].

Secondly, two heat extraction and two heat injection experiments were performed in order to evaluate the thermal performance of each BHE and its surrounding soils. In each operation mode, the BHE was run at a succession of the inlet fluid temperatures, which further determined the fluid temperature the heat pump units. In fact, selecting the appropriate t_{wi} is critical in the design of the GSHP systems. Usually, choosing a value close to the natural ground temperature results in higher system efficiency, but makes the required length of the BHEs very long and thus unreasonably expensive. Choosing a value far from the natural ground temperature allows selection of a small, inexpensive BHE, but the system's heat pumps will have greatly reduced capacity during heating and high demand when cooling.

It show two typical experimental results of the thermal performance of the BHE under a sand-clay and optimal sand-bentonite backfill material, respectively, where the average flow rate through the BHE was 1.05 m/kg. It can be seen that, as the cooling time increased, the heat extraction rate of the BHE dropped gradually and then tended to be relatively steady after 24 to 30 h, and as the heating time increased, the heat injection rate of the BHE increased rapidly, and then dropped gradually to reach relatively steady after 20 to 24 h. Here, the positive and negative sign for the heat transfer rate of the BHEs only represent the direction of thermal energy injected into and extracted from the ground, respectively. It can also be seen by comparison that backfill materials had a great impact on the thermal performance of the BHEs. For example, for the heat extraction operation mode, the heat transfer rate was -29.6 W/m at an average fluid temperature of 9.3° C under sand-clay backfilling and -35.5 W/m at an average fluid temperature of 9.5° C under sand-bentonite backfilling, respectively. For the heat injection operation mode, the heat transfer rate was 34.5 W/m at an average fluid temperature of 28° C under sand-clay backfilling and 38.3 W/m at an average fluid temperature of 26.8° C under sand-bentonite backfilling, respectively.

It can be easily seen that, compared with the case with a common sand-clay material, both the heat injection and heat extraction rate of the BHE with an optimal sand-bentonite backfill material were enhanced. After calculation, for the range of the fluid temperature of 6 to 9° C for heat extraction and 28 to 32° C for heat injection, the enhancement on the heat

transfer of the BHE was 22.2% and 31.1%, respectively. These results are helpful to greatly reduce the required length of the BHEs in the GSHP applications. They also found a 22 to 37% reduction in the required length of the BHEs when cement-sand grouts with a thermal conductivity of 2.2 to 2.5 W/m K were used as a backfill material. By contrast, I can draw on a preliminary conclusion that, for the sand-bentonite backfill material with a thermal conductivity higher than 2.14 W/m K, the reduction in the required length of the BHEs should be at least 20 percent, depending on the soil thermal conductivity and bore diameter, which in turn can be used as one of criterions for choosing backfill materials with a good thermal performance. Therefore, the above optimal sand-bentonite backfill material can be safely used for the construction of the BHEs in the GSHP systems [6].

Overview of ground source heat pump systems

The term “ground source heat pump” has become an inclusive term to describe a heat pump system that uses the earth, ground water, or surface water as a heat source and/or heat sink. The GSHPs utilise the thermal energy stored in the earth through either a vertical or horizontal closed loop heat exchangers buried in the ground. Many geological factors impact directly on site characterisation and subsequently the design and cost of the GSHP systems. The geological prognosis for a site and its anticipated rock properties influence the drilling methods and therefore the system cost. Other factors that are important to system design include predicted subsurface temperatures and the thermal and hydrological properties of strata. The GSHP technology is well established in Sweden, Germany and North America, but has had minimal impact in the United Kingdom space heating and cooling market.

The GSHPs utilise the thermal energy stored in the earth through either vertical or horizontal closed loop heat exchange systems buried in the ground. Many geological factors impact directly on site characterisation and subsequently the design and cost of the system. The solid geology of the varies significantly. Furthermore there is an extensive and variable rock head cover. The geological prognosis for a site and its anticipated rock properties influence the drilling methods and therefore system costs. Other factors important to system design include predicted subsurface temperatures and the thermal and hydrological properties of strata. The GSHP technology is well established in Sweden, Germany and North America, but has had minimal impact in the space heating and cooling market. Perceived barriers to uptake include geological uncertainty, concerns regarding performance and reliability, high capital costs and lack of infrastructure. System performance concerns relate mostly to uncertainty in design input parameters, especially the temperature and thermal properties of the source. These in turn can impact on the capital cost, much of which is associated with the installation of the external loop in horizontal trenches or vertical boreholes. The temperate climate means that the potential for heating in winter and cooling in summer from a ground source is less certain owing to the temperature ranges being narrower than those encountered in continental climates. This project will develop an impartial GSHP function on the site to make available information and

data on site-specific temperatures and key geotechnical characteristics.

The GSHPs are receiving increasing interest because of their potential to reduce primary energy consumption and thus reduce emissions of greenhouse gases. The technology is well established in North America and parts of Europe, but is at the demonstration stage in the. The information will be delivered from digital geoscience's themes that have been developed from observed data held in corporate records. These data will be available to the GSHP installers and designers to assist the design process, therefore reducing uncertainties. The research will also be used to help inform the public as to the potential benefits of this technology.

The GSHPs play a key role in geothermal development in Central and Northern Europe. With borehole heat exchangers as heat source, they offer de-central geothermal heating at virtually any location, with great flexibility to meet given demands. In the vast majority of systems, no space cooling is included, leaving ground-source heat pumps with some economic constraints. Nevertheless, a promising market development first occurred in Switzerland and Sweden, and now also is obvious in Austria and approximately 20 years of research and development focusing on borehole heat exchangers resulted in a well-established concept of sustainability for this technology, as well as in sound design and installation criteria. The market success brought to the third rank worldwide in geothermal direct use. The future prospects are good, with an increasing range of applications including large systems with thermal energy storage for heating and cooling, ground-source heat pumps in densely populated development areas, borehole heat exchangers for cooling of telecommunication equipment, etc.

Efficiencies of the GSHP systems are much greater than conventional air-source heat pump systems. A higher COP (Coefficient of Performance) can be achieved by a GSHP because the source/sink earth temperature is relatively constant compared to air temperatures. Additionally, heat is absorbed and rejected through water, which is a more desirable heat transfer medium because of its relatively high heat capacity. The GSHP systems rely on the fact that, under normal geothermal gradients of about 0.5° F/100 ft (30° C/km), the earth temperature is roughly constant in a zone extending from about 20 ft (6.1 m) deep to about 150 ft (45.7 m) deep. This constant temperature interval within the earth is the result of a complex interaction of heat fluxes from above (the sun and the atmosphere) and from below (the earth interior). As a result, the temperature of this interval within the earth is approximately equal to the average annual air temperature. Above this zone (less than about 20 feet (6.1 m) deep), the earth temperature is a damped version of the air temperature at the earth's surface. Below this zone (greater than about 150 ft (45.7 m) deep), the earth temperature begins to rise according to the natural geothermal gradient [7].

Ground water heat pump systems

Ground Water Heat Pump (GWHP) systems, also referred to as open-loop systems, are the original type of the GSHP system.

The first GWHP systems were installed in the late 1940s. The GWHP systems are not the focus of this thesis, so they will only be briefly described here. A schematic of a GWHP system. In the GWHP systems, conventional water wells and well pumps are used to supply ground water to a heat pump or directly to some application. Corrosion protection of the heat pump may be necessary if ground water chemical quality is poor. The "used" ground water is typically discharged to a suitable receptor, such as back to an aquifer, to the unsaturated zone to a surface-water body, or to a sewer. Design considerations for the GWHP systems are fairly well established; well-drilling technologies and well-testing methods have been well known for decades. Design considerations include: ground-water availability, ground-water chemical quality, and ground-water disposal method. The main advantage of the GWHP systems is their low cost, simplicity, and small amount of ground area required relative to other GSHP and conventional systems. Disadvantages include limited availability and poor chemical quality of ground water in some regions. With growing environmental concerns over recent decades, many legal issues have arisen over ground water withdrawal and re-injection in some localities.

The Direct Expansion (DX) GSHP installed for this study was designed taking into account the local meteorological and geological conditions. The site was at the School of the Built Environment, of where the demonstration and performance monitoring efforts were undertaken. The heat pump has been fitted and monitored for one-year period. The study involved development of a design and simulation tool for modelling the performance of the cooling system, which acts a supplemental heat rejecting system using a closed-loop GSHP system [8].

Ground coupled heat pump systems

Grounds Coupled Heat Pump (GCHP) systems, also referred to as closed-loop ground-source heat pump systems, and were pioneered in the 1970s. Their main advantage over their water-well predecessors is that they eliminate the problems associated with ground water quality and availability and they generally require much less pumping energy than water well systems because there is less elevation head to overcome. The GCHP systems can be installed at any location where drilling or earth trenching is feasible. In GCHP systems, heat rejection/extraction is accomplished by circulating a heat exchange fluid through a piping system buried in the earth. This fluid is either pure water or an antifreeze solution and is typically circulated through High-Density Polyethylene (HDPE) pipe installed in vertical boreholes or horizontal trenches. Thus, these systems are further subdivided into vertical GCHP systems and horizontal GCHP systems.

Vertical ground coupled heat pump systems

Vertical borehole GCHP systems are the primary focus of this entire thesis. Therefore, they are described in some detail here and their design challenges are explained, laying the foundation for the motivation of this study. In vertical borehole GCHP systems, ground heat exchanger configurations typically consist of one to tens of boreholes each containing a U-shaped pipe

through which the heat exchange fluid is circulated. Some Swedish applications use boreholes inclined from the vertical. A number of borehole-to-borehole plumbing arrangements are possible. Typical U-tubes have a diameter in the range of $\frac{3}{4}$ in. (19 mm) to 1 $\frac{1}{2}$ in. (38 mm) and each borehole is typically 100 ft (30.5 m) to 300 ft (91.4 m) deep with a diameter ranging from 3 in. (76 mm) to 5 in. (127 mm). The borehole annulus is generally backfilled with a material that prevents contamination of ground water [9].

The design of vertical ground heat exchangers is complicated by the variety of geological formations and properties that affect their thermal performance. Proper subsurface characterisation is not economically feasible for every project. One of the fundamental tasks in the design of a reliable GCHP system is properly sizing the ground-coupled heat exchanger length (i.e., depth of boreholes). Particularly for large systems, an extensive effort is made to design the ground loop heat exchangers so that they are not too large (resulting in too high of a first cost) or too small (resulting in the building's thermal load not being met).

In the early days of the GCHP technology, the task of sizing the ground-loop heat exchanger was accomplished using rules of thumb (i.e., 250 feet of bore length per ton of heating or cooling capacity). These rules were slightly modified on a case-by-case basis using some estimates of thermal conductivity of the formation or using previous design experience, but additional costs of more detailed testing or calculations was judged to outweigh the costs of a conservative design. This relatively simple approach proved to be successful in most residential and other small applications, but in larger-scale commercial and institutional applications, some ground-loop heat exchangers failed to meet their design loads after the first few years of operation. Further, the practice of greatly over-designing large GCHP systems was found to be unacceptable because the first costs were simply not competitive with the first costs of conventional systems.

Consequently, intensive research regarding methods to optimise ground-loop heat exchanger design has been on-going for the last decade. Simple approaches to sizing the ground-loop heat exchanger in larger-scale applications are inadequate mainly because the heat transfer processes in the ground are complicated by thermally interacting boreholes and hourly periodic heat extraction/injection pulses. Annual heat rejection and heat extraction are usually not equal and peak temperatures rise or fall over a number of years. As a result, ground-loop heat exchanger designers need to consider hourly heating and cooling loads of the building and need to perform some simulation of the ground-loop temperatures over the life-cycle of the building. Recent research efforts have produced several methods and computer software programmes for this purpose. However, none of the programmes consider the effects of ground water flow on ground-loop heat exchanger performance; these effects have not been well understood, perhaps because of the lack of relevant investigations [10].

Another challenge in the design of the GCHP systems arises from the fact that most commercial and institutional buildings, even in moderate climates, are generally cooling dominated and therefore reject more heat to the ground than they extract over

the annual cycle. This load imbalance may require the heat exchanger length to be significantly greater than the length required if the annual loads were balanced. As a result, the GSHP system may be eliminated from consideration early in the design phase of the project due to excessive first cost. This has given rise to the concept of "supplemental heat rejecters" or so-called "hybrid GSHP systems".

Supplemental heat rejecters have been integrated into building designs to effectively balance the ground loads and therefore reduce the necessary length of the ground-loop heat exchanger. In some applications, the excess heat that would otherwise build up in the ground may be used for domestic hot water heaters, car washes, and pavement heating systems. In cases where the excess heat cannot be used beneficially, conventional cooling towers or shallow ponds can provide a cost-effective means to reduce heat exchanger length. Design of these supplemental components adds to the challenge of designing the overall hybrid GCHP system because of their highly transient nature. Heat rejection systems are likely to operate more often during the night time hours or when the building is not in use. Therefore, it is essential that the hourly (or less) behaviour of these systems be examined during their design phase.

Horizontal ground coupled heat pump systems

In horizontal GCHP systems, ground heat exchanger configurations typically consist of a series of parallel pipe arrangements laid out in dug trenches or horizontal boreholes about 3 ft (0.91 m) to 6 ft (1.83 m) deep. A number of piping arrangements are possible. "Slinky" configurations are popular and simple to install in trenches and shallow excavations. In horizontal boreholes, straight pipe configurations are installed. Typical pipes have a diameter in the range of 19 mm to 38 mm and about 400 ft (121.9 m) to 600 ft (182.9 m) of pipe is installed per ton of heating and cooling capacity.

The thermal characteristics of horizontal GCHP systems are similar to those of vertical ones. The main difference is that horizontal ground loop heat exchangers are more affected by weather and air temperature fluctuations because of their proximity to the earth's surface. This may result in larger loop temperature fluctuations and therefore lower heat pump efficiencies. Recent research activities have focused on using these systems as supplemental heat rejecters with vertical borehole GCHP systems. A specific application (i.e., the use of a shallow cooling system) is the focus of this study [11].

Aside from the invention of the slinky coil itself and the use of these systems as supplemental heat rejecters, horizontal systems have received much less attention than vertical systems with respect to recent research efforts. This may be due to the fact that vertical systems tend to be preferred in larger applications since much less ground area is required. Also, since horizontal systems are installed at shallow depths, geologic site characterisation is relatively easier because soils can be readily seen and sampled. Further, over-conservative designs are not as cost prohibitive as with vertical borehole designs because of the relatively low installation costs of the heat exchanger pipe.

Surface water heat pump systems

The third category of the GSHP systems is the Surface-Water Heat Pump (SWHP) system. A specific application of the SWHP systems (i.e., the use of a shallow pond as a supplemental heat rejecter in vertical GCHP systems), and a schematic of a SWHP system. The surface-water heat exchanger can be a closed-loop or open-loop type. Typical closed-loop configurations are the Slinky coil type or the loose bundle coil type. In the closed-loop systems, heat rejection/extraction is accomplished by circulating a heat exchange fluid through HDPE pipe positioned at an adequate depth within a lake, pond, reservoir, or other suitable open channel. Typical pipe diameters range from $\frac{3}{4}$ in. (19 mm) to 1 $\frac{1}{2}$ in. (38 mm) and a length of 100 feet (30.48 m) to 300 feet (91.44 m) per ton of heating or cooling capacity, depending on the climate. In open-loop systems, water is extracted from the surface-water body through a screened intake area at an adequate depth and is discharged to a suitable receptor.

Heat transfer mechanisms and the thermal characteristics of surface-water bodies are quite different than those of soils and rocks. At the present time, design tools for surface-water heat pump systems are in their developmental infancy. However, many successful installations are currently in operation and some guidelines do exist. In short, the loop design involves selection of sufficient length of coil for heat transfer, specifying adequate diameter piping, specifying a sufficient numbers of parallel loops, and locating the coil at a proper depth in a water body with adequate thermal capacity.

Standing column well systems

The fourth category of the GSHP systems is known as a standing column well (SCW) system. These systems are about as old as the ground-water heat pump systems, but are recently receiving much attention. Since these are not the subjects of this communication, they are only briefly discussed here.

A schematic of an SCW system. This type of the GSHP draws water to a heat pump from a standing column of water in a deep well bore and returns the water to the same well. These systems, primarily installed in hard rock areas, use uncased boreholes with typical diameters of about 6 in. (15.24 cm) and depths up to 1500 feet (457.2 m). The uncased borehole allows the heat exchange fluid to be in direct contact with the earth (unlike closed-loop heat exchangers) and allows ground water infiltration over the entire length of the borehole. Properly sited and designed, SCW systems have been shown to have significant installation cost savings over closed-loop GCHP systems. Design guidelines for the SCW systems are currently under development [12].

Soil properties

One of the fundamental tasks in the design of a reliable ground source heat pump system is properly sizing the ground source heat exchanger length (i.e., depth of boreholes). Recent research efforts have produced several methods and commercially available design software tools for this purpose. These design tools are based on principles of heat conduction and rely on some estimate of the ground thermal conductivity and

volumetric specific heat. These parameters are perhaps the most critical to the system design, yet adequately determining them is often the most difficult task in the design phase.

Groundwater management

A further complication in the design of ground source heat pump systems is the presence of ground water. Where groundwater is present, flow will occur in response to hydraulic gradients and the physical process affecting heat transfer in the ground is inherently a coupled one of heat diffusion (conduction) and heat advection by moving ground water. In general, groundwater flow can be expected to be beneficial to the thermal performance of closed-loop ground heat exchangers since it will have a moderating effect on borehole temperatures in both heating and cooling modes.

Groundwater flow

Underground water occurs in two zones: the unsaturated zone and the saturated zone. The term 'groundwater' refers to water in the saturated zone. The surface separating the saturated zone from the unsaturated zone is known as the 'water table'. At the water table, water in soil or rock pore spaces is at atmospheric pressure. In the saturated zone (below the water table), pores are fully saturated and water exists at pressures greater than atmospheric. In the unsaturated zone, pores are only partially saturated and the water exists under tension at pressures less than atmospheric. Groundwater is present nearly everywhere, but it is only available in usable quantities in aquifers. Aquifers are described as being either confined or unconfined. Unconfined aquifers are bounded at their upper surface by water table. Confined aquifers are bounded between two layers of lower permeability materials. In practice, the boreholes of ground-loop heat exchangers may partially penetrate several geologic layers.

Heat transport in groundwater

Heat can be transported through a saturated porous medium by the following three processes:

- Heat transfer through the solid phase by conduction.
- Heat transfer through the liquid phase by conduction, and
- Heat transfer through the liquid phase by advection.

It is necessary to distinguish between the conductivity and thermal capacity of the water and soil/rock in this way to account for the fact that heat is stored and conducted through both the water and soil/rock, but heat is only advected by the water. Similarly, it is necessary to define a retardation coefficient R accounting for retardation of the thermal plume, which results from, differences in the liquid and solid volumetric heat capacities.

Darcy's Law indicates that flow is dependent on both the local hydraulic gradient and the hydraulic conductivity of the geologic material. Heat transfer is dependent on the flow velocity and the thermal properties of the material. The thermal properties of soils and rocks are functions of mineral content, porosity and degree of saturation. Of these, porosity may be considered the

most important property simply because of the origin and nature of soils and rocks. Rocks originate under higher heat and pressure environments than soils and consequently generally possess lower porosities.

Soil thermal measurements

The soil thermal measurements were carried out using KD2 Pro thermal properties analyser. The KD2 Pro is a handheld device used to measure thermal properties. The KD2 Pro is a battery-operated, menu-driven device that measures thermal conductivity and resistivity, volumetric specific heat capacity and thermal diffusivity. It consists of a handheld controller and sensors inserted into the medium to be measured. The single-needle sensors measure thermal conductivity and resistivity, while the dual-needle sensor also measures volumetric specific heat capacity and diffusivity. If the temperature of the sample medium is different from the temperature of the needle, the needle must equilibrate to the surrounding temperature before beginning a reading.

Material thermal properties are determined by fitting the time series temperature data during heating to and during cooling. Thermal conductivity can be obtained from the temperature of the heated needle (single needle), with r taken as the radius of the needle. Diffusivity is best obtained by fitting the temperatures measured a fixed distance (the KD2 Pro uses 6 mm) from the heated needle (k is also determined from these data). Volumetric specific heat (W/mK) is determined from k and D .

In each case, k and D are obtained by a non-linear least squares procedure, which searches for values of k and D , which minimise the difference between modelled and measured sensor temperatures. Most experiments will not occur under constant temperature conditions. An additional linear drift factor is included in the inverse procedure. This reduces errors substantially (Figure 2) [13].



Figure 2: KD2 Pro thermal properties analyser.

Ground characteristics

It is important to determine the depth of soil cover, the type of soil or rock and the ground temperature. The depth of soil cover may determine the possible configuration of the ground coil. If bedrock is within 1.5 m of the surface or there are large boulders, it may not be possible to install a horizontal ground loop. For a vertical borehole the depth of soil will influence the

cost as, in general, it is more expensive and time consuming to drill through overburden than rock as the borehole has to be cased.

The temperature difference between the ground and the fluid in the ground heat exchanger drives the heat transfer so it is important to determine the ground temperature. At depths of less than 2 m, the ground temperature will show marked seasonal variation above and below the annual average air temperature. As the depth increases the seasonal swing in temperature is reduced and the maximum and minimum soil temperatures begin to lag the temperature at the surface. At a depth of about 1.5 m, the time lag is approximately one month. Below 10 m the ground temperature remains effectively constant at approximately the annual average air temperature (i.e., between 10° C and 14° C in the depending on local geology and soil conditions). The annual variation in ground temperatures at a depth of 1.7 m compared to the daily average air temperature measured at the site. It also shows the ground temperature at a depth of 75 m [14].

In order to determine the length of heat exchanger needed to meet a given load the thermal properties of the ground will be needed. The most important difference is between soil and rock as rocks have significantly higher values for thermal conductivity. The moisture content of the soil also has a significant effect as dry loose soil traps air and has a lower thermal conductivity than moist packed soil. Low-conductivity soil may require as much as 50% more collector loop than highly conductive soil. Water movement across a particular site will also have a significant impact on heat transfer through the ground and can result in a smaller ground heat exchanger (Tables 1-2).

Material	Conductivity (Wm-1K-1)	Specific heat (kJkg-1K-1)	Density (kgm-3)	Diffusivity (m2d-1)
Granite	2.1-4.5	0.84	2640	0.078-0.18
Limestone	1.4-5.2	0.88	2480	0.056-0.20
Marble	2.1-5.5	0.8	2560	0.084-0.23
Sandstone				
Dry	1.4-5.2	0.71	2240	0.074-0.28
Wet	2.1-5.2			0.11-0.28
Clay				
Damp	1.4-1.7	1.3-1.7		0.046-0.056
Wet	1.7-2.4	1.7-1.9	1440-1920	0.056-0.074
Sand				
Damp		1.3-1.7		0.037-0.046
Wet*	2.1-26	1.7-1.9	1440-1920	0.065-0.084

* Water movement will substantially improve thermal properties

Table 1: Typical thermal properties of soil.

Ground	Method	Remarks
Soft, sand	Auger	Sometimes temporary casing required
Gravel	Rotary	Temporary casing or mud additives required
Soft, silt/clay	Auger	Usually the best choice
	Rotary	Temporary casing or mud additives required
Medium	Rotary	Roller bit, sometimes mud additives required
	DTH*	Large compressor required
Hard	Rotary	Button bit, very slow
	DTH	Large compressor required
Very hard	Top hammer	Special equipment
	DTH	Large compressor required
Hard under soft	Top hammer	Special equipment
	ODEX#	In combination with DTH

*Down-the-hole-hammer

#Overburden drilling equipment (Atlas Copco, Sweden)

Table 2: Drilling methods for the installation of vertical collectors

A geotechnical survey can be used to reduce the uncertainty associated with the ground thermal properties. More accurate information could result in a reduction in design loop length and easier loop installation. For large schemes where multiple boreholes are required, a trial borehole and/or a thermal properties field test may be appropriate.

The ground temperature is important, as it is the difference between this and the temperature of the fluid circulating in the heat exchanger that drives the heat transfer. At depths of less than 2 m, the ground temperature will show marked seasonal variation above and below the annual average air temperature. As the depth increases, the seasonal swing in temperature

reduces and the maximum and minimum soil temperatures begin to lag the temperatures at the surface (e.g., a time lag of approximately one month at 1.5 m, two months at 4 m). The two rock/soil properties that most affect the design of a heat pump system are the thermal conductivity (k) and the thermal diffusivity (D). The thermal properties of common ground types. The most important difference is between soil and rock because rocks have significantly higher values for thermal conductivity and diffusivity.

The main consideration with installation of the ground coil is to ensure good long-term thermal contact. Only standard construction equipment is needed to install horizontal ground heat exchanger, i.e., bulldozers or backhoes and chain trenchers. In larger installation in Europe, track type machines have been used to plough in and backfill around the pipe in continuous operation. Drilling is necessary for most vertical heat exchanger installations. The drilling equipment required is considerably simpler than the conventional equipment for drilling water wells (Figure 3) (Table 3) [15].

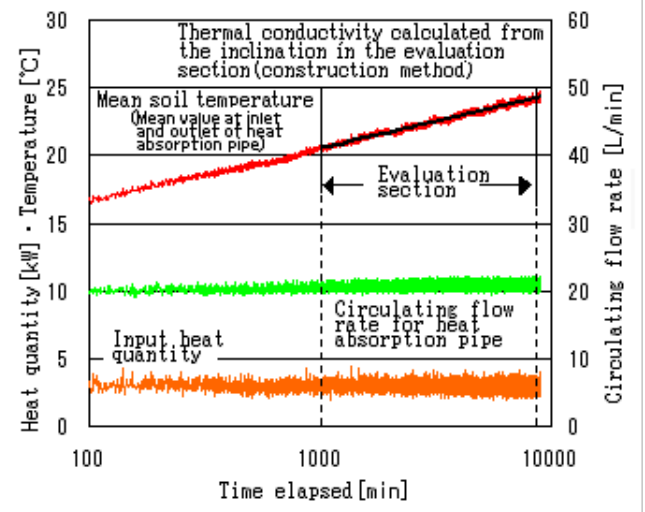


Figure 3: Thermo response test.

Case number	Simulation duration (hr)	Ground thermal conductivity predicted by numerical model Austin et al. 2000 (W/moC)
1	50	1.11
2	50	1.12
3	50	1.26
4	50	1.98
5	50	6.33
6	50	10.51
7	168	1.08

8	168	1.2
9	168	1.66
10	168	3.89
11	168	14.24
12	168	26.14

Table 3: Actual values of thermal conductivity.

For the design of thermally efficient and economically sized borehole heat exchanger systems the soil thermal characteristics, especially the thermal conductivity, borehole resistance and undisturbed ground temperature are essential parameters. The design and economic feasibility of these systems critically depend upon the estimate of the ground thermal conductivity.

Soil thermal heat properties

The ground source heat pump system, which uses a ground source with a smaller annual temperature variation for heating and cooling systems, has increasingly attracted market attention due to lower expenses to mine for installing underground heat absorption pipes and lower costs of dedicated heat pumps, supported by environmentally oriented policies. The theme undertakes an evaluation of heat absorption properties in the soil, and carries out a performance test for a unit heat pump and a simulated operation test for the system. In fact, these policies are necessary for identifying operational performance suitable for heating and hot water supply, in order to obtain technical data on the heat pump system for its dissemination and maintain the system in an effort of electrification. In these circumstances, the study estimated the heat properties of the soil in the city of Nottingham and measured thermal conductivity for the soil at some points in this city, aimed at identifying applicable areas for ground source heat pump system.

Based on existing information regarding Sapporo's subsurface geology (using geologic columnar section, etc.), thermal properties (thermal conductivity, heat capacity, etc.) for the soil, which is typically found 0 to 30 m deep underground, were estimated.

Test of soil thermal conductivity

The sample soil thermal conductivity-measuring instrument was produced to measure the soil thermal conductivity from rises in underground temperature. Thermo response test when a certain amount of heat was conducted into heat absorption soil. According to the measurement result, the soil thermal conductivity was observed slightly higher than the thermal conductivity estimated by the geologic columnar section. The future plan is to predict system operational performance at each observation point, based on the relationship between estimated soil thermal property and measured soil thermal conductivity. It shows the examples of measured and predicted soil temperatures.

It is seen from the temperature drops much faster for granite and slower for the coarse gravelled soil either in the soil. This is mainly due to the fact coarse gravelled material has a higher thermal storage capacity or lower thermal diffusivity than granite. Therefore, the high thermal energy stored found in the coarse gravelled can provide longer heat extraction as summary of the soil thermal properties. The temperature difference between the ground and the fluid in the ground heat exchanger drives the heat transfer so it is important to determine the ground temperature. At depths of less than 2 m, the ground temperature will show marked seasonal variation above and below the annual average air temperature. As the depth increases the seasonal swing in temperature is reduced and the maximum and minimum soil temperatures begin to lag the temperature at the surface. At a depth of about 1.5 m, the time lag is approximately one month. Below 10 m the ground temperature remains effectively constant at approximately the annual average air temperature (i.e., between 10° C and 14° C depending on local geology and soil conditions). The annual variation in ground temperatures at a depth of 1.7 m compared to the daily average air temperature measured at the site. It also shows the ground temperature at a depth of 75 m.

Ground temperature

The temperature difference between the ground and the circulating fluid in the heat exchanger drives the heat transfer. So it is important to know the ground temperature. The profile of soil temperature. As the depth increases the seasonal swing in temperature is reduced and the maximum and minimum soil temperatures begin to lag the temperatures at the surface (Figures 4-5) [16].

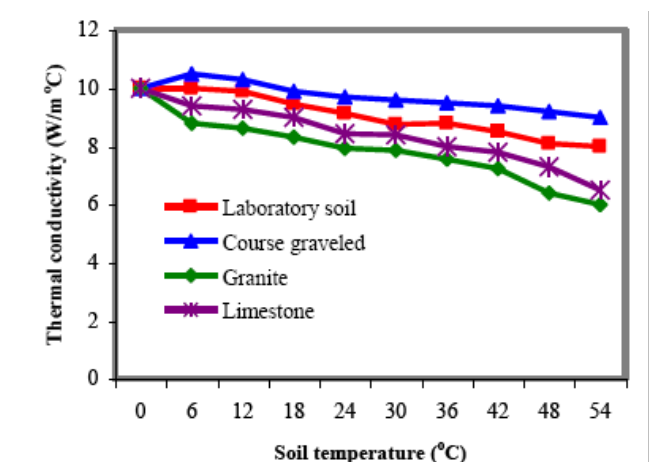


Figure 4: Comparison of thermal conductivity for different soils.

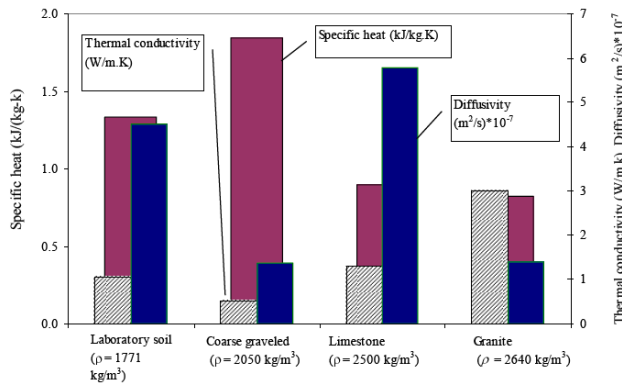


Figure 5: Thermal properties for different soils.

The temperature variation disappears at lower depth and below 10 m the temperature remains effectively constant at approximately the annual mean air temperature. It is important to maximise the efficiency of a heat pump when providing heating, not only to have a low heating distribution temperature but also to have as high a source temperature as possible. Overall efficiencies for the GSHPs are inherently higher than for air source heat pumps because ground temperatures are higher than the mean air temperature in winter and lower than the mean air temperature in summer. The ground temperature also remains relatively stable allowing the heat pump to operate close to its optimal design point whereas air temperatures vary both throughout the day and seasonally and are lowest at times of peak heating demand. For heat pumps using ambient air as the source, the evaporator coil is also likely to need defrosting at low temperatures. It is important to determine the depth of soil cover, the type of soil or rock and the ground temperature. The depth of soil cover may determine the possible configuration of the ground coil. In order to determine the length of heat exchanger needed to meet a given load the thermal properties of the ground will be needed. The most important difference is between soil and rock as rocks have significantly higher values for thermal conductivity. The moisture content of the soil also has a significant effect as dry loose soil traps air and has a lower thermal conductivity than moist packed soil. Low-conductivity soil may require as much as 50% more collector loop than highly conductive soil. Water movement across a particular site will also have a significant impact on heat transfer through the ground and can result in a smaller ground heat exchanger.

Geothermal energy and the other renewable energy sources are becoming attractive solutions for clean and sustainable energy needs. Being environmentally friendly and with the potential of energy-efficiency, the GSHP systems are widely used. Also, the need for alternative low-cost energy resources has given rise to the development of the GSHP systems for space cooling and heating in residential and commercial buildings. The GSHP systems work with the environment to provide clean, efficient and energy-saving heating and cooling the year round. The GSHP systems use less energy than alternative heating and cooling systems, helping to conserve the natural resources. The heat transfer between the GSHP and its surrounding soil affected by a number of factors such as working fluid properties (e.g., 20% glycol) and its flow conditions, soil thermal properties, soil moisture content and groundwater velocity and

properties, etc. Soil was a homogeneous porous medium, with its mass force, heat radiation effect and viscosity dissipation neglected. The local temperature of groundwater and soil arrived at a thermal equilibrium instantly (Figure 6) (Table 4).

Material	Peclet number L= a typical borehole spacing of (4.5 m)
Soil	
Gravel	572
Sand (coarse)	13.4
Sand (fine)	1.15
Silt	0.0128
Clay	0.000032
Rocks	
Limestone, Dolomite	0.00592
Karst limestone	5.28
Sandstone	0.00177
Shale	1.05E-06
Fractured igneous and metamorphic	0.0632
Unfractured igneous and metamorphic	1E-07

Table 4: Peclet numbers corresponding to typical values of thermal properties of soils and rocks.

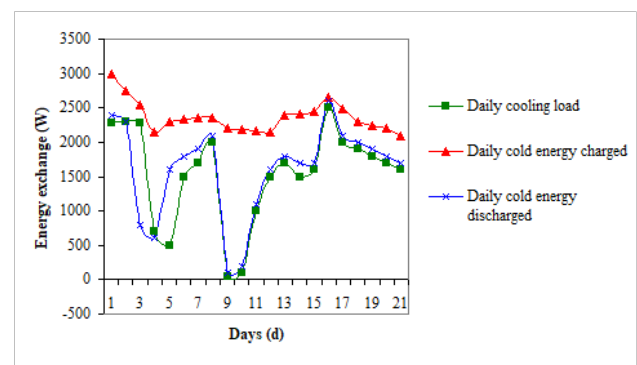


Figure 6: Simulation results in summer.

The thermal and physical properties of soil and its temperature at the far-field boundary remained constant. Heat transfer between a GSHP and its surrounding soil illustrated in, which shows the daily cold energy charged to and discharged from its surrounding soil using DX-GSHP at different days. The daily cold energy charged in the initial pre-cooling period sharply decreased, while during the normal operating period, it increased gradually, and the building cooling load although is

not big. The net energy exchange in the soil after one year of operation was only 3% of the total cold energy charged, which solved the soil temperature changing acutely to some extent after the yearly operation of the GSHP. The system is feasible technically and the operation mode is reasonable [17].

CONCLUSION

In the present work, the effects of sand-bentonite backfill materials on the thermal performance of the BHEs were analysed quantitatively. Laboratory thermal probe tests were conducted to measure the thermal conductivity of sand-bentonite mixtures under different mixed ratios. The mechanism of bentonite affecting heat conduction between the sand grains was revealed from the point of view of microscopic observations. Further, field tests were carried out to compare the thermal performance of two double U-shaped BHEs with different backfill materials. From the experimental results discussed above, the following conclusions can be obtained:

The thermal conductivity of sand-bentonite mixtures first increases with increasing percentage of bentonite by dry mass, then reaches a peak at the range from 10% to 12%, beyond which the thermal conductivity decreases quickly. That is to say, for sand-bentonite mixtures used as a backfill material of geothermal boreholes, there exists an optimal percentage of bentonite by dry mass, i.e., 10-12%. If the requirements on the thermal performance of the BHEs are not very strict, an extended range of 8-12% is also acceptable.

For the BHE with an optimal sand-bentonite backfill material, the heat injection and heat extraction rate can be enhanced on average by 31.1% and 22.2%, respectively, compared with the case with a common sand-clay material. The present results can provide helpful guides for the design of the GSHP systems.

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