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Field Test and Numerical Investigation on Long-term Performance of Deep Borehole Heat Exchanger Heating System Based on Pilot Projects in Xi'an, China

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ABSTRACT

The ground source heat pump is by far the most widely applied technology in geothermal energy utilization. To meet the heating demand in densely populated urban areas, the Deep Borehole Heat Exchanger (DBHE) coupled geothermal heat pump is increasingly being applied in northern China. In this paper, field test data collected from two pilot projects with two types of DBHE (coaxial and U-type) are reported and analyzed. Based on the Dual-continuum Finite Element Method, the heat transfer processes both within the DBHE and in the surrounding formation are simulated by the open-source software OpenGeoSys and validated against the field monitoring data. Long-term energy analysis of DBHE systems shows that the amount of heat extracted by the DBHE is mainly supplied by the thermal energy stored in the subsurface. Furthermore, based on the short-term thermal performance test and long-term thermal response analysis, the long-term performance of the DBHE heating system equipped with coaxial DBHE is then evaluated. Last but not least, considering the official electricity price and dynamic operational consumption of the heat pump and circulation pump, the optimal design of the drilling depth for the coaxial DBHE is determined by conducting an entire lifespan economic analysis. The Levelized cost of heating and net present values are discussed in detail. The related work and recommended design value can serve as a reference for the corresponding decision-makers, researchers, and users in the geothermal community.

1. INTRODUCTION

In order to achieve the goal of limiting global warming to well below 2 °C, preferably to 1.5 °C, compared to pre-industrial levels, countries all over the world are currently pursuing the transition from conventional carbon-intensive energy system to renewable and decarbonized energy supply[1]. It is worth noting that the building sector for heating, cooling, and lighting accounts for about 40 % of the total energy consumption, leading to a significant environmental impact in CO_2 emission[2]. Within the building sector, the proportions of space heating and domestic hot water consume more than 75 %[3] and 40 %[4] of the energy consumption in Europe and China, respectively. For building heating, geothermal energy has attracted growing applications due to its stability, environmental friendliness and wide availability [5,6], which possesses a considerable potential in reducing the carbon emission.

Traditionally, Ground Source Heat Pumps (GSHP) are coupled with multiple Borehole Heat Exchangers (BHEs) to extract or inject heat out of or into the shallow subsurface to provide building heating/cooling. For commercial projects or residential neighborhoods, the high demand for thermal load often prevents its application due to the requirement on a large area to drill hundreds of BHEs, which is often not feasible in densely populated urban areas. In order to further explore the potential of geothermal energy, Compared to the conventional shallow borehole heat exchanger array, the concept of Deep Borehole Heat Exchanger (DBHE), typically with a coaxial pipe which has a depth of more than 2,000 m, was first proposed in the 1990s[7]. A pilot project in Switzerland was constructed with this concept[8]. By circulating fluid inside the DBHE, sensible heat stored in the surrounding rock and soil can be extracted and supplied to the building. Due to its low requirement on large land area and high thermal output, DBHE coupled heat pump has gained lots of attention throughout the world[9]. This technology is especially increasing being utilized in northern China recently, to meet the growing demand for renewable heating sources in the densely populated urban environments. Coupled with heat pump units to elevate the outlet temperature, the DBHE heating system can properly serve for building heating purpose. Thus, DBHE coupled heat pumps is increasingly being applied in northern China since 2013, with a currently installed servicing building areas of 30 million square meters[10].

To investigate the heat extraction performance of DBHE and its sustainability, considerable research work has been carried out. With regard to heat extraction performance, the impact of design and operation parameters has been investigated in the aforementioned studies, involving borehole depth, geological conditions, and circulating flow rate [11]. Related work also aims at the sustainability of DBHE, especially the trend in heat extraction performance under short[12] and long-term operation period[13]. These studies are often carried out by establishing a heat transport model inside and around the DBHE, with either analytical or numerical approaches. Analytical solutions have a great advantage in calculation speed, but they may not be able to precisely handle the complex geological conditions in the deep subsurface[14,15]. Hence numerical models were chosen by many researchers in favor of its versatility and flexibility. Numerical models are usually established with commercial and open-source modeling software, and they have already been successfully used for the analysis of heat extraction performance and sustainability of DBHE, such as using MATLAB (Finite Difference Method[16], Finite Volume Method[17]), COMSOL[18], FLUENT[19], FEFLOW[20] and OpenGeoSys[21]. The hybrid numerical model is also proposed by Pang et al., in which the analytical model is coupled with the 2D numerical domain to accelerate the calculation[22,23]. Except for the conventional coaxial DBHE, a new kind of U-type DBHE is also proposed in recent years. The schematic diagrams for the DCBHE and DUBHE can be seen in Figure 1. There are also several research about the heat extraction performance of DUBHE are reported and analyzed[24-26].

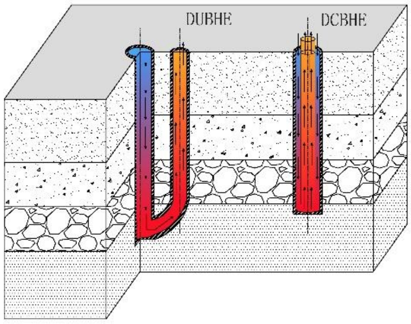

Figure 1: Schematic diagrams for the two types of DBHE (Left: DUBHE; Right: DCBHE).

However, most of the above studies are focusing on the sensitivity analysis for the heat extraction performance of the DBHE, in which the energy transfer features within the 3D domain and the dominant mechanism of the heat extraction process are not depicted. Since the DBHEs are always used for long-term heating and already have two types of pattern, an efficient method to solve the long-term 3D heat transfer process for both two types of DBHE needs to be proposed. Also, a thorough quantified economic analysis procedure for the DBHE system is needed for parameter optimization and project design. Therefore, a series of scientific questions arise when the DBHE system is applied for building heating purposes: How to simulate the long-term 3D heat transfer process of DBHE (including both the coaxial and U-type) in an acceptable computational time? What is the energy source of the heat amount extracted by the DBHE? How to determine the optimal parameters for the DBHE system in the entire lifespan, with the dynamic performance variation of DBHE being carefully considered?

In this work, we would like to answer the above scientific questions by the combination of numerical simulation with monitoring data. First, the numerical models are proposed and developed in OpenGeoSys software for simulating the DBHE system, including coaxial and U-type. Second, long-term field tests for two pilot projects with two types of DBHE are reported and the two corresponding numerical models are validated against the in-situ monitored data. Third, a long-term energy analysis of DBHE systems is further conducted by extended numerical simulations. The method of thermal performance test and thermal response analysis are systematically illustrated. Finally, considering the local electricity price and calculation of power assumed by the heat pump and circulation pump, the economic evaluation of the DBHE heating systems with different drilling depths has been carried out. The entire procedure for optimizing the design parameters for the DBHE system is presented and the importance of long-term dynamic performance is emphasized.

2. METHODOLOGY

In this section, the mathematical framework and governing equations of the DBHE model are introduced.

2.1 Model description

In the present model framework for DBHE simulation, many researchers select different numerical approaches, since they are more capable of handling the flexible initial and boundary conditions that emerge from the field study. Specifically, the two-dimensional (2D) axial-symmetric domain is widely chosen because of its simplicity and potential in saving computational resources. However, when investigating the energy transfer features within the domain and thermal interaction among multiple DBHEs, 2D axial-symmetric domains are no longer sufficient. Especially when the subsurface stratification and heterogeneous thermal characteristics of the layers are considered, a fully discretized 3D domain has to be constructed with DBHEs explicitly depicted in it. If one chooses a 3D, fully discretized numerical model, considering both the kilometer deep subsurface and millimeter-wise borehole details, the size of the mesh will explode exponentially at the location inside and near the borehole, making it virtually impossible to manipulate the mesh with huge elements and run long-term simulations.

In OpenGeoSys (OGS) software, the Dual Continuum Finite Element Method (DC-FEM) has been successfully implemented [21]. This numerical approach was originally proposed by Al- Khoury et al.[27], and extended by Diersch et al.[28,29]. It has been successfully used in the analysis of borehole heat exchangers coupled heat pump system, in which the calculation speed for simulation of long-term operation is kept at an acceptable level.

Following the DC-FEM idea, the model domain is divided into two different compartments, which consist of the borehole and the surrounding subsurface. For the borehole compartment, not all details are discretized and added into the finite element mesh. The boreholes themselves are treated as line elements. Hydraulic and heat processes of the borehole, including fluid circulation in the pipe, together with the associated heat transport through the grout to the soil, are calculated by governing equations on these 1D vertical line elements. For the soil compartment, 3D prism elements are commonly used to discretize the different sediment layers. There the convective and conductive heat balance equation is solved for the 3D model domain, reflecting heat dissipation in the subsurface. This makes the number of mesh nodes in the domain to be dramatically reduced while high-level accuracy is still achieved, so that the long-term simulation of DBHE is made possible. The heat exchange between the borehole and the surrounding soil is then regulated by the heat flux calculation that depends on the temperature difference between the two compartments (see Figure 2). For the DBHE compartment, the heat flux leaving always means that the same amount of heat will be received by the soil compartment, and vice versa. This setup assures the overall thermal balance.

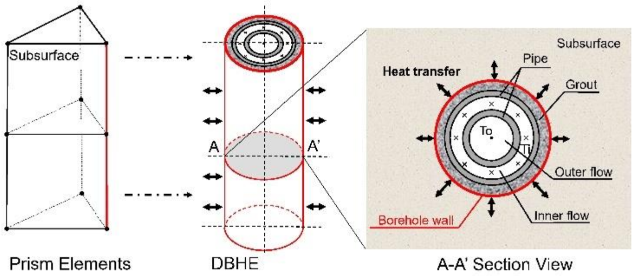

Figure 2: Heat transfer between the coaxial DBHE in borehole and surrounding subsurface.

2.2 Governing equations

In the DBHE calculation module implemented in OpenGeoSys software, several features, including the multi-layer geological conditions, geothermal gradient, and groundwater seepage, can be easily added to the model for precise simulation. The governing equations for heat conduction and convection deployed in the OpenGeoSys software are listed below. The governing equations for the soil surrounding the borehole are given by

$$\frac{\partial}{\partial t}[\varepsilon\rho^f c^f + (1-\varepsilon)\rho^s c^s]T_s + \nabla\cdot(\rho^f c^f \boldsymbol{v}\, T_s) - \nabla\cdot(\boldsymbol{\Lambda}^s \cdot \nabla T_s) = H_s \tag{1}$$

where ρ is density, kg·m^{-3}; c is volumetric heat capacity, J·kg^{-1}·K^{-1}; ε is porosity; $\boldsymbol{v}$ is Darcy velocity, m·s^{-1}; $\boldsymbol{\Lambda}^s$ denotes heat dispersion tensor, W·m^{-1}·K^{-1}; H_s is the source term, W·m^{-3}. *f* and *s* denote fluid and soil, respectively.

with the Robin type of boundary condition (BC):

$$-\Phi_{gs}(T_g - T_s) = q_{nT_s} \tag{2}$$

where Φ is heat transfer coefficient, W·m^{-2}·K^{-1}; T is temperature, K; q_n is surface heat flux, W·m^{-2}. *g* denotes surrounding grout.

For the grout surrounding the pipe, governing equation reads

$$\rho^g c^g \frac{\partial T_g}{\partial t} - \nabla\cdot(\lambda^g \cdot \nabla T_g) = H_g \text{ in } \Omega_g \tag{3}$$

with the Robin type of BC:

$$-\Phi_{ig}(T_i - T_g) - \Phi_{gs}(T_s - T_g) = q_{nT_g} \tag{4}$$

The governing equations for the circulation fluid within the borehole for the CXA type of DCBHE[21] are given by

$$\rho^c c^c \frac{\partial T_o}{\partial t} + \rho^c c^c u \nabla T_o - \nabla\cdot(\lambda^c \cdot \nabla T_o) = H_i \text{ in } \Omega_i \tag{5}$$

$$\rho^c c^c \frac{\partial T_i}{\partial t} + \rho^c c^c u \nabla T_i - \nabla\cdot(\lambda^c \cdot \nabla T_i) = H_o \text{ in } \Omega_o \tag{6}$$

with the Robin type of BC:

$$-\Phi_{oi}(T_i - T_o) = q_{nT_o} \tag{7}$$

$$-\Phi_{oi}(T_o - T_i) - \Phi_{ig}(T_g - T_i) = q_{nT_i} \tag{8}$$

Governing equations for other types of DBHE can be found in the previous publication of our research group. The detailed calculation of thermal resistance between soil/grout and boreholes can also be found in Diersch et al[28].

3. FIELD TEST AND MODEL VALIDATION

In the next step, the DBHE model implemented in OpenGeoSys considering the geothermal gradient impact is verified against the analytical DBHE solution proposed by Beier[15]. The setting of related parameters can be found in Table 1 and the operation time is set as one entire heating season.

Table 1: Detailed parameters of the DBHE verification.

Item	Parameter	Value	Unit
Borehole	Borehole depth	2500	m
	Borehole diameter	0.2413	m
	Outer diameter of inner tube	0.1100	m
	Wall thickness of inner tube	0.0100	m
	Thermal conductivity of inner tube wall	0.42	$W \cdot m^{-1} \cdot K^{-1}$
	Outer diameter of outer pipe	0.1778	m
	Wall thickness of outer pipe	0.0092	m
	Thermal conductivity of outer pipe wall	40	$W \cdot m^{-1} \cdot K^{-1}$
	Heat extraction capacity	250	kW
	Outer diameter of inner tube	0.1100	m
Soil	Density	1.76×10^3	$kg\ m^{-3}$
	Specific heat capacity	1.43×10^3	$J\ kg^{-1}\ K^{-1}$
	Thermal conductivity	2.2	$W \cdot m^{-1} \cdot K^{-1}$
Grout	Density	2.19×10^3	$kg\ m^{-3}$
	Specific heat capacity	1.73×10^3	$J\ kg^{-1}\ K^{-1}$
	Thermal conductivity	1.4	$W\ m^{-1}\ K^{-1}$
Circulating fluid	Thermal conductivity	0.6	$W\ m^{-1}\ K^{-1}$
	Specific heat capacity	4.19×10^3	$J\ kg^{-1}\ K^{-1}$
	Density	998	$kg\ m^{-3}$
	Dynamic viscosity	9.31×10^{-4}	$kg\ m^{-1}\ s^{-1}$

The verification results (see Figure 3) show that the circulation temperatures calculated by the OpenGeoSys match well against Beier's model. At the end of the heating season, the maximum difference between the results calculated by two models is no more than 0.57 °C (less than 2.2 %). Throughout the simulation, the inlet and outlet temperatures calculated by the OpenGeoSys are slightly higher than Beier's model, which can be explained by the different calculation method in non-dimensional number within the DBHE between the OpenGeoSys and Beier's model. This verification ensures that our model has enough accuracy and can be used in conducting the related studies of the DBHE.

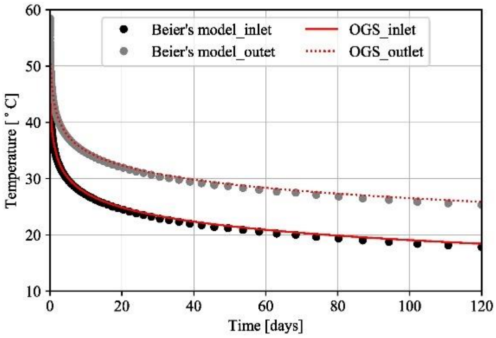

Figure 3: Verification of the proposed DBHE model based on OpenGeoSys against Beier's analytical solution.

Furthermore, to investigate the heat extraction performance of the in-situ DBHE heating system, two pilot projects (a DBHE and a DUBHE) located in the city of Xi'an, China have been built and closely monitored. The corresponding monitoring data from two pilot projects are used to validate the two numerical models in this work. For the initial condition, the in-situ geothermal gradient is measured and used in the simulation (See Figure 4).

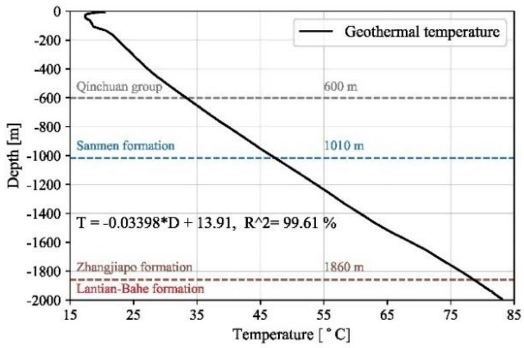

Figure 4: In-situ test of geothermal gradient at the location of pilots projects.

In order to prevent the thermal plume from interfering with the domain boundary, the domain size is set to be 300 × 300 × (Depth + 200) m. As for the model setting, at the top and bottom surface of the model domain, the average ambient air temperature of 14.8 °C and typical geothermal heat flux 60 mW m^{-2} of Xi'an are imposed as Dirichlet and Neumann boundary conditions respectively. The geological parameters are set according to the published geological data[30] and in-situ test results from realistic projects. In addition, the monitored inlet temperature and flow rate are imposed on the inlet of the DBHE as part of the boundary conditions of the numerical model. The calculated outlet temperature is used to compared with the monitored outlet temperature.

3.1 DCBHE project

The pilot project with a DCBHE array is built for a residential community in Xi'an city, China. The DBHE array is coupled with heat pumps to supply heating to a neighborhood with a total floor area of ca. 56,000 m^2. Five deep boreholes were drilled to a depth of 2000 m and serve as the heat source. All other detailed parameters of the DBHEs system are summarized in our previous publication[31]. The thermo-physical parameters of each geological stratification are measured and provided by the building construction company. Since this is a pilot project, a Building Energy Management System (BEMS) was installed to monitor and record all the operational parameters related to heating, lighting and power consumption in the building. The monitor system was in adjustment during the starting couple of days of the heating season, monitoring data was thus only available starting from Nov. 30th, 2018 to Mar. 15th, 2019 (altogether 106 days in total). In this study, our purpose is to investigate the heat extraction performance of DCBHE. Therefore, only monitored data of inlet and outlet temperature of the DCBHE array and flow rate of the ground circulation recorded at a 10 min interval was picked up from the BEMS system. This data set can be used for model validation.

The monitored and simulated temperature profiles are compared in Figure 5. In contrast to the monitored outlet temperature, the simulated values match the measured data quite well. The relative difference between monitored and simulated values is only 1.10 °C (5.01 %), which is well below the accuracy of flow rate sensor. At the end of the heating season (from Mar. 10th to Mar. 15th), due to the low level of heating demand, the heat pump is frequently switched on and off. This leads to a strong oscillation in the temperature profile. Yet, the numerical model is capable of capturing the oscillating feature. For the remaining majority part of the heating season, the simulated results are in good agreement with the monitored data, with the difference typically less than 0.2 °C (ca. 1.0 %). This ensures that the OpenGeoSys model has enough accuracy to capture the heat extraction characteristics of the system.

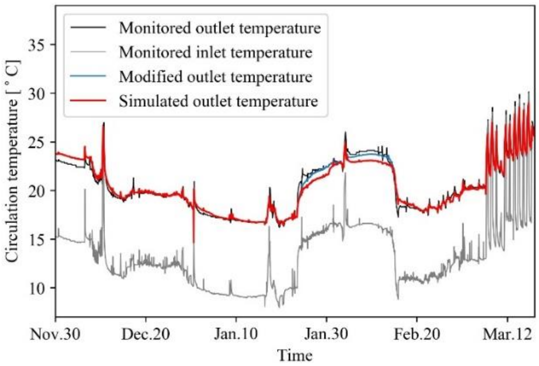

Figure 5: Validation results between monitored data and simulated results for DCBHE system.

3.2 DUBHE project

The pilot heating project equipped with a DUBHE is built in Xi'an, China in 2018 (The borehole drilling part is finished in 2017). After testing and commissioning, the DUBHE heating system starts running in the winter of 2020 officially. Figure 6 shows the detailed parameters of the DUBHE used in the pilot project.

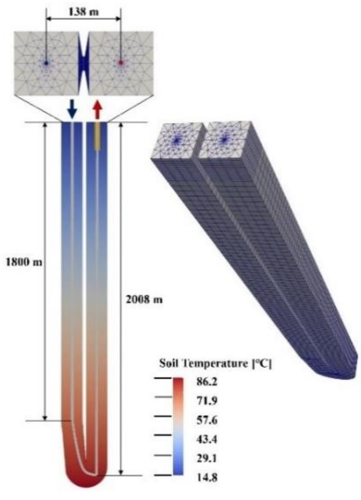

Figure 6: The established DUBHE domain based on the parameters of the pilot project.

The DUBHE has a depth of 2008 m for the upward borehole and 1800 m for the downward borehole. A lateral borehole is constructed to connect the two vertical boreholes by an automatic guidance drill. The ground distance between two boreholes is 138 m to avoid thermal interference with each other. To capture the dynamic performance variation of DUBHE, the electromagnetic flow sensors (Type lks350) with an accuracy of 0.5 % are equipped at the top of boreholes. The thermocouple temperature sensors are also set at both the inlet and outlet of DUBHE, in which its accuracy is 0.2 °C. The results of flow rate and temperature are recorded at an interval of 5 min. The test was conducted from Nov. 16th, 2020 to Jan. 14th, 2021(60 days in total). Figure 7 shows that the monitored circulation temperature of DUBHE tends to gradually decrease through the test period, with an average temperature difference of 8.17 °C between inlet and outlet temperatures. After 60 days of operation, the inlet and outlet temperatures suffer obvious temperature decrements. It can be seen that the circulation temperature drop happens mostly in the first 30 days of operation. Since then, the circulation temperature of DUBHE remains stable. Also, three times of power shut-down can be found in the first half of the operation period. These short-term shut-downs have been confirmed as routine maintenance so that they will not bring visible effects to the heat extraction process of DUBHE. It can be obviously seen that the calculated results from the numerical model are in good agreement with the monitored data, with the average difference being no more than 0.27 °C (ca. 1.02 %). This validation guarantees that the DUBHE model implemented in OpenGeoSys[32] has acceptable accuracy and is capable of capturing the heat transfer characteristic between the subsurface and the boreholes. Overall, the two models implemented in OGS can be used to simulate the DBHE system, including the DCBHE and DUBHE types.

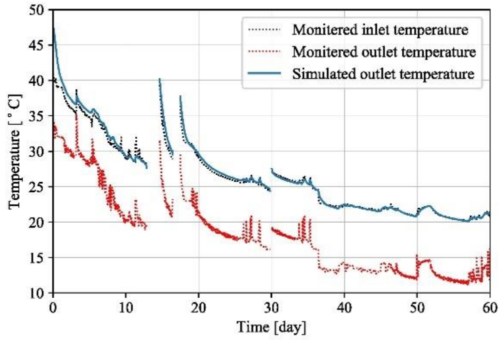

Figure 7: Validation results between monitored data and simulated results for DUBHE system.

4. RESULTS

In this section, energy transfer characteristics within the domain for DBHE system is studied. Moreover, the sustainability of the DBHE system and economic analysis are also evaluated. In order to simplify the description, the DCBHE system is chosen to be presented. The similar methods can also be applied to the DUBHE system.

4.1 Energy analysis

After the calculation of OpenGeoSys finished, the ParaView software[33] is then introduced to conduct the post-process procedure. With help of the Python scripts, the variation of energy within each cell in the domain is captured. Thus, the reduction of heat amount stored in the surrounding soil can be quantitively determined during the operation period. A DCBHE with a depth of 2500 m is selected and heat extraction capacity per length is set as 120 W/m, which means a 3110 GJ of annual heat extraction amount.

Figure 8 illustrates the proportion of the energy sources in the process of heat extraction of DBHE. The total heat extraction amount of the DBHE is 3100 GJ (dotted line in black) during the annual heating season. After post-process and energy analysis, it can be seen that the total amount of energy reduction in the surrounding soil of the domain is slightly decreased, which maintains above 3000 GJ during the operation period. Meanwhile, the heat supply from the bottom of DBHE has a gradual increment from 34 GJ at the 1st year to 79 GJ at the 15th year. Overall, most of the heat amount extracted by the DBHE (more than 98% in the reference case) is provided by the heat amount stored within the surrounding soil/rock.

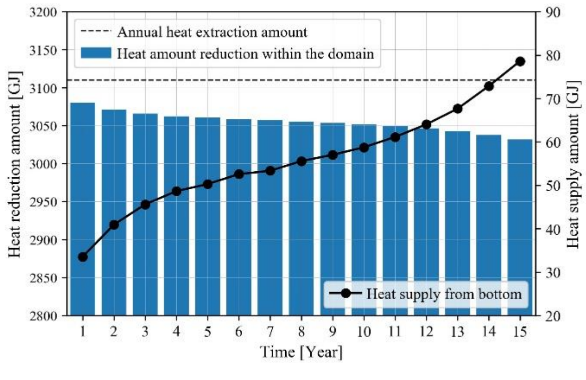

Figure 8: Energy source for heat extraction process of DBHE.

In order to further investigate the impact of the ambient temperature during the heat extraction process of the DBHE, the variation of energy within the control volume near the ground surface is counted. The first type of Dirichlet BC is imposed at the top boundary, with an average temperature of 14.8 °C. It can be seen from Figure 9 that, except for the first two years, the annual energy dissipated from the ground surface during the heat extraction of DBHE is less than 1 GJ. The reason for the high dissipation in the first two years is the relatively high temperature of the shallow ground, which is heated by the high-temperature circulation fluid. Considering the absolute value of dissipated energy, in the modeling of the heat extraction process of the DBHE, a fixed-value set of surface temperature is accepted, and the heat dissipation effect at the top boundary can be neglected.

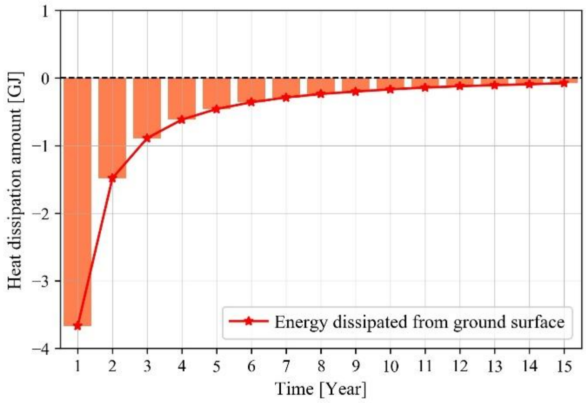

Figure 9: Energy dissipated from ground surface during the heat extraction of DBHE.

4.2 Optimization of the DCBHE with different depths

In this section, a comprehensive approach for the long-term economic evaluation and parameter optimization of the DBHE heating system is proposed, in which the heat extraction performance, electricity consumption of heat pump and circulation pump, and initial costs are all taken into account. To facilitate the economic analysis and not hinder the correctness of the main conclusion, the reference parameters in Xi'an is selected and several assumptions made in this study are listed as follows:

- The economic analysis of the DBHE heating system will just focus on the variation of performance of heat source, which contains the DBHE, circulation pump of heat source, and heat pump. Also, the prescriptive heating season for Weihe Basin, Shaanxi, lasts 4 months, from November 15th to the next March 15th.

- The energy analysis shows that most of the heat amount extracted by the DBHE is from the energy stored within the surrounding soil. The milliwatt-level geothermal flux cannot fill the energy gap within the domain caused by the kilowatt-level heat extraction process of DBHE. Thus, the DBHE will suffer a performance attenuation during long-term operation and the circulation temperature will have a severe fluctuation. Therefore, for the DBHE heating system, dynamic evaluation for the circulation temperature and corresponding values (e.g. COP of heat pump) should be conducted in long-term. Also, to prevent pollution on deep groundwater resources, the anti-freeze solution is not allowed to add to the DBHE system. Thus, the inlet temperature of the DBHE should not fall below 0 °C to prevent freeze in pipes. With these assumptions, the maximum heat extraction capacity will be obtained for the convenience of further economic analysis.

- The circulation temperatures for user side and building of heat pump will be just in correlation to the inlet temperature of heat pump on the source side. According to the reference sample[34], the COP of heat pump is determined by

$$COP_{hp} = a_1 T_{out} + b_1 \quad (9)$$

  where a_1 and b_1 are the coefficients, which are 3.925 and 0.083 while serving for heating purpose, respectively.

- The drilling cost data are acquired from a local drilling company in Xi'an and the official electricity price is set to 0.7669 Yuan/kWh[35]. The electricity consumption of circulation pump is calculated based on the flow friction of the DBHE, which is determined by the Darcy-Weishbach equation. Also, the Darcy friction factor is calculated by Churchill correlation. Then, the Levelized cost of energy (LCOH) and Net present value (NPV) can be calculated by

$$LCOH = \frac{C_{ini} + \sum_{i=1}^{N} \frac{C_{ann}}{(1+r)^i}}{\sum_{i=1}^{N} \frac{Q_{tot}}{(1+r)^i}} \quad (10)$$

$$NPV = \sum_{i=1}^{N} \frac{C_b - C_{ann}}{(1+r)^i} - C_{ini} \quad (11)$$

  where C_{ini}, C_{ann}, and C_b are initial cost, annual cost, and annual benefit of the DBHE heating system, respectively. N is the typical operation period of HVAC system, which is set to 15 years. r is the discount rate, which is 6% for typical HVAC system. Q_{tot} is the total heating amount supplied from the DBHE heating system to the building sector.

4.2.1 Long-term heat extraction performance of the DCBHE

Generally, there are two types of boundary conditions imposed on the DBHE, including fixed inlet temperature and fixed heat extraction rate, which correspond to the so-called thermal performance test and thermal response analysis. For a certain depth of the DBHE, to quantify its maximum heat extraction capacity, the boundary condition of fixed inlet temperature is chosen for the DBHE in this section. All inlet temperatures are fixed at 4 °C, which is the threshold of circulation temperature in the heat pump unit. The flow rate of circulation fluid is 0.01 m^3/s for different depths of the DBHE.

The outlet temperature evolution of DBHEs with different depths over the first heating season is presented in Figure 10. For all the thermal performance tests for the DBHE with different depths, the outlet temperatures tend to have a rapid dropdown at the first couple of days. For example, the outlet temperature of the DBHE with 3,000 m decreases by 10.42 °C in the first 60 days, while the temperature drop is only 1.39 °C in the next 60 days. The trend of outlet temperature variation indicates that the heat extraction rate of the DBHE after 60 days does not change too much. When looking into the outlet temperatures among DBHEs with different depths, it has a higher value with deeper depth. While reaching the end of the heating season (marked in bold in Figure 10), the outlet temperatures for five different depths are 9.87, 13.22, 17.06, 21.34, and 26.01 °C, respectively. In a conservative way of calculating a tentative heat extraction capacity, the corresponding values are calculated according to the temperature difference at the end of the heating season.

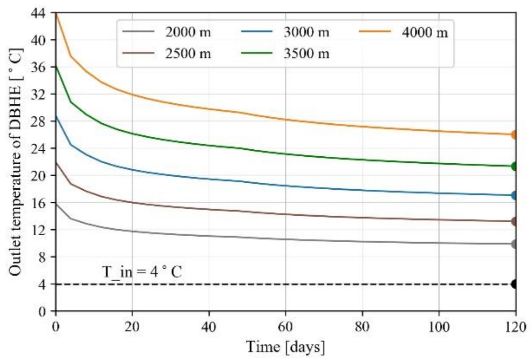

Figure 10: Thermal performance test of heat extraction capacity for the DBHE with different drilling depths.

In a more practical case, the inlet temperature of DBHE cannot be fixed in long-term operation, while the heating demand is usually kept fixed in short term. Therefore, for long-term simulation of the DBHE, the fixed heat extraction rate is imposed to mimic real-world projects. In this section, the fixed heat extraction rate is imposed according to the calculated tentative heat extraction capacities from short- term thermal performance tests in the previous section. If the temperature drop of circulation fluid after the long-term operation is too large (below 0 °C and will have a risk of freeze) or too small (the DBHE can provide higher heating capacity), the heat extraction capacity will be adjusted until a proper value is obtained. For the five scenarios, the adjusted heat extraction rates are determined to reach these upper-limit and then the maximum heat extraction capacity are used for thermal response analysis.

Figure 11 shows the results of the thermal response analysis of DBHE. According to Figure 11, with the increasing operation time, a severe drop in the inlet and outlet temperature of the DBHE can be seen. Also, under a 15-year operation, the inlet temperatures of the five scenarios with their maximum heat extraction capacity just reached the 0 °C threshold at the end of the 15th heating season. This indicates that the corresponding heat extraction rates have reached the upper limit of the heat extraction potential of DBHE. Thus, the calculation results can be used for further economic evaluation.

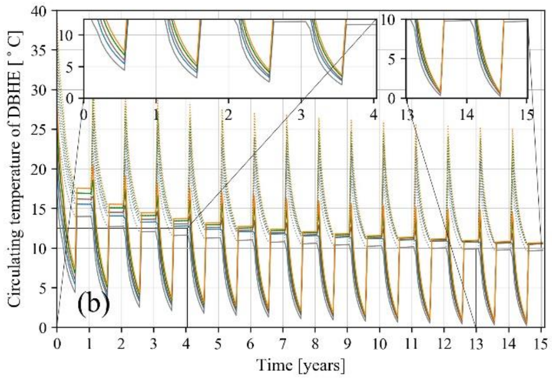

Figure 11: Thermal response analysis for the DBHE with different drilling depths during long-term heat extraction.

4.2.2 Economic analysis for the DCBHE heating system

From the aforementioned investigation, it is clearly known that the DBHE heating system with deeper drilling depth has higher considerable heat extraction rate while it consumes more electricity on heat pump and circulation pump. Therefore, a combined economic analysis for the DBHE heating system during long-term operation is necessary to illustrate the system applicability. Figure 12 and Figure 13 depict the LCOH and NPV for the DBHE heating system with different depths. With deeper depth of the DBHE, the LCOH of the DBHE heating system decreases from 0.391 Yuan (2,000 m) to 0.325 Yuan (3,000 m). Then the LCOH shows a slow increase to 0.347 Yuan (4,000 m), which means that the DBHE heating system with a drilling depth of 3,000 m has the slowest LCOH. For the DBHE heating system with depth of 3,000 m, its levelized cost of total heating amount is lower than other systems with shallower or deeper depths, which can give reference to parameter design in applying the DBHE heating system in Xi'an city. Also, Figure 13 illustrates the NPV variation over long-term operation of the DBHE with the depth of 3,000 m. It can be seen that the NPV value shows an approximate-linear increase over the operation of 15 years. After 10-year operation, the NPV turns to be higher than zero, which illustrates that the pay-off time of the 3,000 m DBHE is around 10 years.

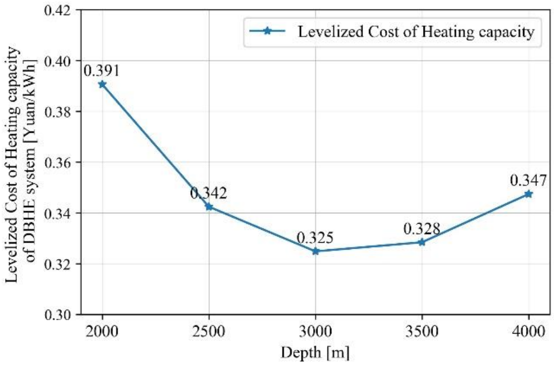

Figure 12: The LCOH value for the DBHE heating system with different drilling depths.

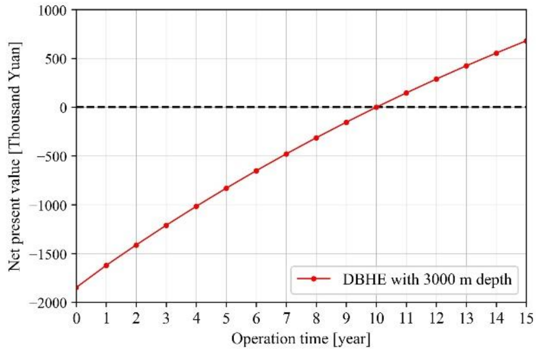

Figure 13: The NPV value for the DBHE heating system with different drilling depths.

5. CONCLUSION

In this study, the two versatile numerical models are developed in the open-source software OpenGeoSys for simulating the DBHE system, which can cope with both the coaxial and U-type patterns. Long-term field tests for two pilot projects with two types of DBHE are conducted and the numerical model is validated against the in-situ monitored data. Long-term energy analysis indicated by numerical models of DBHE systems shows that the amount of heat extracted by the DBHE is mainly supplied by the thermal energy stored within the surrounding formation instead of bottom or ground surface heat flux compensation. The economic feasibility of the DBHE heating systems with different drilling depths has been evaluated as well above the numerical simulations. Then, according to the local electricity price and calculation of power consumed by the heat pump and circulation pump, a combined economic analysis and parameter optimization for the DBHE heating system is further performed and investigated. To be more specific:

- The two versatile numerical models in OpenGeoSys software can rapidly simulate the 3D heat transfer process for both the coaxial and U-type DBHE. Based on the in-situ measured data from pilot projects, the models are validated and proven to have high accuracy.

- Most of the heat amount extracted by the DBHE (more than 98% in the reference case) is provided by the heat amount stored within the surrounding soil/rock. In the modeling of the heat extraction process of the DBHE, a fixed-value set of surface temperature is accepted, and the heat dissipation effect at the top boundary can be neglected.

- Based on the thermal performance test and thermal response analysis, a deeper DBHE has a higher sustainable heat extraction rate in the short and long terms. With the fixed heat extraction rate imposed on the DBHE, the DBHE heating system with a deeper drilling borehole has better performance and efficiency.

- The total electricity consumption of heat pumps and circulation pumps has a prominent promotion with a deeper drilling depth of the DBHE. A thorough analysis of LCOH and NPV values based on the geological and economic conditions in the Weihe basin has been concluded and the depth of 3000 m is the optimal drilling depth under the given scenario. For specific project design, careful long-term performance evaluation for the DBHE system is strongly suggested for the corresponding decision-makers.

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