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EFFECTS OF HEATING LOAD ON HEAT TRANSFER PERFORMANCE OF MEDIUM-DEEP BOREHOLE HEAT EXCHANGER

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ABSTRACT

At present the medium-deep borehole heat exchanger (MDBHE) performance was usually analyzed under the typical condition that inlet fluid temperature is deemed as constant. In practical application, inlet temperature is often related to the heating load. In this paper, the effects of heating load on the heat transfer performance of the MDBHE was investigated based on the proposed numerical model which has been validated. The sensitive analysis was implemented to analyze the variation regulations of inlet and outlet temperatures of pipe and thermal effect radius of rock-soil under different heating loads. Furthermore, the MDBHE performance was compared between the two scenarios: constant heating load and constant inlet temperature. The simulation results indicated that under high heating load, the fluid temperature of MDBHE varies substantially during the heat transfer process. Besides, annual drop of inlet temperature should be paid attention. The rock-soil temperature in vertical direction was influenced significantly by the heating load, while the thermal effect radius of rock-soil was affected slightly.

Keywords: heating load, heat transfer, medium-deep, borehole heat exchanger

1. INTRODUCTION

Utilization of the geothermal energy for building heating contributes to relieve energy pressure and decrease pollution resulted in atmosphere environment. In recent years, the intensive attentions are attracted on the medium-deep geothermal with good renewability and high energy grade in subsurface between 2000-3000 m which is extracted by the medium-deep borehole heat exchanger (MDBHE). The observation of the heating data in field test proved that the MDBHE shows a superior thermal extraction performance than shallow borehole heat exchanger [1,2] and is gradually accepted due to considerable economic benefit in operation and small land demand [3]. Afterwards, thermal behavior of the MDBHE were investigated in detail. Liu [4] analyzed the effects of design parameters on heat transfer capacity, energy efficiency coefficient of the MDBHE. Lous [5] studied the thermal effect radius of rock-soil for MDBHE thermal extraction. Cai [6] investigated the MDBHE performance under different operation modes. Above mentioned researches are quoteworthy for optimizing the thermal performance. Nevertheless, the inlet fluid temperature was deemed constant in previous studies. In practical application (Fig. 1), fluid flows from pipe outlet to building for heating supply and then flows back to pipe inlet. Inlet temperature is related to the heating load. As reported in Ref. [7], the inlet fluid temperature varies with operating time under the condition of constant heating load.

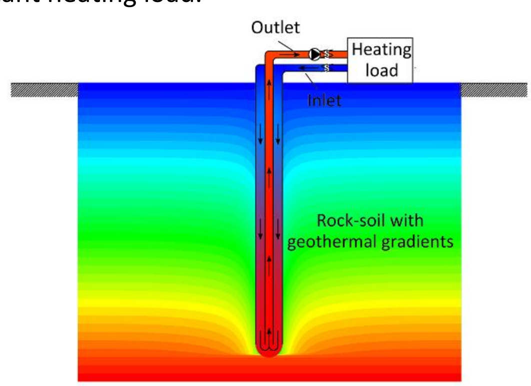

Fig 1 Schematic diagram of thermal extraction of MDBHE

MDBHE performance varies with the heating load, besides MDBHE extracts the medium-deep geothermal in heating season and stops running in non-heating one. Therefore, it is important to investigate the effects of heating load on heat transfer performance of the MDBHE by combining with its operation characteristics, which has not been reported yet.

2. NUMERICAL ANALYSIS

2.1 Numerical model

The presented model consists of a one-dimensional model of MDBHE and a two-dimensional model of rock-soil. The temperature variations of fluid in inner pipe and annular space can be formulated by energy conservation equation (Eq. (1) and Eq. (2), respectively) as follows:

$$\frac{\partial T_{fr}}{\partial t}+\frac{\partial (V_{fr}\cdot T_{fr})}{\partial z}=\frac{k(T_{fR}-T_{fr})}{\rho_f A_r c_{pf}} \quad (1)$$

$$\frac{\partial T_{fR}}{\partial t}+\frac{\partial (V_{fR}\cdot T_{fR})}{\partial z}=\frac{K(T_w-T_{fR})}{\rho_f A_R c_{pf}}-\frac{k(T_{fR}-T_{fr})}{\rho_f A_R c_{pf}} \quad (2)$$

where the subscript "fr", "fR" indicate the fluid in inner pipe and annular space, respectively. "w" indicates the outer pipe wall, and "f" indicates the fluid. A_r , A_R are the cross section areas of inner pipe and annular space, respectively; k is thermal resistance between the fluid in annular space and that in inner pipe; K is the thermal resistance between the fluid in annular space and outer pipe wall (Eq. (4)).

$$k=\frac{\pi}{\frac{1}{2h_r r_1}+\frac{1}{2\lambda_r}\ln\frac{r_2}{r_1}+\frac{1}{2h_R r_2}} \quad (3)$$

$$K=\frac{\pi}{\frac{1}{2h_R}+\frac{1}{2\lambda_R}\ln\frac{R_2}{R_1}} \quad (4)$$

where the subscripts "r", "R" indicate the inner pipe and outer pipe, respectively. r_1 , r_2 are inner radius and outer radius of inner pipe, respectively; R_1 , R_2 are inner radius and outer radius of outer pipe, respectively.

The heat transfer of rock-soil is formulated according to the heat conduction governing equation in cylindrical coordinate as follow:

$$\rho_s c_{ps}\frac{\partial T_s}{\partial t}=\frac{\partial}{\partial z}(\lambda_s\frac{\partial T_s}{\partial z})+\frac{1}{r}\frac{\partial}{\partial r}(r\lambda_s\frac{\partial T_s}{\partial r}) \quad (5)$$

where the subscript "s" indicates the rock-soil.

Eqs. (1), (2) and (5) were discretized by the finite volume method and solved by tridiagonal matrix algorithm. The spatial step size in radial direction varies according to $\Delta r=\ln(1.1\times i)$ (i is the discrete point numbers). Through the grid dependent test, spatial discretization step in vertical direction (Δz) is 5 m and time step (Δt) is 900 s. The radial and vertical boundaries of rock-soil are set as 114.1 and 2200 m, respectively.

2.2 Parameter setting

According to the MDBHE demonstration project in Xi'an, the related parameters used in the simulation were listed in Table 1.

Table 1 Benchmark parameters in the simulation

Parameters	
Borehole depth	2000 m
Outer pipe (177.8 mm × 9.19 mm)	Petroleum casing pipe
Inner pipe (110 mm× 10mm)	High density polyethylene pipe
Ground surface temperature	13 °C
Thermal conductivity of subsurface	2.5 W/ (m·k)
Specific heat capacity of subsurface	1348 J/ (kg·k)
Density of subsurface	1791 kg/m^3
Geothermal gradient	30 °C/km
Initial inlet fluid temperature	17.6 °C
Fluid flow rate	26.34 m^3/h

There exists geothermal gradient below the ground surface. Dirichlet boundary condition was set at the surface and bottom of rock-soil thermal effect area. Heat transfer between the MDBHE and rock-soil meets the third boundary condition. The radial boundary of rock-soil follows the geothermal gradients. Inlet temperature is not constant and varies with outlet fluid temperature under the constant heating load.

2.3 Validation of the numerical model

The model proposed in our study were validated by comparing with the simulated results in Ref. [8] where the model was proposed based on the Beier analytical model. Fig. 2 shows that there exist deviations of fluid temperatures in initial heat transfer process, mainly due to ignoration of effects of backfill area in our study. The relative errors of inlet and outlet temperatures are 7.84% and 7.42%, respectively at 240 hours. After then, the relative errors decrease and simulated results from our model coincide well with those from Ref. [8]. Thus, our proposed model can be used in the following analysis.

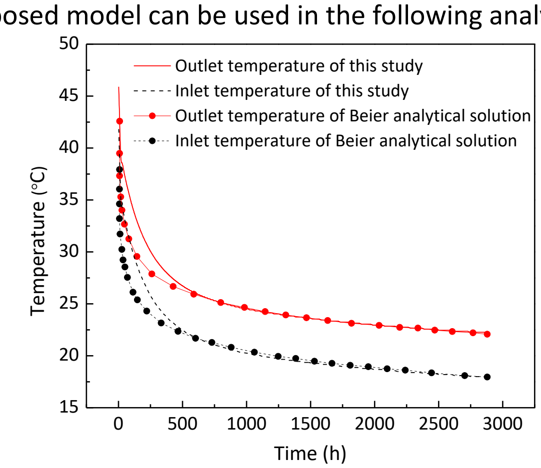

Fig 2 Comparison of inlet and outlet temperatures with operating time

3. RESULTS AND DISCUSSION

Sensitive analysis was implemented to investigate the variation regulations of inlet and outlet fluid temperatures of MDBHE and thermal radius of rock-soil under different heating loads. Heating-season of four months when MDBHE extracts geothermal was selected according to Ref. [7]. And the MDBHE performance under two scenarios i.e., constant inlet fluid temperature and constant heating loads were compared.

3.1 Inlet and outlet temperatures

Fig. 3 shows the variations of inlet and outlet fluid temperatures with operating time under different heating loads during continuous heating seasons. It can be seen that annual fluid temperatures are higher and come to quasi-steady state earlier in the case of lower heating load. The inlet and outlet temperatures change largely under higher heating load. During the first-year heating season, the maximum values of fluid temperature variations are 10.5, 17.0 and 23.6 °C under the conditions of 100, 150 and 200 kW, respectively. Furthermore, the fluid temperature declines with operating year especially in the second year. Since then fluid temperatures hardly decrease with the operating year under 100 kW while the temperature drops continuously even down to 0 °C with 250 kW, which is not allowed in the practical condition. Annual fluid temperature changes depending on the heating load and energy recovery of rock-soil. The fluid temperature will keep stable periodically when the energy recovery can guarantee heating demand and oppositely the fluid temperature will decline continuously.

Above analysis indicates that relatively low heating load contributes to the steady operation of MDBHE. However, in the practical design, the nominal capacity of MDBHE is usually determined according to its maximum heating load in order to fully realize the thermal extraction potential. Therefore, the drop of inlet and outlet fluid temperatures of MDBHE in heating season especially for initial years should be paid attention. There exists a critical value of heating load for long-term steady operation of MDBHE. Besides, MDBHE is usually utilized coupled with the heat pump. Large fluctuations of fluid temperature will result in an unstable operation of the heat pump. Under high heating load, it is indispensable to find a way to match the outlet temperature of MDBHE with rational operating conditions of the heat pump.

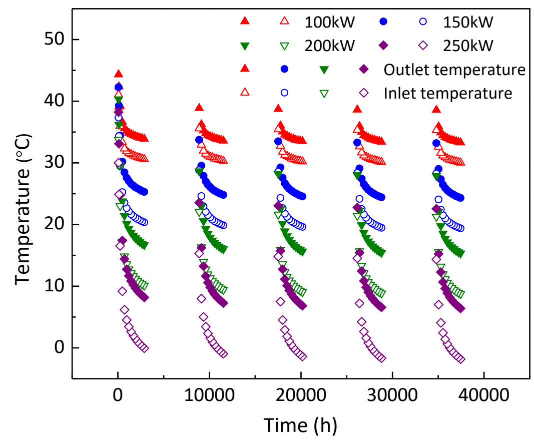

Fig 3 Inlet and outlet temperatures under different heating loads during continuous heating seasons for five years

3.2 Temperature distribution of rock-soil

The rock-soil temperature declining under different heating loads after first-year heating season is presented in Fig. 4. It can be found that with the heating load increases, the surrounding rock-soil temperature declines obviously in the vertical direction and with the depth deepening, the temperature drop is larger. Besides, the thermal effect radius expands with deeper depth and reaches the maximum at depth of borehole bottom. At the pipe bottom, temperature drop of the

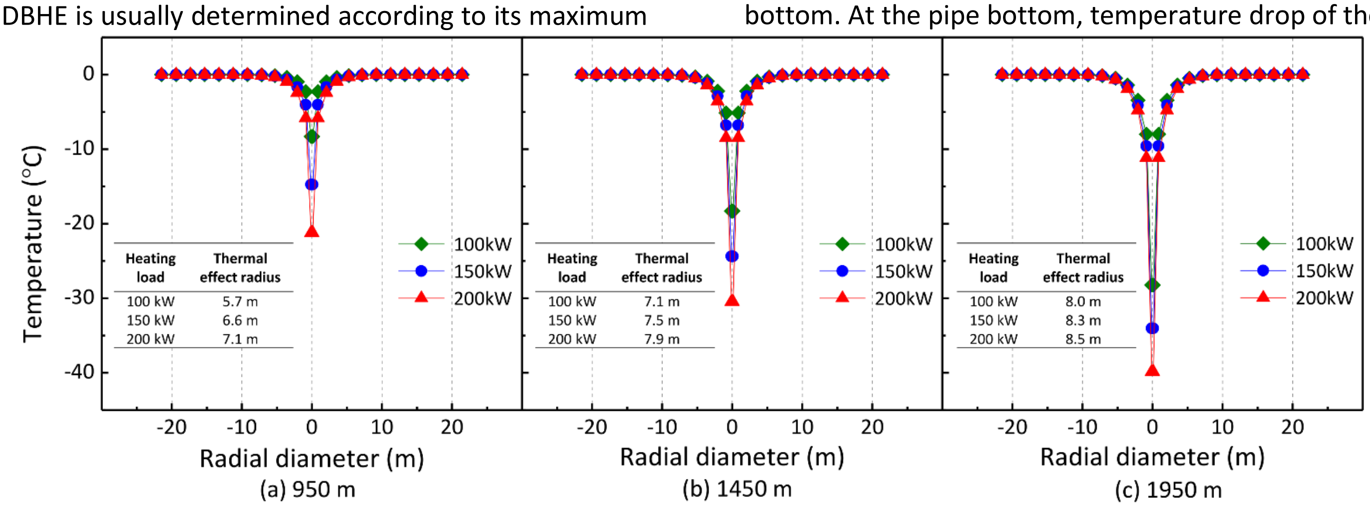

Fig 4 Temperature difference distribution of rock-soil after first-year heating period under different heating loads

rock-soil near the pipe increases by 20.57%, 17.09% respectively when the heating load increasing from 100 to 200 kW with 50 kW increment, while the maximum thermal effect radius (MTER) of rock-soil increases by 3.75%, 2.41% respectively, which indicates the heating load affects the MTER slightly. The annual MTER of rock-soil among five-year operations are shown in Fig. 5. MTER has a sharp increase in the second year and increases slightly after second year. It can be also found the variation regulation of MTER is similar under different heating loads, indicating again the heating load hardly affects the MTER.

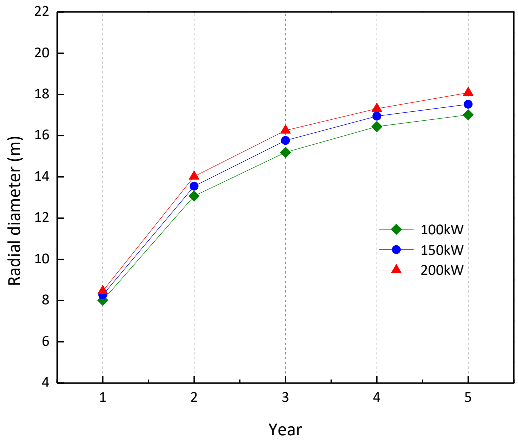

Fig 5 Thermal effect radius during continuous heating period for five years

3.3 Comparison with case of constant inlet temperature

According to benchmark parameters in Table 1, the simulated average heat transfer capacity of MDBHE under the constant inlet temperature of 17.6 °C is 166.65 kW. The MDBHE performance was compared between the two scenarios: a) constant heating load of 166.65 kW, b) constant inlet fluid temperature of 17.6 °C (Fig. 6).

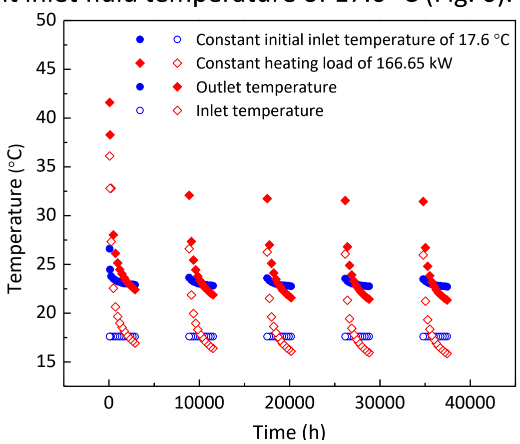

Fig 6 Comparison of the MDBHE performance

It can be found in the case of a), the fluid temperature changes more obviously and needs more time to reach the quasi-steady state. Variation degree of fluid temperatures with operating time are different between the two scenarios. Furthermore, the annual average inlet and outlet temperatures in the quasi-steady state of two scenarios are compared and tabulated in Table 2. The maximum deviation ratios of inlet and outlet temperatures are 10.9% and 3.4% respectively, suggesting the average outlet temperature in the case of b) agrees better with that of a).

Table 2 Average inlet and outlet temperatures in quasi-steady state under two scenarios

Year	Constant heating load (A)		Constant inlet temperature (B)	
	Inlet T /°C	Oulet T/°C	Inlet T/°C	Outlet T/°C
1	16.93	23.90	17.6	23.08
2	16.39	23.28	17.6	22.97
3	16.1	22.97	17.6	22.92
4	15.95	22.79	17.6	22.90
5	15.86	22.69	17.6	22.87

4. CONCLUSIONS

This paper investigated the effects of the heating loads on the thermal performance of MDBHE including heat extraction of MDBHE and energy recovery of rock-soil. Heating load largely affects the variations of inlet and outlet fluid temperatures. The MDBHE can extract the geothermal energy steadily and sustainably for consecutive years under condition of lower heating load. The higher heating load results in much more changes of fluid temperatures during the heat transfer process. In this case, it should be considered to find the matching between the heat pump and the MDBHE when coupled with heat pump unit. The rock-soil temperature in vertical direction was influenced significantly by the heating load, while the thermal effect radius of rock-soil was affected slightly. Under constant heating load, fluid temperatures of MDBHE vary much more obviously than that of the constant inlet fluid temperature. However, the average inlet and outlet temperatures in the quasi-steady state are close under the two scenarios, especially for the outlet temperature.

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