Optimization of Borehole Thermal Energy Storage Operating Parameters for 1000 m Deep Medium- shallow Geothermal Wells

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Abstract. Borehole thermal energy storage system can store thermal energy by adopting the existing borehole heat exchangers, which reduces the cost of constructing the storage system and facilitates the long-term stable operation of borehole heat exchangers. In this paper, the operating parameters of a medium-shallow borehole heat exchanger with depth of 1000 m are optimized for achieving borehole thermal energy storage purposes. The heat source is 65 °C hot water provided by a photovoltaic solar thermal system, and the optimized parameters include heat storage flow rate and heat storage time. The results show that the smaller the heat storage flow rate, the higher the energy storage efficiency, but the less heat is stored; the heat storage time has a small impact on the heat storage efficiency, basically maintained at about 36 %. The research in this paper clarifies the influence of each operation parameter on the performance of the borehole thermal energy storage system, which brings references for the similar borehole thermal energy storage system.

Keywords: Medium and shallow geothermal energy; coaxial cased heat exchanger; borehole thermal energy storage (BTES); thermal storage efficiency

1 Introduction

According to the International Energy Agency (IEA), the operation of buildings accounts for 30 % of global final energy consumption and 26 % of global energy-related emissions [1]. Geothermal energy, as one of the important renewable energy sources, has the advantages of lowering energy consumption of buildings and reducing carbon emissions. Energy storage technology is also one of the hot issues in the field of energy research, and the application of energy storage technology can solve the problem of mismatch between time and space of energy demand. In most current applications, geothermal energy is mainly used to provide heat for buildings in winter, and there are seasonal fluctuations in the demand for energy supply, which makes the temperature of

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the underground geotechnical body slowly decrease with time, affecting the long-term stable operation of geothermal energy[2]. But coupling geothermal energy and energy storage technology can solve this problem well. Underground geotechnical body as a good heat storage body [3], can store a large amount of thermal energy across the season, to solve the problem of energy demand mismatch, while the stored heat can increase the temperature of the underground geotechnical body, to solve the problem of cold buildup, and to ensure the long-term stable operation of the geothermal system.

The most widely used geothermal energy storage technology is borehole thermal energy storage (BTES), which is mainly used to store thermal energy in the underground geotechnical body through the heat exchanger piping circulating in the underground heat exchanger pipe to exchange heat with the ground[4]. Guo et al. [5] set up an experimental platform in Chifeng, storing the solar energy and industrial waste heat in the underground, and injected a total of 33,458.6 GJ of thermal energy into the ground. The average temperature of the soil increased from 10.0 °C to 35.6 °C, the core temperature was about 40.2 °C, the soil temperature 5 m outside the center increased about 2 °C, and the temperature 10 m outside the center did not see a significant increase. The results show that borehole thermal energy storage technology can store a large amount of thermal energy in the ground and does not have a large impact on the surrounding environment. Alessandro et al. [6] used borehole thermal energy storage technology to store solar energy in summer and extract thermal energy for building heating in winter, and the results of the study show that 79 % of the total amount of solar energy stored in the summer can be extracted in the winter for heating, and at the same time, the cost of the system can be reduced to one-third of the original cost. The results of the study show that 79 % of the total solar energy stored in summer can be extracted for heating in winter, and the system cost is reduced to one-third of the original cost, which proves the practicability and economy of borehole thermal energy storage technology.

However, the large-scale application of borehole thermal energy storage technology still has technical difficulties, i.e., low energy storage efficiency. kvalsvik et al. [7] constructed a thermal barrier ring with lower temperature around the borehole heat exchangers to reduce the heat loss from the internal borehole to the surrounding ground, and the results of the study showed that the thermal barrier ring could increase the heat storage by 88MWh. Other researchers[8] have used methods such as increasing soil water content, increasing soil thermal conductivity, and improving the properties of backfill materials to improve energy storage efficiency. However, these methods mentioned above are often difficult to operate, less economical, and not suitable for large-scale popularization and application. Wołoszyn [9] studied the effect of 17 parameters on the long-term operational efficiency of borehole thermal energy storage system, and the results of the study showed that the fluid temperature, flow rate, heat storage time, heat exchanger form, and heat conductivity coefficient of rock and soil during the process of heat storage and extraction have the greatest effect on the efficiency of heat storage. Therefore, it is more feasible and economical to study the influence of operating parameters on heat storage efficiency. In this study, a borehole heat exchanger model with a depth of 1000 meters was built, a coaxial casing heat exchanger was used, a solar photovoltaic system was used as the heat source for heat storage, and the temperature of the heat storage fluid was kept constant at 65°C. The study of the influence concerning the heat storage flow rate and heat storage time on the heat storage efficiency, can guide the optimization of the adjustment of the borehole thermal heat storage system.

2 Research Methodology and Modeling

2.1 Borehole Heat Exchanger Modeling

The heat transfer process between the circulating fluid and the geotechnical soil inside the buried pipe heat exchanger involves heat conduction and heat convection, in order to portray this complex heat transfer process as accurately as possible, the following assumptions are made in this paper during modeling:

(1) The heat transfer process inside the buried pipe is quasi-steady state;

(2) Only consider the heat conduction effect of the inner pipe wall and outer pipe wall, ignoring its heat capacity and heat storage properties;

(3) There is no void or contact thermal resistance between the backfill material and the buried pipe and borehole;

(4) The thermal-physical parameters of each material and continuous medium (e.g., circulating fluid, backfill material, geotechnical thermal-physical parameters, etc.) within the system remain unchanged;

The geologic structure of each layer of the geotechnical soil and the internal seepage of the underground aquifer are uniformly distributed without anisotropy.

2.2 Evaluation Indicators for Thermal Storage Performance

The performance of borehole thermal energy storage system can be evaluated in three aspects, namely temperature enhancement rate, heat extraction enhancement rate, and thermal energy storage efficiency. The heating season set for this simulation is four months, and the remaining eight months are the transition season. The total heat input to the borehole heat exchangers in a heat storage transition season is Q (the calculated temperature difference is based on the outlet water temperature at the end of the first heating season), and the heat stored in the formation at the end of the transition season is q. The total heat extracted in the first heating season is q_0, and the outlet temperature at the end of the second year's heating season under the heat storage condition is T_1, and the total heat extracted in the second heating season is q_1, and the outlet temperature at the end of the second year's heating season under the no-heat-storage condition is T_2, which is a good example of how to evaluate the performance of the borehole heat exchangers. The outlet temperature at the end of the second year heating season without heat storage is T_2, and the total heat extracted during the second heating season is q_2.

Temperature enhancement rate refers to the ratio of water temperature enhancement at the end of the second year heating season compared with the water temperature enhancement without heat storage after a transition season of heat storage, which can be expressed by the following formula, and the temperature enhancement efficiency can most intuitively reflect the influence of heat storage on the water temperature of borehole heat exchangers.

$$\text{Temperature increase rate} = \frac{T_1 - T_2}{T_2} \times 100\% \tag{1}$$

The concept of heat extraction enhancement efficiency is similar to temperature enhancement efficiency, which refers to the ratio of heat extraction enhancement at the end of the second year's heating season at the outlet water temperature compared to the non-heat-storage condition after a heat-storage transition season, and can be expressed by the following formula.

$$\text{Heat gain rate} = \frac{q_1 - q_2}{q_2} \times 100\% \tag{2}$$

Thermal storage efficiency represents the ratio of heat stored in the ground to the total amount of heat admitted to the ground throughout the transitional season of thermal storage, and can be expressed by the following formula. The heat storage efficiency reflects the storage and absorption of heat in the strata, and the higher the heat storage efficiency, the better the overall heat storage performance of the system, which is mainly related to the geological parameters and the heat storage mode.

$$\text{Thermal storage efficiency} = \frac{q}{Q} \times 100\% \tag{3}$$

3 Results and Discussion

3.1 Heat Storage Flow

The heat storage flow rate reflects the ability of the borehole heat storage system to dissipate heat. In order to study the influence law under different flow rates, this study sets up 7 flow rate parameters totaling 0.5 m^3/h, 1 m^3/h, 2 m^3/h, 4 m^3/h, 6 m^3/h, 8 m^3/h and 10 m^3/h, the heat storage temperature is 65 °C, and the heat storage time is 8 months after the heating season.

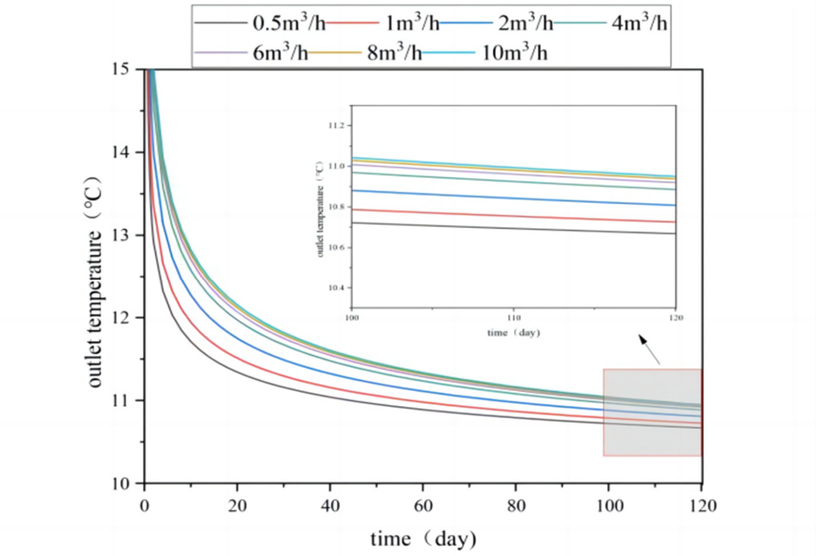

Fig. 1. Variation of outlet temperatures during the second heating season.

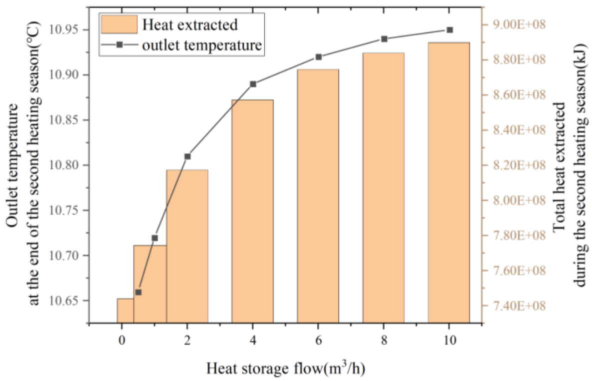

Fig. 2. Variation of outlet temperature and heat withdrawal during the second heating season.

Figure 1 above shows the export water temperature changes in the second heating season under different heat storage conditions, as can be seen from the figure, in the second heating season, with the growth of heating time, the export temperatures are gradually declining and then stabilized, using different heat storage flow rate conditions in the second heating season export temperature is very close. At the end of the second heating season, the export temperature gradually increases with the growth of heat storage flow, the lowest export temperature is 10.66 °C under the condition of 0.5 m^3/h heat storage flow, and the highest export temperature is 10.95 °C under the condition of 10 m^3/h heat storage flow, and the difference between the two is only 2.72 %, which indicates that the effect of increasing the heat storage flow on the enhancement of the export temperature is limited. Figure 2 shows the variation in heat withdrawal within the second heating season, with the growth of the heat storage flow rate of the total heat extracted in the heating season is also gradually increased, the heat storage flow rate of 10 m^3/h condition of the total heat extracted the most, 8.89×10^5 GJ, compared with the heat storage flow rate of 0.5 m^3/h condition of the 19.61 %, indicating that the flow rate during the storage period is reduced to the second heating season to extract the amount of heat has a more obvious effect, cannot blindly reduce the heat storage period flow rate.

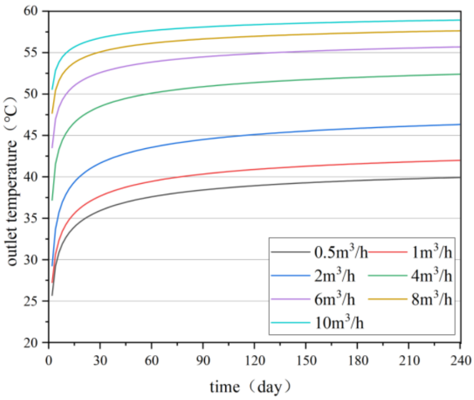

Fig. 3. Variation of export water temperature during the storage season.

Figure 3 for the heat storage season within the export water temperature map, from the figure can be seen, the smaller the flow rate of the export water temperature is lower, that is, the greater the temperature difference between the import and export of heat storage fluid, indicating that the storage of heat within the body of the heat storage fluid more stored in the ground, the higher the efficiency of heat storage. Calculation of heat storage can be obtained from Table 1.

Table 1. Calculation of total heat storage and heat storage efficiency.

Heat storage flow	Total heat fluxed into the ground during the heat storage season GJ	Stored heat GJ	Thermal storage efficiency
0.5 m^3/h	6.86×10^5	3.21×10^5	46.81 %
1 m^3/h	1.37×10^6	5.96×10^5	43.45 %
2 m^3/h	2.74×10^6	9.94×10^5	36.23 %
4 m^3/h	5.48×10^6	1.37×10^6	25.06 %
6 m^3/h	8.23×10^6	1.53×10^6	18.69 %
8 m^3/h	1.09×10^7	1.63×10^6	14.86 %
10 m^3/h	1.37×10^7	1.68×10^6	12.29 %

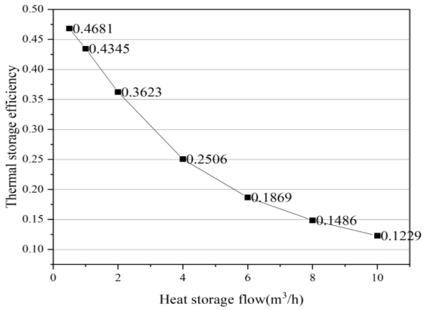

Fig. 4. Variation of heat storage efficiency with heat storage flow rate.

As can be seen from Table 1, with the reduction of heat storage flow, the heat storage efficiency is greatly improved, when the heat storage flow is 0.5 m^3/h, the heat storage efficiency is 46.81 %, which is about 4 times of the heat storage efficiency of the heat storage flow 10 m^3/h . But at this time, the heat storage capacity is only 19 % of the heat storage flow rate of 10 m^3/h, indicating that the heat storage flow rate on the heat storage efficiency and heat storage capacity has a huge impact, the follow-up should be a comprehensive judgment to select the appropriate flow rate for heat storage.

3.2 Heat Storage Time

Heat storage time also has a very big impact on the performance of the borehole heat storage system, so it is crucial to choose a reasonable time for heat storage. The heat storage time set in the previous period is 8 months after the end of the heating season, the overall heat storage time is long, and needs to be optimized for the heat storage time, which is now set to be 1 day, 10 days, 20 days, 1 month, 2 months, 4 months, 6 months, and 8 months, respectively. The heat storage flow rate is 2 m^3/h.

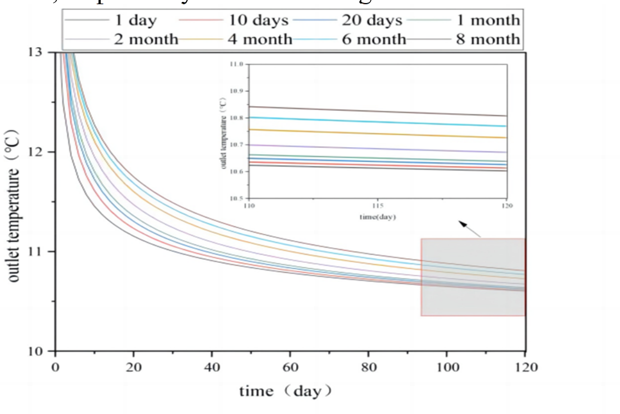

Fig. 5. Variation of outlet temperatures during the second heating season.

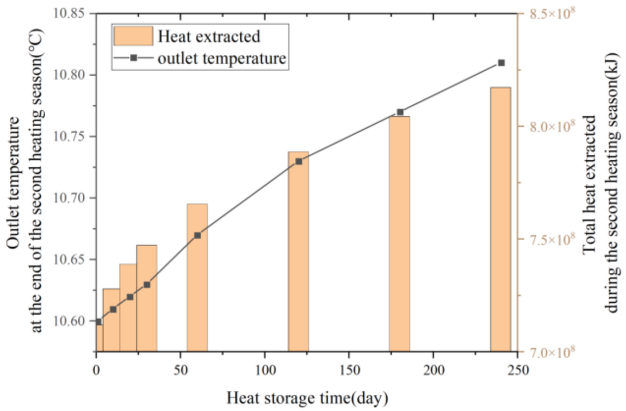

Fig. 6. Variation of outlet temperature and heat extraction power during the second heating season.

Figure 5 above shows the export temperature change in the second heating season after different heat storage time, as can be seen from the figure, in the second heating season, with the growth of heating time, the export temperature are gradually decreased and then stabilized, the export temperature of the second heating season with different heat storage time conditions do not differ much. The export temperature at the end of the second heating season gradually increases with the growth of the heat storage time, as can be seen in Figure 4, with the growth of the heat storage time, the export temperature at the end of the second heating season is basically a linear growth trend. The lowest export temperature under the 1-day heat storage condition is 10.60 °C, and the highest export temperature under the 8-month heat storage condition is 10.81 °C, with a difference of only 1.98 %, indicating that the heat storage time has a limited effect on the enhancement of the export temperature.

Calculation of the total heat extracted in the second heating season can be found, with the growth of the storage time of the total heat extracted in the heating season is also gradually increased, as can be seen in Figure 6 with the increase in the storage time, the incremental amount of heat extracted in the second heating season is gradually reduced and stabilized. The total heat extracted under the 8-month heat storage condition is the most, 8.17×10^5 GJ, which is 14.79 % higher compared to the 1-day heat storage condition, and the overall improvement effect is not significant.

Table 2. Calculation of total heat storage and heat storage efficiency.

Times	Total heat fluxed into the ground during the heat storage season GJ	Stored heat GJ	Thermal storage efficiency
1day	1.14×10^4	5.82×10^3	50.88 %
10days	1.14×10^5	3.80×10^4	33.19 %
20days	2.29×10^5	7.87×10^4	34.40 %

1month	3.43×10^5	1.23×10^5	35.92 %
2months	6.86×10^5	2.54×10^5	36.95 %
4months	1.37×10^6	4.92×10^5	35.88 %
6months	2.06×10^6	7.35×10^5	35.72 %
8months	2.74×10^6	9.94×10^5	36.23 %

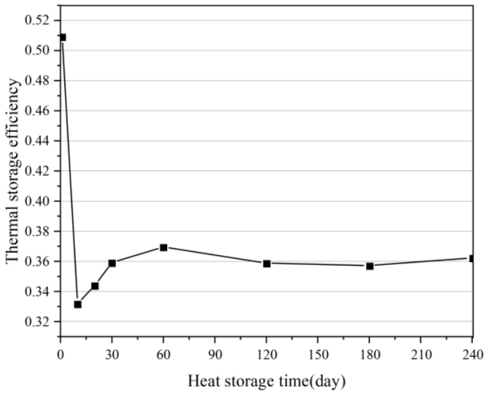

Fig. 7. Graph of thermal storage efficiency under different operating conditions.

Calculate the heat storage capacity and heat storage efficiency in the heat storage period under eight conditions, from Table 2, it can be found that with the increase of the heat storage time, the heat storage capacity increases gradually, and the heat storage capacity under the heat storage condition for 8 months is the highest, which is 9.94×10^5 GJ, and compared with the heat storage capacity of the heat storage condition for 1 day, the heat storage capacity has been improved by 179 times. Figure 7 shows the thermal storage efficiency at different operating conditions. comparing the heat storage efficiency, it can be found that in addition to the 1-day heat storage condition, the heat storage efficiency of the other seven heat storage conditions is not much different, with the increase of the heat storage time, the heat storage efficiency shows an increase and then tends to level off, the final heat storage efficiency stabilized at about 36 %. The heat storage efficiency of 1 day heat storage condition is as high as 50.88 %, preliminary analysis of the reason is that the heat storage has not yet reached the equilibrium, the ground temperature and the temperature of the heat storage fluid is in the stage of rapid change, so the difference between the heat storage efficiency and the other conditions is large.

4 Conclusion

The borehole thermal energy storage system can store heat with the help of existing borehole heat exchangers, reduce the cost of the storage system, guarantee the long-term stable operation of the borehole heat exchangers, and improve the performance of its heat storage to help save energy and protect the environment. In this study, a model of medium-shallow borehole heat exchangers with a depth of 1000 meters was established, and the borehole thermal storage experiment was carried out in the transition season to study the influence of different thermal storage parameters on the performance of the borehole thermal storage system. The specific conclusions are shown below.

(1) The circulating flow rate, storage time and circulating fluid flow mode in the heat storage process all have a very great influence on the performance of the borehole heat storage system.

(2) With the increase of heat storage circulation flow rate, the heat storage capacity and the amount of heat taken within the second heating season both increase gradually, but the heat storage efficiency decreases rapidly, and the heat storage flow rate should be selected by considering the heat storage capacity and the heat storage efficiency comprehensively.

(3)The heat storage time mainly affects the heat storage capacity, and the heat storage capacity increases gradually with the growth of the heat storage time. After the heat storage reaches stability, the heat storage efficiency is basically maintained at about 36 %, and does not change with the change of heat storage time.

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