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In-situ Experiment of Heat Extraction of an Open-Loop Deep Geothermal Single Well Coupled with Heat Pump System

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ABSTRACT

Geothermal resources are abundant in medium-low temperature in China, the geothermal production and reinjection mode has been the main direct utilization way for many years. However, due to the technical bottleneck of reinjection into sandstone, shallow and deep close-loop borehole heat exchangers (BHEs) have received more and more attentions in recent years, and there are also many available practical projects. Since the heat transfer between the formation BHEs are heat conduction, the heat extraction rate is lower and heat/cold accumulation will occur in some areas with unbalanced cooling and heating loads, affecting the long-term operation of the system, especially for the deep BHEs. In contrast, the open-loop deep geothermal single well system (DGSW) has convective heat and mass transfer with the formation, thus the heat extraction rate is much higher than that of the closed-loop system with the same formation conditions. In this paper, an in-situ test of an open-loop DGSW coupled with a heat pump system was carried out in Hebei Province, China, it was shown that the well with a depth of 1400 m and bottom temperature of 67.2ºC would deliver a stable heat output of 450 kW. The heat extraction rate per unit wellbore depth of the open-loop DGSW system is 3 times more than that of a close-loop system with similar formation conditions.

1. INTRODUCTION

Geothermal energy is a clean and efficient non-fossil energy, geothermal heating area in China is nearly 1.4 billion m^2 by 2020 (China Energy, 2021). However, the area heated by deep geothermal energy is only 282 million m^2, which is no longer the main mode of geothermal district heating (Jia et al., 2021). The main technical bottlenecks that limit its utilization are: (1) the traditional mode of doublet or group well production/reinjection has the problems of difficulties in reinjection of some sandstone formations, resulting in water level drop and ever formation subsidence (Su, 2021), some relevant policies have even been issued for this issue (Hebei Province, 2022); (2) as for the close-loop deep borehole heat exchanger system, although there is no reinjection problem, its heat extraction rate is low and the attenuation is fast. Kong et al. (2017) proposed that the sustainable heat extraction rates in all DBHE continuous extraction scenarios are less than 150 W/, this is also supported by other studies (Morita, et al., 1992; Kohl et al. , 2002; Dijkshoorn, et al., 2013; Wang, et al., 2017). In contrast, the open-loop deep geothermal single well system (DGSW) does not have reinjection problem, and the system has high heat extraction rate and stable operation, it is a sustainable and promising mode of deep geothermal energy utilization. The idea of Deep Geothermal Single Well (DGSW) heat production has existed for many years, but there is no consensus on its applicability. So far, only the Geothermal Engineering Ltd (GEL) in UK has conducted a field trial of DGSW, and the heat output of a single well with a depth of 2000 m is 363 kW (Westaway, 2018).

In this paper, we improved the previous field experiments (Dai et al., 2019） and proposed a novel coaxial open-loop heat extraction system. An in-situ test of an open-loop DGSW coupled with a heat pump system with a depth of 1400 m geothermal well was constructed in Tangshan, China, and the heat extraction rate under different geothermal return temperature and circulating flow rate is obtained, which is valuable reference for the system design and engineering application of the open-loop DGSW system.

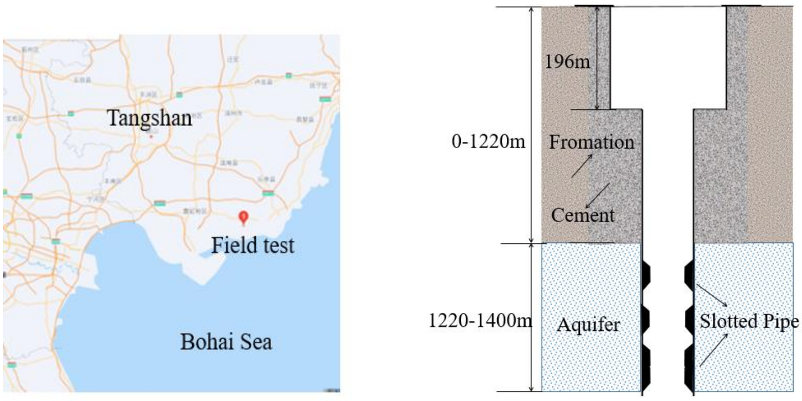
2. IN-SITU TEST

The test well is located in Tangshan, China (Fig. 1a), which is made up of two concentric casings. The well is 1400 m deep and the bottom temperature is 67.2ºC), Fig. 1(b) shows the well structure.

The formation temperature of the geothermal well is shown in Fig. 2 shows, it can be seen that the static water level of the test well is 30 m, after which 30 m to 135 m is the constant temperature layer. The temperature and depth of the well have a linear relationship, which can be fitted as Eq.(1)

$$T = 18.88 + 0.03755H \tag{1}$$

where T and H are formation temperature and well depth, respectively.



(a) Well location **(b) Well structure**

Figure 1:Well (a) location and (b) structure

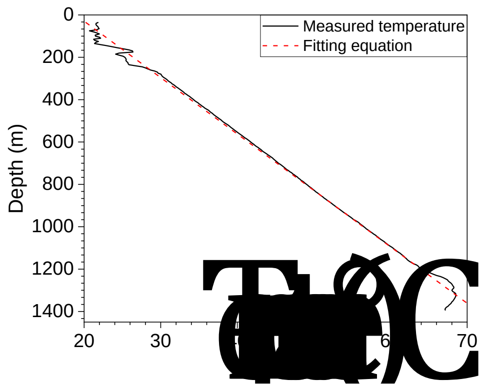


Figure 2:Well temperature profiles with depth

2.1 Experimental System

This paper proposed a novel coaxial open-loop heat exchange system that can achieve 100% reinjection, which includes ground heat supply system, underground heat extraction system, and the necessary data acquisition system. In the ground heat supply system, the higher-temperature geothermal water from a single well exchanges heat with cold circulating water through a heat exchanger, and then completely reinjected. The heated circulating water enters the heat pump system to further increase the temperature and enters the air cooling tower for heat dissipation. The temperature and flow data at different nodes in the system are collected through temperature sensors (T1-T14) and flow meters (M1-M6). In the single-well heat extraction system, a 17.5kW submersible pump was used to pump the geothermal water to the surface through annulus, exchange heat with the circulating fluid, and then return to the same well through the inner pipe. The system schematic is shown in Figure 3 and Figure 2 shows the on-site construction.

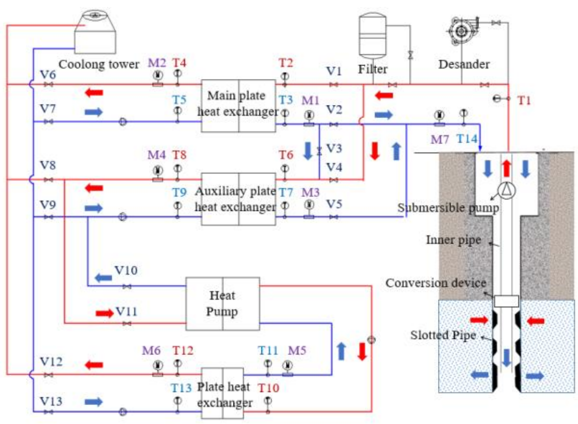


Figure 3: Schematic of the coaxial open-loop heat extraction system

Figure 4: On-site construction

2.2 Test Scenarios

In order to obtain the heat extraction rate of the proposed open-loop geothermal single well system, it is required to test the geothermal return water temperature (T14), outlet water temperature (T1) and fluid flow rate (M7), and then the heat extraction rate Q_s can be calculated by Eq. (2).

$$Q_s = c_{ws} M_7 (T_{14} - T_1) \tag{2}$$

where c_{ws} is the specific heat capacity at the average temperature of inlet and outlet of geothermal water, kJ/(kg K).

The in-situ test was carried out from November 9, 2021 to December 28, 2021. The heat extraction rate of a single well under different test scenarios can be obtained by changing the temperature of the geothermal return water (turning on and off the heat pump) and changing the circulating water flow rate (adjusting the pump power). Table 1 shows the test scenarios.

TABLE 1: Test scenarios of heat extraction of single well

Test scenarios	Test period（2021）	Average ambient temperature (°C)	circulation mass flow（m^3/h）	heat pump on?
Scenario 1	16:00-20:00 (Nov.28)	4.5	33.8	N
Scenario 2	18:00-22:00 (Nov.29)	6.7	33.8	N
Scenario 3	16:00-20:00 (Dec.6)	3.9	37.8	Y
Scenario 4	18:00-22:00 (Dec.10)	2.3	37.5	Y
Scenario 5	12:00-18:00 (Dec.24)	-3.8	37.5	Y
Scenario 6	23:00(Dec.24)-3:00 (Dec. 25)	-10.5	37.5	Y

3. RESULTS AND DISCUSSIONS

The heat extraction rate of a single well under different ambient temperatures (6 scenarios) is shown in Fig. 5. It can be seen that the ambient temperature, fluid flow rate and the heat pump system running or not will all affect the heat extraction rate. The heat extraction rater of each test scenarios fluctuated greatly in the first 48 hours, and then tended to be stable. The heat extraction rate of the system can be stabilized in the range of 300 kW-450 kW, that is, the heat extraction rate per unit wellbore length is 215 W/m-320 W/m.

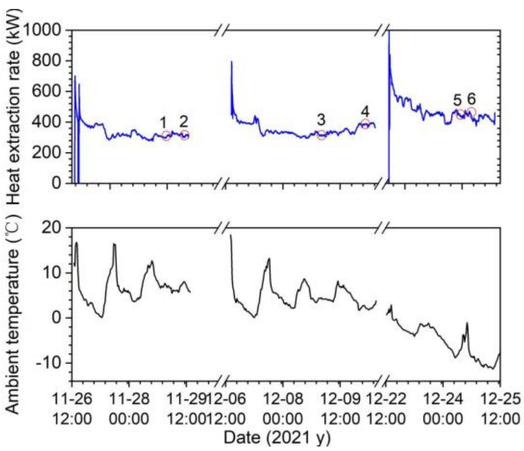


Figure 5: Variation of heat extraction rate of with time under different average ambient temperatures

3.1 Effect of Geothermal Fluid Flow Rate

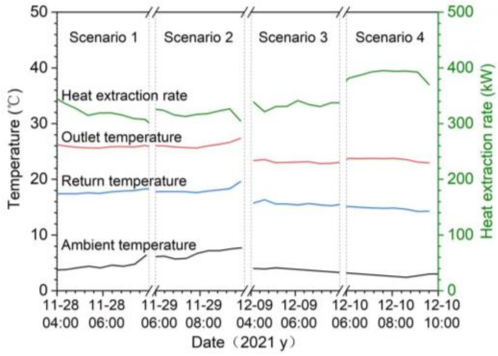


Figure 6: Effect of geothermal fluid flow rate on heat extraction rate

Figure 6 compares the stable heat extraction rate under different geothermal fluid mass flow rates. It can be seen that when the flow rate is 33.8 t/h and the ambient temperature is 4.5 ℃ (scenario1) and 6.7 ℃ (scenario 2), the corresponding average heat extraction rate is 300 kW and 316 kW, respectively; when the flow rate is 37.8 t/h and the ambient temperature is 3.9 ℃ (scenario 3) and 2.3 ℃ (scenario 4), the corresponding average heat extraction rate is 326 kW and 382 kW, respectively, it is obvious that when, the effect of the flow rate on the heat extraction rate is not too much for the similar ambient temperature (scenario 2 and 3). However, when the flow rate is similar, the heat extraction power of a single well increases significantly at a lower outdoor temperature, indicating that the geothermal return water temperature has a greater impact on the heat extraction rate than the flow rate.

3.2 Effect of Geothermal Return Water Temperature

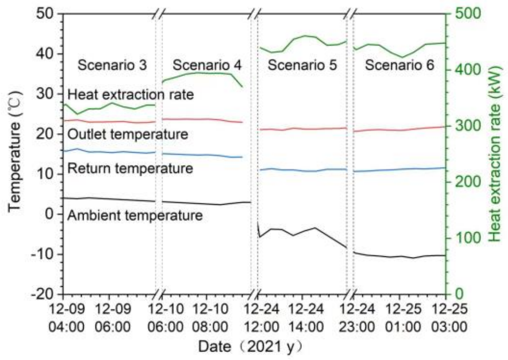


Figure 7: Figure 8: Effect of geothermal fluid return temperature on heat extraction rate

Figure 7 shows the stable heat extraction rate of a single well under different geothermal return water temperatures. It can be seen that for the same flow rate, when the geothermal return water temperature is the same, the average heat extraction rate is also similar, that is, the heat extraction rate of scenario 5 and 6 are 441 kW and 435 kW, respectively. With the decrease of geothermal return water temperature, the heat extraction rate increases significantly, and the stable heat extraction rate corresponding to scenario 4, 5, and 6 is 326 kW, 382, and 441 kW, respectively, thus the heat extraction rate can be increased by reducing the geothermal return water temperature.

3.3 Test Results Analysis

Based on the in-situ test results, we know that the return temperature and flow rate of geothermal water are the main factors affecting the heat extraction rate, and there is a functional relationship between the three, as shown in Figure 1.14. It can be seen the heat extraction rate increases approximately linearly with the decrease of the geothermal return water temperature. By first fitting the heat extraction rate and the geothermal return water temperature, and then combining the flow rate, the binary function relationship between the stable heat extraction rate, the geothermal return water temperature and the circulation flow rate can be obtained, as shown in Eq.(3).

$$Q_s = (34.26 - 2.213T_{in}) \times q - 610.6 + 59.155T_{in} \tag{3}$$

where Q_s is the heat extraction rate of the open-loop geothermal single well, kW; T_{in} is the geothermal return water temperature, ℃; q is the geothermal fluid flow, m^3/h.

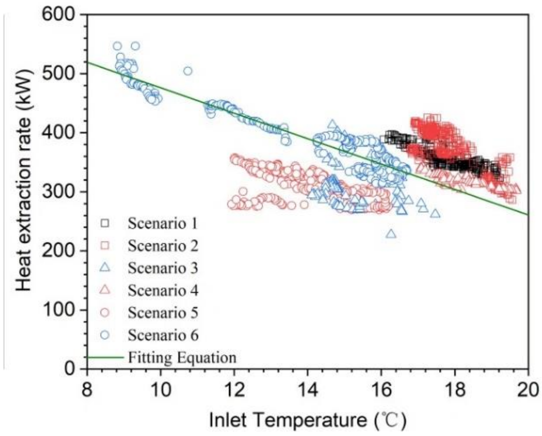


Figure 9: Heat output of geothermal well varies with different inlet temperature

3.4 Heat Extraction Rate Per Unit Wellbore Length of the Open-Loop System

As mentioned in introduction, Kong et al. (2017) proposed that the sustainable heat extraction rate of DBHE under continuous operating conditions does not exceed 150 W/m. The Chinese standard 'Technical regulation for medium deep geothermal buried pipe heating system (DBJ61T166-2020) gives the estimation formula for calculating the heat output of DBHE, as shown in Eq.(4).

$$Q_i = \frac{(17.61Tk_s + 49.2T - 2.23k_s)H}{1000} - 8.63Tk_s - 61.93T - 7.92 \quad (4)$$

where Q_i is the heat output of DBHE, kW; K_s is the thermal conductivity of formation, W/(m ·k); H is the depth of DBHE, m; T is the geothermal gradient, ℃/100 m

Therefore, if a close-loop DBHE system is used for our test well, the heat extraction rate per unit wellbore length calculated according to Eq.(q) is 103 W/m. In contrast, the proposed novel open-loop DGSWs in this paper is 320 W/m after stabilization, which is more than 3 times higher than that of closed DBHE.

4. CONCLUSIONS

In the paper, we proposed a novel coaxial open-loop deep geothermal single well systems(DGSWs) and conducted an in-situ test with a well with 1400 m depth and a bottom temperature of 67℃ under different ambient temperatures, the results showed that:

(1) the maximum stable heat extraction rate of the system can reach 320 kW at a flow rate of 38 m3/h, which is more than 3 times higher than that of closed DBHE with the same geological conditions;

(2) The relationship between the stable heat extraction rate and the inlet temperature and the flow rate of the geothermal well can be obtained, $Q_s = (34.26 - 2.213T_{in}) \times q - 610.6 + 59.155T_{in}$

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REFERENCES

China Energy, https://www.china5e.com/news/news-1124107-1.html,2021

Jia, Y.Y., Chang, Q., and Wang Y.W.: Geothermal Energy Development Amid Carbon Peak and Neutrality in China, *Green Petroleum & Petrochemicals*, **6**, (2021), 5-9.

Su, Y.J.: Genesis and Rational Development of Typical Geothermal Field in the Songliao Basin: A Case study of Lindian Geothermal Field, *PhD Dissertation*, Changhun: Jilin University, China (2021).

The 14th Five-Year Plan for Exploration and Development of Geothermal Resources in Hebei Province, Department of Natural Resources of Hebei Province, Oceanic Adminstration, Hebei Natural Resource Department, (2022). 38http://zrzy.hebei.gov.cn/heb/gongk/gkml/zcwj/zcfgk/zck/10794581499551051776.html, 2022.11

Kong, Y., Chen, C., Shao, H., Pang, Z., Xiong, L., and Wang, J.: Principle and Capacity Quantification of Deep-Borehole Heat exchangers, *Chinese Journal of Geophyscis*, **60**, (2017), 4741-4752.

Morita, K., Bollmeier, WSI., and Mizogami, H.: Experiment to Prove the Concept of the Downhole Coaxial Heat Exchanger (DCHE) in Hawaii, *Annual Meeting of the Geothermal Resources Council*, San Diego, CA, USA, (1992).

Kohl T., Brenni R., and Eugster W.: System Performance of a Deep Borehole Heat Exchanger, *Geothermics*, **31**, (2002), 687-708.

Dijkshoorn, L., Speer, S., and Pechnig, R.: Measurements and Design Calculations for a Deep Coaxial Borehole Heat Exchanger in Aachen, Germany. *International Journal of Geophysics*, (2013). 916541

Wang Z, Wang F, Liu J, Ma Z, Han E, and Song M. Field test and numerical investigation on the heat transfer characteristics and optimal design of the heat exchangers of a deep borehole ground source heat pump system. *Energy Conversion and Management,* **153**, (2017), 603-615.

Westaway,R.: Deep Geothermal Single Well Heat Production: Critical Appraisal under UK conditions, *Quarterly Journal of Engineering Geology and Hydrogeology,* **51**(4), (2018), 424-449.

Dai, C., Li, J., Shi, Y., Zeng, L., and Lei, H.Y.: An Experiment on Heat Extraction from a Deep Geothermal Well Using a Downhole Coaxial Open Loop Design, *Applied Energy*, **252**, (2019), 113447.

Technical regulation for medium deep geothermal buried pipe heating system, Department of Housing and Urban-Rural Development of Shaanxi Province, **5**, (2020).