INFLUENCING LAW OF KEY PARAMETERS ON THE THERMAL EFFICIENCY OF SINGLE-WELL CLOSED-LOOP HEAT EXCHANGER

by

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The single-well closed-loop heat extraction technology can realize efficient exploitation of mid-to-deep geothermal resources. A two-dimension heat transfer model is established. The effects of flow rate, inlet temperature, length and diameter of insulated tubing on heat extraction power and outlet temperature were investigated by the two-way absolute grey correlation analysis method. Results indicate that thermal power increases with the increase of displacement and length of insulated tubing, and decreases with the increase of injection temperature, outer diameter of insulated tubing and inner diameter of insulated tubing.

Key words: *thermal power, parameter influence law, heat insulated tubing, single-well closed-loop geothermal system, geothermal*

Introduction

The development of mid-to-deep geothermal resources is typically categorized into open-loop geothermal systems and closed-loop geothermal systems [1]. Conventional open-loop heat extraction systems face challenges such as reinjection difficulties, high stratum condition requirements, corrosion, and scaling, limiting their application areas [2-4]. As a result, coaxial closed-loop geothermal systems (CCGS) are considered the most viable approach to developing deep geothermal resources. Particularly since 2010, heat extraction technologies that do not rely on water have advanced rapidly. Song *et al.* [5-9] have proposed various single-well closed-loop heat extraction systems. However, the single-well closed-loop geothermal system requires stringent insulation measures to achieve optimal heat extraction during fluid circulation. Consequently, research on insulated oil tubings has become crucial for efficient heat extraction in the single-well closed-loop geothermal system [10-13].

In order to promote the research of single-well heat extraction technology, a two-dimension heat transfer model is established for the single-well closed-loop heat extraction system with a double-layer insulated tubing, and the influence of parameters such as flow rate, inlet temperature, length and diameter of insulated tubing string on heat extraction power and outlet temperature is analyzed. A two-way absolute grey correlation analysis model [14] is utilized to determine the correlation coefficient and rank the related sequences. The findings offer guidance for optimal design and parameter selection of a single-well closed coaxial heat exchanger system.

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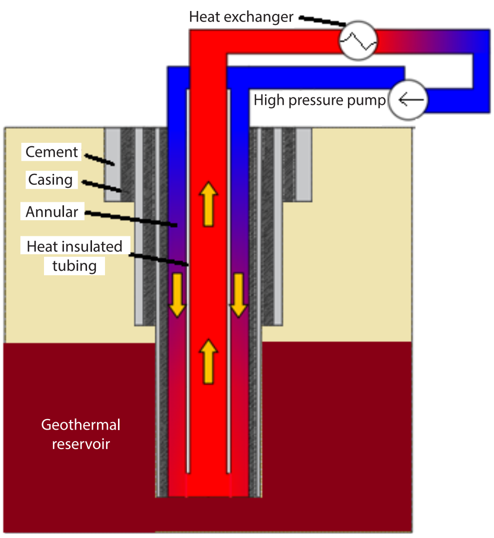

Figure 1. Schematic diagram of single-well closed-loop heat extraction system

Double-layer insulated tubing single-well closed-loop heat extraction system

The principle of single-well closed-loop heat extraction system is shown in fig. 1. First, a vertical well was drilled and insulated tubing was installed inside. The high pressure pump and the ground heat exchanger are installed on the ground. The high pressure pump is connected with the annulus between the insulated tubing and the casing. The heat exchanger is connected with the insulated tubing and high pressure pump. The cryogenic fluid is pumped into the annulus between the insulated tubing and the casing. In the process of flowing to the bottom of the well, the fluid continuously exchanges heat with the formation through the casing and cement, *etc.*, and the temperature gradually rises. When the fluid reaches the bottom of the well, it reaches its highest temperature and then enters the insulated tubing and begins to flow upward. Then it enters the ground heat exchanger, and after the heat exchange is completed, it becomes a low temperature fluid again and enters the circulation again to complete the geothermal single-well heat extraction process. In this study, double-layer insulated tubing is used, that is, it is composed of an inner tubing and an outer tubing, and there is air between them, and its thermal conductivity is 0.023 W/mK.

Model assumptions and governing equations

A model for a single-well closed-loop heat extraction system has been established, as shown in fig. 2, where heat is transferred from the reservoir to the cement, casing, and working fluid in sequence, and the fluid inside the central tubing exchanges heat with the annular fluid through the insulated tubing [15]. The heat transfer model assumptions for the system are:

– Neglect vertical heat conduction.

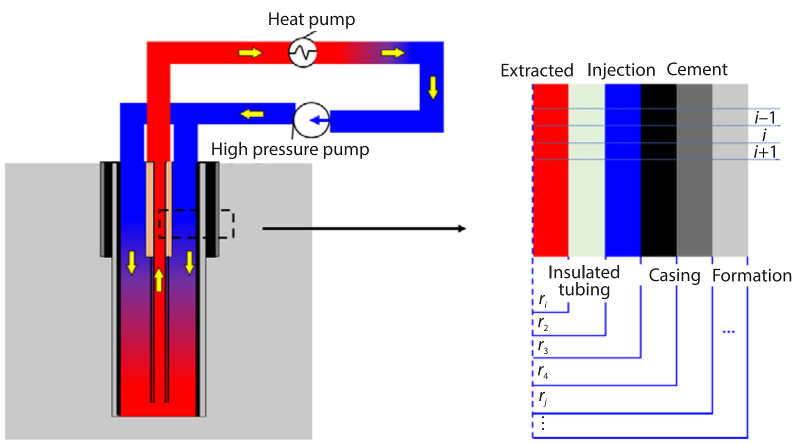

Figure 2. Schematic diagram of heat transfer system and grid

– Forced convection heat transfer between the working fluid and the casing.
– Consider only the variation in physical properties of the working fluid.

The thermal resistance and thermal capacity were calculated in [15]. The energy balance equation for the fluid inside the tubing is represented:

$$Q_1\rho_1c_1\frac{\delta T_1}{\delta z}+\frac{T_2-T_1}{R_1}=a_1\rho_1c_1\frac{\delta T_1}{\delta t} \tag{1}$$

where T_1 is the temperature of the working fluid inside the insulation oil column, T_2 – the temperature of the insulation oil column, z – the depth of the well, t – the time, and R_1 – the thermal resistance between each grid cell.

The energy balance equation for the circulating fluid in the annulus:

$$\frac{\delta(Q_3\rho_3c_3T_3)}{\delta z}+\frac{T_2-T_3}{R_2}+\frac{T_4-T_3}{R_3}=\frac{\delta(a_3\rho_3c_3T_3)}{\delta t} \tag{2}$$

where T_3 is the temperature of the working fluid in the annulus and T_4 – the temperature of the casing.

The energy balance equation for the casing, cement annulus, and reservoir is represented:

$$\frac{T_{j-1}-T_j}{R_{j-1}}+\frac{T_{j+1}-T_j}{R_j}=\frac{\delta(a_j\rho_jc_jT_j)}{\delta t} \tag{3}$$

where j is the number of radial grid cells, T_j – the temperature of the j^{th} grid cell, T_{j-1} – the temperature of the adjacent grid cell on the left side of the j^{th} grid cell, and $T_{j+}1$ – the temperature of the adjacent grid cell on the right side of the j^{th} grid cell.

Model validation

A well at a depth of 2530 m with a sealed wellbore at 1800 m was selected to validate the heat transfer model [15]. The results of on-site experiments [15] or a single-well closed-loop heat extraction system with the insulated tubing was calculated and validated based on this model. The specific wellbore data is shown in tab. 1. As shown in fig. 3. The model can predict well outlet temperature under experimental conditions, and the maximum error is about 4.8%.

Table 1. Field test well operation parameters

Geothermal gradient [°C per 100 m]	Inlet flow rate [m^3 per hours]	Injection pressure [MPa]	Insulated tubing thermal conductivity [$Wm^{-1}°C^{-1}$]	Circulating fluid
2.7	23	10	0.026	Water

Influence of key parameters

For single-well closed-loop coaxial heat exchange systems, the most commonly applied scenarios are newly developed geothermal wells or abandoned oil wells. A 3000 m deep well is taken as an example to carry out a single-well closed-loop heat extraction design. The effects of flow rate, inlet temperature, length of insulated oil tubing, and diameter of insulated tubing on heat extraction power and outlet temperature are studied. Table 2 shows the wellbore structural data and working parameters.

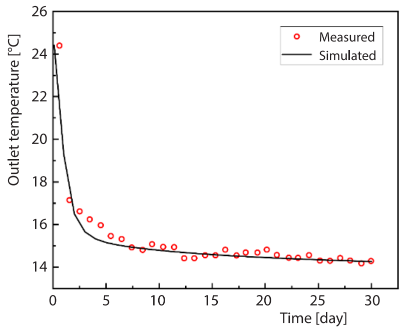

Figure 3. Outlet temperature curve with time

Tabele 2. Wellbore structural data and working parameters

Parameters	Value	Parameters	Value
Depth	3000 m	Inlet flow rate	30~70 m^3 per hours
Wellbore diameter	315.34 mm	Injection temperature	5~25 °C
Geothermal gradient	3 °C per 100 m	Insulation length	500~2500 m
Surface temperature	20 °C	Insulated tubing outer diameter	88.9~114.3 mm
Operation time	30day	Insulated tubing inner diameter	53.1~97.2mm

Firstly, the influence of flow rate on thermal power and outlet temperature is studied. The simulation results after 30 day production are shown in fig. 4. With the increase of displacement, the amount of heat exchanged with strata during the unit time increases, causing increased thermal power, which ranges from 625 kW to about 725 kW. However, at the same time, due to the increase in flow rate, shortening heat exchanging time, and a large amount of heat in the strata was taken away, resulting in a decrease in outlet temperature, which is reduced by about 9 °C. However, with the increase in flow rate, the cycle resistance will increase greatly, the flow rate needs to be optimized according to the situation.

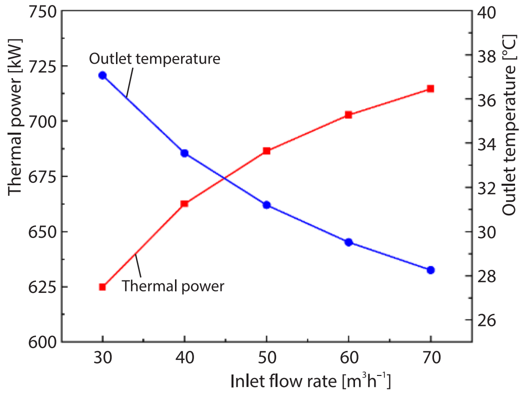

Figure 4. Effect of flow rate on heat recovery

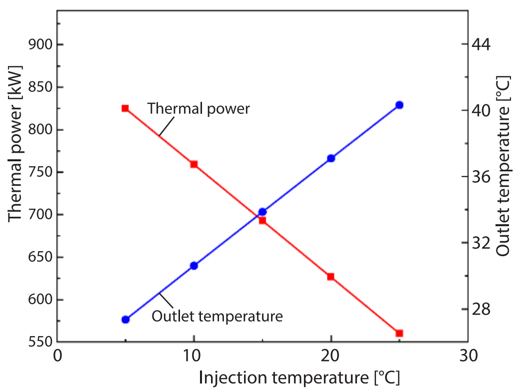

Figure 5. Effect of inlet temperature on heat recovery

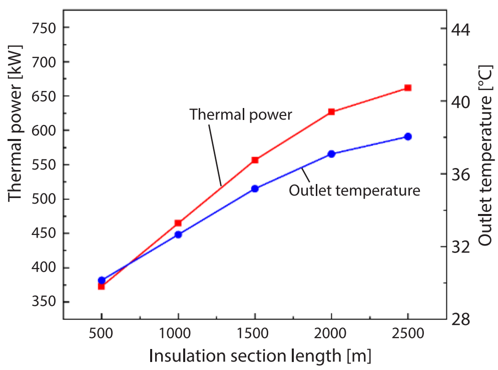

Figure 6. Effect of insulated tubing length on heat recovery

Then the effect of inlet temperature for the 30th day is shown in fig. 5. As the inlet temperature increases, the temperature difference between the cyclic fluid and the formation become less, and the heat exchange is not sufficient, resulting in a decrease in thermal power. At the same time, with the increase of inlet temperature, on the basis of heat extraction with the strata, the outlet temperature also increases accordingly. Therefore, the inlet temperature can be designed according to the requirements of thermal power and outlet temperature.

The effect of insulated tubing length of the 30th day is shown in fig. 6. As the length of the insulated tubing increases, the contact length between the injected low temperature fluid and the return high temperature fluid decreases. Therefore, both the thermal power and the outlet temperature increase. However, as the length of the insulated tubing increases, the operating cost will increase. Therefore, the length of the insulated tubing needs to be determined based on the actual situation. In order to obtain better heat extraction performance, it is recommended to achieve full wellbore insulation.

The effect of outer insulated tubing outer diameter and inner insulated tubing inner diameter of the 30th day is shown in figs. 7 and 8. As the outer insulated tubing outer diameter increases, the annulus between the insulated tubing and the casing becomes smaller, causing the annular flow velocity to be higher and the heat exchange time to shorten, resulting in both thermal power and outlet temperature becoming smaller. When the outer diameter of the outer insulated tubing increases, the inner diameter of the insulated tubing can also increase. At this time, the flow velocity in the tubing decreases and the time for the high temperature fluid to return to the ground becomes longer. Therefore, the thermal power and outlet temperature both decrease. But the absolute value of the decrease is very little. Besides, as the inner diameter of the insulated tubing increases, the fluid-flow resistance decreases. Under the same conditions of the ground pump unit, more fluid can be pumped, thereby obtaining higher thermal power. It is recommended that the outer diameter of the outer insulated tubing be smaller and the inner diameter of the inner insulated tubing be larger.

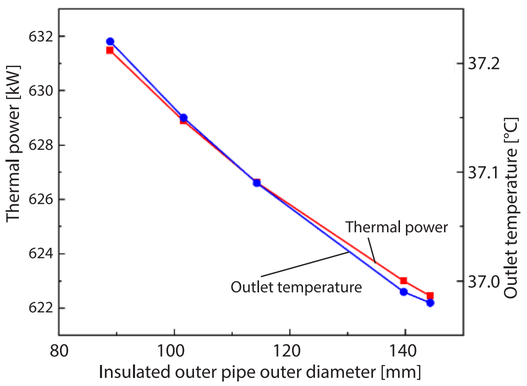

Figure 7. Effect of tubing outer diameter on heat recovery

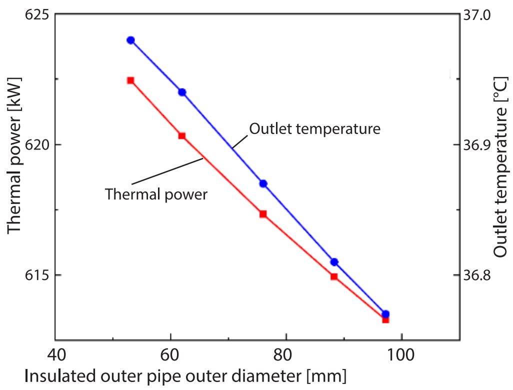

Figure 8. Effect of tubing inner diameter on heat recovery

Bidirectional absolute grey relational analysis

The grey correlation analysis shows potential for quantitatively analyzing influencing factors. However, previous models have limitations when it comes to analyzing multiple factors with both positive and negative correlations [16-18]. The bidirectional absolute grey correlation degree model, enhanced in [14], can analyze factors with positive, negative, and unclear correlations. By comparing reference sequences of heat power and outlet temperature, the factors influencing thermal power and outlet temperature are evaluated.

After obtaining the results, a comparative analysis can be conducted by referring to tab. 3 (Javed's grey incidence). As shown in fig. 9, there is a strong correlation between the injection flow rate and outlet temperature, and a close correlation between the insulated tubing length and thermal power. However, the insulated tubing diameter shows a weak correlation with thermal power and outlet temperature.

Table 3. Javed's grey incidence (JGI) scale

$\lvert \varepsilon^{\pm} \rvert$	[0.5000, 0.6000)	[0.6000, 0.7000)	[0.7000, 0.8000)	[0.8000, 0.9000)	[0.9000, 1.0000)
Categories	Level 1	Level 2	Level 3	Level 4	Level 5
Interpretation	Weak relation	Moderately strong relation	Appropriately strong relation	Sufficiently strong relation	Extremely strong relation

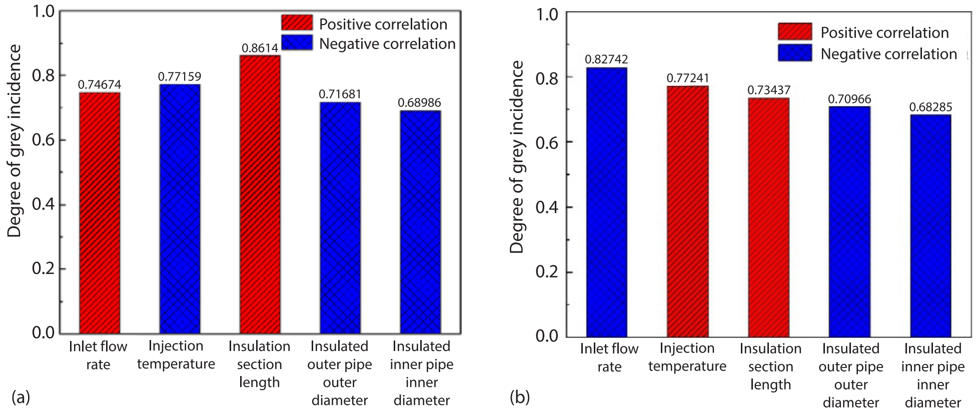

Figure 9. The correlation between different parameters and heat extraction performance; (a) thermal power and (b) outlet temperature

Conclusion

The single-well closed-loop heat extraction technology can realize efficient exploitation of geothermal resources. A 2-D transient heat transfer model was developed to analyze its thermal performance. The bidirectional absolute grey correlation degree method was employed for the analysis. The developed 2-D non-steady-state heat transfer model shows a strong fit with a maximum error of 4.8% in a 30 day field experiment. It shows that as the displacement increases, the thermal power increases, but the outlet temperature decreases.

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Nomenclature

a – area, [m]
c – thermal capacity, [Jkg^{-1}°C^{-1}]
R – thermal resistance, [mKW^{-1}]
T – temperature, [°C]

Greek symbiol

ρ – density, [kgm^{-3}]

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