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Economic Evaluation of the Coaxial Borehole Heat Exchanger

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ABSTRACT

Geothermal energy plays a critical role in energy structure improvement and carbon emissions reduction. A newly-developed geothermal energy extraction technology, the coaxial borehole heat exchanger (CBHE) can produce in most parts of the world. Its application requires neither water containing formation nor multiple wells since the working fluid is circulated and heated inside the coaxial pipe. However, the feasibility of CBHE remains unproved. This paper proposes an improved unsteady-state heat transfer model to evaluate the heat production capacity and the economic benefit of CBHE. The heat transfer model is solved by the finite difference method. Then, this paper presents the economic feasibility analysis of a base case, an insulated case, a high-thermal gradient case, and a case in dry hot rock.

The temperature profile and output performances during certain production time are calculated. The result shows that the outlet fluid temperature and thermal power will be relatively stable in one month after a sharp decrease at the beginning. The paper's base case has a low production efficiency since the CBHE system must be insulated for the effective prevention of fluid loss in the central pipe. The insulated case can double the thermal power and halve the payoff period under the same conditions compared with the base case. The geothermal gradient and well depth play important roles in the CBHE output performance. An insulated CBHE can supply more than 20000m^2 area and need only 5.6 years payoff period once the geothermal gradient and well depth are higher than 0.07K/m and 5000m, respectively. The CBHE is also an economic and environmental method to develop the hot dry rock reservoir. 9.7 years payoff period is needed for a simulated CBHE in a simulated 3500m deep well at Qiabuqia HDR in Gonghe Basin.

1. INTRODUCTION

Geothermal energy is a type of renewable energy produced from the earth. It is believed to substitute part of the fossil fuel, reduce carbon emissions, and modify the energy supply structure. The earth's huge heat content is eight orders of magnitude higher than the total human energy (Council B E, 2013). The available part, however, is only a tiny proportion. Characterized by uneven distribution (Barbier 2002), geothermal energy is hard to be utilized widely despite the area with abundant geothermal sources. Most areas do not have an economic geothermal energy production approach.

To increase geothermal energy production, a universal method, the coaxial borehole heat exchanger (CBHE) was proposed in recent years. The CBHE is believed to be an effective way to utilize deep geothermal resources. Eventually, the need for formation water discharge and fracturing formation is eliminated, so does pipe scaling and formation pollution.

Lots of CBHE thermal performance studies have been investigated. Horne (1980) proposed a full solution to the CBHE temperature profile and the optimum CBHE configuration. Morita et al. (1985) investigated the effect of insulated inner pipe, geothermal gradient and inlet water temperature. Nalla et al. (2004) conducted a comprehensive investigation of operating and design parameters on CBHE, but the ideal case electric power is below 200kW. Acuña et al. (2010,2011) conducted a thermal response test to CBHE in a 189m deep well with fiber optic cables. Zarrella et al. (2011) indicated that CBHE had better thermal behavior than U-tube borehole heat exchangers. Beier et al. (2013) developed an analytical model needless temperature approximation to estimate borehole resistance. Cheng et al. (2013, 2014) built a transient formation heat transfer model of an abandoned well based on a novel transient heat conduction function. Holmberg et al. (2016) investigated the thermal performance of CBHE with depth from 300-1000m. Gordon et al. (2018) experimentally verified a CBHE simulation with the laminar outer flow. Song et al. (2018) built an unsteady-state heat transfer model solved by the finite difference method. Luo et al. (2019) presented a new analytical model for CBHE, considering the geothermal gradient. Huang et al. (2020) analyzed the long-term CBHE thermal performance on an open-source simulator-OpenGeoSys (OGS), which is verified by the field test.

The economic analysis for CBHE is relatively less. Dijkshoorn et al. (2013) thought CBHE could deliver the required heat but not in the long-term. Raymond et al. (2015) presented an optimization method to reduce the overall cost of the CBHE system. Kipsang (2015) divided the drilling process into major categories to summarize geothermal well's drilling cost. Gul et al. (2018) provided a numerical method and codes to calculate the drilling, completion, and testing costs. Pan et al. (2020) conducted a sensitivity analysis of CBHE design parameters and provided a scheme to achieve the lowest average energy cost.

Although the output performance of CBHE is well studied, there are too few practical applications. The feasibility of CBHE still needs to be discussed. Hence, this paper proposes an improved unsteady-state heat transfer model to evaluate the heat production ability of CBHE. The heat transfer model is solved by the finite difference method. Then, this paper presents an economic evaluation. A base case, an insulated case, a high-thermal gradient case, and a case in dry hot rock are analyzed to investigate the economically feasible range of CBHE. The method and results in this paper can be used as a guide for the CBHE application.

2. CBHE SYSTEM

As shown in Figure 1, the CBHE system consists of a vertical well, a tubing (central pipe), a heat pump, and a high-pressure pump. A pipe-in-pipe concentric structure is adopted in CBHE to provide a closed fluid flowing circle. It is normally thought that a "reverse " circulation direction in CBHE can results a better geothermal energy production performance than the "forward" direction. (Horne, 1980. Morita et al., 1985. Luo et al., 2019). The "reverse " circulation direction means that the fluid is pumped into the annular space between the casing and tubing, and it is heated inside the annular and flows back to the surface in the tubing. The heated fluid can be resorted to generate electricity or heat space. After that, the fluid is pressurized by the high-pressure pump and reinjected into the annular. In this paper, CBHE is designed as a third spudding structure for deep geothermal energy development, similar to the well in the petroleum industry.

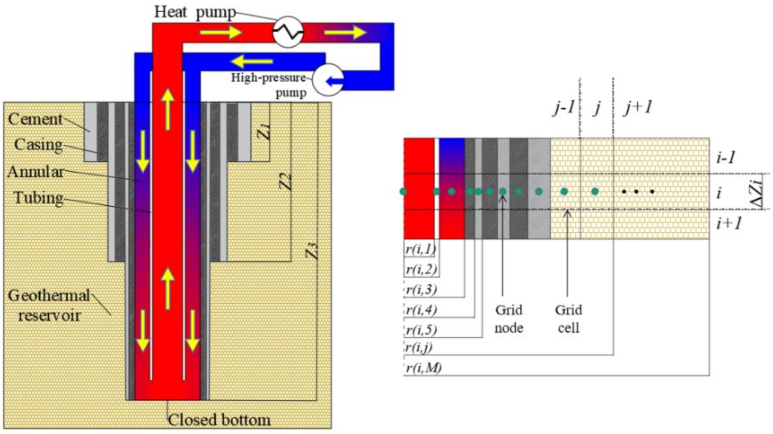

Figure 1: The Schematic diagram of CBHE system and grid division (Modified from Song 2018)

3. HEAT TRANSFER MODEL

3.1 Assumptions

An improved unsteady-state heat transfer model is built to simulate the energy exchange relationship in the CBHE system. As shown in Figure 1, the model is simplified to two-dimensional, as all the heat exchange mediums are symmetrical. Furthermore, the medium in the wellbore is simplified into one-dimensional grids. The assumption is as follows: (1) The vertical heat conduction is negligible, as it is insignificant compared with the radial heat conduction and convection; (2) The radial heat transfer of circulating fluid only considers force convection; (3) The physical properties of the CBHE system do not change with the temperature except for circulation fluid.

3.2 Controlling equations

The model is built based on the energy balance equation. The expression for the energy balance equation of the fluid in the central tube is as shown in formula (1). The first term on the left side refers to the fluid convection, while the second term refers to the heat transfer from the tubing.

$$Q\rho_1 c_1 \frac{\partial T_1}{\partial z} + \frac{T_2 - T_1}{R_1} = a_1 \rho_1 c_1 \frac{\partial T_1}{\partial t} \quad (1)$$

where T_1 and T_2 (℃) are the temperature of circulating fluid and tubing, respectively. $R((m \cdot K)/W)$ is the thermal resistance between each grid cell, defined in Appendix 1.

The energy balance equation of the tubing is as follow:

$$\frac{T_1 - T_2}{R_1} + \frac{T_3 - T_2}{R_2} = a_2 \rho_2 c_2 \frac{\partial T_2}{\partial t} \quad (2)$$

where T_3 is the temperature of the circulating fluid in the annular. The tubing can be insulated to decrease the heat exchange between the circulating fluid in the central tube and the annular. One common method is to substitute steel into thermal insulation material (polyethylene and polypropylene), while another method is to utilize a double-layer tubing with a vacuum inside.

The energy balance equation of the circulating fluid in the annular is as following:

$$Q\rho_3 c_3 \frac{\partial T_3}{\partial z} + \frac{T_2 - T_3}{R_2} + \frac{T_4 - T_3}{R_3} = a_3 \rho_3 c_3 \frac{\partial T_3}{\partial t} \quad (3)$$

where T_4 is the temperature of the casing.

The energy balance equation of cement and formation can be expressed uniformly as:

$$Q\frac{T_{j-1} - T_j}{R_{j-1}} + \frac{T_{j+1} - T_j}{R_j} = a_j \rho_j c_j \frac{\partial T_j}{\partial t} \quad (4)$$

where T_j is the temperature of the cell number j. T_{j-1} and T_{j+1} is the temperature of the adjacent grid cells.

3.3 Model discretization

The CBHE system is numbered in the axial and radial directions. The finite difference method with the fully implicit scheme is adopted to discrete the controlling equations.

The temperature of the circulating fluid cell is defined as:

$$T_{i-\frac{1}{2},(1,3)}^{n+1} = T_{i-1,(1,3)}^{n+1} + T_{i,(1,3)}^{n+1} \tag{5}$$

where *i* represents number of grid cells in axial direction, while *n* represents the time step number.

The discrete equation for the equation (1) can be expressed as:

$$T_{i-\frac{1}{2},1}^{n+1} = 2DT_{i,1}^{n+1} + ADT_{i,2}^{n+1} + BDT_{i-\frac{1}{2},1}^{n} \tag{6}$$

where $A = \frac{\Delta Z_i}{Q_1 \rho_1 c_1 R_1}; B = \frac{a_1 \Delta Z_i}{Q_1 \Delta t}; D = \frac{1}{A+B+2}$.

The discrete equation for equation (3) can be expressed as:

$$-NT_{i,2}^{n+1} + T_{i-\frac{1}{2},3}^{n+1}(2 + N + M + L) - MT_{i,4}^{n+1} = 2T_{i-1,3}^{n+1} + LT_{i-\frac{1}{2},3}^{n} \tag{7}$$

where $L = \frac{a_3 \Delta Z_i}{Q_3 \Delta t}; M = \frac{\Delta Z_i \pi}{R_3 Q_3 \rho_3 c_3}; N = \frac{\Delta Z_j}{R_2 Q_3 \rho_3 c_3}$.

The discrete equation for the equation (2) and (4) can be expressed uniformly as:

$$-\alpha_{j-1} T_{i,j-1}^{n+1} + \left(\alpha_{j-1} + \alpha_j + \xi_{j-1}\right) T_{i,j}^{n+1} - \alpha_j T_{i,j+1}^{n+1} = \xi_{j-1} T_{i,j}^{n} \tag{8}$$

where $\alpha_{j-1} = \frac{1}{R_{j-1}}; \alpha_j = \frac{\pi}{R_j}; \xi_{j-1} = \frac{a_j \rho_j c_j}{\Delta t}$

3.4 Boundary and initial conditions

1. The formation far enough from the wellbore is regarded as the original formation temperature.

$$T_{i,M}^{n+1} = T_0 + gradT \cdot i \cdot \Delta Z_i \tag{9}$$

2. The heat exchange from the well bottom is neglected. Thus, both the circulating fluid at the well bottom T_{inj}

$$T_{NZ,1}^{n+1} = T_{NZ,3}^{n+1} \tag{10}$$

$$T_{NZ,1}^{n+1} = T_{inj} \tag{11}$$

3. All the grids' initial temperature is the original formation temperature.

3.5 Model solution and verification

The discrete equations are solved by the tridiagonal matrix algorithm combined with the iteration method. We use MATLAB as the programming platform. The model is validated by a data set measured in a fluid cooling case, a CBHE well located in Stock, Sweden (Acuña et al., 2010. Beier et al., 2013). The heated water is injected through the central pipe and flows back from the annular. Based on the parameters provided, the axial temperature profile is calculated, as shown in Figure 2. Clearly, the calculated temperature profile matches well with the measured temperature. The maximum error is 1.2%.

However, fluid cooling is only part of CBHE's functions. Further model validation is conducted base on the parameters shown in Appendix 2. As shown in Figure 3, the outlet fluid temperature is calculated under five different time steps (1h, 4h, 8h, 12h, 24h). The result illustrates a sharp increase in the outlet fluid temperature following a decrease to a relatively stable value in one month production. One can observe a convergence of the calculated outlet temperature to the stable value under all time steps. Since the step size has a scant influence on long-term outlet temperature, an important criterion in CBHE economic evaluation, the step size is set to be 8h to maintain computational accuracy while reducing computation burden. Similar to comparison procedure made for the step size, a 1m axial length with 1m radial length grid size is eventually designated.

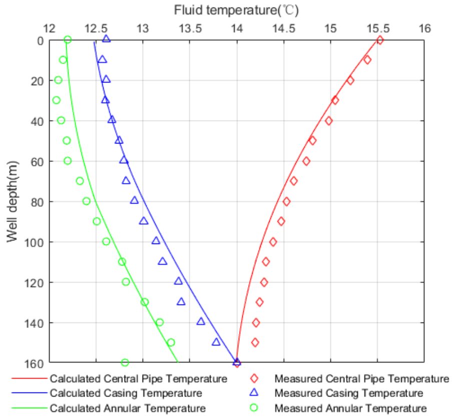

Figure 2: The calculated and measured CBHE axial temperature profile

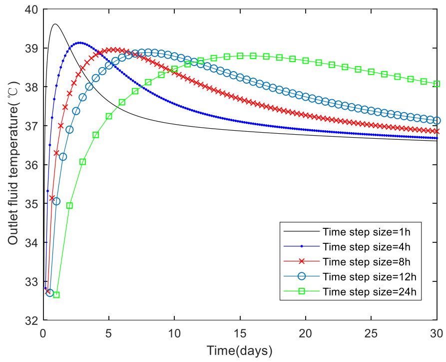

Figure 3: Comparison of outlet fluid temperature under different time step length

3. HEAT TRANSFER MODEL ECONOMIC EVALUATION MODEL

Due to the significance of CBHE's economic value to investors, a simplified economic evaluation model is built.

1. Income. The thermal power of CBHE $P(kW)$can be expressed as:

$$P = \frac{\rho_f c_f Q(T_{outlet} - T_{inlet})}{10^3} \tag{12}$$

where T_{inlet} and T_{outlet} are the outlet and inlet fluid temperature of CBHE, respectively.

The total produce energy $E(kW \cdot h)$ can be expressed as:

$$E = \frac{sum(\Delta t \cdot P)}{3.6 \times 10^6} \tag{13}$$

We assume all the produced thermal is transferred into electrical energy. Thus, the income of CBHE is expressed as:

$$In = E \cdot ec \tag{14}$$

where *ec* the electricity charge. The *ec* is set to 0.12 *USD/(kWh)*in this paper.

2. Cost. The drilling cost of CBHE is the main part of the total CBHE construction costs. In this paper, the drilling cost *Co*(Million USD) is expressed as a linear relationship with respect to the well depth D (m).

$$Co = b_0 + b_1 D \tag{15}$$

Where b_0, b_1 are the linear regression coefficients. $b_0 = -2.472, b_1 = 0.0035$. The linear regression data is derived from Lukawski M Z et al. (2014)

4. BASE CASE ANALYSIS

Figure 4 describes the axial temperature profile of the base case at 120 days, the case without insulated central pipe. It is clear that the injected fluid is heated along with the annular, then cooled back to in the central pipe. The circulating fluid has a temperature of 67℃ at the well bottom while only 30℃ at the outlet. The result evidences the inadequacy of the base case CBHE in prevention of fluid's heat loss in the central pipe.

Figure 5 displays the thermal power, total produced energy, and income of CBHE over time. The thermal power is slowly decreasing with time, while the total produced energy and income increase linearly with time. More than 6 million USD is needed to drill a well, while the payoff period of the base case is as long as 47 years with poor economic feasibility. Therefore, an improvement must be made to optimize the output performance of the CBHE system.

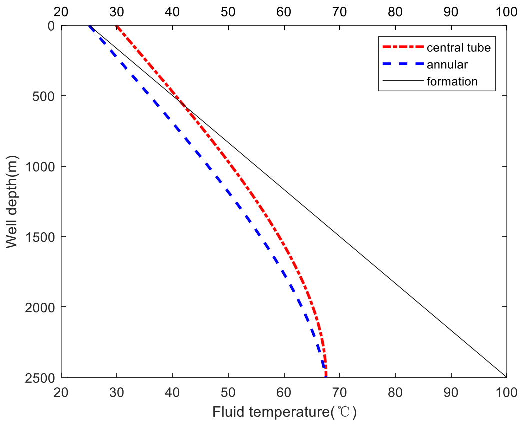

Figure 4: The axial temperature profile after 120 days of production (base case)

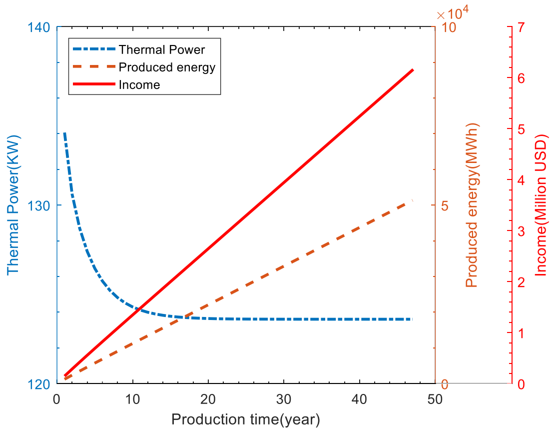

Figure 5: The thermal power, produced energy and income over time (base case)

5. INSULATED CASE ANALYSIS

The insulated central pipe is widely accepted as a method to improve CBHE performance. (Morita et al., 1985. Nalla et al., 2004. Song et al., 2018). To decrease the temperature loss of the circulating fluid in the central pipe, the central steel pipe should be replaced by an insulating central pipe made of polystyrene or dual-layer tubing Figure 6 describes the changes in outlet fluid temperature and thermal power of the insulated case with time. It is obvious that the output performance becomes stable after the first month's production and then gradually decreases with time. The result indicates that the CBHE has a stable long-term working performance.

Figure 7 shows that the bottom fluid temperature is lower, but this case's outlet fluid temperature is higher than that of the base case (120 days). This result indicates that the insulated pipe can eliminate the heat loss of fluid in the central pipe. Therefore, the fluid in the annular cannot be heated by the central pipe's fluid, and there are nearly no temperature changes in the central pipe. Thus, the thermal power is more than twice the base case and the payoff period is shortened to 21.6 years. The result proves the effectiveness of the insulated pipe and suggests that a deeper well is needed for CBHE application in the normal geothermal gradient area. However, the payoff period is still unsatisfying. Therefore, a higher geothermal gradient and well depth are considered to improve the CBHE performance.

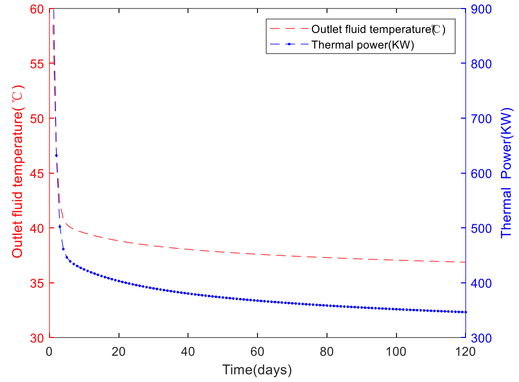

Figure 6: The outlet temperature and thermal power over time during 120 days of production (insulated case)

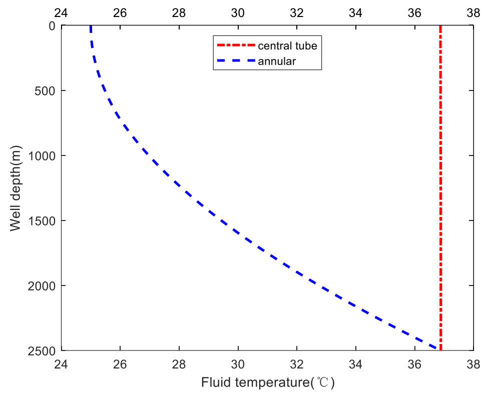

Figure 7: The axial temperature profile after 120 days of production (insulated case)

6. HIGH GEOTHERMAL GRADIENT CASE ANALYSIS

Figure 8 describes the axial temperature profile of insulated CBHE under different thermal gradients. According to the figure, the temperature of the annular increases significantly with the thermal gradient. The reason behind this phenomenon is a greater heat transfer under a higher axial thermal gradient. The outlet fluid temperature under geothermal gradients of 0.03℃/m, 0.05℃/m, and 0.07℃/m is 36.9℃, 44.8℃, and 52.7℃, respectively.

Figure 9 shows changes in the thermal power and payoff years of insulated CBHE with time under different geothermal gradients and well depths. It is evident that the thermal power increases with the well depth, which tends to be more drastic with the increasing well depth. After 120 days of production, the thermal power of 5000m deep CBHE under geothermal gradient of 0.03℃/m, 0.05℃/m, and 0.07℃/m are 3168KW, 5280KW, and 7392KW, respectively. By assuming that 0.35KW is needed per square area, the area more than 20000m^2 can be supplied by an improved CBHE once the geothermal gradient and well depth are higher than 0.07K/m and 5000m, respectively.

Due to the drilling cost's linear relationship with well depth, the payoff period decreases with the well depth. The payoff period of 5000m deep CBHE under geothermal gradient of 0.03℃/m, 0.05℃/m, and 0.07℃/m are 13.8 years, 8.0 years, and 5.6 years respectively. The result illustrates that CBHE has relatively better economic feasibility in a deep well and a high geothermal gradient.

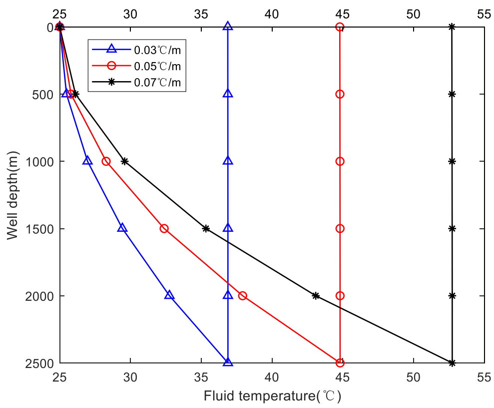

Figure 8: The axial temp. profile of CBHE under different geothermal gradient after 120 days of production

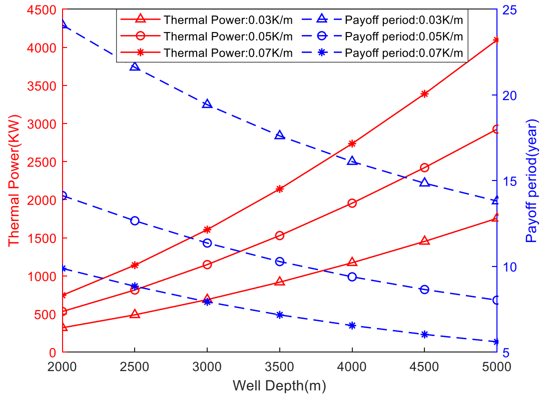

Figure 9: The thermal power relationship with well depth under different geothermal gradient after 120 days of production

7. HOT DRY ROCK CASE ANALYSIS

Figure 10 describes the temperature profile of an insulated CBHE in a 3500m deep well under the geothermal gradient of Qiabuqia HDR in Gonghe Basin, Qinghai Province, China (Zhang, 2018). The formation temperature increases significantly once the depth exceeds 2000m. Therefore, the heating process of annular fluid speeds up after a well depth of 2000m. After 120 days of production, the circulating fluid is injected at a temperature of 25℃, then heated to 64℃ at the bottom. The simulated result shows that the simulated CBHE system has thermal power of 1150KW and 9.7 years payoff period. The result indicates good compatibility of CBHE to the HDR development and that CBHE serves as a pollution-free method as it gets rid of fluid injection process to formation.

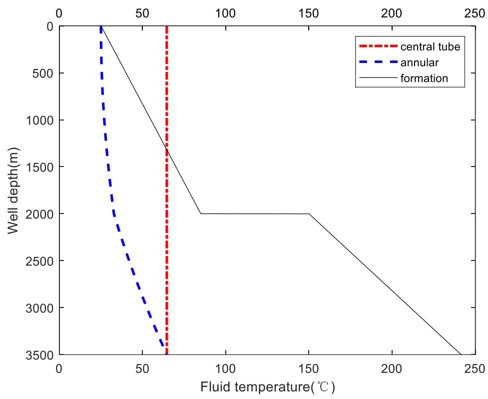

Figure 10: The axial temperature profile of CBHE under hot dry rock after 120 days of production

CONCLUSIONS

The coaxial borehole heat exchanger (CBHE) is an environmental-friendly geothermal energy development method. The closed fluid circulating channel avoids formation pollutions. In this paper, a numerical model is built to simulate the heat transfer process of CBHE. Moreover, a simplified economic model is established to evaluate the CBHE design. The main conclusions are as follows:

1. The outlet temperature and thermal power decrease gradually after one month of production.
2. This paper's base case cannot satisfy the economic demand due to a long payoff period. In contrast, the insulated case can double the thermal power and halve the payoff period under the same geothermal gradient and well depth. The insulted central pipe is necessary for the CBHE system.
3. CBHE has relatively better economic feasibility in a deep well and a high geothermal gradient, since the geothermal gradient and well depth play important roles in the CBHE output performance. More than 20000m^2 area can be supplied and only 5.6 payoff period years are needed by an insulated CBHE once the geothermal gradient and well depth are higher than 0.07K/m and 5000m, respectively.
4. The CBHE is a not only economic but also environmentally friendly method to develop the hot dry rock reservoir. The thermal power after 120 days production can meet 1150KW. 9.7 years payoff period is needed for a insulated CBHE in a 3500m deep well at Qiabuqia HDR in Gonghe Basin.

APPENDIX 1

$R((m \cdot K)/W)$ is the thermal resistance between each grid cell. The specific definition is as follows:

Thermal resistance between central pipe fluid and tubing R_1:

$$R_1 = \frac{1}{2\lambda_2} ln\frac{r_2}{r_1} + \frac{1}{2h_r r_1} \tag{a.1}$$

where $h_r(W/(m^2\ ℃))$ is the convective heat transfer coefficient of central fluid, which is defined as:

$$h_r = \frac{Nu \cdot \lambda_f}{D} \tag{a.2}$$

where D (m) is the hydraulic diameter, Nu is the Nusselt number defined as:

$$Nu = \frac{\left(\frac{f}{8}\right)(Re-1000)Pr}{\left(1+12.7\sqrt{\frac{f}{8}}\right)\left(Pr^{\frac{2}{3}}-1\right)} \tag{a.3}$$

where Re is the Reynolds number. Pr is the Prandtl number. f is the friction factor, that is:

$$\frac{1}{\sqrt{f}} = -1.8\log_{10}\left[\left(\frac{\frac{\Delta}{d_e}}{3.7}\right)^{1.11} + \frac{6.9}{Re}\right] \tag{a.4}$$

Thermal resistance between tubing and annular fluid R_2, thermal resistance between tubing and annular fluid R_3, and other thermal resistance:

$$R_2 = \frac{1}{2h_w r_2} \tag{a.5}$$

$$R_3 = \frac{1}{\lambda_4}\ln\left(\frac{r_4}{r_3}\right) + \frac{1}{2h_w r_3} \tag{a.6}$$

$$R_j = \frac{1}{\lambda_{j+1}}\ln\left(\frac{r_{j+1}}{r_j}\right) \tag{a.7}$$

APPENDIX 2

The base case size parameters and physical properties are shown in Table 1 and Table 2, respectively. Water is chosen for the circulating fluid, of which thermal physical parameters changes with temperature in the model. The water is injected into the annular at flow rate of $25m^3/s$ and temperature of 25℃. The surface temperature is 25℃ and the thermal gradient is $0.03℃/m$.

Table 1: Size parameters of CBHE system (base case)

Depth(m)	Wellbore Diameter(mm)	Casing Outer Diameter(mm)	Casing Inner Diameter(mm)	Tubing Outer Diameter(mm)	Tubing Inner Diameter(mm)
0-200	660.4	508.0	485.7	114.3	82.3
200-700	444.5	339.7	315.3		
700-2500	311.15	244.5	224.4		

Table 2: Physical properties of CBHE system (base case)

Physical properties	Tubing	Casing	Cement	Formation
Density(kg/m^3)	8000	8000	920	2650
Thermal capacity($J/(kg \cdot ℃)$)	460	460	920	920
Thermal conductivity($W/(m \cdot ℃)$)	43.5	43.5	1.1	2.68

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NOMENCLATURE

Variables

$a_{1,2,3,\ldots,j,\ldots,M}$	cross section area of central circulating fluid, tubing, annular fluid, cell numbered j, and boundary cell, (m^2)
$b_{0,1}$	linear regression coefficients
$c_{1,2,3,\ldots,j,\ldots,M}$	specific heat at constant pressure of central circulating fluid, tubing, annular fluid, cell numbered j, and boundary cell, $J/(kg \cdot ℃)$
Co	cost, (USD)
D	hydraulic diameter, (m)
f	friction factor

$h_{r,w}$	convective heat transfer coefficient of central circulating fluid and annular fluid, $(W/(m^2\ ℃))$
In	income, (*USD*)
E	total produced energy, $(kW \cdot h)$
ec	electricity charge
Nu	Nusselt number
n	time step number
P	thermal power, (*kW*)
Pr	Prandtl number
Q	volume flow rate, (m^3/s)
$R_{1,2,3,\dots,j,\dots,M}$	thermal resistance of central circulating fluid, tubing, annular fluid, cell numbered *j*, and boundary cell, $((m \cdot K)/W)$
Re	Reynolds number
$r_{1,2,3,4,\dots,j,\dots,M}$	radius of the inner tubing, outer tubing, inner casing, outer casing, outer cementing, cell numbered *j*,and boundary cell, (m)
T_0	temperature of the ground (*Z=0*), (℃)
$gradT$	geothermal gradient, $(℃/m)$
T_{inj}	injected fluid temperature, (℃)
T_{out}	outlet fluid temperature, (℃)
$T_{1,2,3,\dots,j,\dots,M}$	temperature of central circulating fluid, tubing, annular fluid, cell numbered *j*, and boundary cell, (kg/m^3)
t	time, (*s*)
Δt	time step length, (*s*)
ΔZ_i	axial grid size, (*m*)
Z	well depth, (*m*)
i	number of grid cells in axial direction
j	number of grid cells in radial direction
M	maximum number of grid cells in axial direction
NZ	maximum number of grid cells in axial direction
$\rho_{1,2,3,\dots,j,\dots,M}$	density of the central circulating fluid, tubing, annular fluid, cell numbered *j*,and boundary cell, (kg/m^3)
$\lambda_{1,2,3,\dots,j,\dots,M}$	thermal conductivity of the central circulating fluid, tubing, annular fluid, cell numbered *j*,and boundary cell, $(W/(m \cdot ℃))$
Δ	equivalent absolute roughness, (*m*)

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