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Exploring the Maximum Heat Extraction Potential of Super Long Gravity Heat Pipes in Hot Dry Rock Geothermal Reservoirs

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ABSTRACT

Extracting heat from a deep geothermal reservoir in a clean and efficient manner has always posed a significant challenge in geothermal exploration. This paper presents a numerical study of the heat extraction performance of a perfect super-long gravity heat pipe (SLGHP) under the assumptions of either an infinitely large heat transfer coefficient inside the SLGHP or a constant phase change temperature throughout the SLGHP. As the phase transition temperature of the working fluid in the pipe may be higher than the temperature of the surrounding formation, it is necessary to eliminate the possibility of heat loss at the top of the SLGHP by setting it to zero or providing a fully thermally insulated boundary. The results show that the heat output and heat output per unit wellbore length increase linearly with well depth, and the greater the given geothermal gradient and formation thermal conductivity, the larger the heat output and heat output per unit wellbore length.

Keywords: hot dry rock, supper long gravity heat pipe, upper limit, heat extraction rate, simulation

NONMENCLATURE

Abbreviations	
HDR	Hot dry rock
DBHE	Deep borehole heat exchanger
SLGHP	Supper long gravity heat pipe
Symbols	
b	Geothermal gradient, °C /m
C_p	Specific heat capacity, kJ/(m³·K)
H	Well depth, m
R_{c2}	Total thermal resistance between the annulus section and the porous formation, m·K/W
R	Outer radius, mm
T	Temperature, °C
T_0	Ground surface temperature, °C
λ	Thermal conductivity, W/(m·K)
ρ	Density, kg/m³

1. INTRODUCTION

Hot dry rock (HDR) is a geothermal resource with vast reserves and low-carbon environmental benefits. As drilling technology advances and reaches greater depths, the temperature, or thermodynamic quality, of geothermal resources increases, as does the reserve size. Under deep geological conditions, it is highly probable that target drilling areas of HDR will exist in a dry or near-dry state [1]. Currently, the most commonly applied method for HDR exploitation is the Enhanced Geothermal System, which involves creating artificial fractures in the heat reservoir between wells, allowing the fluid to flow through the reservoir fractures and exchange heat effectively. However, numerous engineering cases have demonstrated that this model suffers from instability and uncertainty in the fractures, leading to issues such as the inability to maintain fractures over the long term and severe fluid loss. Therefore, experts and scholars have proposed using deep borehole heat exchangers (DBHE) and SLGHP to extract heat from HDR [2].

As shown in Fig. 1, the conventional deep geothermal single well system is a closed loop of coaxial pipe-in-pipe structure. The cold fluid flows downward through the outer annulus, extracts heat from the surrounding formation along the wellbore, then returns to the insulated inner pipe at the bottom, and flows up to the ground surface. Horne [3] studied the early theoretical model of DBHE. In 1992, Morita et al. [4] conducted an in-situ experiment of coaxial DBHE in a geothermal well with a depth of 876.5 m and a bottom temperature of 100°C, with the maximum gross and net thermal extraction rates of 540 kWt and 370 kWt, respectively. The effects of various parameters on the heat extraction performance of DBHE have been

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numerically studied [5]. Le Lous et al. found that the soil porosity and the thermal conductivity were the key factors affecting the heat extraction performance of DBHE [6]. Fang et al. showed that well depth, geothermal gradient, and soil thermal conductivity have significant effects on increasing the heat extraction rate of DBHE [7]. It should be noted that although the DBHE system does not have the problem of reinjection and is not subjected to geographical restrictions, its heat extraction performance is generally low, and the heat extraction rate per wellbore length in all continuous heating scenarios does not exceed 150 W/m [8]. This is mainly because the heat transfer mode between DBHE and its surrounding formation is dominated by heat conduction.

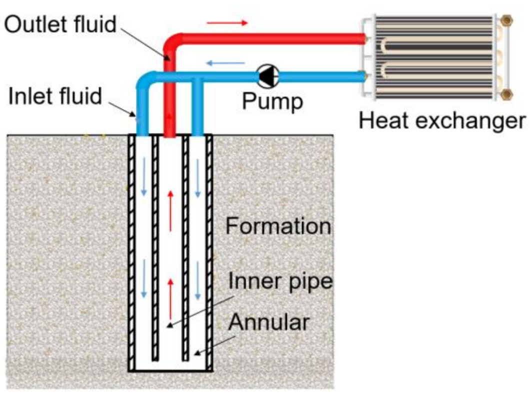

Fig. 1 Conceptual models of DBHE

In order to find a more efficient method of extracting heat from the deep formation, Jiang et al. [9] proposed the idea of using super-long gravity heat pipe for extracting heat from deep geothermal single wells in 2017, as shown in Fig,2.

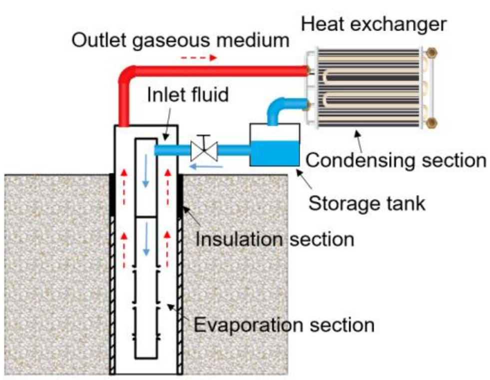

Fig. 2 Conceptual models of SLGHP

Chen et al. [10] subsequently conducted a lab-scale experiment to test this idea. Meanwhile, Huang et al. performed a numerical simulation of SLGHPs in a fractured aquifer of a porous cylindrical enclosure [11]. The simulation results showed that the heat extraction rate of SLGHP was approximately 1.8 times higher than that of DBHE in the same enhanced geothermal system, while considering natural convection in the reservoir. A recent field test by Jiang et al is as follows [12]. In the project, a 3000 m long heat pipe was installed in a 4000 m deep geothermal well with the target layer is a low-permeability zone of hot dry rock. During 30 days continuous heat extraction, the average heat extraction rate achieved 190 kW, and there was no obvious downward trend.

In order to obtain the effects of different geologic parameter on the heat extraction rate, in this paper, a numerical simulation was performed to obtain the upper limit of heat extraction rate using SLGHP in hot dry rock reservoirs without well reconstruction or stimulation. A perfect SLGHP model was established on the basis of ignoring the temperature difference inside the heat pipe and the heat loss at the top section of the well caused by the formation temperature being lower than the phase change temperature.

2. PHYSICAL AND MATHEMATICAL MODELS OF PERFECT SLGHP

2.1 Establishment of physical model of SLGHP

The physical model of SLGHP is shown in Fig. 3. Since both evaporation and condensation of the working fluid happen in the same closed space, the temperature difference between the two ends of the heat pipe is generally small.

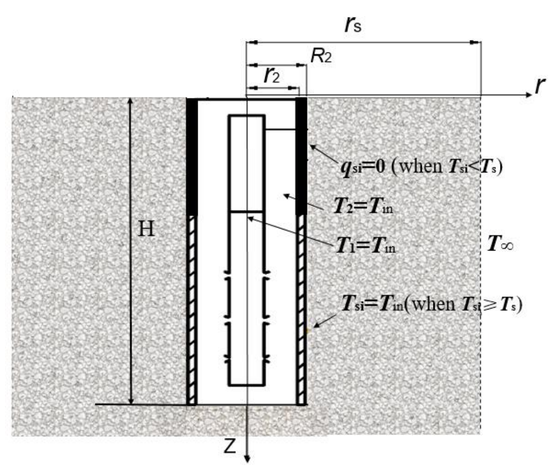

Fig. 3 Heat transfer model of the perfect SLGHP

Therefore, the following assumptions were made in the present model:

(1) The phase change temperature inside the heat pipe is constant,

(2) the thermal resistance of the annular envelope between the outer wall of the heat pipe and the inner wall of the well is ignored,

Table 1. Geometrical and physical parameters given in the simulation

Parameter	value	Parameter	value
Radius of the wellbore, R_2	205 mm	Well depth, H	4000 m
Surface temperature, T_0	20 °C	Phase change temperature, T_{in}	Changeable in 60-120 °C
Geothermal gradient, b_1 (depth < 1400 m)	7°C/100 m	Geothermal gradient, b_2 (depth > 1400 m)	1.5 °C /100 m
Formation radius, r_s	50 m	Inlet temperature, T_1	90 °C
Thermal conductivity of fluid, λ_f	0.6 W/(m·K)	Thermal conductivity of porous formation, λ_s	Changeable in 2.0-3.5 W/(m·K)
Volume specific heat capacity of fluid, $(\rho C_p)_f$	4.2×10^6 J/(m^3·K)	Volume specific heat capacity of formation, $(\rho C_p)_s$	2.16×10^6 J/(m^3·K)

(3) the thermal resistances due to heat conduction of heat pipe wall and well wall is ignored,
(4) the porous formation is isotropic and homogeneous.

2.2 Mathematical model of the perfect SLGHP

As shown in Fig. 3, a 2D axisymmetric heat conduction model was used in the simulation. The governing equations of energy in porous formation are as follows:

$$\left(\rho C_p\right)_s \frac{\partial T_s}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(\lambda_s r \frac{\partial T_s}{\partial r}\right) + \frac{\partial}{\partial z}\left(\lambda_s \frac{\partial T_s}{\partial z}\right) \quad (1)$$

where the subscripts "s" represents the porous formation.

As introduced in the section above, this paper focus on the maximum heat extraction performance of the perfect SLGHP. Since the fluid temperature in the well is assumed to be constant, the whole wellbore surface has a constant temperature, and the outlet and inlet temperatures should also be the same and equal to the phase change temperature T_{in}:

$$T_2\big|_{z=0\sim H} = T_1\big|_{z=0\sim H} = T_{in} \quad (2)$$

if $T_{si} < T_s$, the interface condition between the porous formation and the wellbore wall is given by Dirichlet boundary condition of constant temperature,

$$T_{si} = T_{in} \quad (3)$$

The given boundary condition of Eq. (3) is different from the previous numerical model [13] in that the heat transfer resistance inside the heat pipe is ignored.

And Neumann boundary condition of zero heat flux or the perfect thermal insulation boundary condition if $T_{si} \geqslant T_s$,

$$T_{si} = T_s \text{ or } q_{si} = 0 \quad (4)$$

Eq. (3) indicates that the thermal resistance of heat pipe tends to zero while the working fluid temperature in the heat pipe T_{in}, is smaller than the formation temperature T_s. Eq. (4) indicates that the thermal resistance between the interface of porous formation with the wellbore wall is infinity large or perfect thermal insulated, that is, $q_{si} = 0$.

The initial temperature distribution and the temperature far from the wellbore axial is a linear function of depth and can be written as,

$$T_s\big|_{r=r_s} = T_\infty = T_0 + bz \quad (5)$$

where T_0, b, z are the surface temperature, geothermal gradient, and formation depth, respectively.

The surface temperature T_0 is given by a constant of air temperature, and the bottom is given as a linearly extrapolated boundary condition, i.e., the second order derivative of T with respect to depth is zero. Other parameters used in the simulation were listed in Table 1, and some parameter values refer to the case of Huang et al. [12].

3. RESULTS AND DISCUSSION

3.1 Effect of thermal conductivity of the formation

Fig. 4 shows the numerical results of the time-varying heat extraction rate for different formation thermal conductivities. It can be seen that the total heat extraction rate or the heat extraction rate per unit wellbore length increases with the thermal conductivity of formation, i.e., the larger the thermal conductivity, the more heat can be extracted from the formation. Quantitatively, after 120 days of system operation, the heat extraction rates for the formations with thermal conductivity of 2 W/m·K, 2.5 W/m·K and 3 W/m·K are 38.2 %, 25.1 % and 12.4 % lower, respectively, compare to formation with a thermal conductivity of 3.5 W/m·K. For formations with thermal conductivities of 3.5 W/m·K, 3 W/m·K, 2.5 W/m·K and 2 W/m·K, the corresponding heat extraction rates per unit wellbore length are 204 W/m, 179 W/m, 153 W/m and 126 W/m, respectively.

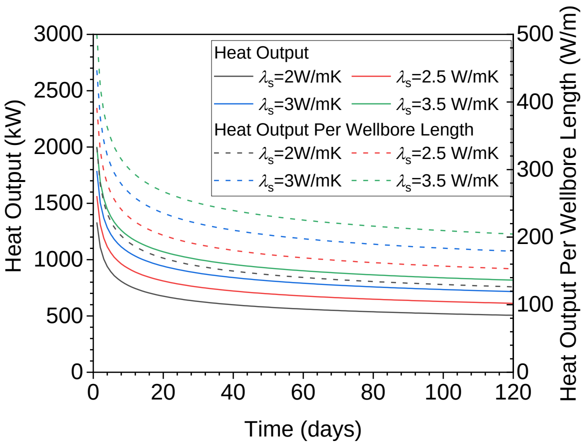

Fig.4 Total heat extraction rates and heat extraction rates per unit wellbore length at various formation thermal conductivity.

3.2 Effect of geothermal gradient of the formation

It is well known that the geothermal gradient is a key parameter for distinguishing geothermal anomalous areas from the normal areas. As shown in Fig. 5, in the geothermal anomalous area with large geothermal gradient, SLGHP can extract more heat from the formation. The bend straight line shown in Fig. 5 is for the case tested by Huang et al. [13], where the geothermal gradient is 7℃/100 m when it is less than 1400 m, and 1.5 ℃/100 m when it goes further down.

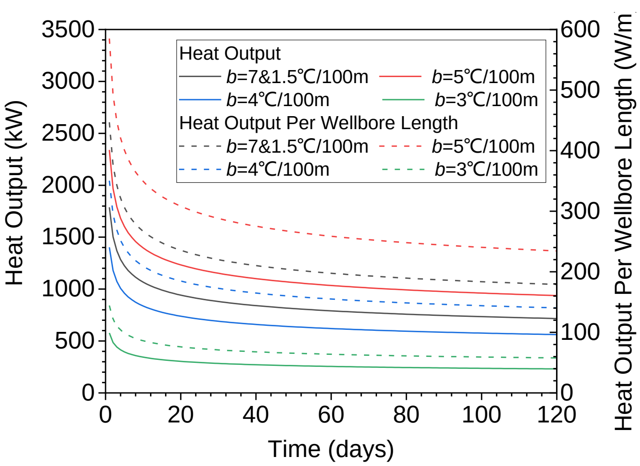

Fig.5 The heat extraction rates and heat extraction rates per wellbore length over time at various geothermal gradients.

Therefore, the average geothermal gradient at a depth of 4000m is about 0.034℃/m. However, it can be seen that the total heat extraction rate for the case of segmented geothermal gradient is higher than that in the case of a uniform geothermal gradient of 0.04℃/m. Therefore, using uniform geothermal gradient to calculate the extracted heat from the formation with segmented geothermal gradients may result in errors.

4. CONCLUSIONS

A heat transfer model of perfect SLGHP is established, and the upper limit of the possible heat extraction rate is numerically analyzed. Two key parameters that affect the upper limit of heat extraction rate, namely the geothermal gradient and thermal conductivity of porous formation. It is worthy to point out that the numerical simulated cases in the present paper does not include the improvement or stimulation reservoir, such as the artificial reconstruction of the to increase the permeability. This is because natural convection induced outside the wellbore may contribute to the heat extraction. The detailed conclusions are as follows:

(1) As thermal conductivity increases, both the heat output and the heat output per wellbore length of the SLGHP increase.

(2) The larger the geothermal gradient, the lower the heat output and the heat output per wellbore length of the SLGHP.

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