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Feasibility analysis of a new single well pumping system

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ABSTRACT

As a new geothermal heat utilization mode, the research and application of single well pumping system are in the initial stage, so it is necessary to establish the system feasibility evaluation standard. Based on the refraction law, an empirical correlation of the heat affected radius of the aquitard is established in this paper. It is found that the heat affected radius of the aquitard can be characterized by the flow parameters (flow rate, recharge temperature), geological parameters (permeability, porosity, thickness) and physical parameters (thermal diffusivity) of the pumping and recharging layer. It is found that the most sensitive factors of thermal performance are permeability, recharge temperature and circulation flow.

Keywords: geothermal, single well pumping system, feasibility analysis

NONMENCLATURE

Symbols	
$C_{p,f}$	the specific heat capacity of injected water, kJ/(kg·k)
$C_{p,s}$	the specific heat capacity of aquifer, kJ/(kg·k)
Qv	the volume of injected water, m^3/h
ρ_f	density of injected water, kg/m^3
ρ_s	aquifer density, kg/m^3
T_f	inlet temperature of injected layer, ℃
T_{in}	injected temperature of wellhole inlet, ℃
T_w	wellbore wall temperature, ℃
T_{ini}	initial soil temperature, ℃
η	heat extraction effiency
$v_{out/inj}$	volume of pumping and recharging in a time step, m^3/h
T_{out}	pumping temperature,℃
T_0	surface temperature, ℃
λ_s	soil thermal conductivity, W/(m·k)
λ_f	thermal conductivity of reinjection water, W/(m·k)
λ_{eq}	equivalent thermal conductivity of aquifer, W/(m·k)
L	characteristic length, m
T_0	urface temperature, ℃
a	ground temperature gradient, ℃/Km
Re	Reynolds number
Pr	Prandtl number
$\vec{u}$	Darcy velocity, m/s
Q_h	source-sink, W/m^3
P	aquifer pressure, Mpa
M_m	aquifer mass flux, kg/(m^3·s)
K	aquifer permeability, m^2
μ_f	hydrodynamic viscosity, Pa·s
D	unit vector of acceleration direction of gravity, m
Q	heat transfer, kW

1. INTRODUCTION

Clean and renewable energy is the strategic goal of current energy transformation efforts. Geothermal energy has several promising features including a high utilization coefficient and stability. The estimated annual utilization of geothermal energy in China is approximately 6.0 × 105 TJ [1], and this energy is dominated by hydrothermal geothermal resources. For hot water geothermal wells, the most common energy generation methodology is to use one pumping well to extract hot water, while the cold water generated after heat exchange is recharged to another well [2]. However, many geothermal wells have no recharge measures, which leads to an imbalance of production and reinjection, i.e. the attenuation of geothermal resources and the subsidence of strata [3]. In addition, the number of abandoned oil wells in China is as high as 10,000, and single well pumping and recharging is preferred for geothermal reutilization of these wells. As a new geothermal heat utilization mode, the research and application of leaky pumping and recharging systems (LPRSs) are in the initial stages, and thus, there is a need to establish a system feasibility evaluation standard. These LPRSs are a new type of technology that has been proposed to overcome the above bottlenecks to geothermal development. In contrast to single well circulation technology [4], most of the water circulating in the wellbore is "dead water," which is also different from shallow pumping and recharging system technology. Only the wellbore is sealed, and the thermal penetration of the aquifer remains very large. The technology for LPRSs makes use of the impermeability of the aquitard to separate an aquifer into a pumping layer and reinjection layer. The casing type is used in the wellbore, and the inner pipe is insulated. A packer is used at the bottom of the wellbore to separate the pumping and return water; hence, the circulating water comes from the aquifer. This technology can effectively reduce the phenomenon of thermal transfixion, and it is conducive to reinjection. Moreover, such technology has several advantages including a small land footprint, low investment cost, and high heat extraction rate. Models of a shallow single well circulation system and LPRS are shown in Figure 1.

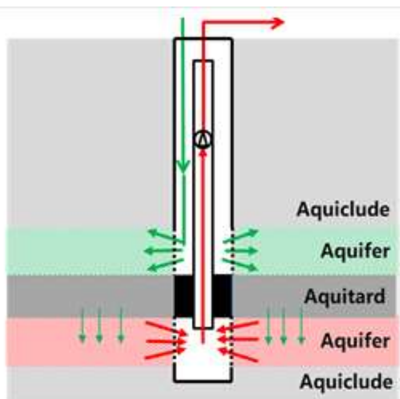

Fig 1 The system diagram of single well pumping

2. MODEL ESTABLISH

2.1 Coupled seepage heat transfer model of thermal reservoir

The system is the confined aquifer of Guantao formation. The upper and lower parts are separated by aquiclude, and the middle of aquifer is divided into recharge layer and pumping layer. as shown in Fig 2. The model is based on the following assumptions:

1. Both aquifer and aquiclude are saturated, homogeneous and anisotropic, with constant thickness and no hydraulic gradient;

2. Ignore the influence of natural cross flow of groundwater;

3. The pumping and irrigating wells of the system are all complete wells, and the pumping and recharging flow is evenly distributed in the whole filter layer of the wells;

4. The porosity and permeability of aquifer and aquiclude are constant, and the ratio of horizontal permeability to vertical permeability is 3:1;

5. The single well circulating well is a complete well, and the pumping and recharging flow is evenly distributed on the pumping recharging filter layer, and the pumping and recharging amount is the same;

6. The temperature of reinjection water is constant in one operation cycle;

7. Ignoring the change of density and viscosity;

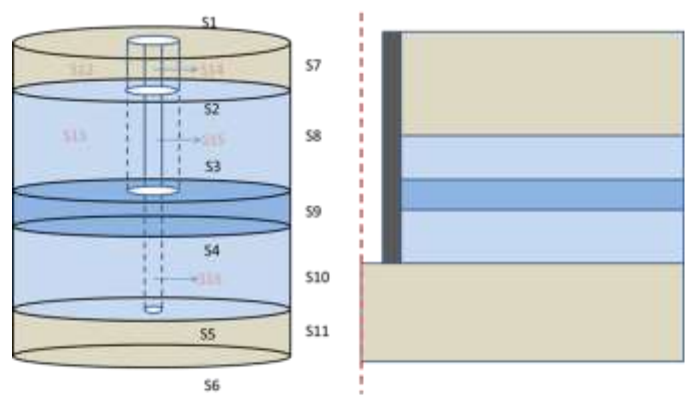

Fig 2 Geometric model

Heat transfer equation is:

$$\begin{aligned}&\frac{\partial}{\partial t}\left[\varphi_i\rho_{f_i}c_{p,f,i}+\left(1-\varphi_i\right)\rho_{s,i}c_{p,s,i}\right]T_i\\&=\nabla\cdot\left(\lambda_{eq,i}\nabla T_i\right)-\nabla\cdot\left(\rho_{f,i}c_{p,f,i}\vec{u}_iT_i\right)+Q_{h,i}\end{aligned} \tag{5}$$

φ_i is aquifer porosity; ρ_{f_i} is fluid density, kg/m^3; $\rho_{s,i}$ is aquifer density, kg/m^3; $c_{p,s,i}$ is specific heat capacity of aquifer, kJ/(kg·k); $c_{p,f,i}$ is specific heat capacity of fluid, kJ/(kg·k); T_i is study area temperature, ℃; $\lambda_{eq,i}$ is equivalent thermal conductivity of aquifer, W/(m·k); $\vec{u}_i$ is Darcy velocity, m/s; $Q_{h,i}$ is source-sink, W/m^3; i=1,2,3, they are recharge layer, aquitard layer and pumping layer.

Continuity equation is:

$$\rho_{f,i}\varphi_i \frac{\partial p_i}{\partial t} + \nabla\left[\rho_{f,i}\vec{u}_i\right] = M_{m,i} \qquad (6)$$

p_i is aquifer pressure, Mpa; $M_{m,i}$ is aquifer mass flux, kg/(m^3·s).

Darcy's equation of motion is:

$$\vec{u}_i = -\frac{k_i}{\mu_{f,i}}\left(\nabla p_i + \rho_{,f} g_i \nabla D\right) \qquad (7)$$

k_i is aquifer permeability, m^2; $\mu_{f,i}$ is hydrodynamic viscosity, Pa·s; D_i is unit vector of acceleration direction of gravity, m.

2.3.2 Boundary condition

(1) For the upper and lower aquifers, the boundary conditions of no flow and constant temperature are adopted;

$$\frac{\partial H}{\partial \mathrm{n}}\Big|s_{1、2、5、6、7、11} = 0, \quad T\Big|s_{1、6、7、11} = T_0 \qquad (8)$$

(2) For the side boundary of pumping, backwater layer and aquitard, no flow boundary condition is adopted; For temperature of backwater layer, outflow boundary is adopted; for far side boundary of pumping layer, constant temperature variable boundary is adopted;

$$\frac{\partial H}{\partial \mathrm{n}}\Big|s_{8、9、10} = 0, \quad -n\cdot(\lambda\cdot\nabla T)\Big|s_{8、9} = 0, \quad T\Big|s_{10} = T_0 \qquad (9)$$

(3) For the interface between inner and outer shaft lining and aquiclude, the boundary conditions of no flow and constant temperature are adopted;

$$\frac{\partial H}{\partial \mathrm{n}}\Big|s_{12、14} = 0, \quad T\Big|s_{12、14} = T_{inj} \qquad (10)$$

(4) For the interface between outer well wall and backwater layer, the boundary conditions of constant flow rate and constant temperature are adopted;

$$q\Big|s_{13} = q_{inj}, \qquad T\Big|s_{13} = T_{inj} \qquad (11)$$

(5) For the interface between inner shaft wall and backwater layer and aquitard ,the boundary conditions of no flow and constant temperature are adopted;

$$\frac{\partial H}{\partial \mathrm{n}}\Big|s_{15} = 0, \qquad T\Big|s_{15} = T_{inj} \qquad (12)$$

(6) For the interface between the inner shaft wall and the pumping layer, the boundary conditions of constant discharge and outflow are adopted;

$$q\Big|s_{16} = q_{out}, \quad -n\cdot(\lambda\cdot\nabla T)\Big|s_{16} = 0 \qquad (13)$$

2.2 Model parameters and operating conditions

This research model is based on a geothermal well in Dagang Oilfield, Tianjin, using a long screen gravel filling well. It is 1764m in depth, 54.5m in the upper aquifer, 10.7m in the aquitard and 23.3m in the lower aquifer. The geothermal gradient is 0.33℃/Km and the bottom hole temperature is 71℃. The aquifer model parameters in this study are shown in Table 1. Set the reference condition, injected temperature is 35℃, and flow rate is 32 m^3/h.

Table 1 Aquiclude , aquifer and aquitard properties for reference case

Parameter	Symbol	Aquiclude （1、5）	Aquifer （2）	Aquitard （3）	aquifer （4）	Units
porosity	φ	/	0.3	0.25	0.3	-
Horizontal permeability	K	/	1.7×10^{-12}	8×10^{-13}	1.7×10^{-12}	m^2
Thermal conductivity of rock	λ	1.5	2.1	1.8	1.8	W/(m · K)
Specific heat capacity of rock	Cp	696	998	1400	1400	J/Kg · K
Density of rock	ρ	2100	2109	2600	2600	Kg/m^3
Study area radius	r	400	400	2400	400	m
Study area thickness	H	200	30	9	15	m

3. ***RESULTS***

The three most important parameters are heat transfer *Q*, kW, pumping temperature T_{out}, ℃ and heat extraction rate η. The heat extraction rate represents the ability to extract heat from the heat storage, which is defined as the ratio of heat transfer to heat injected into aquifer in a cycle cycle.

$$\eta = \frac{\sum C_{pout}\rho_{out}v_{out}(T_{out} - T_{inj})}{\sum C_{pinj}\rho_{inj}v_{inj}(T_0 - T_{inj})} \qquad (14)$$

T_{out} is pumping temperature, ℃; T_{inj} is injected temperature, ℃; T_0 is aquifer temperature, ℃; $C_{\mathrm{p(out/}inj)}$ is pumping / recharging specific heat capacity, kJ/(kg·k); $\rho_{out/inj}$ is pumping / recharging density, kg/m^3; $v_{out/inj}$ is volume of pumping and recharging in a time step, m^3/h.

A sensitivity comparison of the studied parameters is summarized in Fig 3 by taking the heat capacity of the reference case as the basis. The permeability ratio has the greatest influence on the thermal performance of the cycle, followed by the flow rate, the thickness of the aquitard, the thickness of the pumping layer, the injected temperature and the thickness of the reinjection layer.

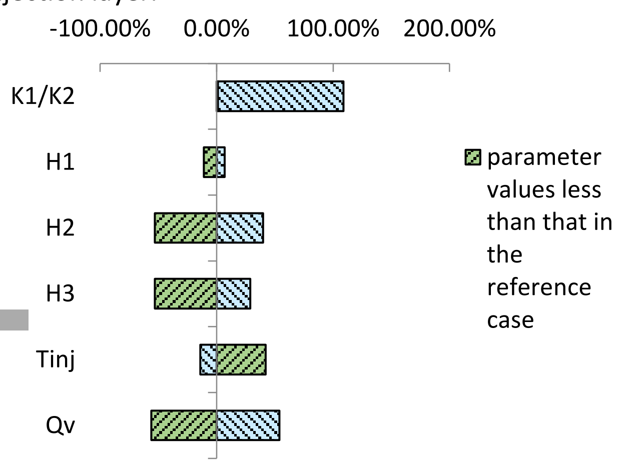

Figure 3 Sensitivity comparison of heat capacity

Variation curve of minimum thickness of aquitard with its permeability is shown in Fig 4.

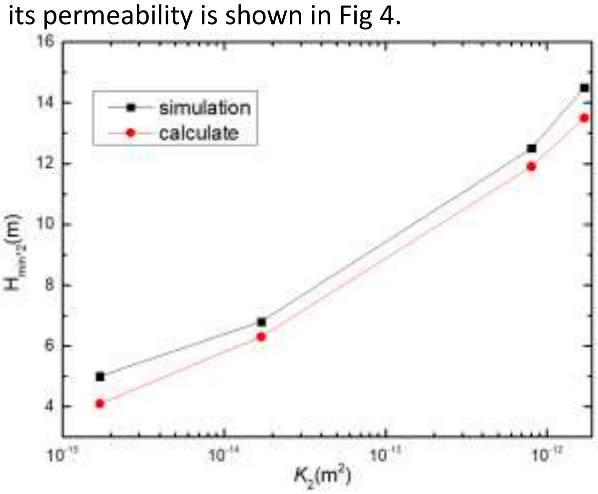

Fig 4 Variation curve of minimum thickness of aquitard with its permeability

4. CONCLUSIONS

In this study, the coupled simulation of seepage and heat transfer in aquifer is carried out considering the heat transfer in LPRS. The sensitivity analysis of flow parameters and geological structure parameters is carried out, and the feasibility of the system is analyzed. The following conclusions are obtained:

(1) The permeability ratio has the greatest influence on the thermal performance of the cycle, followed by the flow rate, thickness of the aquitard, thickness of the pumping layer, reinjection temperature, and thickness of the reinjection layer.

(2) When the permeation ratio is greater than 20, the temperature dominates, and otherwise, the flow rate dominates.

(3) The formula of the heat-affected radius of the aquitard can be deduced as,

$$r_1 = \frac{R_{th1}}{1+\frac{K_2}{K_1}\cdot\frac{1}{H_{21}-|z_1|}\cdot\frac{H_1}{5}},$$

$$r_2 = \frac{R_{th2}}{1+\frac{K_2}{K_3}\cdot\frac{|z_2|+\frac{1}{5}H_3}{H_{22}-z_2}}$$

(4) The proposed critical value criterion formula of the aquitard thickness is,

$$\frac{Da_2}{Da_{1(3)}} = \left(\frac{K_2}{K_{1(3)}}\right)^n \cdot \frac{1}{C\cdot\sqrt{Fo_{21(2)}}}$$, n=0.5, C=4

(5) The comparison curves between the calculated and simulated results of the minimum thickness of the aquitard under different permeability values were provided, and the errors were less than 10%; these findings can be used to guide engineering applications.

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REFERENCE

[1] ZHU J L， HU K Y， LU X L， et al. A review of geothermal energy resources， development， and applications in China ： current status and prospects[J]. Energy， 2015， 93： 466-483.

[2]Babaei M , Nick H M . Performance of low-enthalpy geothermal systems: Interplay of spatially correlated heterogeneity and well-doublet spacings[J]. Applied Energy, 2019, 253(NOV.1):113569.1-113569.18.
[3]Kaya E , Zarrouk S J , O'Sullivan M J . Reinjection in geothermal fields: A review of worldwide experience[J]. Renewable & Sustainable Energy Reviews, 2011, 15(1):47-68.
[4]Sorensen S. N, Reffstrup J. Prediction of Long-Term Operational Conditions for Single-Well Groundwater Heat Pump Plants[J]. 1992, 1.