Analysis on the Influence of Recharge of Sandstone Thermal Storage in Guantao Formation of Lankao County on the Heat Recovery Process

Jiayanyu wangyuxing

Zhengzhou Branch of New Energy Research Institute, SINOPEC Star Petroleum Co. ,Ltd. , Beijing

Key words：Guantao Formation Sandstone；recharge；well spacing；permeability；thermal compensation ; thermal breakthrough.

Abstract：Based on the sandstone thermal storage data of Guantao Formation in Lankao County, Henan Province, based on the simplified multi-porosity model, using COMSOL finite element multi-field coupled numerical simulation software, considering the effect of bedrock and caprock thermal compensation and seepage on the heat transfer process of geothermal reservoirs, a coupled seepage-heat transfer model of geothermal reservoirs with faults is established. The periodical "one production, one injection" model is adopted to simulate the long-term operation process of geothermal wells in different well spacing and different permeability formations. Through the analysis and comparison of the temperature field and flow field changes during the heat recovery operation of the thermal reservoir, the occurrence of the phenomenon of thermal breakthrough in the process of heat recovery on a long-term scale is studied. The research results show that: compared with production well, the bottom hole temperature of injection well has dropped sharply within 10 years, and is rapidly approaching the recharge water temperature (20°C). And because the low temperature area expands over time, the increase in bottom hole temperature of the injection well by thermal compensation is also rapidly reduced. There is a strong correlation between the bottom hole temperature and well spacing. With the increase of well spacing, the decrease of reservoir temperature caused by recharging has less influence on the bottom hole temperature, but it increases with time. During the development and utilization of geothermal resources in Lankao County, the spacing between wells should not be less than 500m, so as not only to ensure no thermal breakthrough during the operating life, but also to ensure the maximum utilization of recharging water.

1. INTRODUCTION

China is currently in the stage of economic structural transformation, and it is urgent to accelerate the development and utilization of green energy and improve the development efficiency of current energy resources.Geothermal energy is divided into three categories according to the burial depth: shallow geothermal energy below 200m; mid-deep geothermal energy from 200m to 3000m; deep geothermal energy below 3000m[1].Among them, the hydrothermal geothermal energy in the middle and deep geothermal energy is the most widely developed and utilized type of geothermal energy in China.At present, China is vigorously promoting the use of geothermal resources to replace traditional resources for building heating to reduce the pressure on resource supply[2]. More than 20 provinces and urban areas use hydrothermal geothermal resources for heating, and the total area of geothermal heating ranks first in the world. The heat transfer medium in hydrothermal geothermal energy is geothermal fluid, which has the characteristics of deep burial and slow natural supply, and is a relatively non-renewable resource. With the large-scale development and utilization of hydrothermal geothermal energy,the imbalance of supplementary production of geothermal fluid has caused a series of geological environmental problems such as reservoir pressure drop, hydrochemical pollution and thermal pollution[3]. Recharge is the most effective way to solve the above problems and ensure the sustainable development and utilization of geothermal resources[4].However, in recent years of recharge research, it was found that the recharge of geothermal tail water has brought new problems, that is, the temperature of the thermal storage around the recharge well is reduced, and it is far from being able to return to the original thermal storage temperature before the next heating season[5]. Recharge also causes the temperature around the production well to drop,a phenomenon known as thermal breakthrough[6]. The thermal breakthrough time directly determines the service life of the geothermal system.Once the thermal breakthrough occurs, the heat production capacity of the thermal storage will gradually decrease or even leads to the complete shutdown of the geothermal system. Therefore, the main purpose of geothermal recharge research is to predict the thermal breakthrough time of the production well, and through various means to reduce the risk of thermal breakthrough of production wells, so as to prolong the service life of the geothermal system and ensure the geothermal system operates efficiently and economically.In addition to field methods such as field recharge tests and monitoring of well temperature during operation [7], it is very important to use numerical simulation to establish the evolution law that can reflect the temperature and flow field of thermal reservoirs over time to predict the time of thermal breakthrough of production wells [8].

Xu Yong simulated the hydraulic connection between the wells,reasonable well spacing, the evolution of chemical field, seepage field and temperature field during the recharge process through numerical simulation, and predicted the water level of underground hot water under different production and irrigation schemes after many years. The factors affecting thermal breakthrough include geothermal well flow, spacing between production and irrigation wells, thermal reservoir lithology, thermal reservoir geological structure and other factors [9].Zhu Jialing focused on the porosity of the Guantao Formation in the Tanggu area of Binhai New Area, Tianjin, and used TOUGH2 software to fit and study the effect of pressure difference compensation between geothermal recharge wells on the recharge efficiency [10].Zhao Zhihong applied the theoretical framework of the equivalent seepage channel model to perform tracer test inversion and thermal breakthrough prediction of production wells[11].Wei Kai established a weakly coupled model of seepage and heat transfer for geothermal reservoirs with fractures, and analyzed the influence of characteristic parameters such as the inclination angle, length and width of fractures on the seepage field and temperature field of the geothermal reservoir[12].Li Jingyan studied the effect of thermal compensation of the upper and lower strata of the thermal storage on the performance of the CO_2 plume geothermal system [13].Cui Hanbo combined the fluid-solid coupling heat transfer theory and used Comsol software to establish a fluid heat transfer model of discrete fractured rock mass [14].

Due to the large geothermal burial depth in the middle and deep layers and the complex geological conditions of thermal reservoirs, it is very difficult to accurately construct the same physical model as the actual situation. Therefore, when constructing large-scale geothermal numerical models, the current geothermal models can be divided into three categories: single-porosity models, dual-porosity models and multi-porosity models [15].Among them, the multi-porosity model takes into account the geometric distribution characteristics of lithology and the spatial distribution of fractures in the actual stratum, and has high accuracy, so that it is not widely used currently.

Therefore, based on the sandstone thermal reservoir data of Guantao Formation in Lankao County, Henan Province, and the simplified multi porosity model, this paper establishes the seepage heat transfer coupling model of fault bearing geothermal reservoir by using COMSOL finite element multi field coupling numerical simulation software, taking into account the influence of thermal compensation and seepage of bedrock and caprock on the heat transfer process of geothermal reservoir.The cycle "one production and one irrigation" injection-production mode is adopted to simulate the long-term operation process of geothermal wells with different well spacing and different permeability formations. By contrast, the occurrence law of thermal breakthrough phenomenon in the process of heat recovery by recharge over a long time scale is studied.

2. OVERVIEW OF THE STUDY AREA

Lankao County belongs to Kaifeng City, Henan Province.The Kaifeng Sag is structurally located at the intersection of the South North China Basin and the Bohai Bay Basin, the intersection of the NE-trending structural belt, adjacent to the Dongpu Sag of the Bohai Bay Basin in the north, and adjacent to the Taikang Uplift of the South North China Basin in the south, consisting of five groups of faults.Kaifeng sunken border.During the Indosinian period, the Kaifeng Sag was uplifted and denuded, and the Cretaceous strata were missing. The Jurassic was only partially developed, and the thickness was thin, but the thicker Triassic strata were retained.The source of geothermal water supply in the Kaifeng Sag is the atmospheric precipitation during the geological history of the western mountainous area.The average terrestrial heat flow in the Kaifeng sag is 56-60mW/m^2, and the geothermal gradient is 2.8-3.6℃/100 m,which increases from west to east according to the extension direction of the sag. The geothermal gradient in the Kaifeng-Lankao area is 3.4-3.6℃/100m.The thermal reservoirs in the study area are mainly sandstones of the Guantao Formation, mainly composed of feldspar lithic sandstone and lithic feldspar sandstone,mostly pore-type cementation,showing the characteristics of near-source deposition. The buried depth of Guantao Formation is about 1250-1350m at the top, 1900-2000m at the bottom, 600m at the bottom, 1.70-1.96g/cm^3 in sandstone density, 15-35% in porosity, 22% on average, and 1×10^{-13} m^2 in permeability. Geothermal water of Guantao Formation in Lankao is NaCL-type water with salinity of 14,000-24,000mg/L, Ca^{2+} content of

390-880mg/L, Mg^{2+} content of 80-120mg/L, pH above 7, and weak alkaline water. The water inflow rate of a single well in Lankao area is 100-155m^3/h,and the water temperature is 68-76℃.

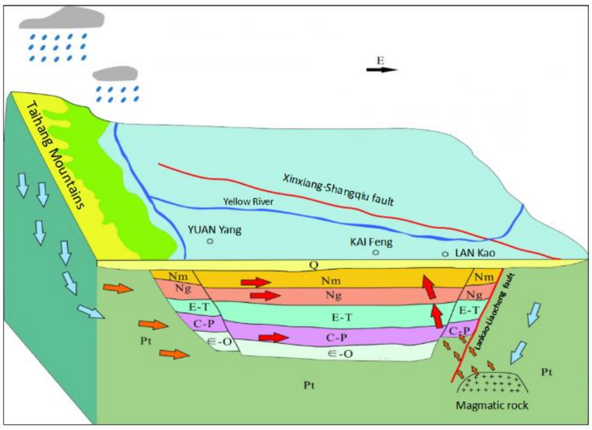


Fig.1: Lankao County Geothermal Geological Model

3. MATHEMATICAL MODEL AND STUDY SETTINGS

3.1 Mathematical model

Assuming that the thermal reservoir, bedrock and caprock are homogeneous porous media, the seepage process of the recharged water satisfies Darcy's law. According to the law of mass conservation of fluid, formula (1) is the seepage control equation of bedrock under steady state, and formula (2) is the seepage control equation of bedrock under transient state.The control of the seepage field inside the fault is described by the equivalent continuous model, formula (3) is the seepage control equation of the fault under steady state, and formula (4) is the seepage control equation of the fault under the transient state.

$$\nabla\cdot(\rho u_{\mathrm{m}})=Q_m \qquad (1)$$

$$\frac{\partial}{\partial \mathrm{t}}(\varepsilon_p\rho)+\nabla\cdot(\rho u_{\mathrm{m}})=Q_m \qquad (2)$$

$$\nabla_T\cdot(d_f\rho u_{\mathrm{f}})=d_fQ_f \qquad (3)$$

$$d_f\frac{\partial}{\partial \mathrm{t}}(\varepsilon_p\rho)+\nabla_T\cdot(d_f\rho u_{\mathrm{m}})=Q_f \qquad (4)$$

$$u_{\mathrm{m}}=-\frac{\kappa_{\mathrm{m}}}{\mu}\nabla p \qquad (5)$$

$$u_f=-\frac{\kappa_{\mathrm{f}}}{\mu}\nabla_T p_f \qquad (6)$$

where:p is the internal pore pressure of the thermal reservoir bedrock;*pf* is the pore pressure inside the fault;u is the seepage velocity of the fluid in the bedrock;*uf* is the seepage velocity of the fluid in the fault;*km* is the bedrock permeability; k*f* is the equivalent permeability of the fault; μ is the dynamic viscosity of the fluid; *Qm* is the mass flow of the fluid in the bedrock per unit thickness; *Qf* is the mass flow of the fluid in the fault per unit height; df is the equivalent of the fault diameter; λ is the fluid density.

For porous media, the heat transfer modes are mainly heat conduction between rock particles, heat conduction between pore fluids and heat convection.If the bedrock is a homogeneous porous medium, according to the principle of energy conservation, the governing equations of heat transfer in the bedrock in steady state and transient state are equations (7) and (8), respectively. The governing equations are equations (9) and (10), respectively.

$$\rho C_p u \cdot \nabla T + \nabla \cdot q = Q \quad (7)$$

$$(\rho C_p)_{eff} \frac{\partial T}{\partial t} + \rho C_p u \cdot \nabla T + \nabla \cdot q = Q \quad (8)$$

$$d_s Q_s - d_s \rho C_p u \cdot \nabla_t T - \nabla_t \cdot d_s q_s = Q_{fac} \quad (9)$$

$$d_s Q_s - d_s (\rho C_p)_{eff} \frac{\partial T}{\partial t} - d_s \rho C_p u \cdot \nabla_t T - \nabla_t \cdot d_s q = Q_{fac} \quad (10)$$

$$q = -k_{eff} \nabla T \quad (11)$$

$$q_s = -k_{eff} \nabla_t T \quad (12)$$

$$k_{eff} = \theta_p k_p + (1-\theta_p) k \quad (13)$$

$$(\rho C_p)_{eff} = \theta_p \rho_p C_{p,p} + (1-\theta_p) \rho C_p \quad (14)$$

where:Cp is the constant pressure heat capacity of the fluid;Cp,p is the constant pressure heat capacity of the bedrock;q is the total conduction heat flux;qs is the conduction heat flux of the inner wall of the fault;Q is the total heat of the heat source;ds is the fault wall thickness;Qs is the thermal reserve of the fault wall;Qfac is the thermal reserve in the fault; keff is the effective thermal conductivity;kp is the thermal conductivity of the bedrock; k is the thermal conductivity of the fluid in the fault; (ρCp)eff is the effective volumetric heat capacity; ρp is the density of the bedrock; θ_p is the volume fraction.

3.2 Study Settings

In this paper, a simplified multi-porosity model is established according to the distribution geometric characteristics of the thermal reservoir in Lankao.As shown in Figure 2, the geometric size of the model is 5000m×5000m×3000m.The depth ranges of caprock, thermal reservoir and bedrock are 0-1300m, 1300m-1900m and 1900m-3000m, respectively.In the model of this paper, the heat recovery well and the recharge well are simplified, only the open well part is considered for production activities, and the seepage and heat transfer effects of other well sections in the formation are ignored, and Geometrically, a straight line perpendicular to the Z direction is used to represent an open hole.The length of the heat recovery well and the recharge well is 200m, and they are symmetrically distributed in the center of the model. The ground temperature gradient is 0.034 °C/m and the surface temperature is 20°C. Thermal breakthrough is defined as a 1 °C decrease in the average temperature of the recovery well.In order to study the effect of well spacing and permeability on temperature and seepage field, four well spacings were set: 300, 400, 500 and 600 m, and four permeability Kn, (n=1, 2, 3, 4), see Table 1 for details of the values, a total of 16 working conditions.One year is set as one operation cycle, the actual operation time of the heat recovery well and the recharge well in each operation cycle is set to 0.4 years, and the recharge rate is set to 100%, that is, the recharge flow rate is equal to the pumping flow rate of the heat recovery well.Set the time period function A, the cycle period is 1 year, see Equation 15 for details.Equation 16 is the water flow control equation of the recharge well and heat recovery well, respectively, and Equation 17 is the heat source equation of the recharge well:

$$A(t)=\begin{cases}1 & (0\le t\le 0.4)\\ 0 & (0.4<t\le 1)\end{cases} \quad (15)$$

$$M_{out}=M_{\text{in}}=\beta\cdot\rho\cdot A(t) \quad (16)$$

$$Q_w=C_p\frac{M_{in}}{l_w}(T_{inj}-T)\cdot A(t) \quad (17)$$

where:t is the running time; M_{in} is the mass flow rate of the recharge well; M_{out} is the mass flow rate of the heat production well; β is the pumping water flow rate of the heat production well; Q_w is the heat loss of the recharge well; T_{inj} is the recharge water temperature of the recharge well, The value in this paper is 20℃. Set a stable pressure boundary condition of 15MPa.

First, the water level of the heat production well is calculated to drop by 100m in the 10th year, and the pumping flow rate at which the pore pressure of the heat production well drops by 2MPa in the 10th year is calculated under each working condition. The temporal and spatial evolution law of temperature field and seepage field under 100-year operation period with permeability.The material parameters of this model are shown in Table 2. The fault thickness is 0.01m, the porosity is 0.2, and the permeability is 1×$10^{-19}$$m^2$. Set the vertical and horizontal analysis planes to analyze the calculation results (Figure 3).

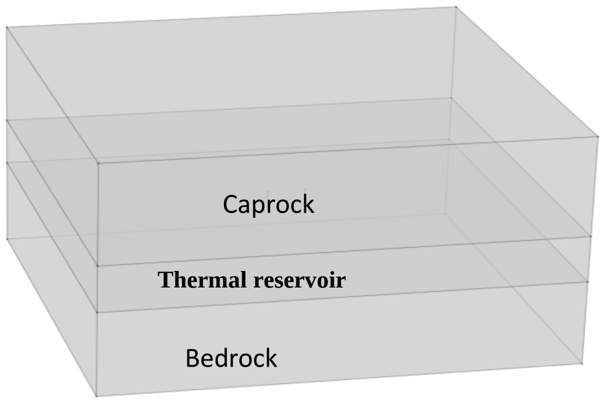


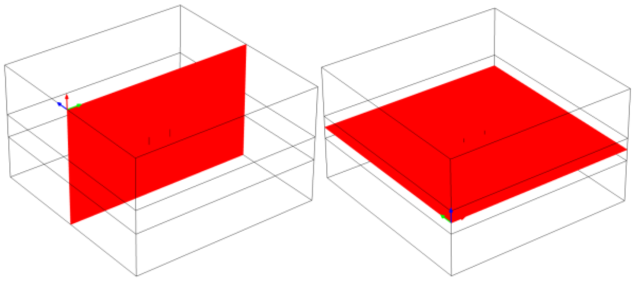
Fig.2: Geometry diagram of the numerical model

Table 1: Permeability variable setting

Numbei	Penetration/(m^2)
K_1	1×10^{-13}
K_2	1.5×10^{-13}
K_3	2×10^{-13}
K_4	2.5×10^{-13}

Table 2: Model material parameters

Medium	lithology	Den/(kg·m^{-3})	λ /(W·m^{-1}·K^{-1})	C/(J·kg^{-1}·K^{-1})	K/(m^2)	Φ/（%）
Caprock	Nm- sandstone	2109	2.596	958	1.91×10^{-17}	0.3
Thermal reservoir	Ng- sandstone	2109	2.596	878	K_n	0.22
Bedrock	O-Carbonate	2475	3.5	900	6.25×10^{-16}	0.006



（a）Vertical plane （b）Horizontal plane

Fig.3: Geometry diagram of the numerical model

4. NUMERICAL ANALYSIS RESULTS

4.1 Pumping flow rate

After trial calculation of the pumping water flow rate of the model, the pumping flow rate of the heat production well that reduces the water level by 20m within 10 years under each working condition is obtained（Fig.4）.As shown in Figure 4, when the well spacing is 300m, there is a maximum pumping flow rate. As the well spacing decreases, the pumping flow rate decreases to the lowest when the well spacing is 500m, while the pumping flow rate increases slightly when the well spacing is 600m compared with 500m.

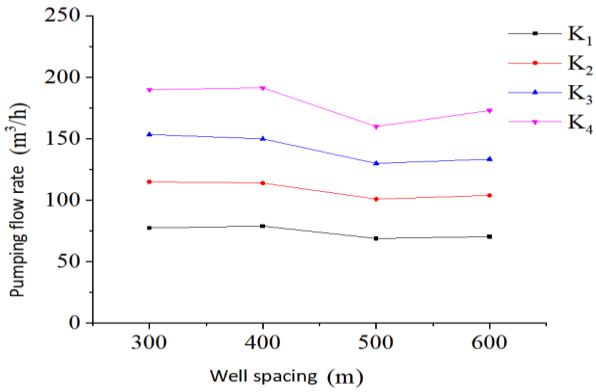


Fig.4: Change of pumping flow rate with well spacing

4.2 Temperature field and seepage field

Fig. 5 is the historical evolution curve of bottom hole temperature of heat producing well under different well spacing. As shown in Figure 5, since the heat production operation is only 0.4 years in the annual time period, the bottom hole temperature during the non-operation period has been compensated by heat, so the bottom hole temperature changes with time in a zigzag shape, in which the more the zigzag undulation is. Vigorous, the better the thermal compensation effect. Compared with other well spacings, when the well spacing is 300m, the bottom hole temperature for heat production decreases the fastest with time. When the permeability is K_1 and K_2, the bottom hole temperature changes little with time when the well spacing is 500m and400m. With the increase of permeability, the effect of well spacing on the time-dependent change of heat production bottom hole temperature gradually increases.Fig. 6 shows the historical evolution curve of bottom hole temperature of recharge wells under different well spacings. Compared with the heat recovery well, the bottom hole temperature of the recharge well drops sharply within 10 years, and it is rapidly approaching the recharge water temperature (20° C), and since the low temperature area expands over time, the thermal compensation of the recharge well has a negative effect. The bottom temperature increase also decreased rapidly. With the passage of time, the temperature at the bottom of the recharge well gradually coincides with the temperature of the recharge water.

Through the analysis of the variation of the heat production bottom hole temperature with the well spacing in the 50th and 100th years, it is found that the heat production bottom hole temperature has a strong correlation with the well spacing. The effect of temperature decrease on the bottom hole temperature of heat production is smaller, but it increases with the increase of time. The bottom hole temperature of heat production at 500m and 600m well spacing changes little with time, and the bottom hole temperature changes greatly when the well spacing is 300m and 400m.As shown in Fig. 8, taking the thermal reservoir permeability K4 as an example to analyze the change of the streamline of the heat production cycle with the well spacing in the 100th year of operation. The well spacing has little effect on the change of the seepage field in the working area, and the characteristics of the seepage field under all well spacings are relatively consistent. When the water enters the ground through the recharge well, due to the suction force caused by the pressure gradient between the heat production well and the recharge well, part of the recharge water flows to the heat production well, and the movement trajectory of the recharge water sucked into the heat production well presents a double elliptical shape .

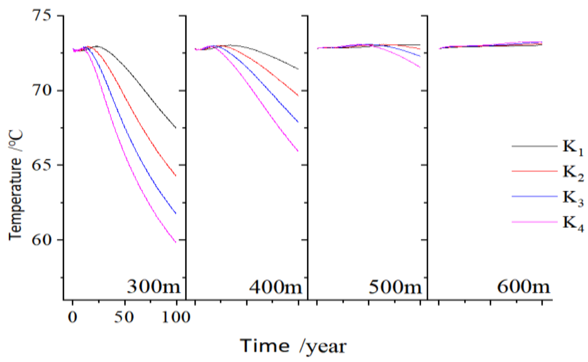


Fig.5: Historical evolution curve of bottom hole temperature of production wells under different well spacing

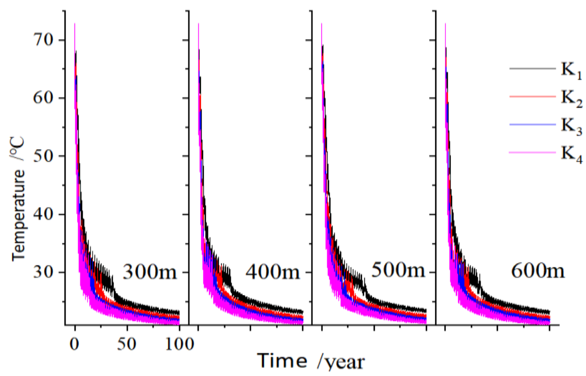


Fig.6: Historical evolution curve of bottom hole temperature of recharge wells under different well spacing

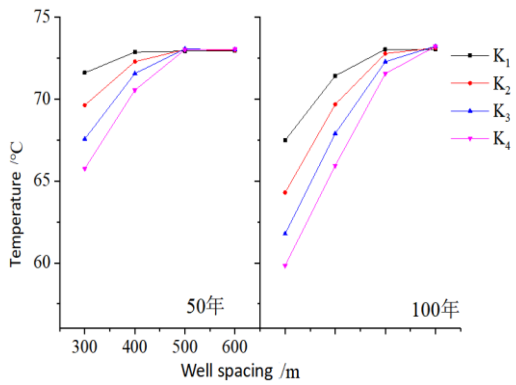
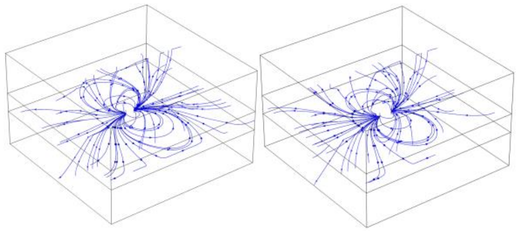
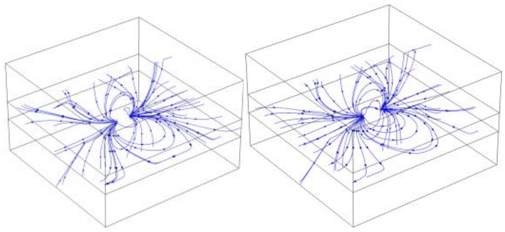


Fig.7: Variation of bottom hole temperature of production wells with well spacing in the 50th and 100th years

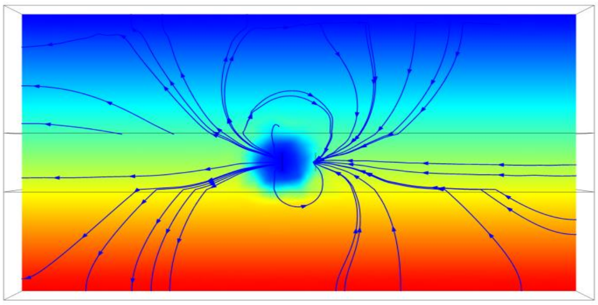


（a）300m　　　　（b）400m

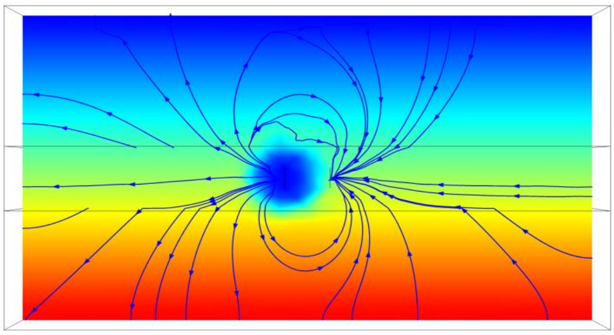


（a）500m　　　　（b）600m

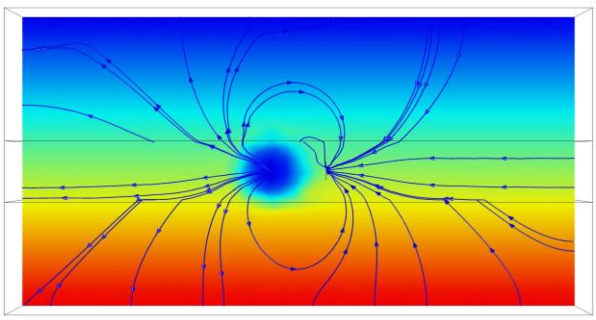
Fig.8: Variation of seepage field with well spacing in the 100th year of operation(K4)



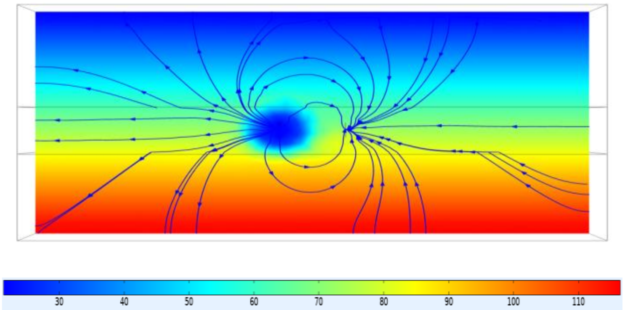
（a）300m



（b）400m



（c）500m



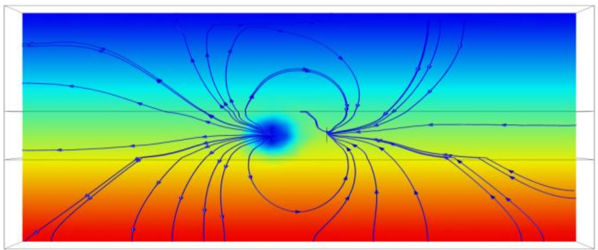
（d）600m

Fig.9: The seepage field and temperature field of different well spacings in the vertical plane of the heat recovery cycle in the 100th year of operation(K4)

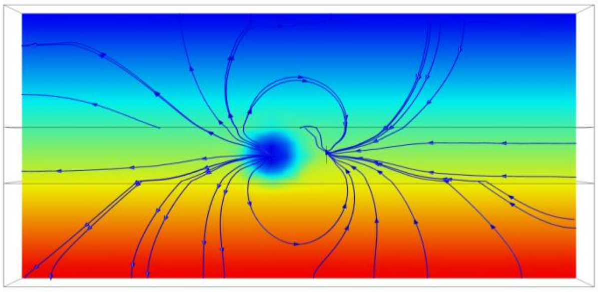
Figure 9 shows the seepage field and temperature field (K_4) at different well spacings in the vertical plane of the 100th year heat production cycle. As shown in Fig. 9, under the 300m well spacing, the heat recovery well is completely wrapped in the low temperature area, and there is no obvious cold front bulge on the right side, indicating that there is thermal breakthrough at the 300m well spacing, and the utilization efficiency of recharge water is the highest. At the well spacing of 400m, only a small part of the cold front bulge is in contact with the heat production well, while at the 500m and 600m well spacing, the heat production well is not covered by the cold front bulge. This phenomenon can be minimized by arranging the reinjection well at a position far away from the production well, while the position of the reinjection well close to the production well can maximize the benefit of the reinjection well. Therefore, an appropriate balance must be found between these two contradictory layouts. Table 3 shows the thermal breakthrough time of the heat producing well. It can be seen from Table 3 that thermal breakthrough occurs at well spacing of 300m and 400m; thermal breakthrough occurs only at K_4 permeability at well spacing of 500m; thermal breakthrough does not occur at well spacing of 600m. This shows that when developing and utilizing geothermal resources in Lankao County, the well spacing cannot be less than 500m, which can not only ensure that no thermal breakthrough occurs during the operating life, but also maximize the utilization of recharge water. As shown in Figure 10, the higher the thermal reservoir permeability, the higher the pumping flow rate, that is, the higher the production efficiency, which means that the higher the thermal reservoir permeability is when the recharge rate is 100%, the higher the cold front bulge. The higher the temperature, the more likely the thermal breakthrough phenomenon will occur.

Table 3　Thermal breakthrough time of production well

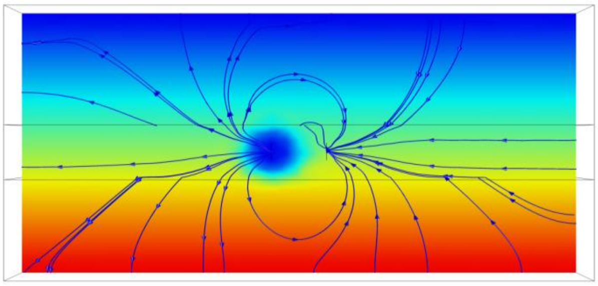
Well spacing/m	Penetration			
	K_1	K_2	K_3	K_4
300	45.9a	32a	24.1a	19.2a
400	89.2a	61.1a	46.1a	35.4a
500	>100a	>100a	>100a	93.3
600	>100a	>100a	>100a	>100a



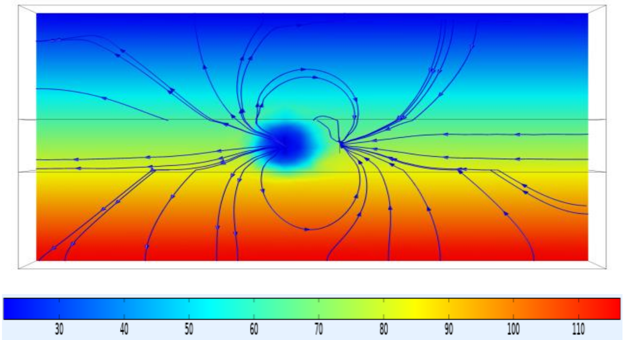
（a）K_1



（b）K2



（c）K3



（d）K4

Fig.10: The seepage field and temperature field of different permeability in the vertical plane of the heat recovery cycle in the 100th year of operation

5. INCONCLUSION

In order to study the effect of mid-deep geothermal recharge on the heat extraction process, relying on the sandstone heat storage data of the Guantao Formation in Lankao County, Henan Province, the COMSOL finite element multi-field coupled numerical simulation software was used to consider the thermal compensation of bedrock and caprock and the effect of seepage on geothermal energy. Under the influence of the heat transfer process of the reservoir, on the basis of the three-dimensional multi-porosity model, Darcy's theorem and the heat transfer formula of porous medium are used to establish the coupled model of seepage and heat transfer in the geothermal reservoir with fractures. The temperature field and flow field changes during thermal operation lead to the following conclusions:

(1) Compared with the heat recovery well, the bottom hole temperature of the recharge well drops sharply within 10 years, and it is rapidly approaching the recharge water temperature (50° C). The well bottom hole temperature rise also decreased rapidly. With the passage of time, the temperature at the bottom of the recharge well gradually coincides with the temperature of the recharge water.

(2) Well spacing has little effect on the change of seepage field in the working area. When the water enters the ground through the

recharge well, due to the suction force caused by the pressure gradient between the heat production well and the recharge well, part of the recharge water flows to the heat production well, and the movement trajectory of the recharge water sucked into the heat production well presents a double elliptical shape .

(3) The bottom hole temperature of heat production has a strong correlation with the well spacing. With the increase of well spacing, the decrease of formation temperature caused by recharge has less effect on the bottom hole temperature of heat production, but it increases with the increase of time.

(4) In the development and utilization of geothermal resources in Lankao County, the spacing between wells should not be less than 500m, which can not only ensure that no thermal breakthrough occurs during the operating life, but also maximize the utilization of recharge water.

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