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Analysis on influencing factors of heat exchange efficiency of the medium-deep U-shaped geothermal wells in Xiong'an New Area, China

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Keywords: medium-deep; U-shaped well; numerical simulation; heat exchange efficiency; influencing factors

ABSTRACT

As carbon dioxide emission becomes the key environmental problem concerned by all countries, the development of clean energy is getting extensive attention. As a kind of clean energy source, geothermal has been widely used in recent years. U-shaped geothermal well is a kind of well type suitable for middle and deep geothermal development, which has the advantages of high heat transfer efficiency and "heat extraction without water extraction". This paper takes the geothermal in Xiong'an New Area as the research object, and uses the fluid dynamics software Fluent to conduct numerical simulation of geothermal development. In the model construction, gravity is ignored and the U-well model is simplified into a straight well model, which can accelerate the calculation speed. In order to verify the accuracy of the model, the simulation results were compared with the field test data. Several factors affecting heat transfer efficiency are systematically analyzed, including reservoir conditions such as formation temperature and thermal conductivity, well depth structures such as casing size and lateral length, and fluid parameters such as flow rate and inlet temperature. Simulation result shows that higher reservoir temperatures, longer lateral lengths, higher fluid flow rates, and lower inlet temperatures can significantly increase heat transfer efficiency.

1. INTRODUCTION

With the increasing global energy consumption, carbon dioxide emission has become an important environmental issue concerned by all countries. In order to ensure sustainable development, clean energy has been widely concerned [1-2]. As a kind of clean energy, geothermal has the characteristics of huge reserves and wide distribution, and has been developed and utilized by governments of all countries [3-8]. The current geothermal development mode includes two types: heat from production and irrigation and heat from water isolation. For reservoirs with high permeability, the heat from production and irrigation can make the fluid fully contact with the formation and heat the fluid to the maximum extent [9]. For reservoirs with low permeability, the fluid flow rate is slow, the recovery efficiency is low, and it is difficult to recharge. For such reservoirs, the water-isolated heat extraction method is more suitable. Through buried tube heat exchanger, the formation and the ground are directly established with high conductivity closed-loop channel, and the formation heat is extracted without contacting groundwater. Current water-isolation heat capture methods include coaxial heat transfer and U-shaped well heat transfer. Coaxial heat transfer mode drilling technology is simple [10], but the heat transfer efficiency is low. U-shaped Wells have a large contact area with high-temperature formations and high heat transfer efficiency. However, due to the difficulty of drilling technology and few current application cases, Shaanxi Coal Geology Group has completed several groups of U-shaped geothermal Wells. However, the U type joint geothermal well system lacks the corresponding theoretical research, and the heat transfer efficiency and wellbore temperature field change law need to be further studied.

U-shaped geothermal Wells are suitable for middle and deep geothermal development, and have the advantages of high heat transfer efficiency and "taking heat without taking water" [11]. Chao Li[12] established numerical models of U-shaped buried pipes of five different sizes, and confirmed that buried depth has a greater impact on heat transfer efficiency. Chen Jingping et al. [13] established a mathematical and physical model of heat transfer in U-shaped geothermal Wells, and used the finite element method to conduct numerical solutions. The established model was used to calculate the heat recovery effect at different flow rates. YuMingzhi et al. [14] simplified the middle-deep U-shaped geothermal well into three independent heat transfer sections: vertical injection section, horizontal section and vertical production section, and discussed the influence of buried pipe depth, thermal conductivity of rock and soil, and heat capacity on heat extraction. Zhou Cong [15] analyzed the test data of two U-shaped geothermal Wells with different burial depths in Xi 'an, and the heat exchange intensity per unit length meter of the two Wells was 111.19 W/m and 140.43W/m respectively. Meanwhile, he proposed that increasing the depth of buried pipes would significantly improve the heat exchange intensity. Li Pengfei [16] used Fluent to simulate the horizontal section of U-shaped well and found that the heat transfer efficiency increased with the increase of displacement. With the increase of horizontal length, the heat transfer efficiency increases. The outlet temperature of horizontal section is negatively correlated with wellbore diameter and positively correlated with heat transfer efficiency. Feng Shaohang [17] considering the deep underground rock and soil temperature gradient, lithological change and the influence of the groundwater seepage effect on heat transfer, the simulation calculation for 4000 m deep u-shaped geothermal

hot Wells of thermal efficiency, and analyses the influence of pipeline flow thermal power and the influence of the radius of the heat transfer, when developing after 120 days, the maximum radius of influence of heat transfer is 15.68 m. Li Junyan et al. [18] established a numerical heat transfer model of deep U-shaped buried tube heat exchanger based on fully hidden scheme finite difference method, and proposed that reducing the inlet temperature would significantly increase the heat transfer efficiency. Zarrella[19], Jalaluddin[20] et al proposed that increasing the heat exchange area reasonably and effectively can improve the heat extraction efficiency. Li Siqi [21] used Fluent software to build a closed numerical model of downhole heat transfer in middle and deep layers, and concluded that the reasonable adiabatic ratio under different well depths was 0.875.

In this paper, a u-shaped well "Heat well 1", which has been developed and used in Xi 'an, is taken as the research object. The physical model of U-shaped well is established, and the heat exchange efficiency is simulated by fluent software. The reliability of the model is proved by comparing with the test data of "Heat well 1". The effects of reservoir conditions such as formation temperature and thermal conductivity, well structure such as casing size and horizontal section length, and fluid parameters such as inlet water temperature and inlet displacement on heat transfer efficiency are systematically analyzed.

2. MODELING

2.1 Physical model

In this paper, an applied geothermal well "Re1 well" in Xi 'an is taken as the research object to establish a physical model. As shown in Figure 1, the well is located in Xi 'an Economic and Technological Development Zone. The geomorphic unit of this well is the first-order terrace above the flood plain of Weihe River. The reservoir thermal and physical parameters and well structure are shown in Table 1, surface temperature table 15, bottom hole temperature is 70.29, and there is a 350m insulation section near the surface of the well. In the field test, the inlet water temperature is 19.5 and the displacement is 40.5m.

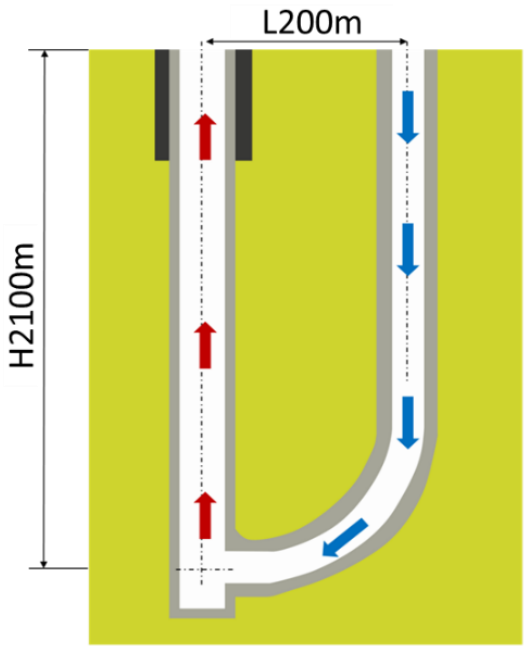

Figure 1: U-shaped geothermal well profile diagram

Table.1 Reservoir thermophysical parameters

geometrical parameter	Density (kg/mm）	Conductivity W/(m.k)	Specific heat capacity (j/kg.k)	T-Z0 (℃）	T-wellbore (℃）
	1950	1.75	1080	15	70.29
wellbore configuration	Depth (m)	Insulation length （m)	Horizontal well （m)	Casing of injection well（mm)	Casing of flowing well（mm)
	2100	350	200	139.7X9.17	177.8X8.05

Feng Shaohang [17] proved through numerical simulation that the influence radius of reservoir temperature around U-shaped well was about 15m during the 4-month heating period. Therefore, in order to speed up the calculation efficiency, only reservoirs within 20m radius near the wellbore were considered in the simulation process. In addition, since gravity has little influence on reservoir and fluid heat transfer effect, this paper ignores gravity and simplifies the U-shaped well model into a vertical well model for the convenience of model construction and post-processing, as shown in Figure 2.

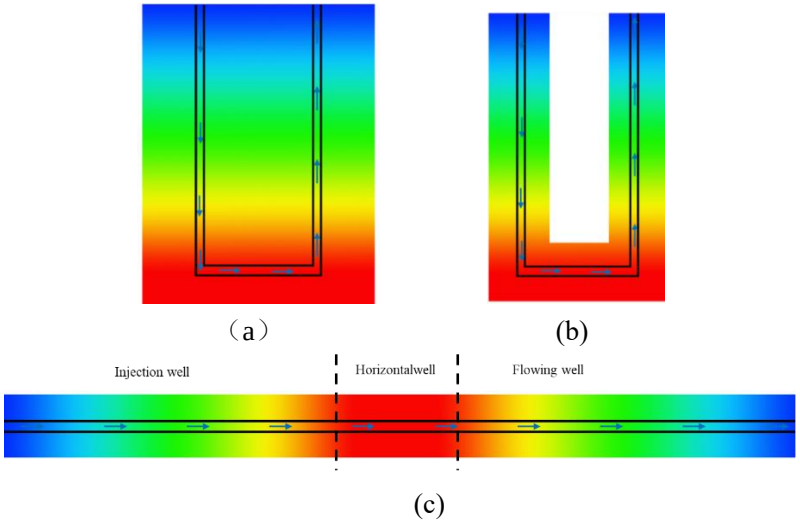

Figure 2: Schematic diagram of simplified structure of U-shaped well

FIG. 3 shows the structure of the model and the result of grid division. The simplified model establishment process is simple, the grids are all structured division, the grid quality is good, the convergence of the simulation process is strong, and the accuracy of the simulation results is improved. FIG. 4-5 shows the meshing result of the cross section of the model. The temperature change in the near-wellbore area is large [22], so the meshing in the near-wellbore area is dense. The fluid boundary layer is taken into account when meshing in the wellbore, and O-section method is adopted, which is more suitable for flow simulation.

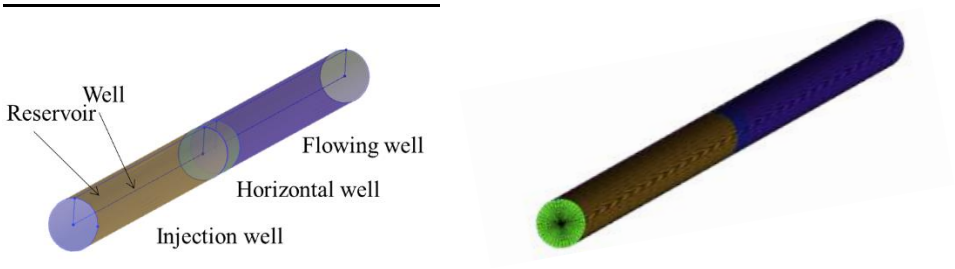

Figure 3: Model structure and meshing



Figure4: Model cross section meshing

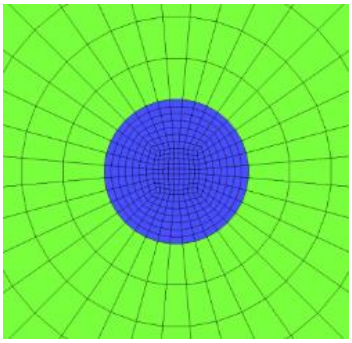

Figure 5: Meshing in wellbore

On the premise of basically not affecting the calculation results, the geothermal well model established in this paper is based on the following assumptions:

a. Ignore the effect of gravity;

b. The strata are homogeneous medium with the same geothermal gradient and thermal physical property parameters;

c. Ignoring the influence of groundwater seepage;

d. The boundary of the simulation region is a constant temperature boundary;

e. Set the surface temperature as constant temperature;

f. Under the initial conditions, the wellbore is filled with fluid, and the fluid temperature is consistent with the outer layer temperature of the cylinder;

2.2 Mathematical model

The heat transfer of the buried pipe includes the convection heat transfer between the circulating water in the pipe and the pipe wall, the heat conduction of the buried pipe wall, the heat conduction of the buried pipe wall and the cementing cement layer, and the heat conduction of the surrounding rock and soil mass. The continuity equation, momentum equation and energy equation describing the heat transfer inside and outside the buried tube can be uniformly written into the general form shown in Equation (1) [23].

$$\frac{\partial(\rho\emptyset)}{\partial t} + \mathrm{div}(\rho U\emptyset) = \mathrm{div}(\Gamma_{\emptyset} grad\emptyset) + S_{\emptyset} \quad (1)$$

Where: ρ -- fluid medium density

$\emptyset$ - General physical quantity

t- time

U -Velocity of fluid medium

$\Gamma_{\emptyset}$ -- diffusion flux

$S_{\emptyset}$ - Source item

3. VERIFICATION

The model established in this paper is basically consistent with the test parameters of "Rei 1 well" in Xi 'an. Considering that the heating period in most areas of north China lasts for 4 months, the heat transfer effect of 120 days is simulated. Figure 6 shows the change of the outlet water temperature over time in this well for 120 days of water isolation and heating. This trend is due to the presence of fluid consistent with reservoir temperature in the wellbore during the initial conditions. As this fluid is discharged, the outlet temperature gradually becomes stable.

Since only the results of the first three days were obtained in the test data, the simulated outlet water temperature obtained in the first three days was compared with that collected in the actual operation, as shown in Figure 7. The simulation results and the test results showed the same variation trend, and gradually converged after long-term operation. At 72h, the temperature difference between the simulation results and the test data is only 0.5 junction, which proves the reliability of the model in this paper.

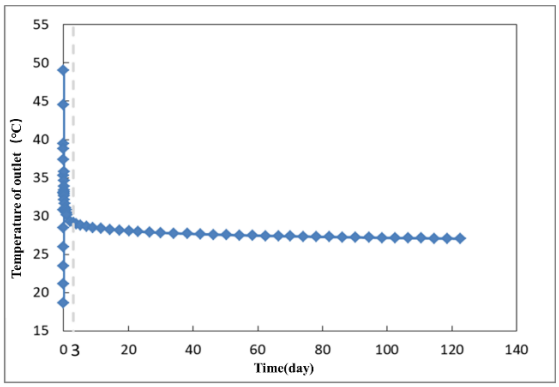

Figure 6: Simulation results of effluent temperature variation with time

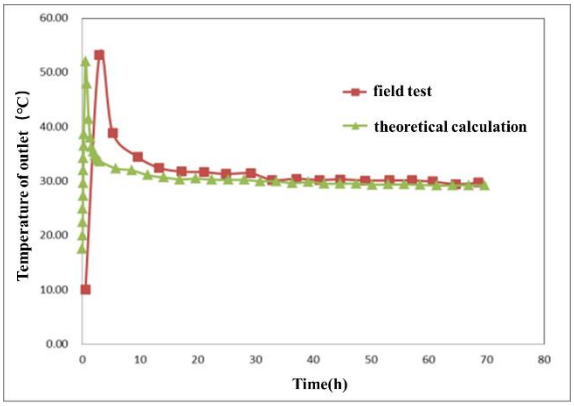

Figure 7: Comparison of 72h simulation results and experimental results

The actual operation time of this simulation is 120 days, FIG. 8 shows the formation temperature distribution in the initial state, and FIG. 9 shows the formation temperature distribution after 120 days of development. It can be found from the axial section diagram of the model that the temperature sweep radius after 120 days is about 10m, which indicates the rationality of the size of the model built in this paper. As can be seen from Figure 10, a "temperature drop funnel" will be formed near the wellbore. The "temperature drop funnel" will be rapidly generated in the initial stage of development, and then gradually expand to the outer, and the outward expansion speed gradually slows down.

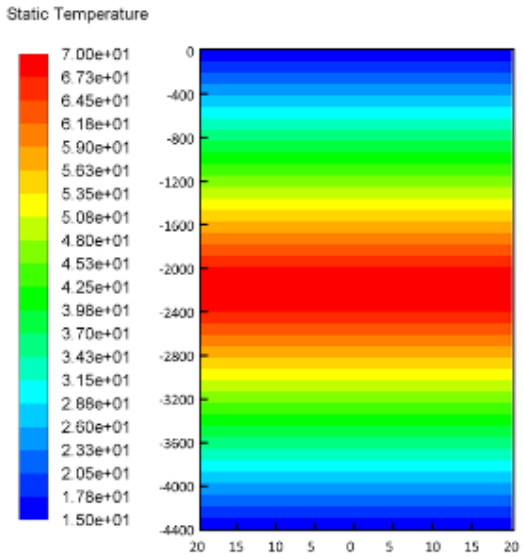

Figure 8: Initial formation temperature profile

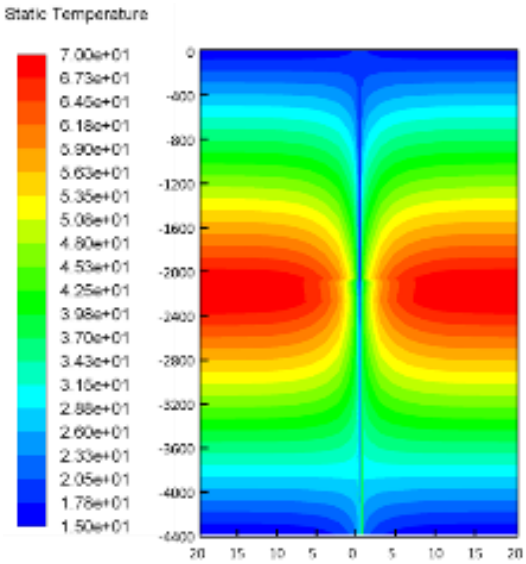

Figure 9: Temperature distribution map after 120 days of development

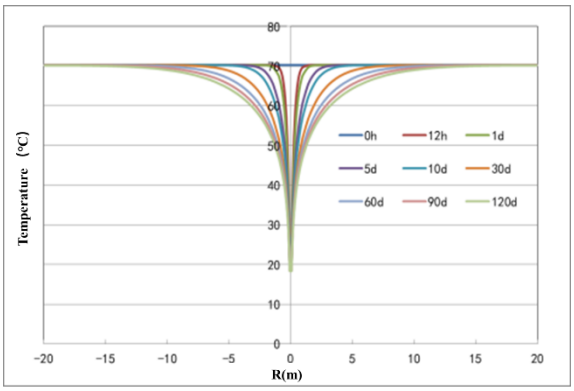

Figure 10: Temperature sweep radius varies with running time

4. ANALYSIS OF HEAT HARVESTING EFFICIENCY IN XIONGAN NEW AREA

Under the same geothermal conditions, the efficiency of heat extraction by water isolation is lower than that of the method of mining and irrigation, so how to improve the efficiency of heat exchange has become the key research content of U-shaped well geothermal development mode. In order to evaluate the influence of different factors on the heat transfer effect, based on the "Reno.1 well" model and according to the formation conditions in Xiongan New Area, this paper systematically analyzes the influence of formation temperature, formation thermal conductivity, well structure, displacement, inlet water temperature and other parameters on the outlet water temperature and heat transfer efficiency.

4.1 Stratigraphic environment

4.1.1 Reservoir temperature

The heat reserve of reservoir itself is the decisive factor to improve the heat recovery efficiency. On the premise of the principle of single variable, heat transfer simulation was carried out under the conditions of bottomhole temperature of 50~110. The results show that: Under each reservoir condition, the water temperature at the outlet increases rapidly and then decreases and then becomes stable. The higher the reservoir temperature is, the longer it takes for the water temperature at the outlet to become stable, as shown in Figure 11. After the water temperature at the outlet was basically stable, the temperature difference between the inlet and outlet water ranged from 6.7 to 15.6 plus with the increase of reservoir temperature, showing a linear increasing trend. The heat transfer efficiency of the 1101 reservoir was 2.3 times that of the 50 reservoir temperature condition.

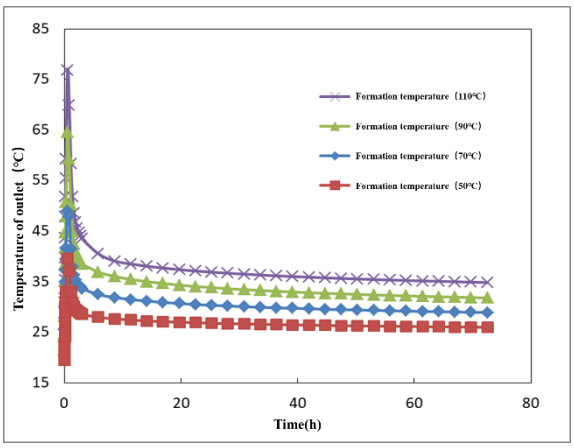

Figure 11: Comparison of outlet temperatures under different formation temperatures

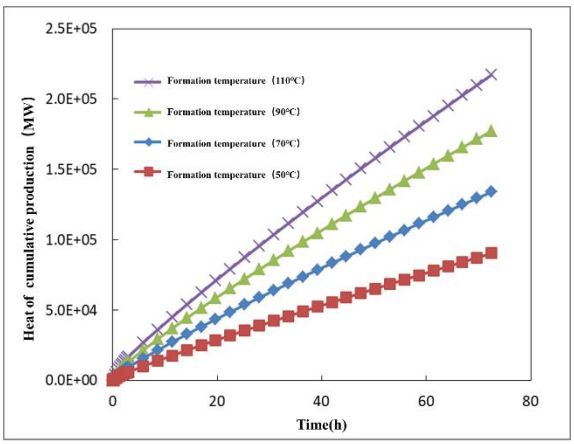

Figure 12: Comparison of cumulative heat transfer under different formation temperatures

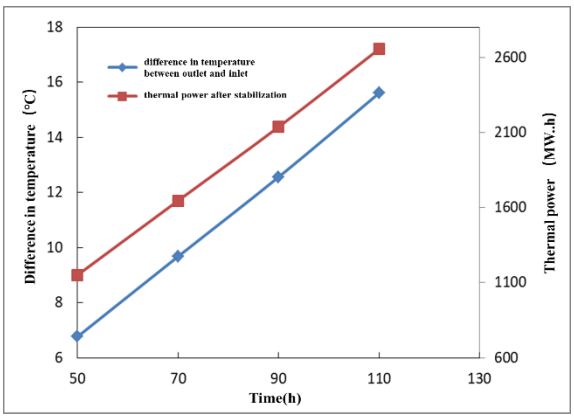

Figure 13: Thermal power comparison at different formation temperatures

4.1.2 Thermal conductivity

Different lithology reservoirs have different thermal conductivity. The thermal conductivity of conventional reservoirs is 1.5~3 W/(m·k), and the thermal conductivity is poor. If the thermal conductivity of the formation can be improved by injecting high thermal conductivity cement and other reservoir reconstruction methods, the heat transfer efficiency can also be improved. Considering the premise of subsequent reservoir reconstruction, this paper simulated U-shaped well geothermal development with thermal conductivity of 2~5 W/(m·k) to verify whether a small increase in formation thermal conductivity can significantly improve heat transfer efficiency. The results show that: The heat transfer efficiency of the reservoir increases linearly with the increase of thermal conductivity, but the increase is small. The heat transfer efficiency ranges from 1692 to 2464MW92. The heat transfer power of the reservoir at 5 W/(m·k) is 1.50 times that of the reservoir at 2 W/(m·k). If thermal conductivity is increased through reservoir modification during development, the thermal conductivity should be significantly improved.

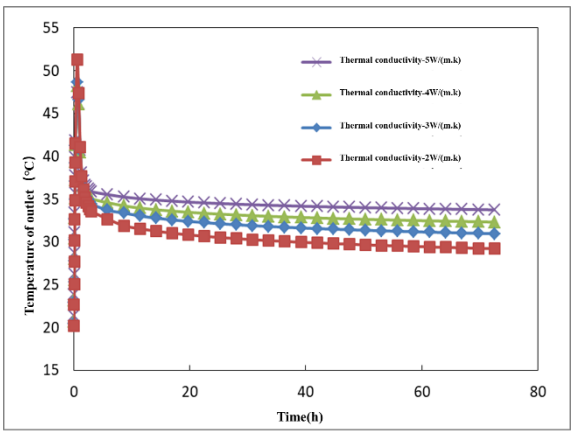

Figure 14: Comparison of outlet temperature under different thermal conductivity

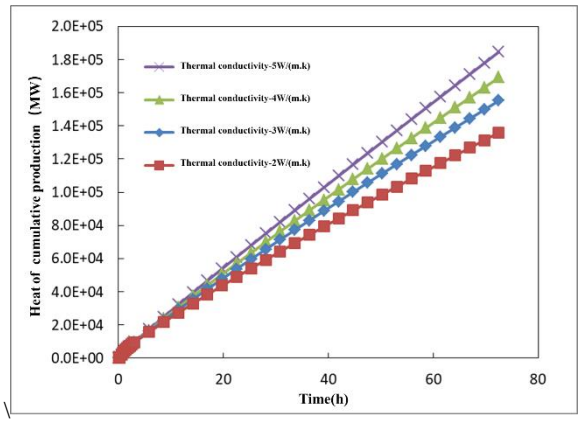

Figure 15: Comparison of cumulative heat transfer under different thermal conductivity conditions

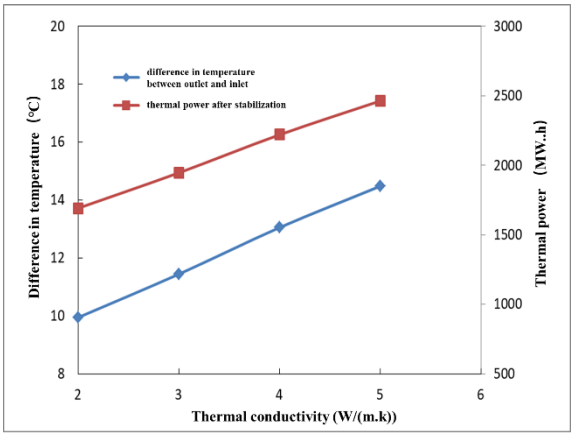

Figure 16: Comparison of thermal power under different thermal conductivity

4.2 Well structure

4.2.1 Casing size

Under the same flow rate, increasing the casing diameter can reduce the flow rate and thus increase the flow time in the reservoir. Casing sizes with internal diameters of 120mm, 160mm, 220mm and 311mm were selected for simulation. The simulation results show that the heat transfer efficiency ranges from 1646 MW·h to 1945 MW·h for the casing diameter of 120~311mm. With the increase of casing size, the heat transfer efficiency increases successively after later stabilization, but the increase gradually decreases. The heat transfer efficiency of the casing with 311mm inner diameter is only 1.18 times of that of the casing with 120mm inner diameter.

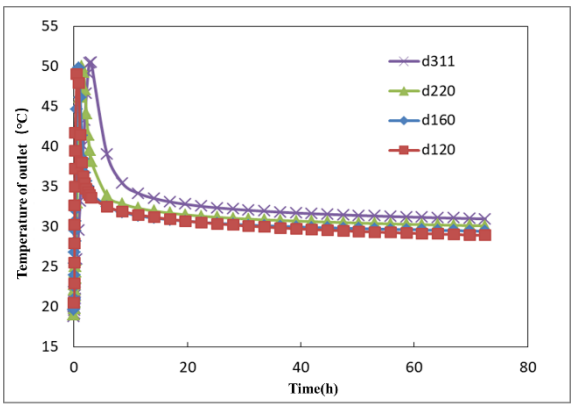

Figure 17: Comparison of outlet temperature under different casing sizes

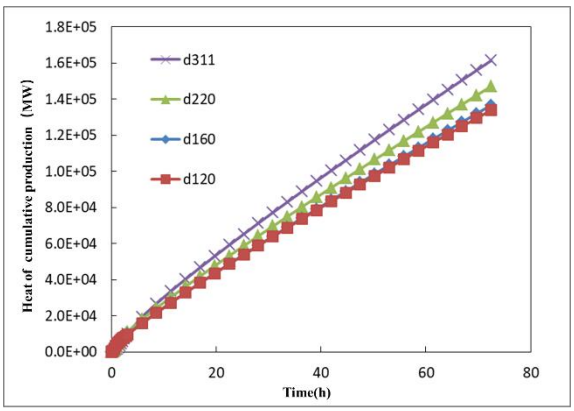

Figure 18: Comparison of accumulated heat transfer under different casing sizes

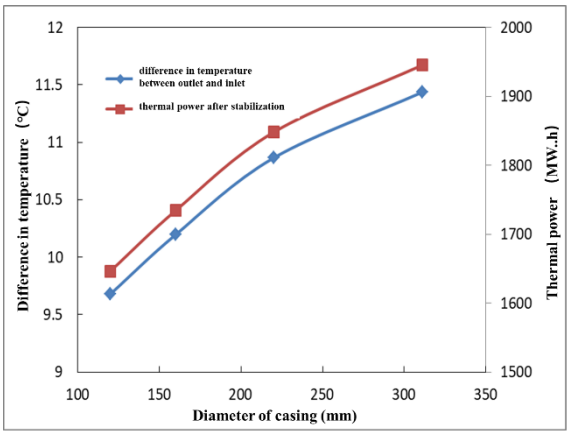

Figure 19: Thermal power comparison under different casing sizes

4.2.2 Length of horizontal section

Increasing the length of the horizontal section of the U-well, which is in contact with the high-temperature part of the reservoir, can increase the efficiency of the reservoir heat transfer. In this paper, the length of 200-2000m is selected, and the heat transfer efficiency is simulated successively. The results show that the heat transfer efficiency of 200-2000m horizontal U-shaped well ranges from 1646 to 2607MW46. With the increase of the horizontal section, the heat transfer efficiency gradually increases, but the increase gradually decreases, and the heat transfer efficiency per extension meter decreases. After stability, the heat transfer efficiency of U-shaped well with 2000m horizontal section is 1.58 times that of U-shaped well with 200m horizontal section.

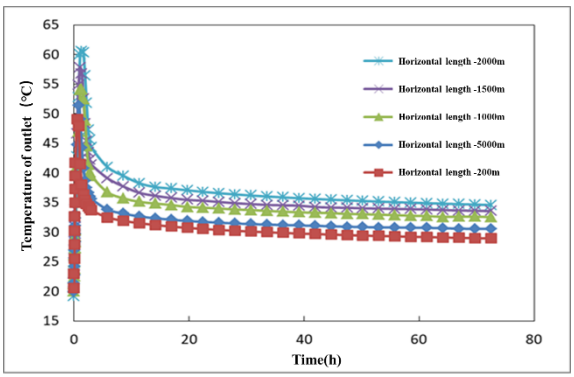

Figure 20: Comparison of outlet temperature under different horizontal section lengths

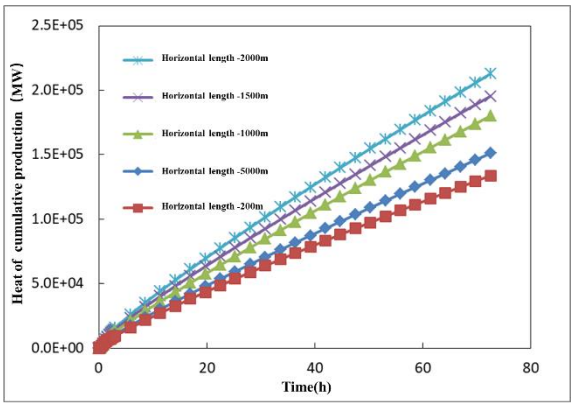

Figure 21: Comparison of cumulative heat transfer under different horizontal section lengths

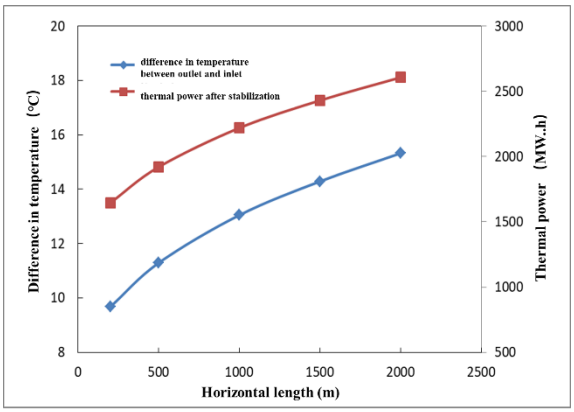

Figure 22: Thermal power comparison under different horizontal section lengths

4.3 Fluid Parameters

When the well structure is fixed, the operating parameters of the fluid will also affect the heat transfer efficiency during operation. In this paper, fluid displacement and inlet temperature are considered to analyze their influence on the heat transfer efficiency.

4.3.1 Displacement

In this paper, the volume of 40~100m and the inflow displacement were set, and the heat transfer simulation was carried out respectively. It can be found that the increase of displacement will lead to the decrease of fluid flow time in the reservoir, the decrease of fluid heat exchange efficiency per unit volume, and the decrease of outlet temperature. However, the heat transfer efficiency in the operation process also needs to consider the fluid displacement per unit time. The results show that: Under the condition that the displacement ranges from 40 to 100m, the heat transfer efficiency ranges from 1646 to 2194MW·h. The larger the displacement, the higher the accumulated heat transfer, and the higher the heat transfer efficiency after stability. Compared with the displacement of 40m, the heat transfer efficiency of 100m is increased by 1.33 times.

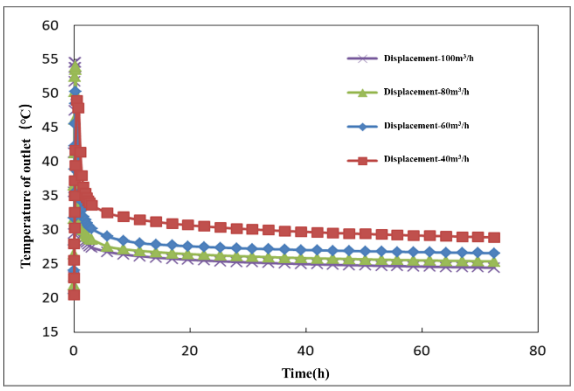

Figure 23: Comparison of outlet temperature under different displacement conditions

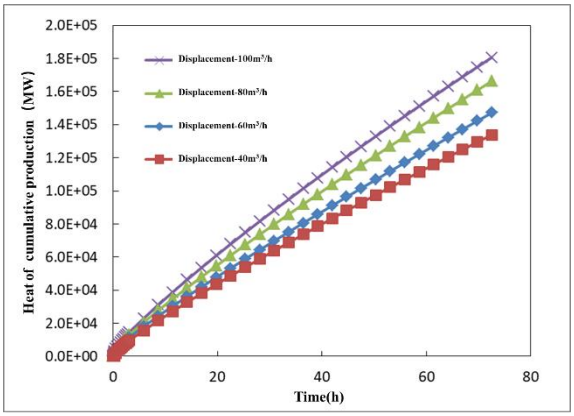

Figure 24: Comparison of cumulative heat transfer under different displacement conditions

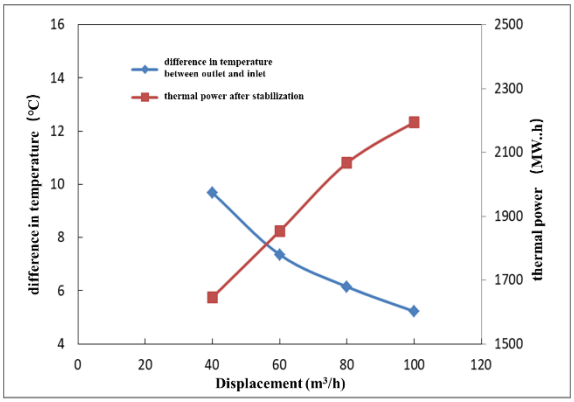

Figure 25: Thermal power comparison under different displacement conditions

4.3.2 Inlet water temperature

The temperature difference between fluid and reservoir is determined by inlet water temperature. In this paper, the simulation of water isolation heating under inlet water temperature ranging from 0℃ to 20℃ was simulated respectively. The results show that: The inlet water temperature ranges from 0 to 20, and the heat exchange efficiency ranges from 1604 to 2110MW. By reducing the inlet water temperature, the heat exchange efficiency can be increased. Compared with the inlet water temperature falling from 20, the heat exchange efficiency is increased by 1.32 times under the condition of 0 inlet water temperature. If the use of lower temperature antifreeze and other materials, heat transfer efficiency will improve more.

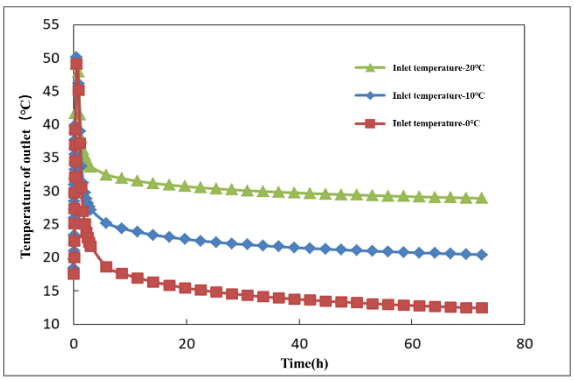

Figure 26: Comparison of outlet temperature under different inlet water temperatures

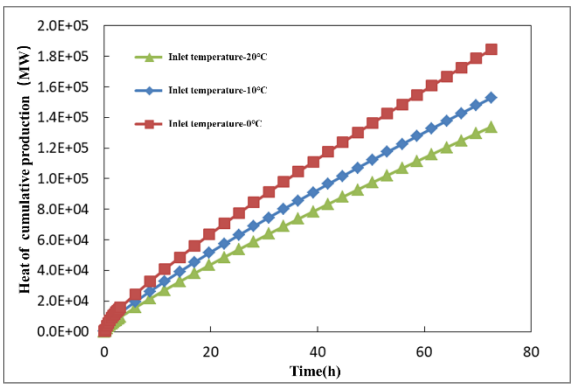

Figure 27: Comparison of cumulative heat transfer under different inlet water temperatures

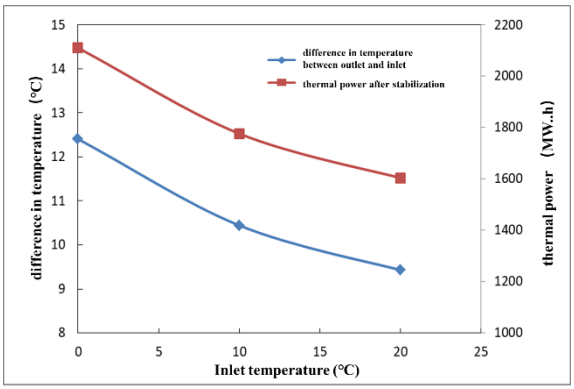

Figure 28: Comparison of thermal power at different inlet water temperatures

5. CONCLUSION

Based on the model of "Re1 Well", a geothermal well in operation in Xi 'an, this paper carries out the numerical simulation of the water isolation and heat extraction development model of mid-deep U-shaped well, and compares the simulation results with the test data to verify the accuracy of the model. The effects of reservoir conditions such as formation temperature and thermal conductivity, well depth structure such as casing size and horizontal length, and fluid parameters such as fluid displacement and inlet temperature on heat transfer efficiency are simulated and analyzed respectively. The results show that:

(1) Relative to the reservoir thermal conductivity, the search for high temperature reservoir can achieve higher heat transfer efficiency. The heat transfer power of 110 rate reservoir reaches 2656MW·h, and its heat transfer efficiency is 2.3 times that of 50 efficiency reservoir.

(2) In terms of well structure, compared with casing size, the heat transfer efficiency is higher when the length of horizontal section is increased. The heat transfer power of U-shaped well in 2000m horizontal section is 2607MW·h, which is 1.58 times higher than that of U-shaped well in 200m horizontal section. However, the heat transfer efficiency of the horizontal section is not proportional to the length. The longer the length is, the heat transfer efficiency per meter will decrease.

(3) In terms of fluid parameters, increasing the displacement and decreasing the inlet temperature can significantly improve the heat transfer efficiency. The heat transfer power at the displacement of 100m is 2194 MW·h, 1.33 times that at the displacement of 40mh. Inlet water temperature is 0; The heat transfer power under the condition is 2110MW power, 1.32 times that under the condition of 201 inlet water temperature. If the antifreeze and other materials with lower temperature are used, the heat transfer efficiency will be improved more.

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