Proceedings World Geothermal Congress 2023
Beijing, China, April 17 – 21, 2023

Influence of the abandoned oil layer on heat mining in U-shape well geothermal system with $ScCO_2$ storage considering the natural convection heat transfer

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Keywords: $ScCO_2$ storage; U-shape well geothermal; Heat mining; Abandoned oil layer; Natural convection heat transfer.

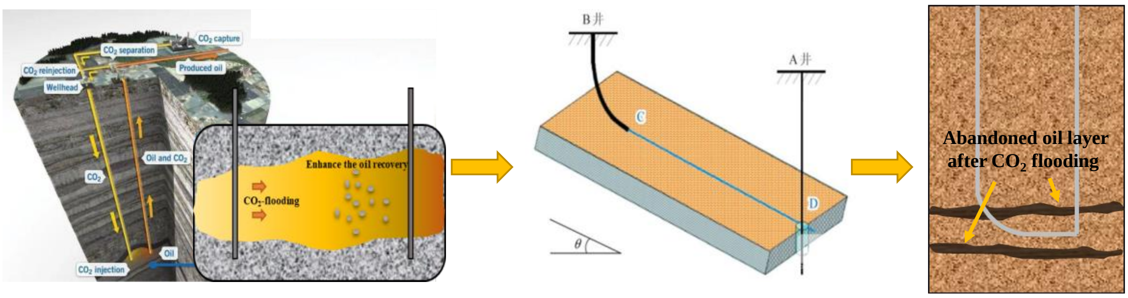
ABSTRACT

In view of the current situation that there are large numbers of high water-cur oil and gas reservoirs, the switching of geothermal development using the available well pattern has become the effective way to reduce carbon emission in oil field. However, the influence of oil layer features (including the inclination, permeability and quantity of the oil layer) on geothermal development and the optimization measures for heat mining are still unclear. This study proposes to use the oil-extracted layer for CO_2 geological storage, and then construct the U-shape well geothermal system with $ScCO_2$ storage based on the existing well pattern. Considering the fluid natural convection in porous medium with temperature gradients, the heat and mass transfer in wellbore and thermal reservoir and the heat transfer between pipes and reservoir are coupled, then the effect of oil layer features, wellbore insulation conditions and injection parameters on heat mining of the U-shape well geothermal system are discussed. The results show that in CO_2 buried oil layer due to the low viscosity of $ScCO_2$ and the sensitivity temperature-independent density, the natural convection of $ScCO_2$ drives the vertical migration of high temperature heat flow, which raise the temperature gradient around the oil layer and then provide more sufficient heating for heat-carrying fluid in wellbore. Comparing the water-flooded abandon layer with the $ScCO_2$-flooded abandon layer, the outlet temperature of geothermal system with $ScCO_2$ storage increased by 4.63% and the heat mining rate increased by 9.49% after 10-year exploitation, and the increment increases with the exploitation duration. The increase of the inclination, permeability and quantity of the oil layers can enhance the natural convection, and raise the outlet temperature and heat mining rate. After 10-year exploitation, the oil layer permeability of $90\times10^{-12}m^2$ increased by 13.25% compared with that of $10\times10^{-12}m^2$, and the heat mining rate raised by 20.23%. With the increase of circulation flow rate, the outlet temperature decreases due to the time shortening of heat transfer, while the heat mining rate increases due to higher mass flow rate. For the insulation of production well, there are optimal location and length of insulation section. And in this case, the optimum insulation length is 1500m. This research will provide technical support for the site selection and exploitation scheme design for geothermal development and CO_2 geological storage in abandon oil reservoirs, and contribute to the carbon reduction in oil field.

1. INTRODUCTION

For the development of geothermal energy in oilfields, the rich geological data, existing wellbore and the advanced fluid extraction technology all provide support for the efficient extraction and utilization of geothermal energy [1-3]. The existing geothermal extraction methods can be mainly divided into open-cycle geothermal system and close-cycle geothermal system. In view of the problems of pipe corrosion, reservoir damage, high fracturing cost of geothermal reservoirs, and the difficulty in downhole communication of fracturing fractures in open-cycle geothermal systems, the close-cycle heat extraction has gradually attracted the attention of most oilfields [4-6]. At the same time, the construction of U-shape geothermal well becomes possible due to the development of downhole well communication and sealing technology [7-8]. Although some scholars have studied the heat mining performance of U-shape well geothermal system, there is no report on the effect of oil layer features on the heat mining performance of close-cycle geothermal system with CO_2 sequestration. In this study, it is proposed to employ the CO_2-flooding to enhance the oil recovery, then based on the oil-extracted abandoned layer to construct the U-shape well geothermal system with $ScCO_2$ storage based on the existing well pattern(Fig.1). Then, the influence of oil layer characteristics, wellbore thermal insulation conditions and injection parameters on heat mining performance of U-shape well geothermal system with $ScCO_2$ storage was investigated.

The key to efficient utilization of geothermal energy is how to efficiently extract underground heat energy to ground [9-11]. Currently, the commonly used heat extraction methods include open-cycle heat extraction (including geothermal recharge, enhanced geothermal system) and close-cycle heat extraction (including tube-buried heat exchange, single well co-axial heat exchange, gravity heat pipe heat extraction and U-shape well heat extraction). For the open-cycle heat extraction, some scholars have carried out the related research. During the development of oil and gas resources in Alberta, Canada, a large amount of hot water at 50-60℃ is required, and the natural gas is usually used to heat the river water, 6% of natural gas consumption is used for this purpose. The development of geothermal energy can effectively reduce natural gas consumption and greenhouse gas emissions. Hofmann et al. optimized the high efficiency development scheme of geothermal through numerical simulation. The results show that the use of natural fracture for shear fracturing has higher economic benefits. The heat mining performance of horizontal wells is better than that of vertical wells [12]. Blöcher et al. established a 3D geological model based on the GerSk geothermal project and analyzed the thermal breakthrough time of the geothermal project [13]. Based on the Soultz project combined with actual geological data, Sebastian et al. established a three-dimensional TH model to simulate the development of fractured geothermal reservoir. The results proved that the multi-well system provides a larger heat exchange area and higher heat mining rate [14]. Bujakowski et al. applied TOUGH2 geothermal simulator to evaluate the thermal extraction of sedimentary reservoir in central Poland. The results show that the heat mining rate is 2-3MW when the injection flow rate is 55l/s in the layer at 5500m with a temperature of 170℃ [15]. Zhang et al. studied the heat mining performance of using horizontal well staged fracturing in geothermal system, and conducted the reinjection of oilfield produced water to generate electricity [16]. Jiang et al. established a three-dimensional TH coupled model based on the local heat balance theory. The results show that the three-well system compared with the general two-well system can prolong the production duration of geothermal production and has better performance[17]. Qu and Zhang et al. carried out a numerical simulation study on heat mining performance of EGS under different fracture morphology based on COMSOL Multiphysics, and discussed the use of water and supercritical CO_2 as heat-carrying medium. The results show that the initial heat mining rate is higher with supercritical CO_2-based geothermal system, but the thermal breakthrough is earlier, and the outlet temperature drops fast after thermal breakthrough [18].



Enhance the oil recovery by CO_2-flooding **Directional sidetracking** **U-shape well geothermal system with ScCO2 storage**

Figure 1: Construction of the U-shape well geothermal system with $ScCO_2$ storage

Although the open-cycle geothermal system has the high heat extraction efficiency, there are still problems such as large loss of working medium, pipeline corrosion and scalling, high fracturing cost and difficult downhole connection of fracturing fractures.[19-23] Kujawa et al. conducted numerical simulation of single well co-axial heat transfer for abandoned wells with a depth of 3950m. The results show that the inlet temperature, flow rate and internal pipe insulation will affect the heat mining performance, and the heat mining rate can be 40-200kW [22]. Noorollahhi et al. conducted a numerical simulation study on single well co-axial heat transfer for abandoned oil wells with well depths of 3861m and 4423m. The results show that the casing geometry still has an impact on heat transfer. The power generation of ZA-II and DQ-II with bottom hole temperatures of 138.7℃ and 159.8℃ respectively reached 138 and 364kW [23]. Sun et al. proposed to use supercritical CO_2 as the circulating medium to extract heat in U-shape well geothermal system, and analyzed the advantages of supercritical CO_2 heat carrying over water carrying by numerical simulation [24]. Liao et al. proposed to adopt the multi-level U-shape well geothermal system for close-cycle heat extraction. The numerical study showed that the multi-level sections can improve the heat mining rate [25]. Li et al. explored the heat transfer performance of horizontal section of U-shape well under the conditions of different water injection flow rates and different horizontal section lengths through physical experiments [26].

Although scholars have carried out experiments and numerical simulation studies on U-shape well geothermal system, there is no report on the influence of the oil layer features on U-shape well heat extraction. In particular, the influence of the water-containing oil layer after water flooding and $SsCO_2$-containing oil layer after CO_2 flooding on U-shape well geothermal mining is worth discussing (after CO_2-flooding, the CO_2 is buried in oil layer and under high-temperature and high-pressure environment the CO_2 exists as supercritical CO_2($ScCO_2$)). In this study, the natural convection of fluid in porous medium is considered, and the coupled model of heat and mass transfer in wellbore and thermal reservoir as well as the heat transfer between pipes and reservoir is constructed. Firstly, the influence of water-flooded oil layer and the $ScCO_2$-flooded oil layer on the heat mining of U-shape well is compared. Then, the influence of oil layer features, wellbore insulation conditions and injection parameters on heat mining performance of U-shape well geothermal system with $ScCO_2$ storage is discussed. The research results will provide important support for the conversion of abandoned oil reservoir to geothermal development.

2. NUMERICAL MODEL

For the U-shape well geothermal system, it involves the flow and heat transfer in wellbore, the heat exchange between wellbore and reservoir, and the flow and heat transfer in thermal reservoir. In review of the research of Jiang et al[27]., it was found that the natural convection of fluid in reservoir promotes the heat extraction of gravity heat pipes due to the disturbance of temperature field during heat mining. Therefore, considering the natural convection of fluid in porous medium, the coupled model of heat and mass transfer in wellbore and thermal reservoir as well as the heat transfer between pipes and reservoir is constructed.

2.1 Flow and heat transfer model in pipeline

2.1.1 Governing equations of fluid flow in pipeline

The following continuity and momentum equations describe the steady flow in pipeline:

$$\nabla \cdot \left(A\rho u \right) = 0 \tag{1}$$

$$0 = -\nabla p - f_D \frac{\rho}{2d_h} u\left|u\right| + F \tag{2}$$

Where, A is the cross-sectional area of pipeline(m^2); ρ is the density of fluid(kg/m^3); u is the flow velocity of fluid(m/s); p represents the flow pressure(Pa); F represents the volumetric force(N/m^3), for example the gravity; f_D is the Darcy friction factor.

2.1.2 heat transfer equation of fluid in pipeline

The energy equation for pipeline flow is:

$$\rho A C_{\mathrm{P}} u \cdot \nabla T = \nabla \cdot A k \nabla T + f_D \frac{\rho}{2 d_h} |u|^3 + Q_{wall} \tag{3}$$

Where, Cp is the heat capacity at constant pressure(J/(kg·K)); T represents the temperature(K); k is the thermal conductivity(W/(m·K)); corresponds to friction heat dissipated due to viscous shear. Q_{wall} is a source/sink term due to heat exchange with the surroundings through the pipe wall.

$$Q_{wall} = hZ\left(T_{\mathrm{ext}} - T\right) \tag{4}$$

Where, Z is the wetted perimeter of the pipe, m; h represents the total heat transfer coefficient(W/(m^2·K)); T_{ext} is the external temperature outside the pipe(K).

2.2 Flow and heat transfer models in porous media

2.2.1 Governing equation of seepage field in porous media

The seepage field governing equation considering the action of mechanical stress and temperature [28-30]:

$$-c_1 \frac{\partial \varepsilon_{\mathrm{v}}}{\partial t} - c_2 \frac{\partial T}{\partial t} + c_3 \frac{\partial p}{\partial t} = \nabla \cdot \left[\frac{k}{\mu} \left(\nabla p + \rho_1 g \nabla z \right) \right] \tag{5}$$

$$\begin{cases} c_1 = 1 - \dfrac{K'}{K_{\mathrm{s}}} \\ c_2 = \phi \alpha_1 + (1-\phi)\alpha_{\mathrm{s}} - \dfrac{\alpha_{\mathrm{T}} K'}{K_{\mathrm{s}}} \\ c_3 = \dfrac{\phi}{\beta_1} + \dfrac{1-\phi}{K_{\mathrm{s}}} \end{cases}$$

Where, ε_v is volumetric strain; φ is medium porosity; α_l is the volume thermal expansion coefficient of fluid (℃$^{-1}$); α_s is the volume thermal expansion coefficient of solid (℃$^{-1}$); B_l is the volume modulus of porous fluid (Pa); K_s is the effective volume modulus of solid(Pa); k is permeability of continuous medium (m^2); μ is dynamic viscosity of fluid (Pa·s); ρ_l is fluid density (Kg/m^3); g is gravity acceleration (m/s^2); z is the coordinates in the vertical direction (m).

2.2.2 Governing equation of temperature field in porous media

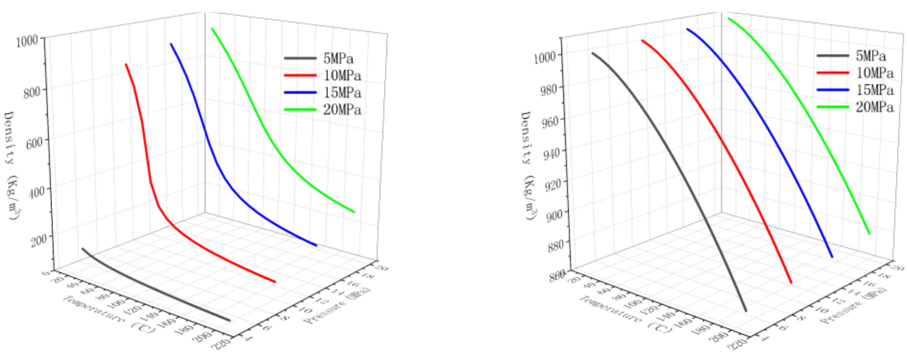
The temperature field governing equation considering thermal convection and mechanical stress [31-34]:

$$\left(\rho C\right)_{\mathrm{M}} \frac{\partial T}{\partial t} + \left(T_0 + T\right) K' \alpha_{\mathrm{T}} \frac{\partial \varepsilon_{\mathrm{T}}}{\partial t} + \rho_1 C_1 \left(T_0 + T\right) \frac{k}{\mu} \nabla p = \lambda_{\mathrm{M}} \nabla^2 T \tag{6}$$

Where, $\lambda_M = \lambda_s(1-\phi) + \lambda_l \phi$, λ_s and λ_l respectively represents the thermal conductivity coefficient of matrix and fluid (W/(m·K)); T_0 is the reference temperature under zero stress state (K); the heat capacity of porous media containing fluid can be described as $(\rho C)_M = \rho_s C_s (1-\phi) + \rho_l C_l \phi$ (KJ·m^3·K^{-1}).

2.2.3 Realization of natural convection of fluid in porous media

The natural convection of fluid in porous medium is realized by the gravity term and viscosity term in equation(5), where the fluid density and viscosity are temperature-dependent parameters [35-36]. As shown in Fig.2, compared with water. the density and viscosity of CO_2 are more sensitive to temperature. And the viscosity of CO_2 is greatly declined compared with that of water.



(1) Density of CO_2 (2) Density of water

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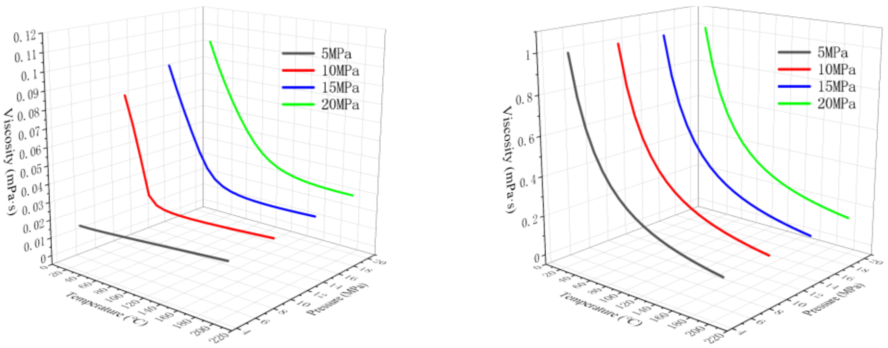


(3) Viscosity of CO_2 (4) Viscosity of water

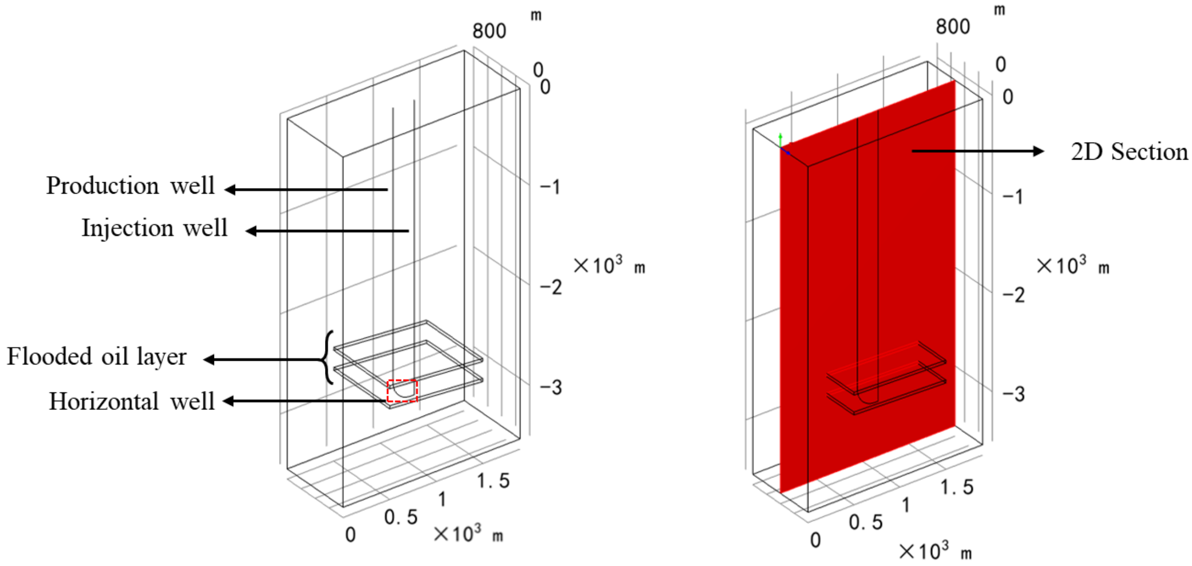
Figure 2: The density and viscosity of CO_2 and water

3. COMPARISON OF HEAT MINING PERFORMANCE OF U-SHAPE WELL GEOTHERMAL SYSTEM AFTER WATER FLOODING AND SCCO$_2$ FLOODING

The mining of geothermal resources in oil field is usually carried out after the completion of oil and gas exploitation, that is when the oil and gas recovery rate is reduced to almost no economic benefits, a geothermal system will be constructed to extract geothermal energy. And water flooding is commonly used to stimulate the output of oil and gas. However, the CO_2 flooding technology proposed in recent years can not only improve the oil and gas recovery, but also play the role of CO_2 geological storage. In fact, under the temperature and pressure environment of reservoir, the CO_2 will be in supercritical state. Therefore, the heat mining performance of U-shape well after water flooding and after CO_2 flooding will be discussed by setting the saturation of water or CO_2 in oil layer.

3.1 Model establishment

The established geometric model includes the reservoir with the height of 3500m, the length of 1900m and the width of 800m. And the thickness of oil layers is 30m, the length is 1000m and the width is 800m., as shown in Fig3(a). The reservoir temperature gradient is determined by the actual temperature measured downhole. The horizontal section of U-shape well is set by the drilling trajectory design. For the heat and mass transfer of the working medium in U-shape wellbore, the formulas in 2.1 is adopted, and for the heat and mass transfer of fluid in reservoir, the formulas in 2.2 is used. Meanwhile, water is employed for heat-carrying medium in the U-shape well system, and the abandoned oil layer is assumed to be the porous with certain saturation of water and CO_2 according to whether it is water-flooded or CO_2 flooded. The model parameters are illustrated in Table1.



(a) U-shape well geothermal system (b) 2D Section of geothermal system

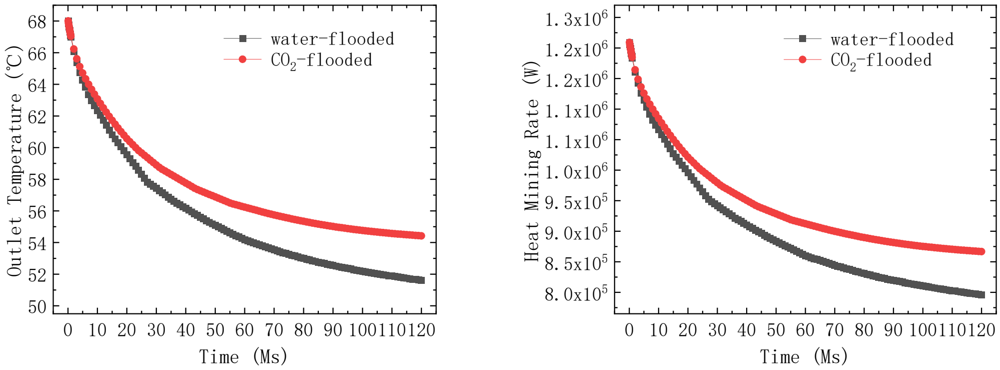
Figure 3: Geometry of U-shape well geothermal system with abandoned oil layer (the 2D Section will be used to describe the distribution of temperature and flow velocity in thermal reservoir)

Table1 Parameters of the U-shape well geothermal system

h_r/(m)	w_r/(m)	l_r/(m)	k_r/(m^2)	k_o/(m^2)	φ_r	φ_o
3500	800	1900	0.1×10^{-12}	10×10^{-12}	0.1	0.3
C_o/(W/(m·K))	C_r/(W/(m·K))	C_{wi}/(W/(m·K))	C_{wo}/(W/(m·K))	C_{wh}/(W/(m·K))	T_{inj}(°C)	U_{inj}(kg/s)
1.9	2.9	2.45	1	2.45	20	6

3.2 Result analysis

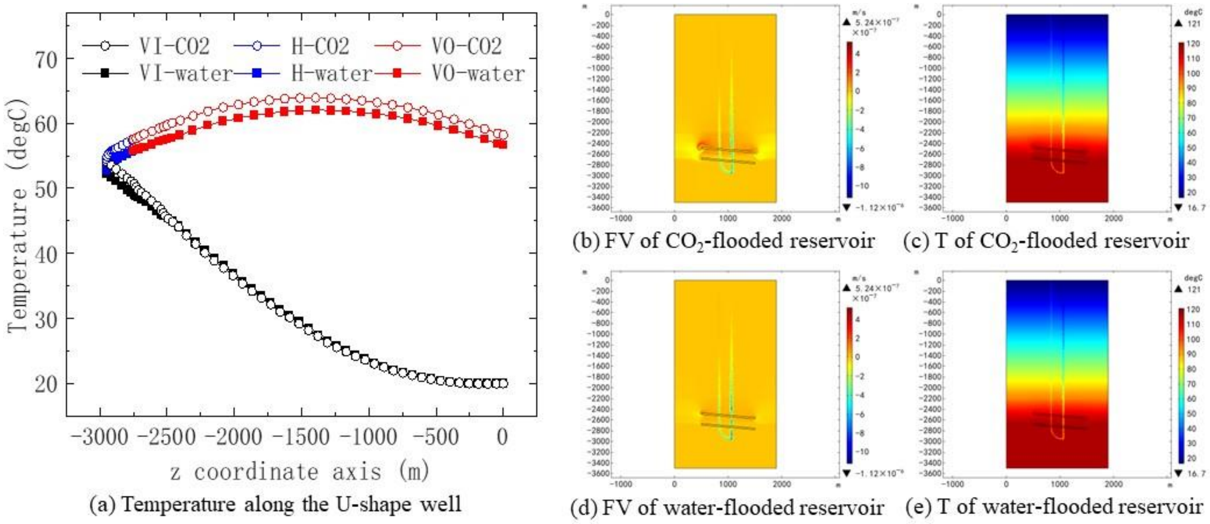
The heat mining performance of U-shape well geothermal system with the abandoned oil layer after water-flooding and after CO_2-flooding is compared for 10-year exploitation. The results show that the outlet temperature and heat mining rate after CO_2-flooding are higher than those after water-flooding under the same conditions of the heat carrying medium and the working parameters. As shown in Fig.4, after 5-year development the outlet temperature in geothermal system after CO_2-flooding is 3.7% higher than that after water-flooding, and the heat mining rate is improved by 6.4%. After 10-year development, compared with the geothermal system after water-flooding, the outlet temperature of geothermal system after CO_2-flooding increase by 4.63% and the heat mining rate increase by 9.49%. It can be seen that the exploitation of U-shape well geothermal system with abandoned oil layer after CO_2-flooding is more effective than with the abandoned oil layer after water-flooding.



(a) outlet temperature (b) heat mining rate

Figure 4: Heat mining performance comparation of the U-shape well geothermal system with water-flooded and CO_2-flooded

Fig.5 and Fig.6 respectively depict the temperature distribution along the U-shape well, the fluid velocity and temperature distribution in reservoir at 36 and 120 months of development. As heat around the wellbore is extracted, the temperature of wellbore surrounding rock decreases, and the density of reservoir fluid increases and moves downward under the action of gravity. Meanwhile, the warmer fluid (with the lower density) at the deeper zone of reservoir flow upwards driven by buoyancy, creating natural convection within the reservoir. Furthermore, the action of natural convection leads to the redistribution of reservoir temperature. For the abandoned oil layer after CO_2-flooding, since the temperature-sensitivity density and viscosity of CO_2 is relatively lower(Fig.2), the CO_2 flow driven by buoyancy has a greater impact on the temperature distribution around the oil layer, then enhance the temperature gradient near the oil layer (the overburn reservoir around the oil layer is heated by the natural convection inside the oil layer), which plays a better role in heating the heat-carrying medium in U-shape wellbore. So the output temperature and heat mining rate are higher.



(a) Temperature along the U-shape well (b) FV of CO_2-flooded reservoir (c) T of CO_2-flooded reservoir (d) FV of water-flooded reservoir (e) T of water-flooded reservoir

VI represents the vertical injection section of U-shape well, H represents the horizontal section of U-shape well, VO represents the vertical outlet section of U-shape well, FV represents the flow velocity, T represents the temperature field

Figure 5: Heat mining performance comparation of the U-shape well geothermal system with water-flooded and CO_2-flooded at 36Ms; (a)temperature distribution along the U-shape wellbore,(b) flow velocity field of CO_2-flooded reservoir,(c)temperature field of the CO_2-flooded reservoir, (d) flow velocity field of water-flooded reservoir,(e) temperature field of water-flooded reservoir;

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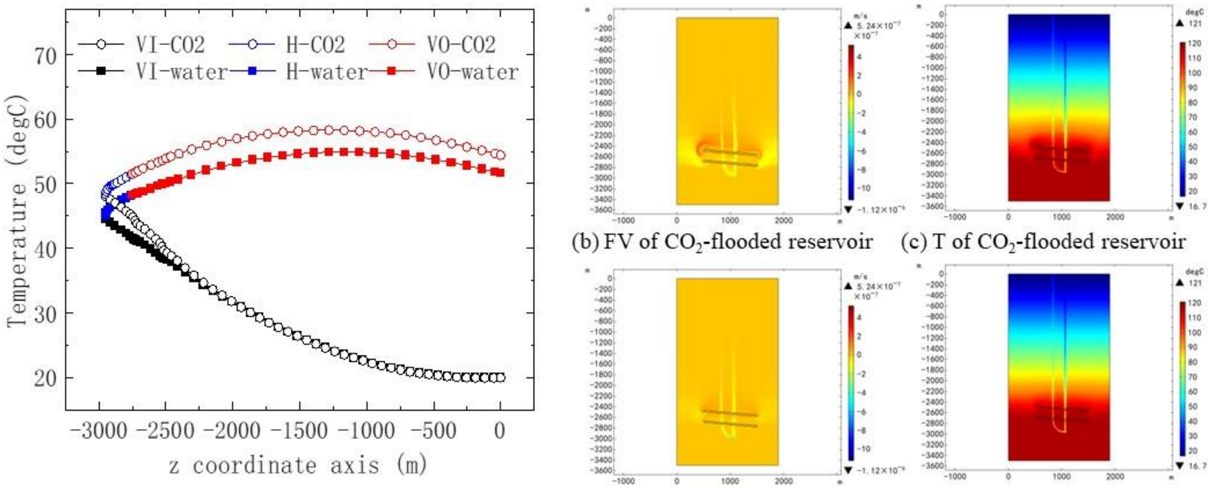


(a) Temperature along the U-shape well (b) FV of CO_2-flooded reservoir (c) T of CO_2-flooded reservoir (d) FV of water-flooded reservoir (e) T of water-flooded reservoir

VI represents the vertical injection section of U-shape well, H represents the horizontal section of U-shape well, VO represents the vertical outlet section of U-shape well, FV represents the flow velocity, T represents the temperature field

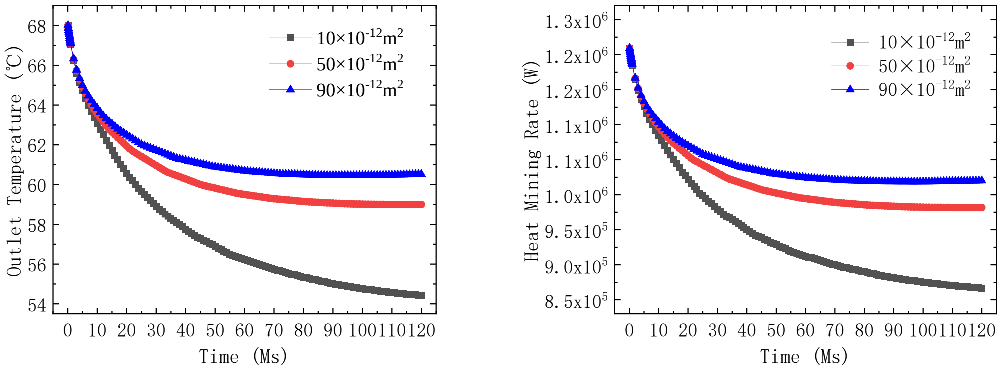
Figure 6: Heat mining performance comparation of the U-shape well geothermal system with water-flooded and CO_2-flooded at 120Ms; (a)temperature distribution along the U-shape wellbore, (b) flow velocity field of CO_2-flooded reservoir, (c)temperature field of the CO_2-flooded reservoir, (d) flow velocity field of water-flooded reservoir, (e) temperature field of water-flooded reservoir

4. INFLUENCE OF OIL LAYER FEATURES ON HEAT MINING PERFORMANCE OF U-SHAPE WELL GEOTHERMAL SYSTEM WITH SCCO2 STORAGE

To clarify the influence of oil layer features on heat mining performance of U-shape well geothermal system, the oil layer permeability, the oil layer number and the inclination of oil layer on heat mining will be discussed.

4.1 Oil layer permeability

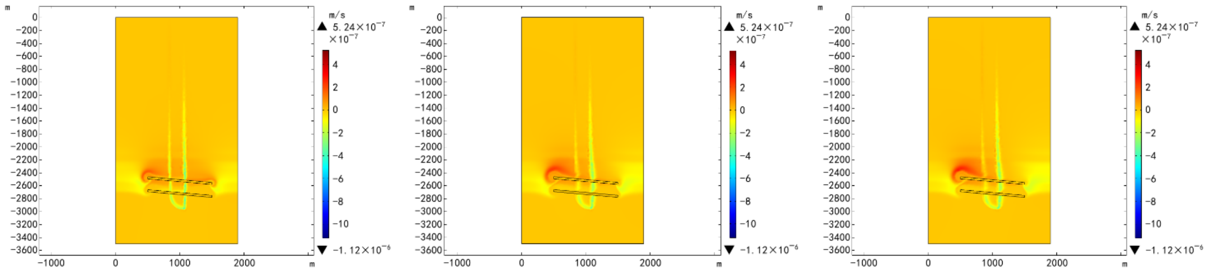
After years of oil extraction, there are large numbers of pores and micro-fractures in oil layer, so the abandoned oil layers usually present the high permeability. In this part, the heat mining performance of U-shape well under the oil layer permeability of $10\times10^{-12}m^2$, $50\times10^{-12}m^2$ and $90\times10^{-12}m^2$ will be researched.



(a) outlet temperature (b) heat mining rate

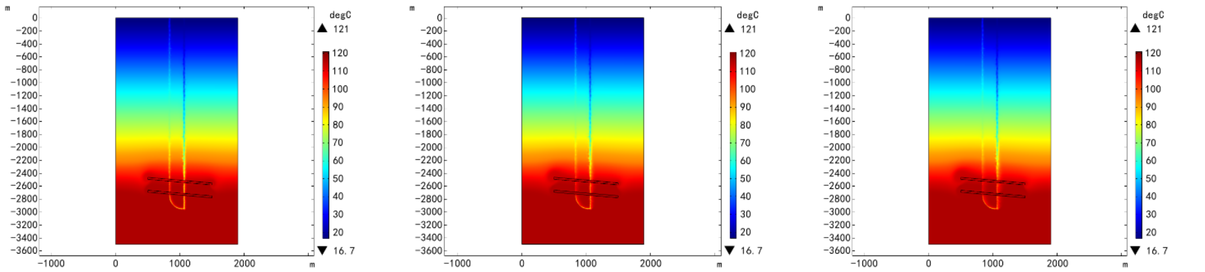
Figure 7: The outlet temperature and heat mining rate under different permeability of oil layer

Fig.7 shows the outlet temperature and heat mining rate of U-shape well geothermal system obtained under different oil layer permeability. In 10-year development when the oil layer permeability increases from $10\times10^{-12}m^2$ to $50\times10^{-12}m^2$, the outlet temperature raises from 54.1℃ to 58.9℃ with the increment of 8.87%, and the heat mining rate raises from 0.86MW to 0.98MW with the increment of 13.9%. However, when the oil layer permeability increases from $50\times10^{-12}m^2$ to $90\times10^{-12}m^2$, the increases of outlet temperature and heat mining rate is respectively 2.2% and 6.05%. And the increment of outlet temperature and heat mining rate is reduced compared to the oil layer permeability increases from $10\times10^{-12}m^2$ to $50\times10^{-12}m^2$. So the heat mining performance raises with the increase of oil layer permeability, but the increase amplitude gradually decreases. Therefore, during the selection of geothermal reservoir, the abandoned oil layers with higher permeability will promote the heat mining performance of U-shape well geothermal system.



(a) 10×10^{-12} m^2 (b) 50×10^{-12} m^2 (a) 90×10^{-12} m^2

Figure 8: Flow velocity distribution of U-shape well geothermal system under different oil layer permeability at 60-Ms development



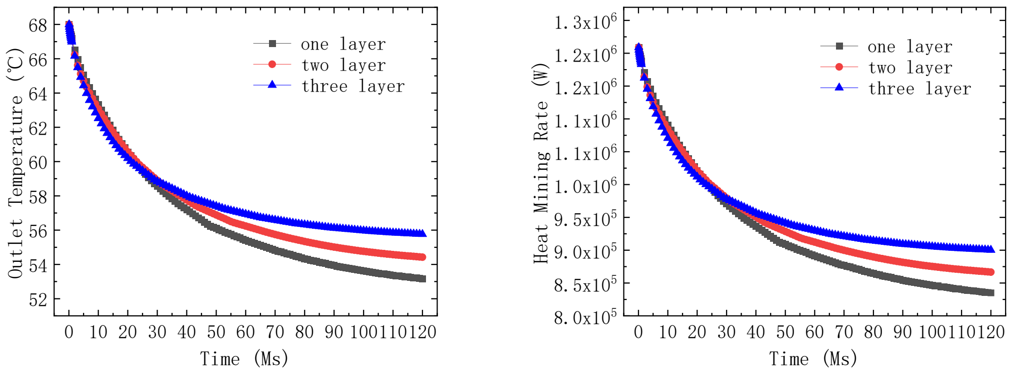
(a) 10×10^{-12} m^2 (b) 50×10^{-12} m^2 (a) 90×10^{-12} m^2

Figure 9: Flow velocity distribution of U-shape well geothermal system under different oil layer permeability at 60-Ms development

Fig.8 and Fig.9 depict the effects of oil layer permeability on seepage and temperature field. With the increase of oil layer permeability, more $ScCO_2$ moves upward under the action of density difference and brings heat to the upper part of oil layer. Meanwhile, the overburden rock around the upper part of the oil layer will be heated, which can generate the natural convection in the overburden thermal reservoir. Furthermore, the heat-carrying medium in wellbore can be heated by the natural convection heat transfer in thermal reservoir.

4.2 Oil layer number

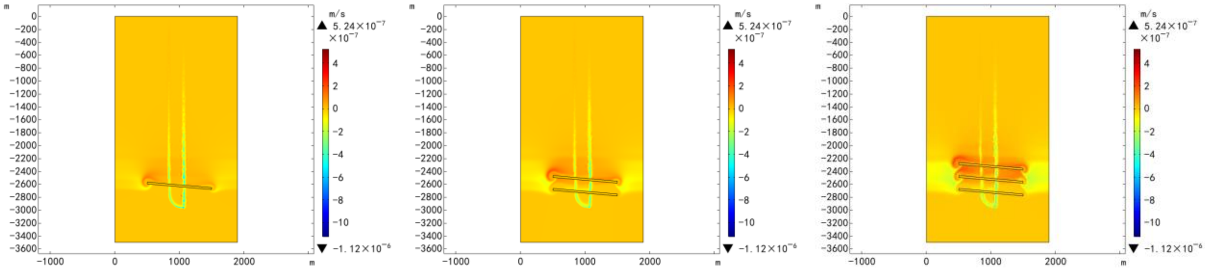
There may be multiple abandoned oil layers in old oil region. In this part, the influence of oil layer number on heat mining performance will be discussed. There are one, two and three abandoned oil layers are respectively set in reservoir, the thickness of each oil layers is 30m, the inclination is 5°, and the interval spacing between the oil layer is 200m. As shown in Fig.10, when two oil layers are installed, the outlet temperature is increased by 2.1%, and the heat mining rate is enhanced by 2.96% compared with that when there is only one oil layer. At 10-year exploitation, when three oil layers are installed, the outlet temperature is increased by 5.6%, and the heat mining rate is increased by 7.1% compared with that when only one oil layer exists.



(a) outlet temperature (b) heat mining rate

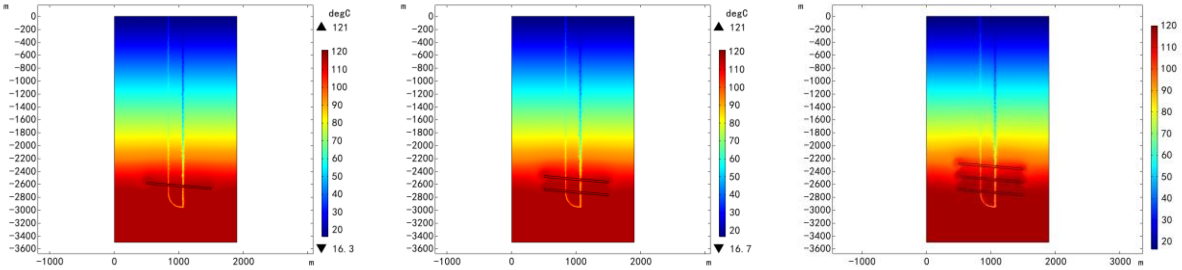
Figure 10: The outlet temperature and heat mining rate under different number of oil layer

Fig.11 and Fig.12 depict the seepage field and temperature field of U-shape well geothermal system after CO_2-flooding under different number of oil layers. The increase in oil layer number enhances the scale and intensity of natural convection, and the $ScCO_2$ stored in abandoned oil layer brings the heat from lower part to upper part under the natural convection action, thereby the wellbore will be better heated. So the increase in oil layer number can improve the heat mining performance of U-shape well geothermal system. This will inspire us that in the layer selection process before the development of U-shape well geothermal system, it is more inclined to choose the abandoned oil region with large number of oil layers. In addition, the employing of CO_2 flooding in oil layer is helpful for the later transformation of close-cycle heat mining.



(a) one oil layer (b) two oil layer (a) three oil layer

Figure 11: Flow velocity distribution of U-shape well geothermal system under different oil layer number at 60-Ms development

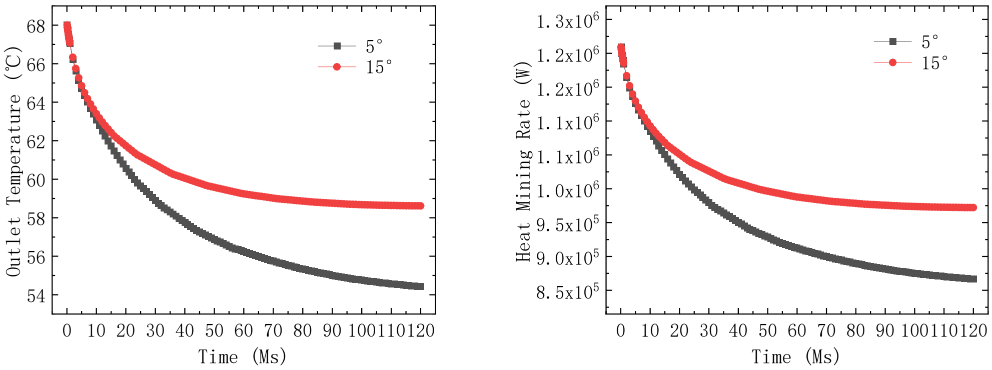


(a) one oil layer (b) two oil layer (a) three oil layer

Figure 12: Temperature distribution of U-shape well geothermal system under different oil layer number at 60-Ms development

4.3 Oil layer inclination

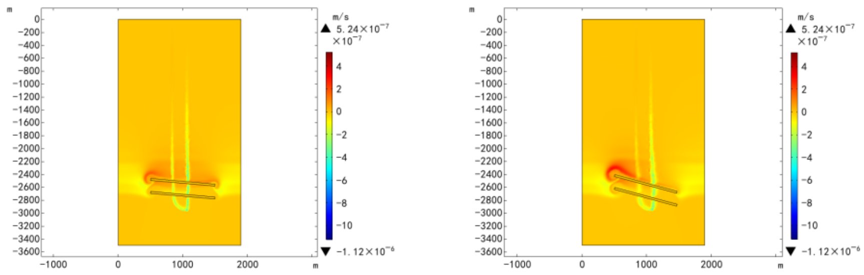
After CO_2-flooding the $ScCO_2$ is buried in the oil layer, and the oil layer usually has a certain inclination, so the high temperature CO_2 tends to flow from the deep part of oil layer to the shallow part under the driven of natural convection. Due to the low viscosity of $ScCO_2$, part of the CO_2 will overflow the oil layer and flow into the upper overburden rock, which will carry the heat upwards in reservoir. In this part, the oil layer inclination are installed to be 5° and 10° respectively to discuss the influence of oil layer inclination on heat mining performance of U-shape well geothermal system with CO_2 storage.



(a) outlet temperature (b) heat mining rate

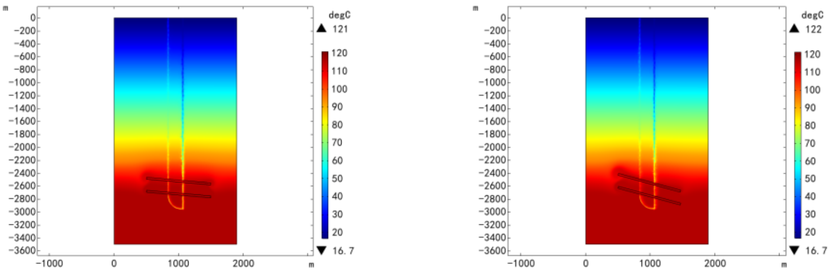
Figure 13: The outlet temperature and heat mining rate under different oil layer inclination

As shown in Fig.14, as the oil layer inclination increases, the natural convection in oil layer is more obvious, and more heat energy in deeper thermal reservoir can be transferred to lower part, which generate the larger scale of natural convection in overburden thermal reservoir. Therefore, the raises in oil layer inclination enhances the temperature gradient around the oil layer (Fig.15). In Fig.13, when the oil layer inclination is 15° in 10-year development, the outlet temperature is raised by 7.93% and the heat mining rate is increased by 13.4% compared with that at 5°. So the oil layer with a larger inclination can be selected for the heat mining of close-cycle geothermal system with $ScCO_2$ storage.



(a) oil layer inclination of 5°　　　(b) oil layer inclination 15°

Figure 14: Flow velocity distribution of U-shape well geothermal system under different oil layer inclination at 60-Ms development



(a) oil layer dip angle of 5°　　　(b) oil layer dip angle of 15°

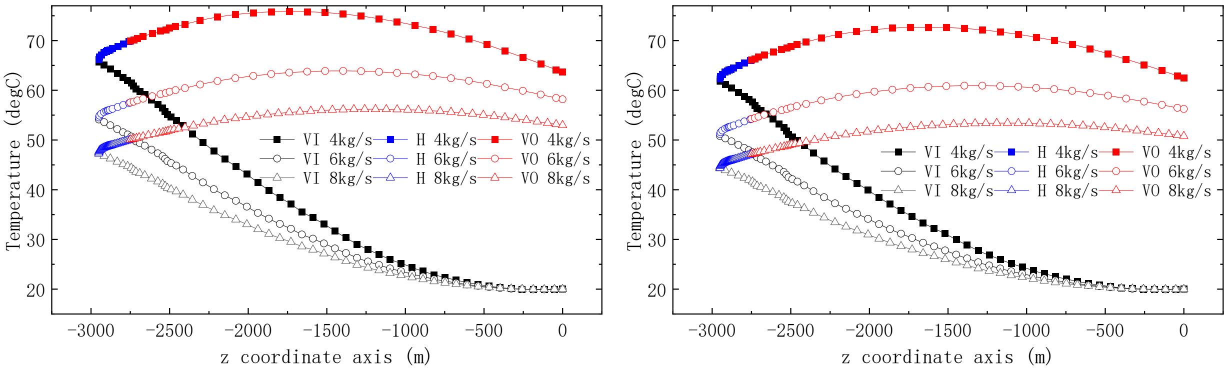
Figure 15: Temperature distribution of U-shape well geothermal system under different oil layer inclination at 60-Ms development

5. INFLUENCE OF KEY DEVELOPMENT PARAMETERS ON HEAT MINING PERFORMANCE OF U-SHAPE WELL GEOTHERMAL SYSTEM WITH SCCO$_2$ STORAGE

5.1 Mass flow rate of heat-carrying fluid

During the development of U-shape well geothermal system, the mass flow rate of heat-carrying fluid has an important influence on the outlet temperature and heat mining rate. To clarify the influence of mass flow rate on heat mining performance of U-shape geothermal well with CO_2 storage, the mass flow rate of 4kg/s, 6kg/s, 8kg/s are respectively set.

The increase in mass flow rate leads to the insufficient heat transfer, as shown in Fig.16, the temperature of each position along the U-shape wellbore decreases with the raise in mass flow rate. In early stage of geothermal development, the outlet temperature decreases with the raise of mass flow rate, and the temperature dropping enhances with the prolong of heat mining duration. As shown in Fig.17, at 10-year development the outlet temperature is reduced by 8.3% when the mass flow rate is 8kg/s compared to 6kg/s, and reduced by 19.5% compared to when the mass flow rate is 4kg/s. The heat mining rate is a comprehensive reflection of outlet temperature and mass flow rate. Although the outlet temperature decreases with the raise of mass flow rate, the heat mining rate shows the increasing trend with the raise of mass flow rate.



(a) geothermal mining at 36Ms　　　(b) geothermal mining at 60Ms

Figure 16: Temperature distribution along the U-shape wellbore under different mass flow rate of heat-carrying fluid

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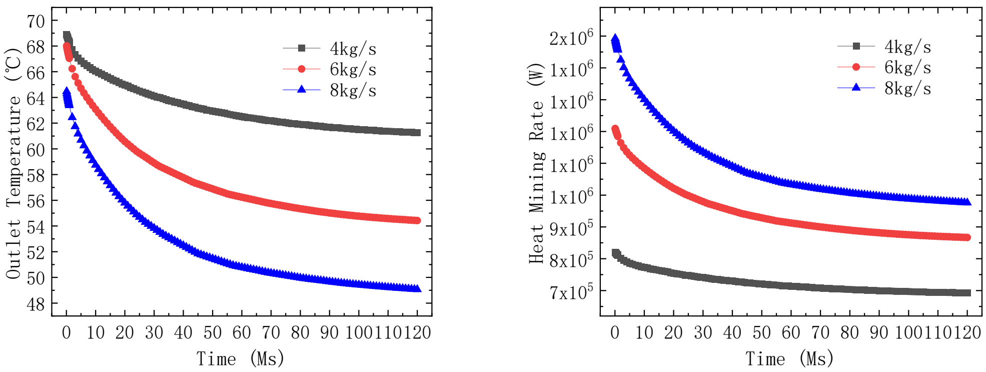


(a) outlet temperature (b) heat mining rate

Figure 17: Outlet temperature and heat mining rate under different mass flow rate of heat-carrying fluid

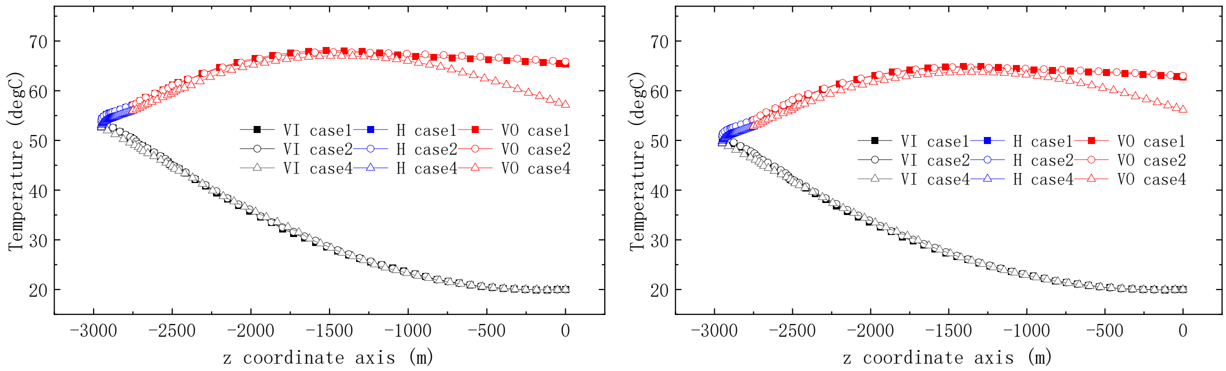
5.2 Wellbore insulation measures

During the process of converting abandoned oil layers to U-shape well geothermal system, wellbore reconstruction and development parameters determination should be carried out after the well and layer selection. During the well reconstruction part, in addition to connecting the two wells through sidetrack drilling, the production wellbore needs to be insulated to obtain a higher outlet temperature at the wellhead. In this part, four different thermal insulation measures are set in production wellbore, respectively the Case1 with thermal insulation of 1000m from the wellhead, Case2 with thermal insulation of 1500m from the wellhead, Case3 with thermal insulation of 2000m from the wellhead and Case4 with no insulation measure. The detailed parameters of the thermal conductivity along the wellbore are shown in Table2.

As shown in Fig.18, when no insulation measure is installed, obvious temperature decay appears above 1300m downhole. While when the thermal insulation measure is installed, the temperature attenuation is greatly reduced.

Table2 Items of wellbore insulation measures

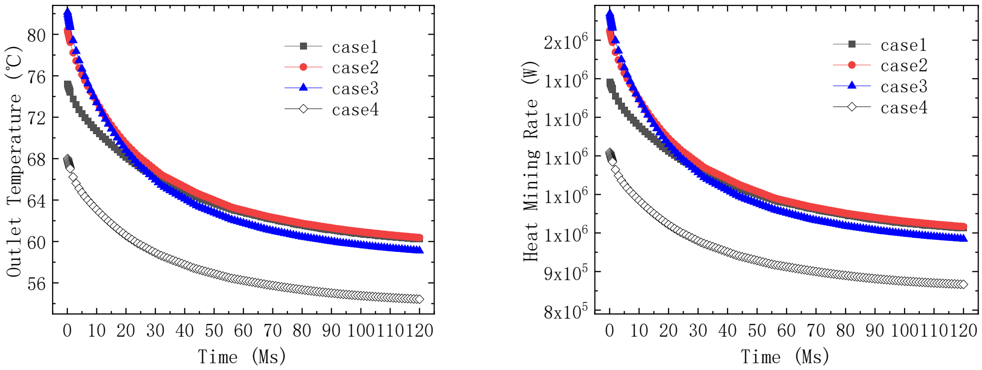
Items	Insulation length /(m)	Conductivity of Insulation Section /(W/(m·K))	Conductivity of Uninsulated Section(W/(m·K))
Case1	1000	0.1	2.45
Case2	1500	0.1	2.45
Case3	2000	0.1	2.45
Case4	0	0.1	2.45



(a) geothermal mining at 36-Ms (b) geothermal mining at 60-Ms

Figure 18: Temperature distribution along the U-shape wellbore under different wellbore insulation measures

In early stage of geothermal development, the outlet temperature of Case1 increased by 10.3% compared with that of Case4(without thermal insulation), the outlet temperature of Case2 increased by 8% compared with that of Case1. But the outlet temperature of Case3 is only increased by 1.2% compared with that of Case2. Due to the long thermal insulation section is installed in Case3, the thermal energy in rock matrix around the wellbore cannot be effectively transferred to the fluid in wellbore after 20Ms of development, so the outlet temperature drops. Therefore, the outlet temperature increment decreases with the increase of insulation length, and when the wellbore insulation section increases to the length of 2000m, the outlet temperature decreases due to the loss of formation temperature replenishment. The same rule is also presented for the heat mining rate. In Fig.19, the outlet temperature and heat mining rate of Case3 with the thermal insulation of 2000m presents the lowest mining performance after 24Ms heat extraction.



(a) outlet temperature (b) heat mining rate

Figure 19: Outlet temperature and heat mining rate under different wellbore insulation measures

6. CONCLUSIONS

In this study, considering the natural convection of fluid in porous medium, the coupled model of heat and mass transfer in wellbore and thermal reservoir as well as the heat transfer between pipes and reservoir is constructed. Firstly, the influence of water-flooded oil layer and the CO_2-flooded oil layer on the heat mining of U-shape well geothermal system is compared. Then, the influence of oil layer features, wellbore insulation conditions and injection parameters on heat mining performance of U-shape well geothermal system with $ScCO_2$ storage is discussed. The conclusion shows that:

(1) $ScCO_2$ buried in oil layers moves upward under the action of density difference and brings heat to the upper part of the oil layer. The overburden rock around the upper part of the oil layer will be heated, which can generate the natural convection in the overburden thermal reservoir. Furthermore, the heat-carrying medium in wellbore can be heated by the natural convection heat transfer in thermal reservoir.

(2) The natural convection effect is stronger in CO_2-flooded oil layer compared with that after water-flooded. The temperature distribution is seriously disturbed by the CO_2 flow driven by buoyancy, and the temperature gradient near the oil layer raises, which lead to a better heating effect on U-shape wellbore and higher outlet temperature. At 10-year development, the outlet temperature and the heat mining rate of the U-shape well geothermal system with $ScCO_2$ storage respectively increases by 4.63% and 9.49%, and the increment growth larger with the extension of development.

(3) The increase of oil layer permeability, number and inclination can enhance the natural convection in U-shape well geothermal system with $ScCO_2$ storage. At 10-year development, when the oil layer permeability increases from $10\times10^{-12}m^2$ to $50\times10^{-12}m^2$, the outlet temperature increases by 8.87% and the heat mining rate increases by 13.9%. When two oil layers are installed, the outlet temperature increases by 2.1% and the heat mining rate increases by 2.96% compared with that when there is only one oil layer. When the oil layer inclination is 15°, the outlet temperature increases by 7.93% and the heat mining rate increases by 13.4% compared with that when the inclination is 5°.

(4) The heat mining rate enhances with the raise of mass flow rate, while the outlet temperature decreases with the raise of mass flow rate.

(5) The outlet temperature increment decreases with the increase of insulation length, and when the wellbore insulation section increases to the length of 2000m, the outlet temperature decreases due to the loss of formation temperature replenishment.

ACKNOWLEDGMENTS

This research was supported by the National Natural Science Foundation of China (42102338); China Postdoctoral Science Foundation (2022M712210); Natural Science Foundation of Shandong Province (ZR2020QE115); the Fundamental Research Funds for the Central Universities (27R1902010A); the Opening Fund of Key Laboratory of Unconventional Oil & Gas Development (China University of Petroleum (East China)), Ministry of Education.

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