

Research on SC-CO₂ Heat Extraction from Abandoned Oil and Gas Wells for Geothermal Resource Development in Horizontal Wells

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ABSTRACT

In order to study the design and performance analysis of the SC-CO₂ extraction system of side wells for geothermal resource development of abandoned oil and gas wells, a model of SC-CO₂ extraction in the middle and deep layers was established, and the extraction performance of geothermal resource modification of abandoned oil and gas wells was evaluated. The pumping schemes of one injection, two injections and four injections were designed. The effects of high-temperature reservoir size, well diameter and well depth on the performance of the geothermal system were analysed. The results show that the temperature field decreases gradually after SC-CO₂ injection, which is especially obvious in the large fracture zone. Four injection schemes, increasing the number of injection wells and deepening the reservoir can improve the heat extraction efficiency and cumulative extraction of the geothermal system. Increasing the injection temperature can extend the operating time of the geothermal system.

KEYWORDS

Geothermal Resources; SC-CO₂ Heat Extraction; Abandoned Oil And Gas Wells; Sustainable Development.

1. INTRODUCTION

The development of geothermal resources from abandoned oil and gas wells has received more and more attention as the global energy demand grows and the awareness of environmental protection increases. Geothermal energy, as a kind of clean and sustainable energy, has the advantages of large resource reserves, strong stability, good continuity, high utilization factor, etc., and its development and utilization is of great significance for reducing greenhouse gas emissions and alleviating the energy crisis [1]. Currently, geothermal modification of abandoned oil and gas wells can not only effectively utilize geothermal resources, but also reduce the environmental problems caused by abandoned wells. Kong et al [2] studied the calculation method of single-well recharge rate of groundwater ground source heat pump, pointed out the insufficiency of the conventional calculation method through the case analysis of the actual project, and proposed a new calculation idea and process in order to improve the scientificity and accuracy of the recharge rate calculation. Gui et al [3] investigated the heat transfer performance of piled buried pipe heat exchanger and drilled buried pipe heat exchanger in ground source heat pump, and verified that the piled buried pipe heat exchanger has obvious advantages in heat transfer efficiency and economy through the analysis of actual measurement and numerical simulation. However, it has not considered that the design and construction of the buried pipe heat exchanger on pile foundation may be affected by various factors such as geological conditions and building structure. Tian et al [4] studied the conceptual model of geothermal energy development system of abandoned oil and gas wells, proposed the system model

of single well single-worker, single well double-worker and double-well double-worker, and constructed the "1+N" comprehensive utilization system with geothermal energy as the core, combined with other renewable energy sources, such as wind energy and solar energy. Guo et al [5] analyzed the factors affecting the heat transfer performance of abandoned or shut-in oil and gas wells converted to geothermal wells using medium-depth submerged pipe heat transfer technology by numerical simulation methods, including geological parameters, well parameters, and working condition parameters. Teng Zhao et al [6] developed a set of system models for geothermal power generation using abandoned oil and gas wells, especially using an organic Rankine cycle (RORC) with return heat for thermal calculations, which showed that increasing the geothermal water temperature and the mass flow rate of the mass of the worker can significantly improve the thermal efficiency and net power of the system. Zhang et al [7] developed and analyzed an analytical model for heat transfer of buried pipe heat exchangers considering the stratified homogeneous characteristics of geotechnical structures to more accurately predict the heat transfer characteristics of buried pipes in stratified geotechnical structures. However, the heat transfer due to subsurface seepage is neglected, which may result in large deviations when the buried pipe acts for a long period of time. Duo et al [8] discussed the importance, technical challenges and future directions of deep geothermal resource exploration and development, emphasizing the potential role of geothermal resources in the energy decarbonization revolution. Kan et al [9] explored how to retrofit abandoned oil wells for geothermal energy development, describing the principles of abandoned well selection, the conceptual design of the heating system, and the selection of the heating method. Pu et al [10] established the flow heat transfer equation of circulating fluid and the heat exchange equation of circulating fluid and rock in abandoned oil and gas wells, and investigated the heat transfer volume, power generation, rock temperature change and the stable operation of the system under different flow rates and ground temperature gradients by numerical simulation. However, specific factors such as stratigraphic properties and tectonics properties were not considered. Robert et al [11] Heat transfer model calibration and parameterization study of geothermal energy piles to optimize heat exchanger configurations and evaluate energy pile performance through numerical simulations and field data calibration. However, assumptions about the dry state of the soil, not all surface phenomena are considered. Faizal et al [12] explored a multidisciplinary approach to improve the thermal performance of individual elements in geothermal energy piles to enhance the heat exchange between the heat carrier fluid and the ground through geometric optimization, application of nanofluids as the main loop fluid, improvement of piping materials and concrete mixes but were able to explore these methods in detail did not analyze the degree of heat transfer from the wellbore. Bu et al [13] investigated the feasibility of using abandoned oil and gas wells for geothermal energy development for power generation, analyzing the two main factors affecting heat exchange and power output-fluid flow rate and ground temperature gradient-but not in detail. Kiaghadi [14] and others explored the conversion of abandoned oil and gas wells into geothermal wells and the use of low temperature geothermal resources to desalinate the resulting brackish water in order to generate a sustainable freshwater supply, but did not propose a model for SC-CO₂ heat extraction. Fei et al [15] investigated an organic Rankine cycle system integrating geothermal energy from abandoned extraction wells and waste cooling energy from a satellite LNG station to improve the system performance through horizontal well extension and thermal energy storage techniques, but their findings were in specific geographic and geologic conditions, and the generalizability of the results needs to be further investigated and verified under different conditions. However numerous studies this have not examined lateral well development in the development of geothermal resources from abandoned oil and gas wells. In this paper, we focus on the SC-CO₂ heat extraction system of lateral wells in the development of geothermal resources from abandoned oil and gas wells, and investigate the influence of the changing law of thermal reservoir temperature and porosity on the production temperature, heat yield and thermal efficiency of lateral wells. In response to changes in these parameters, the geothermal collector is adjusted to achieve optimal efficiency. The effects of different injection and extraction methods on the heat extraction efficiency and system lifetime of enhanced geothermal

harvesting systems were investigated. The heat extraction efficiency of geothermal resources from abandoned oil and gas wells was evaluated and optimized.

2. NUMERICAL MODEL

2.1. Basic parameters

Regarding the structural design of geothermal transformation of waste oil and gas wells, based on the traditional medium-depth heat extraction model, the SC-CO₂ heat extraction model of lateral wells for geothermal resource development of waste oil and gas wells was designed to evaluate the heat extraction performance of waste oil and gas wells geothermal resource transformation with SC-CO₂ as the heat extraction mass, and the systematic heat extraction analysis was based on the initial parameters of the medium-depth geothermal model, and the structural design parameters of the model were as follows:

The design size of the heat extraction model is a high-temperature thermal storage with a length and width of 200 m and a height of 100 m. The design of the well position and penetration system can be decided according to the size of the thermal storage;

The input and output wells have a diameter of 0.6 m to accommodate the heat extraction mass flow rate of 50 kg/s;

The depth of the well is 2000m, the length difference of the input well is 200m and the length difference of the output well is 350m.

2.2. Extraction program design

The transformation of abandoned oil and gas wells into geothermal energy production is an effective sustainable energy solution. Transverse well technology, by increasing the contact surface with the geothermal heat source, can improve the efficiency of heat extraction. In addition, the use of SC-CO₂ as a thermal extraction work mass promotes fracture generation and enhances the development efficiency of geothermal reserves. Based on the structure of existing abandoned oil and gas wells, design of geothermal heat extraction systems with one injection, two injections and four injections. Low-temperature fluids are injected into the thermal reservoir through injection wells, and after receiving the geologic temperature, the thermal fluids are returned to the surface from the heat-producing wells. As shown in Fig. 1, a horizontal well SC-CO₂ heat extraction model for geothermal resource development of abandoned oil and gas wells is designed, which adopts a four-injection and one-extraction method, with the injection wells about 30 meters above the production wells and the injection wells are in four large cracks.

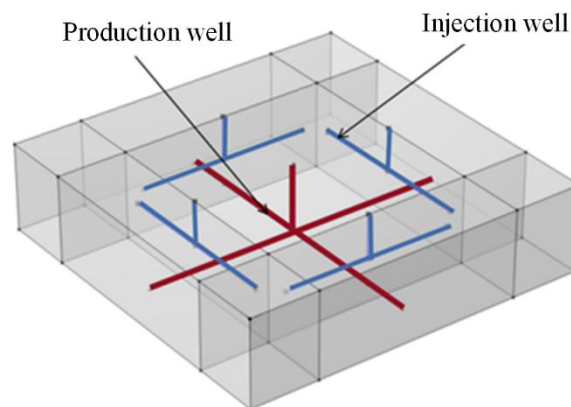


Fig. 1 Structure of the model

2.3. Extraction methods and underlying assumptions

The model uses constant flow rate injection to analyze the effect of each parameter on the power and effect of heat extraction through the change of each parameter, and the effect of the pressure of the liquid caused by gravity needs to be considered due to the deeper depth.

When considering the use of SC-CO₂ as a heat extraction medium in a geothermal retrofit project for waste oil and gas wells, the following assumptions need to be made to ensure the accuracy and validity of the calculations: (1) To simplify the calculations and model creation, it is assumed that the thermodynamic properties (e.g., thermal conductivity, specific heat capacity, and viscosity) of supercritical carbon dioxide remain constant throughout the journey from the bottom of the well to the surface; (2) During the heat transfer between the well wall and SC-CO₂, a steady state is assumed, i.e., there is no significant temperature change within a certain time frame; (3) The geothermal gradient is assumed to be known in advance and to be constant over the entire range of well depths; (4) The formation is assumed to be homogeneous with constant porosity and permeability excavation; (5) It is assumed that the oil and gas wells are intact to guarantee that the supercritical CO₂ circulates efficiently and that there are no well breaks or leaks to generate losses; (6) It is assumed that SC-CO₂ can be used stably and safely throughout the operation without the risk of chemical reaction or reaction with other materials, and that the geothermal energy is constant and sustainable.

2.4. Temperature field spatial and temporal distribution

The temperature field of SC-CO₂ heat extraction system of lateral wells for geothermal resource development of abandoned oil and gas wells is plotted with time as shown in Fig. 2. As can be seen from the figure, the temperature around the lateral production wells gradually decreases as lower temperature SC-CO₂ is injected into the waste oil and gas wells. This temperature drop suggests that a cold front of low-temperature SC-CO₂ fluid is gradually encroaching and expanding its area of influence. With time, the low-temperature SC-CO₂ is expanding in all directions along the axial direction of the waste oil and gas wells, and this change is more distinctive in the large fracture zone. Since the permeability of the fractures is higher than that of the rock mass, the cold-front diffusion of the heat-exchanging agent in these fractures is more significant. In year 6, the convergence of two producing wells with low-temperature SC-CO₂ fluids resulted in a rapid decrease in the temperature of the producing wells. For waste oil and gas wells after geothermal modification, the injection of low-temperature heat transfer media at a constant flow rate causes a significant change in the temperature field near the geothermal well, forming a cold front that spreads in all directions. And after a long period of operation, the cold front reaches the zone adjacent to the production wells, causing the temperature of the production wells to have a tendency to drop rapidly.

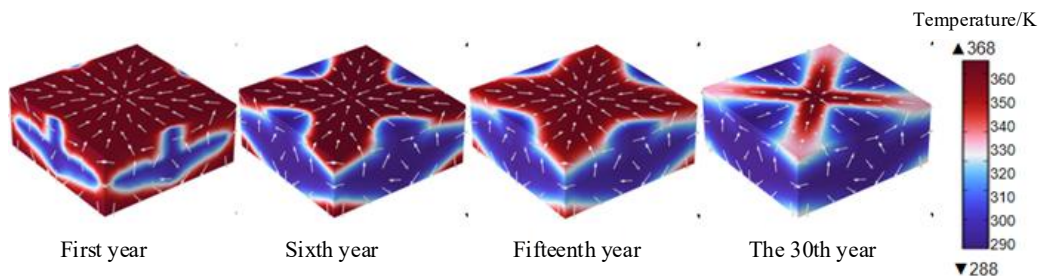


Fig. 2 Temperature field of SC-CO₂ heat extraction system of lateral wells for geothermal resource development of abandoned oil and gas wells over time

2.5. Impact of well placement

In the process of geothermal renovation of waste oil and gas wells, in order to study the influence of different well distribution methods on the heat extraction performance of the system, the parametric

analysis is carried out by using the control variable method, keeping the other initial parameters unchanged, and analyzing the heat extraction performance of the geothermal renovation of waste oil and gas wells by changing the arrangement of the wells. As shown in Fig. 3, the temperature field distribution of the reservoir in 30 years under the geothermal system development schemes with different well deployment methods is shown in the cloud map. Based on the four-injection and one-extraction scheme, one-injection and two-injection and one-extraction schemes are designed for the development of the geothermal system, and the injection rate of the injector wells in each scheme is kept in the same way as the original one, and the production rate of the production wells varies linearly with the number of the injector wells. In Fig. (a), a cloud map of the temperature field distribution in the reservoir over a 30-year period under the one-injection, one-take geothermal system development scenario is shown. In Fig. (b) a cloud map of the temperature field distribution in the reservoir over a 30-year period under the two-injection-one-extraction geothermal system development scenario is shown. With the different well deployment methods, the range of low-temperature cold fronts is small at the beginning of the system's heat extraction, the system's production temperature has a limited range of variability, and the reservoir temperature decreases significantly after more than six years of operation. However, with the different ways of well distribution, the production temperature of the heat extraction system also has a great difference, four injection and one extraction well distribution program due to more injection wells, can be in a wider range of heat storage for effective heat exchange, can improve the rate of heat extraction. However, over long periods of operation, the potentially stronger cooling effect of more injection wells results in relatively low production temperatures for the four-injection, one-pickup well spreading program.

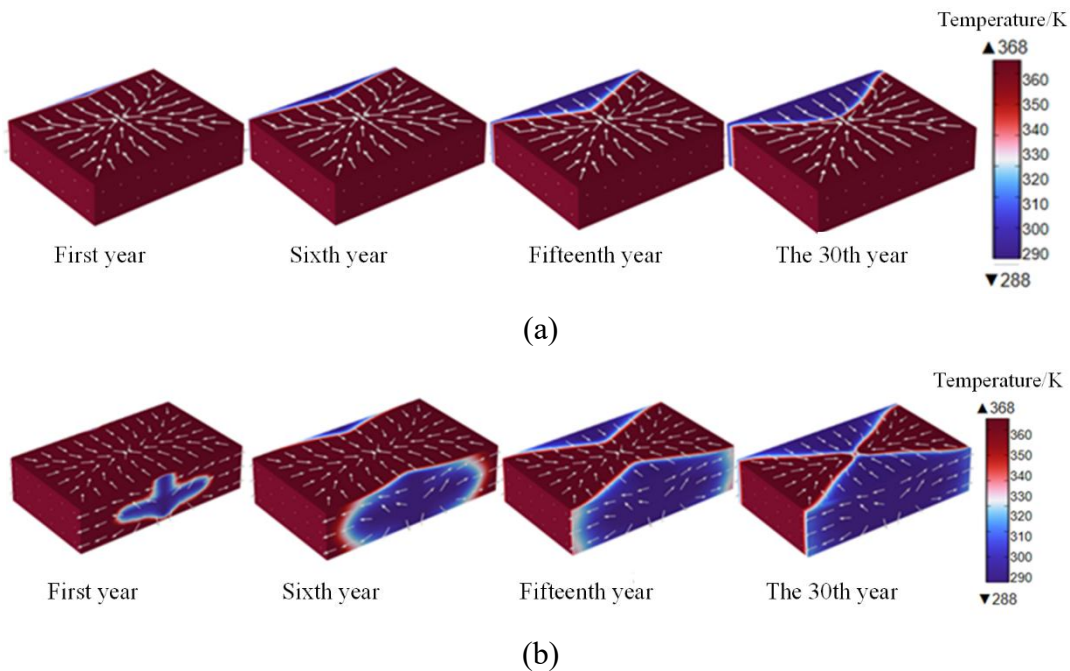


Fig. 3 Cloud map of temperature field distribution in the reservoir over 30 years under different well deployment methods for geothermal system development scenarios. (a) One injections and one procurement. (b) Two injections and one procurement

As shown in Figure 4(a), at 30 years, the production temperature is reduced by about 25 K compared to the one-injection, one-extraction well deployment scheme. Due to the relatively large water injection volume of the four-injection and one-recipient well distribution scheme, the heat transfer in the thermal storage system is more dispersed, which improves the heat extraction rate and cumulative heat extraction, and the instantaneous production temperature of the production wells of the multi-injection well distribution method decreases in Fig. 4(b) and Fig. 4(c) because the whole reservoir is affected by the cold effect of the low-temperature SC-CO₂. The results show that the four-injection and one-extraction well distribution method significantly improves the system heat extraction

efficiency as well as the total heat extraction, and the selection of the appropriate well distribution method can maximize the heat extraction performance of the whole geothermal reforming system.

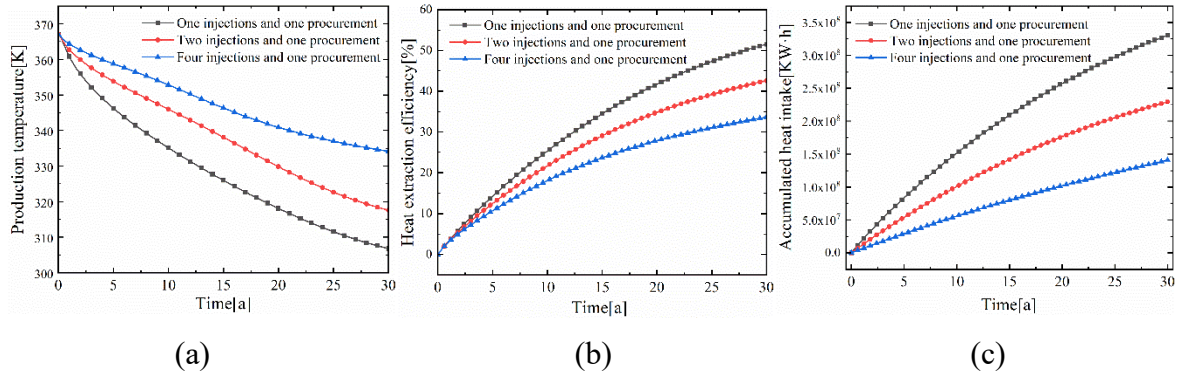


Fig. 4 Heat extraction performance of the system with different well distribution methods. (a) Graph of changes in production temperature. (b) Graph of changes in heat extraction efficiency. (c) Graph of changes in cumulative heat extraction

3. INFLUENCE OF INJECTION PARAMETERS

3.1. Parameterized analysis of injection temperature

Keeping the other initial parameters unchanged, only the injection temperatures were changed to 288.15 K, 298.15 K, 308.15 K, and 318.15 K, respectively. A parametric analysis of temperature was performed to evaluate the heat extraction rate, instantaneous production temperature, and total heat withdrawal of the geothermal system. In Figure 5(a), as the injection temperature increases from 288.15 K to 318.15 K, the termination production temperature of the producing wells increases accordingly, and for every 10 K change, the termination temperature of the producing wells over 60 years rises by about 8 K each. In Fig. 5(b), the heat extraction and heat transfer efficiencies of the system are relatively stable when the injection temperature increases, and there is no significant change in the injection temperature on the heat extraction efficiency. In Fig. 5(c), since the thermal storage will be affected by a certain cold effect during the process of injecting low-temperature fluids, this will lead to a gradual decrease in the cumulative heat extraction from the production wells, and at the same time, since higher injection temperatures will lead to a decrease in the total enthalpy change of the entire thermal storage system, the heat conversion is lower, leading to a corresponding decrease in the total heat extraction from the system, which indicates that higher injection temperatures can prolong the operation time of the geothermal reforming system for waste oil and gas wells, but may lead to a decrease in the cumulative heat extraction from the production wells. system's operating time, but may lead to lower cumulative heat extraction.

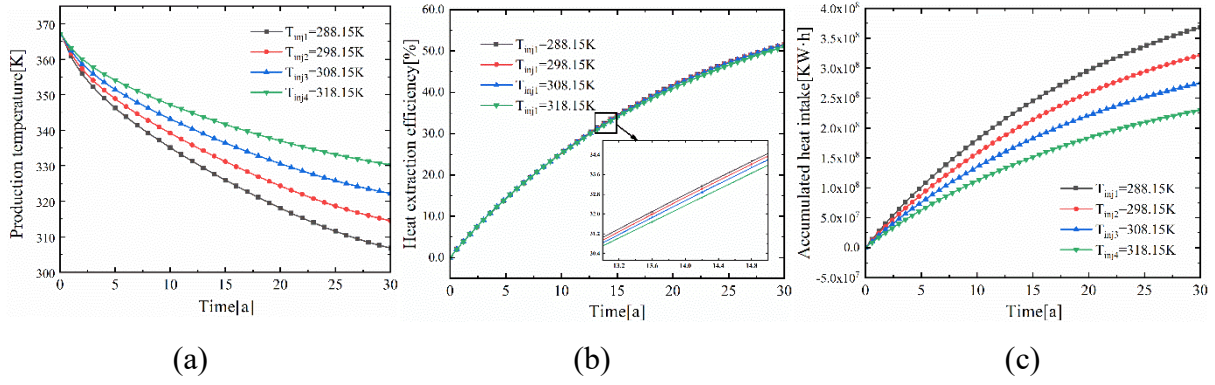


Fig. 5 Heat extraction performance of the system at different injection temperatures. (a) Plot of variation in production temperature. (b) Plot of variation in heat extraction efficiency. (c) Plot of variation in cumulative heat extraction

3.2. Parameterized analysis of injection flow rate

Based on the geothermal reforming system of waste oil and gas wells, the injection flow rates were set to 40kg/s, 50kg/s, 60kg/s, and 70kg/s to investigate the effect of different injection flow rates on the system's heat extraction performance. As shown in Fig. 6(a), the excessive injection flow rate will reduce the production temperature of the system, and the instantaneous production temperature of the production well is the lowest when the mass flow rate is 70 kg/s, which indicates that the larger the mass flow rate is, the smaller the total heat exchange duration is, making the heat exchange between the workpiece and the thermal storage reduced, and in the 30th year, the production temperature of the waste Oil and gas wells geothermal modification of waste oil and gas wells geothermal modification system corresponds to the production temperatures of 312.84 K, 306.78 K, 303.02 K, and 300.42 K, respectively. As shown in Figs. 6(b) and 6(c), when the lower mass flow rate is operated, the corresponding production temperature is higher and the service life of the geothermal reforming system for waste oil and gas wells is longer, but the transient mass heat extraction in the outflow is relatively less, and the heat extraction and heat extraction rate are relatively low, therefore, when the geothermal reforming of waste oil and gas wells is performed, the injection flow rate is set too low, which may lead to a high production temperature but the transient outflow of the heat extraction is heat extraction is low. Therefore, when setting the injection flow rate for geothermal modification of waste oil and gas wells, a series of factors such as flow rate, production temperature, and heat extraction rate can be designed to maximize the effectiveness of the heat extraction system according to the specific situation and demand.

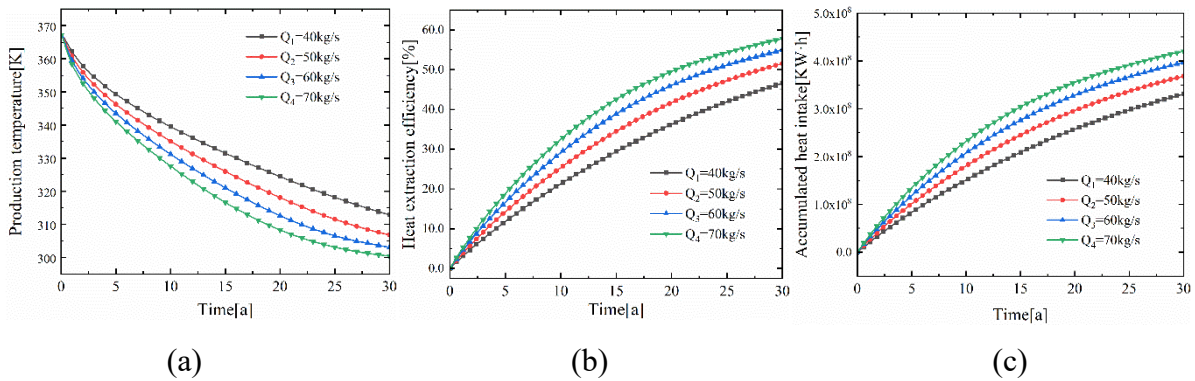


Fig. 6 Heat extraction performance at different injection flow rates. (a) Graph of production temperature variation. (b) Graph of heat extraction efficiency variation. (c) Graph of cumulative heat extraction variation

3.3. Effect of reservoir depth

In the process of geothermal retrofit of waste oil and gas wells, the depth of the reservoir can have a significant impact on the heat extraction performance of the system. Based on the geothermal reforming system for waste oil and gas wells, the reservoir depths were set to 2000 m, 2400 m, 2800 m and 3200 m to investigate the effect of different reservoir depths on the system's heat extraction performance. As shown in Fig. 7(a), there is a direct relationship between the reservoir depth and the ground temperature, and usually the ground temperature rises by 3-5 degrees for every 100 meters increase in the depth of the formation, and the production temperature of the system will gradually increase as the reservoir depth slowly increases. The corresponding production temperatures of the geothermal reforming system for waste oil and gas wells are 306.78 K, 310.39 K, 313.81 K, and 317.36 K for reservoir depths of 2,000, 2,400, 2,800, and 3,200 meters, respectively, which indicates that the conversion efficiency of geothermal energy increases with the increase of the depth of the reservoir, which increases the thermal conversion efficiency of the system. As shown in Figs. 7(b) and 7(c), deeper reservoirs also imply a larger heat storage capacity, and thus deeper reservoirs result in an increase in the cumulative heat extraction from the geothermal system, but there is no significant change in the heat extraction efficiency. In the process of geothermal modification of waste oil and gas wells, the deeper the reservoir the higher the production temperature and heat extraction rate can be obtained while ensuring the safety and stability of the system.

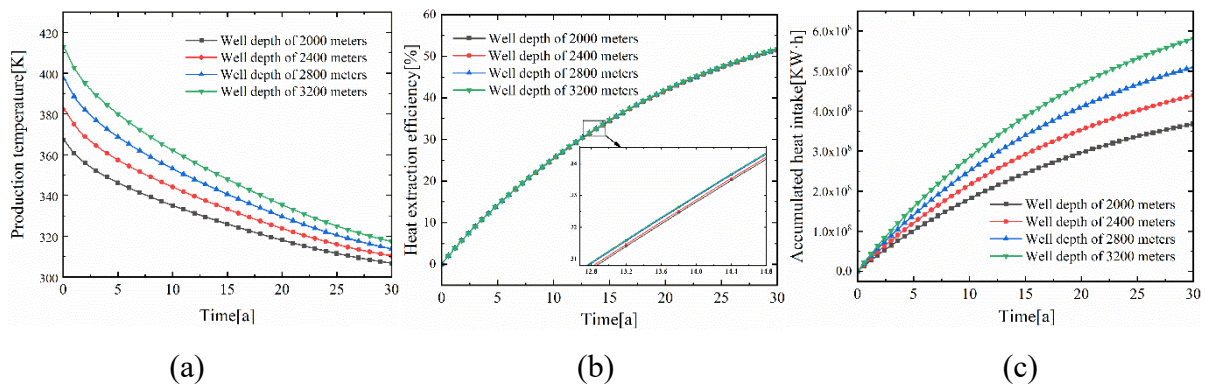


Fig. 7 Heat extraction performance of the system at different reservoir depths. (a) Variation of production temperature. (b) Variation of heat extraction efficiency. (c) Variation of cumulative heat extraction

3.4. Influence of reservoir porosity

Porosity determines the amount of fluid that can be stored in the formation and has a direct effect on the resistance to fluid flow as well as the rate of heat transfer, therefore, based on the geothermal reforming system for waste oil and gas wells, the porosities of the reservoirs were set to be 0.05, 0.1, 0.15, and 0.2, respectively, in order to study the effect of porosity on the system's performance in heat extraction. As shown in Fig. 8(a) and Fig. 8(b), when the porosity is larger, the resistance to fluid flow inside the rock is reduced, and the movement speed of the work material inside the formation increases, so that more heat can be taken away in a short period of time, increasing the production temperature and the cumulative heat extraction. As shown in Fig. 8(c), when the porosity is small, the fluid flow resistance inside the rock is larger, and the movement speed of the work material inside the formation is slower, increasing the residence time of the work material inside the formation, and improving the heat exchange efficiency between the work material and the geothermal reservoir and the heat extraction efficiency.

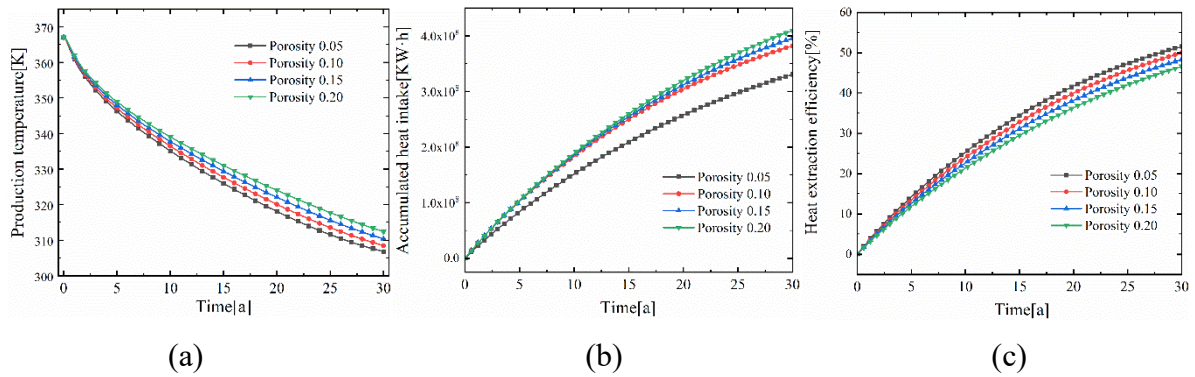


Fig. 8 Heat extraction performance of the system with different porosities. (a) Production temperature. (b) Plot of cumulative heat extraction variation. (c) Plot of heat extraction efficiency variation

4. CONCLUSION

SC-CO₂ Heat Extraction System for Geothermal Resources from Abandoned Oil and Gas Wells was established. Based on the simulation data, the effects of injection temperature, injection flow rate, well deployment method, reservoir depth and reservoir porosity on the heat extraction performance of the system were analyzed under constant injection flow rate. The results showed that:

- (1) With the injection of SC-CO₂, the temperature field gradually decreases and spreads around. The four injection and one extraction well distribution method will increase the heat extraction efficiency and production temperature of the geothermal system. Increasing the number of injection wells can increase the heat extraction rate and cumulative heat extraction, but it also enhances the cold effect and decreases the production temperature.
- (2) Increasing the injection temperature extends the operating time of the geothermal system, but results in a lower total heat withdrawal. A proper injection flow rate optimizes the system's production temperature, heat extraction efficiency and total heat extraction. Too much or too little injection flow can negatively affect system performance.
- (3) With the injection of SC-CO₂, the temperature field gradually decreases and spreads around. The four injection and one extraction well distribution method will increase the heat extraction efficiency and production temperature of the geothermal system. Increasing the number of injection wells can increase the heat extraction rate and cumulative heat extraction, but it also enhances the cold effect and reduces the production temperature.

ACKNOWLEDGEMENT

This research work was supported by the Sichuan Natural Science Foundation (24NSFSC4082).

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