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

Influences of Geological Heterogeneity on Heat Extraction from Deep High Water Cut Oil Reservoirs by Flue Gas Recycling: Insights from Numerical Simulations

Yanyong Wang, Liangjie Zhao, Xiaoguang Wang, Xiyi Peng

College of Energy, Chengdu University of Technology, Chengdu, 610059, China

State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Chengdu University of Technology, Chengdu, 610059, China

E-mail address: wangyanyong@cdut.edu.cn

Keywords: Heat mining; Oil reservoir; Flue gas; Formation heterogeneity; CO_2 storage

ABSTRACT

Heat extraction from high temperature oil reservoirs featured with high water cut is a promising way for geothermal exploitation. Heat mining via flue gas recycling is considered as an alternative way for water or CO_2 circulation. However, how permeability heterogeneity and flue gas composition impact the heat extraction efficiency are not clearly understood. In this work, heat extraction from high water cut oil reservoirs via flue gas recycling based on existing inverted five-spot well pattern is systematically investigated through geostatistical modelling and numerical simulations. The influences of horizontal autocorrelation length, global permeability heterogeneity (in terms of Dykstra-Parsons coefficient), averaged permeability, and flue gas composition on the heat extraction performance are comprehensively explored. The simulation results indicate that the increase of horizontal autocorrelation length can improve the heat mining rate to a certain degree. The enhancement of global permeability heterogeneity can obviously deteriorate the heat mining performance. High water cut oil reservoirs with a moderate mean permeability (e.g., 100 mD) may be more feasible for heat extraction via flue gas recycling. Flue gas with higher CO_2 contents is more suitable for being as working fluids for heat extraction. The findings of this research can provide meaningful guidance for the selection of feasible high temperature post waterflooded oil reservoirs for heat production via flue gas circulation.

1. INTRODUCTION

With the constant increase of global energy consumption and public trepidation about climate change, more and more attentions have been paid to the development and utilization of sustainable energy (e.g., geothermal energy) in the past decades (Li et al., 2022). Geothermal energy is a renewable source of clean and baseload energy, which is available 24/7/365. In addition, geothermal energy can work regardless of weather conditions or the day-night cycle. In comparison with geothermal energy exploitation from saline aquifer or hot dry rock, heat extraction from depleted oil/gas reservoirs through current well configuration can be more attractive from technical and economic points of view. Heat mining from depleted natural gas/condensate reservoirs have been extensively investigated in the past years and proved as a feasible way for heat mining (Zhang et al., 2017; Cui et al., 2021; Guo et al., 2021; Zhang et al., 2022). The conventional working fluids for heat extraction are water and carbon dioxide (i.e., CO_2), and CO_2 recycling can obtain a higher heat mining rate in comparison with water circulation (Wang et al., 2022). In addition, the injection of CO_2 into geothermal reservoir can also achieve its geological storage (Randolph and Saar, 2011). However, pure CO_2 injection can be very costly due to its high separation cost from flue gas. In such context, flue gas is proposed to be as a working fluid for heat mining. The injection of flue gas into enhanced geothermal systems for heat mining has been investigated (Li et al., 2020), and direct flue gas recycling has been proved as an alternative way for heat extraction. However, there are few studies about the injection of flue gas into mature oil reservoir featured water cut for heat mining. How reservoir heterogeneity and flue gas composition impact the effectiveness of heat extraction has been not clearly understood.

In this research, we firstly construct a comprehensive reservoir simulation model of heat extraction from high temperature oil reservoir with high water cut through flue gas recycling. Then, we conduct a series of numerical simulations to explore the impacts of permeability heterogeneity and flue gas composition on heat mining performance. The results outlined in this study can be of benefit to understanding the effectiveness of heat extraction by flue gas recycling and can provide some guidance for its field application in future.

2. THEORY AND APPROACH

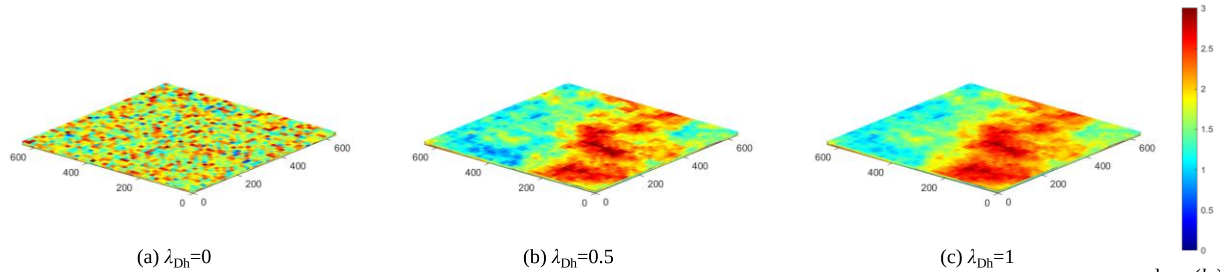
2.1 Geological modeling

In this study, a three-dimensional (3D) reservoir simulation model is constructed for subsequent numerical simulations. The reservoir model represents a typical inverted five-spot well pattern for oil production and has a physical dimension of 645 m in length, 645 m in width and 10 m in thickness. The computation domain is then discretized into a regular Cartesian grid system, with the size of each individual block of 15 m×15 m×2 m. The oil reservoir is assumed to be buried at the depth of 3000 m. The original reservoir pressure is 30 MPa at a reference depth of 3000 m, and the initial reservoir temperature is of 120℃, with a geothermal gradient of 40℃/km. The averaged permeability of the oil reservoir is of 100 mD, and the mean porosity is of 0.25. The oil reservoir is assumed to be waterflooded for several decades, and the current oil saturation is reduced to 0.16 that approaches the residual oil saturation, and the water saturation is about 0.86.

To estimate the effect of permeability heterogeneity on the heat extraction performance by flue gas circulation, we generate a series of permeability fields by utilizing geostatistical modeling method. The permeabilities of the high water cut oil reservoir are assumed to follow a log-normal distribution. In such context, the sequential Gaussian simulation method (Deutsch and Journel, 1997) is adopted to construct different synthetic permeability distributions (as shown in Figure 1). In the geostatistical modelling, an exponential variogram model is applied to corelate the spatial variability of permeability, and the nugget effect is neglected. Based on the constructed distributions of intrinsic permeability, the porosity distributions for the oil reservoir are then calculated based on an empirical correlation proposed by the Holtz (2002), given as:

$$\phi = \left(\frac{k}{7 \times 10^{7}} \right)^{1/9.61} \tag{1}$$

where ϕ denotes porosity, and k is intrinsic permeability of the reservoir.



(a) λ_{Dh}=0 (b) λ_{Dh}=0.5 (c) λ_{Dh}=1 $\log_{10}(k_h)$

Figure 1: Synthetic permeability distributions for oil reservoirs. The V_{DP}, k_v/k_h, and k_{avg} for all cases are equal to 0.63, 0.5, and 100 mD, respectively.

The heterogeneity of permeability fields is quantified by using two metrics, i.e., the dimensionless autocorrelation length (λ_D) and the Dykstra-Parsons coefficient of permeability variation (V_{DP}). λ_D is defined as the ratio of autocorrelation length (λ) over the model dimension with respect to corresponding directions. The autocorrelation length (λ) is primarily controlled by the sedimentary depositional environments and processes, which influences the spatial continuity of permeabilities. V_{DP} is a dimensionless number which is usually adopted to quantify the permeability heterogeneity, and can be defined as,

$$V_{DP} = \frac{k_{50} - k_{84.1}}{k_{50}} \tag{2}$$

where k_{50} refers to the permeability at which 50% portion of total samples have higher permeabilities, and $k_{84.1}$ represents permeability at which 84.1% portion of total samples have higher permeabilities.

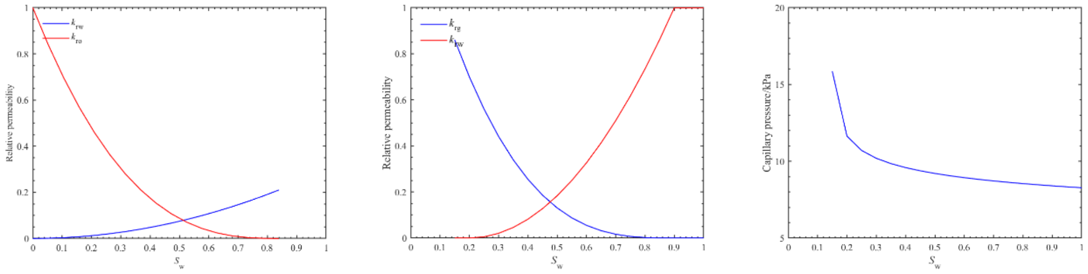
To explore the influence of permeability heterogeneity on heat extraction performance, we design 5 representative permeability fields for numerical simulation, and the parameter settings for different cases are listed in Table 1.

Table 1 Geological conditions for different permeability fields.

Case no.	$\lambda_{Dx}\times\lambda_{Dy}\times\lambda_{Dz}$	V_{DP}	k_{avg} (mD)	k_v/k_h
1	0×0×0	0.63	100	0.5
2	0.5×0.5×0	0.63	100	0.5
3	1×1×0	0.63	100	0.5
4	0.5×0.5×0	0.39	100	0.5
5	0.5×0.5×0	0.78	100	0.5
6	0.5×0.5×0	0.63	50	0.5
7	0.5×0.5×0	0.63	200	0.5

2.2 Numerical model set-up

In the simulation model, the reservoir fluids are composed of free gas, oil and formation water, and the phase behavior is modeled by using K-values. In flow simulations, the subsurface flow for three different phases is assumed to follow Darcy's law, and the relative permeability curves and capillary pressure curves adopted are given in Figure 2, and for three phase flow, the relative permeability for oleic phase is calculated according to Stone II model. The boundaries of the oil reservoir are fully close to flow in both horizontal and vertical directions. The heat loss to the overburden and underburden layers is taken into account in the simulation model. The simulation model is solved by a conventional reservoir simulator.



(a) water oil relative permeability curves (b) water oil relative permeability curves (c) capillary pressure curve

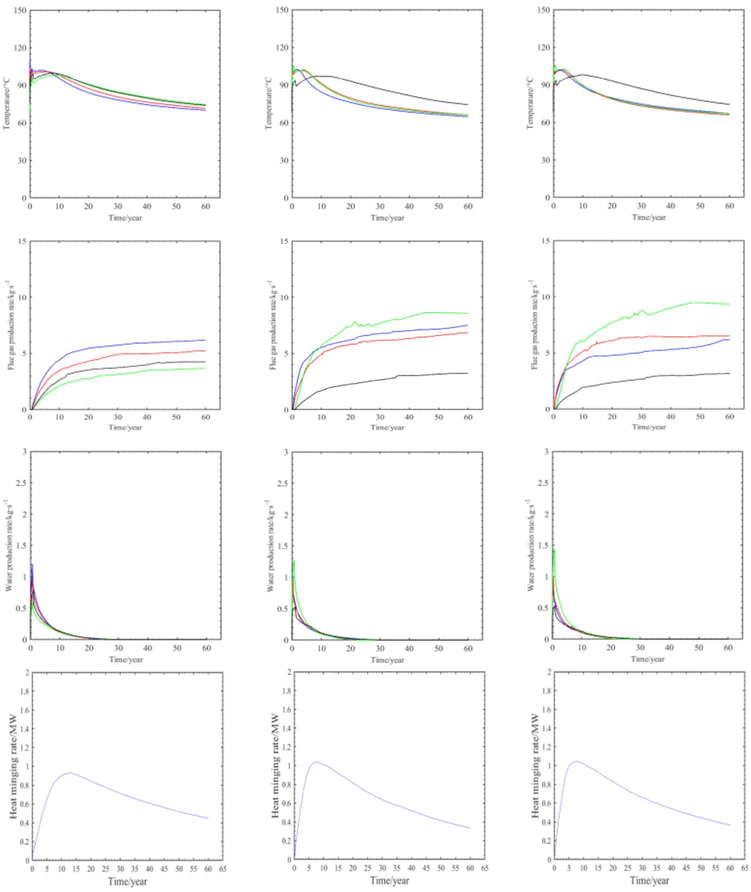
Figure 2: Relative permeability curves and capillary pressure curves adopted in the simulation model.

The heat extraction process is conducted based on the existing inverted five-spot well pattern. In the heat mining process, cold flue gas is continuously injected into the hot oil reservoir, and the injection of flue gas is constrained by a constant bottomhole pressure of 32 MPa. The flue gas injected has a temperature of 60℃, and the contents of CO_2 and N_2 in flue gas are assumed to be of 40% and 60%, respectively. Hot fluids are produced through the four production wells, which are constrained using the same bottomhole pressure of 29 MPa. The production fluids are pumped to the heat exchanger at surface and the flue gas is then separated from the production fluids and reinjected into the high water cut oil reservoir.

3. RESULTS AND DISCUSSION

3.1 Effect of autocorrelation length

To explore the impacts of horizontal autocorrelation length of permeability field on the heat mining performance via flue gas recycling, we conduct three different numerical simulation with λ_{Dh} of 0, 0.5, and 1. The dynamic profiles of the surface temperature of production fluids, production rates and heat mining rate are presented in Figure 3. From the upper panel pictures in Figure 3, we can see that the surface temperature of production fluids for oil reservoirs with uncorrelated permeability fields (i.e., λ_{Dh}=0) follows the same downward trend. For high water cut oil reservoirs with correlated permeability fields, the dynamic variation of the surface temperature of production fluids shows different trends. In addition, the increase of autocorrelation length imposes an obvious influence on the production rates of flue gas and formation water, and in such contexts, the heat extraction is accelerated and the peak heat mining rate is elevated to a certain degree.

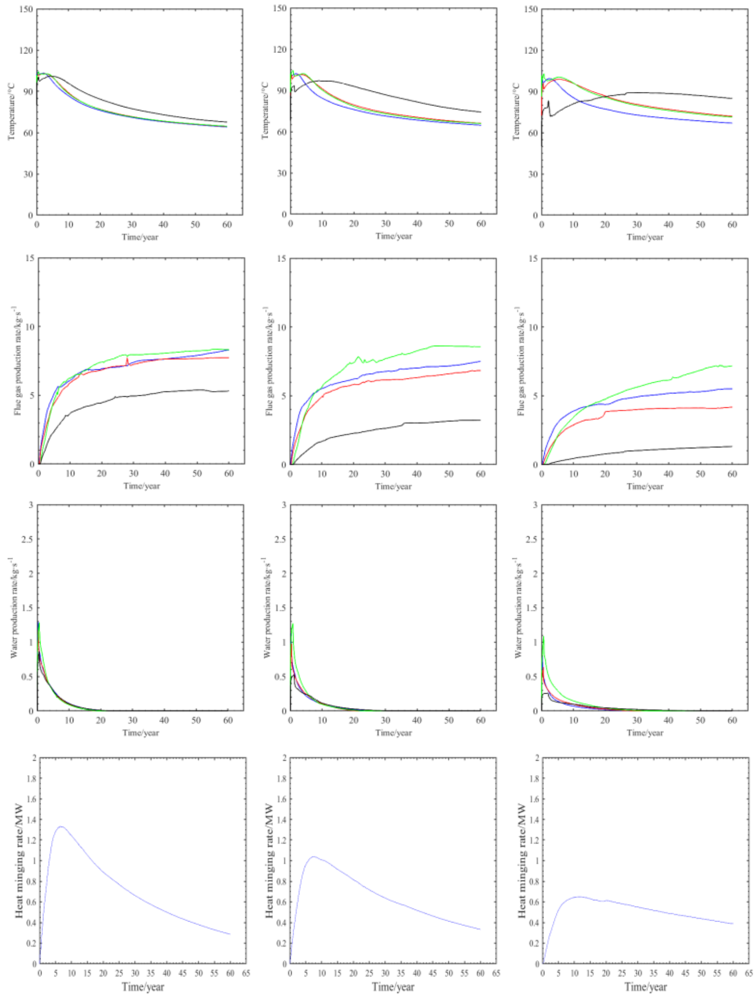


(a) λ_{Dh}=0 (b) λ_{Dh}=0.5 (c) λ_{Dh}=1

Figure 3: The temporal evolution of heat mining performance by flue gas recycling with the influence of horizontal autocorrelation length. The V_{DP}, k_v/k_h, and k_{avg} for all cases are equal to 0.63, 0.5, and 100 mD, respectively. The dynamic profiles of the four production wells are represented by curves with different colors in the upper three panels.

3.2 Effect of global permeability heterogeneity

We investigate the effect of global permeability heterogeneity on the heat mining performance of flue gas recycling in high water cut oil reservoirs. The permeability field with V_{DP} of 0.39 represents oil reservoir of low degree of heterogeneity, while permeability field with V_{DP} of 0.78 represents oil reservoir with high degree of heterogeneity. The dynamic profiles of the surface temperature of production fluids, production rates and heat mining rate are given in Figure 4. It can be seen that, with the increase of global permeability heterogeneity (i.e., the value of V_{DP}), the production rates of flue gas and formation water have been effectively deteriorated, and the difference of the dynamic temperature profile among different producers are enlarged. The reduction of fluids production can prohibit the decrease of surface temperature of production fluids. The heat mining rate is obviously reduced with the increase of global reservoir heterogeneity. Therefore, high water cut oil reservoirs with a severe permeability heterogeneity (e.g., V_{DP} of 0.78) are not feasible for heat extraction via flue gas recycling.

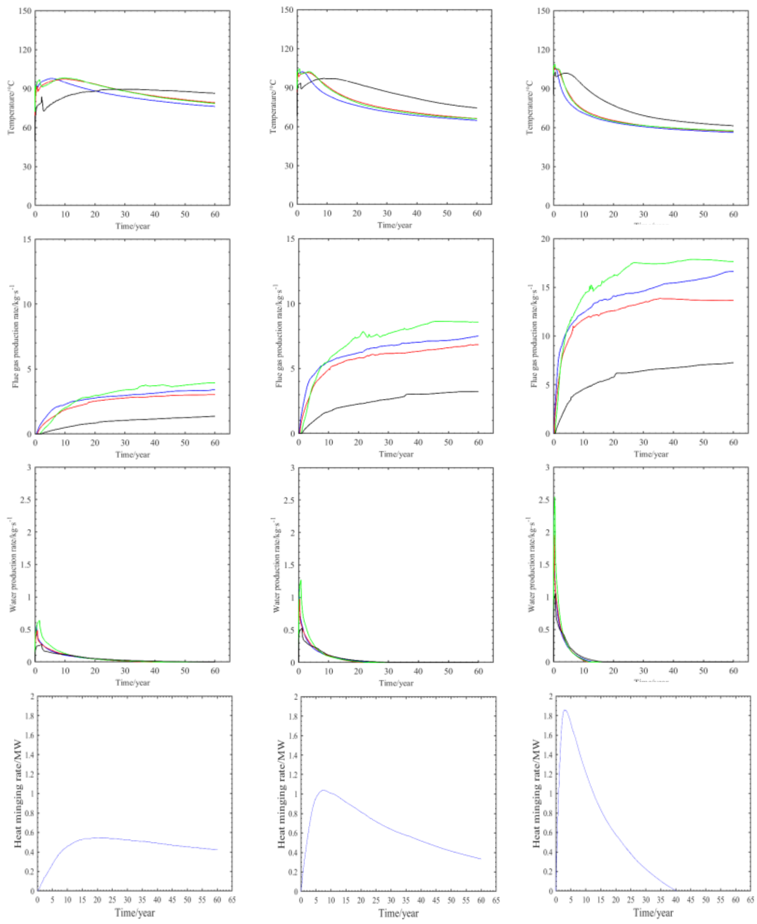


(a) V_{DP}=0.39 (b) V_{DP}=0.63 (c) V_{DP}=0.78

Figure 4: The temporal evolution of heat mining performance by flue gas recycling with the influence of global permeability heterogeneity. The λ_{Dh}, k_v/k_h, and k_{avg} for all cases are equal to 0.5, 0.5, and 100 mD, respectively. The dynamic profiles of the four production wells are represented by curves with different colors in the upper three panels.

3.3 Effect of mean permeability

To examine the influence of mean permeability of oil reservoir on the heat mining performance by flue gas circulation, we conduct numerical simulations by utilizing three high water cut oil reservoirs with different mean permeabilities. The dynamic profiles of the surface temperature of production fluids, production rates and heat mining rate are shown in Figure 5. With the increase of reservoir permeability, the production rates of hot fluids can be effectively enhanced, but when the average permeability reaches 200 mD, the surface temperature of the production fluids are dropped to a very low level that approaches the temperature of injection fluids. For oil reservoir with k_{avg} of 50mD, the heat mining rate can be maintained at a certain level. As for oil reservoirs with k_{avg} of 200mD, the heat mining rate firstly rises to the peak quickly in the early years and then drop to a very low level. In such condition, high water cut oil reservoirs with moderate averaged permeabilities (e.g., 100 mD) will be more beneficial to the heat mining process by flue gas recycling. When the mean permeability of oil reservoirs is larger than 200 mD, the heat mining process may be unable to be maintained at a sustainable level.



(a) k_{avg}=50 mD (b) k_{avg}=100 mD (c) k_{avg}=200 mD

Figure 5: The temporal evolution of heat mining performance by flue gas recycling with the influence of mean permeability. The λ_{Dh}, V_{DP}, and k_v/k_h for all cases are equal to 0.5, 0.63, and 0.5, respectively. The dynamic profiles of the four production wells are represented by curves with different colors in the upper three panels.

3.3 Effect of flue gas composition

In the field application, the composition of flue gas that comes from different sources (e.g., the extent of CO_2) may vary over a very broad range. To understand the influence of flue gas composition on the heat mining performance, we carry out numerical simulations using flue gas with four typical composition scenarios. The dynamic profiles of the surface temperature of production fluids, production rates and heat mining rate are given in Figure 6. With the increase of CO_2 content, the production rates of flue gas for different producers are enhanced significantly, as a result of which, the decrease of the surface temperature of production fluids is accelerated. In addition, the heat mining rate is improved evidently. Therefore, it is recommended that flue gas with a higher CO_2 content is more suitable for heat extraction from high water cut oil reservoirs.

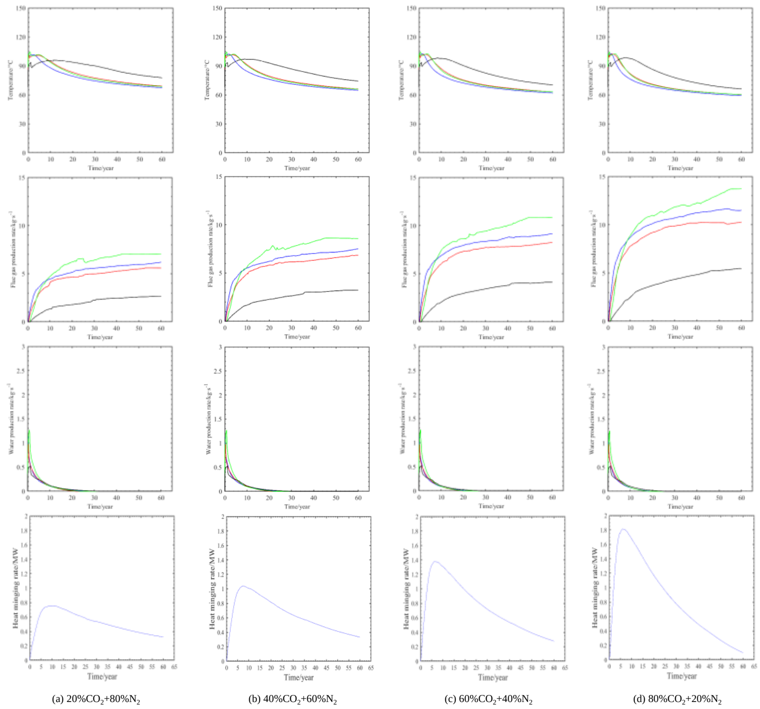


Figure 6: The temporal evolution of heat mining performance by flue gas recycling with the influence of flue gas composition. The λ_{Dh}, V_{DP}, k_v/k_h, and k_{avg} for all cases are equal to 0.5, 0.63, 0.5, and 100 mD, respectively. The dynamic profiles of the four production wells are represented by curves with different colors in the upper three panels.

4. CONCLUSIONS

In this study, heat extraction from high water cut oil reservoirs by flue gas recycling is investigated by numerical modeling. The effects of horizontal autocorrelation length, global permeability heterogeneity, mean permeability and flue gas composition are explored and quantified. The findings drawn from numerical simulation results can be concluded as follows,

(1) The increase of horizontal autocorrelation length can improve the heat mining rate to a certain degree, and the enhancement of global permeability heterogeneity (in terms of V_{DP}) will obviously deteriorate the heat mining performance.

(2) High water cut oil reservoirs with moderate averaged permeabilities (e.g., 100 mD) will be more beneficial to heat mining process by flue gas recycling. When the mean permeability of oil reservoirs is larger than 200 mD, the heat mining process may be unable to be maintained at a sustainable level.

(3) Injection of flue gas with a higher CO_2 content is more suitable for heat extraction from high temperature oil reservoirs featured with high water cut.

ACKNOWLEDGEMENT

The authors are grateful for the financial support from National Natural Science Foundation of China (Grant No. 52192622) and Science & Technology Department of Sichuan Province (Grant No. 2021ZYCD004).

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