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Research Article

Study on the Variation of Crude Oil and Flue Gas Components in Flue-Gas-Assisted Steam Flooding

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In heavy oil development, flue-gas-assisted steam flooding can not only improve oil recovery but also reduce carbon emissions and realize the resource utilization of flue gas. In this paper, the variation in crude oil components produced by steam flooding and flue-gas-assisted steam flooding was studied by indoor displacement experiments and component determination, and the production properties of different components in flue gas, and the influence of flue gas proportion on residual oil components was explored. The results indicate that flue gas can enhance distillation and the production of light components in the steam flooding process. When the ratio of flue gas to steam ranges from 1 : 1 to 3 : 1, the larger the proportion of flue gas injection is, the larger the scope of steam thermal sweep is, the stronger the steam distillation effect is, and the greater the content of light components in residual oil and the change value of each component at the outlet and inlet are. Due to the difference in the dissolution of N_2 and CO_2 in heavy oil, at the early stage of displacement, the retention rate of CO_2 in the formation in the early stage of displacement was higher, and the proportion of CO_2 output was lower than the initial injection proportion. With the progress of displacement, the proportion of CO_2 gradually increased, and the proportion of N_2 gradually decreased. After gas channeling occurs, the N_2 proportion increases and gradually approaches the injection proportion. The dissolution and precipitation of flue gas contribute to the formation of foam oil and improve the flow and production of crude oil. The research results are helpful to further understand the mechanism of flue-gas-assisted steam flooding and provide a theoretical basis for the improvement of this technology.

1. Introduction

With the improvement of global industrialization and the sharp increase in greenhouse gases, reducing CO_2 emissions has become a guide for the development of all countries [1–3]. Petroleum, natural gas, and other fossil fuels as the world's main energy source will continue for nearly half a century, and the CO_2 produced by fossil fuel combustion exceeds 2/3 of the total emissions [4–6]. At present, to alleviate the greenhouse effect caused by CO_2 emissions, CO_2 capture, utilization, and storage (CCUS) have attracted great attention in various fields, especially geology and oil and gas development [7–10]. The application of CO_2 in crude oil development can not only realize carbon sequestration but also effectively improve oil recovery [11–15].

Globally, heavy oil is abundant and widely exploited. In the future, the exploitation of heavy oil will occupy a dominant position in oil and gas development [16–18]. However, heavy oil is developed by thermal recovery, which requires a large amount of fossil fuels to produce steam, and the boiler produces a lot of flue gas containing greenhouse gases, aggravating the greenhouse effect, which is contrary to today's economic and green development concept. Recently, many researchers have found that the synergistic displacement of flue gas and steam can greatly improve the production of heavy oil [19–22]. Moreover, the direct recovery and utilization of the flue gas generated by the boiler avoid the complex CO_2 treatment process and save the cost of steam injection. It is an essential path for the oil field to carry out CO_2 capture, utilization, burial, and economic development of heavy oil.

Since the discovery of the application potential of flue gas, the oil displacement mechanism of flue-gas-auxiliary steam injection has attracted much attention. However, due to the large injection components in flue-gas- auxiliary steam flooding, the mechanism is very complex. High-temperature steam can decrease the viscosity of crude oil and improve the fluidity of crude oil [23–25]. The main components of flue gas are N_2 and CO_2. N_2 can compensate for the formation energy deficit, maintain reservoir pressure, and increase the oil production rate [26]. CO_2 dissolved in heavy oil can affect the volume and viscosity of heavy oil and facilitate its expansion and overflow [27–31]. At the same time, CO_2 can gasify the light components in crude oil to decrease the interfacial tension and realize miscible flooding [32–35]. Wu et al. [36] explored the influence of gas on steam flooding by using the 2D visualization model, and found that in the displacement process, injected gas formed bubbles in the pore throat of the model and the Jamin effect occurred. At the same time, the gas reacted with heavy oil to improve the macrosweep area and displacement efficiency [37, 38]. Lu et al. [39] explored the influence of flue gas on steam heat dissipation characteristics by using cold condensate with a thermocouple and found that flue gas can reduce the heat dissipation rate of steam in the formation, strengthen steam seepage to the deep oil region, and expand the expansion range of the steam chamber. Although the understanding of the mechanism of flue-gas-assisted steam flooding is still deepening and improving, there are few studies on the influence of flue-gas-assisted steam flooding about the properties of crude oil, distillation, and retention characteristics of flue gas in the formation.

The change in crude oil and gas composition can directly reflect the change law of crude oil properties, the strength of distillation, and the migration characteristics of flue gas in the process of the displacement and deeply clarify the role of flue gas in strengthening steam flooding. Therefore, it is necessary to conduct research on the variation law of crude oil and gas components in this displacement. In this paper, the 1D sandpack simulation experiments of steam flooding and flue-gas-assisted flooding were carried out. In the experiment, the composition changes of heavy oil output at different periods of the two displacement patterns are compared and analyzed. The law of flue gas retention was studied by recording the gas production characteristics in the process of flue-gas-assisted steam flooding. Furthermore, the compositional changes of residual oil in flue-gas-assisted steam flooding under different flue gas-steam ratios were studied, and the effect of the flue gas ratio on steam distillation was analyzed. These findings are of extreme importance to improve the oil displacement mechanism of flue-gas-assisted steam flooding and improve its field application effect.

2. Experimental Section

2.1. Materials. The flue gas used in the experiments was prepared by hand and was a compound of N_2 and CO_2 in molar ratios of 80% and 20%, and N_2 and CO_2 with a purity of 99.9 mol% were produced from Tianyuan, Inc., China. The crude oil used in the experiment was sampled from the Cao 20 block of Shengli Oilfield, China. The viscosity-temperature curve of the crude oil is shown in Figure 1, and the viscosity of dehydrated crude oil was 5170 mPa·s at 50.0°C. The saturated content of crude oil is 41.36 wt%, the aromatic content is 21.38 wt%, the resin content is 36.8 wt%, and the asphaltene content is 0.46 wt%. The water used to generate steam during the experiment was distilled water, which was produced by the distillation method, and the resistivity was 15 MΩ·cm. The 1D displacement model in the experiment was filled with a certain mesh of quartz sand. To ensure that the permeability of the sandpacks was between 3200 mD and 3400 mD, the model was filled with 80 mesh and 110 mesh quartz sand at 1 : 1. The specific dimensional data of the model are shown in Table 1.

2.2. Apparatus. The main contents of the experiment are a physical simulation experiment and the determination of crude oil components. The flow chart of displacement experiment is shown in Figure 2, which included mainly a steam generator, ISCO pump, gas mass-flow controller, sandpack model, intermediate container, pipeline heating belt, check valve, and back-pressure regulator (PBR). ISCO pumps (Model 100DX, Teledyne Co., Ltd., USA) provided power for flooding and controlled the injection rate of steam, heavy oil, and water with an accuracy of ±0.001 mL. The steam generator (model GL-1, Haian Petroleum Equipment Company) produces steam at a rate consistent with the rate at which distilled water is injected through the pump, the temperature range of the generated steam was 100-350°C, and its maximum pressure resistance was 25 MPa. The gas injection rate was controlled by a gas flowmeter (model Sla5861, Brooks, USA). The number of gas mass-flow controllers was the flow rate under standard conditions, which needed to be converted according to the experimental conditions. The sandpack model (Model 304, Nantong Research Instrument Co., Ltd) had a pressure resistance of 40 MPa and a temperature resistance of 300°C, with a length and an inner diameter of 60 cm and 2.54 cm, respectively, and was wrapped with a temperature-controlled heating sleeve. The check valve was set before the outlet of the gas mass-flow controller to prevent liquid backflow and damage to the gas flowmeter.

2.3. Experimental Procedures

2.3.1. Experimental Procedure of Displacement

(1) The sandpack model was prepared; the sandpack was filled with mixed quartz sand after ensuring that the airtightness of the sandpack was good

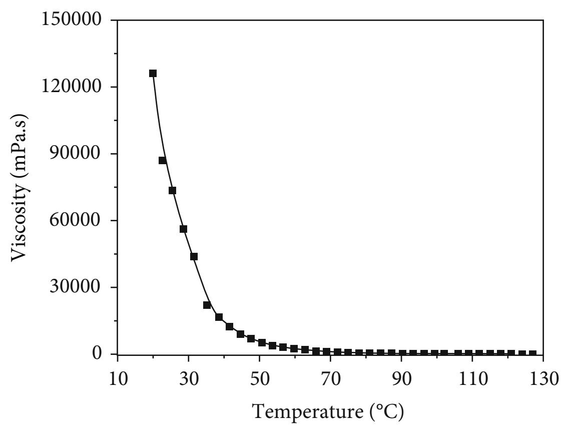


Figure 1: Viscosity-temperature curve.

(2) The sandpack was saturated with water after vacuum-pumping for 4 h; then, its porosity was calculated according to the weight difference. The water flooding was carried out and the permeability of the model was determined by the Darcy equation

(3) The sandpack was heated by the heating sleeve to a preset initial temperature of 60°C. After the model reached the set temperature, the sandpack was saturated with heavy oil at a rate of 0.5 mL·min^{-1}. The sandpack was placed in a 60°C environment for 24 h aging after it was saturated with crude oil

(4) The steam generator was set at 300°C for preheating, during which distilled water was injected continuously until the steam generator produced stable steam

(5) The displacement experiments were carried out after ensuring the complete connection of the experimental devices. The back pressure was set at 2 MPa. According to the experimental scheme, the injection ratio of flue gas/steam was set as 1 : 1, 2 : 1, and 3 : 1, and the exact injection rates of flue gas and steam are shown in Table 1. When the temperature and pressure reached stability, and the water content in the output liquid exceeded 98%, it was regarded as the end of displacement

(6) During displacement, the production characteristics of flue gas, crude oil, and water were recorded. After displacement, the oil sand in the sandpack was dug out, placed according to the position, photographed, and sampled for analysis

(7) Four components of produced oil and residual oil in oil sand were measured

(8) The experimental equipment was cleaned and sorted, and steps (1)–(6) were repeated for the next experiment

2.3.2. Determination of Four Components of Heavy Oil. The four components of heavy oil include saturates, aromatics, resins, and asphaltenes, and their content determination procedures refer to NB/SH/T 0509-2010.

(1) The heavy oil was dissolved with n-heptane, placed in the dark, and allowed to settle for 1 h. After filtration, n-heptane was used for reflux in the precipitate to obtain the insoluble and soluble fractions

(2) For the insoluble fraction, toluene that could dissolve the insoluble fraction was added and refluxed for more than 1 h or until the droplets were colourless. Then, asphaltenes were obtained by steaming out toluene

(3) The soluble fraction was adsorbed on the aluminium oxide chromatographic column. The desorbed substance obtained by washing with n-heptane was saturated, while the remaining adsorbed substance was washed with toluene and toluene-ethanol in turn. The desorbed substances were aromatics and resins. The determination flow chart of the four-component contents is shown in Figure 3

3. Results and Discussion

3.1. Variation Characteristics of Recovery and Displacement Pressure Difference. Since oil recovery could directly reflect the quality of displacement and the change in displacement pressure difference could reflect the flow characteristics of heavy oil in the process of displacement from the side, the differences between steam flooding and flue-gas-assisted steam flooding were compared on oil recovery and pressure difference. The experimental data are from experiments #1 and #2 in Table 1.

Figure 4 depicts the variation in crude oil recovery and displacement pressure difference with injection volume in steam flooding and flue-gas-assisted steam flooding. The change trends of the recovery factor and flooding pressure difference under the two displacement patterns are roughly similar. The crude oil is pushed by piston propulsion at the beginning of displacement. With the increase in injection volume, oil recovery factor increases rapidly, and the displacement pressure difference increases continuously. In the middle and late stages of displacement, due to the formation of high-permeability channels, the growth rate of crude oil recovery began to slow down and gradually stabilized, and the displacement differential pressure also began to decline rapidly. The recovery factor of steam flooding is 62%, and the recovery factor of flue-gas-assisted steam flooding is 72%, which is approximately 10% higher than the recovery factor of steam flooding. The maximum flooding pressure difference of flue-gas-assisted steam flooding is 2.75 MPa, lower than 1.91 MPa of steam flooding, although the addition of flue gas increases the equivalent volume of injected fluid, the displacement differential pressure decreases to a certain extent.

There are three main reasons for the higher displacement efficiency and lower pressure of flue-gas-assisted steam

Table 1: Displacement experimental parameters.

Test no.	Flooding pattern	Initial temperature of sandpack (°C)	Porosity (%)	Permeability (mD)	Injection rate ($mL\cdot min^{-1}$) Steam	Injection rate ($mL\cdot min^{-1}$) Flue gas
#1	Steam flooding	60	35.86	3350	1	0
#2	Flue-gas-assisted steam flooding	60	33.66	3260	1	1
#3	Flue-gas-assisted steam flooding	60	33.56	3210	1	2
#4	Flue-gas-assisted steam flooding	60	33.72	3286	1	3

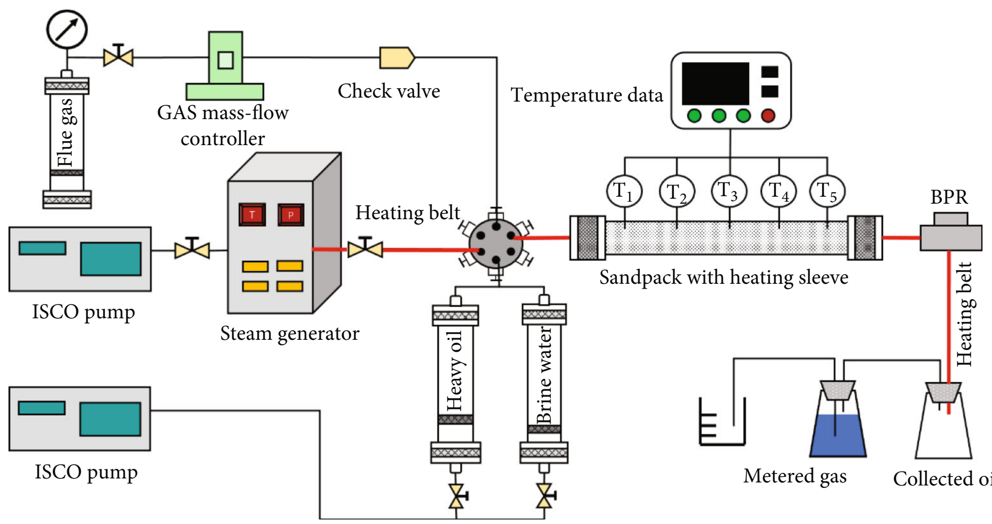


Figure 2: Flow chart of displacement experiment.

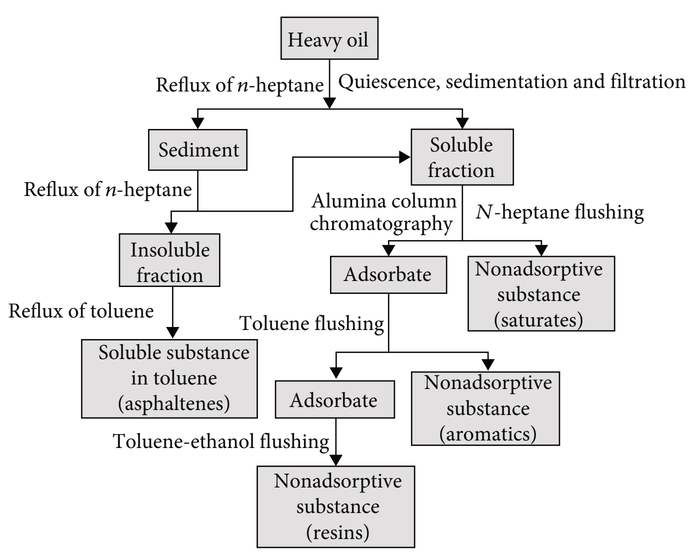


Figure 3: Flow chart of the four-component determination of heavy oil.

flooding: Flue gas dissolves in crude oil, which can reduce crude oil viscosity to a certain extent and improve crude oil fluidity. The high seepage capacity of flue gas can open up channels for the flow of steam and reduce the flow resistance. More importantly, flue gas, as the noncondensable gas, is able to enrich on the surface of low-temperature objects, increasing the heat transfer resistance of steam to low-temperature objects and thus inhibiting steam condensation [40], which expands the steam heat swept volume and thick oil flowable area.

3.2. Composition Variation Properties of Produced Crude Oil. Among the four components of crude oil, the saturates and aromatics can be equivalent to the solvent in crude oil. The

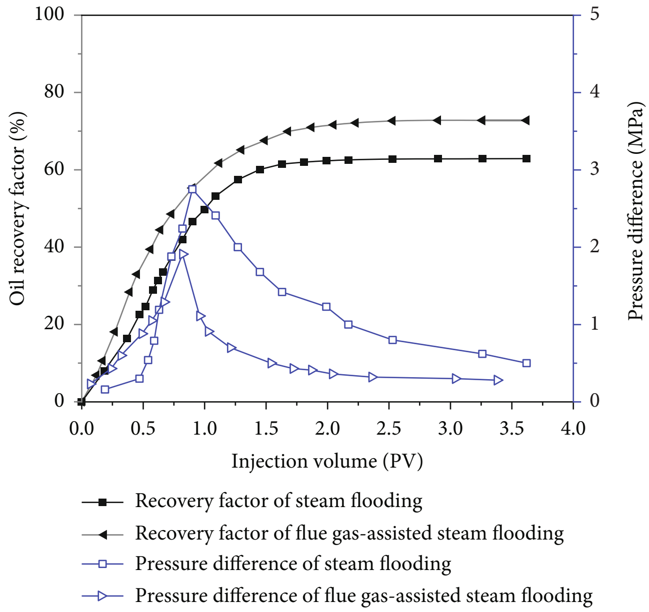


Figure 4: Variation curve of crude oil recovery and displacement pressure difference with injection volume.

Table 2: Four-component content data of produced crude oil.

Displacement pattern	Sampling stage	Saturate content (wt%)	Aromatic content (wt%)	Resin content (wt%)	Asphaltene content (wt%)
/	Initial sample	41.36	21.38	36.8	0.46
Steam flooding	Before water channeling	46.24	21.51	31.82	0.43
	After water channeling	43.53	21.18	34.56	0.73
Flue-gas-assisted steam flooding	Before gas channeling	47.71	21.8	30.08	0.41
	Before water channeling	45.46	21.49	32.56	0.49
	After water channeling	43.91	21.40	34.04	0.65

higher the content is, the better the flow performance of crude oil, the lower the friction resistance between fluids and the smaller the viscosity. As polar substances in crude oil, resins and asphaltenes not only have an important impact on the pour point reduction of crude oil but also make an important contribution to the relative molecular weight and viscosity of crude oil. The experimental data in Table 2 in this section are from experiments #1 and #2 in Table 1. According to the gas and water breakthrough of the collected liquid, steam flooding was divided into two stages before and after water channeling, and flue-gas-assisted steam flooding was divided into three stages: before gas channeling, before water channeling, and after water channeling. Samples were taken in different stages of two groups of displacement experiments, and 2-3 samples were taken in each stage to determine the saturated, aromatic, resin, and asphaltene content of each sample. The measurement was repeated three times, and the average value was selected.

Figure 5 shows the comparison of four components of crude oil produced in steam flooding. During the whole displacement process, compared with the initial oil sample, the content of saturates and aromatics of the produced crude oil is higher, the content of resins is lower, and the content of asphaltenes is lower than the initial oil sample before water channeling and higher than the initial oil sample after water channeling. Compared with the two stages before and after water channeling, the saturated and aromatic content decreased by 2.71 wt% and 0.33 wt%, respectively, and the total content of resins and asphaltenes increased after water channeling because in the process of flooding, light components with low viscosity and strong fluidity are extracted first. After the formation of the hyperosmotic channel, the content of light components that flow easily decreases, and

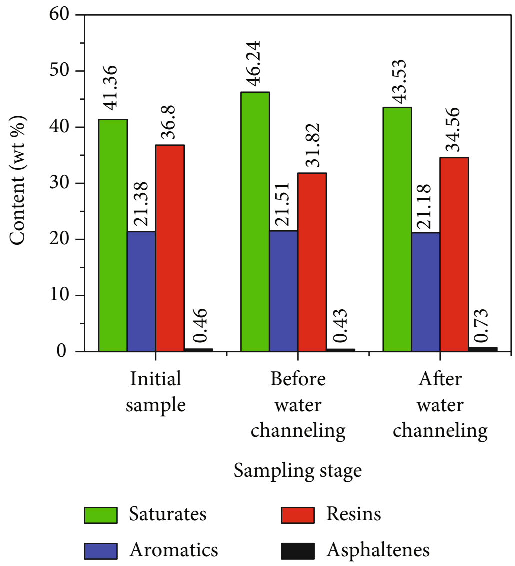


FIGURE 5: Comparison of four components of crude oil produced during steam flooding.

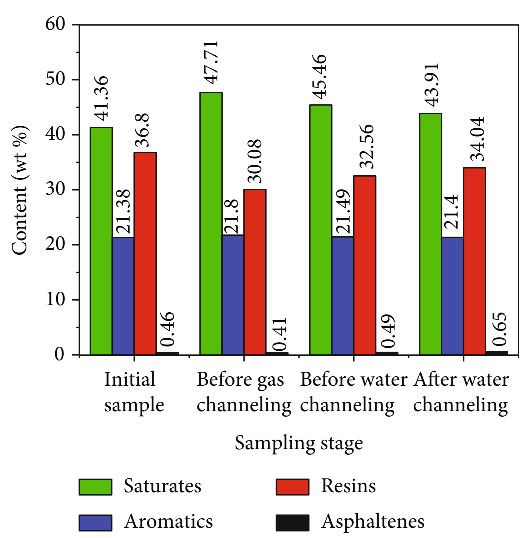


FIGURE 6: Comparison of four components of crude oil produced during flue-gas-assisted steam flooding.

the heavy components that flow with difficulty are gradually extracted under the scraping and scouring of fluid. Therefore, in the later stage of steam flooding, the produced crude oil contains less light components and more heavy components.

Figure 6 shows the comparison of four components of heavy oil produced during the process of flue-gas-assisted steam flooding. It is easier to produce light components under distillation of steam, and the content of saturated and aromatic components of the crude oil is higher than the content of saturated and aromatic components of the initial oil sample in the process of steam flooding and flue-gas-assisted steam flooding. In the process of flue-gas-assisted steam flooding, because the mobility of gas is greater than the stability of steam, gas channeling will occur before

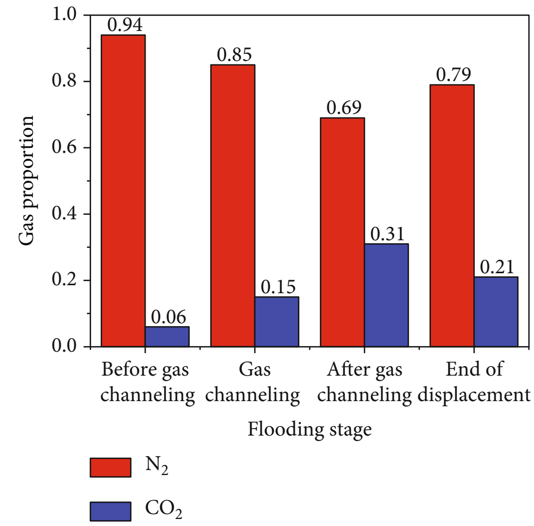


FIGURE 7: Comparison of gas components produced in different displacement stages.

the collected liquid meets water. The light component content of crude oil before gas channeling is slightly higher than that before water channeling, while the content of resins and asphaltenes is slightly lower because the flue gas has a certain solubility in crude oil. This is due to the process of gas dissolution and precipitation before gas channeling; more light components are brought to the outlet section and recovered. Comparing the two displacement patterns, the proportion of light components of oil produced by flue-gas-assisted steam flooding is higher than the proportion of light components of oil produced by steam flooding. In the process of flue-gas-assisted steam flooding, the maximum saturated hydrocarbon content is 47.71 wt%, which is 1.5% higher than the maximum saturated hydrocarbon content of steam flooding. The reason for this phenomenon is that flue gas can not only expand the transmission distance of heat carried by steam but also strengthen the distillation of steam on crude oil in the process of displacement and promote the precipitation and stripping of light components in crude oil.

3.3. Gas Production Properties. After the flue gas and steam are injected into the sandpack together, there are complex interactions between flue gas and oil, such as multiphase flow, gas dissolution and diffusion, and gas retention, which have an important impact on enhanced oil recovery (EOR). Therefore, the gas production law and composition change of produced gas were studied, and the influence and mechanism of gas on EOR were analyzed. The experimental data in this section are from experiment #2 in Table 1. Based on the fluid production characteristics of gas, the whole displacement process can be classified into four stages, as shown in Figure 7: before gas channeling, gas channeling, after gas channeling, and at the end of displacement.

Figure 7 presents the variation of gas components produced in each displacement stages. The proportions of N_2 and CO_2 before gas channeling are 0.94 and 0.06, respectively, and the proportions of N_2 and CO_2 in gas channeling

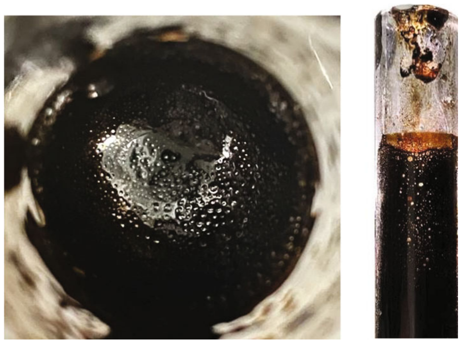


Figure 8: Foam form of produced oil.

are 0.85 and 0.15, respectively. After gas channeling, the proportions of N_2 and CO_2 are 0.69 and 0.31, respectively, and the proportions of N_2 and CO_2 are 0.79 and 0.21, respectively, at the close of displacement. In the early stage of displacement, the proportion difference between N_2 and CO_2 is easily found to be the largest because the solubility of CO_2 in heavy oil is better than the solubility of N_2. Most of the CO_2 in the beginning of displacement is dissolved in crude oil and retained in the sandpack model, resulting in a higher proportion of N_2 output. With the progress of displacement, the proportion of N_2 gradually decreases, and the proportion of CO_2 gradually increases. The analysis shows that the occurrence of gas channeling will lead to a sharp drop in pressure and energy deficit in the model. At this time, CO_2 dissolved in crude oil gradually precipitates, and the output proportion increases; N_2 is used mostly to fill the pores and supplement the energy of the oil layer, and the output proportion decreases. At this time, the proportion of output N_2 is lower than its injection proportion, and as the displacement progresses, the hypertonic channel is well developed and gradually reaches a stable state, during which the proportion of output gas gradually converges to that of injection gas, and thus there is a trend of increasing the proportion of N_2 at the end of the displacement.

The above analysis and comparison illustrate that flue gas can combine the advantages of N_2 and CO_2, which can not only reduce the viscosity of crude oil but also supplement model/formation energy. The dissolution and precipitation of flue gas can enhance the interaction between displacement media and crude oil and effectively promote the formation of foam oil, as presented in Figure 8.

Figure 9 depicts the retention characteristics of flue gas during flue-gas-assisted steam flooding. The flue gas retention rate refers to the ratio of the volume of flue gas trapped in the oil layer/sandpack to the total volume of flue gas injected. With the increase in injection volume, the injection and production rates of flue gas increase first and then decrease sharply, but the peak value of the flue gas production rate increases by 6.33 mL/min compared with the injection rate. The appearance of the peak value lags behind the injection rate by 0.11 PV. The retention rate of flue gas decreased slowly in the early stage, which is due mostly to the dissolution of CO_2 in flue gas. When the peak gas generation rate appears, flue gas retention rate drops sharply and then gradually stabilizes, remaining at 21-23%. The occurrence of gas channeling greatly worsens the retention effect of flue gas, which can only be dissolved in the residual oil or fill the pores in the sandpack.

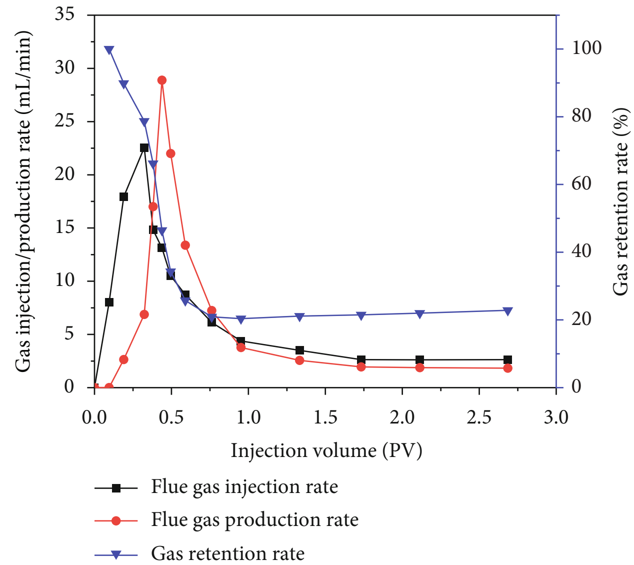
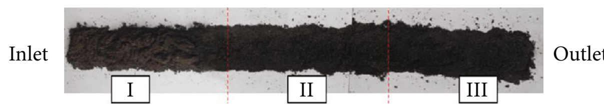


Figure 9: Volume variation of produced gas in flue-gas-assisted steam flooding.

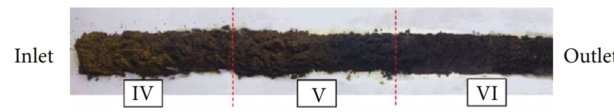
3.4. Effect of Flue-Gas Ratio on Residual Oil Composition. Steam distillation is crucial to enhance the development effect of heavy oil. Combined with 3.2, distillation can be seen to occur in the development process of flue-gas-assisted steam flooding. Therefore, a four-component analysis of oil sand after displacement is performed to explore the influence of the flue gas ratio to steam distillation. The experimental data in this section are from experiments #1, #2, and #3 in Table 1.

Figure 10 shows the distribution of oil sand in the one-dimensional sandpack model after flue-gas-assisted steam flooding. The colour of the oil sand gradually darkens from the entrance to exit of the model. When the ratio of flue gas to steam is 1 : 1, the colour of oil sand in the middle and rear of the sandpack is darker, and the colour of oil sand in the sandpack changes little after saturated oil, indicating that there is still more remaining oil at the middle and rear of the sandpack, and the distillation effect of steam is weak. When the ratio of flue gas to steam is 3 : 1, the lighter colour range of oil sand in the sandpack is improved to varying degrees compared with the first two groups. The higher the flue gas injection ratio is, the larger the area where the colour lightens is, and the oil sand at the same position is further cleaned. This result reflects that the increase in the ratio of flue gas can enhance the vapor transmission range and oil washing effect.

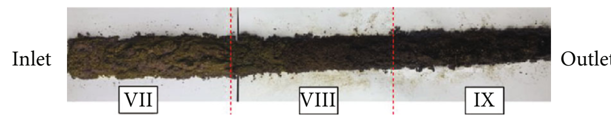
The variations of the four components in the residual oil can effectively reflect the strength of steam distillation in the displacement process. The contents of the four components were determined and analyzed for nine samples in the three groups of experiments, and the sampling locations are presented in Figure 10. Figure 11 presents the comparison of the four-component contents of residual oil under different



(a) Flue gas-steam injection ratio of 1 : 1

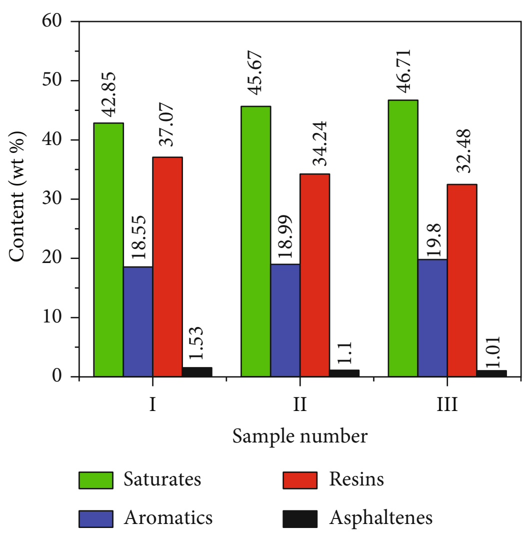


(b) Flue gas-steam injection ratio of 2 : 1

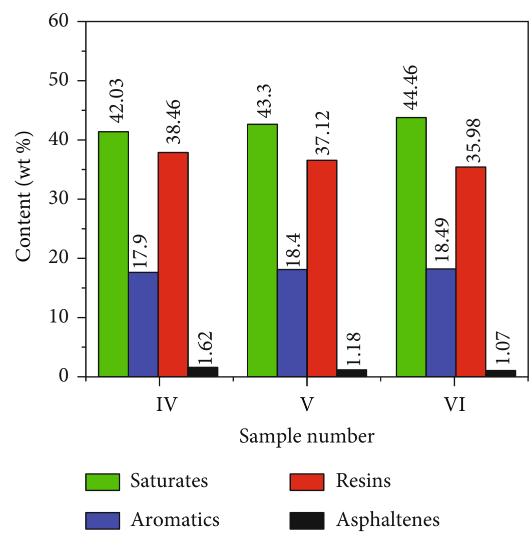


(c) Flue gas-steam injection ratio of 3 : 1

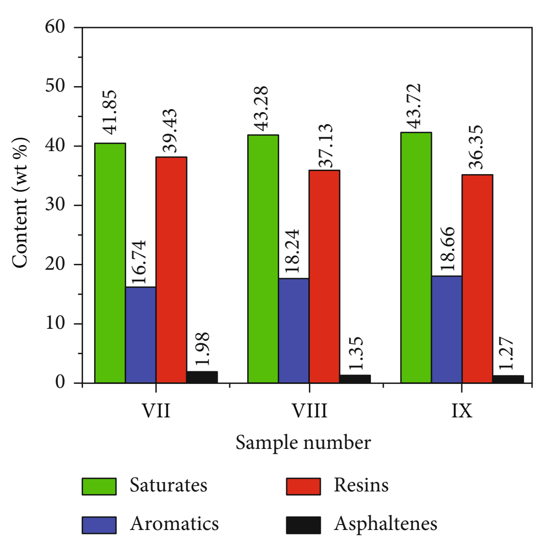
Figure 10: Distribution of oil sand in a one-dimensional sandpack under different injection ratios of flue gas to steam.



(a) Flue gas-steam injection ratio of 1 : 1



(b) Flue gas-steam injection ratio of 2 : 1



(c) Flue gas-steam injection ratio of 3 : 1

Figure 11: Comparison of the four-component contents of residual oil under different injection ratios of flue gas and steam.

injection ratios of flue gas and steam. In each experiment, the export, saturates, and aromatic contents in residual oil are higher, and the resin and asphaltene contents are lower because in the flue-gas-assisted steam displacement, within the scope of the spread of steam, the longer the distance the entrance is, the lower the temperature of the steam, the steam distillation effect is weak, and the worse the effect on the extraction of the light components. The light components of the crude oil are more likely to flow than the heavy components, and the light components are more likely to be recovered after displacement and remain at the end of the core pipe, while the heavy components remain in the porous

Table 3: Comparison of the content of heavy and light components at the inlet and outlet.

Injection ratio of flue gas and steam	Content of light components (wt%)		Content of heavy components (wt%)		Difference between inlet and the outlet (wt%)
	Inlet	Outlet	Inlet	Outlet	
1 : 1	61.99	65.31	38.01	34.69	3.32
1 : 2	59.53	62.95	40.47	37.05	3.42
1 : 3	58.59	62.38	41.41	37.62	3.79

medium. As the amount of flue gas injection increases, the content of light components at the same position gradually reduces, and the content of crude components gradually increases, indicating the higher the flue gas injection ratio is, the stronger the steam distillation effect when the ratio of flue gas to steam is from 1 : 1 to 3 : 1.

Table 3 shows the changes in the light component and heavy component of the remaining oil at the entrance and exit at different flue gas injection ratios. Light components represent saturates and aromatics, and heavy components represent resins and asphaltenes. Numerically, the increase in the flue gas ratio not only reduces the light components at the inlet and outlet but also increases the difference between the entrance and exit. The same is true of changes in the content of heavy components, further confirming the conclusion that when the content of flue gas in the injected gas increases, the distillation effect of steam on the crude oil in the sandpack will be intensified, and the production of light components will be promoted.

4. Conclusions

(1) During steam flooding, the light components of heavy oil are easily recovered under the action of distillation. Flue gas can enhance distillation effect and increase the output proportion of light components in the process of steam flooding, increasing the recovery of steam flooding by 10%

(2) Due to the difference in the dissolution of N_2 and CO_2 in heavy oil, the retention rate of CO_2 in the formation in the early stage of displacement is higher, and the proportion of CO_2 output is 0.06, which is lower than the initial injection proportion. After gas channeling, some dissolved CO_2 begins to precipitate, and the proportion of CO_2 reaches 0.31. As the displacement progresses, the proportion of CO_2 gradually decreases and keeps approaching the initial injection proportion

(3) The dissolution and release process of flue gas can help to produce foam oil. The formation of foam oil can expand the volume of original crude oil and promote the flow of crude oil while improving the output of crude oil, which reduces the maximum displacement pressure difference by 0.84 MPa

(4) The larger the proportion of flue gas in the injected fluid is, the more significant the steam distillation effect is, the less light components in the residual oil is, and the larger the variation range of the four components of heavy oil along the sandpack is. When the proportion of flue gas to steam changes from 1 : 1 to 3 : 1, the variation of light/heavy components between the outlet and the inlet of the sandpack increases from 3.32% to 3.79%.

Data Availability

The underlying data support in the results of this study is reported in the figures and tables.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] G. Kindermann, M. Obersteiner, B. Sohngen et al., “Global cost estimates of reducing carbon emissions through avoided deforestation,” *Proceedings of the National Academy of Sciences*, vol. 105, no. 30, pp. 10302–10307, 2008.

[2] S. Adams and A. Acheampong, “Reducing carbon emissions: the role of renewable energy and democracy,” *Journal of Cleaner Production*, vol. 240, article 118245, 2019.

[3] M. Allen, D. Frame, C. Huntingford et al., “Warming caused by cumulative carbon emissions towards the trillionth tonne,” *Nature*, vol. 458, no. 7242, pp. 1163–1166, 2009.

[4] H. Liu, B. Tellez, T. Atallah, and M. Barghouty, “The role of CO_2 capture and storage in Saudi Arabia’s energy future,” *International Journal of Greenhouse Gas Control*, vol. 11, pp. 163–171, 2012.

[5] E. Rubin, J. Davison, and H. Herzog, “The cost of CO_2 capture and storage,” *International Journal of Greenhouse Gas Control*, vol. 40, pp. 378–400, 2015.

[6] M. Anwar, A. Fayyaz, N. Sohail et al., “CO_2 capture and storage: a way forward for sustainable environment,” *Journal of Environmental Management*, vol. 226, pp. 131–144, 2018.

[7] C.-F. Tsang, S. Benson, B. Kobelski, and R. Smith, “Scientific considerations related to regulation development for CO_2 sequestration in brine formations,” *Environmental Geology*, vol. 42, no. 2-3, pp. 275–281, 2002.

[8] W. Pu, B. Wei, F. Jin et al., “Experimental investigation of CO_2 huff-n-puff process for enhancing oil recovery in tight reservoirs,” *Chemical Engineering Research and Design*, vol. 111, pp. 269–276, 2016.

[9] S. Bachu, “Identification of oil reservoirs suitable for CO 2 -EOR and CO 2 storage (CCUS) using reserves databases, with

application to Alberta, Canada," *International Journal of Greenhouse Gas Control*, vol. 44, pp. 152–165, 2016.

[10] I. Kolenković and B. Saftić, "Geological storage of carbon dioxide," *Rudarsko-geološko-naftni zbornik*, vol. 28, no. 1, pp. 9–21, 2014.

[11] L. Melzer, "Carbon dioxide enhanced oil recovery (CO_2 EOR): factors involved in adding carbon capture, utilization and storage (CCUS) to enhanced oil recovery," *Center for Climate and Energy Solutions*, pp. 1–17, 2012.

[12] V. Núñez-López, R. Gil-Egui, and S. Hosseini, "Environmental and operational performance of CO_2-EOR as a CCUS technology: a Cranfield example with dynamic LCA considerations," *Energies*, vol. 12, no. 3, p. 448, 2019.

[13] L. Eide, M. Batum, T. Dixon et al., "Enabling large-scale carbon capture, utilisation, and storage (CCUS) using offshore carbon dioxide (CO_2) infrastructure developments—a review," *Energies*, vol. 12, no. 10, p. 1945, 2019.

[14] Z. Xu, S. Li, B. Li, D. Chen, Z. Liu, and Z. Li, "A review of development methods and EOR technologies for carbonate reservoirs," *Petroleum Science*, vol. 17, no. 4, pp. 990–1013, 2020.

[15] Y. Xiang, C. Song, C. Li, E. Yao, and W. Yan, "Characterization of 13Cr steel corrosion in simulated EOR-CCUS environment with flue gas impurities," *Process Safety and Environmental Protection*, vol. 140, pp. 124–136, 2020.

[16] P. Briggs, P. Baron, R. Fulleylove, and M. S. Wright, "Development of heavy-oil reservoirs," *Journal of Petroleum Technology*, vol. 40, no. 2, pp. 206–214, 1988.

[17] R. Santos, W. Loh, A. Bannwart, and O. Trevisan, "An overview of heavy oil properties and its recovery and transportation methods," *Brazilian Journal of Chemical Engineering*, vol. 31, no. 3, pp. 571–590, 2014.

[18] K. Guo, H. Li, and Z. Yu, "*In-situ* heavy and extra-heavy oil recovery: a review," *Fuel*, vol. 185, pp. 886–902, 2016.

[19] D. Liu and W. Li, "Flue gas enhanced oil recovery (EOR) as a high efficient development technology for offshore heavy oil in China," *Journal of Petroleum and Gas Engineering*, vol. 4, no. 5, pp. 127–142, 2013.

[20] L. Monte-Mor, P. Laboissiere, and O. Trevisan, "Laboratory study on steam and flue gas co-injection for heavy oil recovery," in *Proceedings of the SPE heavy oil conference*, Canada. Alberta, Canada, June 2013.

[21] L. Zhong, Z. Dong, J. Hou et al., "Investigation on principles of enhanced offshore heavy oil recovery by coinjection of steam with flue gas," in *Proceedings of the SPE Enhanced Oil Recovery Conference*, Kuala Lumpur, Malaysia, July 2013.

[22] R. Srivastava, S. Huang, and M. Dong, "Comparative effectiveness of $_{CO2,}$ produced gas, and flue gas for enhanced heavy-oil recovery," *SPE Reservoir Evaluation & Engineering*, vol. 2, no. 3, pp. 238–247, 1999.

[23] C. Wu, "A critical review of steamflood mechanisms," in *Proceedings of the SPE California Regional Meeting*, Bakersfield, California, April 1977.

[24] F. Kirmani, A. Raza, R. Gholami, M. Haidar, and C. S. Fareed, "Analyzing the effect of steam quality and injection temperature on the performance of steam flooding," *Energy Geoscience*, vol. 2, no. 1, pp. 83–86, 2021.

[25] S. Ali, "Current status of steam injection as a heavy oil recovery method," *Journal of Canadian Petroleum Technology*, vol. 13, no. 1, 1974.

[26] R. Srivastava, S. Huang, and F. Mourits, "A laboratory evaluation of suitable operating strategies for enhanced heavy oil recovery by gas injection," *Journal of Canadian Petroleum Technology*, vol. 36, no. 2, 1997.

[27] S. Li, Z. Li, and X. Sun, "Effect of flue gas and *n*-hexane on heavy oil properties in steam flooding process," *Fuel*, vol. 187, pp. 84–93, 2017.

[28] C. Wang, P. Liu, F. Wang, B. Atadurdyyev, and M. Ovluyagulyyev, "Experimental study on effects of CO_2 and improving oil recovery for CO_2 assisted SAGD in super-heavy-oil reservoirs," *Journal of Petroleum Science and Engineering*, vol. 165, pp. 1073–1080, 2018.

[29] Y. Wang, X. Wu, R. Wang, and F. Lai, "Study on multiple thermal fluid applied in heavy oil development," *Metalurgia International*, vol. 18, no. 9, p. 98, 2013.

[30] Q. Zhao, Z. Li, S. Wang, F. Lai, and H. Li, "Phase behavior measurements and modeling for N_2/CO_2/extra heavy oil mixtures at elevated temperatures," *Industrial & Engineering Chemistry Research*, vol. 58, no. 1, pp. 428–439, 2019.

[31] J. Fan, J. Yang, X. Fan, and L. Wu, "Experimental study on the mechanism of enhanced oil recovery by non-condensable gas-assisted steam flooding process in extra-heavy oil reservoir," *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, vol. 43, no. 4, pp. 444–460, 2021.

[32] J. Welker, "Physical properties of carbonated oils," *Journal of Petroleum Technology*, vol. 15, no. 8, pp. 873–876, 1963.

[33] S. Li, B. Li, Q. Zhang, Z. Li, and D. Yang, "Effect of CO_2 on heavy oil recovery and physical properties in huff-n-puff processes under reservoir conditions," *Journal of Energy Resources Technology*, vol. 140, no. 7, 2018.

[34] S. Kokal and S. Sayegh, "Phase behavior and physical properties of CO_2-saturated heavy oil and its constitutive fractions: experimental data and correlations," *Journal of Petroleum Science and Engineering*, vol. 9, no. 4, pp. 289–302, 1993.

[35] A. Khatib, R. Earlougher, and K. Kantar, "CO_2 injection as an immiscible application for enhanced recovery in heavy oil reservoirs," in *Proceedings of the SPE California Regional Meeting*, Bakersfield, California, March 1981.

[36] Z. Wu, L. Wang, C. Xie, and W. Yang, "Experimental investigation on improved heavy oil recovery by air assisted steam injection with 2D visualized models," *Fuel*, vol. 252, pp. 109–115, 2019.

[37] A. Mohsenzadeh, M. Escrochi, M. Afraz, G. Karimi, Y. Al-Wahaibi, and S. Ayatollahi, "Non-hydrocarbon gas injection followed by steam-gas co-injection for heavy oil recovery enhancement from fractured carbonate reservoirs," *Journal of Petroleum Science and Engineering*, vol. 144, pp. 121–130, 2016.

[38] R. Bora, B. Maini, and A. Chakma, "Flow visualization studies of solution gas drive process in heavy oil reservoirs with a glass micromodel," *SPE Reservoir Evaluation & Engineering*, vol. 3, no. 3, pp. 224–229, 2000.

[39] T. Lu, Z. Xu, X. Ban, D. Peng, and Z. Li, "Cyclic in-situ combustion process for improved heavy oil recovery after cyclic steam stimulation," *SPE Journal*, vol. 27, pp. 1–15, 2022.

[40] Z. Wang, S. Li, and Z. Li, "A novel strategy to reduce carbon emissions of heavy oil thermal recovery: condensation heat transfer performance of flue gas-assisted steam flooding," *Applied Thermal Engineering*, vol. 205, article 118076, 2022.