Experimental study on the mechanism and development effect of multi-gas assisted steam huff and puff process in the offshore heavy oil reservoirs

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Abstract

Multi-gas assisted steam huff and puff process is a relatively new thermal recovery technology for offshore heavy oil reservoirs. Some blocks of Bohai oilfield have implemented multi-gas assisted steam huff and puff process. However, the development mechanism still requires further study. In this paper, high-temperature high-pressure (HTHP) PVT experiments and different huff and puff experiments of sand pack were carried out to reveal the enhanced production mechanism and evaluate the development effect of multi-gas assisted steam huff and puff process. The results indicated that viscosity reduction and thermal expansion still were the main development mechanism of multi-gas assisted steam huff and puff process. Specifically, CO₂ easily dissolved in the heavy oil that made it mainly play the role of reducing oil viscosity, N₂ was characteristics of small solubility and good expansibility, and it could improve formation pressure, increase steam sweep volume and even reduce the heat loss. Meanwhile, injecting multi-gas and steam could break the balance of heavy oil component that made the content of resin reduce and the content of saturates, aromatics and asphaltene increase so as to further reduce the viscosity of heavy oil. Compared with steam huff and puff process, multi-gas assisted steam huff and puff process increased the recovery by 2–5%. The optimal water–gas ratio and steam injection temperature were 4:6 and 300°C, respectively. The results suggested that multi-gas assisted steam huff and puff process would have wide application prospect for offshore heavy oil reservoirs.

Keywords Offshore heavy oil · Multi-gas assisted steam huff and puff · Mechanism · Development effect · Recovery

Introduction

As one of main methods for producing heavy oil, steam huff and puff process is characterized of simple process and wide applicability for heavy oil reservoirs. However, steam huff and puff process is classified into primary oil recovery mainly depending on natural energy (Liu 2013; Wang et al. 2004; Sun et al. 2017, 2018a, b, 2019; Yoelin 1970; Bao et al. 2016). For the conventional steam huff and puff process, specifically in the later stage of steam huff and puff process, the thermal efficiency of steam is dramatically reduced

that leads to the recovery decrease. Thus, an improvement recovery process is required.

Previous research results show that injecting gas such as CO₂, N₂ or flue gas can increase the steam sweep volume, supplement the formation energy and further reduce the viscosity of heavy oil and residual oil saturation (Gao et al. 2003; Firouz and Torabi 2014; Mohsenzadeh et al. 2016; Wang et al. 2018, Fan et al. 2019). For example, at the same time as steam injection, injecting CO₂ can reduce the viscosity of heavy oil and thereby increase the recovery of heavy oil (Li et al. 2017; Liu et al. 2016; Wang et al. 2018; Dong and Huang 2002; Dong et al. 2014; Song and Yang 2017). Specifically, CO₂ is easily dissolved into crude oil, which increases the volume of crude oil by 10–30%, and then the viscosity of crude oil will appear a certain degree decline which depends on pressure, temperature and the properties of crude oil. Meanwhile, crude oil extraction by CO₂ is a process where the interfacial tension between CO₂ and crude oil continuously decreases.

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N_2 injection will help maintain formation pressure, prolong the huff and puff cycle, improve the steam sweep volume and increase the displacement efficiency in the immediate vicinity of wellbore (Wu et al. 2018; Liu et al. 2011; Dong et al. 2016). Considering that N_2 has lower thermal conductivity, after injecting N_2 into reservoir, steam could be brought into the further area of reservoir which increases the heating volume and sweep efficiency of steam. What's more, as the pressure decreases in the course of development, CO_2 and N_2 will extract from crude oil and generate dissolved gas drive in the later stage. In view of these, injection CO_2 and N_2 would have positive effect for production heavy oil in the course of steam injection (Hong and Ault 1984; Butler et al. 2000; Fan et al. 2016; Jin et al. 2017; Yan et al. 2020).

Heavy oil resource is abundant in the Bohai oilfield of China. Heavy oil with the viscosity of less than 350 mPa·s can be effectively developed by cold recovery technology, such as water flooding, chemical flooding and well pattern thickening. However, for heavy oil with the viscosity of greater than 350 mPa·s, just limited reserves could be developed with the cold recovery technology. At this time, steam huff and puff process will become an effective way of development. But the reservoir type of Bohai oilfield is complex and diverse, viscosity of heavy oil in some blocks can exceed 10000 mPa·s, the development effect of simple steam huff and puff process is not ideal for this kind of heavy oil, a more reasonable development method is needed. Injecting gas such as CO_2 , N_2 and flue gas during steam huff and puff process has been generally applied to develop heavy oil reservoirs in onshore oilfield and achieved success. Therefore, multi-gas assisted steam huff and puff process should improve the production effect of offshore heavy oil reservoirs like Bohai oilfield (Liu et al. 2011; Gu et al. 2007).

In this paper, firstly, the influence of CO_2 and N_2 injection on the solubility, density and viscosity of heavy oil was studied by HTHP PVT experiments based on the offshore heavy oil of Bohai oilfield. Then sand pack experiments were carried out to compare the development effect of different huff and puff process and the change of crude oil component so as to further reveal the development mechanism of multi-gas assisted steam huff and puff process. Finally, 10 groups of sand pack experiments were conducted to optimize the key parameters of water–gas ratio and steam injection temperature. All the study results could provide theoretical and application support for the multi-gas assisted steam huff and puff process in offshore heavy oil reservoirs like Bohai oilfield.

Table 1 The properties of degassed heavy oil

Parameter	Value
Viscosity of heavy oil at 50 °C/mPa·s	12,574.2
Density of super-heavy oil at 20°C/g·cm ⁻³	0.943
SARA/%	
Asphaltene	21.94
Resin	23.53
Aromatics	22.36
Saturates	32.17

Fig. 1 Relation between viscosity of heavy oil and temperature

Experiment

HTHP PVT experiment

Experimental sample

The crude oil was collected from the Bohai oilfield which is a heavy oil reservoir with the formation depth of 1510.2 m and original pressure of 15.06 Mpa. The oil sample was cleaned by using a centrifuge to remove any sand particles and brine. Table 1 shows the physical properties of oil sample. Density and viscosity of the oil sample were, respectively, measured by a densitometer (DMA 4200 M, Anton Paar, Austria) and a rheometer (MCR302, Anton Paar, Austria). The asphaltene content of the crude oil was measured by using the standard ASTM D2007-03 method and filter papers with a pore size of 2.5 μ m. Figure 1 displays the oil viscosity under different temperature.

Fig. 2 Schematic apparatus of HTHP PVT experiment

Experimental apparatus

Figure 2 shows the experimental apparatus for measuring the solubility, density and viscosity of heavy oil saturated with CO₂ or N₂. The experimental apparatus mainly included sample mixer, intermediate container, flash separator, densitometer, rheometer and computer.

Experimental procedure

Figure 3 displays the experimental process. Firstly, the degassed heavy oil and enough CO₂ or N₂ were injected into the sample mixer and mixed well under the designated temperature (80 °C, 100 °C, 150 °C, 200 °C) and pressure (3 MPa, 5 MPa, 8 MPa, 10 MPa, 12 MPa) and, secondly, opened the valve between the sample mixer and intermediate container and injected the mixed heavy oil into the 50-mL intermediate container until it was full. Thirdly, the heavy oil

saturated with CO₂ or N₂ was moved into the flash evaporator, densitometer or rheometer from the intermediate container to test the parameter under the designated temperature and pressure. Finally, the solubility was calculated by the computer connected to the gas flow meter. The density and viscosity were measured by the densitometer and rheometer (Jha 1986; Srivastava et al. 1997; Kavousi et al. 2014; Telmadarreir et al. 2016; Hatzikiriakos 2014).

Huff and puff experiment

Experimental sample

The heavy oil sample was from Bohai oilfield, and the initial oil saturation of the reservoir was 72%. The physical properties of heavy oil sample are shown in Table 1 and Fig. 1. Purity of CO₂ and N₂ (Tianyuan, Co., Ltd., China) was 99.99 mol%. The property of the formation water is

Fig. 3 Schematic process of HTHP PVT experiment

Table 2 The properties of formation water

$\text{Na}^+ + \text{K}^+/\text{mg}\cdot\text{l}^{-1}$	$\text{Mg}^{++}/\text{mg}\cdot\text{l}^{-1}$	$\text{Ca}^{++}/\text{mg}\cdot\text{l}^{-1}$	$\text{Cl}^-/\text{mg}\cdot\text{l}^{-1}$	$\text{SO}_4^{2-}/\text{mg}\cdot\text{l}^{-1}$	$\text{HCO}_3^-/\text{mg}\cdot\text{l}^{-1}$	$\text{CO}_3^{2-}/\text{mg}\cdot\text{l}^{-1}$	Total mineralization/ $\text{mg}\cdot\text{l}^{-1}$	Water type
958.3	3.6	6.0	443.3	9.6	857.1	90.0	2388.0	NaHCO_3

shown in Table 2, with a density of 1.01 g/cm^3 under standard condition.

Experimental apparatus

As shown in Fig. 4, the experimental apparatus mainly consisted of sand pack, steam generator, plunger pump, flowmeter, calorstat and beaker, etc. The maximum steam output temperature and pressure of steam generator were 400°C and 35 MPa, respectively. Operating range of calorstat was $0\text{--}350^\circ\text{C}$. Working range of pressure meter was $0\text{--}30 \text{ MPa}$. Working range of plunger pump was $0\text{--}50 \text{ mL/min}$, and maximum pressure was 25 MPa. The size of sand pack model was $48 \text{ mm} \times 340 \text{ mm}$, its maximum bearing pressure was 35 MPa.

Experimental procedure

The specific experimental procedures are as follows:

- (1) Filled sand: erected the model, filled simulated sand from the upper port and blocked the port after the sand reached the filling port, shook the model by small amplitude in the middle axis and static 1 h, opened the port and continued to fill the sand. Repeated the opera-

tion several times until the sand was no longer reduced from the filling port.

- (2) Saturated formation water: constant temperature 70°C , injected formation water into the sand pack at 25 mL/min until the producing port met the water, continuously injected formation water 1 h. Stopped injecting water and kept the temperature. The sand pack had a permeability of water phase between 3574 and 3862 md, and porosity between 33.7 and 37.6%.
- (3) Saturated oil: Injected oil into the sand pack at 20 mL/min , drained off water until the output liquid of model was not hydrated and continuously injected oil 1 h. Stopped injecting oil and kept the constant temperature. The oil saturation of sand pack was between 71 and 73%.
- (4) Different huff and puff experiment: injected hot water/steam into the sand pack at 20 mL/min . During the multi-gas assisted steam huff and puff experiment, the water–gas ratio was 1:2.

Fig. 4 Schematic apparatus of huff and puff experiment

Fig. 5 Relationship between CO₂ solubility and pressure at different temperature in heavy oil

Fig. 7 Relationship between density of heavy oil saturated with CO₂ and pressure at different temperature

Fig. 6 Relationship between N₂ solubility and pressure at different temperature in heavy oil

Fig. 8 Relationship between density of heavy oil saturated with N₂ and pressure at different temperature

The results and discussion of experiment

The results and discussion of HTHP PVT experiment

The solubility of CO₂ and N₂ in the heavy oil

Figures 5 and 6 show the relationship between solubility of CO₂ and N₂ in the heavy oil and pressure at different temperature. It can be seen that the solubility of CO₂ and N₂ in degassed heavy oil increased as the pressure increased. With the increase in temperature, the solubility of CO₂ decreased and the solubility of N₂ increased. When the pressure was fixed at 12 MPa, the solubility of CO₂ in heavy oil decreased from 60.2 to 26.8 Sm³/m³ as the temperature increased from 80 to 200 °C, but the solubility of N₂ in heavy oil increased from 2.9 to 8.1 Sm³/m³ in the process. Under the same condition, the solubility of CO₂ was obvious higher than that of N₂. When the pressure

was 3 MPa and temperature was 200 °C, the solubility of CO₂ and N₂ in the heavy oil was 13.35 and 2.1 Sm³/m³, respectively. In summary, although a high temperature had a negative effect on the solubility of CO₂ in the heavy oil, CO₂ still had a better solubility in heavy oil at 200 °C.

The effect of CO₂ and N₂ on the density of heavy oil

Figures 7 and 8 show the relationship between density of heavy oil saturated with gas and pressure at different designated temperature. As the pressure and temperature increased, the density of heavy oil saturated with CO₂ or N₂ decreased. The reason might be when the temperature increased, the volume of heavy oil expanded and the space between molecular increased, so the density decreased. When the pressure increased, more CO₂ or N₂ dissolved into the heavy oil that increased the space between molecular; hence, the density of heavy oil would also decreased. When the temperature was 200°C, the density of heavy oil

saturated with CO₂ decreased from 0.853 to 0.834 g/cm³ as the pressure increased from 3 to 12 MPa, which of heavy oil saturated with N₂ decreased from 0.872 to 0.856 g/cm³ as the pressure increased from 3 to 12 MPa.

The effect of CO₂ and N₂ on the viscosity of heavy oil

Figures 9 and 10 show the relationship between viscosity of heavy oil saturated with gas and pressure at a given temperature. Compare the change of density and viscosity with pressure and temperature in Figs. 7, 8, 9, and 10. It was found that the density and viscosity had the same change trend with pressure and temperature. The viscosity of heavy oil saturated with CO₂ or N₂ decreased with the increase in pressure and temperature. It was because the change of pressure and temperature influenced the solubility of CO₂ or N₂ in heavy oil and the space between molecular. When the temperature was 200°C, the viscosity of heavy oil saturated with CO₂ decreased from 18.4 to 12.1 mPa·s as the pressure increased from 3 to 12 MPa, which of heavy oil saturated with N₂ decreased from 21.6 to 15.7 mPa·s as the pressure increased from 3 to 12 MPa.

In summary, dissolution of CO₂ or N₂ in heavy oil will expand the volume of heavy oil and decrease the density and viscosity. The solubility of CO₂ in heavy oil is bigger than that of N₂, so CO₂ is more easily dissolved in the heavy oil and mainly plays the role of reducing oil viscosity. Although the effect of N₂ injection on reducing density and viscosity is not obvious, N₂ has a large compression coefficient due to its lower critical temperature and minimal dependence on temperature. As shown in Fig. 11, the compression coefficient of N₂ increases with the increase in pressure, which is much higher than that of CO₂, because the critical temperature of N₂ is low, and the compressibility coefficient of N₂ is less affected by temperature (Li 2017). So N₂ injection will help maintain formation pressure, improve the steam

Fig. 9 Relationship between viscosity of heavy oil saturated with CO₂ and pressure at different temperature

Fig. 10 Relationship between viscosity of heavy oil saturated with N₂ and pressure at different temperature

sweep volume and increase the displacement efficiency, in addition, considering the lower thermal conductivity of N₂, which is 0.0228 W/(m K) At 0.1 MPa and 0 °C. N₂ injection will promote steam migration, enhance the heat carrying capacity of steam and improve the heat utilization of steam.

The results and discussion of huff and puff experiment

The development effect of different huff and puff experiments

In order to compare the development effect of different huff and puff process and further reveal the development mechanism of multi-gas assisted steam huff and puff process, different huff and puff experiments were carried out at different designed temperature; namely, hot water huff and puff process, steam huff and puff process, multi-gas assisted steam huff and puff process were studied at 150 °C and 250 °C, respectively.

Fig. 11 Comparison of compressibility coefficient for N₂, air and CO₂ at 200 °C

Table 3 The change of four components after different huff and puff experiments

Temperature/°C	Recovery methods	Asphaltene/%	Resin/%	Aromatics/%	Saturates/%
150	Heavy oil	21.94	23.53	22.36	32.17
	Hot water huff and puff	22.61	22.67	22.41	32.31
	Steam huff and puff	22.89	18.2	22.89	36.02
	Multi-gas assisted steam huff and puff	23.05	17.65	23.03	36.27
250	Hot water huff and puff	22.73	22.31	22.54	32.42
	Steam huff and puff	23.23	17.44	22.12	37.21
	Multi-gas assisted steam huff and puff	23.95	16.19	22.43	37.43

Fig. 12 The recovery of hot water huff and puff process at different temperature **Fig. 13** The SARA change of hot water huff and puff process at different temperature

Heavy oil is a complex and multi-component mixture that includes saturates, aromatics, resin and asphaltene (SARA, also called four components). Different development methods may destroy the component balance of heavy oil, which results in the change of four components content in the developed heavy oil (Kokal et al. 1992; Monin and Audibert 1987). In order to further study the development mechanism of different huff and puff process, as shown in Table 3, the SARA was analyzed after each huff and puff experiment. The results show that the content of saturates, aromatics and asphaltene increased, but the content of resin reduced from hot water huff and puff process to steam huff and puff process, and then to multi-gas assisted steam huff and puff process at each experiment temperature. Meanwhile, a higher content of asphaltene and lower content of resin appeared with the temperature increase.

Thermal expansion and viscosity reduction are still the main mechanism of thermal recovery. As shown in Fig. 1, the viscosity of heavy oil was very sensitive to the temperature. The viscosity of degassed heavy oil decreased exponentially as the temperature increased. But when the temperature was more than 150 °C, the viscosity of heavy oil changed little with the increase in temperature.

Figure 12 shows the relation between huff and puff cycle and recovery of hot water huff and puff process. Figure 13

Fig. 14 The Recovery of hot water/steam huff and puff process at different temperature

shows the change of four components content after hot water huff and puff process at different temperature. As shown in Fig. 13, when the temperature rose from 150 °C to 250 °C, the four components of heavy oil changed little after hot water huff and puff process. It indicated that heavy oil had not occurred obvious physicochemical reaction, so the main mechanism of hot water huff and puff process was viscosity reduction and thermal expansion.

Figure 14 compares the recovery between hot water huff and puff process and steam huff and puff process. As shown

Fig. 15 The SARA change of hot water/steam huff and puff process at 150°C

Fig. 16 The SARA change of hot water/steam huff and puff process at 250°C

in Fig. 14, compared with hot water huff and puff process, the recovery of steam huff and puff process had obviously increased. Figures 15 and 16 show the change of four components content after hot water huff and puff process and steam huff and puff process at different temperature. In the course of steam huff and puff, when the temperature increased from 150 to 250 °C, the content of saturates, aromatics and asphaltene increased, but the content of resin reduced. It indicates that the aquathermal cracking reaction had occurred in the steam huff and puff process. In the later period of experiment, the condensate of liquid hydrocarbon appeared in the beaker wall, which proved that steam distillation also had occurred. Therefore, in addition to viscosity reduction and thermal expansion, the recovery mechanism of steam huff and puff process also consisted of hydrothermal cracking reaction and steam distillation.

Figure 17 shows the recovery of three different huff and puff experiments. As shown in Fig. 17, the recovery of multi-gas assisted steam huff and puff process was further improved compared with hot water/steam huff and puff process due to the synergistic effect of multi-gas and steam. The

Fig. 17 The recovery of three different huff and puff process at different temperature

Fig. 18 The SARA change of three different huff and puff process experiment at 150°C

recovery of multi-gas assisted steam huff and puff at 150 °C and 250 °C was 11.9% and 22.3%, respectively, which was 7.9% and 2% higher than that of hot water huff and puff and steam huff and puff at 150 °C, and 13.4% and 5% higher than that of hot water huff and puff and steam huff and puff at 250 °C.

Figures 18 and 19 compare the change of four components content after three different huff and puff experiments at different temperature. As shown in Figs. 18 and 19, compared with hot water/steam huff and puff process, the four components content in the developed heavy oil of multi-gas assisted steam huff and puff process had exhibited more obvious change. What's more, at the same temperature, the content of asphaltene in the developed heavy oil of multi-gas assisted steam huff and puff process was the highest (Clark et al. 1984, 1987a, b; Clark and Hyne 1990). With the increase in temperature from 150 to 250 °C, the content of saturates, aromatics and asphaltene obviously increased, but which of resin reduced. The result indicates that multi-gas injection in the process of steam huff and puff process had further broken the balance of heavy oil components and the

Fig. 19 The SARA change of three different huff and puff process experiment at 250°C

aquathermal cracking reaction had played an important role during the multi-gas assisted steam huff and puff process. In addition, in the later period of multi-gas assisted steam huff and puff experiments, the condensate of liquid hydrocarbons also appeared in the beaker wall, and the amount was obviously more than that of steam huff and puff experiments. It indicates that injecting multi-gas had enhanced the steam distillation. What's more, from the HTHP PVT experiment, we have known that the CO_2 and N_2 could increase the expansion ratio, reduce the density and viscosity by dissolving in heavy oil, and N_2 could maintain formation pressure, improve heating range and heat utilization of steam. All of the development mechanism further improved the recovery of multi-gas assisted steam huff and puff process.

The optimization of key parameters for multi-gas assisted steam huff and puff process

1) Water–gas ratio

Ensured that other parameters remain unchanged, which was to ensure the size of sand pack, initial pressure, initial porosity, initial saturation, steam injection temperature 250 °C and so on were the same. Six different water–gas volume ratio (2:8, 3:7, 4:6, 5:5, 6:4, 7:3) experiments of multi-gas assisted steam huff and puff process with 6 cycles were studied. The each cycle recovery and cumulative recovery of multi-gas assisted steam huff and puff process are shown in Figs. 20 and 21. It can be seen that with the increase in steam injection, cumulative recovery increased. When the water–gas ratio reached 4:6, the cumulative recovery began to decrease and the maximum cumulative recovery was acquired when the water–gas ratio was 4:6.

It could be known from the results of previous experimental studies that CO_2 and N_2 could dissolve into the heavy oil and reduce the viscosity and interfacial tension; furthermore, N_2 had a low thermal conductivity that increased the sweep

Fig. 20 Each cycle recovery of multi-gas assisted steam huff and puff process with different water–gas ratio

volume and heat utilization of steam. As a result, multi-gas assisted steam huff and puff process could more effectively improve the micro-displacement efficiency of steam and reduce residual oil saturation than steam huff and puff process. In the process of experiments, with the increase in steam ratio, the heat injection increased greatly, which increased the steam sweep volume and viscosity reduction area, thus effectively improved the development effect of thermal recovery. However, as the water–gas ratio increased, the Jia Min effect would be formed at the throat to prevent the flow of gas and increase the pressure in immediate vicinity of wellbore due to the heat loss and steam transforming to hot water, which made the injection difficult and a large amount of fluid cannot be effectively injected. At the same time, due to the decrease of the amount of injected gas, the dissolved gas of oil was reduced, which weakened the expansion energy and viscosity reduction of heavy oil, so the cumulative recovery would reduce. Therefore, the optimal water–gas ratio was 4:6.

2) Steam injection temperature

Fig. 21 The cumulative recovery of multi-gas assisted steam huff and puff process with different water–gas ratio

Fig. 22 Each cycle recovery of multi-gas assisted steam huff and puff process at different injection temperature

Fig. 23 The cumulative recovery of multi-gas assisted steam huff and puff process at different injection temperature

Ensured that other parameters remain unchanged, which was to ensure the size of sand pack, initial pressure, initial porosity, initial saturation, water–gas ratio 4:6 and so on were the same. Four different steam injection temperature (250 °C, 280 °C, 300 °C, 350 °C) experiments of multi-gas assisted steam huff and puff process with 6 cycles were studied.

The each cycle recovery and cumulative recovery are shown in Figs. 22 and 23. As the steam injection temperature rose, the cumulative recovery increased. The cumulative recovery of 4 groups of experiments was 24.93%, 27.61%, 29.32% and 30.35%, respectively, the cumulative recovery was the highest at 350 °C, but the cumulative recovery was little different between 300 and 350 °C. The reason could be that as the steam injection temperature increased, both viscosity reduction degree of heavy oil and oil flow capacity in the formation increased; in addition, the thermal expansion of heavy oil increased the oil saturation in the formation. However, constantly increasing steam injection temperature would reduce the dissolved

gas and weaken the amplitude of volume expansion and viscosity reduction of heavy oil. Therefore, after reaching a certain steam injection temperature, although steam injection temperature still increased, volume expansion and viscosity reduction of heavy oil were not obvious. And the excessive temperature easily caused the heavy components of heavy oil to coke, which led to the blockage of the pore, and reduced the permeability and cumulative recovery. So the optimal steam injection temperature was 300 °C.

Conclusions

1. After injecting CO₂ or N₂, the solubility of gas in degassed heavy oil increased as the pressure increased. With the increase in temperature, the solubility of CO₂ decreased and the solubility of N₂ increased. Under the same condition, the solubility of CO₂ was obvious higher than that of N₂. Due to the dissolving of N₂ and CO₂, the density and viscosity of heavy oil decreased as the pressure increased.
2. Injecting multi-gas and steam could break the balance of heavy oil component. With the increase in temperature, the content of resin reduced and the content of saturates, aromatics and asphaltene increased. Except for thermal expansion and viscosity reduction, the hydrothermal cracking reaction and steam distillation were also the important mechanism of enhanced oil recovery for multi-gas assisted steam huff and puff process.
3. Multi-gas assisted steam huff and puff process increased the recovery by 2–5% compared with steam huff and puff process. The optimal water–gas ratio and steam injection temperature which were 4:6 and 300 °C, respectively, were optimized by experiment. Considering that multi-gas assisted steam huff and puff process had higher recovery, it is suggested to further study the optimal value of injection–production parameters to excavate the greatest potential of multi-gas assisted steam huff and puff process for developing the offshore heavy oil reservoirs.

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Declarations

Conflict of interest On behalf of all the co-authors, the corresponding author states that there is no conflict of interest.

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