

An evaluation on phase behaviors of gas condensate reservoir in cyclic gas injection

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Abstract. Maintaining the reservoir pressure by gas injection is frequently adopted in the development of gas condensate reservoir. The aim of this work is to investigate the phase behavior of condensate oil and remaining condensate gas in the formation under gas injection. The DZT gas condensate reservoir in East China is taken as an example. The multiple contact calculation based on cell-to-cell method and phase equilibrium calculations based on PR Equation of State (EOS) were utilized to evaluate the displacement mechanism and phase behavior change. The research results show that different pure gas has different miscible mechanism in the displacement of condensate oil: vaporizing gas drive for N_2 and CH_4 ; condensing gas drive for CO_2 and C_2H_6 . Meanwhile, there is a vaporizing gas drive rather than a condensing gas drive for injecting produced gas. When the condensate oil is mixed with 0.44 mole fraction of produced gas, the phase behavior of the petroleum mixture reverses, and the condensate oil is converted to condensate gas. About the reinjection of produced gas, the enrichment ability of hydrocarbons is better than that of no-hydrocarbons. After injecting produced gas, retrograde condensation is more difficult to occur, and the remaining condensate gas develops toward dry gas.

1 Introduction

During the development of gas condensate reservoir, the retrograde condensation happened when the reservoir pressure drops below the dew point pressure. Generally, the condensate oil cannot flow in the porous media until its saturation is greater than a threshold value that is called the critical flowing saturation. Hence, a larger amount of condensate oil is trapped in the formation and is hard to be produced to the surface. Worse, the condensate oil blocks the flow path of gas and decreases the productivity of gas well (Fetkovich, 1973; Fevang and Whiston, 1996; Muskat, 1950). In order to prevent the participation of condensate oil, maintaining the reservoir pressure is significant for the efficient development of gas condensate reservoir.

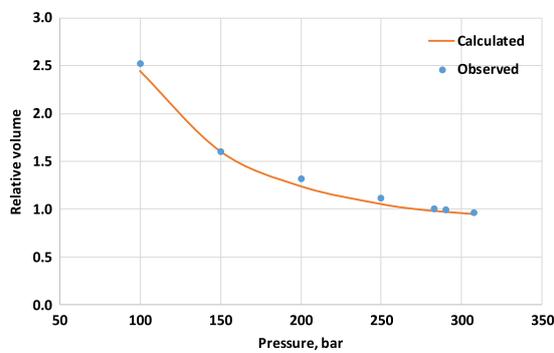
At present, there are two ways to maintain the reservoir pressure: water injection and gas injection. Although many scholars have conducted a lot of research on the water injection of gas condensate reservoir (Cason, 1989; Fishlock and Probert, 1996; Henderson *et al.*, 1993; Matthews *et al.*, 1988), there are still disadvantages such as the gas trapping and water breakthrough. Thus, gas injection is still the preferred option for the development of gas condensate reservoir (Ayala and Ertekin, 2005; Chen *et al.*, 2012; Diamond and Rondon, 1990; Jessen and Orr, 2003; Li *et al.*, 2016). Standing *et al.* (1948) pointed out that all

the condensate oil can be produced if there are enough gas to be injected into the reservoir. Abel *et al.* (1970) concluded that increasing the gas-injection pressure is beneficial to enhance the recovery of condensate oil by performing laboratory experiment on the actual reservoir. Shtepani (2006) found that CO_2 injection can generate a vaporizing gas drive for the condensate oil trapped in the formation, and improve the recovery efficiency of condensate oil. Li *et al.* (2001) summarized that dry gas injection can evaporate both the intermediate and heavy components of the condensate in the formation. Taheri *et al.* (2013) studied the mechanism of enhancing condensate recovery by gas injection, and found that the vaporizing gas drive is the main reason by comparing three injected gas of CH_4 , N_2 and CO_2 . Li *et al.* (2004) pointed out the alternate injection of dry gas and N_2 is better to enhance the condensate recovery than natural depletion or pure N_2 injection. Guo *et al.* (2004) carried out the depletion experiment of actual condensate gas in both the PVT tube and long core, and concluded that the condensate recovery in the long core is greater than that in the PVT tube. Jiao *et al.* (2012) found that the phase envelope of condensate gas shrinks and develops to the shape of dry gas during the Constant Volume Depletion (CVD). Zhu (2015) took Yaha gas condensate reservoir as an example to investigate the phase behavior of condensate gas, and drawn the conclusion that the recovery percent of condensate oil increases by 13.55% after injecting 0.85 PV of dry gas.

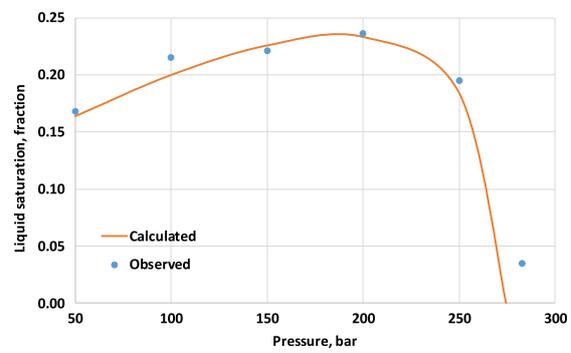
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Table 1. The pseudo-composition of condensate gas and the critical parameters of EOS.

Components	Mole fraction (%)	Mole weight (g/mol)	Critical pressure (bar)	Critical temperature (K)	Omega A	Omega B	Acentric factor
CO ₂	1.22	44.0	73.9	304.7	0.4572	0.0778	0.225
N ₂	2.13	28.0	33.9	126.2	0.4572	0.0778	0.040
C ₁	65.80	16.0	46.0	190.6	0.4572	0.0778	0.013
C ₂	8.51	30.1	48.8	305.4	0.4572	0.0778	0.099
C ₃	5.86	44.1	42.5	369.8	0.4572	0.0778	0.152
C ₄₋₆	9.89	66.9	36.6	447.7	0.4572	0.0778	0.200
C ₇₊₁	4.89	107.8	29.7	567.1	0.4572	0.0778	0.345
C ₇₊₂	1.45	198.5	18.2	713.6	0.4572	0.0778	0.645
C ₇₊₃	0.25	335.1	10.2	851.2	0.4572	0.0778	1.067



(a) Relative volume versus pressure from CCE



(b) Liquid saturation versus pressure from CVD

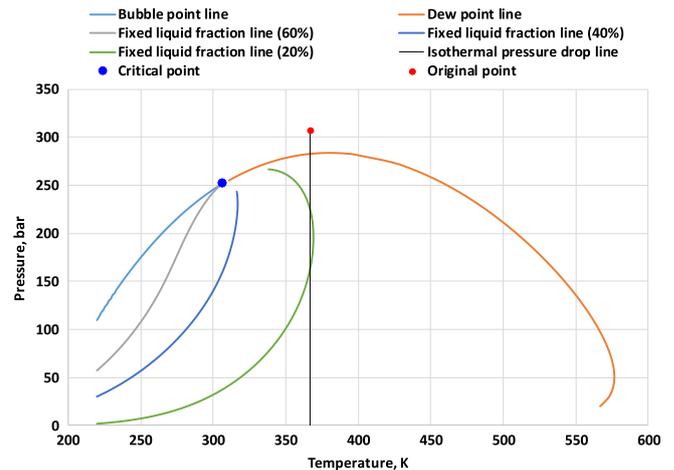
Fig. 1. The fitting results of PVT experimental data.

The main focus of this paper is to evaluate the phase behavior of condensate oil and remaining condensate gas in the formation with gas injection. In this paper, the multiple contact between different pure gas and condensate oil in the formation were firstly performed based on the cell-to-cell method. Then, the phase behavior of condensate oil mixed with different mole fraction of produced gas was evaluated. Minimum Miscible Pressure (MMP) and Minimum Miscible Enrichment (MME) for injecting produced gas were obtained by multiple-contact calculations. Finally, the phase behavior of remaining condensate gas mixed with different mole fraction of produced gas was analyzed in detail.

2 Model description

The condensate gas of the DZT reservoir in East China was divided into nine pseudo-components according to its characterization. The composition of original condensate gas is given in Table 1. The mole fraction of C₁ is 65.8%, the mole fraction of C₂–C₆ adds up to 24.26%, and the mole fraction of C₇₊ is 6.59%. The dew point pressure is about 280 bar at the reservoir temperature of 366.5 K.

Based on the software of PVTi simulator, the critical parameters of Equation of State (EOS) for each component were obtained through fitting the experimental results

**Fig. 2.** Phase plot of the gas condensate reservoir under original condition.

which include the experiments of Constant Composition Expansion (CCE) and Constant Volume Depletion (CVD). Figure 1 shows that the fitting results coincide with the experiment data very well. The critical parameters of EOS are also presented in Table 1. The phase plot of this gas condensate reservoir is shown in Figure 2. And the crit-

Table 2. Properties of the one-layer gas model.

Parameter	Value
Grid size	100 × 100 × 1
Grid increment	5 m × 5 m × 5 m
Porosity	15%
Permeability	40 mD
Connate water saturation	0.15
critical flow saturation of condensate oil	0.1
Reservoir temperature	366.5 K
Original reservoir pressure	308 bar

ical pressure and critical temperature is 252.0 bar and 306.7 K, respectively.

In order to gain the composition of each component in the reservoir fluid during the natural depletion, we resort to numerical simulation of one-layer model on the basis of E300 compositional simulator. The properties of this one-layer gas condensate model are given in Table 2. The producer is located in the corner of the model respectively, and was produced by the fixed gas rate of $10 \times 10^3 \text{ m}^3/\text{d}$.

When the reservoir pressure was depleted to 219.3 bar, the composition of remaining condensate gas and condensate oil in the reservoir is shown in Table 3. Under this reservoir pressure, the condensate oil consists of 50.1% light component ($C_1 + N_2$), 30.85% intermediate component ($C_{2-6} + CO_2$) and 18.05% heavy component (C_{7+}). And the remaining condensate gas contains 72.66% light component, 23.79% intermediate component and 3.55% heavy component. The phase plot of condensate oil and remaining condensate gas is shown in Figure 3. It can be easily seen from Figure 3, the condensate oil belongs to the type of volatile oil. Compared to the original condensate gas, the two-phase zone of the remaining condensate gas shrinks, and both the critical pressure and critical temperature decrease. This indicates that the remaining condensate gas develops toward the dry gas, and the condensate content is getting lower and lower.

3 Phase behavior evaluation of reservoir fluid under gas injection

3.1 Condensate oil

3.1.1 Pure gas injection

In order to evaluate the influence of injected gas type on the phase behavior of condensate oil in the formation, the multiple contact between different pure gas and condensate oil were performed using the cell-to-cell calculation method presented by Metcalfe *et al.* (1973), Pederson *et al.* (1986) and Jaubert *et al.* (1998). This method simulates a mass of cells of equal volume in a series, of which the temperature and pressure keep the same. Ternary plot is usually used to determine whether or not the miscibility has been achieved. Three groups of components including light component ($C_1 + N_2$), intermediate component ($C_{2-6} + CO_2$) and

heavy component (C_{7+}), were used to demonstrate the phase behavior in ternary plot. Figure 4 shows the ternary plots for pure CH_4 , N_2 , CO_2 and C_2H_6 injection when Multiple Contact Miscibility (MCM) was achieved. From Figure 4, it can be easily found that the phase envelopes of different pure gas are quite different. The bell-shaped phase envelopes were generated for pure CH_4 and N_2 , and hourglass-shaped phase envelopes for pure CO_2 and C_2H_6 .

Figure 5 shows the minimum pressure of MCM and FCM (First Contact Miscibility) with different gas type. From Figure 5, the miscibility ability increases in the following order: N_2 , CH_4 , CO_2 and C_2H_6 . N_2 injection has the maximum value of 274 bar for MCM and 1162 bar for FCM; C_2H_6 injection has the minimum value of 116 bar for MCM and 230 bar for FCM. It indicates that the greater the content of CO_2 and C_2H_6 , the easier the miscibility.

The pressure-composition diagram for different gas type is presented in Figure 6. It can be seen that the saturation pressure of N_2 keeps increasing rapidly, while that of CH_4 increases first then decreases and that of CO_2 and C_2H_6 keeps decreasing. The pressure-composition diagram also indicates that a vaporizing gas drive for N_2 and CH_4 since the critical point is to the left of the cricondenbar, and a condensing gas drive for CO_2 and C_2H_6 as the critical point is to the right of the cricondenbar. It should be noted that the displacement of crude oil by enriched gas exhibits the mechanism of both condensing gas drive and vaporizing gas drive (Zick, 1986). He addressed that the combined condensing/vaporizing mechanism can generate displacements that are effectively miscible, but true miscibility may not actually occur.

3.1.2 Produced gas injection

Based on the phase equilibrium model (Chueh and Prausnitz, 1967; Obut *et al.*, 1986; Yang and Wei, 2004) and PR EOS (Peng and Robinson, 1976), the phase behavior of condensate oil mixed with different mole fraction of produced gas were performed as shown in Figure 7. Here, the injection-gas refers to the produced gas. The mole fraction of injection gas (f) is defined as the mole ratio of injection gas to condensate oil. And the composition of produced gas is given by Table 3. Figure 7 shows that when the mole fraction of injection gas is greater, the critical point of condensate oil moves closer to the original reservoir conditions (the original pressure and temperature are 308 bar and 366.5 K respectively). For example, the critical pressure and temperature of condensate oil is 234.9 bar and 497 K, and they move to 303.1 bar and 388.8 K when the mole fraction of injection gas is 0.4. It means that the greater the mole fraction of injection gas, the more volatile the condensate oil. It can also be easily found that when the mole fraction of injection gas is up to 0.5, the shape of phase plot begins to change and the critical temperature is less than the reservoir temperature. It indicates that the reversal of phase behavior occurs; that is, the condensate oil is converted to condensate gas.

Figure 8 shows the relationship between the volume of condensate oil and reservoir pressure when the condensate oil was mixed with different mole fraction of produced

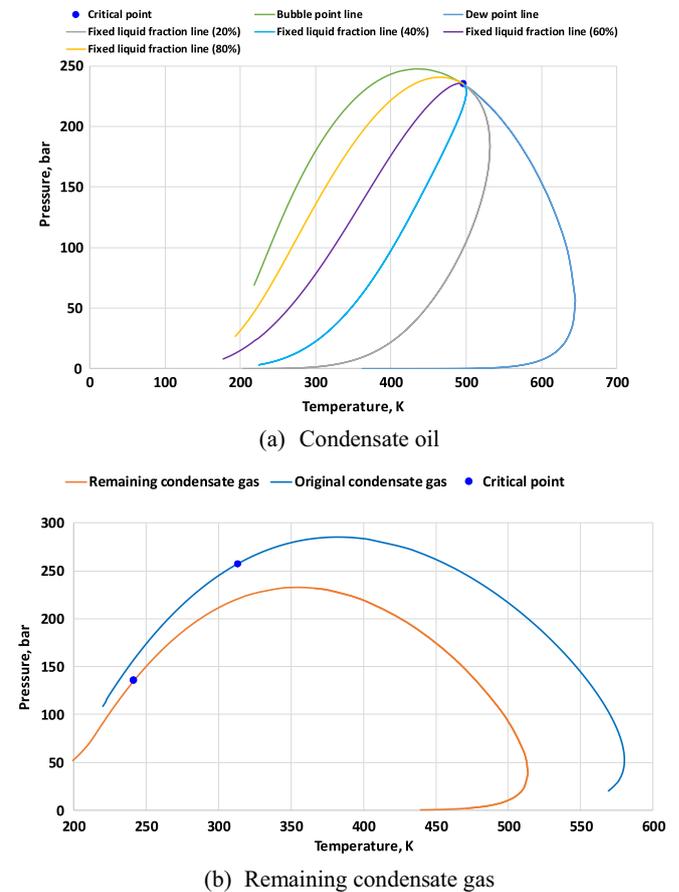
Table 3. Component mole fraction of reservoir fluid and produced gas at the reservoir pressure of 219.3 bar.

Component	Mole fraction of the reservoir fluid			Mole fraction of the produced gas (re-injected gas) (%)
	In the liquid phase (condensate oil) (%)	In the vapor phase (remaining condensate gas) (%)	Total mole fraction (%)	
CO ₂	1.18	1.22	1.21	1.27
N ₂	1.21	2.13	1.92	2.21
C ₁	48.89	70.53	65.5	73.52
C ₂	8.71	8.69	8.69	8.93
C ₃	7.04	5.61	5.94	5.53
C ₄₋₆	14.92	8.27	9.82	7.17
C ₇₊₁	10.97	3.09	4.92	1.37
C ₇₊₂	5.57	0.44	1.64	0
C ₇₊₃	1.51	0.02	0.37	0

gas. It can be seen from Figure 8, the shrinkage of condensate oil becomes higher when the mole fraction of injection gas is greater. For instance, at the same pressure of 200 bar, the mole fraction of condensate oil in the mixture system declines from 80.43% to 25.15% when the mole fraction of injection gas increases from 0 to 0.6. Furthermore, the curve shape in Figure 8 begins to change when the mole fraction of injection gas is 0.5. The volume of condensate oil decreases with reservoir pressure when the mole fraction of injection gas is less than 0.5; however, when the mole fraction of injection gas is greater than 0.5, it increases first and then decreases as the reservoir pressure declines. It also means that the phase behavior of the mixture system reverses, that is, the condensate oil is converted to condensate gas after injecting enough produced gas. Figure 9 shows the pressure-composition relation for injecting produced gas. The critical mole fraction of injection gas is defined as the one which make the reversal of phase behavior happen. In the pressure-composition diagram, the critical mole fraction of injection gas corresponds to the critical point. From Figure 9, it can be seen that the critical mole fraction of injection gas is 0.44. Figure 9 also indicates a vaporizing gas drive rather than a condensing gas drive for injecting produced gas.

The multiple contact between condensate oil and produced gas can be also simulated by cell-to-cell method. Figure 10 shows the ternary plot from multiple contact calculation for injecting produced gas. Figure 10a shows a vaporizing gas drive at the pressure of 250 bar; as the envelope for the vaporizing process is not closed, the miscibility was not achieved. As the reservoir pressure grows up to 274 bar, the envelope closes indicating the MCM occurs, as shown in Figure 10b. It means that increasing the gas-injection pressure can achieve the miscibility under the reservoir temperature of 366.5 K.

Besides, the miscibility can also be achieved by increasing the content of intermediate component (C₂₋₆ + CO₂) in the produced gas at the current reservoir pressure (219.3 bar) and reservoir temperature (366.5 K). This process is usually called the injection-gas enrichment. Based on the predictive method presented by Jaubert *et al.* (1995), we obtained the MME of different enrichment agent

**Fig. 3.** Phase plot of condensate oil and remaining condensate gas in the reservoir at the pressure of 219.3 bar.

(CO₂, C₂H₆, C₃H₈ and C₄₋₆). The ternary plots for different enrichment agent when the miscibility was achieved are shown in Figure 11. As can be seen from Figure 11, the phase envelopes for different enrichment agent are different. The triangle-shaped curves are formed for the make-up gas (enrichment agent) of CO₂ and C₂H₆, and

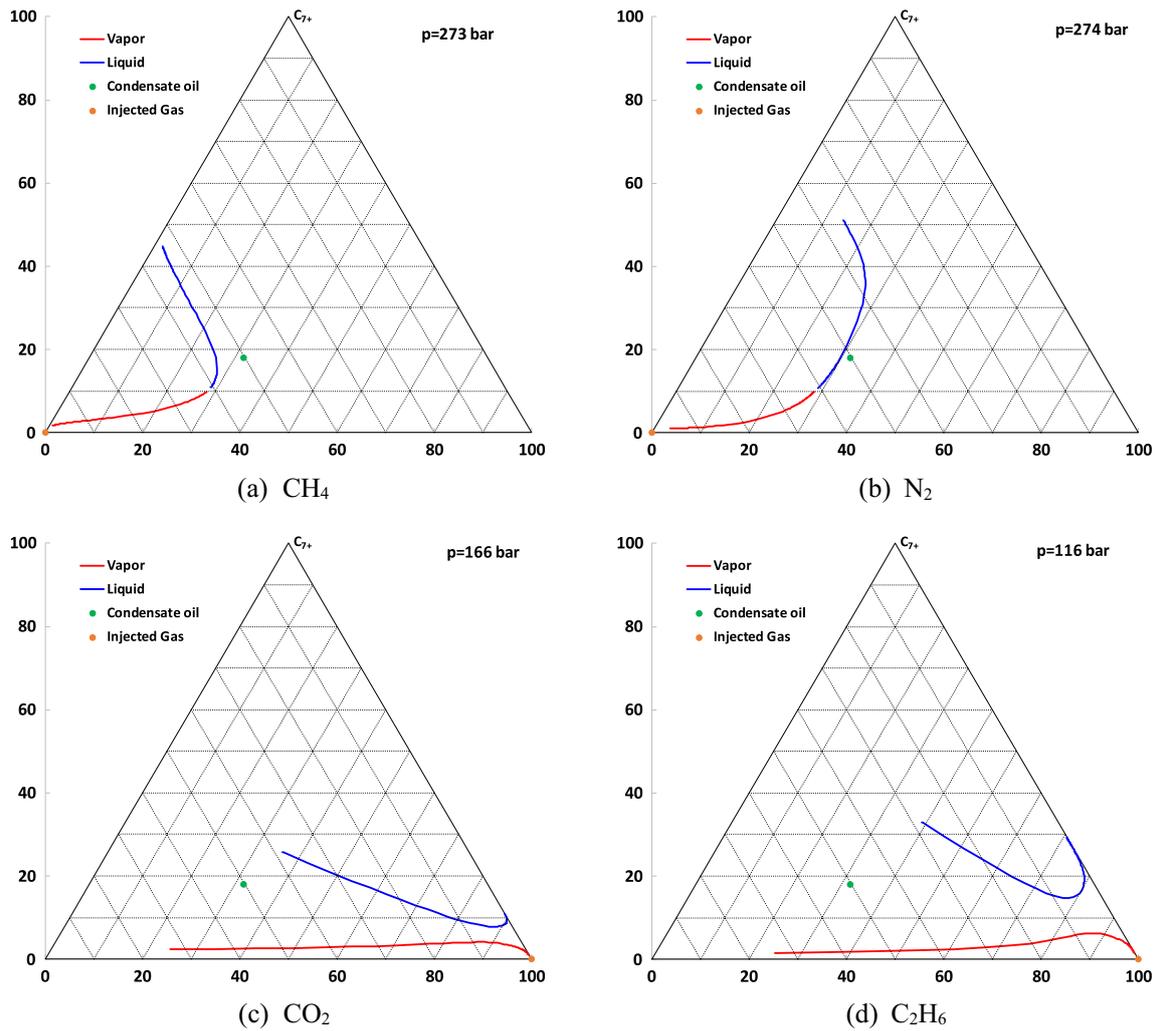


Fig. 4. Ternary plots for pure CH₄, N₂, CO₂ and C₂H₆ injection at 366.5 K.

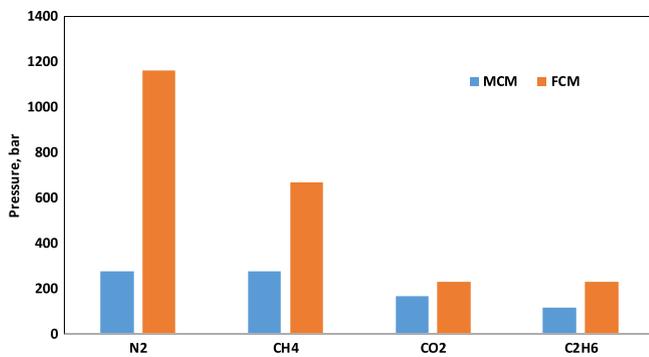


Fig. 5. Minimum pressure of MCM and FCM with different gas type.

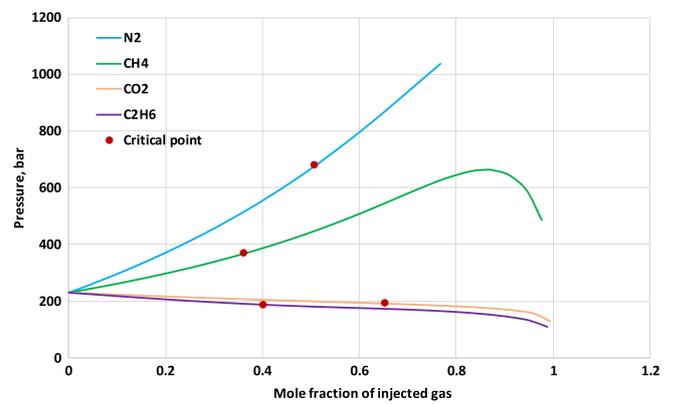


Fig. 6. Pressure-composition diagram for different gas type.

half-hourglass-shaped curves for C₃H₈ and C₄-6. The MME of different enrichment agent decreases as follows: CO₂, C₂H₆, C₃H₈ and C₄-6. The MME of CO₂ has the maximum

value of 0.71, and that of C₄-6 has the minimum value of 0.10. It also indicates that the enrichment ability of hydrocarbons is better than that of no-hydrocarbons as expected.

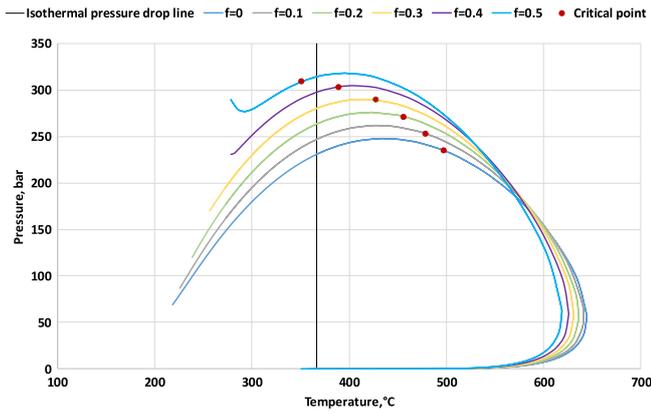


Fig. 7. Phase plot of condensate oil mixed with different mole fraction of produced gas.

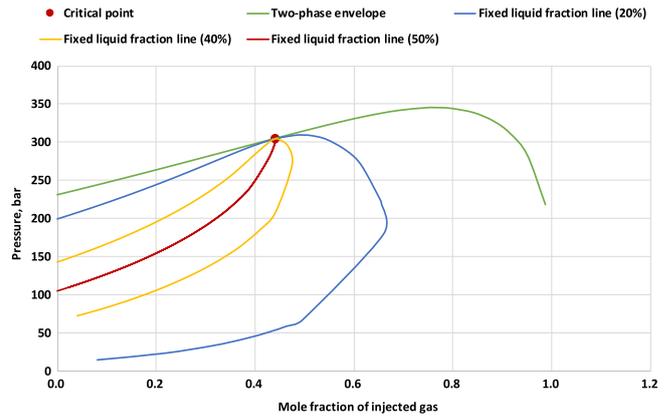


Fig. 9. Pressure-composition diagram for injecting produced gas.

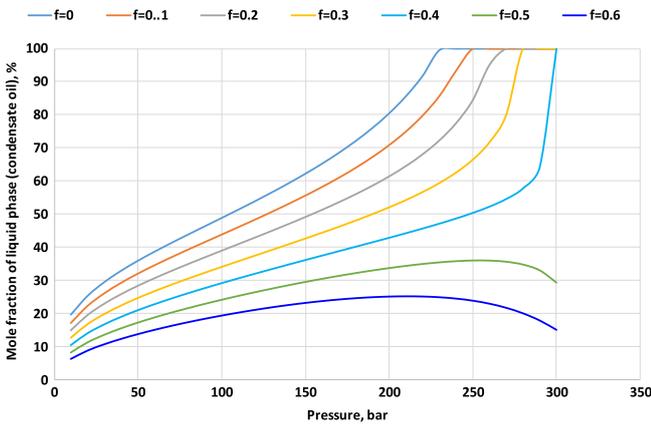


Fig. 8. The effect of mole fraction of injection gas (produced gas) on the condensate oil volume.

3.2 Remaining condensate gas

In order to investigate the effect of gas injection on the remaining condensate gas, the phase behavior of remaining condensate gas mixed with different mole fraction of produced gas was performed based on the PR EOS (shown in Fig. 12). Here, the type of injection gas is set to the produced gas as shown in Table 3. It can be easily found that at the reservoir temperature of 366.5 K, the dew point pressure of remaining condensate gas decreases with the increase of mole fraction of injection gas. For example, the dew point pressure is 231.7 bar at first, and drops to 182.6 bar when the mole fraction of injection gas is 0.8. It means that the retrograde condensation is more difficult to occur after injecting produced gas, which is beneficial to enhance the recovery of condensate oil. Furthermore, the greater the mole fraction of injection gas, the smaller the two-phase region. This indicates that the remaining condensate gas develops toward dry gas after injecting gas.

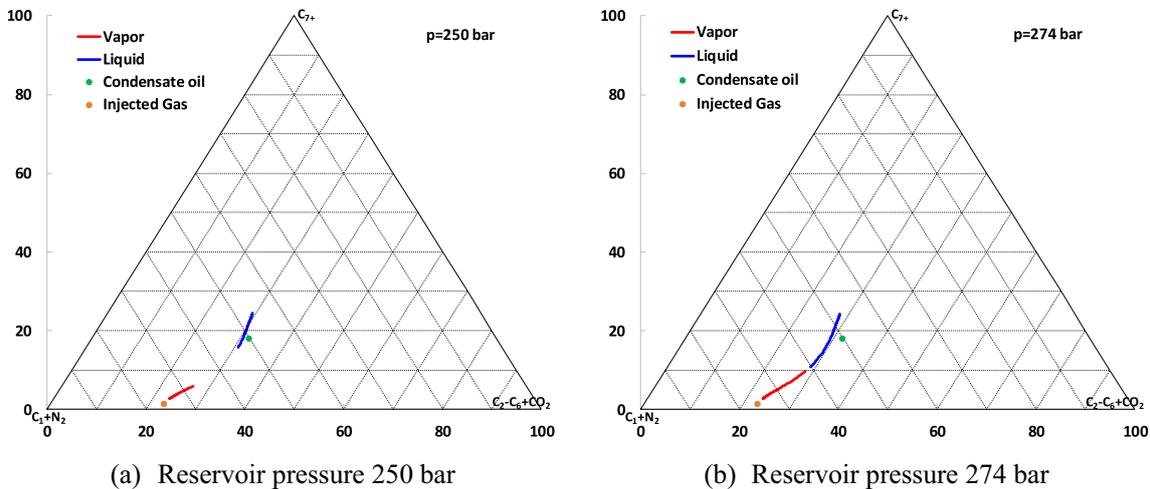


Fig. 10. Ternary plot from multiple contact calculation for injecting produced gas at 366.5 K.

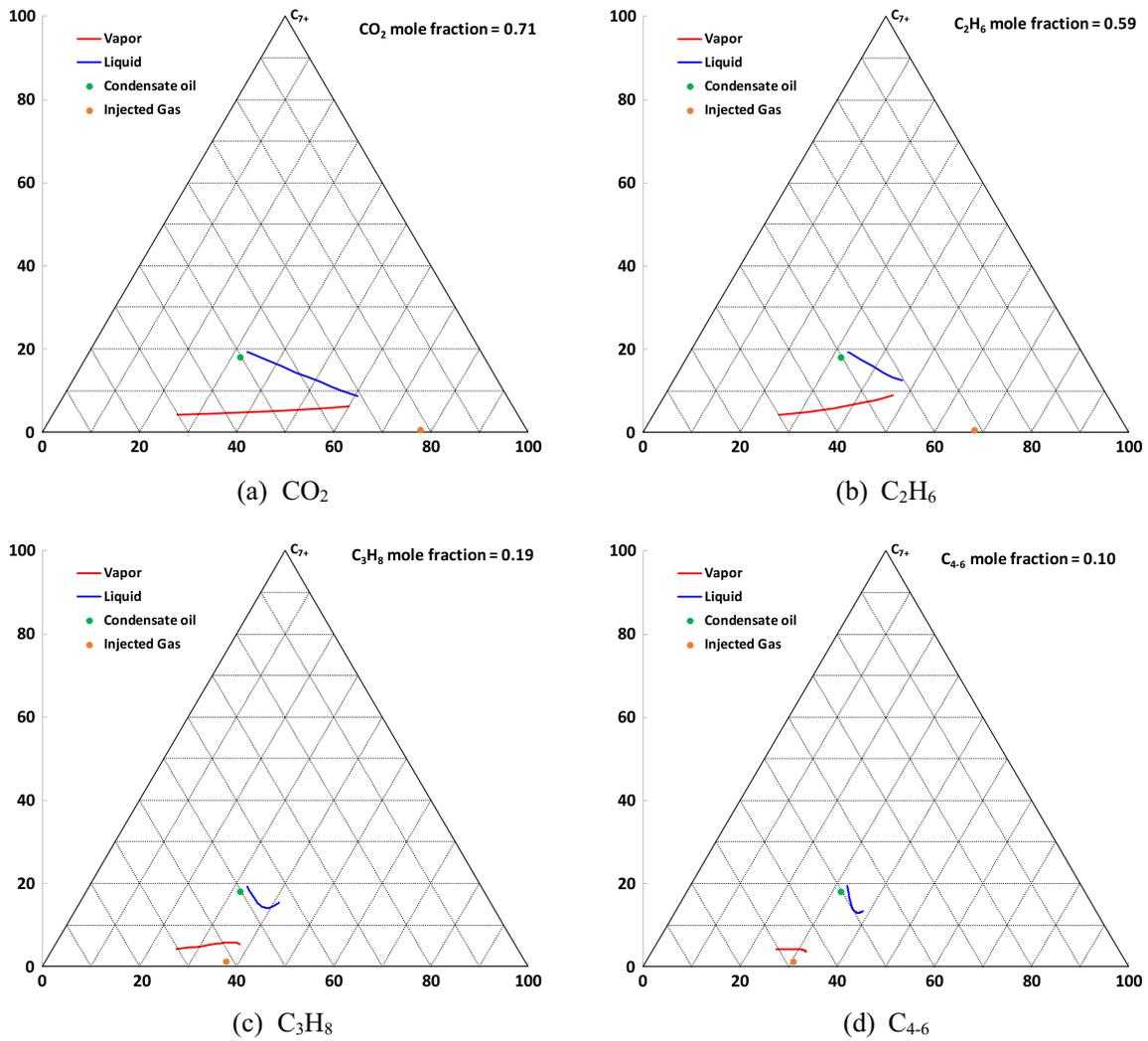


Fig. 11. Ternary plot for different enrichment agent at 366.5 K.

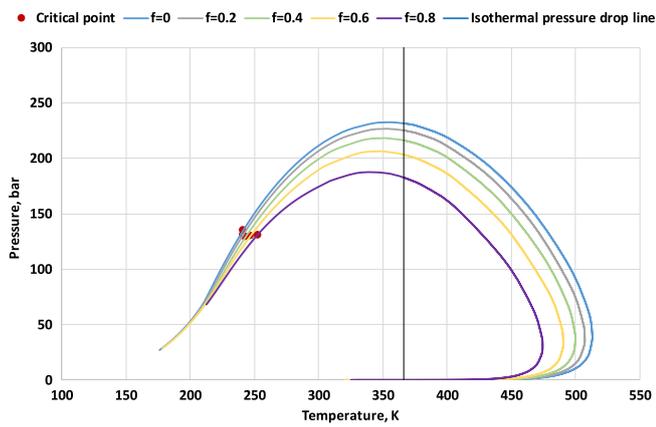


Fig. 12. Phase plot of remaining condensate gas mixed with different mole fraction of produced gas.

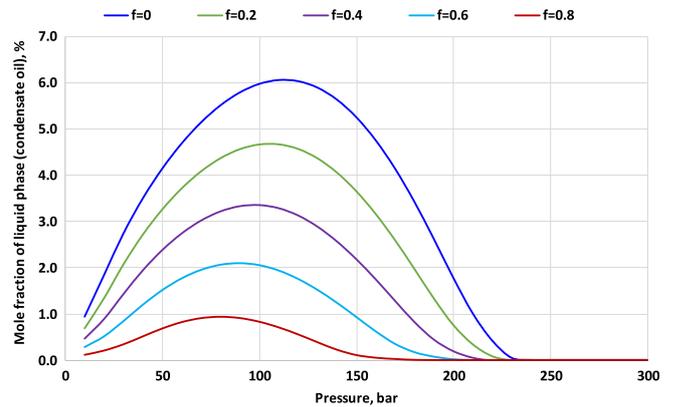


Fig. 13. The influence of injection-gas mole fraction on the condensate oil saturation precipitated from the remaining condensate gas.

Figure 13 shows the influence of injection-gas mole fraction on the condensate oil saturation precipitated from the remaining condensate gas. As shown in Figure 13, the larger the mole fraction of injection gas, the less condensate oil is precipitated from the remaining condensate gas. For example, at the pressure of 150 bar, the condensate oil saturation is 5.3% with no gas injection, but it declines to 0.1% when the injection-gas mole fraction increases to 0.8. This also indicates that the injection of produced gas can prevent the further precipitation of condensate oil.

4 Conclusion

The following conclusions can be summarized from the results of this work:

1. The phase envelopes of different pure gas in the multiple contact with condensate oil are quite different. The bell-shaped phase envelopes were generated for pure CH₄ and N₂, and hourglass-shaped phase envelopes for pure CO₂ and C₂H₆. Different pure gas has different miscible mechanism in the displacement of condensate oil: vaporizing gas drive for N₂ and CH₄; condensing gas drive for CO₂ and C₂H₆.
2. The greater the mole fraction of injection gas (produced gas), the more volatile the condensate oil. The main mechanism of injecting produced gas is the vaporizing gas drive. Phase-behavior reversal of petroleum mixture occurs when the condensate oil is mixed with 0.44 mole fraction of produced gas, that is, the condensate oil is converted to condensate gas.
3. The dew point pressure of remaining condensate gas decreases with the increase of mole fraction of injection gas (produced gas). The remaining condensate gas develops toward dry gas after gas injection. The injection of produced gas can prevent the further precipitation of condensate oil.

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