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Research Article

Experimental Study on the Effect of CO_2 on Phase Behavior Characteristics of Condensate Gas Reservoir

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In this paper, the DBR all-visible mercury-free high-temperature and high-pressure multifunctional formation fluid PVT analyzer developed and produced by Schlumberger company is used to conduct an experimental study on phase behavior characteristics of one offshore high CO_2 condensate gas wells. The experiments include two-phase flash experiment, constant composition expansion experiment (CCE experiment), and constant volume depletion experiment (CVD experiment). Experimental results show that the higher the CO_2 content in the condensate gas system, the higher the gas-oil ratio of condensate gas, the greater the density of condensate oil, the higher the dew point pressure of condensate gas, the greater the relative volume of condensate gas, the smaller the amount of retrograde condensate oil. And the higher the CO_2 content in the condensate gas system, the phase diagram is shifted to the left and up, the critical point of the phase diagram is shifted to the lower left, the smaller the area of the two-phase envelope, the lighter the condensate gas system, the condensate oil recovery is higher. The above experimental results revealed that CO_2 is well soluble with condensate gas, the expansion capacity of the condensate gas system was slightly enhanced, and because CO_2 has a good extraction capacity, the light components of condensate gas were constantly extracted, the retrograde condensate rate of condensate oil decreases, and the maximum retrograde condensate volume also decreased. However, the condensate oil was produced along with the natural gas, and the higher the CO_2 content, the stronger the extraction, the more condensate oil was produced. It is mainly because CO_2 has the strong gasification and extraction capacity, on the one hand, the retrograde condensation of condensate gas was inhibited, and on the other hand, reverse evaporation of condensate oil was enhanced. The above experimental results indicate the law of the effect of CO_2 on the phase behavior characteristics of condensate gas reservoirs, providing theoretical basis and guidance for the efficient development of condensate gas reservoirs at sea.

1. Introduction

With the development of natural gas industry and the improvement of exploration and development technology, more and more CO_2-containing natural gas reservoirs have been discovered. Volcanic gas reservoirs containing CO_2 have been found in Songliao, Bohai Bay, and Junggar basins. respectively [1–4], and the CO_2 mole fraction of gas reservoirs is 20%~98%. Recently, a highly CO_2-containing condensate gas reservoir has been discovered in the Bohai Bay of China, which is very rare at home and abroad and different from conventional CO_2-containing natural gas reservoirs. It does not belong to the pure condensate gas reservoir and also does not belong to the pure CO_2 gas reservoir [5, 6]. The high CO_2 content in condensate gas reservoir, as a special type of reservoir, the biggest difference with conventional containing CO_2 gas reservoir is that the complex phase behavior characteristics were presented in the process of development. At the same time, as CO_2 is quite different from natural gas in critical pressure, critical temperature, viscosity, etc, the research of phase behavior characteristics of high CO_2 content in condensate gas reservoir is more important [7–9]. Therefore, understanding the phase behavior characteristics of high CO_2 condensate gas reservoirs is the key problem to develop high CO_2 condensate gas reservoirs and enhance recovery of condensate oil and natural gas. Previous studies have been conducted on the phase behavior characteristics of natural gas reservoirs and condensate gas containing CO_2, N_2, or water vapor [10–25]. Vogel and Yarborough studied on the effect of N_2 on the phase behavior and physical properties of reservoir fluids, which include gas condensate and black oil in 1980 [10]. Sahimi et al. established thermodynamic modeling of phase and tension behavior of CO_2/hydrocarbon systems in 1981 [11]. Kuan et al. established a multicomponent phase behavior modeling for CO_2/water/hydrocarbon system in 1983 [12]. Ng and Robinson carried out an experimental study on the influence of water and carbon dioxide on the phase behavior and properties of a condensate gas fluid in 1986 [13]. Flroozabadi et al. established an EOS for predicting the compressibility and phase behavior containing water, hydrocarbons, and CO_2 in 1986 [14]. Chaback and Williams conducted research on the P-X phase behavior characteristics and retrograde condensate liquid volume of CO_2 and $CO_2 + N_2$ injected into the condensate gas reservoir at different temperatures in 1994 [15]. Zuo et al. carried out a simulation study on phase equilibria of hydrocarbon-water/brine systems in 1996 [16].Kokal et al. experimentally studied on the phase behavior of gas condensate/water system in 2000 [17]. In 2004, Pedersen and Milter experimentally studied on phase equilibrium between gas condensate and brine at HT/HP conditions and carried out a simulation study for the above experimental study [18]. In 2011, Gachuz-Muro et al. experimentally studied on the phase behavior characteristics of CO_2 and N_2 injected into the condensate gas reservoir under the conditions of 334°F and 8455 psia and compared the relationship between condensate oil and gas recovery in several ways (natural pressure drop and injection of CO_2 and N_2) [19]. Mohebbinia et al. studied on the four-phase equilibrium calculations of CO_2/hydrocarbon/water system with a reduced method in 2013 [20]. Hou et al. carried out the phase behavior characteristics of a near-critical condensate and the phase behavior characteristics of the residual condensate oil and gas system CO_2 injected in 2013 [21]. Yushchenko and Brusilovsky established mathematical modeling for predicting PVT properties of gas condensate and brine mixture in 2016 [22]. Feng studied on the phase behavior characteristics of CO_2 injection in Lian 4 condensate gas reservoir in Fushan oilfield and CO_2 injection to enhance condensate oil recovery in 2016 [23]. In 2017, Abbasov et al. experimentally studied on the solubility of the gas components in the natural gas-condensate systems. Experimental data demonstrate that the vaporized volume of condensate in the gas phase decreases while the volume of N_2 increases in the fluid. Conversely, the volume of vaporized condensate increases if CO_2 increases in the fluid. And the values of dew pressures increase with the increase of N_2 and, vice versa, increasing the portion of the CO_2 in the gas-condensate fluid decreases the dew pressures. The reason for this is that the solubility of CO_2 is better than that of N_2 [24]. In 2017, Wang et al. carried out an experimental study on gas-condensate system with water vapor and used several equations of state (PR, PR78, SRK, SRK-HV, and CPA-SRK) to demonstrate the solubility data and the prediction of gas-related properties [25]. In 2019, Huang Liu et al. carried out the phase behavior experiment of CO_2-crude oil system in porous media and PVT test units, respectively. And the experimental results were analyzed. Meanwhile, based on the experimental data, an improved equation of state was established to describe the phase behavior characteristics of CO_2-crude oil system in porous media and PVT test units [26]. From the above literature review, the fluid samples used in the experiments and simulation studies on the effect of CO_2 on the phase characteristics of condensate gas reservoirs and crude oil are mostly simulated samples, rather than real reservoir fluid samples. However, according to the experimental and simulation results, when the content of N_2 or CO_2 in the condensate gas reservoir increases, the dew point pressure of the condensate gas will increase, and the dew point pressure of the condensate gas reservoir will decrease due to the gaseous water, while the bubble point pressure of the crude oil will increase. In summary, there are few studies and field tests on the influence of CO_2 on the phase behavior characteristics of condensate gas reservoirs and on the rational utilization of CO_2 to improve the recovery of condensate gas reservoirs.

Therefore, two-phase flash experiment, constant composition expansion experiment, and constant volume depletion experiment were carried out by using three high CO_2 condensate gas samples from Bohai Bay reservoir. Based on the experimental results, the PVT phase behavior characteristics and physical and chemical properties of the reservoir fluid during the development of condensate gas reservoirs with different CO_2 content were revealed, which provides a more reliable theory basis for the reasonable development of the condensate gas reservoirs and enhances the recovery of condensate oil and natural gas.

2. Experiment

2.1. Sample Preparation. The samples in this study were taken from the Qin Huangdao 29-2 oilfield with an oil ring condensate gas reservoir with high CO_2 content, located in Bohai Bay, China. Phase behavior experiment for three groups of condensate gas samples with different CO_2 content was carried out in this study, including two-phase flash experiment, constant composition expansion experiment, and constant volume depletion experiment. Among them, the condensate gas with CO_2 content of 41.554% is the sample taken from the Qin Huangdao 29-2 oilfield, which is compounded with the samples obtained by the surface separator and compounded according to the original formation conditions. The original reservoir conditions are shown in Table 1. Since the sample is an oil ring condensate gas reservoir with extra high CO_2 content, that is, saturated

Table 1: Experimental conditions (original reservoir conditions).

Sample no.	Reservoir temperature (°C)	Reservoir pressure (MPa)	Gas-oil ratio (m^3/m^3)	CO_2 content (mol%)
1	113.6	31.08	1715	41.554
2	The sample was prepared by adding a certain proportion of pure CO_2 to condensate gas with CO_2 content of 41.554% in the laboratory, and the CO_2 content of the compound sample was 51.611 mol%			
3	The sample was prepared by adding a certain proportion of pure CH_4 to condensate gas with CO_2 content of 41.554% in the laboratory, and the CO_2 content of the compound sample was 24.011 mol%			

sample, the difference between reservoir pressure and dew pressure is 0. So the sample compounding process is conducted in strict accordance with Chinese oil and natural gas industry standard "SY/T 5542-2009 fluid property analysis method for oil and gas reservoirs" [27]. Sample 2 was prepared by adding a certain proportion of pure CO_2 to condensate gas with CO_2 content of 41.554% in the laboratory. Sample 3 was prepared by adding a certain proportion of pure CH_4 to condensate gas with CO_2 content of 41.554% in the laboratory. The well fluid composition of three groups of samples is calculated from the flash gas composition, flash oil composition, and gas-oil ratio (as shown in Table 2). The detailed calculation process refers to the Chinese oil and natural gas industry standard "SY/T 5542-2009 fluid property analysis method for oil and gas reservoirs" [27].

2.2. Experimental Equipment and Process. The PVT phase behavior characteristic experiment of reservoir fluid was carried out in DBR all-visible mercury-free high-temperature and high-pressure multifunctional PVT analyzer (Figure 1) developed and produced by Schlumberger. The device is equipped with a 100 ml whole visible high-temperature and high-pressure PVT test unit, and the test accuracy is 0.01 ml; temperature ranges from 0 to 200°C, and the test accuracy is 0.1°C; pressure ranges from 0.1 to 103 MPa, and the test accuracy is 0.01 MPa. The PVT test unit of DBR reservoir fluid analyzer is equipped with a cone piston, which forms a small annular volume space between the inner wall of the visible PVT cylinder and the piston, and can accurately test a small amount of liquid in the sample by external altimeter. Thus, the instrument can adapt the requirement of studying the phase behavior characteristics of various oil and gas systems.

The main experiments carried out in this study include two-phase flash test, constant composition expansion experiment, and constant volume depletion experiment. The details of experimental procedures and procedures have been described in previous articles [28], which are not elaborated here.

3. Results and Discussions

3.1. Two-Phase Flash Experimental Results. Under the condition of reservoir pressure, the condensate samples were tested by two-phase flash test to measure the condensate oil volume, gas volume, and condensate oil density and calculate the flash gas-oil ratio and reservoir volume factor. The well fluid composition is calculated by the composition of the flash oil and gas obtained by chromatographic analysis. Two-phase flash test results of condensate gas with different CO_2 content are shown in Table 3. It can be seen from Table 3 that the flash gas-oil ratio of sample 1 is 1720 m^3/m^3, which is very close to the gas-oil ratio of production. It proves that the compounded fluid sample can well represent the reservoir fluid sample. Under the standard conditions (0.1 MPa and 20°C), the condensate density is 0.7796 g/cm^3, and the reservoir volume factor of condensate gas is 0.00369. The flash gas-oil ratio of sample 2 is 2179 m^3/m^3, and the condensate density was 0.7804 g/cm^3 under standard conditions (0.1 MPa and 20°C), and the reservoir volume factor of condensate gas is 0.00355. The flash gas-oil ratio of sample 3 is 1350 m^3/m^3, and the condensate density was 0.7772 g/cm^3 under standard conditions (0.1 MPa and 20°C), and the reservoir volume factor of condensate gas is 0.00398.

According to the national standard, sample 1, sample 2, and sample 3 are typical fluids of condensate gas reservoir with low gas-oil ratio and light condensate oil. At the same time, it can be seen from Table 3 that the higher the CO_2 content in the condensate gas, the higher the gas-oil ratio of condensate gas, the higher the condensate oil density, and the reservoir volume factor of condensate gas is smaller. It is showed that CO_2 can be well mutually soluble with condensate gas, which makes the gas-oil ratio of condensate gas increase. At the same time, as CO_2 has a good extraction capacity, the light components of condensate oil are continuously extracted, which makes the flash condensate oil density increase and the reservoir volume factor of condensate gas decrease.

3.2. Constant Composition Expansion Experimental Results. Constant composition expansion (CCE) experiment, also known as test P-V relation experiment, is under constant reservoir temperature the relationship between the relative volume (that is, the ratio of the volume of each pressure in reservoir temperature and the volume of the dew point pressure) and pressure of condensate gas samples in condensate gas reservoirs was measured. At the same time, the relationship between the amount of retrograde condensate oil and pressure was obtained. While measuring the relationship between the relative volume and pressure, the phase change of condensate gas can be observed through the observation window. When the first droplet is formed in the gas phase in the PVT test unit, the pressure at this time should be recorded. Raise the pressure again and return to the original reservoir pressure, stir and make the fluid to its original state, and repeat the process for 2-3 times, record the pressure of the first droplet appears every time, and take the

Table 2: The well fluid composition of three condensate gas samples with different CO_2 content.

Component	The well fluid composition of sample 1 (mol%)	The well fluid composition of sample 2 (mol%)	The well fluid composition of sample 3 (mol%)	C_{11+} properties of the three samples
N_2	0.983	0.960	1.278	
CO_2	41.554	51.611	24.011	The well fluid composition of sample 1 C_{11+} relative density. The well fluid composition of sample 1 molecular mass: 0.8259, 188.95 g/mol
C_1	42.136	35.786	54.782	
C_2	3.615	3.002	4.700	
C_3	2.503	2.110	3.254	
iC_4	0.519	0.431	0.675	
nC_4	1.167	0.941	1.517	The well fluid composition of sample 2 C_{11+} relative density. The well fluid composition of sample 2 molecular mass: 0.8456, 195.82 g/mol
iC_5	0.463	0.350	0.602	
nC_5	0.506	0.348	0.658	
C_{6+}	0.524	0.292	0.681	
C_7	0.439	0.303	0.571	
C_8	0.807	0.558	1.049	The well fluid composition of sample 3 C_{11+} relative density. The well fluid composition of sample 3 molecular mass: 0.8006, 175.64 g/mol
C_9	0.843	0.583	1.096	
C_{10}	0.842	0.582	1.095	
C_{11+}	3.101	2.143	4.032	

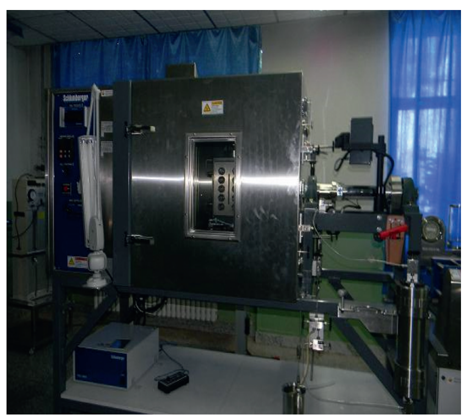

Figure 1: DBR all-visible mercury-free high-temperature and high-pressure multifunctional PVT analyzer.

Table 3: Two-phase flash experimental results of condensate gas with different CO_2 content.

Parameter	CO_2 content		
	41.554 mol% (sample 1)	51.611 mol% (sample 2)	24.011 mol% (sample 3)
GOR, m^3/m^3	1720	2179	1350
Condensate oil density, g/cm^3	0.7796	0.7804	0.7772
Formation volume factor, B_g	0.00369	0.00355	0.00398

average value of the above pressure as dew point pressure [27]. The constant composition expansion experimental results of condensate gas with different CO_2 content are shown in Table 4 and Figures 2 and 3. As can be seen from Table 4 and Figures 2 and 3, the higher the CO_2 content in the condensate gas, the lower the dew point pressure of condensate gas, the greater the relative volume of condensate gas, the smaller the amount of retrograde condensate oil, which shows that CO_2 can be well mutually soluble with condensate gas, the elastic expansion capacity of condensate gas is slightly enhanced, the volume of fluid is slightly larger, the retrograde condensate velocity of condensate oil is slowed down, and the maximum retrograde condensate oil volume is also reduced. It is mainly because the CO_2 has a strong gasification and extraction capacity, on the one hand, it can restrain the retrograde condensation of condensate gas, and on the other hand, the extraction and evaporation of condensate oil were enhanced.

3.3. Constant Volume Depletion Experimental Results. The condensate gas samples with different CO_2 content were carried out by constant volume depletion experiment to simulate the depletion production process of condensate gas reservoir with different CO_2 content and the condensate oil recovery under different depletion pressure. Experimental results of constant volume depletion of condensate gas with different CO_2 content are shown in Figure 4 and Figure 5. It

TABLE 4: Dew point pressure experimental results of condensate gas with different CO_2 content.

Sample	Sample 1 (CO_2 content is 41.554 mol%)		Sample 2 (CO_2 content is 51.611 mol%)		Sample 3 (CO_2 content is 24.011 mol%)	
Parameter	Temperature (°C)	P_d (MPa)	Temperature (°C)	P_d (MPa)	Temperature (°C)	P_d (MPa)
Experimental values	*113.6	30.85	*113.6	29.77	*113.6	31.46

*Reservoir temperature; P_d is the dew point pressure.

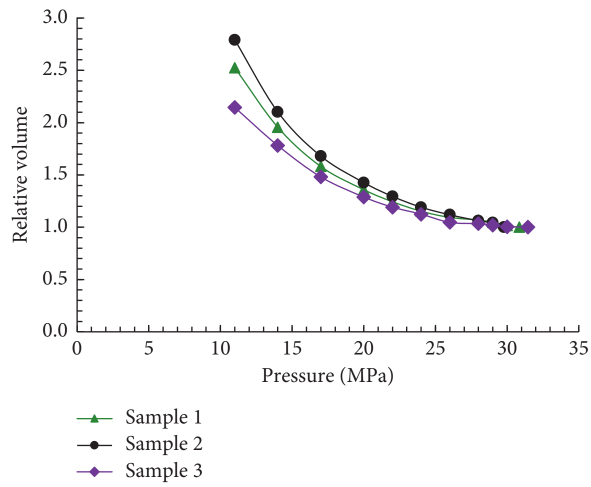

FIGURE 2: P-V diagram of condensate gas with different CO_2 content.

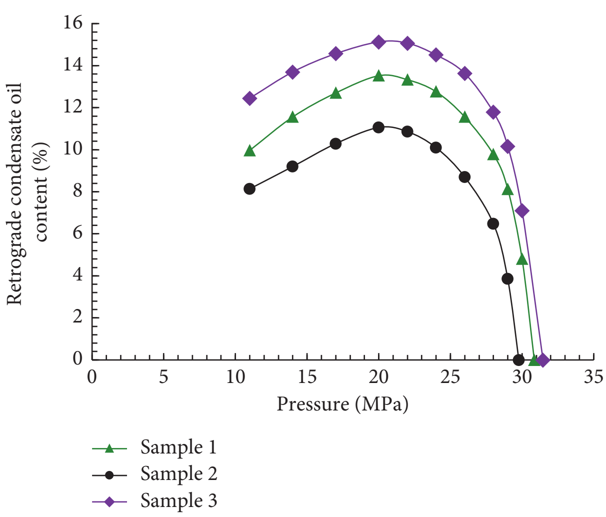

FIGURE 3: The relationship diagram between retrograde condensed liquid volume and pressure of condensate gas with different CO_2 content.

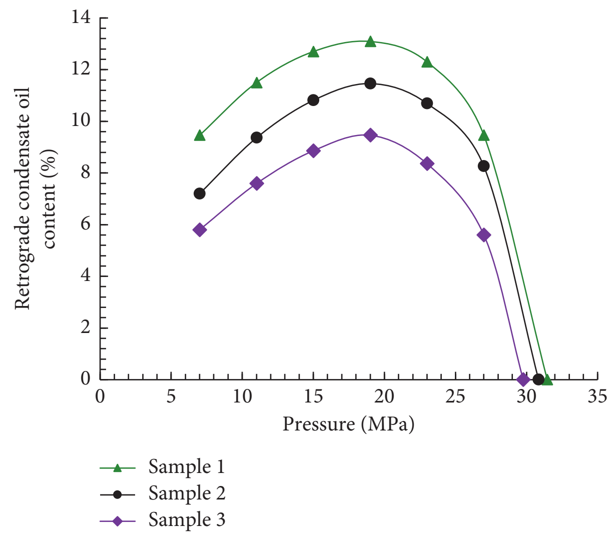

FIGURE 4: The relationship diagram between retrograde condensate liquid volume and pressure of condensate gas with different CO_2 content.

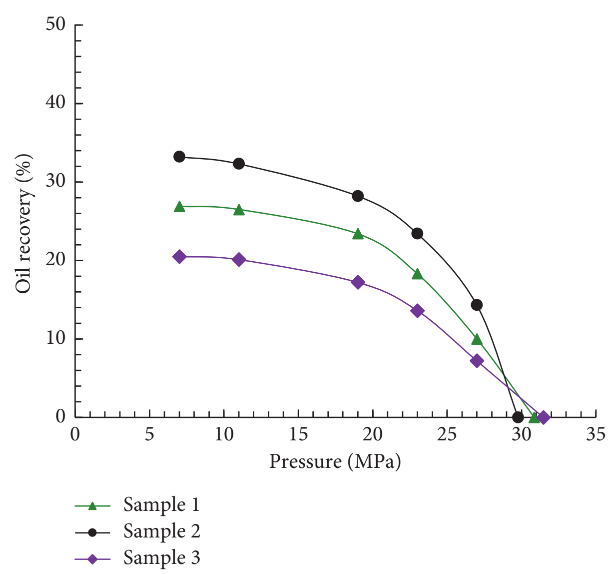

FIGURE 5: The relationship diagram between the condensate oil recovery and pressure of condensate with different CO_2 content.

can be seen from Figure 4 that the higher the CO_2 content in the condensate gas, the retrograde condensate velocity of condensate oil is slowed down, and the maximum retrograde condensate oil volume is also reduced. It is mainly because the CO_2 has a strong gasification and extraction capacity, on the one hand, it can restrain the retrograde condensation of condensate gas, and on the other hand, the extraction and evaporation of condensate oil were enhanced. As can be seen from Figure 5, the higher the CO_2 content in the condensate gas, the higher the recovery of condensate oil, indicating that CO_2 is constantly extracting light components from the condensate oil and as the gas is produced. The higher the CO_2 content, the stronger the extraction ability, and the more condensate oil is produced. At the same time, the condensate oil recovery increases with the decrease of pressure, but the slope of the curve becomes smaller and

Table 5: Matching results of dew point pressure, gas-oil ratio, and condensate oil density between the experimental data and calculated values.

Parameter	Experiment	Calculation	Relative error %
Sample 1 (CO_2 content is 41.554 mol%)			
Dew point pressure (MPa)	30.85	30.88	0.10
Gas-oil ratio (m^3/m^3)	1720	1764	2.56
Condensate oil density (0.1 MPa and 20°C) (kg/m^3)	0.7796	0.7817	0.27
Sample 2 (CO_2 content is 51.611 mol%)			
Dew point pressure (MPa)	29.77	29.56	0.71
Gas-oil ratio (m^3/m^3)	2179	2249	3.21
Condensate oil density (0.1 MPa and 20°C) (kg/m^3)	0.7804	0.7971	2.14
Sample 3 (CO_2 content is 24.011 mol%)			
Dew point pressure (MPa)	31.46	31.55	0.29
Gas-oil ratio (m^3/m^3)	1350	1364	1.04
Condensate oil density (0.1 MPa and 20°C) (kg/m^3)	0.7772	0.7785	0.17

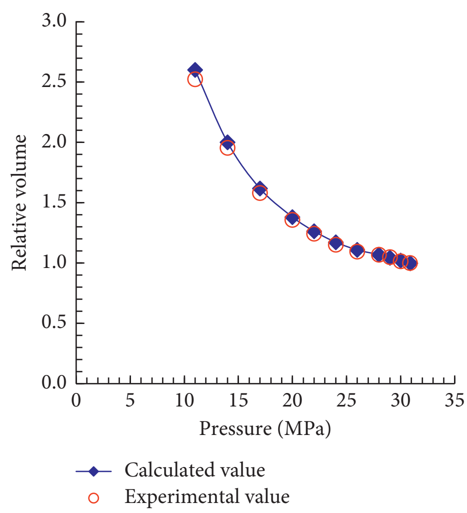

Figure 6: Comparison for sample 1 of calculated and experimental relationship diagram between relative volume and pressure.

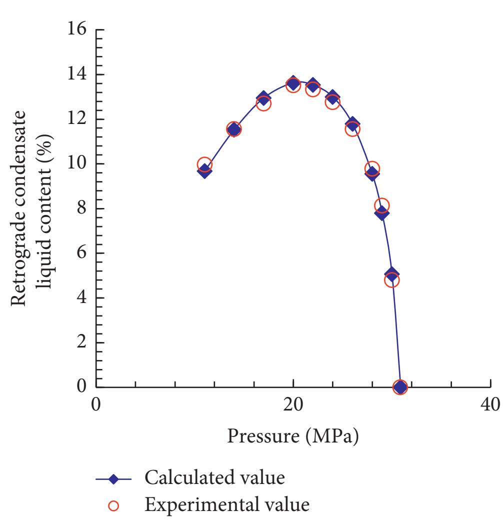

Figure 7: Comparison for sample 1 of calculated and experimental relationship diagram between retrograde condensate liquid volume and pressure.

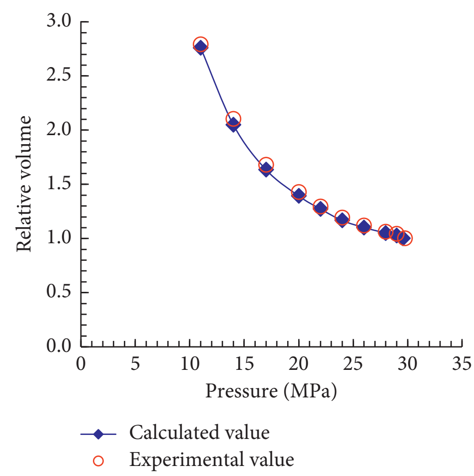

Figure 8: Comparison for sample 2 of calculated and experimental relationship diagram between relative volume and pressure.

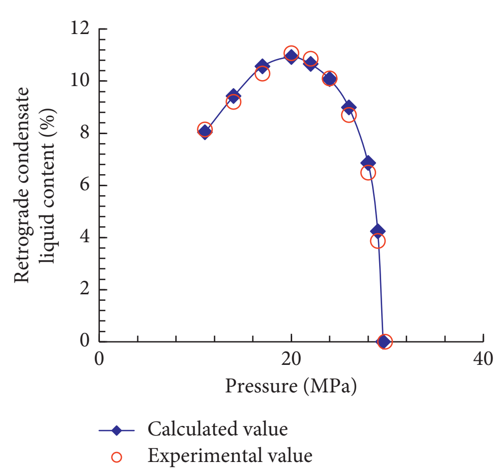

Figure 9: Comparison for sample 2 of calculated and experimental relationship diagram between retrograde condensate liquid volume and pressure.

smaller, and the growth rate slows down with the decrease of pressure, and the curve shows an upward trend. It is mainly due to the decrease of pressure, the more retrograde

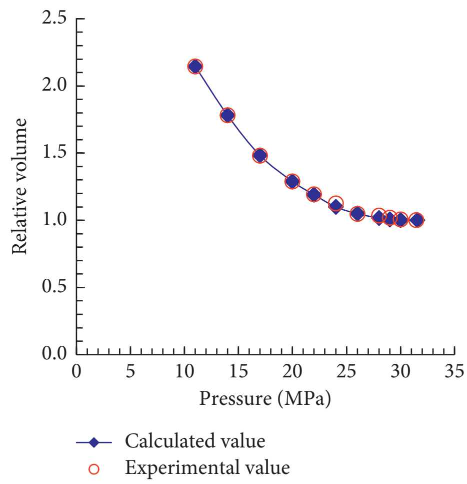

FIGURE 10: Comparison for sample 3 of calculated and experimental relationship diagram between relative volume and pressure.

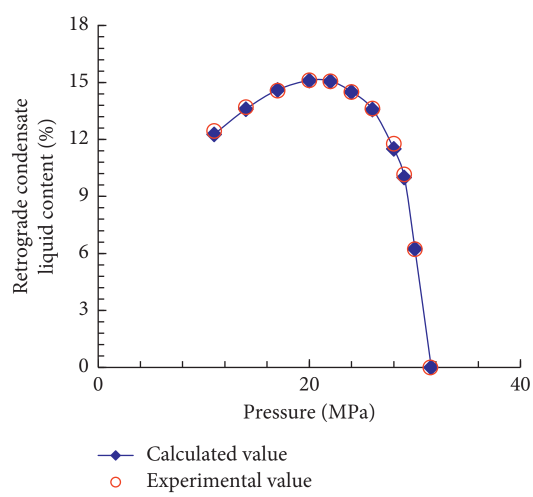

FIGURE 11: Comparison for sample 3 of calculated and experimental relationship diagram between retrograde condensate liquid volume and pressure.

condensate oil volume, the more deposition of heavy components, the condensate gas produced is lighter, the condensate oil content produced is lower, and the production speed is slower.

3.4. Simulation Study of Phase Behavior. On the basis of the experiment, CMG numerical simulation software was used to fit the experimental data, and the P-V relationship, dew point pressure, gas-oil ratio, condensate density (0.1 MPa and 20°C), retrograde condensed liquid volume, and P-T phase diagram of sample 1, sample 2, and sample 3 reservoir fluid were calculated, respectively. The calculated values are very close to the experimental values, and the relative errors are all less than 4%. The fitting results and the calculated P-T phase diagram are shown in Table 5 and Figures 6~12. As can be seen from Table 5 and Figures 6–12, sample 1 sample 2, and sample 3 are typical reservoir fluids of condensate gas with low gas-oil ratio and light condensate oil. Meanwhile, it

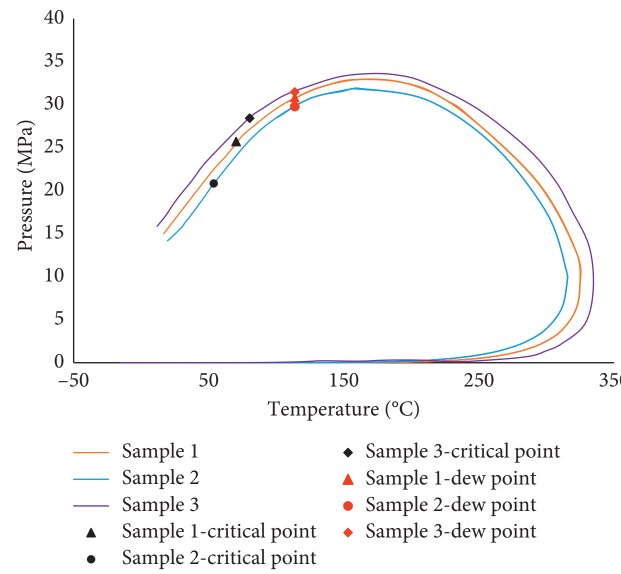

FIGURE 12: Comparison diagram of P-T phase diagram between sample 1, sample 2, and sample 3.

can be seen from the comparison P-T phase diagram between sample 1, sample 2, and sample 3 that the higher the CO_2 content in the condensate gas, the critical point is shifted to the lower left, the phase diagram is shifted to the left, and the envelope area of the two phases becomes smaller, and it means the system is getting lighter.

4. Conclusion

(1) Because CO_2 has a good extraction capacity, the light components and intermediate components of condensate gas are continuously extracted, which makes the flash condensate oil density increase, the reservoir volume factor of condensate gas decrease, and the recovery of condensate oil increase and the more condensate oil is produced.

(2) Because CO_2 has a strong ability to gasify and extract crude oil and dissolve crude oil, which leads to the higher the CO_2 content in the condensate gas, the lower the dew point pressure of condensate gas, the greater the relative volume of condensate gas, the smaller the amount of retrograde condensate oil.

(3) The higher the CO_2 content in the condensate gas, the critical point is shifted to the lower left, the phase diagram is shifted to the left, and the envelope area of the two phases becomes smaller, and it means the system is getting lighter.

Data Availability

The data used to support the findings of this study are available from the relative bioinformatics database.

Conflicts of Interest

All authors solemnly declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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