



Analysis on PVT test and empirical formula of Bohai heavy oil with different types of dissolved gases

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Abstract

Accurate prediction of PVT properties of heavy oil system is of great significance to the design of injection–production parameters and dynamic analysis of multi-thermal fluid stimulation in heavy oil reservoir. The saturation pressure and viscosity of Bohai heavy oil system at different temperature and different gas oil ratio conditions were tested and analyzed. The functional relations of regression equations for saturation pressure and viscosity are constructed based on classical PVT correlations, but the parameters in the equations different from classical correlations are obtained from present experiment test data with multiple regression method. The empirical formula analysis results indicate that the 2-parameter equation can almost completely fit the experimental data, but its application scope is narrow. Although the 4-parameter equation has an extensive adaptability, its fitting accuracy is very low. The 3-parameter equation can not only better fit the saturation pressure and viscosity of heavy oil for the same gas under different dissolved gas oil ratios and different temperatures, but also has a wide application range. It is recommended to use the 3-parameter equation for physical property analysis and calculation of heavy oil. The research results provide a basis for the accurate prediction of heavy oil PVT parameters.

Keywords Heavy oil · Dissolved gas oil ratio · Saturation pressure · Viscosity · Empirical formula

Introduction

The heavy oil reservoirs have wide distributions in the world. It is very difficult to develop the heavy oil reservoirs because of extra high viscosity. The horizontal well multi-thermal fluid stimulation technology is an important way to enhance heavy oil production rate and recovery, especially for the offshore heavy oil reservoir influenced by the factors including limited platform space, economic benefit, environment pollution and operation security (Dong et al. 2014, 2016; Ge et al. 2019; Liu et al. 2020). This technology can effectively increase the production rate of heavy oil by huff and puff or displacement with multi-thermal fluid (Liu et al. 2010; Sun et al. 2011; Hou et al. 2016). Heating and dissolving to reduce viscosity, aquathermal cracking reaction, increasing swept volume, developing hot fluid

chamber, forming non-miscible displacement, reducing heat loss and maintaining pressure are the important mechanisms of enhancing oil recovery by multi-thermal fluids (Liu et al. 2012; Huang et al. 2018; Wang et al. 2019).

Multi-thermal fluid is a mixture of injection water and high temperature and high pressure gas generated by combustion of diesel and air. Multi-thermal fluid is mainly composed of steam, hot water, CO₂, N₂, etc. (Hou et al. 2016). Among them, N₂ and CO₂ are two important non-condensable gases. Both of them can be dissolved in heavy oil and play the role of dissolving, reducing viscosity and improving the steam dryness, but their dissolving abilities in heavy oil are not the same (Li et al. 2010, 2017). Generally speaking, the solubility of gas in heavy oil is affected by composition, pressure and temperature of heavy oil and gas. At low temperature condition, PVT properties of heavy oil are mainly influenced by gas solubility. As temperature increases, the influences of heating effect are more obvious (Chen et al. 2018). Within a certain range of pressure and temperature, both gas dissolution and heating have important influences. At present, many scholars have done a large number of experimental tests on the physical properties of heavy oil under high temperature

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and high pressure conditions, but the existing empirical formulae are not adaptable enough to meet the test results (Sidrouhou and Korichi 2013; Nourozieh et al. 2016; Izurieta and Iza 2017). In order to get more accurate results, some advanced mathematical methods including genetic programming algorithm and neural network models are used to predict oil PVT properties (Fattah 2014; Rammay and Abdulraheem 2017). Because of the complexity of algorithm and uncertainty of model, these methods have not been widely used in prediction of oil PVT properties. In many commercial software, oil PVT properties are usually predicted through interpolation method, especially the prediction points are within the range of existing data. If the prediction points are out of the range, the interpolation method will generate obvious error, and the empirical formulas verified by experimental data has better application effect.

The classical empirical formulas including Standing (1947), Glaso (1980), Vasquez and Beggs (1980) and Al-Marhoun (1988) are widely used to predict PVT properties of oil and gas system. Although these formulas have a certain application scope, they are all regression analysis of specific samples, and are often difficult to be extended to other oil–gas systems in other oil fields. The application effect can often be improve if the functional relation of classical empirical formula remains unchanged, but the coefficient of formula is determined according to specific samples (Petrosky and Farshad 1993; Omar and Todd 1993; Hemmati and Kharrat 2007). In this paper, the saturation pressure and viscosity of heavy oil system with different types of gas including N_2 , CO_2 , CO_2 - N_2 mixture at different temperature and gas oil ratio conditions are tested using high temperature and high pressure PVT instrument. Based on the functional relation of Standing formula, the empirical formula with three parameters for Bohai heavy oil system is obtained with multiple regression method and the application effect is good.

Experimental method and procedure

Experimental equipment and parameters

The main equipment used in this experiment is high temperature and high pressure heavy oil PVT tester, capillary viscometer, sample distributor, electric high pressure metering pump, constant temperature control system, gas booster pump, gas cylinder (CO_2 , N_2 , mixed gas), high temperature and high pressure piston vessel, precise pressure gauge, etc. Among them, heavy oil PTV tester is composed of PVT host and other auxiliary equipment (Figs. 1 and 2). The indexes of PVT host are as follows.



Fig. 1 High temperature and high pressure heavy oil PVT testing equipment

- Temperature regulation range, 0–300 °C, temperature control accuracy ± 0.1 °C.
- Pressure testing range, 0–70 MPa, pressure display accuracy ± 0.1 MPa.
- Volume testing range, 0–300 mL, volume display accuracy 0.01 mL.

Capillary viscometer tests fluid viscosity by testing the flow rate and pressure difference through the capillary tube (Fig. 3). The indexes of capillary viscometer are as follows.

- Pressure testing range, 0–70 MPa
- Pressure display accuracy, 0.01 MPa
- Temperature testing range, 0–300 °C
- Viscosity range, 0–50000 mPa s (according to different size of capillary tube)

Experimental method

At a certain temperature, a certain volume of degassed heavy oil is transferred into the PVT cylinder, and then a certain amount of N_2 , CO_2 or mixed gas is injected into the PVT cylinder through the intermediate container and fully stirred (sample preparation can also be completed in the sample distributor, and then transferred into the PVT cylinder, Fig. 4). According to the development practice of Bohai heavy oil reservoir, the ratio of N_2 and CO_2 in multi-thermal fluid is 85%:15%. For each gas content, depressurize at each temperature, then draw the P – V relationship curve between the heavy oil–gas mixture volume V and the pressure P . At the same time, calculate the gas oil ratio and other parameters.

After P – V relationship curve test, the samples can be transferred to the capillary viscometer to test the viscosity of heavy oil containing dissolved gas. To avoid the difficulty of sample transfer, the sample can also be prepared in the

Fig. 2 Heavy oil PVT testing host

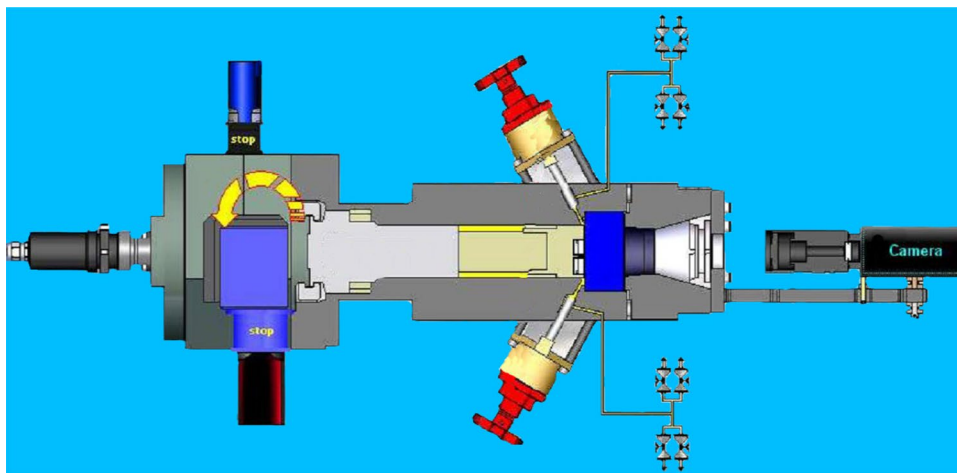
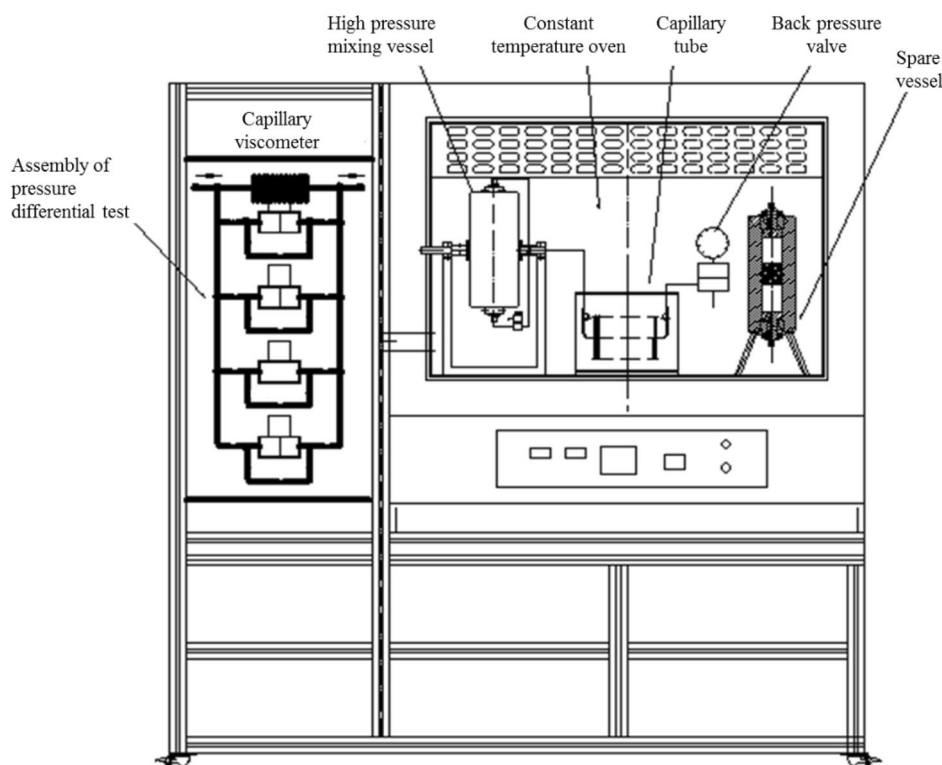


Fig. 3 Structure diagram of capillary viscometer



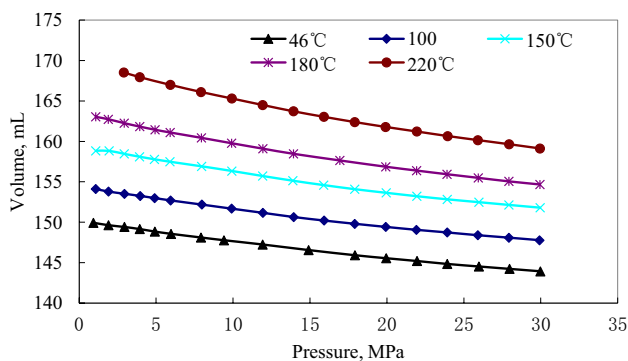
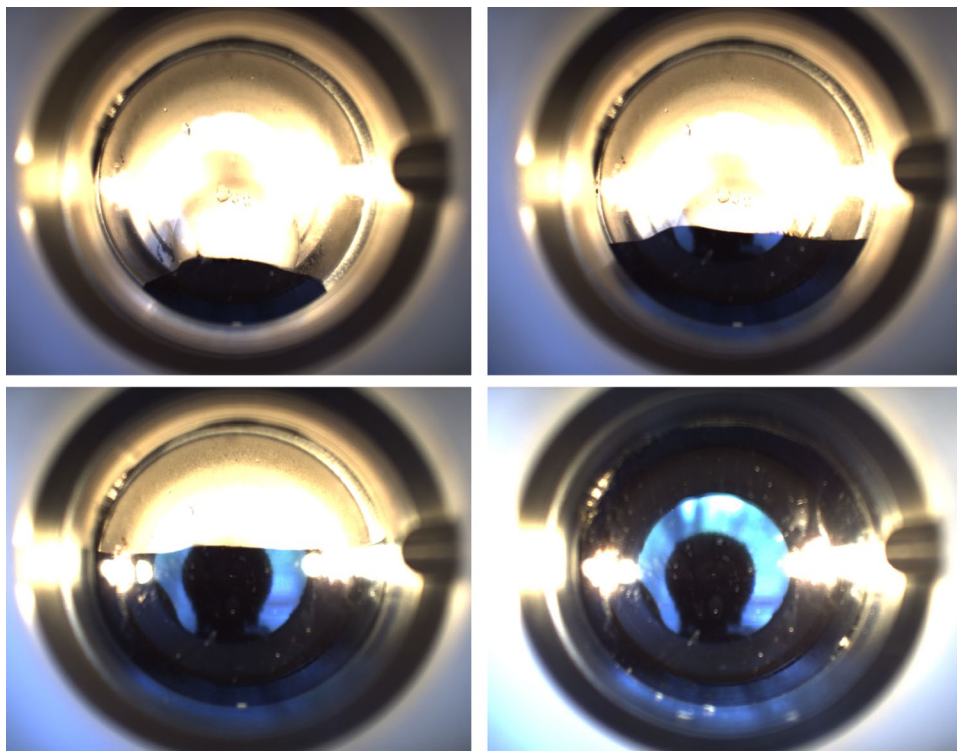
capillary viscometer, in which there are high pressure mixing vessel.

Experiment test results and analysis

Characteristic analysis of PV relationship curve

The test results of PV relationship curve show that in the case of without dissolved gas (Fig. 5), the volume of degassed heavy oil decreases with the increase in pressure and increases with the increase in temperature, and the P – V

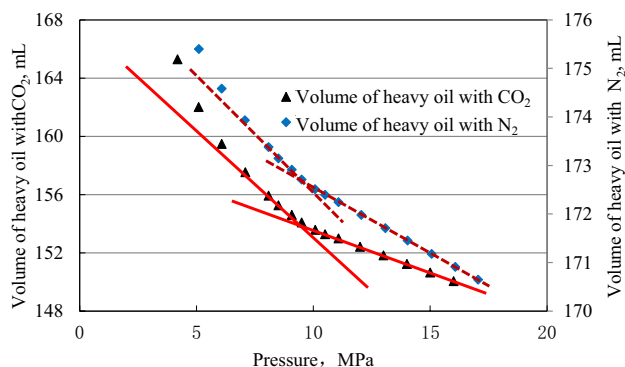
relationship is nearly linear. In the case of existing dissolved gas, PV test result at the same pressure drop rate is shown in Fig. 6. It is shown that the volume of heavy oil increases with the decrease in pressure, and the curve turns around the saturation pressure point. With the further decrease in pressure, the volume of heavy oil with dissolved gas will deviate from the straight line again. The analysis shows that when the P – V curve first turns, the heavy oil containing gas is in the state of foam oil flow. Foam oil flow is an important cold production mechanism of heavy oil. At the same pressure drop rate, the dissolved gas is released more slowly in the state of foam oil flow than other state. When the P – V curve

Fig. 4 Fluid sample preparation**Fig. 5** The PV relationship for heavy oil without dissolved gas

deviates for the second time, the heavy oil containing gas has degassed a lot, so the volume increases rapidly.

Solubility of different gases in heavy oil

At a certain temperature, transfer a certain volume of degassed heavy oil into the PVT cylinder; add a certain amount of N_2 , CO_2 or mixed gas with gradually increased gas oil ratio, and stir it fully; test the saturation pressure of each sample at different temperatures, and draw the relationship curve between solubility and saturation pressure (Fig. 7, 8 and Fig. 9).

**Fig. 6** The PV relationship for heavy oil with dissolved gas ($T=46\text{ }^\circ\text{C}$)

The test results show that the heavy oil has greater solubility under higher pressure. When the amount of dissolved gas is the same, the higher the temperature is, the greater the saturation pressure is. Under the same pressure and temperature conditions, the solubility of $CO_2 > \text{mixed gas} > N_2$. The solubility of CO_2 is directly proportional to the relative molecular weight of crude oil and is related to the chemical composition of crude oil. CO_2 is easy to dissolve in the crude oil with high wax content, but not easy to dissolve in the crude oil with high naphthenic and aromatic hydrocarbon content. Under the conditions of temperature ($46\text{ }^\circ\text{C}$) and pressure (9.5 MPa) in Bohai LD reservoir, the solubility of

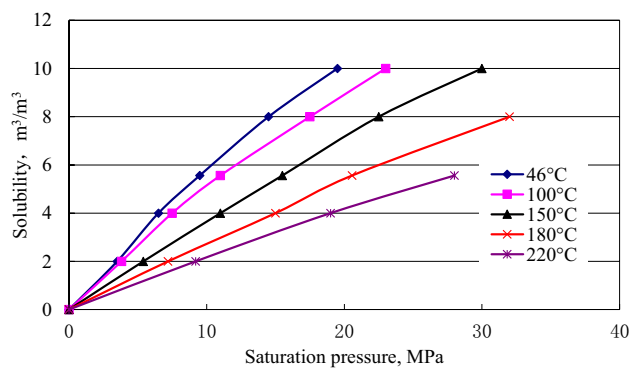


Fig. 7 The solubility test results of N_2 in heavy oil

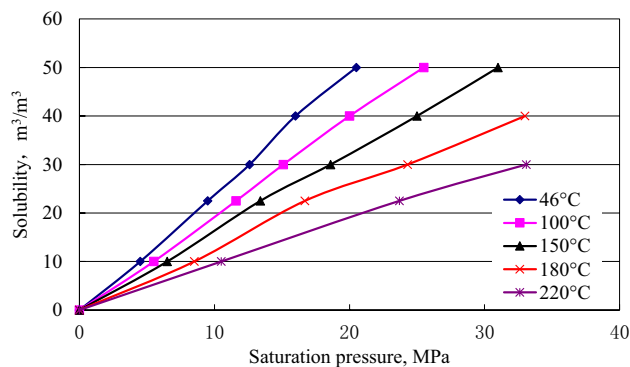


Fig. 8 The solubility test results of CO_2 in heavy oil

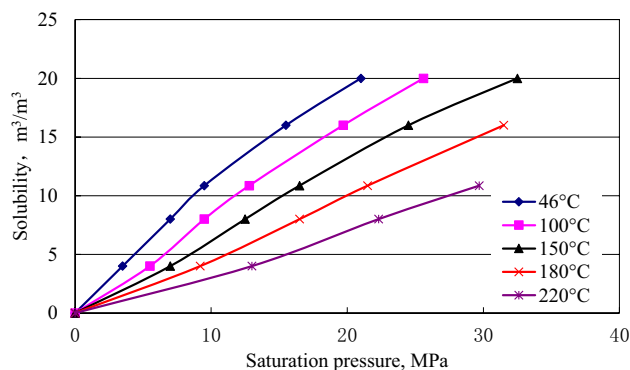


Fig. 9 The solubility test results of mixed gas ($85\%N_2 + 15\% CO_2$) in heavy oil

CO_2 is $22.51 \text{ m}^3/\text{m}^3$, which is significantly higher than that of N_2 . Although the solubility of mixed gas ($85\% N_2 + 15\% CO_2$) $10.86 \text{ m}^3/\text{m}^3$ is lower than that of CO_2 , due to good expansibility and large elastic energy of N_2 in mixed gas, it can save gas injection amount during oil displacement (Sun 2003). Moreover, N_2 is less dissolved in heavy oil, which is beneficial to maintain formation pressure during

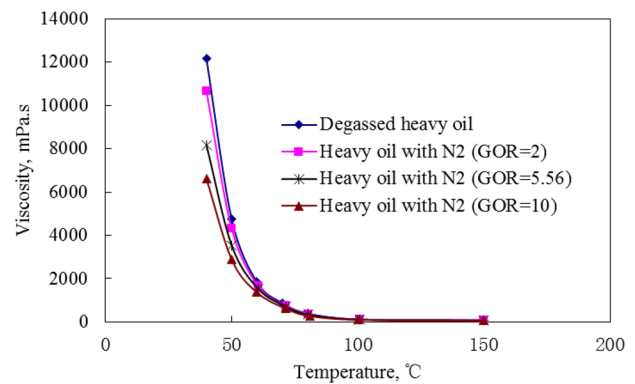


Fig. 10 The viscosity test results of heavy oil with N_2

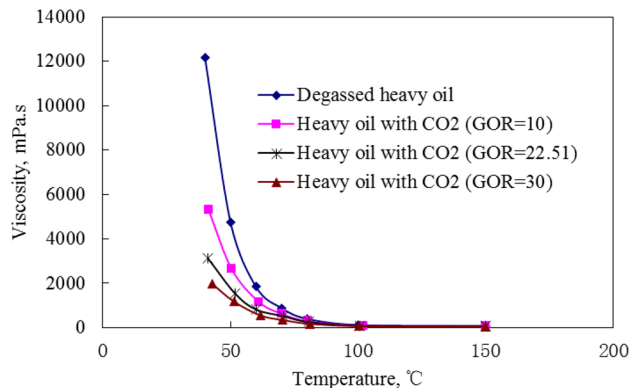


Fig. 11 The viscosity test results of heavy oil with CO_2

N_2 injection, and therefore mixed gas plays an important role in heavy oil production.

Viscosity of heavy oil containing dissolved gas

The degassed and dehydrated heavy oil is fully mixed with N_2 , CO_2 and mixed gas in the high pressure mixing vessel of capillary viscometer. Under different temperatures, according to the tested saturation pressure, the inlet pressure and outlet pressure of the capillary tube are adjusted to make the pressure in the capillary tube be above the saturation pressure, and make the gas–heavy oil mixture be single-phase flow state. After the temperature is stable, the viscosity of the heavy oil with dissolved gas is tested. The viscosities of all samples with different gas oil ratios are tested at different temperatures (Figs. 10, 11, Fig. 12).

The test results show that the viscosity of heavy oil with dissolved gas decreases with the increase in temperature and dissolved gas oil ratio. The viscosity reduction ability of different gases are that $CO_2 > \text{mixed gas} > N_2$. Under the reservoir temperature ($46 \text{ }^\circ\text{C}$) and reservoir pressure (9.5 MPa) conditions, the viscosity of heavy oil without dissolved gas is 6718 mPa s. The viscosity of heavy oil with fully saturated N_2

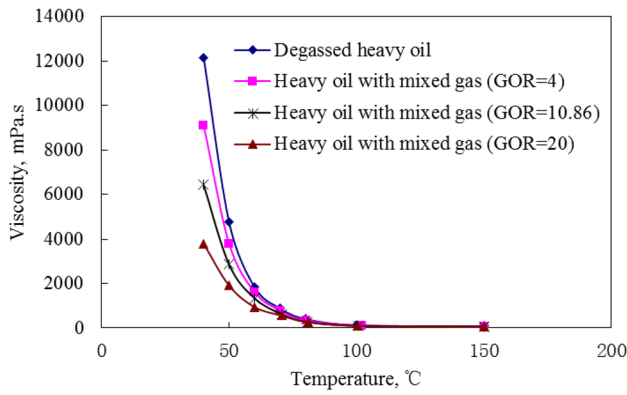


Fig. 12 The viscosity test results of heavy oil with mixed gas (85%N₂+15% CO₂)

(5.56 m³/m³), CO₂ (22.51 m³/m³) and mixed gas (10.86 m³/m³) are 4809 mPa s, 2128 mPa s and 3837 mPa s, with reduction amplitude of 28.42%, 68.32% and 42.88%, respectively.

Analysis of experimental data

Following formulae are widely used to predict the saturation pressure of oil–gas system.

The Standing (1947) formula

$$P_b = a_1 \left[\left(\frac{R_s}{\gamma_g} \right)^{a_2} \cdot 10^{a_3 T - a_4 \cdot \text{API}} - a_5 \right] \tag{1}$$

Table 1 The parameters in Eqs. (1)–(6)

Parameters	The standing formula (1947)	The Vazquez and Beggs formula (1980)		The Glaso formula (1980)	The Al-Marhoun formula (1988)
		API ≤ 30	API > 30		
a ₁	18.2	27.64	56.06	1.7669	0.00538088
a ₂	0.83	1.0937	1.187	1.7447	0.715082
a ₃	0.00091	11.172	10.393	0.30218	−1.877840
a ₄	0.0125			0.816	3.143700
a ₅	1.4			0.172	1.326570
a ₆				−0.989	

Table 2 Application ranges of different formulae

Application ranges	The standing formula (1947)	The Vazquez and Beggs formula (1980)	The Glaso formula (1980)	The Al-Marhoun formula (1988)
B _o (bbl/stb)	1.0240–2.150	1.028–2.226	1.032–2.588	1.032–1.997
T (°F)	100–258	75–294	80–280	74–240
R _s (scf/stb)	20–1425	0–2199	90–2637	26–1602
API°	16.5–63.8	15.3–59.3	22.3–48.1	19.4–44.6
γ _g	0.59–0.95	0.65–1.28	0.65–1.276	0.75–1.367
P _b (psi)	130–7000	15–6055	165–7142	130–3573

where, P_b is saturation pressure, psi; R_s is dissolved gas oil ratio, scf/stb; γ_g is specific gravity of gas (the air is 1); T is temperature, °K; API is API gravity of oil, °API.

The Vasquez and Beggs (1980) formula

$$P_b = \left[\left(a_1 \frac{R_s}{\gamma_{gs}} \right) \cdot 10^{-a_3 \frac{\text{API}}{460+T}} \right]^{\frac{1}{a_2}} \tag{2}$$

$$\gamma_{gs} = \gamma_g \left[1 + 5.915 \times 10^{-5} T_{\text{sep}} \cdot \text{API} \cdot \lg \frac{P_{\text{sep}}}{114.7} \right] \tag{3}$$

where, T_{sep} is the temperature of separator, °K; P_{sep} is the pressure of separator, psi.

The Glaso (1980) formula

$$P_b = 10^{a_1 + a_2 \lg G - a_3 (\lg G)^2} \tag{4}$$

$$G = \left(\frac{R_s}{\gamma_g} \right)^{a_4} \cdot T^{a_5} \cdot \text{API}^{a_6} \tag{5}$$

The Al-Marhoun (1988) formula

$$P_b = a_1 R_s^{a_2} \gamma_g^{a_3} \gamma_o^{a_4} (T + 460)^{a_5} \tag{6}$$

where, γ_o is the specific gravity of oil (the water is 1).

The parameters a₁–a₆ in above formulae are in Table 1.

The application ranges of above formulae are as Table 2. They are mainly applicable to conventional light oil, and the prediction effect of heavy oil is poor. The test temperature of Bohai heavy oil sample reaches up to 220 °C, which exceeds

the application range of above formula. The errors between the formula calculation results and the tested data reach up to more than 80%. Due to different composition of oil and gas, above calculation formulae of saturation pressure cannot be easily extended to other oilfields, nor can it be arbitrarily used for heavy oil, but should be modified. According to the regression analysis of experiment data, the proper formula can be obtained.

The above formulae all show the rules that the saturation pressure P_b increases with the increase in gas oil ratio R_s and temperature T . Petrosky and Farshad (1993), Omar and Todd (1993), Hemmati and Kharrat (2007) have improved the formula of Standing (1947). The functional relation of improved formula is the same as the original formula, but the coefficient of the formula has changed, and the fitting effect is good.

In Figs. 7, 8 and 9, the experimental data have different curve series. Based on the functional relation of Standing formula, if a single curve is fitted, i.e., only the relationship between dissolved gas oil ratio R_s and saturation pressure P_b is fitted, the equation with two parameters can be used:

$$P_b = a_1 R_s^{a_2} \tag{7}$$

where, P_b is saturation pressure, MPa; R_s is dissolved gas oil ratio, m^3/m^3 ; a_1, a_2 are fitting parameters.

If a series of curves for the same gas at different temperatures are fitted, the equation with three parameters can be used. According to the basic characteristics of the Standing formula, the following formula is used to fit the experiment data of Bohai heavy oil.

$$P_b = a_1 R_s^{a_2} \cdot 10^{a_3 T} \tag{8}$$

where, T is temperature, °C; a_3 is fitting parameter.

To fit all the curves for different gas types at different temperatures and different gas oil ratios, the following equation with four parameters can be used:

$$P_b = a_1 R_s^{a_2} \cdot 10^{a_3 T - a_4 \rho_g} \tag{9}$$

where, ρ_g is relative density of dissolved gas, which are, respectively, 1.5172, 0.9655, 1.0483 for CO_2, N_2 and mixed gas; a_4 is fitting parameter.

Taking CO_2 -heavy oil systems as examples, two-parameter equations are fitted for each curve at 46 °C, 100 °C, 150 °C, 180 °C, 220 °C, and five equations are obtained, respectively:

$$P_b = 0.5219R_s^{0.9339}, P_b = 0.6166R_s^{0.9454}, P_b = 0.6710R_s^{0.9769}, P_b = 0.8752R_s^{0.9736}, P_b = 0.9612R_s^{1.036}$$

Each equation is applicable to corresponding temperature. The values of R^2 are 0.9993, 0.9992, 0.9979, 0.9907 and 0.9990, respectively (Fig. 13).

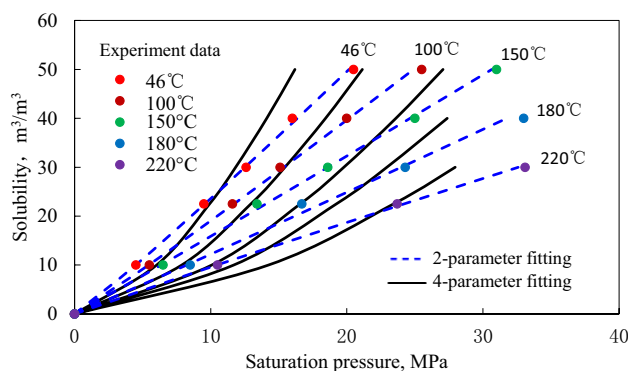


Fig. 13 The 2-parameter and 4-parameter curve fitting for CO_2 -heavy oil system

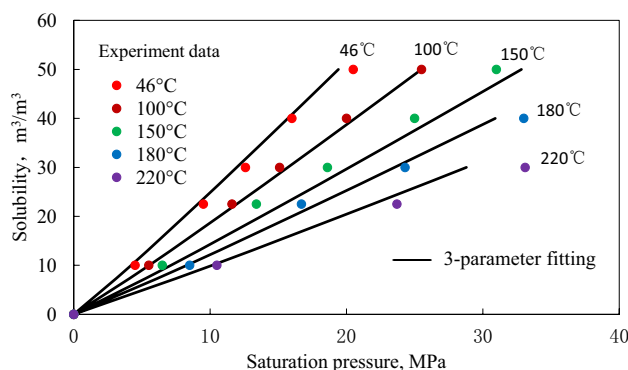


Fig. 14 The 3-parameter curve fitting for CO_2 -heavy oil system

A series of curves for CO_2 -heavy oil system at 5 temperatures (46 °C, 100 °C, 150 °C, 180 °C, 220 °C) are fitted and three-parameter equation is obtained with multiple regression method.

$$P_b = 0.3751R_s^{0.9494} \cdot 10^{0.002195T} \tag{10}$$

The equation can be applied to predict the saturation pressure P_b of CO_2 -heavy oil system under different dissolved gas oil ratios and different temperatures. The values of R^2 is 0.9863 (Fig. 14). If the functional relation of Glaso (1980) formula is used, the regression equation is $P_b = 0.07164R_s^{0.9283} \cdot T^{0.5027}$ ($R^2 = 0.9539$), whose fitting effect is worse than Eq. (10).

Similarly, the fitting formula of saturated pressure for N_2 -heavy oil system can also be obtained:

$$P_b = 1.09512R_s^{1.0832} \cdot 10^{0.002579T} \tag{11}$$

where, the values of R^2 is 0.9819.

The fitting formula of saturation pressure for mixed gas-heavy oil system:

$$P_b = 0.7599R_s^{0.9408} \cdot 10^{0.002742T} \quad (12)$$

where, the values of R^2 is 0.9859.

All the curves including CO₂-heavy oil, N₂-heavy oil and mixed gas-heavy oil systems at different temperatures and different dissolved gas oil ratios are fitted with four-parameter equation, which is

$$P_b = 2.0794R_s^{0.6140} \cdot 10^{0.002147T-0.1652\rho_g} \quad (13)$$

The equation can be used to predict the saturation pressure of different gas types under different dissolved gas oil ratios and different temperatures. However, the fitting accuracy is relatively low, with R^2 value of 0.7207 (Fig. 13).

Comprehensive analysis results show that the 2-parameter equation can almost completely fit the experimental data, but its application scope is narrow, and it needs to fit individual equation for each curve. The 4-parameter equation can be used to predict the saturation pressure of different gas types under different dissolved gas oil ratio and different temperature, but its fitting accuracy is poor. The 3-parameter equation can not only better fit the saturation pressure of heavy oil for the same gas under different dissolved gas oil ratios and different temperatures, but also has a wide application range. It is recommended to use the 3-parameter equation for saturation pressure analysis and calculation of heavy oil.

Similar to the equation of saturation pressure, the three-parameter viscosity calculation equation of heavy oil with dissolved gas can be written as

$$\mu = a_1R_s^{a_2} \cdot e^{a_3/T} \quad (14)$$

For N₂-heavy oil system, the fitting formula of viscosity is

$$\mu = 13.467R_s^{-0.1650} \cdot e^{281.014/T} \quad (15)$$

where, the value of R^2 is 0.9696.

For CO₂-heavy oil system, the fitting formula of viscosity is

$$\mu = 40.074R_s^{-0.4636} \cdot e^{252.356/T} \quad (16)$$

where, the value of R^2 is 0.9642.

For mixed gas-heavy oil system, the fitting formula of viscosity is

$$\mu = 20.239R_s^{-0.2741} \cdot e^{266.698/T} \quad (17)$$

where, the value of R^2 is 0.9649.

On the whole, the 3-parameter equation can well fit the viscosity of heavy oil for the same gas under different dissolved gas oil ratios and different temperatures, and it has a wide range of application (Fig. 15). It is recommended to use the 3-parameter equation for viscosity fitting. At

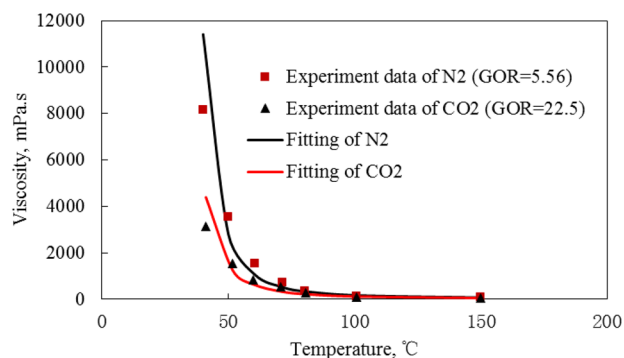


Fig. 15 The 3-parameter curve fitting for heavy oil with dissolved gas

a certain temperature, according to the saturation pressure, the dissolved gas oil ratio R_s can be calculated with Eq. (10)–(12), and then the viscosity of heavy oil can be predicted with Eq. (15)–(17). The research results provide a basis for the accurate prediction of heavy oil PVT parameters.

Conclusions

1. The Bohai heavy oil has obvious characteristics of foam oil, whose dissolved gas is released slowly below the saturation pressure. Generally, the dissolved gas oil ratio of Bohai heavy oil is low and the viscosity is high. The dissolving and viscosity reduction ability of Bohai heavy oil are influenced by the factors including pressure, temperature and gas types.
2. Although the widely used empirical formulas have a certain application scope, they are obtained from regression analysis of specific samples and cannot be arbitrarily applied to heavy oil reservoirs. Keeping the functional relation of empirical formula unchanged, but the coefficient is fitted according to actual test data, the application effect can be improved.
3. Based on the functional relation of Standing formula, the empirical equations of saturation pressure and viscosity for Bohai heavy oil were regressed. The results show that the 2-parameter equation can almost completely fit the experimental data, but its application scope is narrow. Although the 4-parameter equation has an extensive adaptability, its fitting accuracy is very low. The 3-parameter equation can not only better fit the saturation pressure and viscosity of heavy oil for the same gas under different dissolved gas oil ratios and different temperatures, but also has a wide application range. It is recommended to use the 3-parameter equation.

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