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Application of Fluid Phase Recovery Method in the Early Development of BZ26-6 Volatile Oil Field in Bohai Sea

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Abstract

BZ26-6 Oilfield is a kind of deep metamorphic rock buried-hill volatile oilfield in Bohai Sea, China. Its early development plan is restricted due to the simultaneous production of oil and gas in large sections of reservoirs, unclear understanding of formation fluid properties and uncertainty of gas-oil interface. Through theoretical research on phase recovery and experimental analysis of crude oil phase characteristics in the original formation, characteristic parameters of the equilibrium condensate gas fluid are restored and calculated. Through the superimposed phase diagram of volatile oil and condensate gas, BZ26-6 Oilfield is determined to be a volatile oil reservoir with a condensate gas cap, with formation pressure and saturation pressure of 36.1 MPa, respectively. Based on the research results of oil-gas phase behavior characteristics, the thermodynamic equations and equation of state are jointly used to solve the problem, and the content change curves of each component at different depths are drawn. Combined with the sensitivity analysis of numerical simulation, the gas-oil interface is determined to be −3726 m above sea level. The fluid phase analysis software, Fluidmodeler, is used to simulate volatile oil degassing and condensate gas separation experiments. In combination with oil and gas production data obtained through the production test, the specific oil recovery index and the specific gas recovery index are determined to be 0.408 $m^3/(MPa·d·m)$ and 1195 $m^3/(MPa·d·m)$, respectively. And the reasonable production capacity prediction is conducted on the early development of BZ26-6 Oilfield. The research results can provide a theoretical basis for the efficient development of similar complex oil and gas reservoirs.

Keywords

Volatile Oil Field, Phase Fitting, Fluid Recovery, Gas-Oil Interface, Productivity Evaluation

1. Introduction

Research on the phase behavior of formation fluids figures prominently in the early stage of oilfield development. For deep oil and gas reservoirs, fluid types and properties are complex and variable under the conditions of high temperature and pressure (Hou et al., 2013; Tong et al., 2004). Therefore, it is crucial to accurately understand the changing patterns of fluids during oilfield development (Li et al., 2004). In some deep oil and gas fields with thick reservoir development, it is difficult to accurately distinguish the location of oil and gas fluids in the reservoir due to the uncertainty of early seismic and logging data understanding. In this case, a commingled production method for large reservoirs is adopted in production testing, resulting in the test output being a mixture of oil and gas, with condensate and volatile oil in the oil, and condensate and dissolved gas in the gas, making it difficult to accurately recognize the fluid properties and oil-gas production (Li et al., 2006). Currently, there are many studies on the analysis of fluid phase states and fluid recovery of unqualified samples, while there is relatively little research on the fluid phase states of oil and gas coexistence under thick reservoir conditions, which needs to be further studied (Shi & Hu, 2017; Zhao et al., 2023).

BZ26-6 Oilfield is located in the southern sea area of Bohai Sea. The main oil-bearing series is the Archaean metamorphic rock buried-hill oil-gas reservoir. The reservoir depth is −3550 m - 4050 m above sea level, the formation temperature is 154.2˚C, and the formation pressure is 36.8 MPa. Underground sampling may be not accurate because of high formation pressure and complex reservoir conditions. Since we cannot accurately determine the fluid properties of the formation, we conduct production testing using the development method of oil-gas simultaneous production in a nearly 100-meter reservoir, with a gas-oil ratio of 1000. Based on the oil and gas samples from the separator, the original formation oil fluid was mixed, with a gas-oil ratio of only 273 m^3/m^3, which is much lower than the tested gas-oil ratio. Therefore, it is determined that there is a gas cap in the upper part of the test reservoir. However, the phase change of the formation gas occurred under the separator conditions, making it impossible to separate the oil-gas mixture and carry out their original formation. The unclear understanding of the phase characteristics of the formation fluid in BZ26-6 Oilfield, the uncertainty of the gas-oil interface, and the unclear proportion of oil-gas production during production testing severely restrict the understanding of oil-gas reservoir types, reserve evaluation, and the determination of initial reasonable production capacity. Through theoretical research on phase recovery and experimental analysis on phase characteristics of the original formation oil, the characteristic parameters of equilibrium condensate gas fluid are restored and calculated, and the gas-oil interface is predicted and reasonable production allocation is formulated, which can provide key parameters for the rational and efficient development of BZ26-6 Oilfield.

2. Research on Phase Restoration Theory

Under the original formation conditions, each fluid in the reservoir is in phase equilibrium, and the same component is in dynamic equilibrium between different phases (Ministry of Energy, 2011; Zhao et al., 2011). For example, the rate at which the methane molecules in the gas phase change to the liquid phase is equal to the rate at which the methane molecules in the liquid phase change to the gas phase (Guo, 2004). If the composition of each component in crude oil and the rate of evaporation into the gas phase are known, the composition of the unknown gas and its variation with temperature and pressure can be calculated based on phase equilibrium conditions (Danesh, 2000; Li, 2000).

Phase Balance theory includes two aspects, namely, material balance and thermodynamic fugacity balance.

Material balance equations:

$$Z_{ik} - X_{ik}L_k - Y_{ik}V_k = 0$$

$$\sum\left(X_{ik} - Y_{ik}\right) = 0$$

$$L_k + V_k - 1 = 0$$

Thermodynamic fugacity equilibrium equations:

$$K_i = \frac{y_{ik}}{x_{ik}} = \frac{f_{iLk}}{f_{iVk}}$$

$$f_{iLk}\left(P, X_{1k}, \cdots, X_{nk}\right) - f_{iVk}\left(P, Y_{1k}, \cdots, Y_{nk}\right) = 0$$

Among them, material balance determines the total conservation of components, and thermodynamic equilibrium determines the oil-gas distribution. The distribution ratio X_i and Y_i of each component in oil and gas is related to fugacity, and fugacity f is related to thermodynamic properties, temperature, and pressure, that is, to the PVT parameter field.

$$RT\ln\frac{f_{iLk}}{X_i p} = \int_{V_L}^{\infty}\left[\left(\frac{\partial P}{\partial X_i}\right)_{V_L,T,x_j} - \frac{RT}{V_L}\right]\mathrm{d}V_L - RT\left(\ln Z_{iL}\right)$$

$$RT\ln\frac{f_{iVk}}{Y_i p} = \int_{V_V}^{\infty}\left[\left(\frac{\partial P}{\partial Y_i}\right)_{V_V,T,y_j} - \frac{RT}{V_V}\right]\mathrm{d}V_V - RT\left(\ln Z_{iV}\right)$$

In the formula, Z_{ik}, X_{ik} and Y_{ik} are the Mole fraction of the component i in the mixture, liquid and gas under the state k, respectively, which are dimensionless. L_k is the Mole fraction of the balance oil in the state k, which is dimensionless. V_k, V_L and V_V are the Mole fraction of the equilibrium gas phase in the state k, liquid and gas respectively, which are dimensionless. K_i is the distribution ratio of equilibrium composition, defined as the ratio of the Mole fraction y_{ik} of the component i in the gas phase to the Mole fraction X_{ik} in the liquid phase, which is dimensionless. f_{iLk} and f_{iVk} are the fugacity of the component i in the mixture of gas and liquid phases, respectively, which is dimensionless. P is the pressure at which the hydrocarbon system is subjected, MPa. R is the molar gas constant. T is the temperature at which the hydrocarbon system is located, K. Z_{iL} and Z_{iV} are mole fractions of the component i in liquid and gas, respectively, which are dimensionless.

3. Phase Recovery Technology Process

Based on the research of phase recovery theory and combined with the fluid characteristics of BZ26-6 Oilfield, a phase recovery technology process is proposed, which mainly includes the following parts.

1) Qualification inspection of known fluid samples. Phase equilibrium testing should be first conducted on known fluid samples according to national standard methods. The composition of the separator oil and gas samples in equilibrium is from methane to hexane, and the relationship between $\lg K_i \cdot p_{sep}$ and $b_i\left(\frac{1}{T_{bi}}-\frac{1}{T_{sep}}\right)$ should be linear. The correlation coefficient of over 95% indicates that the experimental sample separator oil and gas samples are in a stable equilibrium state, and subsequent experiments can be conducted.

$$\lg K_i \cdot p_{sep} \propto b_i\left(\frac{1}{T_{bi}}-\frac{1}{T_{sep}}\right)$$

$$K_i = \frac{Y_{si}}{X_{si}}$$

$$b_i = \frac{\lg p_{ci} - \lg(0.101)}{\frac{1}{T_{bi}} - \frac{1}{T_{ci}}}$$

where, K_i is the equilibrium constant of separator gas component i; p_{sep} is the pressure of the first stage separator, MPa; b_i is the characteristic constant of the gas component i in the separator; T_{bi} is the boiling point of the gas component i in the separator, K; T_{sep} is the temperature of the primary separator, K; Y_{si} is the Mole fraction of gas component i in the separator; p_{ci} is the critical pressure of the gas component i in the separator, MPa; T_{ci} is the critical temperature of the gas component i in the separator, K.

2) High temperature and high pressure physical properties experiment of formation fluid. The physical properties of crude oil and natural gas under geological conditions are significantly different from those of ground conditions. Oil-gas balance can be disrupted with the changes in reservoir temperature and pressure. Oil and gas phase states have significantly different change law. It is of great significance to master the phase characteristics and variation patterns of fluids in the early stage of oilfield development. Generally, there are constant composition expansion experiment, constant volume depletion experiment, multiple degassing experiment, etc.

3) Calculation of known fluid characteristic parameters. To ensure the computational efficiency and fitting accuracy of the fluid phase analysis software,

considering the operational efficiency of subsequent reservoir numerical simulation, the components are split and merged according to the similarity criterion for physical and chemical properties, and the fluid characteristic parameters are corrected through indoor experiments (see Figure 1).

4) According to the classical calculation formula of Wilson K value and the known fluid properties, the vapor-liquid equilibrium constant plate under different temperature and pressure conditions are calculated (see Figure 2).

5) According to the proportion of each component of the known fluid, the components of the unknown fluid under the condition of phase equilibrium and the corresponding characteristic parameters of high temperature and high pressure are calculated through Raoult's law and Henry's law. After obtaining the properties of the formation fluid, it is possible to calculate the gas-oil ratio of the oil and gas phases, as well as the changes in the content of each component at different temperatures and pressures, so as to provide support for oilfield development design.

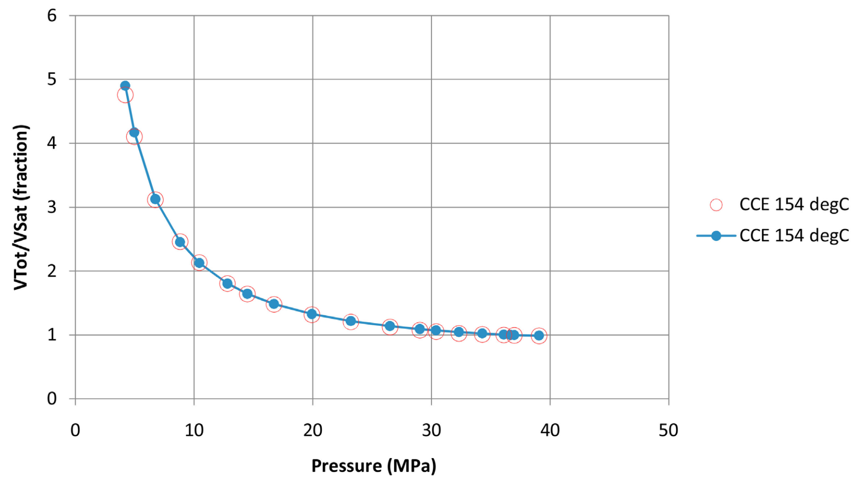

Figure 1. Fitting diagram of constant composition expansion experiment.

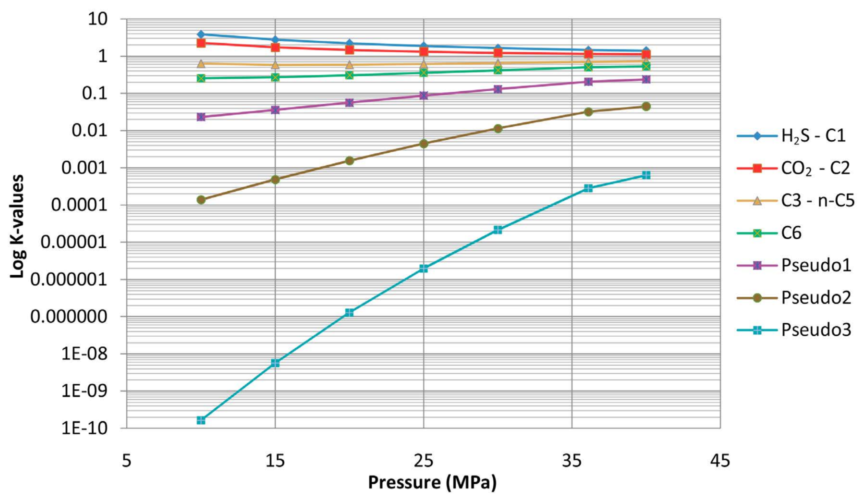

Figure 2. Equilibrium constant plate.

4. Outcome Application

4.1. Understanding of the Phase State Characteristics of Fluids

Qualification inspection is conducted on the formation oil fluid samples of BZ26-6 Oilfield, then indoor high-temperature and high-pressure PVT experiment is carried out. In the original formation oil well flow, the Mole fractions of C_1 + N_2, C_2 - C_6 + CO_2, and C_7+ are 50.45%, 23.26%, and 26.29%, respectively. The viscosity of the formation crude oil is 0.30 mPa·s, the gas-oil ratio is 273 m^3/m^3, and the crude oil volume coefficient is 1.727. Taken together, the formation crude oi belongs to a weakly volatile oil reservoir. After high-temperature and high-pressure experimental fitting, the P-T phase diagram of BZ26-6 original formation oil is obtained (see **Figure 3**), with a critical temperature of 420.2˚C, a critical pressure of 27.8 MPa, and a saturation pressure of 36.1 MPa at reservoir temperature.

Fluidmodeler software from Schlumberger is used to fit the high temperature and high pressure physical property experiment of fluids, and then determine the characteristic description parameters of crude oil fluid in BZ26-6 formation. The equilibrium constant plates of each component under different temperature and pressure conditions are calculated using Wilson's K-value classic formula. In combination with the composition of the formation's raw oil fluid, the composition proportion of each component of the equilibrium gas phase fluid is calculated. After fitting the key experiments such as dew point pressure, gas-oil ratio, etc., characteristic description parameters of formation gas are corrected. The P-T phase diagram of the original formation gas fluid calculated by BZ26-6 recovery (see **Figure 4**), with a critical temperature of 4.8˚C, a critical pressure of 31.2 MPa, a dew point pressure of 36.1 MPa at reservoir temperature, and a maximum retrograde condensate volume of 11%.

Figure 5 shows the superimposed phase diagram of the BZ26-6 formation crude oil system and condensate gas system. It can be seen that the formation

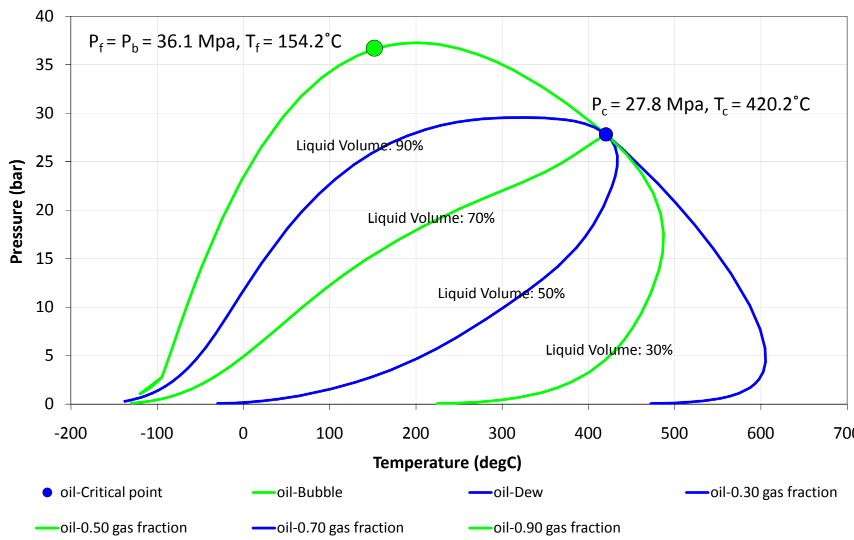

Figure 3. P-T phase diagram of formation crude oil.

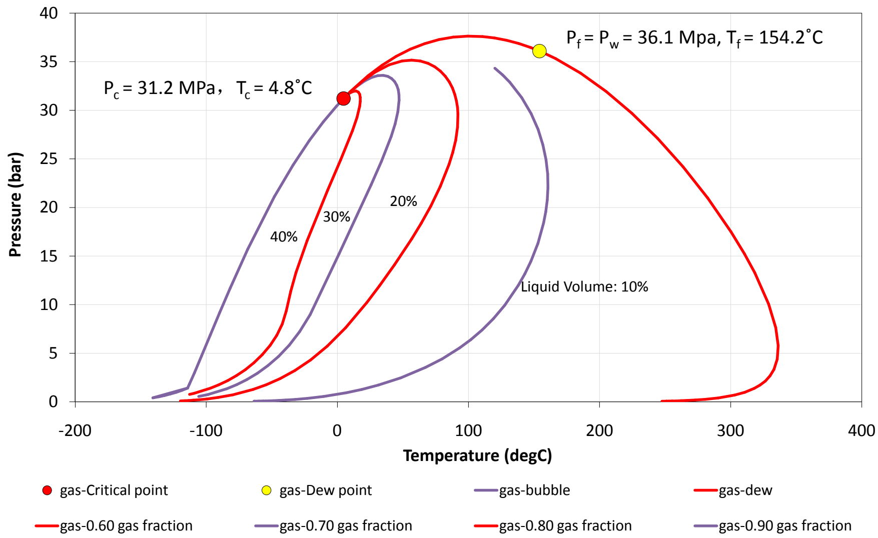

Figure 4. P-T phase diagram of formation condensate gas.

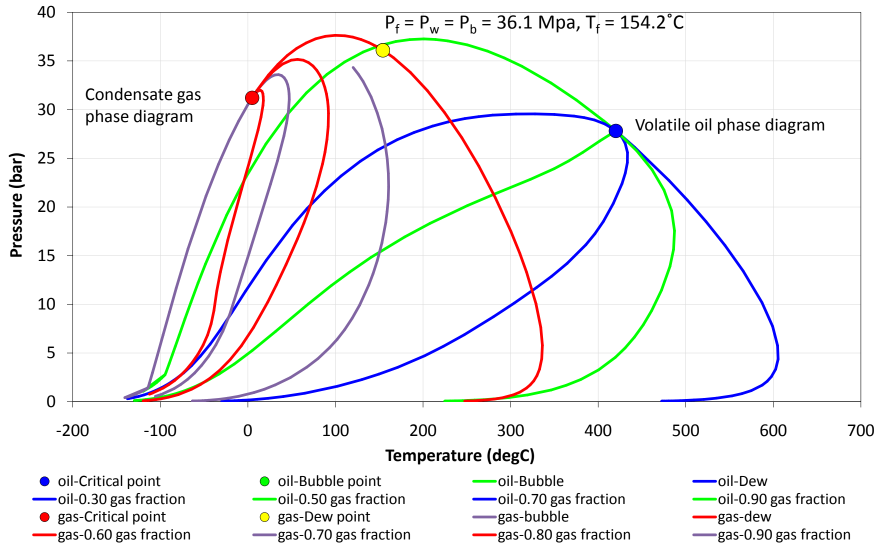

Figure 5. Superimposed phase diagram of formation crude oil and condensate gas.

condensate gas system and the formation crude oil system intersect at a point where the condensate gas system and the volatile oil system are in a state of oil and gas equilibrium. The point pressure is not only the dew point pressure of the formation condensate gas system, but also the bubble point pressure of the formation volatile oil system, and both are equal to the formation pressure of 36.1 MPa. Therefore, BZ26-6 Oilfield is a volatile oil reservoir with a condensate gas cap.

4.2. Gas-Oil Interface Prediction

Based on the research results of oil-gas phase behavior characteristics, the Thermodynamic equations and Equation of state are jointly used to solve the problem, and the content change curves of each component at different depths are drawn. Since the molar content of each component in different gas-liquid phase states will have an obvious inflection point, the gas-oil interface can be predicted on this basis. As shown in Figure 6, the gas-oil interface is between −3696 m and −3726 m above sea level.

To verify the reliability of the phase theory calculation method for gas-oil interface, and obtain more accurate gas-oil interface positions, a dual-medium composition model is established. Sensitivity analysis of gas-oil interface parameters was conducted using oil-gas production data from the oilfield trial production process (see Figure 7). Finally, the gas-oil interface is predicted to be at the position of −3726 m, and the thickness of the volatile oil reservoir was determined to be 33 m, and the thickness of the condensate gas reservoir was 44 m, which can provide key parameters for reserve calculation and scheme research.

4.3. Evaluation of Reasonable Production Capacity of Oilfield

Reasonable production capacity of oilfields is of great significance for efficient

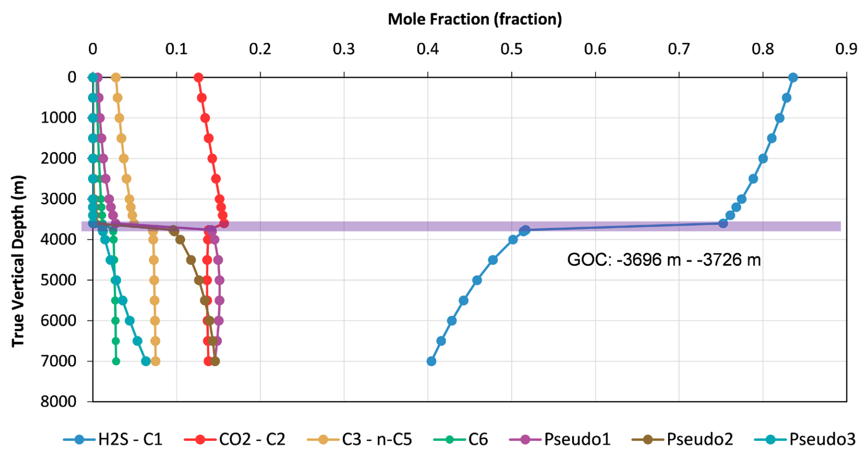

Figure 6. Variation curve of mole fraction of each component at different depths.

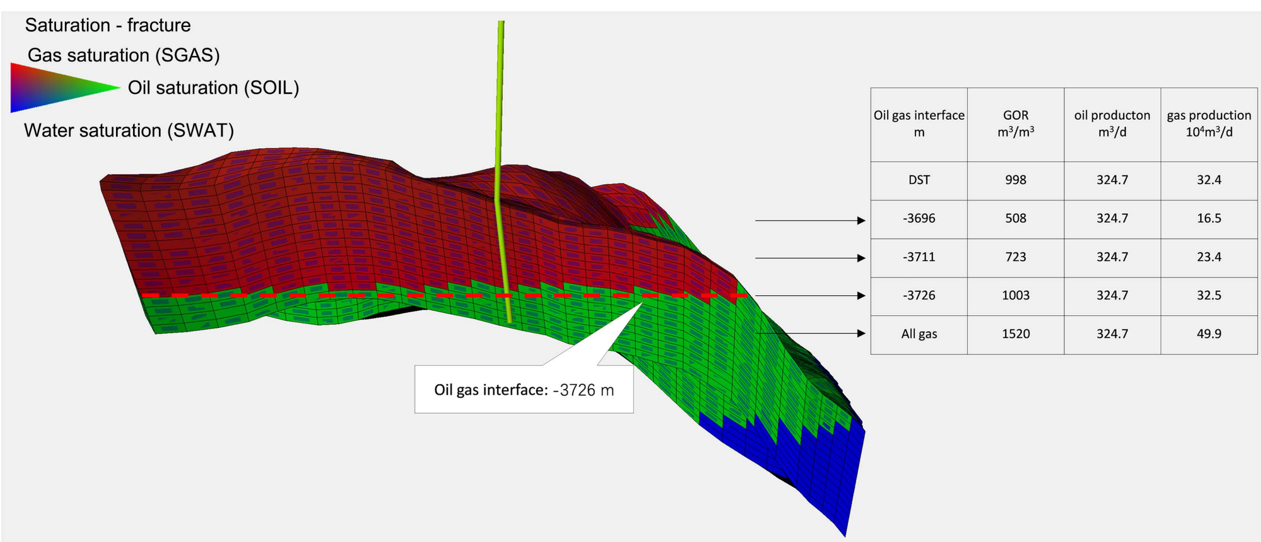

Figure 7. Sensitivity analysis of gas-oil interface in reservoir numerical simulation.

development in the early stage, as well as sustainable and stable production in the future. Generally, the measured specific oil recovery index is used for production allocation during the initial development of an oilfield. Simultaneous production of oil and gas is conducted during the trial production process of BZ26-6 Oilfield. For rational production allocation of the oilfield, it is crucial to determine the oil and gas recovery indices corresponding to the oil and gas layers. Based on the phase changes of the original formation oil and condensate gas in the BZ26-6 Oilfield, the volatile oil degassing process and condensate gas separation experiment are simulated using fluid analysis software under different temperature and pressure conditions. According to the ground conditions during the oilfield trial production process, the gas-oil ratios of the oil and gas phases are calculated to be 235 m^3/m^3 and 1433 m^3/m^3, respectively. In combination with oil and gas production data in actual production and testing, the actual production proportions of volatile oil and condensate gas are split. Thereinto, volatile oil accounts for 28.4%, and condensate gas accounts for 71.6%. The specific production index is calculated based on the predicted thickness of oil and gas reservoir, with a specific production index of 0.408 $m^3/(MPa \cdot d \cdot m)$ and a specific gas production index of 1195 $m^3/(MPa \cdot d \cdot m)$. Production allocation for BZ26-6 Oilfield is carried out based on research results of reservoir.

5. Conclusion

1) Under the original geological conditions, the fluids in the reservoir are in phase equilibrium. Through theoretical research on phase recovery and experimental analysis on phase characteristics of original formation oil, the composition of equilibrium condensate gas fluid and its variation with temperature and pressure are restored and calculated. Through the superposition phase diagram of volatile oil and condensate gas, the BZ26-6 Oilfield is determined to be a volatile oil reservoir with a condensate gas cap, with both formation pressure and saturation pressure of 36.1 MPa.

2) Based on the research results of oil-gas phase behavior characteristics, the thermodynamic equations and equation of state are jointly used to solve the problem, and the content change curves of each component at different depths are drawn. The range of gas-oil interface is preliminarily predicted according to the inflection point of change of molar content. Combined with the sensitivity analysis of numerical simulation, the gas-oil interface is determined to be −3726 m above sea level.

3) The fluid phase analysis software, Fluidmodeler, is used to simulate volatile oil degassing experiment and condensate gas separation experiment. In combination with oil and gas production data in actual production and testing, the specific oil recovery index and the specific gas recovery index are determined to be 0.408 $m^3/(MPa \cdot d \cdot m)$ and 1195 $m^3/(MPa \cdot d \cdot m)$, respectively. And the reasonable production capacity prediction is conducted on the early development of BZ26-6 Oilfield.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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