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Numerical Simulation of Oil and Gas Two-Phase Flow in Deep Condensate Gas Reservoirs in Bohai Buried Hills

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Abstract

The BZ19-6 gas field is characterized by high temperature and high pressure (HTHP), high condensate content, little difference between the formation pressure and dew point pressure, and large amount of reverse condensate liquid. During the early stage of depletion development, the production gas-oil ratio (GOR) and production capacity remain relatively stable, which is inconsistent with the conventional reverse condensate seepage law. In view of the static and dynamic conflict in development and production, indoor high-temperature and high-pressure PVT experiment was carried out to reveal the mist-like condensation phenomenon of fluids in the BZ19-6 formation. And the seepage characteristics of condensate gas reservoirs with various degrees of depletion under the condition of HTHP were analyzed based on production performance. The change rule of fluid phase state was analyzed in response to the characterization difficulties of the seepage mechanism. The fluid state was described using the miscible mechanism. And the interphase permeability interpolation coefficient was introduced based on interfacial tension. By doing so, the accurate characterization of the "single-phase flow of condensate gas - near-miscible mist-like quasi single-phase flow - oil-gas two-phase flow" during the development process was achieved. Then the accurate fitting of key indicators for oilfield development was completed, and the distribution law of formation pressure and the law of condensate oil precipitation under different reservoir conditions are obtained. Based on research results, the regulation strategy of variable flow rate production was developed. Currently, the work system has been optimized for 11 wells, achieving a "zero increase" in the GOS of the gas field and an annual oil increase of 22,000 cubic meters.

Keywords

High Temperature and High Pressure, Condensate Gas Reservoirs, Mist

Flow, Characterization of Seepage Flow, History Match, Production Regulation

1. Introduction

BZ19-6 is the largest buried-hill metamorphic condensate gas field in Bohai Bay, which is characterized by high temperature and pressure, high condensate content, little difference between the formation pressure and dew point pressure, and large amount of reverse condensate liquid. Conventionally, when the formation pressure is lower than the dew point pressure, a large amount of condensate will be precipitated and remain lost in the pores, which will then block the seepage channel, resulting in a significant increase in gas-oil ratio, and a sharp decrease in production capacity of the gas well [1] [2] [3] [4] [5]. During the early stage of depletion development in the BZ19-6 gas field, on-site monitoring showed that the formation pressure was much lower than the dew point pressure, while the production-GOR and production capacity remained relatively stable. There was no significant retrograde condensation. The above results are seriously inconsistent with the conventional understanding of condensate gas reservoir development. This contradiction seriously restricts subsequent development strategies. Indoor high-temperature and high-pressure PVT experiment was carried out to reveal the mist-like condensation phenomenon of fluids in the BZ19-6 formation. The seepage mechanism of condensate gas reservoirs under the condition of HTHP was analyzed based on production performance. And mathematical characterization research was conducted. The on-site control of BZ19-6 gas field was optimized under the guidance of research results. Taken together, these approaches are of great significance for the efficient development of complex fluid oil and gas reservoirs in similar deep buried hills.

2. Geological Reservoir Characteristics

BZ19-6 structure is located in the southwest of Bozhong Sag, Bohai Bay. It is an anticlinal block structure complicated by strike-slip faults and their derivatives. The structure is high in the south and low in the north, with developed faults. The lithology of buried-hill reservoir is dominated by metamorphic granite and Gneiss. The reservoir space is dominated by pores, supplemented by fractures, and the combination type is dominated by fracture-pore type. It is vertically divided into semi-weathered zones and buried-hill interiors, with the semi-weathered zone being of pore type or fracture-pore type, and the buried-hill interiors being of fracture type or pore-fracture type. The BZ19-6 gas field exhibits a buried-hill formation pressure of 46.927 MPa, and a dew point pressure of 45.610 MPa. Its original volume coefficient of condensate gas is 0.00381, condensate GOR is 1095 m^3/m^3, and the condensate oil content is 884 cm^3/m^3. During the depletion period, the maximum amount of reverse condensate liquid is 40.97%, and the maximum reverse condensate pressure is 28.620 MPa.

3. Seepage Flow Characterization of Condensate Gas Reservoirs under the Condition of High Temperature and High Pressure Based on Phase Change

3.1. Fluid Phase Experiments under the Condition of High Temperature and High Pressure

Compared with other conventional gas condensate reservoirs in China, BZ gas condensate field shows a formation temperature of 152˚C and a formation pressure of 46.9 MPa, which belongs to high temperature and high pressure conditions. The condensate content of BZ gas field is as high as 751 - 884 cm^3/m^3, which belongs to extremely high condensate content. The dew point pressure of formation fluid ranges from 42.980 to 45.610 MPa, while the ground dew pressure difference ranges only from 0.211 to 2.915 MPa. Under this condition, obvious reverse condensate phenomenon will occur in the early development stage of gas field. When the pressure drops about 15 MPa, the maximum retrograde condensate saturation is 19.7% - 41.0%, which is significantly higher than that of the maximum retrograde condensate saturation (15% - 30%) in Yaha, Kekeya and Tazhong 4 condensate gas reservoirs in the Tarim Basin. As shown in the P-T phase diagram, the critical temperature is 52.4˚C, the critical pressure is 40.76 MPa, and the formation conditions (152˚C, 46.93 MPa) are located above the critical point, in the near critical region. The close gas-oil composition and low interfacial tension will lead to more severe gas-oil phase change. And the formation fluid may form a supercritical state [6] [7] [8] [9]. Therefore, the fluid needs to be further studied through experimental research (**Figure 1**).

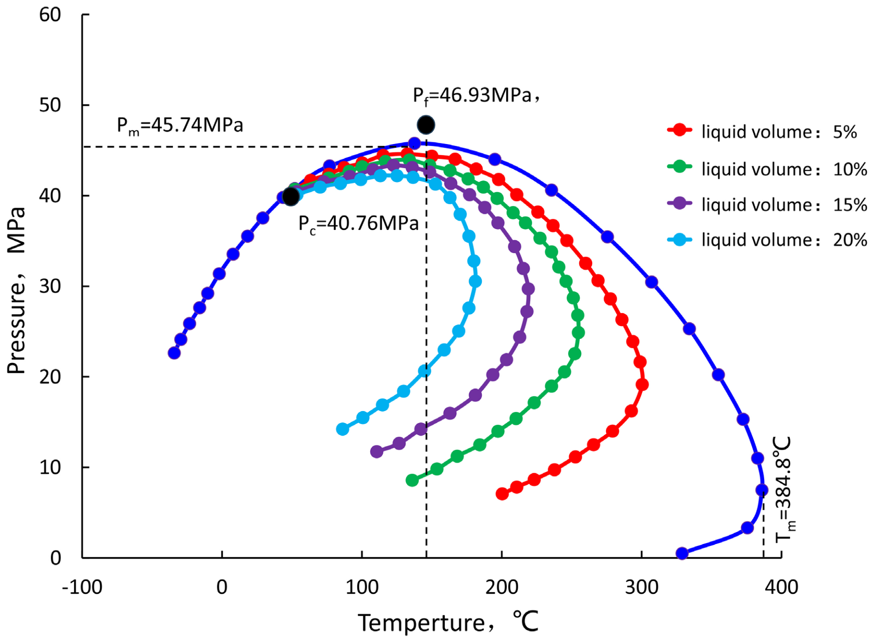

Figure 1. P-T phase characteristics of well BZ-2. P_m-cricondenbar; T_m-cricondentherm; P_f-formation temperature; T_f-formation temperature; P_c-critical pressure; T_c-critical temperature.

3.2. Experimental Study on Quasi Stable Mist Flow of Depressurization and Depletion

Conduct depletion experiments on fluids according to industry standards. When the pressure drops to the dew point pressure, a mist like mixed fluid with approximately uniform distribution appears. Afterwards, condensate oil appears and the mist-like fluid disappears. The reason for such quasi stable mist-like flow opalescence phenomenon is mainly because the BZ19-6 condensate gas fluid is in a nearly saturated state under formation conditions, and the condensate oil will be rapidly precipitated when the local formation pressure quickly drops to around the dew point pressure. At the same time, due to HTHP conditions, the density and viscosity of natural gas and crude oil are close, and the interfacial tension approaches zero, therefore the condensate is precipitated in the form of small oil droplet molecules. The oil drop molecules have difficult in effectively collision and connection to form a continuous oil phase due to its limited irregular thermal motion range. Therefore, the oil drop molecules mix with the gas to form a quasi-stable near-miscible mist-like mixed fluid with highly dispersed particles and near zero interfacial tension. The reasonable pressure window of mist flow obtained through experiments is the dew point pressure to 35 MPa (**Figure 2**).

3.3. Analysis of Seepage Characteristics at Different Levels of Depletion Development

The seepage characteristics of phase states and flow states of the condensate oil/gas fluids in porous medium vary with different development stages [10]-[16]. Based on the characteristics of phase behavior experiment in the BZ19-6 formation under HTHP conditions, as well as actual production performance data in the experimental area, the development process of the BZ19-6 condensate gas field is divided into three seepage stages: 1) Formation condensate gas single-phase flow stage. At this stage, the pressure of gas wells (such as A10 well) remains at a high level, higher than the dew point pressure (44 MPa), without retrograde condensation. Oil and gas production remains stable, and the production-GOR remains at the original level; 2) Mist flow quasi-single-phase flow stage. At this stage, the near wellbore pressure of gas wells (such as A6 well) has decreased, slightly below the saturation pressure, while above the mist-flow pressure window (35 MPa). The condensate is highly dispersed in the gas phase after its precipitation, and produced in a carried form. Similar to the flow characteristics of single-phase gas, its oil and gas production remains stable, while GOR shows a slight increase; 3) Two-phase flow stage. At this stage, the near wellbore pressure of gas wells (such as A5H well) is lower than 35 MPa, and the condensate forms a continuous oil phase and the saturation continues to increase. As a result, part of the condensate oil remains in the formation and cannot be extracted, thereby affecting the permeability of the reservoir. Oil and gas production decreases, and the GOR rapidly increases, resulting in unfavorable outcomes for gas well production.

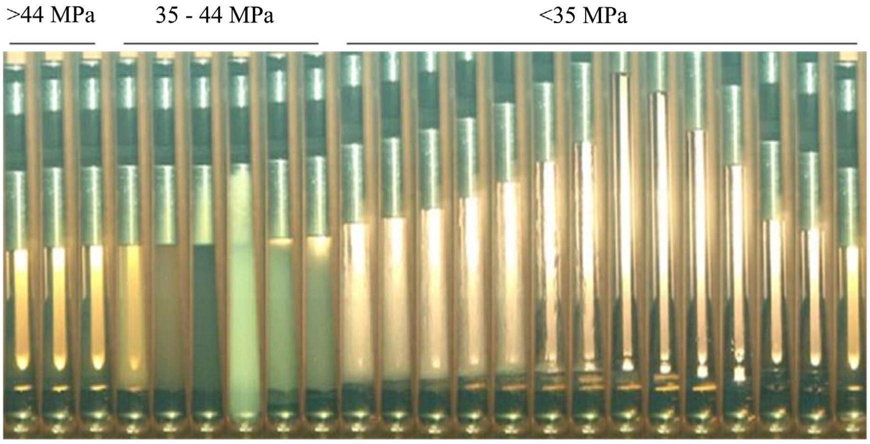

Figure 2. Constant mass expansion experiment of condensate gas fluid under HTHP conditions.

4. Study on Mathematical Model Characterization of Seepage Mechanism Based on Fluid Phase Change

4.1. Characterization of the Law of Fluid Phase State Changes in Reservoirs under the Condition of High Temperature and High Pressure

Experimental fitting was conducted on the BZ19-6 fluid using the professional fluid analysis software FluidModeler, and characteristic parameters of fluid were obtained. Then, the law of fluid phase state changes after oilfield development was characterized and predicted using mathematical models. It can be seen that the fluid composition of the formation near the gas producing well will change under different formation pressures. The condensate oil will be precipitated due to the decrease in formation pressure. Compared with the initial condensate gas fluid, the proportion of light hydrocarbon components in the formation condensate gas increased from 61.2% to 65.6%, the proportion of medium hydrocarbon components increased from 25.6% to 26.7%, and the proportion of heavy hydrocarbon components decreased from 7.9% to 2.7%. In this effect, the P-T phase diagram shifts to the bottom left, and the dew point pressure and critical pressure show a gradually downward trend, thus increasing the pressure window of the mist flow. At the same time, the maximum amount of retrograde condensate decreases from 41% to 26%, which is beneficial for delaying the precipitation of condensate oil. Therefore, in the mist flow stage, the production pressure difference can be appropriately enlarged to improve the recovery efficiency of condensate oil (Figure 3).

4.2. Equivalent Characterization of Quasi-Stable Misty Mixed Fluid State

The high-temperature and high-pressure physical experiments, as well as depressurization and depletion experiments of the formation condensate gas fluid show that, when the local formation pressure drops below the dew point pressure, the condensate oil will be precipitated in the form of liquid phase oil droplets

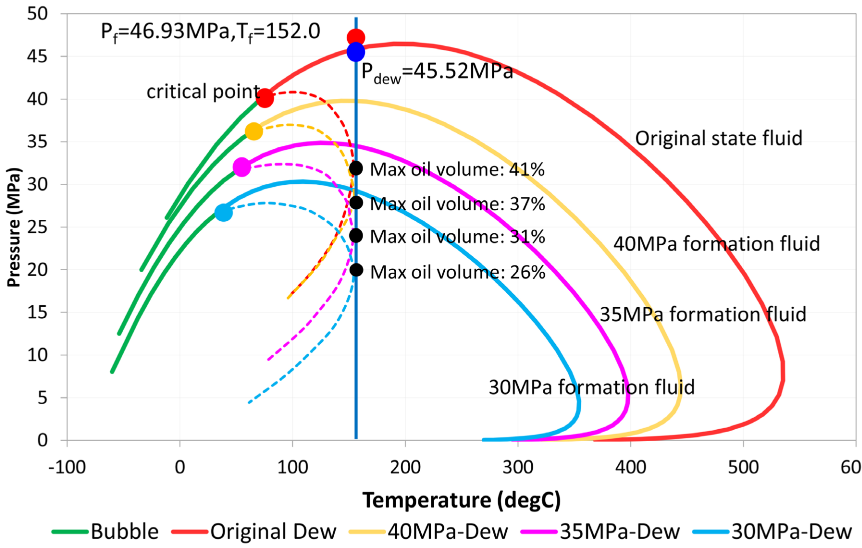

Figure 3. P-T phase diagram of residual fluid under different depletion pressures.

and will be uniformly and stably highly dispersed in the gas phase (with the same composition ratio of oil and gas components per unit volume), forming a relatively stable and near-miscible state of a mist-like mixed fluid. Given that oil and gas are stably produced in a constant proportion within the same time period, which is the same as the proportion of oil and gas in the mixed phase state, the description method of mixed phase mechanism is therefore used to equivalently characterize the state of the misty-like mixed fluid.

$$\sigma = \left[\sum_{i=1}^{N_{comps}} [P]_i \left(b_L^m x_i - b_V^m y_i \right) \right]^4$$

σ : surface tension of oil and gas, dynes/cm,

x_i : Mole fraction of liquid phase, %,

y_i : Mole fraction of gas phase, %,

b_L^m : Molar density of liquid phase, gm-M/cc,

b_V^m : Molar density of gas phase, gm-M/cc,

P: Component isotonic volume.

The formation fluid is produced as the development progresses. As a result, the formation pressure gradually decreases, leading to an increase in Mole percentage of liquid phase and a decline in Mole percentage of gas phase. The interfacial tension between oil and gas gradually increases with the decrease of pressure. The plate of oil-gas interfacial tension changing with the formation pressure was calculated through the formula. It can be seen that the fluid in the BZ19-6 reservoir has an interfacial tension of 0.02 mN/m under formation conditions (152˚C, 46.9 MPa). When the formation pressure drops to 35 MPa, the interfacial tension exhibits a low level of 0.08 mN/m, during which oil-gas mixing is prone to occur, thus increasing the production of condensate oil (**Figure 4**).

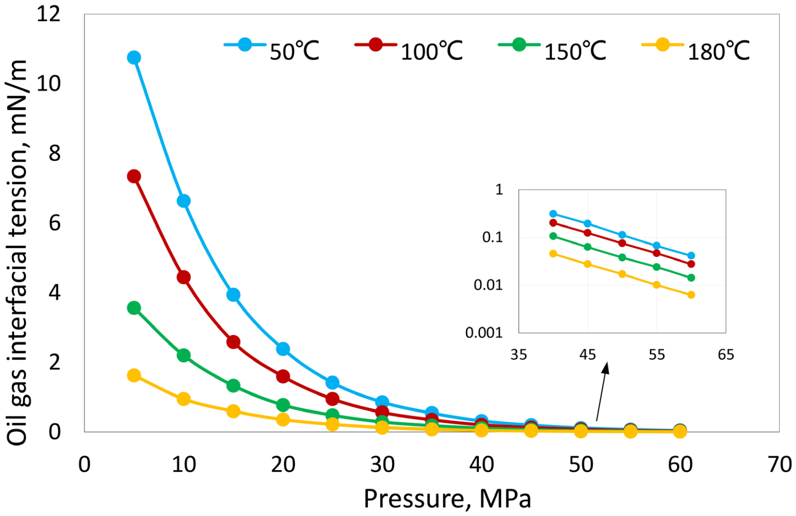

Figure 4. Oil gas interface tension diagram under different temperature and pressure.

4.3. Characterization of the Seepage Mechanism of Mist-Like Mixed Fluids

According to mist flow experiments and production performance analysis, the seepage characteristics of formation fluids are divided into three stages respectively: single-phase flow of condensate gas above dew point pressure, mist-like quasi single-phase flow of condensate oil and gas above 35 MPa, and two-phase flow of oil and gas below 35 MPa. Thereinto, the (1) and (3) stages can be described using the conventional method of phase permeability curve for seepage, and the following research and analysis will be conducted for the (2) stage of mist flow. In the stage of mist flow, based on the high-temperature and high-pressure experiments of the formation fluid, the pressure range for the existence of mist flow is determined to be from the dew point pressure to 35 MPa, and the maximum amount of condensate in this pressure range is 38.6%. Since the high-pressure physical property experiment is a PVT barrel oil gas two-phase experiment, which is currently condensate oil. In actual reservoir pores, the bound water saturation is 34.0%. Saturation can be corrected based on the available pore volume of hydrocarbon fluids. The lower limit of the pressure range of the mist flow corresponds to a correction of natural gas saturation of 27.3%. Therefore, the gas saturation in the quasi single-phase flow range of the mist flow is determined to be 27.3% - 66.0%. At the same time, an interface tension infiltration influence coefficient is introduced considering the influence of the degree of condensate precipitation on the sorting flow ability of oil-gas mist-like mixed fluid infiltration under different depletion pressures during the development process. The interfacial tension is calculated through the oil-gas components, as well as fluid characteristic parameters during the development process. Then the interpenetration coefficient of interfacial tension is obtained.

$$F_k = \min\left(\frac{\sigma}{\sigma_o}\right)^4$$

σ_o : Reference oil-gas interfacial tension, dynes/cm,

σ : Current temperature pressure interfacial tension, dynes/cm,

N: interfacial tension ratio index.

As the interfacial tension gradually decreases to 0, the seepage characteristics of oil-gas mist-like mixed fluid tend to be similar to the unidirectional gas flow, and the condensate oil mixed phase permeability is set on this basis. The oil-gas interfacial tension is calculated according to different degree of condensate precipitation. And the interpolation coefficient of oil phase relative permeability is calculated according to the reference interfacial tension ratio. The values under different temperatures and pressures are calculated according to the following formula:

$$K_r = F_k \cdot K_r^{imm} + \left(1 - F_k\right) K_r^{mis}$$

K_r : relative permeability curve,

K_r^{imm} : relative permeability curve in immiscible phase,

K_r^{mis} : relative permeability curve in miscible phase,

F_k : the interpolation coefficient of interfacial tension.

The partition characterization of the relative permeability curve shows that when the pressure is greater than 44 MPa and the gas saturation is greater than 66.0%, the reservoir fluid is single-phase flow of pure condensate gas. When the pressure ranges from 35 MPa to 44 MPa and the gas saturation ranges from 27.3% to 66.0%, the reservoir fluid is a mist-like mixed fluid quasi single-phase flow. When the pressure is less than 35 MPa and the gas saturation is less than 27.3%, the reservoir fluid is a conventional oil gas two-phase flow. Ultimately, we successfully describe the accurate seepage characteristics of "single-phase flow of condensate gas - near-miscible mist-like quasi single-phase flow - oil-gas two-phase flow" during the entire development process of condensate gas reservoir in the BZ19-6 gas field under HTHP conditions (**Figure 5**).

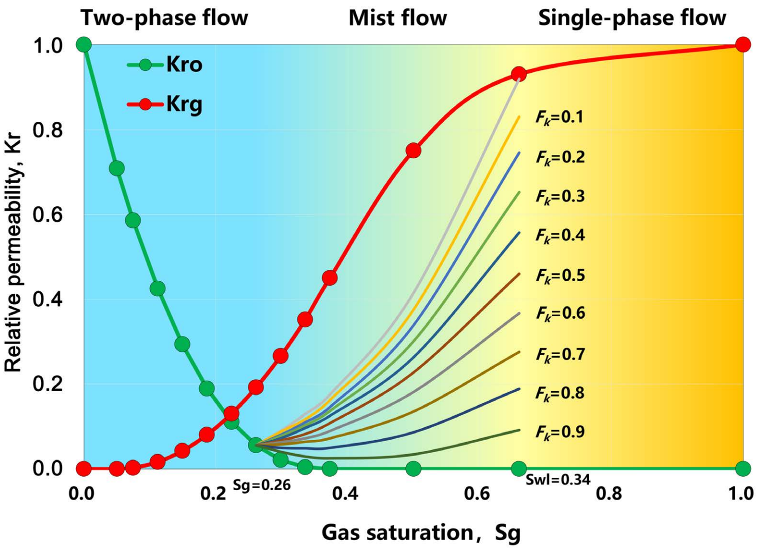

Figure 5. Schematic diagram of condensate gas reservoir seepage characteristics.

4.4. Research on Numerical Simulation of Oil Reservoirs

Through the study of the phase changes and flow characterization of fluids in the high-temperature and high-pressure formation of BZ19-6, accurate fitting of key indicators for oilfield development has been achieved, which shows a significant improvement compared with that before characterization. Taking well A6 as an example, the formation pressure near the well has depleted to around 38 MPa. According to the conventional understanding of the phase change law, the precipitation of condensate oil will cause a rapid increase in the gas-oil ratio and a decrease in condensate production. The initial model in the figure reveals a significant difference from the actual situation. The full cycle seepage mechanism of condensate gas reservoirs under HTHP conditions better characterizes the seepage characteristics between the dew point pressure and the lower limit of mist flow pressure after condensate oil precipitation in actual production. The results show a favourable fitting effect with daily gas production of 100,000 cubic meters per day, daily oil production of 100 cubic meters per day and a stable gas-oil ratio of around 1100 m^3/m^3 (**Figure 6**).

In combination with the development of reservoir fractures, the history matching of reservoir numerical simulation was conducted on BZ19-6 test area, and the pressure distribution law and condensate saturation distribution law were obtained. As show in the figure, fractures are developed near the A4H well, with sufficient pressure supply, and the formation energy is basically maintained near or above the dew point pressure. Unidirectional flow predominates in the reservoir fluids, and the condensate oil is basically not precipitated. The fractures near the well A6 are relatively developed, and the formation energy has decreased to around 38 MPa. However, due to the location in the mist flow zone, the condensate oil is carried out by gas, resulting in its lower saturation. The fractures near well A5 are less developed, with dismal reservoir connectivity and

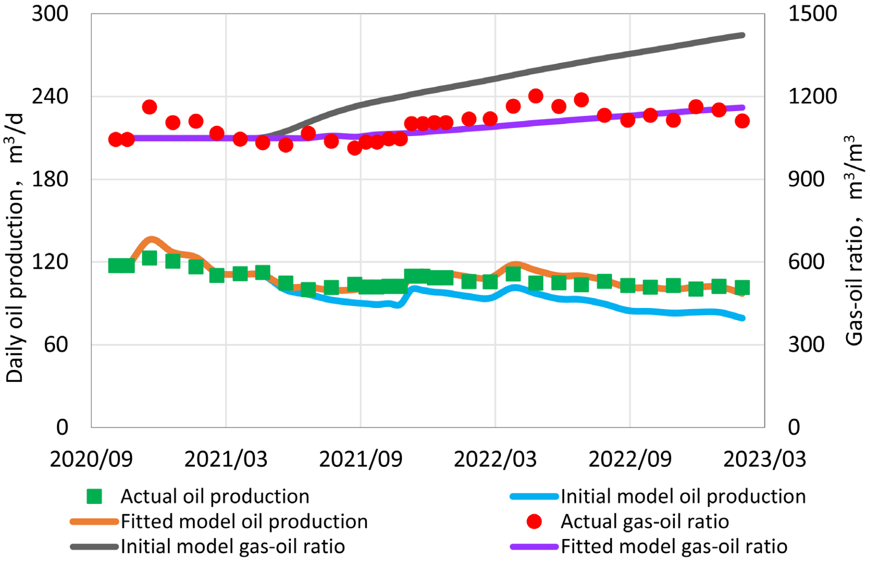

Figure 6. Production curve fitting of well BZ19-6-A6.

insufficient formation energy supply. The pressure drops to around 28 MPa, which is lower than the lower limit of mist flow. The reservoir fluid is two-phase flow, with great loss of condensate oil, resulting in high condensate oil saturation of around 25%. Therefore, extending the single-phase flow and mist-flow time of reservoir fluid and reducing the time of oil-gas two-phase flow figure prominently in improving production capacity and recovery efficiency of the BZ19-6 gas field (**Figure 7** and **Figure 8**).

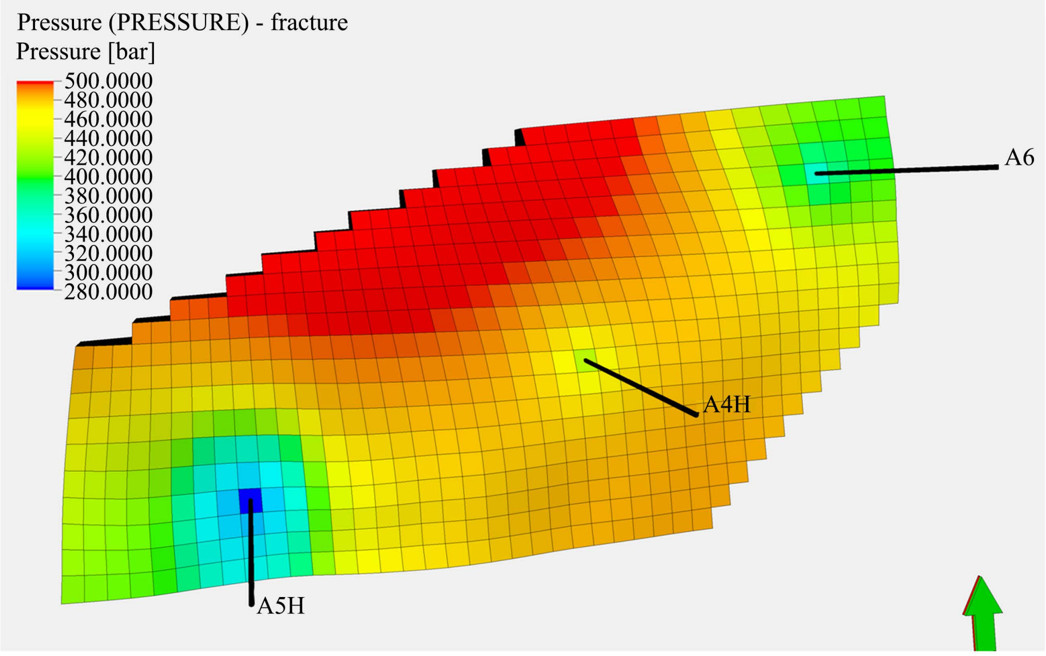

Figure 7. Formation pressure distribution model.

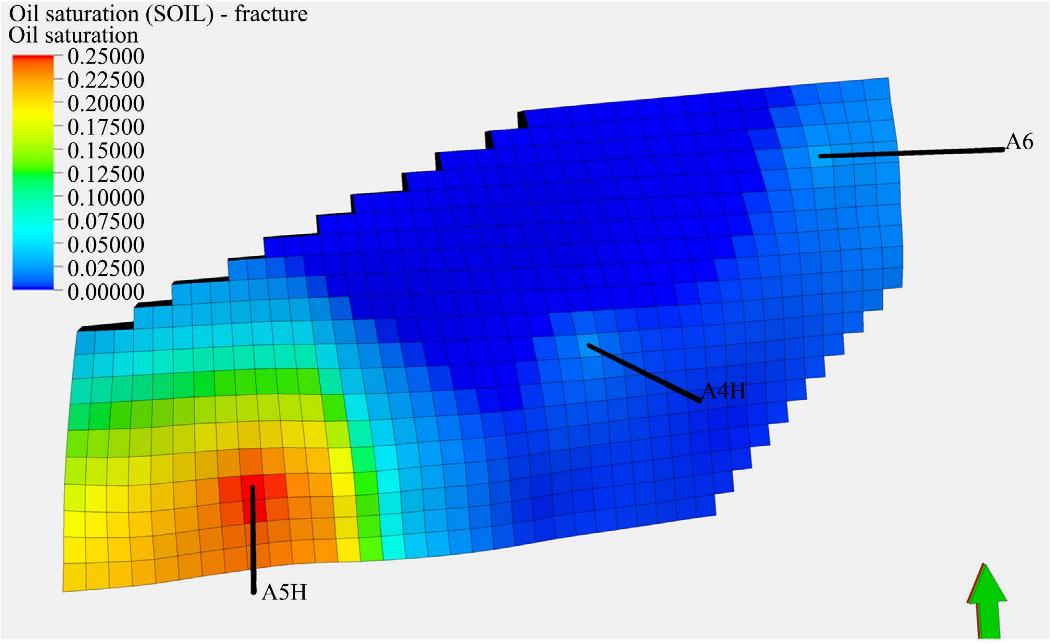

Figure 8. Condensate saturation distribution model.

5. The Control Effect of Mist-Like Reverse Condensation during Development and Production

Based on the above experimental and numerical characterization results, as well as actual oilfield production performance and reservoir development, a production control strategy for the BZ19-6 condensate gas reservoir is formulated: 1) Stable production strategy in the single-phase flow stage: maintaining stable oil-gas production, while considering the production time of single-phase flow, and delaying the time of entering into the mist flow and two-phase flow; 2) Increasing pressure difference in the mist-flow stage: fully considering the velocity stripping effect and mist-flow effect, and appropriately increasing oil-gas production capacity; 3) Reducing pressure difference in the two-phase flow stage: controlling the production speed, activating the energy supply of the matrix system, restoring the phase state of oil-gas mist flow, thereby increasing oil-gas production.

The plane well network structure of the BZ19-6 gas field has been adjusted through the above production control strategy of “one well, one scheme”. In 2022, the implementation of the work system in the pilot area was optimized for 11 wells, achieving a “zero increase” in the gas-oil ratio of the gas field, showing an annual increase of 22,000 cubic meters of oil and a predicted increase in reserve recovery rate of 1.2%.

6. Conclusions

1) The formation temperature of BZ 19-6 gas field is 152˚C, and the formation pressure is 46.9 MPa, which is lower than the dew point pressure within a certain range (>35 MPa). The formation fluid will appear mist-like critical opalescence phenomenon. Condensate is highly dispersed in the gas phase in the form of mist-like oil droplets, which is conducive to improving the condensate recovery;

2) By characterizing the permeability zones, accurate description of the seepage characteristics of the entire development process “single phase flow of condensate gas - near miscible mist like quasi single phase flow - oil gas two phase flow” can be achieved, and accurately fit the key indicators of oilfield production.

3) Based on experimental results and numerical characterization, a production control strategy for condensate gas reservoirs was developed, and the gas production structure of the gas reservoir was adjusted. In 2022, the implementation of the work system in the pilot area was optimized for 11 wells, achieving a “zero increase” in the gas-oil ratio of the gas field, with an annual oil increase of 22,000 cubic meters.

Conflicts of Interest

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

References

[1] Sun, L.D., Song, W.J. and Jiang, T.W. (2003) The Development Study on Gas Recycling Injection in Yaha Gas Condensate Field, Tarim Basin, China. *Science in China Series D*: *Earth Sciences*, **46**, 561-568. https://doi.org/10.1007/BF02984534

[2] Li, S.L., Wang, M.H. and He, J.C. (2004) Gas Field and Condensate Field Development. Petroleum Industry Press, Beijing, 105-125.

[3] Yu, H.J. (2016) Research on Enhancing Oil Recovery for Gas Cap Reservoir with High CO_2 and Condensate Oil & Gas on the Sea. *Well Testing*, **25**, 10-13.

[4] Hu, W., Lv, C.Y., Lun, Z.M., *et al.* (2019) Constant Volume Depletion Experiment and Phase Characteristics of Condensate Gas in Dense Porous Media. *Acta Petrolei Sinica*, **40**, 1388-1395.

[5] Tong, M., Li, X.F., Hu, Y.L., *et al.* (2004) Experimental Study on Influence of Porous Media on Phase Behavior of Gas Condensate. *Journal of the University of Petroleum*, *China*, **28**, 61-64.

[6] Shen, P.P., Zheng, X.T., Li, S., *et al.* (2001) Near-Critical Phenomenal of Rich Gas Condensate Systems: An Experimental Investigation. *Acta Petrolei Sinica*, **22**, 47-51.

[7] Wang, C.Q., Tang, Y., Du, Z.M., *et al.* (2013) Phase Behaviors of Condensate Gas with Vaporous Water and Liquid Production Characteristics in a Non-Equilibrium Pressure Drop Process. *Acta Petrolei Sinica*, **34**, 740-746.

[8] Guo, P., Sun, L., Song, W.J., *et al.* (2001) Study on the Phase-State Restorarion of Gas Condensate Reservoirs. *Journal of Southwest Petroleum Institute*, **23**, 25-29.

[9] Zhong, T.X., Yuan, S.Y., Hu, Y.L., *et al.* (2004) Complex Phase Behavior of Gas Condensate Systems. *Petroleum Exploration and Development*, **31**, 125-127.

[10] Fan, J.M., Guo, P., Deng, L., *et al.* (2008) The Influence of Water Content in Gas on Reservoir Fluid Performance and the Flow through Porous Media. *Journal of Southwest Petroleum University*: *Science & Technology Edition*, **30**, 100-102.

[11] Jiang, T.W., Wang, Z.B. and Xie, W. (2017) Cyclic Gas Injection Development Practice and Development Law of Yaha Condensate Field. Petroleum Industry Press, Beijing, 322-325.

[12] Guo, P., Wang, J., Liu, W., *et al.* (2013) Dynamic Experiment Study on Depletion Development of Condensate Gas Reservoir with Fracture and Cave. *Oil Drilling & Production Technology*, **35**, 67-70.

[13] Zhang, G.L., He, Z.Q., Zhu, J.J., *et al.* (2016) Experiment on the Influencing Factors of the Natural Depletion Development for Condensate Gas Reservoirs. *Petroleum Geology and Oilfield Development in Daqing*, **35**, 62-65.

[14] Zhu, W.Y. (1988) Study on Gas-Liquid Two-Phase Seepage Mechanism of Condensate. *Petroleum Exploration and Development*, **15**, 63-65.

[15] Liu, Y.J., Li, X.F. and Kang, X.D. (2006) Determination of Reasonable Pressure Difference for Condensate Gas Reservoir. *Acta Petrolei Sinica*, **27**, 85-88.

[16] Kang, X.D., Li, X.F., Liu, Y.J., *et al.* (2005) Simulation and Mechanism of High-Velocity Two-Phase Flow in Gas Condensate Reservoir. *Journal of Engineering Thermophysics*, **26**, 261-263.