

Research Article

Influence of Compositional Gradient Effect on Tight Condensate Gas Reservoir Development

Jing Chen ¹, Xinmin Song,¹ Baozhu Li,¹ Xiaoli Luo,² Youjing Wang,¹ and Jinfang Wang¹

¹Research Institute of Petroleum Exploration & Development, PetroChina, Beijing 100083, China

²Southwest Oil & Gas Field Company, PetroChina, Chengdu, Sichuan 610041, China

Correspondence should be addressed to Jing Chen; chenjingcycc@163.com

Received 6 April 2022; Revised 17 May 2022; Accepted 19 May 2022; Published 15 June 2022

Academic Editor: Zheng Sun

Copyright © 2022 Jing Chen et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Condensate gas is a transition fluid between oil and gas, which is sensitive to the reservoir temperature and pressure. In condensate gas reservoir, especially in the moderate-giant one, fluid composition often varies with depth. This phenomenon has important influences on development. Anisothermal compositional gradient theory is used to analyze the main factors influencing the compositional gradient distribution to understand the basic regularities of the compositional variation with depth. Geothermal gradient, fluid composition, reservoir temperature, and reservoir pressure will affect the compositional gradient, of which geothermal gradient has the most direct and obvious influence. Furthermore, fluid model with compositional gradient was built in a tight condensate gas reservoir of the Middle East, and the influence of compositional gradient on dynamic performance is evaluated. The results show that the compositional gradient has a significant influence on the original gas in place, development strategy, central processing facilities, and so on. Therefore, compositional gradient requires more attention while exploiting moderate-giant condensate gas reservoirs in order to achieve more economical benefits.

1. Introduction

In the last decades, a large number of oil and gas reservoirs have been developed in the Middle East [1–7], including many transitional fluid reservoirs [8, 9], such as volatile reservoirs with high gas-oil ratio and rich condensate reservoirs. A common feature of these reservoirs is that the composition of the fluid changes with depth, a phenomenon known as compositional gradient effect. This phenomenon is particularly obvious in moderate-giant carbonate reservoirs and has an important impact on every link of oil-gas field development [7]. Previously, due to lack of understanding of the compositional gradient effect, this phenomenon was often ignored in the development of such critical reservoirs, resulting in poor recovery and economic benefits [8, 9].

As early as 1939, Sage and Lacey [10] pointed out that volatile oil reservoirs and condensate gas reservoirs rich in condensate are special reservoirs with component gradient distribution when discussing the phenomenon of component classification. However, it was not until the early

1980s that a large number of deep near-critical oil and gas reservoirs were found to have significant vertical compositional changes in the world that people paid more attention to this problem and proposed that the compositional gradient should be fully considered in the development of such reservoirs.

At present, some scholars at home and abroad have carried out many in-depth studies on the compositional gradient effect based on sage's research findings [11–16], but most of them focus on the composition variation with depth under isothermal conditions and there are few relevant literatures. Li [16] proposed to use isothermal compositional gradient model to show the distribution characteristics of fluid compositions and properties with depth. However, in some moderate-giant condensate reservoirs, reservoir temperatures increase with depth. The effect of reservoir temperature on compositional gradient cannot be ignored. In this paper, the anisothermal compositional gradient theory model is used to analyze the main factors affecting the distribution of compositional gradient and to evaluate its influence on the main links of oil and gas field development.

2. Anisothermal Compositional Gradient Theory Model

Before 1970s, Sage and Lacey [10] and Haase [17] proposed that in a gravitational field, when a multicomposition system is in real thermodynamic equilibrium, the system should be isothermal, and the sum of chemical and gravitational potentials of each composition in the system should be constant. In 1980, Schulte [18] proposed a calculation model of compositional gradient under the influence of gravity only based on the previous two scholars. With the additional term of gravity, the vertical equilibrium condition of a multicomposition system in the gravitational field can be expressed as

$$d\mu_i + M_i g dh = 0 \quad i = 1, 2, \dots, n. \quad (1)$$

Both m_i and g are constant against h , and equation (1) can be rewritten as

$$\mu_i(h) - \mu_i(h^0) = M_i g (h - h^0); \quad i = 1, 2, \dots, n, \quad (2)$$

where n is the number of compositions in a system, i is the composition number, M_i is the molar mass of composition i , μ is the chemical potential of composition i , g is the gravitational acceleration, and h is the reservoir depth.

The relation between chemical potential μ and fugacity f_i of composition i is as follows:

$$\partial\mu_i = RT \ln f_i, \quad (3)$$

where R is the gas universal constant and T is the system temperature.

By combining equations (2) and (3), the fugacity relation equation of composition i at depth h and h^0 can be obtained:

$$\ln f_i^h - \ln f_i^{h^0} = \frac{M_i g (h - h^0)}{RT}. \quad (4)$$

The relation between fugacity f_i and fugacity coefficient φ_i is as follows:

$$\ln f_i = \varphi_i Z_i P, \quad (5)$$

where Z_i is the molar content of composition i in the system, and P is the system pressure.

Equation (4) is combined with equation (5), and the further deformation is

$$\ln \left(\varphi_i^h Z_i^h P^h \right) - \ln \left(\varphi_i^{h^0} Z_i^{h^0} P^{h^0} \right) = \frac{M_i g (h - h^0)}{RT}. \quad (6)$$

Equation (6) was applied to any composition i in the system, and there are n equations for the n -composition sys-

tem, plus an additional equation, that is, the sum of the mole fraction values of all compositions in the system is 1:

$$\sum_{i=1}^n Z_i = 1. \quad (7)$$

Given the pressure P^{h^0} at depth h^0 and the composition content ($Z_i^{h^0}$, $i = 1, 2, \dots, n$), the P^h and Z_i^h of each composition at depth h can be solved by using the $n + 1$ equations, where the fugacity coefficient φ_i can be obtained from the equation of state.

In fact, not very reservoirs have constant temperature. For thin reservoirs, the changes of reservoir temperature be ignored, but for thicker reservoirs, especially some moderate-giant carbonate reservoirs in the Middle East, temperature increases usually on the order of $0.02^\circ\text{C}/\text{m}$ from top to bottom of the reservoir.

The changes of reservoir temperature need to be considered when solving the compositional gradient. In 2003, Pedersen and Lindeloff [19] proposed a compositional gradient calculation model under anisothermal conditions based on Haase's research.

Based on the irreversibility of the thermal process, the equation of molar compositions in the heat source with thermal gradient was established to solve this problem. The system is assumed to be in a steady state to simplify this problem. That means all composition fluxes were zero, the compositional gradient is assumed to be constant in time, and the effects of capillary force, composition convection and secondary migration are not considered. According to the equation (6), an additional term is added to express the influence of geothermal gradient, which also includes the average molecular weight M , the molecular weight M_i of all compositions, the partial molar enthalpy of the mixture \widetilde{H} , and the partial molar enthalpy of composition i \widetilde{H}_i . A dynamic and stable system is established in the equilibrium of gravity and heat convection effect.

$$\begin{aligned} & RT \ln \left(\varphi_i^h Z_i^h P^h \right) - RT \ln \left(\varphi_i^{h^0} Z_i^{h^0} P^{h^0} \right) \\ &= M_i g (h - h^0) - M_i \left(\frac{H}{M} - \frac{\widetilde{H}_i}{M_i} \right) \frac{\Delta T}{T}; \quad i = 1, 2, \dots, n, \end{aligned} \quad (8)$$

where

$$\widetilde{H} = H_i^{ig} + \widetilde{H}_i^{res}, \quad (9)$$

$$\widetilde{H}_i^{res} = -RT^2 \frac{\partial \varphi_i}{\partial T}, \quad (10)$$

$$H = \sum_{i=1}^n Z_i \widetilde{H}_i = \sum_{i=1}^n Z_i H_i^{ig} + \sum_{i=1}^n Z_i \widetilde{H}_i^{res}, \quad (11)$$

where H_i^{ig} is ideal gas enthalpy of composition i ; \widetilde{H}_i^{res} is partial molar residual enthalpy of composition i .

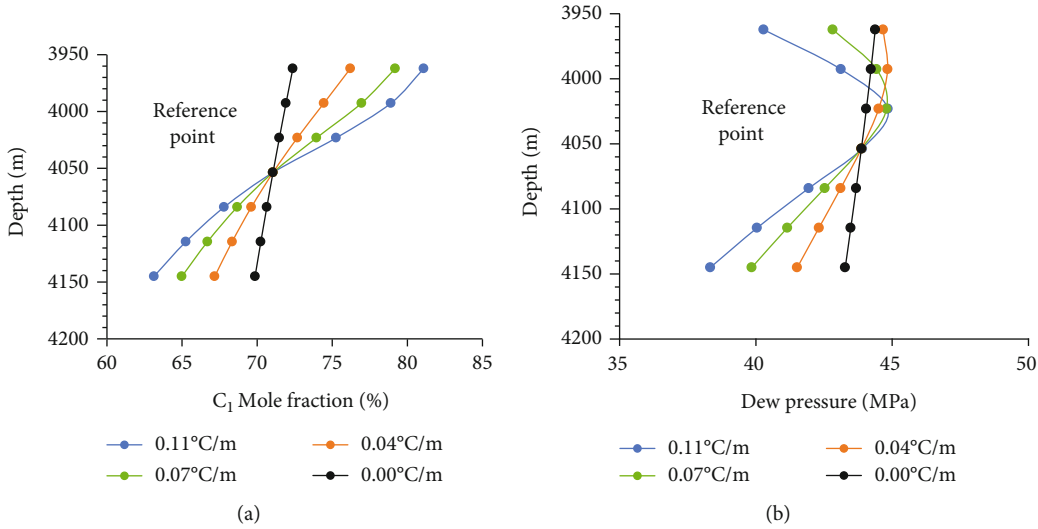


FIGURE 1: (a) Effect of geothermal gradient on compositional gradient. (b) Effect of geothermal gradient on dew point pressure.

When calculating the change of compositions with depth, an appropriate equation of state is firstly selected to obtain the vapor and liquid phase compressibility factors. And the equation of fugacity coefficient is applied to obtain the vapor and liquid phase fugacity coefficients of each composition [20–23]. Then, the compositions’ fugacity coefficients, ideal gas enthalpy H_i^{ig} , and the compositional gradient are calculated according to equation (8). There is a trial calculation process in the solution process. The initial vapor-liquid ratio of composition i is preset to calculate the vapor and liquid fugidity coefficients under the equilibrium state. If they are equal, the trial calculation succeeds; if they are not equal, the initial setting value is returned to be modified. The calculation process must be repeated iteratively, usually completed by computer program.

3. Influence Factors of Compositional Gradient Distribution

Since the anisothermal compositional gradient model is built into the commercial software PVTsim, a multifunctional equation of state simulation software, it was used to analyze the influence factors of compositional gradient distribution by selecting SRK Peneloux equation of state, which has good adaptability to condensate gas and volatile oil. In this paper, the influence factors are divided into two categories: one is direct influence factors, such as gravity field and geothermal gradient, and the other is indirect influence factors, such as fluid composition, reservoir temperature, and reservoir pressure.

3.1. Geothermal Gradient. It can be deduced from the above equations that the most direct cause of the compositional gradient effect is the rebalancing of the chemical potential of each composition caused by gravity field and geothermal gradient. Therefore, the vertical compositional gradient effect and fluid properties will be different under different geothermal gradient. Taking the condensate gas sample as

an example, C_1 and dew point pressure were taken as the observation objects (Figures 1(a) and 1(b)). When the local geothermal gradient is $0.00^\circ\text{C}/\text{m}$, only gravity differentiation plays a role in the compositional gradient, and the variation of fluid compositions within the thickness of 100 m was only about 1%. When the local geothermal gradient increases to $0.04^\circ\text{C}/\text{m}$, $0.07^\circ\text{C}/\text{m}$, and $0.11^\circ\text{C}/\text{m}$, respectively, the variation of fluid composition increases to 5%, 8%, and 10%. It can be seen that geothermal gradient is the most important factor leading to compositional gradient effect. Therefore, for reservoirs with large geothermal gradient, such as some ultrahigh temperature reservoirs, the compositional gradient effect has aroused great attention.

3.2. Fluid Composition. In order to investigate the influence of different fluid types on the distribution of compositional gradient under the same formation conditions, this paper selected three critical fluids, including volatile oil, rich condensate gas, and condensate gas, as the research objects. Composition data of fluid samples are shown in Table 1. Calculation results show that the contents of light compositions decrease, and the contents of heavy compositions increase in all three fluid samples with the increase of reservoir depth, especially C_1 and C_{7+} . The decrease of C_1 is almost equal to the increase of C_{7+} (Figure 2). The lighter fluid samples, the more obviously the fluid compositions change with depth. As shown in Figure 3, only C_1 and C_{7+} composition in the volatile oil obviously change with depth. For rich condensate of which fluid properties are lighter, composition $C_2 - C_6$ increase with depth, and their molar contents present obvious increasing trend. For condensate gas whose compositions are the lightest, the contents of $C_2 - C_6$ have the largest variation with depth, indicating that the lighter the fluid sample is, the more obvious the compositional gradient effect of the light composition is.

3.3. Reservoir Temperature. Taking rich condensate gas sample as an example, C_1 and dew point pressure are taken as

TABLE 1: Composition content of three fluid samples.

| Composition | Volatile oil | Rich condensate gas | Condensate gas |
|-------------|--------------|---------------------|----------------|
| N2 | 0.73 | 0.11 | 0.10 |
| CO2 | 2.35 | 2.82 | 3.31 |
| H2S | 0.03 | 0.03 | 0.05 |
| C1 | 57.71 | 71.06 | 81.52 |
| C2 | 8.07 | 6.32 | 4.51 |
| C3 | 5.45 | 3.71 | 2.10 |
| iC4 | 1.05 | 0.76 | 0.44 |
| nC4 | 2.66 | 1.76 | 0.88 |
| iC5 | 1.05 | 0.79 | 0.44 |
| nC5 | 1.21 | 0.91 | 0.50 |
| C6 | 0.24 | 1.24 | 0.77 |
| C7+ | 19.46 | 10.49 | 5.38 |

observation objects to study the compositional gradient effect and the variation of fluid properties of the same fluid at different reservoir temperatures. It can be seen from Figures 4(a) and 4(b) that the vertical fluid composition and fluid properties are different due to the different reservoir temperature at the reference depth. The higher the reservoir temperature is, the smaller the variation of fluid compositions and fluid properties is. It indicates that the increase of reservoir temperature will weaken the compositional gradient effect. Therefore, it can be seen that the fluid compositions and fluid properties vary with depth slightly in ultrahigh temperature reservoirs.

3.4. Reservoir Pressure. Reservoir pressure is one of the indirect factors affecting the distribution of fluid compositions and fluid properties with depth. The vertical fluid composition and properties are different due to the different reservoir pressure at the reference depth. As can be seen from Figures 5(a) and 5(b), the higher the reservoir pressure is, the weaker the vertical compositional gradient effect is, and the smaller the corresponding dew-point pressure changing with the depth is. Therefore, for reservoirs with high reservoir pressure, such as the deep buried reservoirs or ultrahigh pressure reservoirs, the compositional gradient effect will be weakened.

4. Typical Tight Condensate Gas Reservoir Development and Production Strategy

4.1. Brief Introduction of Gas Reservoir. *S* condensate gas reservoir located in the Middle East is a typical moderate-giant gas reservoir rich in condensate. The net pay of the reservoir is about 50 m, and the middle depth of reservoir is -4035 m. It belongs to a weak edge aquifer, low-porosity, and tight condensate gas reservoir with no stable buffer and good interlayer connectivity. Before this condensate gas reservoir was put into development, as shown in Figure 6 the original fluid samples were obtained from the high, middle, and low parts of the reservoir structure, and the gas-oil ratios were $1696 \text{ m}^3/\text{m}^3$, $754 \text{ m}^3/\text{m}^3$, and $445 \text{ m}^3/\text{m}^3$, respectively, showing obvious compositional gradient effect.

4.2. Original Gas in Place. The composition gradient effect results in the different composition in different reservoir depths, and the corresponding fluid parameters such as formation volume factor, dew point pressure, and gas-oil ratio also are great differences. The formation volume factor is one of the core parameters in the calculation of original gas in place. If the constant formation volume factor is used to calculate the original gas in place in oil reservoirs with obvious composition gradient, the calculated original gas in place will have obvious deviation from the actual value.

As shown in Figure 7, formation volume factor of the fluid in *S* tight condensate gas reservoir increases with the reservoir depth, from 0.0034 to 0.0049. Compared with the gas formation volume factor at -4035 m which is the middle depth of reservoir, the formation volume factor above -4035 m is smaller, while the formation volume factor below -4035 m is larger, with the maximum deviation ranges of -7% and 35%, respectively. If the formation volume factor at -4035 m is used to calculate the original gas in place of the entire condensate gas reservoir, the original gas in place of the reservoir above the -4035 m is smaller (blue shade in Figure 7), and the original gas in place below -4035 m is larger (red shade in Figure 7). *S* is a gently structured layered reservoir, most of the hydrocarbon is located above -4035 m. If the compositional gradient effect is neglected, that means the formation volume factor at -4035 m is used to calculate the original gas in place, and the surplus of the original gas in place below -4035 m cannot offset the shortage of original gas in place above -4035 m, resulting in the total original gas in place are about 5% smaller than the actual.

4.3. The Development Strategy. As shown in Figure 8, due to the compositional gradient effect, the fluid dew point pressure in the *S* tight condensate gas reservoir increases with depth, varying up to 2 MPa across the reservoir depth range. In the middle of the reservoir, the fluid became the rich condensate gas, and in the bottom of the reservoir, the fluid has developed from rich condensate to the volatile oil. So it can get better economic benefits to firstly develop the middle and lower part of the reservoir with more oil compositions. Therefore, the condensate gas reservoir adopts a development strategy of prioritizing the deployment of development wells in the structural wing and the perforation of the lower part of the reservoir. On the one hand, the gas cap expansion energy can maintain formation pressure, and the expansion energy of gas cap is used to maintain formation pressure, which is particularly important for tight gas condensate reservoirs. On the other hand, a large amount of high-quality condensate oil can be obtained quickly. However, due to the weak aquifer of the tight condensate gas reservoir and the high dew point pressure of fluid in the wing structure, it is necessary to carry out the pressure holding measures before the pressure at the bottom of the reservoir drops to the dew point pressure to avoid the impact of condensate banking on the overall recovery of the condensate gas reservoir.

The emphasis on the compositional gradient effect and such development strategy is very important for the tight condensate gas reservoir, because the reservoir property of

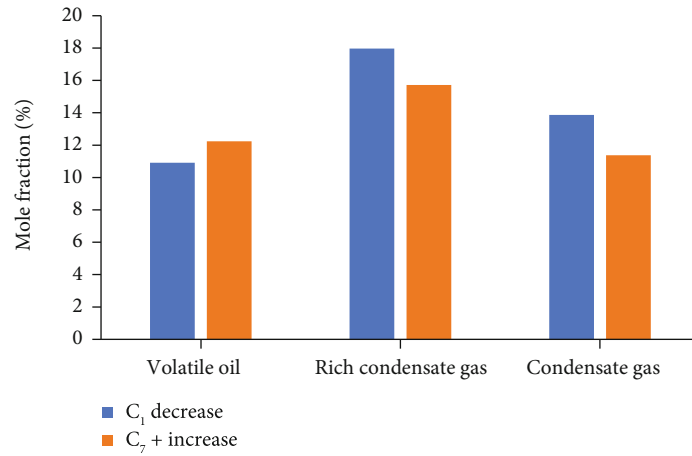


FIGURE 2: C_1/C_{7+} content variation with depth for different fluid samples.

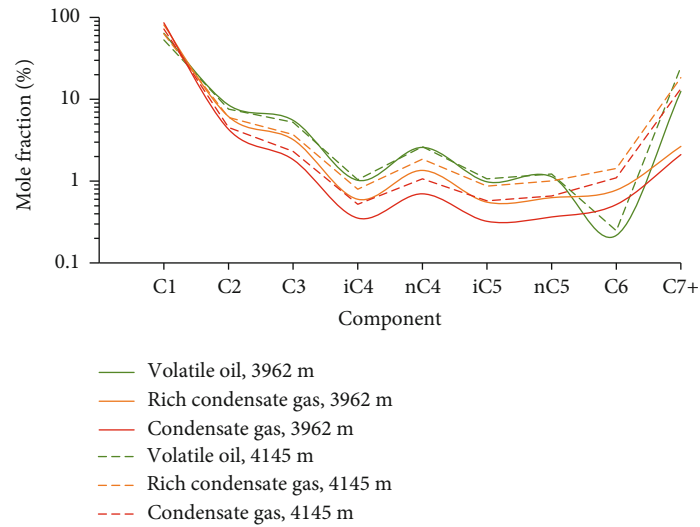


FIGURE 3: C_1/C_{7+} contents varying with depth for different fluid samples.

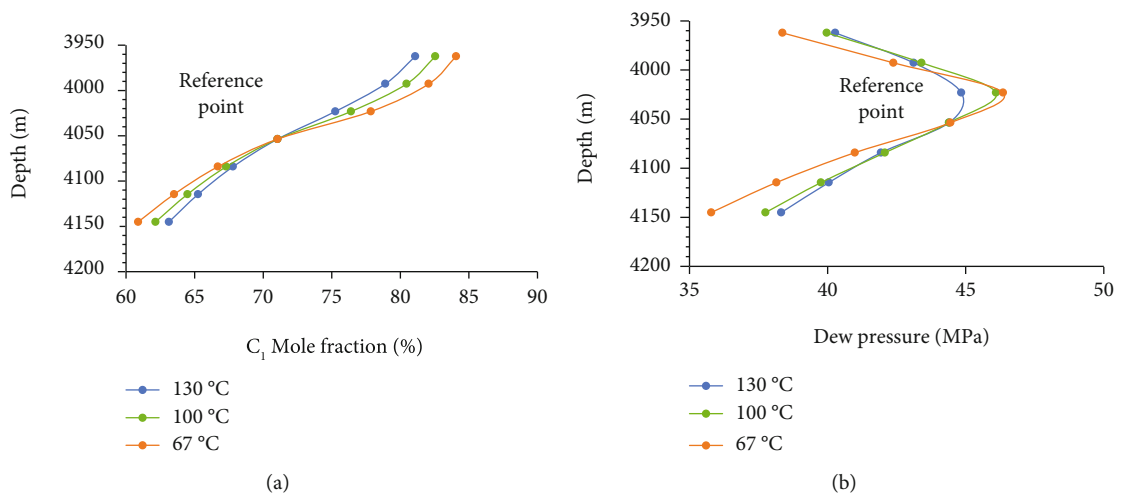


FIGURE 4: (a) Effect of reservoir temperature on compositional gradient. (b) Effect of reservoir temperature on dew point pressure.

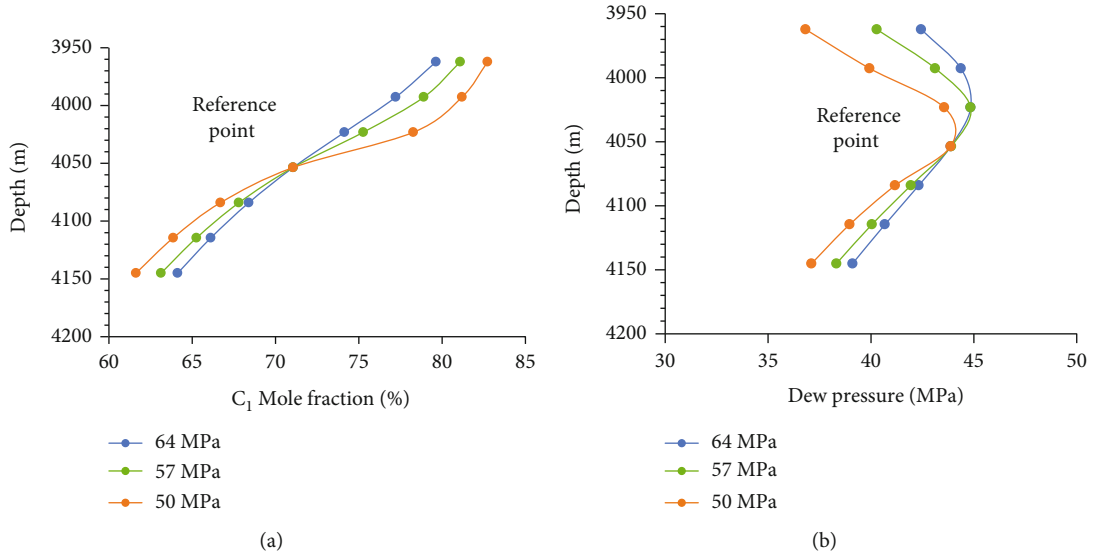


FIGURE 5: (a) Effect of reservoir pressure on compositional gradient. (b) Effect of reservoir pressure on dew point pressure of fluid.

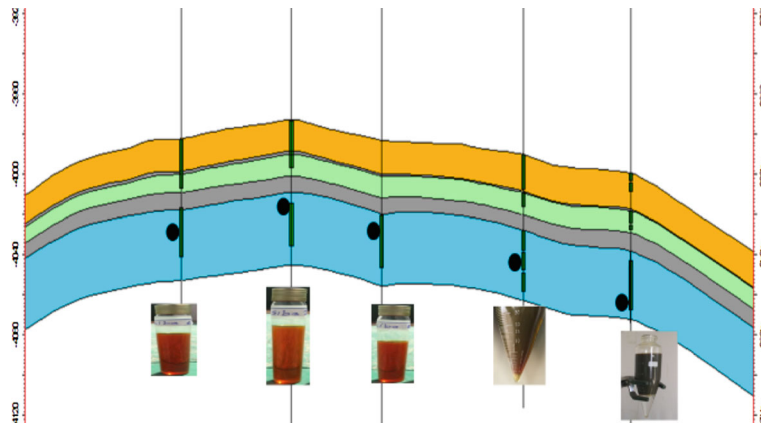


FIGURE 6: Sampling location of the original fluid in S tight condensate gas reservoir.

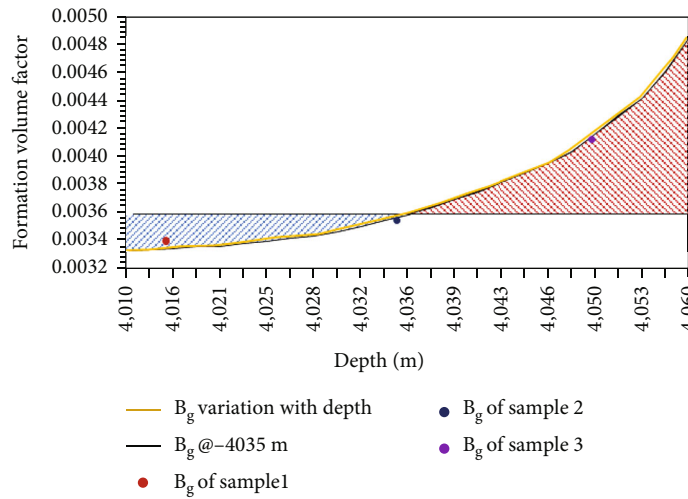


FIGURE 7: Formation volume factor of the original fluid in S condensate reservoir.

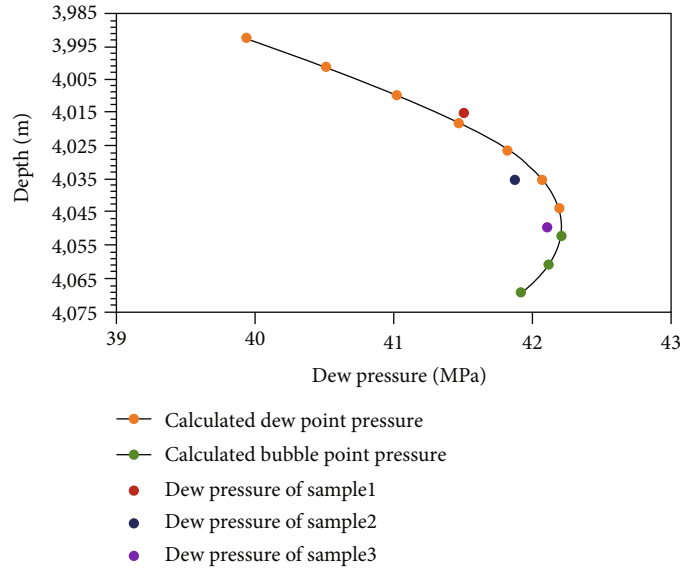


FIGURE 8: Dew point pressure of the original fluid in S condensate reservoir.

this type of condensate reservoir is very tight, and due to reservoir pressure lower than dew point pressure, the precipitation of condensate will seriously block the reservoir pores and the throats. This will cause the fluid to not flow smoothly in the reservoir, which in turn lead to a sharp reduction in recovery factor.

Thereby, it is necessary to consider the variation of oil/gas ratio and dew point pressure with depth caused by compositional gradient effect when developing development strategy, so as to achieve better development effect.

4.4. Surface Engineering Design. Compositional gradient effect also has great influence on oil and gas central processing facilities. The processing capacity of the oil and gas surface processing plants should be consistent with the sub-surface production capacity. If the processing g capacity of the plants is too large, the economic benefit of the whole project will be adversely affected, while if it is too low, the production will be restricted. Therefore, the fluid properties and development steps of oil and gas reservoirs should be considered comprehensively in the construction of oil and gas central processing facilities.

As shown in Figure 9, the high, medium, and low gas/oil ratios in S condensate gas reservoir are $1696 \text{ m}^3/\text{m}^3$, $754 \text{ m}^3/\text{m}^3$, and $445 \text{ m}^3/\text{m}^3$, respectively. If the production gas/oil ratio of samples in middle depth is used in the design of the processing capacity of various plants in S condensate gas reservoir, it will lead to the situation that the surface plants cannot meet the production demand. In the early stages of development, production may be constrained by the ability of condensate processing units due to the priority of producing the condensate in the middle and lower parts of the reservoir. Also, in the middle and high part of the reservoir, as well as dissolved gas precipitation and other factors, the natural gas processing plant may not be able to handle all the produced gas,

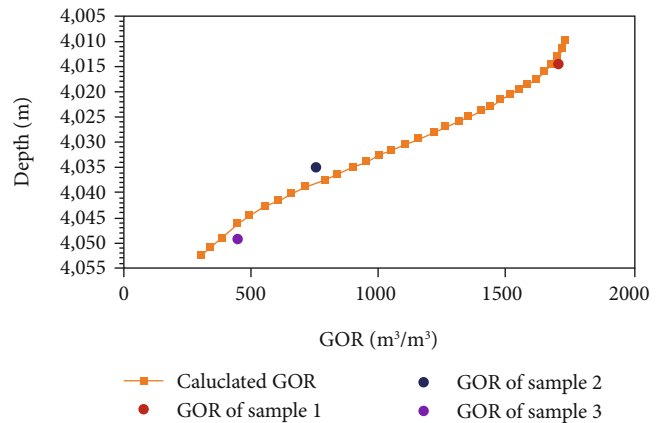


FIGURE 9: Gas oil ratio of the original fluid in S condensate reservoir.

resulting in production limit, which affects the development process and economic benefits of the whole project.

Therefore, in the development of a condensate gas reservoir with composition gradient effect, such as a condensate gas reservoir, before designing surface oil and gas processing facilities, on the one hand, original fluid samples at different depths should be obtained as much as possible for better understanding of reservoir fluids. On the other hand, in the preparation of the initial development plan, the integrated development strategy, zoning development or step by step production, or even combined with the surplus surface processing capacity of oil and gas in the adjacent oil and gas fields, should be adopted to improve the loading rate of processing facilities as much as possible to increase economic benefits.

5. Conclusion

Due to the influence of gravity field and geothermal gradient, transitional fluids such as condensate gas or volatile oil

always have compositional gradient effect, which is most obvious in moderate-giant reservoirs.

Geothermal gradient, fluid composition, reservoir temperature, and reservoir pressure all have varying degrees of influence on compositional gradient effect, and the geothermal gradient has the most direct and obvious influence. The larger the geothermal gradient is, the stronger the compositional gradient effect is. The larger the reservoir temperature and pressure are, the weaker the compositional gradient effect is. C_1/C_{7+} has the most obvious compositional gradient effect among all fluid compositions, and the increase of C_{7+} content is almost equal to the decrease of C_1 content.

Compositional gradient effect has important influence on the calculation of original gas in place, development strategy, surface engineering design, and so on. When an oil and gas field reservoir with compositional gradient effect is put into development in an all-round way, the original fluid samples at different depth should be taken as much as possible, so that a more clear understanding of reservoir fluid provides the solid material foundation for the entire development process and obtains maximum economic benefits.

Nomenclature

| | |
|-----------------------|--|
| n : | Number of compositions in a system |
| i : | Composition number |
| M_i : | Molar mass of composition i |
| μ_i : | Chemical potential of composition i |
| g : | Gravitational acceleration |
| h : | Reservoir depth |
| R : | Universal constant of the gas |
| T : | System temperature |
| Z_i : | Molar content of composition i |
| P : | System pressure |
| f_i : | Fugacity of composition i |
| φ_i : | Fugacity coefficient of composition i |
| p^{h^0} : | Pressure at depth h^0 |
| $Z_i^{h^0}$: | Composition i at depth h^0 |
| p^h : | Pressure at depth h |
| Z_i^h : | Composition at depth h |
| M : | Average molecular weight of the mixture |
| H_i^{ig} : | Ideal gas enthalpy of composition i |
| \tilde{H}_i^{res} : | Partial molar residual enthalpy of composition i |
| \tilde{H} : | Partial molar enthalpy of the mixture |
| \tilde{H}_i : | Partial molar enthalpy of composition i . |

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

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

Acknowledgments

This study was supported by CNPC science and technology project (kt2021-07-02).

References

- [1] Z. Ningning, H. Dengfa, S. Yanpeng, and L. Haowu, "Distribution patterns and controlling factors of giant carbonate rock oil and gas fields worldwide [J]," *China Petroleum Exploration*, vol. 19, no. 6, pp. 54–65, 2014.
- [2] L. Sun, Y. Yong, and B. Z. Li, "Classified evaluation methods and waterflood development strategies for carbonate reservoirs in the Middle East [J]," *Acta Petrolei Sinica*, vol. 43, no. 2, pp. 270–280, 2022.
- [3] X. M. Song and Y. Li, "Optimum development options and strategies for water injection development of carbonate reservoirs in the Middle East," *Petroleum Exploration and Development*, vol. 45, no. 4, pp. 723–734, 2018.
- [4] Y. L. Wang, X. M. Song, G. H. Wang et al., "Key technologies and practices for rapid and large-scale production increase in cooperation oil and gas fields of the Middle East [J]," *Acta Petrolei Sinica*, vol. 41, no. 12, pp. 1633–1642, 2020.
- [5] L. Yisheng, L. Yuetian, and L. Changyong, "Division of flow units in thick carbonate reservoirs [J]," *Journal of Xi'an Shiyou University (Natural Science Edition)*, vol. 34, no. 2, pp. 104–111, 2019.
- [6] H. Liu, Z. Tian, B. Liu, R. Guo, K. Shi, and Y. Ye, "Classification and prediction of giant thick strongly heterogeneous carbonate reservoirs in the Middle East area [J]," *Acta Petrolei Sinica*, vol. 40, no. 6, pp. 678–690, 2019.
- [7] H. T. Sun, J. He, L. Wang, H. Q. Wang, and L. N. Guo, "Fracture characteristics of carbonate reservoirs in Asmari formation of a oil field in Iraq and its influence on reservoir development [J]," *Journal of Northeast Petroleum University*, vol. 44, no. 6, pp. 12–20, 2020.
- [8] Y. C. Zhang, L. Yang, W. H. Gu et al., "Study on the variation law of gas oil ratio in gas injection development of deepsea volatile reservoirs and its application [J]," *China Offshore Oil and Gas*, vol. 31, no. 5, pp. 108–109, 2019.
- [9] Y. C. Zhang, L. Yang, W. H. Gu, C. P. Dai, L. Deng, and Y. Ying, "Analysis on abnormal gas-oil ratio in condensate gas reservoir [J]," *Development Engineering*, vol. 31, no. 6, pp. 63–65, 2011.
- [10] B. H. Sage and W. N. Lacey, "Gravitational concentration gradients in static columns of hydrocarbon fluids," *Transactions of AIME*, vol. 132, no. 1, pp. 120–131, 1939.
- [11] F. Montel and P. L. Gouel, *Prediction of Compositional Grading in a Reservoir Fluid column*, SPE 14410, 1985.
- [12] J. L. Greek and M. L. Schrader, *Reservoir: An Example of a Compositional Gradient from a Gravitational Field*, SPE14411, 1985.
- [13] L. Hoier and C. H. Whitson, *Compositional grading-theory and practice*, SPE63085, 2000.
- [14] H. Gurtis and U. Whison, *Compositional gradients in petroleum reservoirs [R]*, SPE 28000, 1994.
- [15] J. H. Li, T. Jiang, and B. Liu, "Study on the composition distribution of volatile oil reservoir [J]," *Xing Jiang Petroleum Geology*, vol. 31, no. 1, pp. 81–84, 2010.
- [16] J. H. Li, T. Jiang, S. M. Chen, and W. M. Bao, "Numerical simulation of gas injection drive in volatile reservoirs with

- compositional gradient [J],” *Journal of Petroleum and Gas*, vol. 34, no. 5, pp. 107–111, 2012.
- [17] R. Haase, *Thermodynamik der Irreversiblen Prozesse*, Dietrich Steinkopff Verlag, Darmstadt, 1963.
- [18] A. M. Schulte, *Compositional variations within a hydrocarbon column due to gravity*, SPE 9235, 1980.
- [19] K. S. Pedersen and N. Lindeloff, *Simulations of compositional gradients in hydrocarbon reservoirs under the influence of a temperature gradient*, SPE 84364, 2003.
- [20] A. Danesh, “PVT and Phase Behavior of Petroleum Reservoir Fluids [M],” in *Trans*, P. P. Shen and D. Han, Eds., Petroleum Industry Press, Beijing, 1991.
- [21] S. L. Yang, J. Z. Wei, and R. Z. Jiang, *Physics of Petroleum Reservoirs [M]*, Petroleum Industry Press, Beijing, 2006.
- [22] H. Q. Jiang, J. Yao, and R. Z. Jiang, *Fundamentals and Methods of Reservoir Engineering [M]*, China University of Petroleum Press, Beijing, 2006.
- [23] P. C. Liu, *Fundamentals of Numerical Reservoir [M]*, Petroleum Industry Press, Beijing, 2014.