Journal of Marine Science and Application (2025) 24: 1027-1036
https://doi.org/10.1007/s11804-024-00604-1

RESEARCH ARTICLE

Gas Injection for Improving Oil Recovery in Highly Volatile Fractured Reservoirs with Thick Buried Hills in Bohai Sea

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Received: 12 July 2024 / Accepted: 26 August 2024

Abstract

The BZ oilfield in the Bohai Sea is a rare, highly volatile reservoir with fractures in the metamorphic rocks of buried hills. Clarifying the mechanism of gas injection for improving oil recovery and determining the optimal way to deploy injection-production well networks are critical issues that must be urgently addressed for efficient oilfield development. Experimental research on the mixed-phase displacement mechanism through gas injection into indoor formation fluids was conducted to guide the efficient development of gas injection in oil fields. We established a model of dual-medium reservoir composition and researched the deployment strategy for a three-dimensional well network for gas injection development. The coupling relationship between key influencing factors of the well network and fracture development was also quantitatively analyzed. The results show that the solubility of the associated gas and strong volatile oil system injected into the BZ oilfield is high. This high solubility demonstrates a mixed-phase displacement mechanism involving intermediate hydrocarbons, dissolution and condensation of medium components, and coexistence of extraction processes. Injecting gas and crude oil can achieve a favorable mixing effect when the local formation pressure is greater than 35.79 MPa. Associated gas reinjection is recommended to supplement energy for developing the highly volatile oil reservoirs in the fractured buried hills of the BZ oilfield. This recommendation involves fully utilizing the structural position and gravity-assisted oil displacement mechanism to deploy an injection-production well network. Gas injection points should be constructed at the top of high areas, and oil production points should be placed at the middle and lower parts of low areas. This approach forms a spatial three-dimensional well network. By adopting high inclination well development, the oil production well forms a 45° angle with the fracture direction, which increases the drainage area and enhances single-well production capacity. The optimal injection-production well spacing along the fracture direction is approximately 1 000 m, while the reasonable well spacing in the vertical fracture direction is approximately 800 m. The research results were applied to the development practice of the buried hills in the BZ oilfield, which achieved favorable development results. These outcomes provide a valuable reference for the formulation of development plans and efficient gas injection development in similar oil and gas fields in buried hills.

Keywords Buried hills; Fractures; Highly volatile oil reservoirs; Gas injection development; Well network; Mixed-phase mechanism

Article Highlights

- A dual medium reservoir composition model for buried hills was established based on the fluid phase and reservoir fracture development characteristics, targeting rare and highly volatile reservoirs with thick metamorphic rock fractures at home and abroad.
- A three-dimensional well network deployment strategy for gas injection development was studied, and the key influencing factors of gas injection development well network and the coupling relationship between fracture development were quantitatively analyzed. The research results were applied to the development practice of the buried hills in the BZ oilfield, which achieved favorable development results.
- These outcomes provide a valuable reference for the formulation of development plans and efficient gas injection development in similar oil and gas fields in buried hills.

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1 Introduction

The BZ oilfield is a highly volatile fractured reservoir of Archean metamorphic rocks discovered in the Bohai Bay area. Its oil and gas reserves reach billions of tons, with a burial depth of 5 000 m and a thickness of 600–800 m in the buried hill section. The reservoir has low porosity, low permeability, strong heterogeneity, complex spatial structure, random distribution of fractures, and large dip angles. The fluid exhibits a high dissolved gas–oil ratio, large volume coefficient, and small ground saturation pressure difference. The complexity of reservoirs and fluids presents great challenges to the development of such reservoirs. At present, many studies have been conducted by predecessors on the development of buried hill reservoirs in terms of production capacity, development methods, and well network design (Zhang et al., 2017; Tong et al., 2017; Kang et al., 2021; Zheng and Wang, 2017; Ma and Li, 2022; Liu et al., 2015). Chen investigated the well network pattern of buried hill fractured reservoirs using the water injection development of the JZ25-1S reservoir in the Bohai Sea as an example (Chen et al., 2015). Cheng explored the development methods for the buried hill reservoirs in the metamorphic rocks of Caotai (Cheng, 2006). Chen studied the mechanism of gas injection and oil recovery, as well as the design of development plans, for the buried hill oil reservoirs in the metamorphic rocks of Xinggu (Chen and Zhang, 2012). Ding used numerical simulation methods to study and compare the seepage characteristics and development effects of thick buried hill reservoirs under different development methods (Ding et al., 2013). Liang analyzed gas injection development technology for fractured buried hill reservoirs using the buried hill reservoir in Liaohe as an example (Liang, 2013). Ge conducted a three-dimensional physical simulation experiment to improve oil recovery after water flooding in fractured buried hill reservoirs. This experiment aimed to address the challenges of strong heterogeneity, low matrix permeability, and poor water flooding development in these reservoirs (Ge et al., 2018). Jin explored stratified water injection in buried mountain reservoirs (Jin et al., 2019). Ma improved oil recovery by unstable water injection in fractured buried mountain reservoirs (Ma et al., 2023). Guo conducted an indoor experimental study on improving oil recovery by injecting hydrocarbon gas into the fractured ultralow permeability carbonate reservoir in Daanzhai (Guo et al., 2001; Liang et al., 2018).

The physical and fluid properties of buried hills determine the development mode of the oilfield. In addition, the development degree, occurrence, and aperture of reservoir fractures directly influence the well layout and the form of the injection-production well network. A model of dual-medium reservoir composition was established to create a highly volatile fractured reservoir in the thick buried hill of the BZ oilfield in the Bohai Sea. A coupling optimization study on the three-dimensional well network and fracture development for gas injection was performed. The deployment of injection and production well networks should comprehensively account for structural location, fracture development, and the advantages of different well types. A spatial three-dimensional well network pattern should be developed based on the characteristics of thick reservoirs to enhance the efficiency of gas flooding. Simultaneously, research should be conducted on three-dimensional design for injection and production well trajectory and reasonable well spacing. This analysis is crucial for improving oil well productivity and enhancing the efficiency of gas injection development.

2 Study area

The target layer of the BZ oilfield is the buried hill of Archean metamorphic granite, with a reservoir depth of 4 500–5 300 m. The lithology is mainly composed of metamorphic granite, with a reservoir of pore fracture type. It has an average porosity of 3.5% and a permeability of 1.2 mD. It also exhibits features of ultralow porosity and ultralow permeability. The inclination angle of the cracks is mainly distributed between 50° and 80°. Oblique joints of medium to high angles are the main trend, with a southward inclination. The linear density of single-well fractures is 3.4–4.2 per meter. The distribution range of crack opening is 32.2–175.7 μm. Ground crude oil has low density, low viscosity, low sulfur content, high wax content, and high solidification point. The density of surface crude oil is 0.811 t/m^3, and the viscosity of surface crude oil is 2.400 mPa·s. The formation crude oil exhibits strong volatile oil characteristics, such as low viscosity, high dissolved gas–oil ratio, and large volume coefficient. The PVT analysis results of formation fluids show that under the formation temperature of 175.1 ℃ and the original formation pressure of 46 MPa, the viscosity of formation crude oil is 0.270 mPa·s, the gas–oil ratio of single degassing of crude oil is 682 m^3/m^3, and the volume coefficient of formation crude oil is 3.06. These properties are typical of near-critical strong volatile oil (Figure 1).

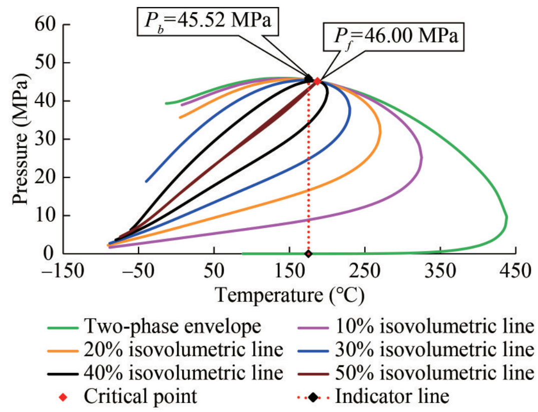


Figure 1 PT Phase Diagram of BZ-5 Well

For fractured buried hill reservoirs, water or gas injection is mainly used to maintain pressure for development (Song, 2019; Wang, 2023; Wang, 2018; Ma, 2015; Liu, 2016; Lv, 2013; Zhao, 2012), which prevents crude oil shrinkage and oil well degassing and improves crude oil recovery rate. Given the characteristics of ultralow porosity and ultralow permeability in the BZ oilfield reservoir, the water injection pressure is limited by the formation fracture pressure during the water injection process. As a result, the water injection cannot meet the needs of reservoir development. Therefore, the water injection development maintains a low level of formation pressure and low recovery rate. The use of gas injection development can improve the recovery rate of volatile oil. 1) Oil fields typically exhibit high temperature and high pressure. Under such conditions, the interfacial tension between oil and gas is low, which enables gas injection development to form mixed-phase flooding. 2) Gas injection development can also utilize crude oil in a medium to low porosity, which effectively displaces residual oil in matrix pores and increases the swept volume of low-permeability reservoirs. The BZ oilfield belongs to a highly volatile oil reservoir with a high gas–oil ratio. By using gas injection development, associated gas resources can be fully utilized, which improves the economic benefits of the oilfield.

3 Experimental study on the mixed-phase mechanism of gas injection for improving oil recovery

3.1 Multiple contact mixing experiment of oil and gas

The mechanism of mixed-phase displacement between injected gas and formation fluid is analyzed by conducting multiple forward and backward contact experiments of formation fluid under indoor experimental conditions.

Forward contact experiment: The front edge of the injected gas continuously contacts the crude oil in the formation. Mass transfer occurs through dissolution, condensation, and evaporation extraction. This process simulates the phase change of the injected gas during forward oil displacement in the reservoir, as shown in Figure 2.

Backward contact experiment: The injection well continuously injects gas, which contacts the fluid in the formation. Interphase mass transfer occurs through dissolution, condensation, and evaporation extraction. This process simulates the phase change at the tail of the injected gas, as shown in Figure 3.

The experimental results show that, during forward contact, the intermediate hydrocarbon content in the gas phase gradually decreases, while the intermediate component ($C_{10}-C_{15}$) content gradually increases. After the first contact, the intermediate hydrocarbon content in fresh crude oil does not change significantly. This condition indicates a displacement mechanism characterized by the

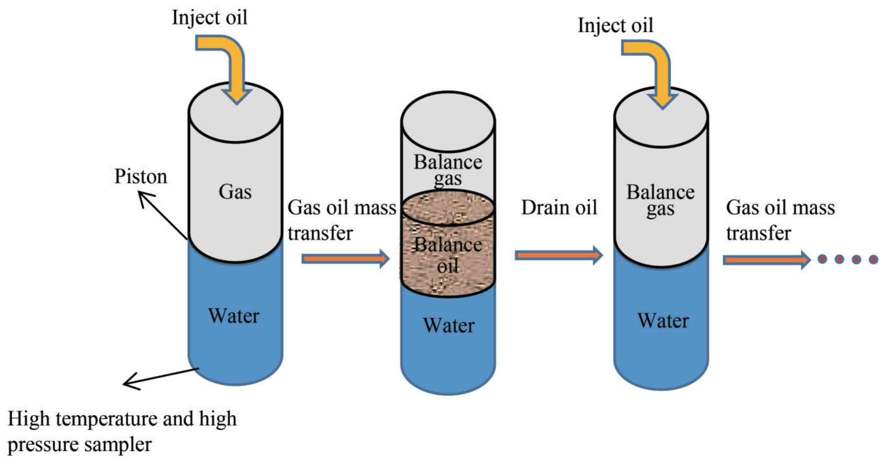


Figure 2 Flowchart of multiple forward contact experiments

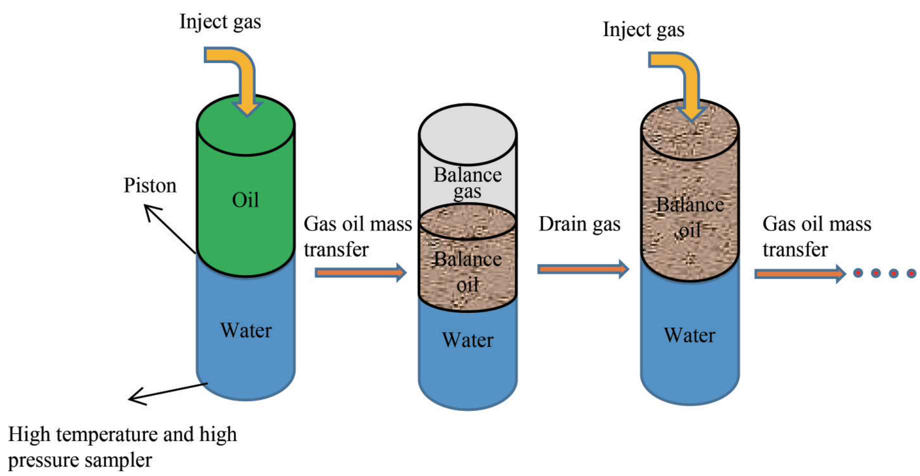


Figure 3 Flowchart of multiple backward contact experiments

coexistence of intermediate hydrocarbons and components through dissolution, condensation, and extraction, as shown in Figure 4.

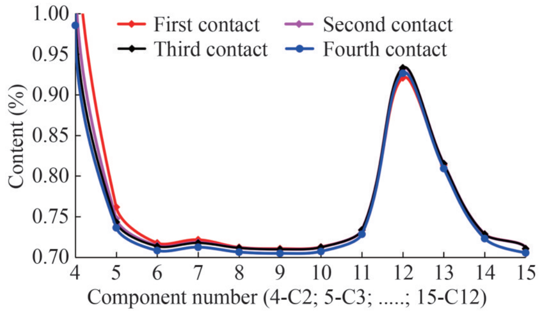


Figure 4 Distribution diagram of intermediate hydrocarbons during forward contact with various gas phase components

During backward contact, the intermediate hydrocarbon content in the gas phase gradually increases, while the intermediate component (C_{10}–C_{15}) content gradually decreases. After the first contact, the intermediate hydrocarbon content in the injected gas is the lowest, while the intermediate component content is the highest. This condition indicates a displacement mechanism characterized by the coexistence of intermediate hydrocarbons and components through dissolution, condensation, and extraction, as shown in Figure 5.

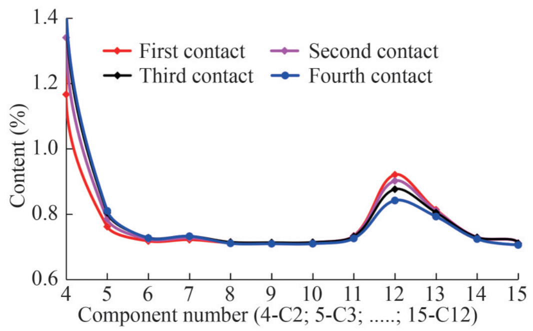


Figure 5 Distribution diagram of intermediate hydrocarbons during backward contact with various gas phase components

Owing to the relatively high content of intermediate hydrocarbons in the fluid components of the BZ oilfield and the presence of a certain amount of CO_2, the use of associated gas reinjection for gas development results in strong solubility between injected gas and formation fluids. Therefore, the main manifestation is the mixed-phase oil displacement mechanism of gas injection through backward contact.

3.2 Determination of minimum mixing pressure

Given that the BZ oilfield is deeply buried, the interfacial tension between oil and gas is reduced under high temperature and high-pressure conditions of the formation. Gas injection development can achieve miscible displacement. Experimental research on the minimum miscible pressure was conducted to guide the optimization of gas injection parameters. The experiment utilized a thin tube to measure the miscibility pressure between injected gas and formation fluid. The thin tube experiment clarified the miscibility characteristics of injected associated gas and crude oil in the BZ oilfield, which helped determine the minimum miscibility pressure of formation crude oil. These findings provide a theoretical basis for designing gas injection for improving oil recovery in reservoirs.

The experimental temperature is 175.1 °C. The pressures at the test points are 28, 32, 34, 35, 37, and 39 MPa. The injected gas is associated with gas produced by the oilfield. Gas injection initiates under different formation pressure conditions, and the changes in gas–oil ratio and oil displacement efficiency with the increase in injected pore volume are shown in Figures 6 and 7. With the continuous increase in injected pore volume, the displacement efficiency gradually improves. Meanwhile, as the injection pressure increases, the breakthrough time of injected gas is relatively late, and the oil recovery rate is higher. By conducting displacement experiments on porous media under different pressures, the relationship curve between displacement efficiency and displacement pressure was obtained, and the pressure corresponding to the inflection point is the minimum miscibility pressure (Yang and Yu, 2019; Zhao et al., 2017; Zhou et al., 2021).

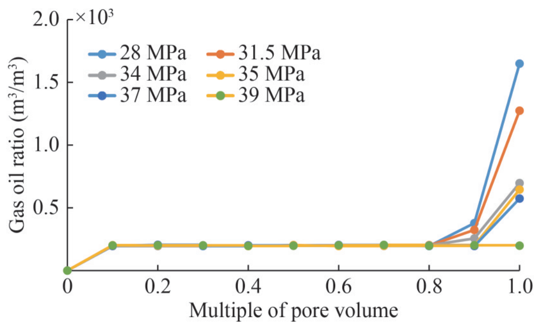


Figure 6 Relationship between volume multipliers of injected pores and gas–oil ratio under different pressures

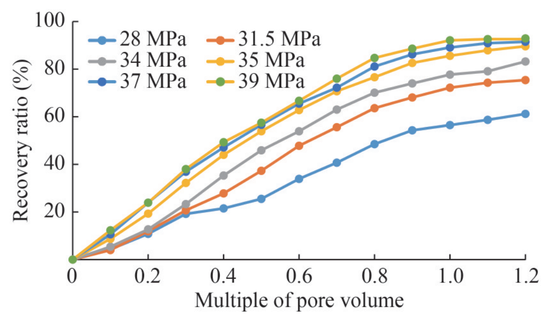


Figure 7 Relationship between the number of pore volume multiples injected under different pressures and oil displacement efficiency

After the experimental displacement reached 1.2 times the pore volume, the maximum displacement efficiency at different pressures was plotted on the same graph. The pressure at the intersection of the trend lines for the unmixed and mixed pressure points is the minimum miscible pressure. The relationship between injection pressure and oil displacement efficiency is shown in Figure 8. As observed, the pressure corresponding to the inflection point is 35.79 MPa, and the corresponding oil displacement efficiency is 90.3%. Therefore, a mixed-phase drive effect is achieved.

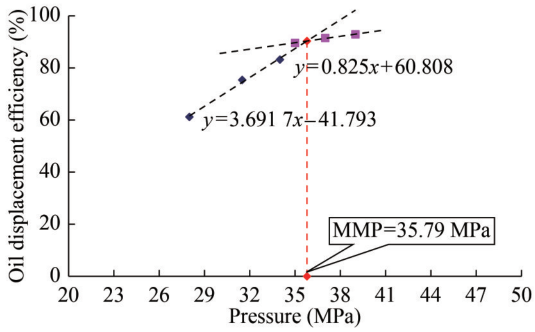


Figure 8 Relationship between injection pressure and oil displacement efficiency

Given that the BZ oilfield is a highly volatile reservoir with buried mountain fractures, the injection and production intensity during the gas injection stage is too high. A higher reinjection rate leads to a faster rise in the gas–oil ratio in the fracture system, which results in poor matrix utilization. Reducing the formation pressure appropriately during the gas injection stage helps slow down gas channeling and fully utilizes the matrix elasticity to increase the deployment of matrix reserves. Based on the experimental research results of the minimum mixed-phase pressure using long and thin pipes, the gas injection-reinjection rate of the oilfield is recommended to be 0.8. Moreover, maintaining the formation pressure near the mixed-phase pressure range during gas injection ensures a high recovery rate and good economic benefits.

4 Design of a three-dimensional well network for gas injection development

Based on experimental understanding and the geological reservoir characteristics of the BZ oilfield, a dual-medium geological model was established, as shown in Figures 9 and 10. The model grid system has a dimension of 205 × 62 × 170, with a grid step size of 100 m in the x and y directions and 4 m in the z direction. The reserve ratio of the fracture system to the matrix system is approximately 1 ∶ 9. The average permeability of the matrix is 0.54 mD, with a porosity of 2.8%, and the average permeability of the fractures is 20.9 mD, with a porosity of 0.19%. The reservoir has a closed outer boundary and contains bottom water. We used Eclipse numerical simulation software for PVTI component fitting and established a model of dual-medium reservoir components. Numerical simulation was conducted to study the well network for circulation gas injection development in the BZ oilfield, which could guide the efficient development of gas flooding in the oilfield.

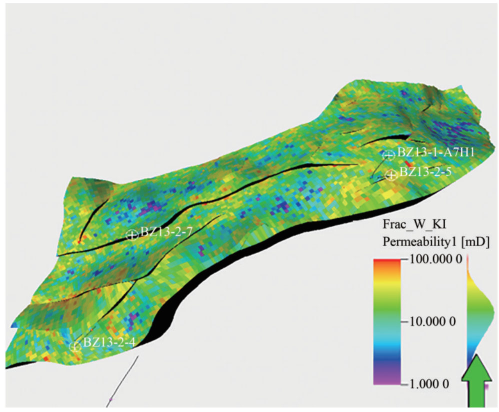


Figure 9 Distribution of crack permeability

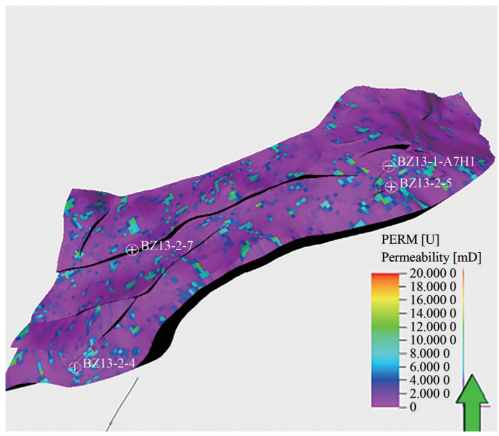


Figure 10 Distribution of matrix permeability

4.1 Well type selection

The selection of well types is closely related to the inclination angle of fractures. The buried hill reservoir in the BZ oilfield has a large vertical thickness, complex zoning, and strong vertical heterogeneity. The design adopts a development plan using high-angle wells and vertical wells, and their development effects under different fracture inclination angles are shown in Figure 11. The results show that 1) as the inclination angle of fractures increases, the production capacity of vertical wells decreases, which indicates that vertical well development has advantages for reservoirs with horizontal fractures. 2) The initial production capacity of highly deviated wells increases with the fracture dip angle. When the fracture dip angle is below 45°, the initial production capacity increases significantly. When the fracture dip angle is above 45°, although the initial increase in production capacity slows down, the production capacity is still significantly higher than that observed in vertical wells. Therefore, for reservoirs with medium to high-angle fractures, the development effect of highly deviated wells is better. High-angle fractures are developed in the buried hill reservoir of the BZ oilfield, and the vertical distribution of the reservoir is complex. High-angle wells should be used to diagonally penetrate the reservoir to ensure its drilling rate. This approach leverages the advantages of strong fracture communication, a large oil drainage area, and high oil well productivity.

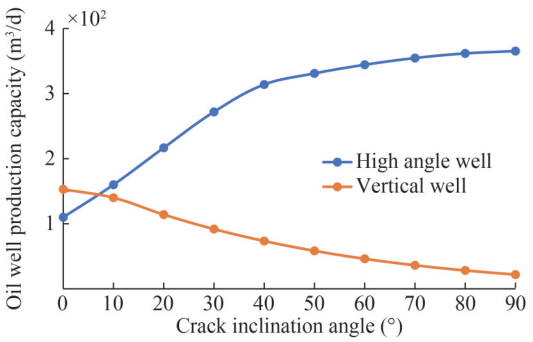


Figure 11 Relationship between the production capacity of different well types and the inclination angle of fractures in oil wells

4.2 Optimization of three-dimensional location of injection-production wells

The deployment of spatial three-dimensional well networks is primarily influenced by reservoir lithology and the locations of injection and production wells. Using numerical simulation analysis, the effects of gas injection development under different vertical well layout methods were analyzed. Three well layout schemes were designed: 1) gas injection at the bottom of low positions and oil extraction at the top of high positions, 2) gas injection at the top of high positions and oil production in the middle and lower parts of low positions, 3) gas injection at the top of the high section and oil production at the top of the low section. Figure 12 shows the comparison of changes in the production gas–oil ratio at different vertical well positions. Figure 13 shows the distribution of oil and gas saturation at different vertical well positions during the gas injection stage.

The research results show that, in the BZ oilfield, medium to high-angle fractures are developed. Moreover, the scheme of bottom injection and top production is prone to gas channeling along the fractures. The production gas–oil ratio of the oil well increases rapidly, the injection gas breakthrough

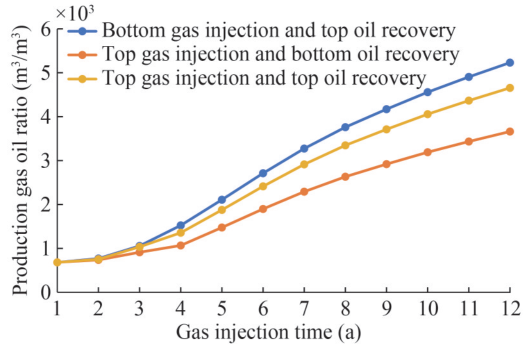


Figure 12 Comparison of gas–oil ratio changes in production at different vertical well layout positions

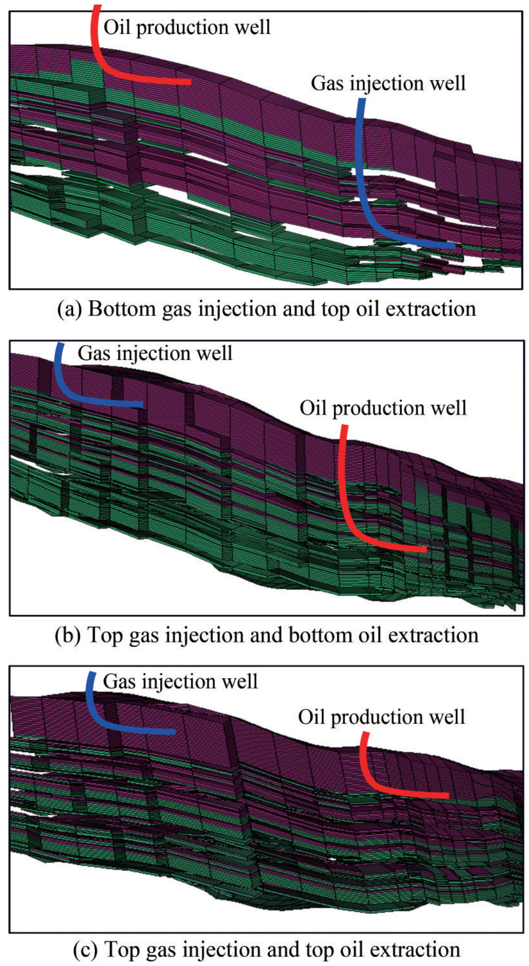


Figure 13 Distribution of oil and gas saturation at different vertical well positions

time is early, the production effect is poor, and the recovery rate is 23.4%. However, adopting the scheme of top injection and top production causes difficulty in utilizing the reserves in the lower part of the reservoir. This complexity results in a relatively low gas drive efficiency and a crude oil recovery rate of 24.1%. Using the scheme of gas injection at the top of high positions and oil extraction at the middle and lower parts of low positions can form a spatial three-dimensional well network that fully utilizes the fluid density difference. It also achieves gravity-assisted oil displacement. This scheme results in the highest gas–oil displacement efficiency, the best development effect, and a recovery rate of up to 28.4%.

4.3 Coupling optimization of well trajectory and fracture direction

The development of reservoir fractures directly influences the design of well trajectories. The direction of fractures in the BZ oilfield is related to the direction of faults, which are primarily oriented northeast, with inclination angles mainly ranging from 50° to 80°. Three well layout plans were designed, with angles of 0°, 45° and 90° between the well layout direction and the fracture direction for the production well. The development effects under different well trajectory directions were compared and analyzed. When the angle between the well layout direction and the fracture direction is 45°, the initial production capacity increases by 28% compared with that in the 0° well layout, and the recovery rate improves by 2.7%. Compared with the 90° angle, the production capacity of the well increases by 12%, and the recovery rate is enhanced by 1.3%, as shown in Figure 14. The main reason is that when the angle between the well trajectory direction and the fracture direction is 45°, the fracture communication ability is strong. The oil well leakage area and gas injection affected volume are the largest. As a result, the oil well productivity and recovery rate are the highest, and the development effect is the best. When the angle between the direction of the well trajectory and the direction of the fractures is 0°, fewer fractures are encountered during drilling, which results in low productivity and low gas drive efficiency. When the angle between the direction of the well trajectory and the direction of the fracture is 90°, the drainage area and gas drive affected volume in the oil well are relatively small. Therefore, when the reservoir develops multi-directional fractures, the production well should diagonally penetrate as many fractures as possible. At the same time, a certain angle exists between the trajectory of the production well and the main direction of the fractures, which increases the gas drive sweep volume.

4.4 Coupling optimization research on well spacing, fracture direction, and fracture development degree

Gas injection development mainly targets the reserves within fracture systems. High-angle fractures are prevalent in the oilfield, and the network characteristics of these fractures are prominent. The relationship among injection-

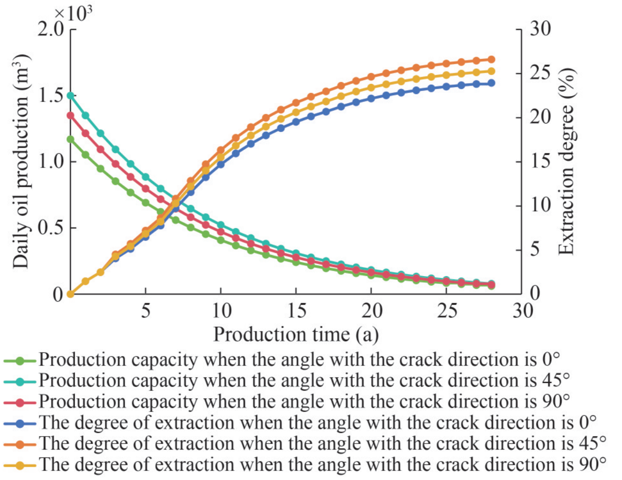
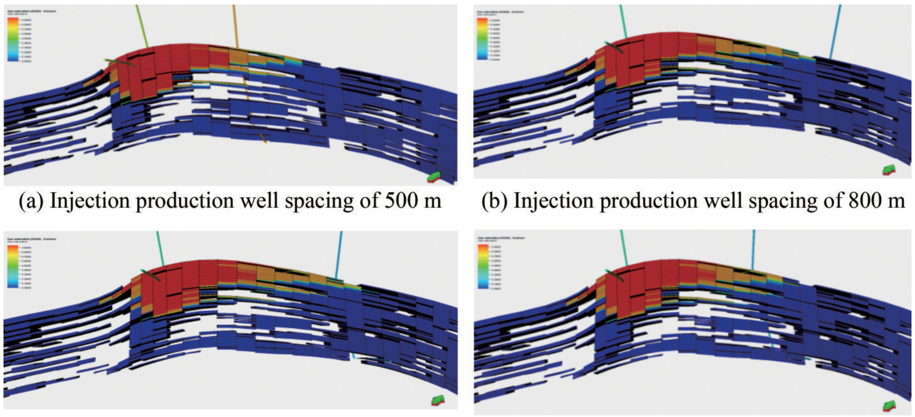


Figure 14 Comparison of development effects between oil well and fracture angle

production well spacing, fracture direction, and fracture development degree was determined by comparing and analyzing the development effects under different injection-production well spacings. Four well layout plans were designed, with injection-production well spacings of 500, 800, 1 000, and 1 200 m.

The results show that when the injection-production well spacing is too small at 500 m, the gas breakthrough time of the oil well is earlier, and the gas–oil ratio rises rapidly. After 3 years of gas injection, the production gas–oil ratio reaches 1 569 m^3/m^3. When the injection-production well spacing is too large at 1 200 m, although the rise in the gas–oil ratio is relatively slow, the production gas–oil ratio after 3 years of gas injection is 956 m^3/m^3. However, the efficiency of the oil well after gas injection is poor, the gas drive efficiency is low, and the recovery rate is 26.3%. When the injection-production well spacing is 800 or 1 000 m, the gas drive effect is relatively good, and the final recovery rate can reach approximately 28%. Figure 15 shows the distribution of oil and gas saturation in fractures after 3 years of gas injection for different injection-production well spacings.

Numerical simulation analysis results and investigations into the development effects of different injection-production well distances in fractured buried hill reservoirs (Sun et al., 2012; Song, 2018; Wei et al., 2018; Feng et al., 2018; Tan et al., 2021) suggest that the injection-production well spacing in the BZ oilfield should be 800–1 000 m. This spacing allows for an average well-controlled reserve of nearly 1 million cubic meters per well. Considering the strong communication ability along the fracture direction, the injection-production well spacing is designed to be approximately 1 000 m. By contrast, in the vertical fracture direction, where the communication ability is relatively weak, the spacing is designed to be approximately 800 m.



(a) Injection production well spacing of 500 m (b) Injection production well spacing of 800 m

(c) Injection-production well spacing of 1 000 m (d) Injection-production well spacing of 1 200 m

Figure 15 Distribution of oil and gas saturation after 3 years of gas injection under different well spacing (along the direction of fractures)

5 Field application

The BZ oilfield adopts a spatial three-dimensional well network with high gas injection and low oil production, as shown in Figure 16. The well type is a highly deviated well, and the deployment direction of the production wells is approximately 45° with the direction of the fractures. The well spacing along the fracture direction is nearly 1 000 m, and the vertical fracture direction is approximately 800 m. The controlled reserves of a single well are 800 000–1 150 000 m^3. The pilot experimental well area of the oilfield deploys 13 wells, with a designed peak oil recovery rate of 4% and a crude oil recovery rate of 28.4% for gas injection development. The development well encountered an oil layer with a thickness of 90–346 m, a crack inclination angle distribution of 50°–80°, a crack density of 3.8–4.2 piece/m, and a crack opening of 90–176 μm. The oilfield operated in August 2020 through self-spraying production. In the initial stage of a single well, the daily oil production reached 132–340 m^3. Currently, this block has contributed a cumulative production of 1.26×10^6 m^3, achieving good development results.

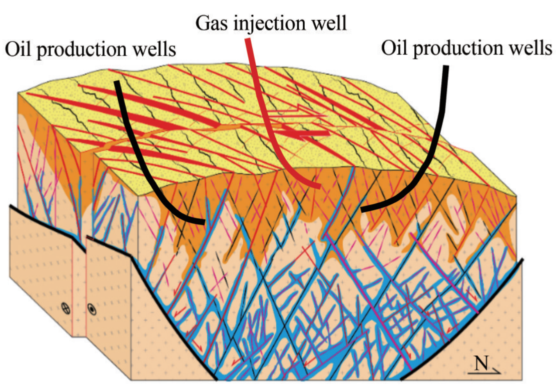


Figure 16 Schematic of the three-dimensional well network for gas injection deployment in the BZ oilfield

6 Conclusions

This article focuses on the BZ buried hills fractured oil reservoir, the mechanism of gas injection miscible displacement was clarified through experimental research, and the impact of gas injection on oil displacement efficiency was analyzed. The minimum miscible pressure of the oilfield was obtained. The deployment strategy of gas injection development well network was studied through numerical simulation, and the following insights were mainly obtained.

1) A laboratory experiment was conducted to investigate the mechanism of gas injection mixed-phase displacement in the highly volatile oil reservoirs in the fractured, thick buried hills of the BZ oilfield in the Bohai Sea. Based on the characteristics of fluid and reservoir development, a model of dual-medium oil reservoir components was established. Moreover, the coupling optimization of gas injection development three-dimensional well network and fracture development was studied.

2) The experimental results show that the solubility of the associated gas and strong volatile oil system injected into the BZ oilfield is high. This high solubility is manifested by a mixed-phase displacement mechanism of intermediate hydrocarbons, dissolution and condensation of medium components, and coexistence of extraction processes. When the local formation pressure is greater than 35.79 MPa, injecting gas and crude oil can achieve good mixing effects.

3) The BZ oilfield should adopt associated gas reinjection to supplement energy development. It should fully utilize the structural position and gravity-assisted oil displacement mechanism to deploy the injection-production well network. This recommendation involves gas injection at the top of high positions and oil production at the middle and lower parts of low positions. This approach forms a three-dimensional well network with a staggered top and bottom space.

4) The well type should be developed using highly deviated wells, with an angle of 45° between the production well and the direction of the fracture. This way increases the drainage area and improves the single-well production capacity. The optimal injection-production well spacing along the direction of the fracture is approximately 1 000 m, and the reasonable injection-production well spacing along the vertical fracture direction is nearly 800 m.

5) The practice of oilfield development has shown that the initial production capacity of oil wells in the BZ oilfield reaches 132–340 m^3/d. The production characteristics show high production capacity, which achieves good development results. The peak oil recovery rate is 4%, and the predicted recovery rate of gas injection development can reach 28.4%. The research results have certain reference importance for the development plan formulation and efficient gas injection development of similar oil and gas fields in buried hills.

Competing interest The authors have no competing interests to declare that are relevant to the content of this article.

References

Chen JB, Zhang ZN, Zheng H (2015) Optimization and development practice of well pattern in buried mountain fractured oil reservoirs. China Offshore Oil and Gas 27(3): 66-72. DOI: 10.11935/j.issn.1673-1506.2015.03.010

Chen Y, Zhang Y (2012) Gas injection development and oil displacement mechanism and scheme optimization of thick metamorphic rock buried hill reservoirs. Oil and Gas Geology and Recovery 34(5): 119-123. DOI: 10.13673/j.cnki.cn37-1356/te.2016.01.006

Cheng DW (2006) Research on the development method of Caotai metamorphic rock high pour point oil buried hill. China Petroleum and Chemical Standards and Quality 15(5): 177-178.(in Chinese)

Feng Li, WQ, Liu WP (2018) Optimization design and understanding of oil production engineering scheme for buried hill reservoir in sudert oilfield. Daqing Petroleum Geology and Development 37 (6): 72-78. DOI: 10.19597/J.ISSN.1000-3754. 201805060

Ge LZ, Wang J, Zhu ZQ (2018) Three dimensional physical simulation of enhanced oil recovery after water flooding in fractured reservoirs in Qianshan. China Offshore Oil and Gas 30(5): 81-86. DOI: 10.11935/j.issn.1673-1506.2018.05.010

Guo P, Li SL, Zhang S (2001) Laboratory experimental study on hydrocarbon gas flooding in fractured ultra-low permeability carbonate reservoirs. Petroleum Exploration and Development 28(2): 76-78

Jin HL, Yu XJ, Chang YZ (2019) Exploration and practice of stratified water injection in buried hill reservoirs. Petroleum Geology and Engineering 31(5): 14-15

Kang K, Zhao L, Luo XB (2021) A new method for evaluating the productivity of fractured buried hill gas reservoirs and its application. China Offshore Oil and Gas 33(3): 100-105. DOI: 10.11935/j.issn.1673-1506.2021.03.011

Liang F (2013) Research and practice on gas injection development technology for fractured buried hill reservoirs. China Petroleum and Petrochemical 30(1): 117-118. (in Chinese)

Liang F (2018) Analysis of the development effect of non miscible gravity stable flooding on thick metamorphic rock buried hill reservoirs. China Petroleum and Chemical Standards and Quality 13(2): 99-101. (in Chinese)

Liu J, Liu YT, Nie B (2015) Method for adjusting the vertical well spacing of horizontal wells in buried hill reservoirs. Oil and Gas Geology and Recovery 22(4): 103-107. DOI: 10.13673/j.cnki.cn37-1359/te.2015.04.019

Liu WW (2016) Evaluation and potential analysis of the development effect of Nanpu No. 2 buried hill reservoir. Daqing Petroleum Geology and Development 35(6): 48-52. DOI: 10.3969/.T.ISSN.1000-3754.2016.06.009

Lv YX (2013) Efficient development of difficult to produce gas reservoirs such as buried hills using multi branch horizontal well technology. Chemical Management 9(2): 114-118

Ma D, Li Z (2022) Efficient development strategy and application of offshore mid to deep buried hill oil and gas reservoirs. Petrochemical Applications 41(6): 81-84

Ma KQ, Fang N, Lv Z (2023) Quantitative research and application of unstable water injection in fractured reservoirs of buried hills. Natural Gas and Petroleum 41(5): 44-48. DOI: 10.3969/j.issn.1006-5539.2023.05.007

Ma W (2015) Research on optimization technology for gas injection development in Xinggu Qianshan Reservoir. Inner Mongolia Petrochemical 19(3): 115-117

Song XL (2018) Research on development methods of Qianshan Reservoir. Inner Mongolia Petrochemical 2(13): 117-120

Song XL (2019) Research on horizontal and development technology for thick fractured buried hills. Chemical Management 23(6): 56-62

Sun XX, Yang SL, Wu XiY (2012) Numerical simulation study on gas injection in fractured bottom water buried hill reservoirs. Complex Oil and Gas Reservoirs 5(1): 63-66. DOI: 10.16181/j.cnki.fzyqc.2012.01.019

Tan XH, Fan TG, Fan HJ (2021) Research on the three-dimensional well network deployment of fractured, low-permeability, and thick reservoirs in the Bozhong 19-6 gas field. China Offshore Oil and Gas 33(3): 107-113. DOI: 10.11935/j.issn.1673-1506.2021.03.012

Tong KJ, Li B, Dai WH (2017) Efficient development technology for thin well network in metamorphic rock buried hill reservoirs in the Bohai Sea. Petroleum Exploration and Development 44(4): 590-598. DOI: 10.11698/PED.2017.04.012

Wang CX (2018) Study on prediction of fractures and well location deployment in Sheng602 Burial Hill. Petrochemical Applications 20 (5): 121-123

Wang P (2023) Optimization of gas drive enhanced oil recovery technology in Qianshan Reservoir. China Petroleum and Chemical Standards and Quality 6(1): 112-115

Wei W, Liu CC, Zhao X (2018) Comprehensive evaluation of water injection development effect of horizontal wells in Qianshan Reservoir. Petrochemical Application 6(3): 52-57

Xiao ZP, Liu SQ, Li YM (2023) Feasibility experiment of gas injection mixed phase flooding after water flooding in hilly oilfield. Oil and Gas Geology and Recovery 30(2): 68-76. DOI: 10.13673/j.cnki.cn37-1359/te.202211045

Yang FL, Yu P (2019) Technical standard for determining minimum mixed phase control pressure through fine tube experiments. Special Oil and Gas Reservoir 26(6): 118-122. DOI: 10.3969/j.issn.1006-6535.2019.06.022

Zhang ZN, Meng ZQ, Zhu ZQ (2017) Research on matrix flooding efficiency of fractured buried hill reservoir in JZS oilfield.

Special Oil and Gas Reservoirs 24(4): 101-105. DOI: 10.3969/j.issn.1006-6535.2017.04.019

Zhao F (2012) Application of branch horizontal well technology in buried hill formation of Liaohe Oilfield. Petroleum Drilling and Production Technology 5(34): 28-32. DOI: 10.13639/j.odpt.2012.05.009

Zhao YJ, Song KP, Fan GJ (2017) Study on the minimum miscibility pressure of supercritical carbon dioxide and crude oil system under reservoir conditions. Journal of Dalian University of Technology 57(2): 119-125. DOI: 10.7511/dllgxb201702002

Zheng H, Wang YJ (2017) Research on efficient development strategies for fractured reservoirs in Bohai Burial Mountains. Reservoir Evaluation and Development 7(4): 16-21.(in Chinese) DOI:10.13809/j.cnki.cn32-1825/te.2017.04.004

Zhou X, Zhou D, Deng JS (2021) Experimental study on improving the recovery rate of tight oil reservoirs by supercritical CO_2 flooding. Special Oil and Gas Reservoirs 28(3): 118-123. DOI: 10.3969/j.issn.1006-6535.2021.03.018