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Research on the integrated calculation method of current recovery and limited recovery in tight sandstone gas reservoirs

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Considering the differences in reserves and their utilization among gas reservoir area, utilization area and swept area, a reserves zoning producing model was established, and a method for integrating current recovery and limited recovery in gas reservoirs, the reserve analysis method, was proposed. The method was applied to calculate the current recovery and limited recovery of the gas reservoir and assess the potential of the gas reservoir to enhance the recovery, taking the Zizhou gas field in the Ordos Basin of China, the Shan2 tight sandstone gas reservoir, as an example. The results show that the method is able to simultaneously determine the current recovery, limited recovery, planar sweep efficiency, vertical sweep efficiency and gas driving efficiency of a gas reservoir by using four reserve parameters such as the gas reservoir area geological reserves, the producing area geological reserves, the swept area geological reserves, and the remaining geological reserves in the swept area when abandoned. This method is simple and easy to implement, and provides a new way for the evaluation of gas reservoir recovery potential and the study of improving the development method of gas reservoirs.

KEYWORDS

tight sandstone gas reservoirs, current recovery, limited recovery, recovery enhancement potential, calculation methods

1 Introduction

Reservoir recovery is an important technical index to measure the effect of comprehensive development of gas reservoirs, and it is also a regular research topic for gas field development researchers (Guo et al., 2018; Zhang et al., 2023). Determination of gas recovery is generally divided into two steps, firstly, the recoverable reserves of the gas reservoir when it is abandoned in a specific well network are obtained, and then the ratio between the recoverable reserves of the gas reservoir and its original geological reserves is calculated (Mu et al., 2018; Lu et al., 2024). As the original geological reserves is the natural gas gathering volume in the original geological conditions of the gas reservoir, which is the material basis for the exploitation of the gas reservoir, it can be regarded as a fixed value. Therefore, the key to determine the recovery of the gas reservoir lies in the calculation of recoverable reserves. Recoverable reserves are calculated by different methods, and there are various

methods for determining gas reservoir recovery. For example, material balance method, decreasing production method, elastic two-phase method, pressure build-up curve method, logistic method, dynamic reserve analysis method and numerical simulation method (Ren et al., 2018; Yang et al., 2024).

Scholars have shown that gas recovery is closely related to the degree of well network control, and the higher the degree, the greater the gas recovery (Chen et al., 2009; Ren et al., 2018; Wu et al., 2023; Zhang et al., 2023; Sun et al., 2024). In order to characterize the dynamic change of recovery with well network conditions, the author divided the recovery into current recovery and limited recovery. Among them, the current recovery is the recovery of gas reservoir at present well network condition, which can reflect the current development effect of gas reservoir; the limited recovery is the recovery of gas reservoir at perfect well network condition (100% well network control degree), which can reflect the limiting development effect of gas reservoir; the difference between the current recovery and the limited recovery can be used to evaluate the potential of gas reservoir to enhance the recovery. Obviously, according to this categorization, the recoveries that are usually calculated are the current recoveries of the gas reservoir (Chen et al., 2009; Guo et al., 2018; Mu et al., 2018; Ren et al., 2018; Wu et al., 2023; Zhang et al., 2023; Lu et al., 2024; Sun et al., 2024; Yang et al., 2024). However, in the process of gas reservoir development, in order to evaluate the potential of enhancing the recovery of a gas reservoir, in addition to clarifying the current recovery, it is more necessary to implement the limited recovery. Therefore, it is of great significance to consider the current recovery and the limited recovery of a gas reservoir in a unified way, and to establish an integrated calculation method of the current recovery and the limited recovery of a gas reservoir, which is of great significance to effectively assess the potential of gas reservoirs to enhance the recovery, and to guide the adjustment of the development and the excavation of the potentials.

Thus, this paper carries out the research on the integrated calculation method of current recovery and limited recovery of gas reservoirs by taking the example of Shan2 tight sandstone gas reservoir in Zizhou gas field, Ordos Basin, China. Firstly, from the distribution of gas reservoir reserves and its producing law, a reserves zoning producing model is established and an integrated calculation method of current recovery and limited recovery is proposed - the reserve analysis method. Then, the current recovery and limited recovery of the gas reservoir were simultaneously calculated by this method, taking the Shan2 gas reservoir in Zizhou field as an example. Finally, through the comparison of current recovery and limited recovery, the potential of the gas reservoir to enhance the recovery was evaluated, and a proposal for the adjustment of gas reservoir development was given.

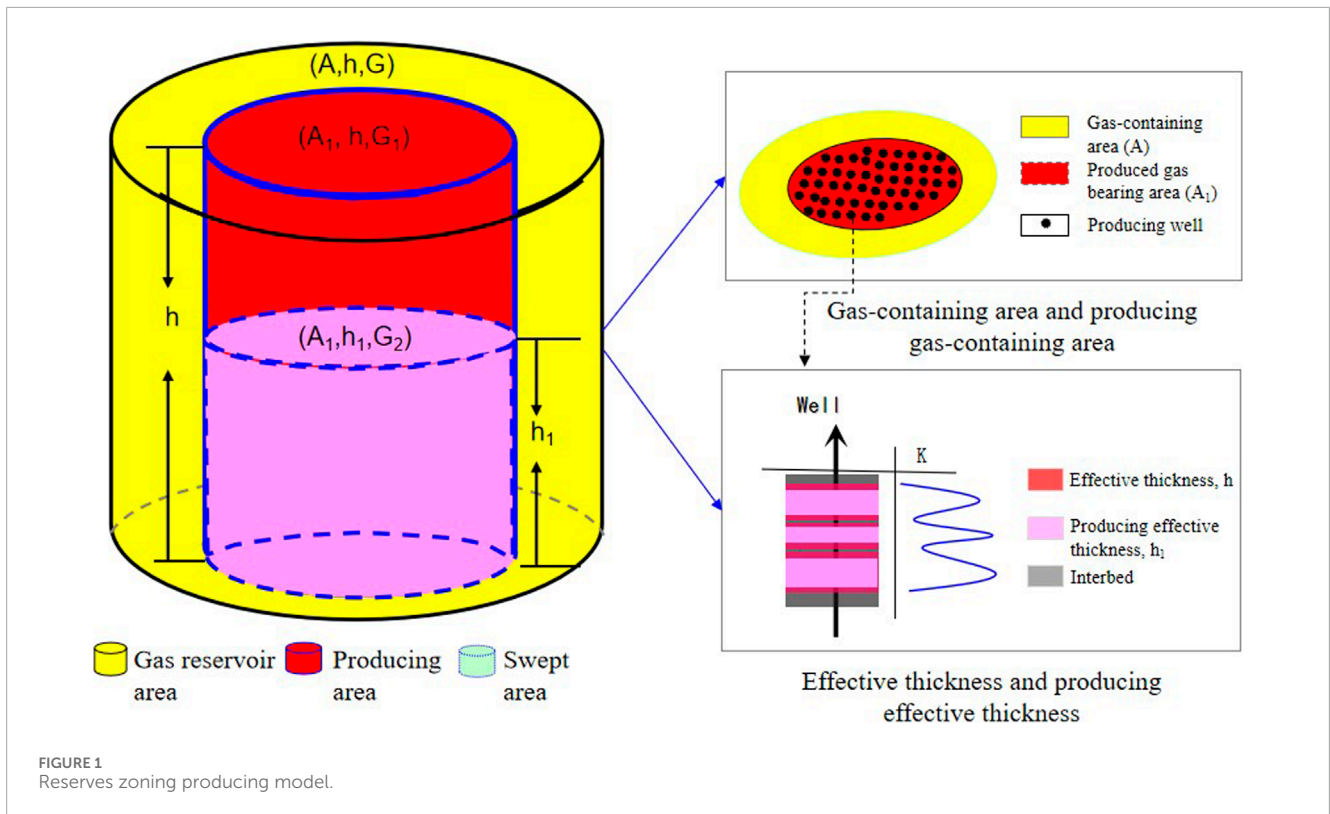
2 Methods

2.1 Reserves zoning producing model

The distribution and utilization of gas reservoir reserves are regular and characterized by space zoning. Based on this, the reserves zoning producing model is established, which is divided into three spatial areas, including gas reservoir area, producing area and swept area (Figure 1).

As shown in Figure 1, each of the three regions is characterized by different characteristics:

- 1) Different connotation. The gas reservoir area represents the overall distribution space of the gas reservoir, and the reserves in this area are the original geological reserves of the gas reservoir; the producing area represents the part of the gas reservoir area controlled by the well network, and the reserves in the producing area are the geological reserves in the part of the gas reservoir area controlled by the well network; and the swept area represents the part of the producing area that is involved in the seepage, and the reserves in the swept area are the geological reserves in the part of the producing area that is involved in the seepage.
- 2) Different geometric scales. The gas reservoir area corresponds to the reservoir gas-containing area (A) and the total effective thickness (h), with the largest geometric volume (Ah); the producing area corresponds to the producing gas-containing area (A_1) and the total effective thickness (h), with the medium geometric volume (A_1h); and the swept area corresponds to the producing gas-containing area (A_1) and the producing effective thickness (h_1), with the smallest geometric volume (A_1h_1).
- 3) Different reserve sizes. Gas reservoir area geologic reserves (G) are the largest; producing area geologic reserves (G_1) are medium-sized; and swept area geologic reserves (G_2)-also known as dynamic geologic reserves (or producing area geologic reserves)-are the smallest of the three.
- 4) Different stability of reserves. The gas reservoir area geological reserve is the natural gathering amount of gas under the original geological conditions of the gas reservoir, which is the material basis for the development of the gas reservoir, and does not change with the development process, so it can be regarded as a constant value. The producing area geological reserve is related to the degree of well network control and it changes with the development process, so it is a variable value. In general, the more perfect the well network is, and the closer the producing gas-containing area is to the gas-containing area, the larger the geological reserve of producing area is. When the perfect well network (well network control degree 100%) is reached, the producing gas-containing area is equal to the gas-containing area, and the producing area reserve is equal to the gas reservoir area reserve. The swept area geologic reserve is related to both the degree of well network control and the vertical heterogeneity, and changes with the development process as a variable. The gas reservoir area geological reserve is the natural gathering amount of gas under the original geological conditions of the gas reservoir, which is the material basis for the development of the gas reservoir, and does not change with the development process, so it can be regarded as a constant value. The producing area geological reserve is related to the degree of well network control and it changes with the development process, so it is a variable value. In general, the more perfect the well network is, and the closer the producing gas-containing area is to the gas-containing area, the larger the geological reserve of producing area is. When the perfect well network (well network control degree 100%) is reached, the producing gas-containing area



is equal to the gas-containing area, and the producing area reserve is equal to the gas reservoir area reserve. The swept area geologic reserve is related to both the degree of well network control and the vertical heterogeneity, and changes with the development process as a variable. The weaker the vertical heterogeneity is, the closer the producing effective thickness is to the effective thickness, and the closer the swept area reserve is to the producing area reserve.

- 5) Different impacts on recovery. Gas recovery is the ratio of the recoverable reserves of a gas reservoir when abandoned to its original geologic reserves under specific well network conditions. Therefore, the gas recovery mainly depends on the relative sizes of the swept area and the gas reservoir area under specific well network conditions. Generally, the closer the producing area (A_1) of the swept area is to the gas-containing area (A) of the gas reservoir and the closer the effective thickness (h_1) of the producing area is to the total effective thickness (h), the higher the recovery of the gas reservoir.

2.2 Current recovery and limited recovery integration calculation methods

2.2.1 Reserve forms of recovery

For a given gas reservoir, the recovery is the ratio of the final volume of natural gas recovered (or recoverable reserves) to the original geologic reserves of the gas reservoir, i.e.,:

$$E_R = \frac{G_R}{G} \times 100\% \tag{1}$$

Considering the reserves zoning producing model (Figure 1), Equation 1 can be expressed as:

$$E_R = \frac{G_1}{G} \times \frac{G_2}{G_1} \times \frac{G_R}{G_2} \times 100\% \tag{2}$$

Since the recoverable reserves (G_R) all come from the swept area geological reserves (G_2), set the remaining geological reserves in the swept area when abandoned as G_{2a} . According to the principle of material balance, it is obtained that:

$$G_R = G_2 - G_{2a} \tag{3}$$

Therefore, the gas reservoir recovery can be fully expressed in reserve form by Equations 2 and 3:

$$E_R = \frac{G_1}{G} \times \frac{G_2}{G_1} \times \frac{G_2 - G_{2a}}{G_2} \times 100\% \tag{4}$$

Equation 4 provides a method for calculating the gas reservoir recovery, showing that to calculate the gas reservoir recovery, it is only necessary to determine four macroscopic reserve parameters such as the gas reservoir area geologic reserve (G), the producing area geologic reserve (G_1), the swept area geologic reserve (G_2), and the remaining geologic reserve in the swept area when abandoned (G_{2a}).

In the formula: E_R -- recovery, %; G_R -- recoverable reserves, m^3 ; G -- gas reservoir area geological reserves, m^3 ; G_2 -- swept area geological reserves, m^3 ; G_{2a} -- remaining geologic reserve in the swept area when abandoned, m^3 .

2.2.2 Reserve calculation methods

For constant-volume reservoirs, the gas reservoir geologic reserves (G), the producing area geologic reserves (G_1), the

producing area geologic reserves (G_2), and the remaining geologic reserves in the swept area when abandoned (G_{2a}) are respectively denoted as:

$$G = Ah\phi S_{gi}/B_{gi} \quad (5)$$

$$G_1 = A_1 h \phi S_{gi}/B_{gi} \quad (6)$$

$$G_2 = A_1 h_1 \phi S_{gi}/B_{gi} \quad (7)$$

$$G_{2a} = A_1 h_1 \phi S_{gi}/B_{ga} \quad (8)$$

Equations 5–8 Explanation:

- 1) All four geologic reserves can be expressed by the volumetric method formula.
- 2) Although all four geological reserves can be expressed by the volumetric method, the methods used to verify the four geological reserves are not the same in the process of gas reservoir development. Among them, gas reservoir area geological reserves and producing area geological reserves are generally accounted for by static method, and the volumetric method is mainly used; because it is difficult to accurately calibrate the producing area effective thickness h_1 in the process of development (Deng et al., 2024), the swept area geological reserves and the remaining geological reserves in the swept area when abandoned are generally accounted for by dynamic method, which mainly includes the material balance method, the pressure-drop curve method, and the rate transient analysis method (RTA), and so on. In the early stage of development, the material balance method and pressure drop curve method are mainly used. While in the middle and late stages of development, the production dynamic information is very rich, and the rate transient analysis method is more effective (Zhang, 2010; Wang et al., 2016).

In the formula: G -- gas reservoir area geological reserves, m^3 ; G_1 -- producing area geologic reserves, m^3 ; G_2 -- swept area geological reserves, m^3 ; G_{2a} -- remaining geologic reserves in the swept area when abandoned, m^3 ; A -- Gas-containing area of gas reservoirs, m^2 ; h -- total effective thickness of the gas reservoir, m ; A_1 -- producing gas-containing area, m^2 ; h_1 -- producing effective thickness, m ; ϕ -- effective porosity, decimal; S_{gi} -- initial gas saturation, decimal; B_{gi} -- initial natural gas volume factor, decimal; B_{ga} -- natural gas volume factor at abandonment, decimal.

2.2.3 The coefficient form of recovery

Substituting Equations 5–8 into Equation 4 gives the coefficient form of the gas reservoir recovery:

$$E_R = \frac{G_1}{G} \times \frac{G_2}{G_1} \times \frac{G_2 - G_{2a}}{G_2} \times 100\% = \frac{A_1}{A} \times \frac{h_1}{h} \times \left(1 - \frac{B_{gi}}{B_{ga}}\right) \times 100\% \\ = E_{VA} \times E_{Vh} \times E_D \times 100\% \quad (9)$$

Where, A is the planar sweep efficiency, B is the vertical sweep efficiency, and C is the gas driving efficiency, and the expressions are respectively:

$$E_{VA} = \frac{G_1}{G} \times 100\% = \frac{A_1}{A} \times 100\% \quad (10)$$

$$E_{Vh} = \frac{G_2}{G_1} \times 100\% = \frac{h_1}{h} \times 100\% \quad (11)$$

$$E_D = \frac{G_2 - G_{2a}}{G_2} \times 100\% = \left(1 - \frac{B_{gi}}{B_{ga}}\right) \times 100\% = \left(1 - \frac{P_a/Z_a}{P_i/Z_i}\right) \times 100\% \quad (12)$$

In the formula: E_R -- recovery, %; A -- Gas-containing area of gas reservoirs, m^2 ; h -- total effective thickness of the gas reservoir, m ; A_1 -- producing gas-containing area, m^2 ; h_1 -- producing effective thickness, m ; ϕ -- effective porosity, decimal; S_{gi} -- initial gas saturation, decimal; B_{gi} -- initial natural gas volume factor, decimal; B_{ga} -- natural gas volume factor at abandonment, decimal; E_{VA} -- planar sweep efficiency, %; E_{Vh} -- vertical sweep efficiency, %; E_D -- gas driving efficiency, %; P_a -- abandoned formation pressure, MPa; Z_a -- gas deviation coefficient at abandonment, decimal; $G_2 = A_1 h_1 \phi S_{gi}/B_{gi}$ -- initial formation pressure, MPa; $E_{Vh} = \frac{h_1}{h} \times 100\%$ -- initial gas deviation coefficient, decimal.

Equations 9–12 illustrate:

- 1) The gas recovery is essentially the multiplication of the planar sweep efficiency, the vertical sweep efficiency and the gas driving efficiency.
- 2) The planar sweep efficiency, the vertical sweep efficiency and the gas driving efficiency can be determined by four macro reservoir parameters. That is, the reservoir form of recovery and the coefficient form can be converted to each other. Equations 10–12, which establish the conversion relationship between four reserve parameters (G , G_1 , G_2 , G_{2a}) and three coefficient parameters (E_{VA} , E_{Vh} , E_D), provide a basis for the interpretation of gas reservoir recovery causes.
- 3) Producing area geological reserves are related to the degree of well network control, so the planar sweep efficiency is also related to the well network perfection; Swept area geological reserves are related to vertical heterogeneity, so the vertical sweep efficiency is also related to vertical heterogeneity; Remaining geological reserves in the swept area at the time of abandoned are related to the abandoned pressure, so the gas driving efficiency is also related to the abandoned pressure.
- 4) In the production process, the well network is adjustable and controllable, and with the improvement of well network control, the planar sweep efficiency increases gradually; while the vertical heterogeneity belongs to the geological factors, which is difficult to be adjusted, so the vertical sweep efficiency in the development process is relatively stable; the gas driving efficiency is only related to the reservoir abandoned pressure, which is limited by the reservoir process technology and the development level, which is difficult to be adjusted, so the gas driving efficiency is generally also relatively stable. Therefore, improving the planar sweep efficiency is an important way to improve the recovery of the gas reservoir when the specific gas reservoir process technology and development level are certain (Dai et al., 2018; Chen et al., 2024).

2.2.4 Current recovery and limited recovery calculations

As gas field exploitation progresses and the well network is improved, the recovery of the gas reservoir will also change. In order to characterize the current and final state of the dynamic change of the recovery, it is divided into current recovery and limited

recovery. Among them, the current recovery is the recovery under the current well network conditions of the gas reservoir, which is an important index to measure the effectiveness of the current gas reservoir exploitation, and is also a regular research topic for gas field development workers.

Since gas reservoirs have current recovery in both reserve and coefficient form, there are, in principle, 2 methods of calculating current recovery. Among them, it is calculated by utilizing the coefficient form, as in Equation 9; and it is calculated by utilizing the reserve form, as in Equation 4.

Limited recovery refers to the recovery under the condition of perfect well network of the gas reservoir, which is an important index to measure the development effect of the gas reservoir at the time of perfect well network, and is of great significance in determining the medium and long term development potential of the gas reservoir. If it is assumed that the planar sweep efficiency under perfect well network condition is 100%, then the limited recovery is essentially the multiplication of gas driving efficiency and vertical sweep efficiency, that is, the coefficient corresponding to the limited recovery is in the form of:

$$E_{R_{\max}} = E_{Vh} \times E_D \times 100\% = \frac{h_1}{h} \times \left(1 - \frac{B_{gi}}{B_{ga}} \right) \times 100\% \quad (13)$$

Substituting Equations 11, 12 into Equation 13, the form of reserves corresponding to the limited recovery can be obtained as:

$$E_{R_{\max}} = \frac{G_2}{G_1} \times \frac{G_2 - G_{2a}}{G_2} \times 100\% \quad (14)$$

In the formula: $E_{R_{\max}}$ -- limited recovery, %.

Since gas reservoir limited recovery has both reserve and coefficient forms, there are, in principle, 2 methods of calculating the limited recovery. Among them, it is calculated by using the coefficient form, as in Equation 13, and by using the reserve form, as in Equation 14.

It is well known that in the process of gas reservoir development, four reserve parameters (G , G_1 , G_2 , G_{2a}) are important basic parameters characterizing the development of gas reservoirs and have exact calculation methods (volumetric method or dynamic method), while the accurate calibration of three coefficient parameters (E_{vA} , E_{vh} , E_D) are more difficult. Therefore, the integrated calculation method of current recovery and limited recovery in this paper refers specifically to the reservoir form of recovery, that is, the Equation 4 is used to calculate the current recovery and Equation 14 is used to obtain the limited recovery. Since there is no restriction on the type of gas reservoir during the derivation of the method, the method has wider applicability.

3 Applications

The Zizhou gas field Shan2 gas reservoir is located in Yulin City, Shaanxi Province, China, within the territory of Mili, Zizhou, Suide and Qingjian counties, the regional tectonics is in the eastern part of the Yi-Shaan slope in the Ordos Basin, and the main producing layer is the Shan2 section of the Shanxi Formation of the Upper Paleozoic Permian Lower Series. The Zizhou gas field Shan2 gas reservoir is located in Yulin City, Shaanxi Province, China, within

the territory of Mili, Zizhou, Suide and Qingjian counties, the regional tectonics is in the eastern part of the Yi-Shaan slope in the Ordos Basin, and the main producing layer is the Shan2 section of the Shanxi Formation of the Upper Paleozoic Permian Lower Series. The gas reservoir is a typical tight sandstone gas reservoir, with outside-source forming and near-source storage characteristics (Zhao et al., 2013); the reservoir is offshore lake braided river delta plain deposition (An et al., 2014), and currently the reservoir has evolved to the mesogenetic B stage (Gao et al., 2013); the reservoir has low porosity and low permeability, with an average porosity of 4.94%, and an average permeability of $0.78 \times 10^{-3} \mu\text{m}^2$ (Wang et al., 2022). The gas reservoir was put into development in 2007, and is currently in the middle to late stage of development, and the core area in the part of the main sand zone has been basically produced (Figure 2).

Taking the Shan2 gas reservoir in Zizhou gas field as an example, reserve analysis method is applied to carry out the integrated calculation of current recovery and limited recovery in the gas reservoir and evaluate the potential of the gas reservoir to improve the recovery. The specific calculation process is shown in Figure 3:

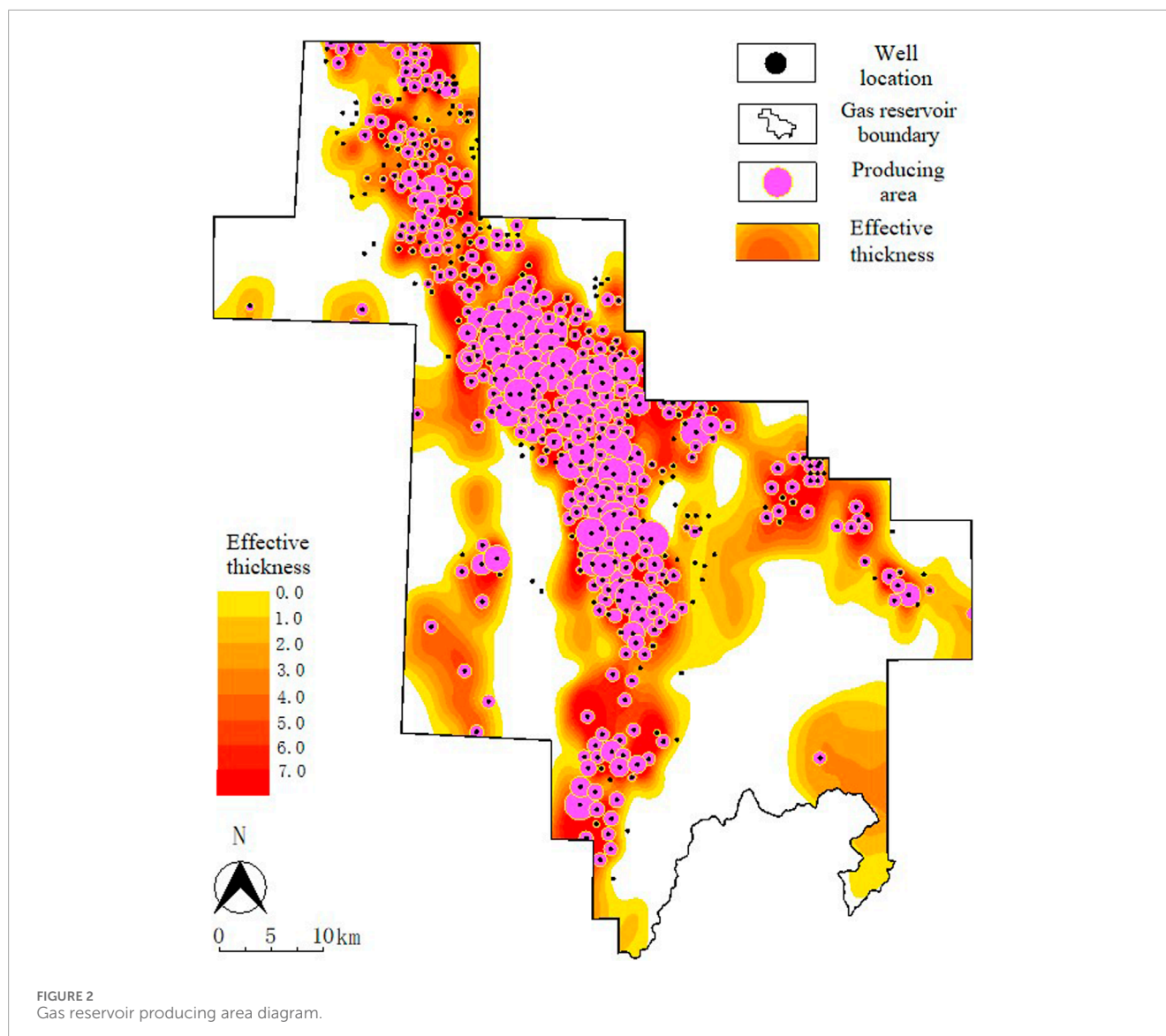
3.1 Verification of 4 geological reserves

- 1) Verification of gas reservoir area geological reserves (G) and producing area geological reserves (G_1) by volumetric method:

The Shan2 gas reservoir in Zizhou gas field is in the middle to late stage of development, and the dynamic and static data accumulated in the gas reservoir over the years are very rich, which provide a reliable data base for the reserve calculation by the volumetric method. Using the drilling, logging interpretation, high-pressure physical properties and production dynamic data of 492 wells, we circled the gas-containing area and gas-containing area of the gas reservoir (Figure 2), determined the gas reserves parameters, and verified the gas-containing area geologic reserves and the producing area geologic reserves by using the volumetric method. Calculation results (Table 1) show that the gas reservoir area has a geological reserve of $1083.4 \times 10^8 \text{ m}^3$ and the producing area has a geological reserve of $679.3 \times 10^8 \text{ m}^3$.

- 2) The rate transient analysis method (RTA) was used to determine the swept area geologic reserves (G_2) and the remaining geologic reserves in the swept area when abandoned (G_{2a}):

At present, the wellhead external delivery pressure (or booster suction pressure) optimized for booster extraction in Zizhou gas field is 2.0 MPa, and according to the method of calculating the pressure drop of the gas-phase vertical pipe flow, the bottomhole flow pressure is back-calculated downward from the wellhead external delivery pressure, and then the abandonment formation pressure is calculated by using the production capacity equation (Hao and Yan, 1999). According to the above method, the abandoned formation pressure of the gas reservoir is 3.5 MPa. Based on the determination of the abandoned pressure, considering the characteristics of low permeability, strong heterogeneity, and large differences in the drainage area of gas wells in tight sandstone



reservoirs, in order to ensure the accuracy of the calculations, the rate transient analysis method (RTA) is used to verify the dynamic geological reserves and the remaining geological reserves when abandoned for each well. Finally, the swept area geological reserves and the remaining geological reserves when abandoned were determined based on the cumulative results of a single well (Fan et al., 2024). Calculation results (Table 1) show that the swept area geological reserve of the gas reservoir is $383.1 \times 10^8 \text{ m}^3$, and the remaining geological reserve in the swept area when abandoned is $49.4 \times 10^8 \text{ m}^3$.

3.2 Calculation of current recovery and limited recovery and assessment of the potential for enhanced recovery in gas reservoirs

Based on the four reserve parameters, the current recovery was calculated by Equation 4, the limited recovery was calculated

by Equation 14, and the difference between the two was used to evaluate the potential of the reservoir to enhance the recovery. The calculation results show that (Table 2), the current recovery of Shan2 gas reservoir in Zizhou gas field is 30.8%, and the limited recovery is 47.9%. Overall, the current recovery of the reservoir is very low and the limited recovery is not good, and both of them are less than 50%.

The geological reserve of Shan2 gas reservoir in Zizhou gas field is $1083.4 \times 10^8 \text{ m}^3$, and the current recovery is 30.8%, indicating that the recoverable reserve of the gas reservoir under the current well network condition is $333.7 \times 10^8 \text{ m}^3$; the limiting recovery of the gas reservoir is 47.9%, indicating that the recoverable reserve of the gas reservoir under the condition of perfecting the well network is $518.9 \times 10^8 \text{ m}^3$; there is a difference of 17.1% between the current recovery and the limiting recovery. The difference between current recovery and limited recovery is $185.3 \times 10^8 \text{ m}^3$, indicating that this gas reservoir has a great potential to enhance the recovery.

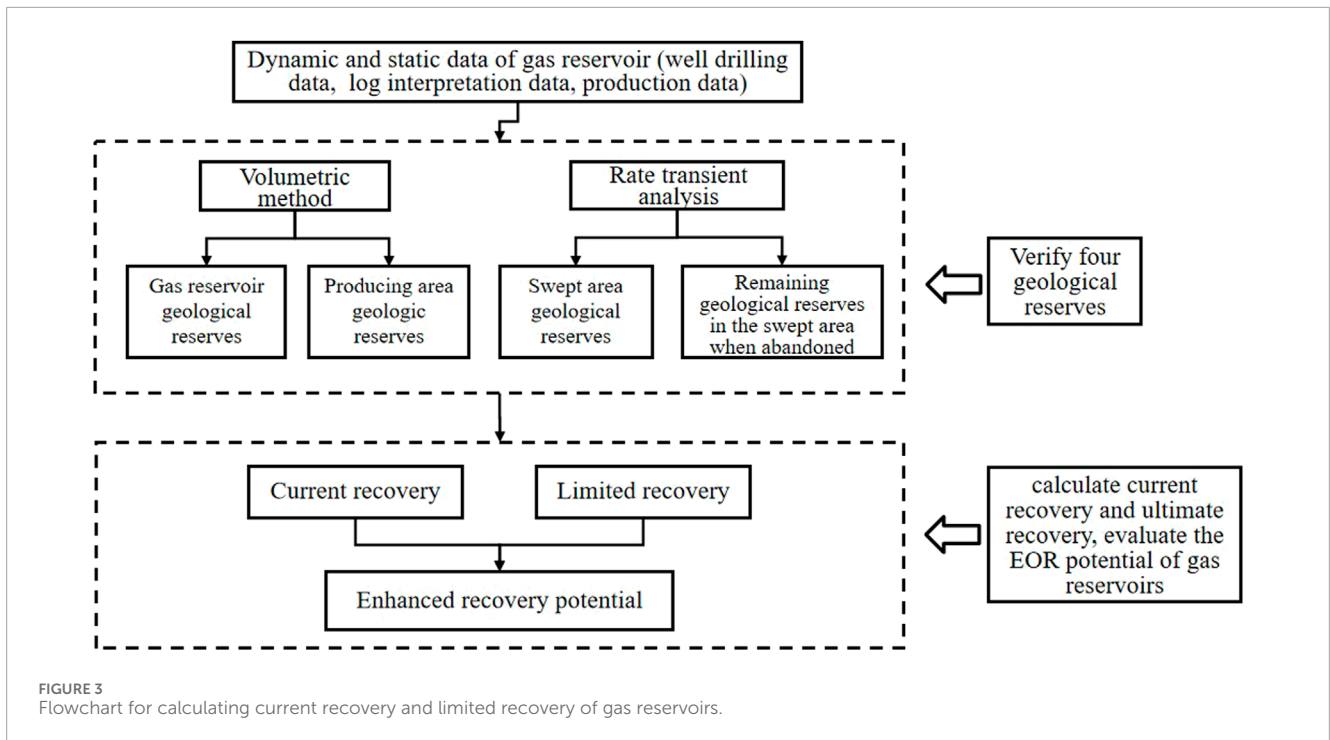


FIGURE 3 Flowchart for calculating current recovery and limited recovery of gas reservoirs.

TABLE 1 Table of calculation results of geological reserves of Shan2 gas reservoir in Zizhou gas field.

Parameters	Gas reservoir geological reserves (10^8m^3)	Producing area geological reserves (10^8m^3)	Swept area geological reserves (10^8m^3)	Remaining geological reserves in the swept area when abandoned (10^8m^3)
Symbolic	G	G_1	G_2	G_{2a}
Parameter value	1083.4	697.3	383.1	49.4

TABLE 2 Table of calculation results of current recovery and limited recovery of Shan2 gas reservoir in Zizhou gas field.

Parameters	Current recovery (%)	Limited recovery (%)	Potential for enhanced recovery (%)
Symbolic	E_R	E_{Rmax}	$E_{Rmax}-E_R$
Parameter value	30.8	47.9	17.1

3.3 Method reliability test

In order to test the reliability of the reserve analysis method on the calculation results of the current recovery and limited recovery of the gas reservoir, numerical simulation method was used to predict the recoverable reserves when abandoned of the gas reservoir under the current well network conditions. The result shows that the final recoverable reserve of the gas reservoir when abandoned is $329.2 \times 10^8 \text{ m}^3$, and based on this prediction result, combined with the gas reservoir area geologic reserve ($1083.4 \times 10^8 \text{ m}^3$) and producing area geologic reserve ($679.3 \times 10^8 \text{ m}^3$), the current recovery of the gas reservoir is determined to be 30.4%, and the limited recovery is determined

to be 47.2% respectively by using the Equations 4, 14. This result is in good agreement with the current recovery (30.8%) and limited recovery (47.9%) calculated by the reserve analysis method, indicating that the calculation results of the reserve analysis method are reliable (Figure 4).

4 Discussion

Reserve and coefficient forms of recovery can be converted to each other. Equations 10–12, establish the conversion relationship between 4 reservoir parameters (G, G_1, G_2, G_{2a}) and 3 coefficient parameters (E_{vA}, E_{vh}, E_D). For this reason,

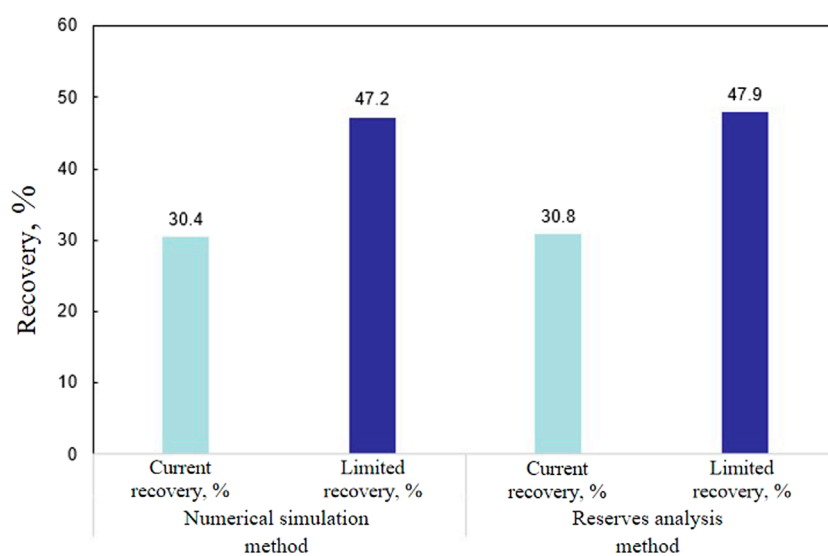


FIGURE 4 Comparison of recovery calculation results between numerical simulation method and reserves analysis method for Shan2 gas reservoir in Zizhou gas field.

TABLE 3 Table of calculation results of planar sweep efficiency, vertical sweep efficiency and gas driving efficiency of Shan2 gas reservoir in Zizhou gas field.

Parameters	Planar sweep efficiency (%)	Vertical sweep efficiency (%)	Gas driving efficiency (%)	Current recovery (%)	Limited recovery (%)
Symbolic	E_{vA}	E_{vh}	E_D	E_R	E_{Rmax}
Parameter value	64.4	54.9	87.1	30.8	47.9

according to the four reserve parameters, the planar sweep efficiency, vertical sweep efficiency and gas driving efficiency of Shan2 gas reservoir in Zizhou gas field were calculated by using Equations 10–12, so as to analyze the main controlling factors affecting the recovery of the gas reservoir, and to formulate the adjustment direction of the development of the gas reservoir.

Calculation results show that (Table 3), the planar sweep efficiency of Shan2 reservoir in Zizhou gas field is 64.4%, which is not high; the vertical sweep efficiency is 54.9%, which is low; and the gas driving efficiency is 87.1%, which indicates that the gas driving efficiency of pressure boosting production is high. According to this analysis, it is believed that the low planar sweep efficiency and low vertical sweep efficiency of Shan2 gas reservoir are the main reasons for the low current recovery (30.8%) of the gas reservoir. As it is difficult to fundamentally change both the vertical sweep efficiency and the gas driving efficiency under the condition that the existing process technology and development level remain unchanged. Therefore, maximizing the planar sweep efficiency is still an effective way to substantially increase the recovery of this gas reservoir.

Of course, further increasing the vertical sweep efficiency or gas driving efficiency is also very important to enhance the recovery of the gas reservoir. However, the premise is that the existing

technology and development level of the gas reservoir also need to be significantly improved. Therefore, how to increase the vertical sweep efficiency and gas driving efficiency is still an important issue in gas reservoir development research. Especially for tight sandstone gas reservoirs, how to improve the vertical sweep efficiency is particularly important.

5 Conclusion

In this paper, the differences in reserves and their production and utilization among gas reservoir area, swept area and producing area are considered comprehensively, a reserves zoning producing model is established, and a method for integrating current recovery and limited recovery in gas reservoirs, the reserve analysis method, is proposed. The method can utilize four macroscopic storage parameters, including the gas reservoir area geological reserves, producing area geological reserves, swept area geological reserves, and the remaining geological reserves in the swept area when abandoned, to find the current recovery and the limited recovery of the gas reservoir, and evaluate the potential of gas reservoirs to improve the recovery. At the same time, the method can also determine the reservoir planar sweep efficiency, vertical sweep efficiency and gas driving efficiency, which can help to clarify the

main controlling factors affecting the recovery of the gas reservoir and improve the development method of the gas reservoir. The method is simple and easy to implement, with wide applicability, and provides an effective technical way for the assessment of gas reservoir recovery potential, which is of great significance for improving the development method and enhancing the recovery of the gas reservoir.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

JD: Conceptualization, Funding acquisition, Investigation, Software, Supervision, Validation, Writing—original draft, Writing—review and editing, Methodology, Project administration, Data curation, Formal Analysis, Resources, Visualization. JW: Writing—review and editing, Data curation, Formal Analysis, Investigation, Methodology, Visualization. YS: Formal Analysis, Investigation, Methodology, Visualization, Writing—review and editing. XL: Data curation, Methodology, Writing—review and editing. SP: Investigation, Visualization, Writing—review and editing.

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Conflict of interest

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