Study on Ultimate Recovery Efficiency and Tapping Potential of Tight Sandstone Gas Reservoirs- Taking Shan2 Gas Reservoir of Zizhou Gas Field as an Example

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Abstract. Ultimate recovery efficiency is the recovery efficiency of gas reservoir with perfect well pattern. It is of great significance to evaluate the ultimate recovery efficiency of gas reservoir and to determine the tapping potential of gas reservoir. At present, there are few researches on ultimate recovery efficiency, and the main reason is the lack of effective evaluation methods. This paper starts from the reserves and their utilization laws of gas fields, and establishes a reserves utilization zoning model and proposes a method for determining the ultimate recovery efficiency of gas fields - reserves analysis method. Taking the Shan2 tight sandstone gas reservoir in Zizhou gas field of Ordos Basin as an example, this method is applied to evaluate the ultimate recovery efficiency of gas reservoir and determine the tapping potential of gas reservoir. The results show that the ultimate recoverable reserves of Shan2 gas reservoir in Zizhou Gas field are $517.9\times10^8 m^3$ and the ultimate recovery efficiency is 47.8%, the current recoverable reserves are $333.7\times10^8 m^3$ and the current recovery efficiency is 30.8%, the potential recoverable reserves of the gas reservoir are $184.2\times10^8 m^3$ and the recovery potential is 17%. The research results provide a new technical approach for assessing the ultimate recovery efficiency of tight sandstone gas reservoirs, and have important guiding significance for similar gas reservoirs.

Keywords: tight sandstone gas reservoir; ultimate recovery efficiency; latent capacity of tapping potential; determination method; Zizhou gas field; Shan-2 gas reservoir;

1 Introduction

Recovery efficiency is an important technical index to measure the comprehensive development effect of gas reservoirs, and it is also one of the important parameters for development program formulation, planning, dynamic analysis and economic evaluation [1-2]. Gas reservoir recovery efficiency can be divided into current recovery efficiency and ultimate recovery efficiency [3-4]. Among them, the current recovery

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efficiency is the recovery efficiency under the current well pattern condition of the gas reservoir, which can reflect the current development effect of the gas reservoir. The current recovery efficiency is a frequent research topic for gas field developers, and there are many related research results [5-10]. The main idea is to obtain the recoverable reserves when the gas reservoir is abandoned under the well network, and then use the ratio of recoverable reserves to geological reserves to calculate. According to different calculation methods of recoverable reserves, there are many methods to determine the current recovery efficiency, such as material balance method, production decline method, elastic two-phase method, pressure recovery curve method, Rogersti function method, dynamic reserves analysis method and numerical simulation method [11-12]. The main shortcoming of current recovery efficiency is that it does not consider the perfection of gas reservoir well pattern, and can not predict the final production effect of gas reservoir under the perfect well pattern. Especially for the tight sandstone gas reservoir, poor reservoir physical property, strong heterogeneity, and the well pattern perfection have an important impact on the recovery efficiency, the current recovery efficiency and the ultimate recovery efficiency may be very different.

Ultimate recovery efficiency is the recovery efficiency of gas reservoir with perfect well pattern, which can reflect the ultimate development effect of gas reservoir. The difference between the current recovery efficiency and the ultimate recovery efficiency can be used to evaluate the tapping potential of the gas reservoir. Considering the limited guiding effect of current recovery efficiency on gas reservoir exploitation, the study of ultimate recovery efficiency is of great guiding significance for evaluating the ultimate development effect and gas reservoir exploitation. Therefore, the author takes Shan2 tight sandstone gas reservoir in Zizhou gas field as an example to study the ultimate recovery efficiency and tapping potential of tight sandstone gas reservoir.

Firstly, based on the gas reservoir reserves and its utilization law, the paper puts forward a reserve utilization zoning model, and establishes a method of determining the ultimate recovery efficiency of gas reservoirs-the reserve analysis method. Secondly, taking Shan2 tight sandstone gas reservoir of Zizhou gas field as an example, the ultimate recovery efficiency of the gas reservoir is evaluated by using this method. Finally, by comparing the current recovery efficiency with the ultimate recovery efficiency, the tapping potential of gas reservoir is indicated. This study provides a new technical approach for evaluating the ultimate recovery efficiency of tight sandstone gas reservoirs and has important reference significance for guiding the calculation of the ultimate recovery efficiency of tight sandstone gas reservoirs and the tapping potential.

2 New Method for Calculating Ultimate Recovery Efficiency

Compared with the current recovery efficiency, there are few related studies on ultimate recovery efficiency of gas reservoir. The main reason is that the perfect well pattern is abstract and difficult to determine, which limits the ultimate recovery efficiency of gas reservoir and leads to the lack of effective evaluation methods. This paper starts from the reserves and utilization laws of gas fields, and establishes a reserves utilization zoning model and proposes a method for determining the ultimate recovery efficiency of gas fields - reserves analysis method.

2.1 Reserve Utilization Zone Model

The reserve size and spatial distribution of the reserves in the original state of the gas field are constrained by the industrial oil and gas flow standards and economic technical conditions, and have a determined distribution range (the gas field area). Gas reservoir zone is the material basis of gas reservoir production, but due to the lateral heterogeneity of the reservoir, the gas reservoir zone controlled by the production well pattern during production (that is the utilization zone) is often smaller than the actual range of the gas reservoir zone, and the drilling in the utilization zone cannot be repeated. At the same time, affected by the longitudinal heterogeneity of the reservoir, the produced thickness is generally less than the total effective thickness even in the utilization area.

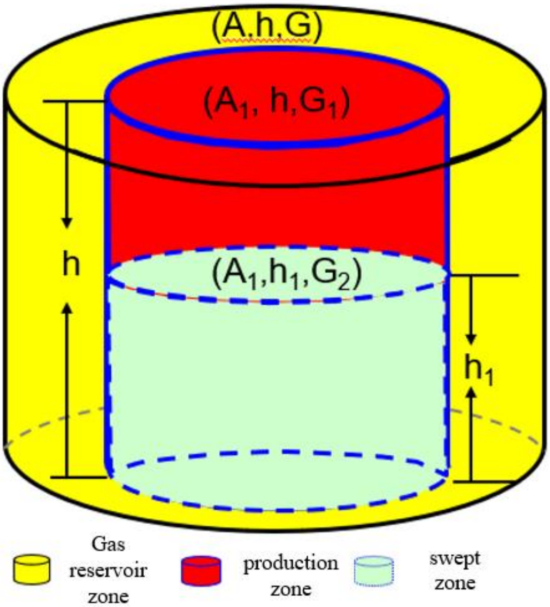

Fig. 1. Schematic diagram of reserve production zone.

In order to reflect the gas reservoir reserves and utilization rule, a reserve utilization zone model is established (Fig. 1), the gas reservoir is subdivided into three zones, namely, gas reservoir zone, utilization zone and swept zone. Among them, the main difference between the utilization area and the swept area is that the utilization area is the apparent utilization area of the gas reservoir (limited by the range of plane utilization and the total effective thickness), and the swept area is the actual utilization area of the gas reservoir (limited by the range of plane utilization and the effective thickness of utilization).As can be seen from Fig 1, there are significant differences in the geometric size and reserves of the three zones. In terms of geometric size, the gas reservoir area corresponds to the gas bearing area (A) and the total effective thickness (h) of the gas reservoir, and the effective volume is the largest; the utilization area corresponds to the utilization gas bearing area (A_1) and the total effective thickness (h), and the effective volume is medium; the swept area corresponds to the utilization gas bearing area (A_1) and producing effective thickness(h_1), and the effective volume is the smallest. In terms of reserves, the geological reserves in the gas reservoir region(G) are the largest; the scale of geological reserves in the production area(G_1) is medium; the geological reserves in the swept zone(G_2), also known as dynamic geological reserves (or producing geological reserves), are the smallest of the three.

The model takes into account both vertical and horizontal heterogeneity of the reservoir, as well as the non-repeatability of drilling wells in the range of plane utilization, which provides a basis for determining the ultimate recovery efficiency.

2.2 Calculation Method of Ultimate Recovery Efficiency

For a particular gas reservoir, the recovery efficiency is the ratio of the final amount of gas produced (or recoverable reserves) to the original geological reserves of the gas reservoir, that is:

$$E_{\mathrm{R}} = G_R / G \times 100\% \tag{1}$$

Considering the reserves utilization zoning model, formula (1) can be expressed as:

$$E_{\mathrm{R}} = \frac{G_R}{G_2} \cdot \frac{G_2}{G_1} \cdot \frac{G_1}{G} \times 100\% \tag{2}$$

Because the recoverable reserves (G_R)all come from the dynamic geological reserves of the swept area (G_2), according to the principle of material balance:

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

Therefore, gas reservoir recovery efficiency can be fully expressed in the form of reserves:

$$E_{\mathrm{R}} = \frac{G_2 - G_{2a}}{G_2} \cdot \frac{G_2}{G_1} \cdot \frac{G_1}{G} \times 100\% \tag{4}$$

For the constant volume gas reservoir, the geological reserves of the gas reservoir, the geological reserves in the utilization area, the dynamic geological reserves and the remaining geological reserves in the swept area when abandoned respectively are:

$$G = Ah\phi S_{gi} / B_{gi} \tag{5}$$

$$G_1 = A_1 h\phi S_{gi} / B_{\mathrm{gi}} \tag{6}$$

$$G_2 = A_1 h_1 \phi S_{gi} / B_{gi} \tag{7}$$

$$G_{2a} = A_1 h_1 \phi S_{gi} / B_{ga} \; G_{2a} = A_1 h_1 \phi S_{gi} / B_{ga} \tag{8}$$

By substituting formula (5)-(8) into formula (4), we get:

$$E_R = (1 - \frac{B_{gi}}{B_{ga}}) \cdot \frac{h_1}{h} \cdot \frac{A_1}{A} \times 100\% \tag{9}$$

Among them:

$$E_{VA} = \frac{A_1}{A} \times 100\% \tag{10}$$

$$E_{Vh} = \frac{h_1}{h} \times 100\% \tag{11}$$

$$E_D = (1 - \frac{B_{gi}}{B_{ga}}) \times 100\% = (1 - \frac{P_a / Z_a}{P_i / Z_i}) \times 100\% \tag{12}$$

In the Formula:
E_R——recovery efficiency, %;
G_R——recoverable reserves,$10^6 m^3$;
G——original geological reserves of gas reservoir,$10^6 m^3$;
G_2—— dynamic geological reserves, $10^6 m^3$;
G_{2a}——remaining geological reserves in the swept area when abandoned, $10^6 m^3$;
G_1——geological reserves in utilization area, $10^6 m^3$;
A ——gas bearing area of gas reservoir, km^2;
h ——total effective thickness of gas reservoir, m;
A_1 ——produced gas bearing area, km^2;
h_1 ——producing effective thickness, m;
ϕ ——effective porosity, decimals;
S_{gi} ——original gas saturation, decimals;
B_{gi} ——original gas formation volume factor, decimals;
B_{ga} ——gas formation volume factor when abandoned, decimals;
E_D ——gas displacement efficiency, %;
E_{vA} ——areal sweep efficiency, %;
E_{vh} ——vertical sweep efficiency, %;
P_a ——the formation pressure when abandoned, MPa;

Z_a——gas deviation coefficient when abandoned, decimals;

P_i——original formation pressure, MPa;

Z_i——original gas deviation coefficient, decimals.

It is not difficult to see from the above derivation process:

①Gas reservoir recovery efficiency is essentially the product of areal sweep efficiency, vertical sweep efficiency and gas displacement efficiency. At the same time, to calculate the areal sweep efficiency, vertical sweep efficiency, gas displacement efficiency and recovery efficiency, only four reserve parameters such as gas reservoir geological reserves (G), utilization area geological reserves (G_1), dynamic geological reserves (G_2) and remaining geological reserves in the swept area when abandoned (G_{2a}) are needed.

②Although the four kinds of geological reserves can be expressed by volumetric formula, the actual calculation methods are different. Among them, the geological reserves of gas reservoirs and the geological reserves of utilization areas are generally calculated by static method, and mainly by volumetric method; due to the difficulty of accurate calibration of the producing effective thickness(h_1), dynamic geological reserves and remaining geological reserves in the swept area when abandoned are generally calculated by dynamic methods, including material balance method, pressure drop curve method and production transient analysis (RTA). In the early stage of development, material balance method and pressure drop curve method were mainly used. In the middle and late stage of development, the dynamic data of production is very rich, and production transient analysis method is better [13-14].

With the development of gas field and the improvement of well pattern, the recovery efficiency of gas reservoir will also change. In order to characterize the current and final state of dynamic change of recovery efficiency, recovery efficiency is divided into current recovery efficiency and ultimate recovery efficiency. Among them, the current recovery efficiency is the recovery efficiency under the current well network of the gas reservoir, which is an important index to measure the development effect of the gas reservoir, and it is also a regular research topic for the gas field development workers. The current recovery efficiency can be calculated directly from formula (4).

Ultimate recovery efficiency refers to the recovery efficiency of gas reservoir under perfect well pattern. It is an important index to measure the gas reservoir development effect when the well pattern is perfect, and it is of great significance to determine the medium and long term development potential of gas reservoir. If the areal sweep efficiency is assumed to be 100% in a perfect well network, the ultimate recovery efficiency is essentially the product of gas displacement efficiency and vertical sweep efficiency, that is:

$$E_{\mathrm{Rmax}} = (1 - \frac{B_{gi}}{B_{ga}}) \cdot \frac{h_1}{h} \times 100\% \tag{13}$$

The corresponding reserve form is:

$$E_{\mathrm{Rmax}} = \frac{G_2 - G_{2a}}{G_2} \cdot \frac{G_2}{G_1} \times 100\% \tag{14}$$

In the Formula: E_{Rmax} ——ultimate recovery efficiency, %.

Therefore, the ultimate recovery efficiency can be calculated according to formula (14).

Equation (14) shows that the ultimate recovery efficiency can be obtained according to the ratio of the current recoverable reserves to the geological reserves in the utilization area. This is due to the non-repeatability of the drilling area and the perfection of the well pattern.

3 Calculation Examples of Ultimate Recovery Efficiency

The Shan2 gas reservoir of Zizhou Gas field is located in Mizhi, Zizhou, Suide and Qingjian counties of Yulin City, Shaanxi Province, the regional structure is in the east of Yishan slope of Ordos Basin, and the main production layer is Shan2 member of the Lower Permian Shanxi Formation of Upper Paleozoic. The gas reservoir is a typical tight sandstone gas reservoir with the characteristics of accumulate outside but maintained near to the source [15]; the reservoir is deposited in braided river delta plain of paralic lake [16], at present, the reservoir has evolved to meso-diagenetic phase B [17]; the reservoir has low porosity and low permeability, with an average porosity of 4.94% and an average permeability of $0.78 \times 10^{-3} \mu m^2$[18]. Shan2 gas reservoir in Zizhou Gas field has been developed and constructed since 2007, and is currently in the middle and late stages of development, the core area of the main sand body belt has been basically utilized (Fig. 2).

Taking Shan2 gas reservoir of Zizhou gas field as an example, the current recovery efficiency and ultimate recovery efficiency are calculated by using the reserve analysis method.

1) Firstly, using the dynamic and static data of the gas reservoir, the abandonment pressure is determined, and four kinds of geological reserves (geological reserves of gas reservoir, geological reserves in production area, dynamic geological reserves and remaining geological reserves when abandoned) are verified. ①Determine gas reservoir abandonment pressure. According to the calculation method of gas phase vertical pipe flow pressure drop, the bottom hole flow pressure can be calculated backwards from the wellhead external pressure, and then the abandoned formation pressure can be calculated by productivity equation [13]. At present, the wellhead external delivery pressure (or booster suction pressure) of optimized boosting mining in Zizhou gas field is 2.0MPa. According to the above method, the abandoned formation pressure of the gas reservoir is3.5MPa. ②On the basis of determining abandonment pressure, using the drilling, logging interpretation, high pressure physical properties and production dynamic data of 492 Wells accumulated over the years in Shan2 gas reservoir of Zizhou Gas field, and on the basis of determining the calculation parameters of reserves and the producing gas bearing area (Fig. 2), the volumetric method is adopted to calculate the geological reserves of gas reservoir (G)and geological reserves in production area

(G_1); at the same time, considering the characteristics of tight sandstone gas reservoir with low permeability, strong heterogeneity and large difference of gas well drainage area, in order to ensure the calculation accuracy, production transient analysis (RTA) is used to verify the dynamic geological reserves and the remaining geological reserves in the swept area when abandoned, finally, the dynamic geological reserves (G_2) of the gas reservoir and the remaining geological reserves of the swept area when abandoned (G_{2b})are determined according to the cumulative results of single well. The calculation results are shown in Table 1, it can be seen that the geological reserves of the gas reservoir are $1083.4 \times 10^8 m^3$> the producing geological reserves are $679.3 \times 10^8 m^3$> the dynamic geological reserves are $383.1 \times 10^8 m^3$> the remaining geological reserves in the swept area are $49.4 \times 10^8 m^3$.

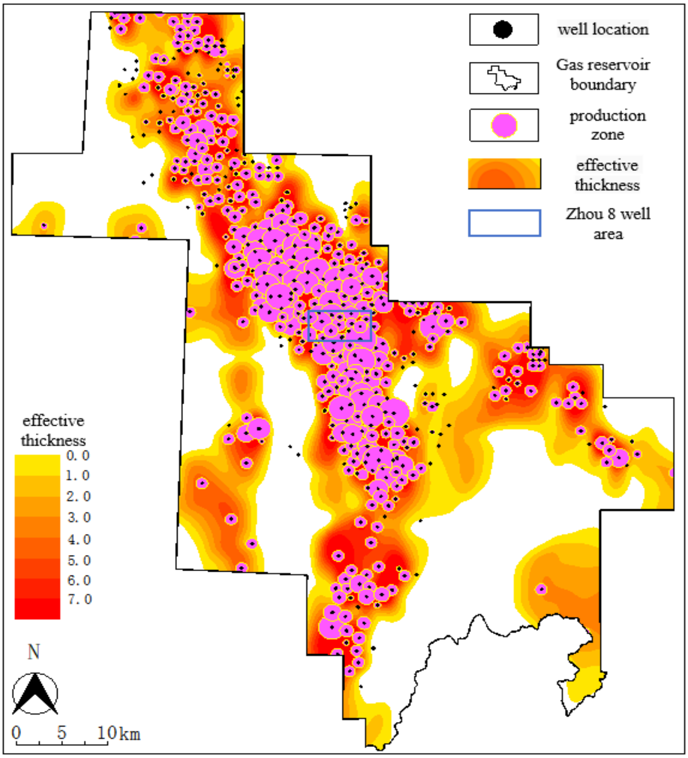

Fig. 2. Producing area diagram of gas reservoir.

Table 1. Table of geological reserves, producing area geological reserves, dynamic geological reserves and remaining geological reserves in the swept area of Shan 2 gas reservoir in Zizhou Gas field.

parameter	geological reserves /($10^8 m^3$)	producing area geological reserves /($10^8 m^3$)	dynamic geological reserves /($10^8 m^3$)	remaining geological reserves in the swept area /($10^8 m^3$)
symbol	G	G_1	G_2	G_{2a}
values	1083.4	697.3	383.1	49.4

2) Secondly, according to 4 kinds of geological reserves, the current recovery efficiency and ultimate recovery efficiency of gas reservoir are calculated. The calculation results show (Table 2) that the areal sweep efficiency of Shan2 gas reservoir in Zizhou gas field is 64.4%, the vertical sweep efficiency is 54.9%, the gas displacement efficiency is 87.1%, the current recovery efficiency is 30.8%, and the ultimate recovery efficiency is 47.8%. In general, the current recovery efficiency of the gas reservoir is very low, and the ultimate recovery efficiency is not high, both of which are less than 50%. Compared with conventional gas reservoirs, the recovery efficiency of this gas reservoir is at a lower level.

3) The ultimate recovery efficiency of Shan2 gas reservoir in Zizhou gas field is 47.8%. In order to verify the calculation results of ultimate recovery efficiency, Zhou 8 well area, with a relatively perfect well pattern in the middle of Zizhou gas field, was selected for numerical simulation (Fig. 2). On the basis of geological model building and production history fitting, the recovery efficiency at abandonment is predicted. The results show that the ultimate recovery efficiency of well area Zhou 8 is 47.2%, which is in good agreement with the ultimate recovery efficiency calculated by the above reserves analysis method (47.8%), indicating that the calculation result of the reserves analysis method is reliable for the gas reservoir ultimate recovery efficiency.

Table 2. Calculation result table of areal sweep efficiency, vertical sweep efficiency, gas displacement efficiency and recovery efficiency of Shan2 gas reservoir in Zizhou gas field.

parameter	areal sweep efficiency/%	vertical sweep efficiency /%	gas displacement efficiency /%	current recovery efficiency /%	ultimate recovery efficiency /%
symbol	E_{VA}	E_{Vh}	E_D	E_R	E_{Rmax}
values	64.4	54.9	87.1	30.8	47.9

4 Tapping Potential

The current recovery efficiency (30.8%) of Shan2 gas reservoir in Zizhou Gas field indicates that the recoverable reserves of the gas reservoir under the current well pattern condition is $333.7\times10^8m^3$. The ultimate recovery efficiency is 47.8%, indicating that the recoverable reserves of the gas reservoir under the condition of well pattern improvement is $517.9\times10^8m^3$. The comparison shows that the recoverable reserve potential of the tight sandstone gas reservoir is $184.2\times10^8m^3$, and the recovery efficiency improvement potential is 17%. It can also be seen from Fig 2 that the well pattern of Yu69, Yu48, Qilin Gou and Yu29 surrounding the main sand body is not perfect and the production effect is poor, which is the key point of potential exploration of gas reservoir in the future.

5 Conclusion

Based on the gas reservoir reserves and their utilization law, a reserves utilization zoning model was proposed, and a method for determining the ultimate recovery efficiency of a gas reservoir - reserves analysis method, was established. Taking Shan2 tight sandstone gas reservoir in Zizhou gas field as an example, this method is applied to evaluate the ultimate recovery efficiency of the gas reservoir, and the potential of the gas reservoir is pointed out by comparing the current recovery efficiency with the ultimate recovery efficiency. The results show that the ultimate recoverable reserves of Shan2 gas reservoir in Zizhou Gas field are $517.9\times10^8 m^3$ and the ultimate recovery efficiency is 47.8%, the current recoverable reserves are $333.7\times10^8 m^3$ and the current recovery efficiency is 30.8%, the recoverable reserves potential of the tight sandstone gas reservoir is $184.2\times10^8 m^3$ and the recovery efficiency potential is 17%. The research results provide a new technical approach for assessing the ultimate recovery efficiency of tight sandstone gas reservoirs, and have important guiding significance for similar gas reservoirs.

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