Study on "Utilization Efficiency of Oil and Gas" in Oilfield Production Affected Zone

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Abstract: Not all reserves in the production affected zone are utilized during the development of oil fields. It is of great significance for the efficient development of oil fields to clarify the utilization degree of oil and gas in the production affected zone. A quantitative characterization parameter of the utilization degree of oil and gas in production affected zone is proposed, which is the utilization efficiency of oil and gas. Mathematical and physical models were established, and combined with the example of the X well area of Xifeng Oilfield, Ordos Basin, China, a systematic study was conducted on the physical meaning, influencing factors, determination methods, and production significance of utilization efficiency of oil and gas. Studies have shown that the utilization efficiency of oil and gas is the ratio of the volume of oil and gas utilized to the volume of oil and gas in the production affected zone. For a particular reservoir, it is mainly affected by two factors: driving pressure and accumulation force. Among them, the driving pressure affects the volume of oil and gas utilized, and the accumulation force affects the volume of oil and gas accumulated. The relative size of the two determines the utilization efficiency of oil and gas. When the driving pressure is less than the accumulation force, oil and gas are partially utilized. When the driving pressure is equal to the accumulation force, all oil and gas are utilized. When the driving pressure is greater than the accumulation force, all the oil and gas are utilized and the formation water is produced. This study shows that optimizing the driving pressure (or production pressure difference) with accumulation force can improve the utilization efficiency of oil and gas and avoid or reduce formation water production. This research provides a new basis for the optimal adjustment of production pressure difference, and has important reference significance for water control and oil stabilization and efficient development in oil fields.

1. Introduction

In the process of oilfield exploitation, the development zone is composed of two parts, the production affected zone and the unaffected zone (Figure 1). The production affected zone is a space controlled by the well pattern and able to participate in seepage. Conversely, the space in the development zone other than the production affected zone is production unaffected zone. Generally, the thickness of oil layer, oil-bearing area and volume scale in the production affected zone are always smaller than those in the development zone. In the study of reserves utilization degree, people pay more attention to how to expand the scope of production affected zone, so as to maximize the utilization degree of oilfield geological reserves [1-14], and pay less attention to utilization condition of oil and gas in production...
affected zone. In fact, although the reservoir fluids in the production affected zone participate in the seepage, the oil and gas accumulated in the reservoir are not 100% utilized. Since the utilization of oil and gas is a prerequisite for oil and gas production, a higher utilization efficiency of oil and gas is also a necessary condition for improving the effectiveness of oil and gas production. Therefore, it is very necessary to evaluate the utilization of oil and gas in the production affected zone, which has important guiding significance for the efficient development of oil fields.

To this end, a quantitative characterization parameter for the utilization degree of oil and gas in the production affected zone is proposed—utilization efficiency of oil and gas. Mathematical and physical models were established, and combined with the example of the X well area of Xifeng Oilfield, Ordos Basin, China, a systematic study was conducted on the physical meaning, influencing factors, determination methods, and production significance of utilization efficiency of oil and gas.

Figure 1  Schematic diagram of production affected zone

2. The physical meaning of the utilization efficiency of oil and gas
As we all know, the oil and gas deposited in the reservoir's large pore throat network is easier to flow during oilfield exploitation. As the driving pressure increases, the oil and gas in the reservoir's small pore throat network is gradually utilized. When the driving pressure reaches a certain level, the oil and gas accumulated in the reservoir happens to be fully utilized. The driving pressure is different, and the utilization degree of oil and gas in the production affected zone is also different. To this end, the concept of the utilization efficiency of oil and gas is proposed, and the mathematical model is as follows:

$$\omega = \frac{V_{of}}{V_o} = \frac{A_1 \cdot h_1 \cdot \phi \cdot S_{of}}{A_1 \cdot h_1 \cdot \phi \cdot S_{oc}} = \frac{\phi \cdot S_{of}}{\phi \cdot S_{oc}}$$  \hspace{1cm} (1)

Where $V_{of}$ represents the volume of oil and gas utilized in the production affected zone, $V_o$ represents the volume of oil and gas accumulated in the production affected zone, $A_1$ represents oil-bearing area in production affected zone, $h_1$ represents effective thickness in production affected zone, $\phi$ represents reservoir flowing porosity, $\phi$ represents reservoir connected porosity, $S_{of}$ represents oil saturation of flowing pores and $S_{oc}$ represents oil saturation of connected pores.

Equation (1) shows that the utilization efficiency of oil and gas is the ratio of the volume of oil and gas utilized to the volume of oil and gas accumulated in the production affected zone. The utilization efficiency of oil and gas is proportional to the multiplication of reservoir flowing porosity and oil saturation of flowing pores, and inversely proportional to the reservoir connected porosity and oil saturation of connected pores.

3. Factors influencing the utilization efficiency of oil and gas
Establish a physical model for the utilization efficiency of oil and gas (Figure 2). Decompose the reservoir in the affected area into three parts: rock skeleton, formation water and oil and gas. It is assumed that the volume of the reservoir rock is $V_r$. The volume of the connected pore throat is $V_t$ and the volume of the formation water in the connected pore throat is $V_w$. Under the action of
accumulation force $\Delta p$, the volume of oil and gas accumulated in the connected pore throat is $V_o$.

Under the action of driving pressure $\Delta p$, the volume of fluid utilized in the connected pore throat is $V_f$.

During the reservoir-forming process, under the action of accumulation force and filtration resistance, oil and gas first enters the large pore throat network with less resistance in the reservoir. After the macro pore throat network is saturated, it gradually enters the relatively smaller reservoir pore throat network in turn. This process continues until the pore throat network matching the accumulation force is fully saturated. After the end of the accumulation process, with the pore throat radius $R_{min}$ corresponding to the accumulation force as the boundary, the formation water is finally bound to the reservoir connected pore throat with pore throat radius $< R_{min}$. The oil and gas occupy the connected pore throat with pore throat radius $> R_{min}$.

In the process of oil and gas production: 1) When the driving pressure is greater than the accumulation force, the volume of fluid utilized is greater than the volume of oil and gas accumulated and the volume of oil and gas utilized is equal to the volume of oil and gas accumulated. At this time, the utilization efficiency of oil and gas is equal to 1, and all the oil and gas are utilized and produce formation water. 2) When the driving pressure is equal to the accumulation force, the volume of fluid utilized, the volume of oil and gas utilized, and the volume of oil and gas accumulated are equal. At this time, the utilization efficiency of oil and gas is equal to 1, and all the oil and gas are utilized. 3) When the driving pressure is less than the accumulation force, the volume of fluid utilized is equal to the volume of oil and gas utilized and the volume of oil and gas utilized is less than the volume of oil and gas accumulated. At this time, the utilization efficiency of oil and gas is less than 1, and the oil and gas are utilized partially.

The above analysis shows that the utilization efficiency of oil and gas is mainly affected by the driving pressure and the accumulation force for a particular reservoir. Among them, the driving pressure affects the volume of oil and gas utilized, and the accumulation force affects the volume of oil and gas accumulated. The relative size of the two determines the utilization efficiency of oil and gas.

4. Method for determining the utilization efficiency of oil and gas

As shown in Figure 3, the determination of the utilization efficiency of oil and gas includes three steps: ① The analysis of accumulation force and driving pressure: Mainly to determine the accumulation force, driving pressure and their relative sizes. ② Parameter determination: Mainly to determine connected porosity, oil saturation of connected pores and flowing porosity. ③ Determining the utilization efficiency of oil and gas: Since the driving pressure is greater than or equal to the accumulation force, the utilization efficiency of oil and gas is equal to 1; therefore, in this case, the parameter calculation step can be omitted. The specific process is as follows:
4.1. Analysis of accumulation force and driving pressure

For specific reservoirs, accumulation force is a key factor affecting the hydrocarbon accumulation volume. However, the determination of accumulation force is very complicated, including many experiments and simulations [15], and the accuracy is difficult to guarantee within a reasonable range. Therefore, the accurate determination of the accumulation force is difficult.

Considering that the mercury intrusion process is a process in which the non-wet-phase fluid displaces the wet-phase fluid, it is equivalent to the reservoir-charging process of oil-flooded water. If the mercury saturation is regarded as oil saturation and the displacement pressure is regarded as accumulation force, the mercury intrusion curve actually reflects the correspondence between the oil saturation of a particular reservoir and the accumulation force (Figure 4). The greater the accumulation force, the higher the oil saturation of the reservoir, and vice versa. Therefore, mercury intrusion pressure corresponding to the original oil saturation on the mercury intrusion curve is the accumulation force. Take Figure 4 as an example, assuming that it is the mercury intrusion curve of a particular reservoir, and the original oil saturation of the reservoir is 78%, then point A in the figure is the accumulation force point, and the corresponding accumulation force is 3MPa.

For a specific reservoir, the driving pressure is a key factor affecting the volume of oil and gas utilized. When an oilfield is developed with a fixed well pattern, the driving pressure mainly refers to the production pressure difference, and its size can be obtained statistically based on the oilfield production dynamic data. Taking Figure 4 as an example, assuming that it is the mercury intrusion curve of a particular reservoir, and the production pressure difference of the reservoir is 1 MPa, then point B in the figure is the driving pressure point. Based on the determination of accumulation force and driving pressure, the relative sizes of the two are judged, and the characteristics of oil and gas are initially grasped. As can be seen from the comparison of points A and B in Figure 4, the driving pressure of this reservoir is less than the accumulation force, and part of the oil and gas is utilized.
4.2. Parameter determination
When the driving pressure is less than the accumulation force, the oil saturation of flowing pores $S_{oil}$ is 100%. It can be seen from equation (1) that only three parameters, such as connected porosity ($\varphi_c$), oil saturation of connected pores ($S_{oil}$), and flowing porosity ($\varphi_f$), are required to calculate the utilization efficiency of oil and gas.

Connected porosity and oil saturation of connected pores are conventional parameters for calculation of reserves, which can be measured directly in the laboratory or indirectly based on well log interpretation. The flowing porosity is related to the driving pressure. The larger the driving pressure, the higher the flowing porosity. Therefore, the porosity corresponding to the driving pressure point on the mercury intrusion curve is the flowing porosity. The calculation equation is:

$$\varphi_f = \varphi_c \cdot S_{oil} (\Delta \rho)$$  \hspace{1cm} (2)

Where $S_{oil} (\Delta \rho)$ represents mercury saturation corresponding to the driving pressure point on the mercury intrusion curve.

Taking Figure 4 as an example, if the connected porosity of the reservoir is known to be 20% and the mercury saturation corresponding to the driving pressure point is 38%, then the reservoir flowing porosity is 20%×38%=7.6%.

4.3. Calculation of utilization efficiency of oil and gas
Based on the analysis of driving pressure and accumulation force, and the calculation of parameters, the utilization efficiency of oil and gas is calculated according to equation (1). Taking the reservoir in Figure 4 as an example, the flowing porosity of the reservoir is 7.6%, the oil saturation of the flowing pores is 100%, the connected porosity is 20%, and the original oil saturation of the connected pores is 78%, then the utilization efficiency of oil and gas is 48.7%.

5. The production significance of the efficiency of oil and gas
The following is an example of the X well area of Xifeng Oilfield, Ordos Basin, China, to illustrate the production significance of the utilization efficiency of oil and gas.

5.1. Basic situation
The X well area of Xifeng Oilfield is located in Qingyang City, Gansu Province, southwest of the Yishan Slope, with an area of 90km$^2$ and geological reserves of 2000×10$^4$t. The pay zone is the Chang 8t oil group of the Upper Triassic Yanchang Formation in the Triassic system, which is dominated by the frontal subfacies deposition in the delta sedimentary system. The formation thickness is about 40m and the oil layer thickness is about 14m. The oil layer is strictly controlled by sedimentary facies and reservoir physical properties. Both sides of the reservoir are blocked by the mudstone or silty mudstone between the diversion bays, and the whole is a lithological reservoir. At present, there are
316 wells of various types in the area. The diamond-shaped reverse nine-point injection-production well pattern is used for mining. The water-flooding control degree is 84%, and the recovery degree of geological reserves is 4.3%. Since it was put into development in 2006, the block has exposed outstanding problems such as low recovery degree, uneven distribution of plane pressure, severe water production in the formation, and rapid increase in water cut. Among them, wells that produce formation water as soon as they are put into production account for more than 60%, and the average initial water cut is 11%. Due to high-intensity water injection (average injection-production ratio 2.5), the formation pressure remains at a high level (91.5%).

According to the statistics of well logging interpretation data in X well area (Figure 5-7), the reservoir of Chang 81 oil group has low porosity and low permeability. Among them, the connected porosity is distributed between 6% and 16%, with an average porosity of 11.2%. The permeability of Chang 81 oil group is between 0.01 and 4.8×10^{-3} μm², the average permeability is 0.84×10^{-3} μm². The original oil saturation of the connected pores of the Chang 81 oil group is distributed between 40% and 85%, with an average oil saturation of 57.1%.
5.2. Utilization efficiency of oil and gas

Based on the high-pressure mercury intrusion test of five rock samples (Figure 8), the mercury intrusion curve of Chang 81 oil group was obtained by using the J function method (Figure 9). Based on the mercury intrusion curve of Chang 81 oil group, the accumulation force is determined according to the original oil saturation of the reservoir (57.1%). Point A in Figure 9 is the accumulation force point, and the corresponding accumulation force is 11.6 MPa (laboratory conditions).

The statistics of the production performance data of 210 production wells (Figure 10) show that the original formation pressure in X well area is 17 MPa, the current formation pressure is 15.5 MPa, the average bottom hole flow pressure is 8.4 MPa, and the average production pressure difference is 7.1 MPa (formation conditions). It is known that the oil-water interfacial tension of Chang 81 reservoir is 25 mN/m, the oil-water wetting angle is 0°, the mercury surface tension is 480 mN/m, and the mercury wetting angle is 140°. According to the conversion of the Young-Laplace equation, the average production pressure difference is 104.4 MPa (laboratory conditions).

Since the production pressure difference (104.4 MPa) is greater than the accumulation force (11.6 MPa), the utilization efficiency of oil and gas is 1. This shows that, theoretically, all the oil and gas in the production affected zone of X well area is utilized. However, in fact, due to the uneven pressure distribution in the formation plane, the production pressure difference between the wells is quite different, and together with the formation water production, the utilization efficiency of oil and gas can not reach 1. It can only be said that in general, the utilization efficiency of oil and gas is higher.

Figure 9  Mercury pressure curve of Chang 81 oil group

Figure 10  Statistical histogram of formation pressure of Chang 81 oil group
5.3. Production meaning

The production practice in X well area shows that although the utilization efficiency of oil and gas in this block is high, the actual development effect is not satisfactory. The main performance is: the proportion of wells that produce formation water immediately after putting into production is higher (>60%), and the water cut increases faster with the development time. The overall oil recovery rate and recovery degree of the reservoir are low (4.3%). This shows that the utilization efficiency of oil and gas is not completely consistent with the effect of oilfield development.

The analysis believes that the main reason for the unsatisfactory oilfield development effect is the excessive difference between driving pressure and accumulation force. Since the driving pressure in X well area is much greater than the accumulation force (the driving pressure is 9 times that of the accumulation force), most of the wells immediately produce water immediately after they are put into production. The initial water production of the formation has a very adverse effect on the development of the oil field. For example, the permeability of the oil phase decreases rapidly and the permeability of the water phase rises significantly. The seepage resistance increases, which in turn leads to a reduction in production and oil recovery rate. The probability of formation water channeling increases, leading to premature water production by oil wells, which greatly increases the difficulty of mining and the cost of mining. This shows that the driving pressure in the initial stage of oilfield exploitation should not be too different from the accumulation force. When the driving pressure is too high, although the utilization efficiency of oil and gas is high, the formation water production is serious, which affects the development effect. Conversely, when the driving pressure is too small, the utilization efficiency of the oil and gas is low, which also affects the development effect. Therefore, optimizing the production pressure difference with the goal of accumulation force can be an effective way to improve the utilization efficiency of oil and gas, and to avoid or reduce formation water production, which is very necessary for oil field water control and oil stabilization and efficient development.

This understanding provides a new basis for the optimal adjustment of production pressure difference, which is of great significance to the water control and stabilization of oil fields and efficient development.

6. Main conclusion

The utilization efficiency of oil and gas is the ratio of the volume of oil and gas utilized to the volume of oil and gas accumulated in the production affected zone. It can quantitatively reflect the microscopic utilization of oil and gas in the production affected zone. The utilization efficiency of oil and gas is mainly influenced by driving pressure and accumulation force. When the driving pressure is less than the accumulation force, the oil and gas are utilized partially. When the driving pressure is equal to the accumulation force, the oil and gas are fully utilized and no formation water is produced. When the driving pressure is greater than the accumulation force, all the oil and gas are utilized and the formation water is produced.

An example of production in X well area of Xifeng Oilfield in the Ordos Basin shows that when the driving pressure is too small during oilfield exploitation, the utilization efficiency of oil and gas is low, which affects the development effect. When the driving pressure is too high, although the utilization efficiency of oil and gas is high, the formation water production is serious, which also affects the development effect. Only when the driving pressure matches the accumulation force, the utilization efficiency of oil and gas is high and no formation water is produced, and the development effect is the best. Therefore, optimizing the driving pressure (or production pressure difference) with the goal of accumulation force can not only improve the utilization efficiency of oil and gas, but also avoid or reduce formation water production, which is very necessary for oil field water control and oil stabilization and efficient development.

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