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Effect of drawdown pressure on water production in gas reservoir

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Abstract. The water production is widespread in the exploitation of gas reservoir. The drawdown pressure is the main force that drives the formation water. Based on the integration of relative permeability curve and mercury intrusion curve, the analysis of the effect of drawdown pressure on the water production is conducted. As shown by the research result, when the drawdown pressure is different, the water that starts to flow belongs to distinct category, and the water producing degree varies. Larger drawdown pressure results in higher water producing degree. If $P_2<P_0$, the produced water merely contains condensate water; if $P_0<P_2<P_1$, the produced water includes condensate water and free water; if $P_1<P_2$, the produced water contains condensate water, free water and movable water as components, where P_0 and P_1 represent drawdown pressures corresponding to the original water saturation and irreducible water saturation respectively, and P_2 represents the practical drawdown pressure. Directly affected by the exploitation condition, the formation water production can be controlled by constraining the drawdown pressure. The research result can provide the reference for the management of water-producing well in gas reservoir.

1. Introduction
Widespread in gas reservoir development, the water production has considerable effect on gas production and recovery, therefore becoming the worldwide focus of research [1]. The essence of the water production in gas reservoir is the gas–water percolation driven by drawdown pressure [2]. Thus, when the drawdown pressure, the driving force of water, varies, the water starting to flow belongs to different kind. Consequently, the water producing degree and the water production differ. In a word, drawdown pressure controls the amount of and the category of the produced water. Therefore, clearly understanding the effect of drawdown pressure on water production is of great importance in the determination of the water production feature and the gas-water percolation regularity in different drawdown pressure, the choice of reasonable development pattern and improvement of development effect. Now, the report concerning the effect is rarely seen. Therefore, the analysis of the effect is conducted both in theory and in its practical application in a gas reservoir, based on the integration of relative permeability curve and mercury intrusion curve.

2. Theory analysis
The relative permeability curve and mercury intrusion curve can be obtained from the relative permeability experiment and mercury intrusion experiment respectively. Being the responding curve of gas-water percolation, the two curves can be integrated for the research of fluid percolation in the reservoir exploitation (Figure 1). In the Figure 1, the relative permeability (Kg, Kw) and the water

saturation change when the capillary pressure alters. In the practical production, a certain amount of water is produced (the change in water saturation) when the drawdown pressure overcomes a certain capillary pressure. Whether the formation water can be produced is mainly dependent on whether the driving force (the drawdown pressure) can overcome the capillary pressure. Thus, according to the relationship between drawdown pressure and capillary pressure, the formation water in the rock pore can be divided into 3 categories in the view of percolation (Figure 1):

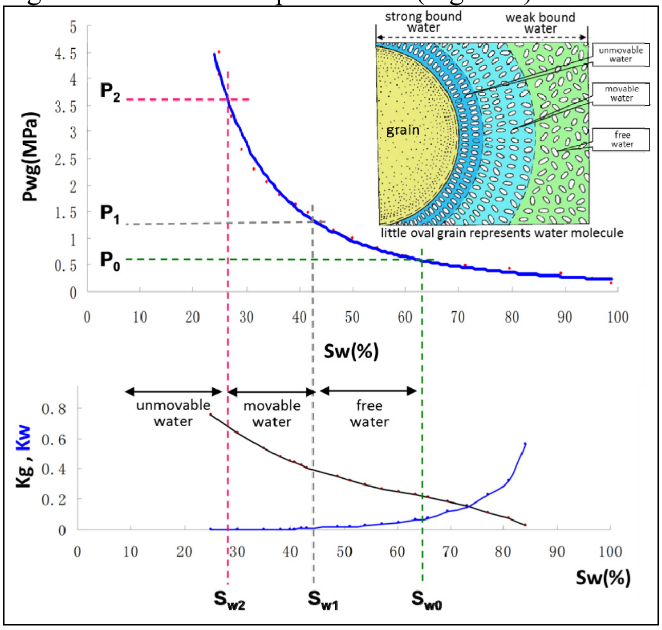

Figure 1. Illustration of unmovable water, movable water and free water

(1) Unmovable water: the water that cannot be moved because the drawdown pressure is not sufficient to overcome the capillary pressure corresponding to this kind of water. Having the appearance of film, unmovable water is strong bound water that is strictly attached to the surface of the rock grain. The corresponding water saturation is defined as unmovable water saturation, whose maximum value is S_{w2}. In Figure 1, the value of S_{w2} is determined by the practical drawdown pressure value P_2. Higher value of P_2 means lower value of S_{w2}.

(2) Movable water: the water that starts to flow when there is high drawdown pressure in the production. This kind of water is moderate bound water, being in the layer outside the unmovable water. The water saturation corresponding to it is defined as movable water saturation, whose maximum value is S_{w1}. S_{w1} is equivalent to the water saturation in relative permeability curve where formation water starts to flow, namely irreducible water saturation. S_{w1} corresponds to the drawdown pressure P_1.

(3) Free water: the water that starts to flow when the drawdown pressure is low. This kind of water is weak bound water, being in the layer outside the movable water. The saturation corresponding to it is defined as free water saturation, whose maximum value is S_{w0}. S_{w0} is equivalent to the original water saturation of the reservoir. S_{w0} corresponds to the drawdown pressure P_0.

When the drawdown pressure is low, the free water starts to flow firstly; as the drawdown pressure increases gradually, the movable water starts to be driven out apart from the free water, which means the obvious increase in the volume of flowing water. Free water, movable water and unmovable water are identical in essence and continuous in distribution without clear boundary between them, the main distinction between them being the different extent of adhesion. Thus, in practical development, whether the water can be produced and the amount of water production are mainly dependent upon the magnitude of the drawdown pressure P_2. If $P_2<P_0$, condensate water is the single component of produced water [3]; if $P_0<P_2<P_1$, both condensate water and free water are included in the produced water; if $P_1<P_2$, condensate water, free water and movable water are driven out.

Moreover, because there are large change in the water saturation and small change in the drawdown pressure in the range of free water, the free water is sensitive to the change in drawdown pressure, therefore being the major component of the produced water; as the water saturation experiences small change when the drawdown pressure changes largely, the movable water is less sensitive to the drawdown pressure than the free water, therefore being the minor part of the produced water.

For a certain water-producing gas reservoir, S_{w0} is determined by core analysis, and P_0 is obtained through the two curves; S_{w1} is from the relative permeability curve, and P_1 is obtained through the two curves; P_2 is the practical drawdown pressure from the performance data, and S_{w2} is obtained through the two curves. Based on the data of core analysis, development performance, relative permeability and mercury intrusion, the maximum value of the saturation of unmovable water, movable water and free water, and their corresponding drawdown pressure value can be determined. Further, the effect of drawdown pressure on the water production can be quantified.

3. Method application

The method is applied in Tai2 reservoir of Liuyangbao gas field [4].

Firstly, the S_{w0} is determined from the statistical analysis of the water saturation of 327 pieces of core in 11 wells of Tai2 gas reservoir (Figure 2); then the S_{w1} is determined from the average relative permeability curve whose data are from the statistically processed data of 8 gas-drive-water permeability experiments (Figure 3); finally, the average mercury intrusion curve is the normalized capillary pressure curve in the gas reservoir condition, which is calculated from the capillary curve in the experiment condition that is based on 7 group of mercury intrusion data (Figure 4) [5].

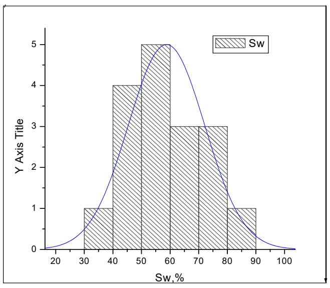

Figure 2. Histogram of original water saturation in cores

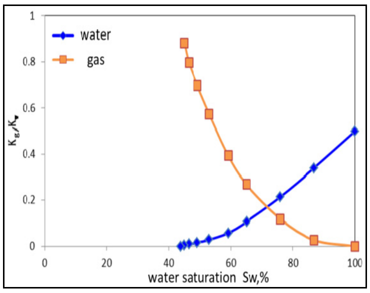

Figure 3. Average relative permeability curve of Tai2 gas reservoir

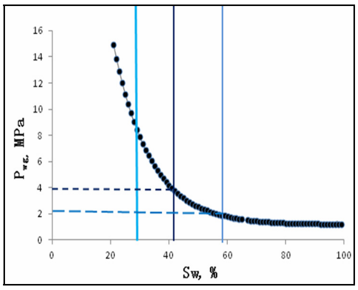

Figure 4. Average mercury intrusion curve in gas reservoir condition

As shown in Figure 2~Figure 4, S_{w0} is 58.74%, and corresponding P_0 is 2.3MPa; S_{w1} is 42%, and P_1 is 3.9MPa; P_2, the practical drawdown pressure that is calculated statistically, is 8.6MPa, and corresponding S_{w2} is 30%; in the range of free water, there are large change in water saturation S_{w0}-S_{w1}=16.74% and small change in drawdown pressure P_1-P_0=1.6Mpa, which indicates that the free water is sensitive to drawdown pressure and that it is the major component of the produced water; in the range of movable water, there are small change in water saturation S_{w1}-S_{w2}=12% and large change in drawdown pressure P_2-P_1=4.7Mpa, which shows that the movable water is not sensitive to drawdown pressure and that it is the minor part of the produced water; the ratio of free water to movable water(S_{w0}-S_{w1})/(S_{w1}-S_{w2})is 1.395.

Therefore, for the Tai2 reservoir, if the drawdown pressure is controlled <2.3Mpa, condensate water is produced as the single component; if the drawdown pressure is constrained between 2.3-3.9Mpa, there are condensate water and free water in the produced water; if the drawdown pressure is controlled >3.9Mpa, condensate water, free water and movable water are produced.

4. Discussion

In the previous research, the irreducible water saturation is viewed as the ratio of the volume of the water that cannot be driven out to the volume of the overall pore in the rock, namely the critical saturation when the water starts to flow in the driving experiment. The irreducible water is considered as a definite value, because the water in the saturation range lower than the irreducible water saturation is in the single phase flowing area, being unable to be driven out (Figure 1) [6]. However, in the author's opinion, the free water, movable water and unmovable water are identical in essence and continuous in distribution, without clear boundary, their differences being the variation in the extent of adhesion. When the drawdown pressure increases, the irreducible water saturation changes dynamically, as shown in the gradual enlargement of the water range that starts to flow, the convert of more formation water to free water and movable water and the gradual reduction of unmovable water; therefore, the irreducible water saturation obtained from the relative permeability experiment cannot completely represents the saturation value in the practical exploitation condition, and in contrast, the irreducible water saturation corresponding to the drawdown pressure is more likely to reflect the practical condition, being the genuine saturation value in the gas reservoir development.

If the S_{w2} is the genuine irreducible water saturation, the 0 value of relative permeability in the saturation range [S_{w2}, S_{w1}] of relative permeability curve cannot be interpreted. This may be related to the experiment condition (the property of the core, fluid and displacing agent which are used for driving, equipment ability, operation procedures and operation people). Because there are variations between relative permeability curve and practical driving curve owing to the deviation between experiment condition and actual formation condition, the correction of the relative permeability curve is needed.

5. Conclusion and Understanding

(1) The research of the effect of drawdown pressure on water production is conducted based on the integration of relative permeability curve and mercury intrusion curve. As shown by the result, when the drawdown pressure is different, the water that starts to flow is of distinct kind, and the water producing degree varies. The low drawdown pressure activates free water firstly; as the drawdown pressure increased, movable water starts to flow apart from free water. In the actual exploitation, whether water is produced and the amount of water production is closely related to drawdown pressure.

(2) Based on core analysis, performance data, relative permeability and mercury intrusion data, the maximum value of unmovable water, movable water, free water and their corresponding drawdown pressures are determined (S_{w2}, P_2; S_{w1}, P_1; S_{w0}, P_0). If $P_2<P_0$, the produced water merely contains condensate water; if $P_0<P_2<P_1$, the produced water includes condensate water and free water; if $P_1<P_2$, the produced water contains condensate water, free water and movable water as components. The free water is characterized by its weak adhesion, easily flowing property and sensitivity to drawdown pressure, being the major part of produced water.

(3) In Liuyangbao gas reservoir, S_{w2} is 30%, and P_2 is 8.6MPa; S_{w1} is 42%, and P_1 is 3.9MPa; S_{w0} is 58.74%, and P_0 is 2.3MPa. If the drawdown pressure is controlled <2.3Mpa, condensate water is produced as the single component; if the drawdown pressure is constrained between 2.3-3.9Mpa, there are condensate water and free water in the produced water; if the drawdown pressure is controlled >3.9Mpa, condensate water, free water and movable water are produced.

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