Effect of drawdown pressure on water production in gas reservoir

Dai Jinyou, Ren Qianying, Kong Meng, Li Zilong, Wang Jing, Mu Zhongqi
Petroleum Engineering College, China University of Petroleum-Beijing, 102249, 18 Fuxue Road, Changping, Beijing, China
E-mail: 840647593@qq.com

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):

(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.

Figure 1. Illustration of unmovable water, movable water and free water
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) \([5]\).

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 $S_w^2$ is the genuine irreducible water saturation, the 0 value of relative permeability in the saturation range $[S_w^2, S_w^1]$ 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 ($S_w^2$, $P_2$; $S_w^1$, $P_1$; $S_w^0$, $P_0$). 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, $S_w^2$ is 30%, and $P_2$ is 8.6MPa; $S_w^1$ is 42%, and $P_1$ is 3.9MPa; $S_w^0$ 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.

Acknowledgements
This study is supported by National Science and Technology Major Project “Geology and technology of enhancing recovery efficiency in complicated oil and gas field” (No. 2008ZX05009-004-03), Foundation of China University of Petroleum-Beijing “Gas-water distribution regularity and water production mechanism in Liuyangbao gas field” (No.2462015YQ0214) and National Natural Science Foundation of China “Controlling mechanism on brittleness of tight sandstone and evaluation of acoustic emission in tight sandstone” (No. 51404282).

Reference
[1] Zhu Yadong, Wang Yuncheng and Tong Xiaohua 2008 Recognition and genesis of water
formation in He-8 gas reservoir of Sulige gas field Natur Gas Ind 28 46

[2] Cui Yingchun, Li Tiantai, Li Tiancai Hong Hong and Hao Yuhong 2008 Water producing character and influencing factors of Shan2 gas reservoir in Yulin Gasfield Petroleum Geology and Recovery Efficiency 15 86

[3] Wu Danshi 2014 Formation water category and its distribution regularity in Honghe oil field Petroleum Geology and Engineering 28 49

[4] Chen Lin, Zhang Youcai, Tang Tao, Su Jing, Ji Chunhai and Wang Jiong 2013 Analysis and identification of producing water source in reef-bank gas reservoirs Fault-Block Oil & Gas Field 20 481

[5] Dong Jiaxin, Tong Min, Wang Bin and Liu Jinxia 2013 Comprehensive analysis of produced water source in Kelameili volcanic gas field, Junggar basin Xinjiang Petroleum Geology 34 202

[6] Li Jin, Wang Xinhai, Zhu Liyao and Liu Jinxia 2012 A study of comprehensive discriminant methods of the source of water-yielding in gas reservoirs Natural Gas Geoscience 23 1185

[7] Guo Chunhua, Zhou Wen, Kang Yili and Yang Yu 2007 Comprehensive estimation method on the origin of water produced in gas wells of Jingbian gas field Natur Gas Ind 27 97

[8] Tian Leng, He Shunli, Liu Shengjun and Lan Chaoli 2009 Features of gas and water distribution in the Xujiahe formation gas reservoir of Guang'an area Natur Gas Ind 29 23

[9] Chen Jun, Fan Huaicai, Du Chen, Xu Guangpeng and Yuan Fufeng 2008 Study on water producing character and development adjustment of Xu’er gas reservoir in Pingluoba Gas field Special Oil and Gas Reservoir 15 53

[10] Xiong Yu, Chen Yan and Deng Xuefeng et al 2009 Gas/water distribution in the condensate gas reservoir of Qianmiqiao main buried hill Special Oil and Gas Reservoir 16 48

[11] Qiu Zhongxian, Liu Yuetian and Tu Bin 2009 Theoretical study on low velocity non-Darcy gas flow in low-permeability water-bearing porous medium Special Oil and Gas Reservoir 16 79

[12] Song Hongqing, Zhu Weiyao, Zhang Yuguang, Cui Yinghuai and He Dongbo 2008 Theoretical study on development of low-permeability water-bearing gas reservoir with different horizontal heterogeneous conditions Special Oil and Gas Reservoir 15 45

[13] Zhu Lin, Bai Jian and Wang Zhijiang 2003 Formulated calculation method of water content in natural gas Natur Gas Ind 23 118

[14] Cao Tongsheng, Zhao Ronghua and Luo Xiangjian 2013 Application of single sand body description in the horizontal well deployment in Liuyangbao Tai2 gas reservoir Science and Technology of West China 12 30

[15] Cao Tongsheng, Gao Qingsong, Zhao Ronghua, Fan Yu and Wang Zhouhong 2013 Single sand body identification and horizontal well development countermeasures of Tai2 gas reservoir in Liuyangbao gas field Petroleum Geology and Engineering 27 56

[16] Li Jiudi, Yan Tao and Zhao Tianpei 2005 Uncertainty analysis of calculating original oil & gas saturation using capillary pressure data Ocean petroleum 25 11

[17] Zhou Dezhi 2006 Study of the relation between immobile water saturation and critical water saturation Petroleum Geology and Recovery Efficiency 13 81