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Evaluation Method for Mobile Water Saturation of Tight Sandstone Gas Reservoir

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Abstract
We propose an approach to test the mobile water saturation of tight sandstone gas reservoir using well logs, Nuclear Magnetic Resonance(NMR) and core experiment. Our approach follows a three-step procedure. Firstly, we have to get the initial water saturation in the pore of the tight sandstone gas reservoir, which is one of the basic condition for movable water. We get that usually from well logs or from the test of fresh rock which has not been polluted in new drilling well. Secondly, we apply NMR and core experimental techniques to identify and characterize the distribution of the initial water saturation in different pores, throats and fractures, which is also one of the basic condition to decide the water move or not. Thirdly, we use NMR and gas drive water experimental techniques to evaluate the mobile water saturation of tight sandstone gas reservoir in different permeability formation and under different producing pressure drop. Our proposed method has been successfully applied to the Sulige and BAKA Gas Field which are the typical and big tight gas reservoirs in China. From the study we realize that under the forces such as surface tension, capillary pressure and gas reservoir pressure, the pore water distributed in different rock pore by different occurrence types. It is bound water before gas development, but with formation pressure declining and the producing pressure drop increasing during gas developing, part of the bound water transformed to movable water. The result is very important for development plan of tight gas reservoir.

Key Word and Phrases
Tight Sandstone Gas Reservoir, Mobile Water Saturation, The Evaluation Method.

1. Introduction
Water and movable water saturation estimation is a critical aspect for a gas reservoir development, especially the tight sandstone gas reservoir [1]-[3]. Usually, most of the tight sandstone gas formation's permeability is very low [4], [5] and the water saturation in rock pore is relatively high. For example, the two case in the paper, Baka and Sulige are typical tight sandstone gas field, the middle value of permeability is 0.36md inSulige gas field and is 0.061md in Baka gas field (Fig.1), the middle value of water saturation is 38% in Sulige gas field and is 55% in Baka gas

field (Fig.2).

In addition, from the gas well production performance, we know that the water in pores may change to movable water and migrate, redistribution or producing out with gas from well during gas developing. For example: there are 22 wells (50 well total) in Sulige gas field producing water (Fig.3) and in Baka gas field almost all wells are producing water at the beginning of development. As we all know, the water is a serious bad factor for gas production, which may decline greatly and quickly when well produce water, so it is important and necessary for us to research the movable water in gas formation.

We have used many methods such as log interpretation, NMR and gas drive water experiments to research the occurrence and distribution characteristics and acting force between the water and the gas formation rock or pore-throat, also to evaluate the water's mobility and the conditions for moving.

We study that the water distributed in different pores by different occurrence types under the force such as surface tension, capillary pressure and gas reservoir pressure. Those water is bound water before gas development, but with formation pressure declining and the driving pressure increasing during gas reservoir development, part of the bound water may be transformed to movable water, which may be controlled by three factor: the content and distribution of initial water in the pore, the permeability of gas formation, the gas drive pressure. The frontal two factors are the natural characteristics for one gas reservoir, so the gas drive pressure can be controlled to delay bound water transforming to movable water, to avoid the formation polluted by movable water when it flow from this pore to other pore or redistribute in pore-throat. Those are very important for development plan of a tight sandstone gas reservoir.

2. Methodology

In this section, we briefly discuss the method to test the mobile water saturation of tight sandstone gas reservoir follows a three-step procedure. Firstly, analyze the initial water saturation of gas formation. Secondly, identify and characterize the distribution of the initial water saturation in different pores, throats and fractures. Thirdly, evaluate the mobile water saturation of tight sandstone gas reservoir during developing.

The initial water saturation of gas formation analysis.

Is there movable water or not in gas formation? The initial water saturation is a basic condition, so, first, we must to analyze it. It is very difficult to make it clear, usually there are two methods, the first is the well logs (Fig.4) and the other is the test of fresh rock which has not been polluted in new drilling well (Fig.5).

Two core samples has been selected to be researched in the paper, all of them are natural core, the permeability are 0.04md, 0.221 md, the initial water saturation is 64.0%,48.5%, which has been tested by the method above.

The occurrence and distribution characteristics of water in rock pore analysis.

The occurrence of water in rock pore is controlled by the size and shape of rock pore and throat, and the rock property. in the section, we study the pore-throat structure, build an idealized model which is used to analyze the occurrence and distribution characteristics of water in pore and the force between water and rock surface. This is the base to study the mobility of water in pore.

The pore-throat structure analysis.

We apply techniques such as mercury penetration (Fig.6) and cast thin section analysis (Fig.7) to study the pore-throat structure. the result shows that the structure of sandstone in Sulige and Baka gas field is very complex and the size of pore and throat is very small. For example, more than 50% throat radius of core sample (0.04md) are smaller than 0.086 μm (Fig.8).

The occurrence characteristics of water in rock pore analysis.

We apply NMR (Fig.9) technique to analysis the occurrence characteristics of water in rock pore. The water distributes in almost all types of pore and throat after long accumulation, especially in the thin pore and throat. We build an idealized pore model which is used to analyze the occurrence and distribution characteristics of water in pore and the force between water and rock surface (Fig.10), the occurrence characteristics of water in rock pore can be classified to four types:

(1) in big pore and nature fracture, it is thin water film under surface tension, part of which can move easily during gas developing. (2) in small pore and major throat, it is thick water film under surface tension and capillary pressure, which is the main resource for producing water in the early development.(3) in small throat, it is water column under big capillary pressure, which is difficult to move and need big driving force.(4) in the dead end pore, it is water globule under the gas reservoir pressure, which is non-movable water.

Mobility evaluation of water in tight sandstone gas formation.

The water and gas in the rock pore keep balance before gas development. It is bound water. During the gas reservoir development, with the reservoir pressure decline, under the force of water and gas expandability or gas drive pressure, part of the bound water can change to movable water, which can flow together with gas in the flow matrix.

We apply NMR and gas drive water experiment techniques to test the smallest pressure that is the driving force for the bound water beginning to move and to study the changing rule of bound water with the gas driving pressure increasing, analyze the reciprocal transformation between bound water and movable water during gas reservoir developing.

The movable condition and changing rule of water in rock pore.

Our experiment follows a two-step procedure, first, we re-establish water saturation in the core similar to the initial water saturation. Secondly, we study the movable condition and changing rule of water in rock pore by using gas to drive it from low pressure to high pressure. The result shows that the bound water in the rock pore can move only when the gas drive pressure big enough, and with gas pressure increasing, the movable water increase early and then decline (Fig.11).

The reciprocal transformation between bound water and movable water.

We apply NMR technique to test the water distribution in different pore at the end of experiment under different gas drive pressure, that can help us to study the changing rule and redistribution of water in the communicating interstices after gas driving. The result shows that on the one hand, part of the bound water in the communicating interstices can change to movable water only when gas driving pressure big enough to some value, and the bound water distributed in small pore and throat is major to be changed (Fig.12-①). On the other hand, the movable water may redistribute in different pores especially in big pore and fracture and change to bound water again when it flows on the flow matrix (Fig.12-②).

3. Case Study

We use the method introduced in the paper to research the movable water of Sulige and BAKA Gas Field (Fig.13).

For Sulige gas field, the permeability of main gas formation is about 0.1-1.0 md, so we select the core whose permeability is 0.221md for the research, the result shows that the water in the core begin to move when the gas drive pressure is big enough to 4MPa, and the cumulative movable water will increase as gas drive pressure increase, but when the gas drive pressure increase to 6MPa, the rate of growth of movable water will slow down. The total mobile water saturation of this formation is about 13% during developing.

For Baka gas field, the permeability of main gas formation is lower than 0.1md, so we select the core whose permeability is 0.04md for the research, the result shows that the water in the core begin to move when the gas drive pressure is big enough to 5MPa, and the cumulative movable water will increase as gas drive pressure increase, but when the gas drive pressure increase to 7MPa, the rate of growth of movable water will slow down. The total mobile water saturation of this formation is about 10% during developing.

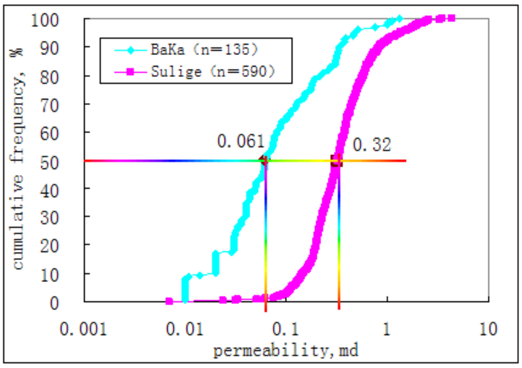

Fig.1 The cumulative frequency of permeability in Sulige and Baka gas field.

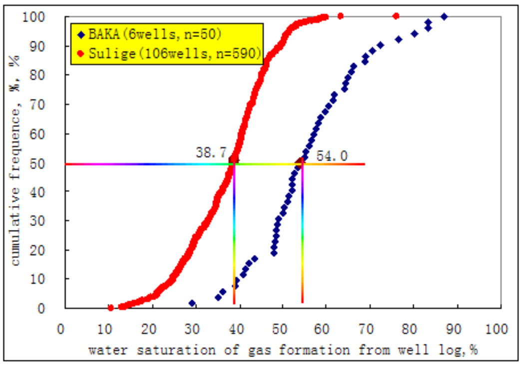

Fig.2 The cumulative frequency of water saturation in Sulige and Baka gas field.

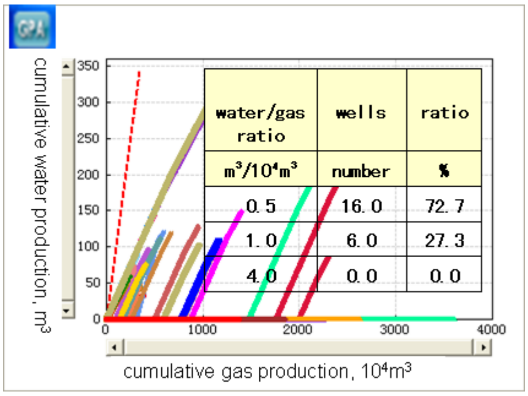

Fig.3 The relationship between cumulative gas production and cumulative water production in Sulige gas field.

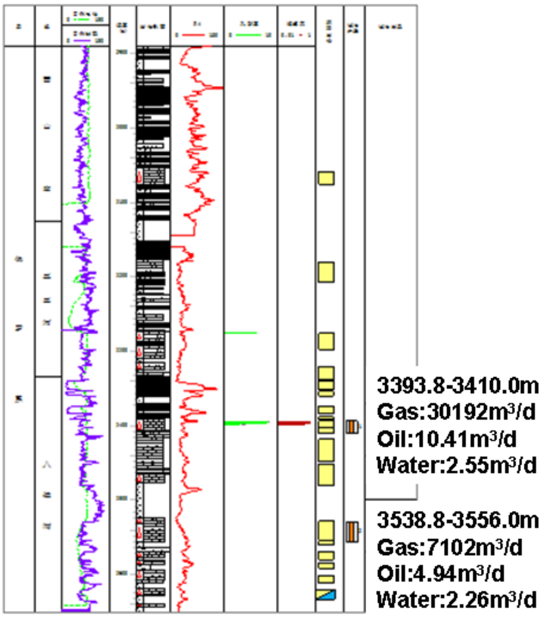

Fig.4 The well log curve.

Fig.5 The fresh rock which has not been polluted in new drilling well.

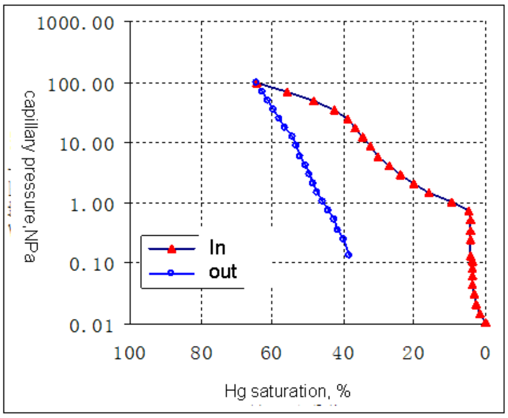

Fig.6 Mercury penetration (0.04md).

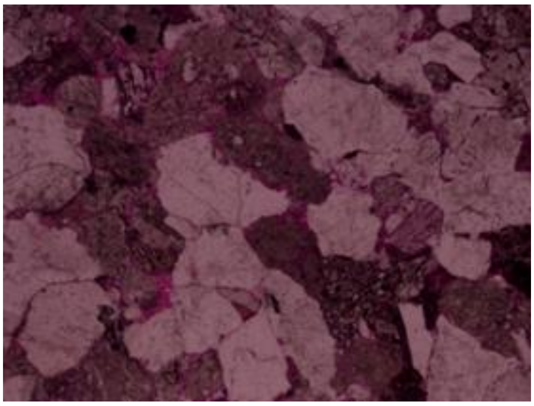

Fig.7 Cast thin section analysis (0.04md).

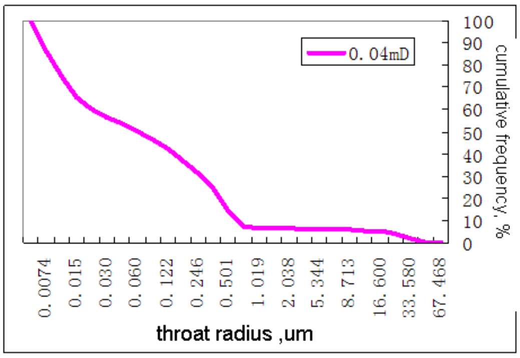

Fig.8 Throat radius of core sample(0.04md).

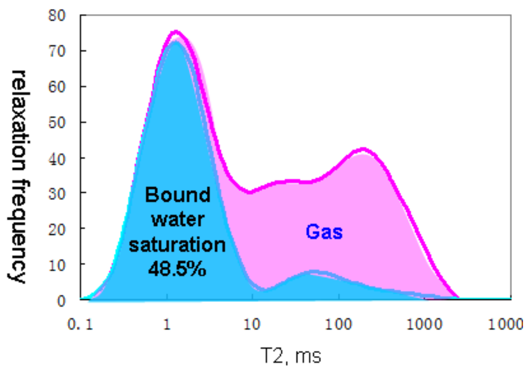

Fig.9 The occurrence and distribution characteristics of initial water in rock pore analysis by NMR.

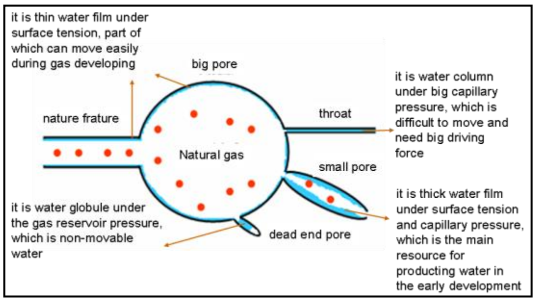

Fig.10 The idealized pore model which is used to analyze the occurrence and distribution characteristics of water in pore and the force between water and rock surface.

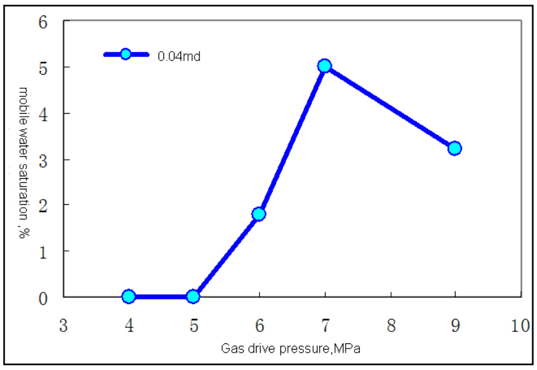

Fig.11 The movable condition and changing rule of water in rock pore.

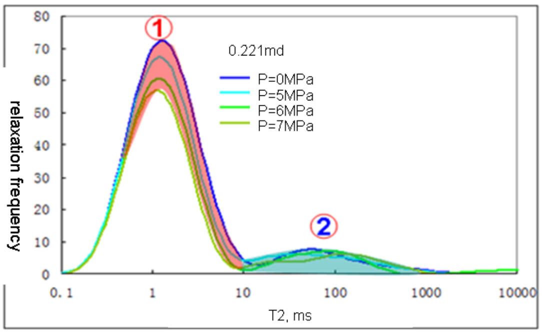

Fig.12 The reciprocal transformation between bound water and movable water.

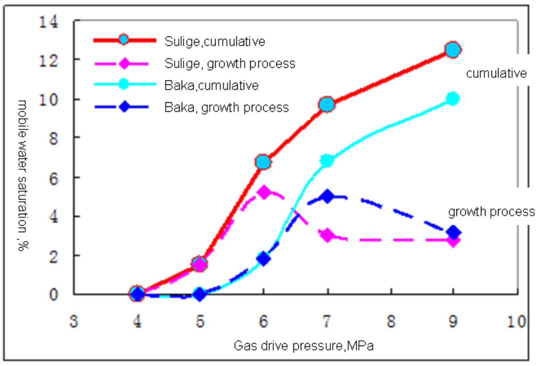

Fig.13 The case study on Sulige and Baka gas field.

4. Conclusions

The principal purpose of this paper is to introduce a method to quantitatively evaluate the mobile water saturation in tight sandstone gas reservoir. According to the research we have done, the following conclusions can be drawn based on the results presented here.

1. For most of the gas reservoir, there are some water in the pore of gas formation even though long accumulation, they are bound water before develop and controlled by different force, but they may changed to movable water during the gas reservoir developing as the gas drive pressure increasing.

2. The content and distribution of initial water in the pore, the permeability of gas formation and the gas drive pressure are the three factors which controlled the bound water to move or not. For

one gas reservoir, the frontal two factors are the natural characteristics of formation, so, the gas drive pressure can be controlled to delay bound water transforming to movable water, to avoid the formation polluted by movable water when it flow from this pore to that pore or redistribute in pore-throat. those are very important for development plan of a tight sandstone gas reservoir.

3. The reciprocal transformation between bound water and movable water is very complicated.

(1) conditional move：the bound water in the interconnected pores can move only when the gas drive pressure increase to big enough.

(2) reciprocal transformation：the movable water may change back to bound water on the flow matrix, which may decrease the gas production.

(3) first increased and then decreased：the gas well may production some water when the gas drive pressure is big enough, it is first increased and then decreased.

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