AN EXPERIMENTAL STUDY OF IRREDUCIBLE WATER SATURATION ESTABILISHMENT

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ABSTRACT

Irreducible water saturation is one of the most important parameters to evaluate the reservoir reserves. To establish the irreducible water saturation in laboratory is a vital step to restore the core to its underground condition, which highly affects the results of relative permeability measurement and other displacement experiments. Three methods are usually taken in laboratory to establish the irreducible water saturation, porous plate method, oil displacement method and centrifugation method. However, a large amount of experimental data shows significant discrepancy among these methods, which arises the question that which method best represents the underground condition of the core. To answer this question, systematical comparison between the observations from the above methods and the original reservoir formation data shall be performed, whereas so far few studies on this topic has been reported. In this work, we carried out an experimental study of irreducible water saturation establishment by the methods mentioned above over hundreds of core sample from the same reservoir formation with air permeability range from 1.11mD to 1725mD. The result shows that, in general, for water-wet cores, the irreducible water saturation decreases with the increasing of the air permeability. The irreducible water saturation obtained by oil displacement method is close to the in-situ initial water saturation. So oil displacement technique is faster and easier way to set irreducible water saturation, it is convenient because the sample is mounted in the coreholder used later for the flooding process, be aware that capillary end-effect produces a non-uniform saturation profile. The irreducible water saturation from air-brine porous plate technique is over estimated for low permeability samples because limitation of the porous plate entry pressure. In centrifuge test, absence of high centrifuge speed or enough equivalent capillary pressure may result in higher saturation than the in-situ initial water saturation. Therefore, the irreducible water saturation data could become misleading.

INTRODUCTION

A lot of core analyses data show that, even in the “pure oil and gas reservoir”, there is some stagnant water which is usually called "irreducible water" or "initial water". It often exists on the surface of sand, contacts between the sands and inside of the micro-capillary. The irreducible water is mainly composed of capillary irreducible water and film irreducible water. The capillary irreducible water is the residual water in the micro capillary and on the contact surface of the particles that cannot be displaced during the process of reservoir formation. The film irreducible water is the bonded water on water wetting rock surface by the molecules interactions [1]. Irreducible water saturation is one of the most important parameters to evaluate the hydrocarbon reserves of reservoirs. It is the reflection of overall characteristics of the interaction between fluid and rock, and it mainly depends on the rock capillary force and the wettability of rock. Establishing irreducible water is a vital first step of core preparation in special core analysis experiments. There are three methods to establish the irreducible water in laboratory, air-brine porous plate method, oil displacement method and centrifugation method. However, a large amount of experimental data show significant discrepancy among these methods, the objective of this paper is to compare these three different methods and find out which method is best way to represent the underground condition of the reservoir.

EXPERIMENTAL

Core Sample and Fluid

In order to make the experiment representative, 97 sandstone core samples from the Shengli oil field with different permeability ranges were chosen (table 1). Samples were cleaned by benzene/alcohol (75/25) mixture, dried in oven at 105 degree C until weight is constant. Analysis of data from 37 samples shows that average clay content is 8.11%, clay with 67.5% kaolinite. Water sensitivity from 9 samples was weak to moderate. The porosity and air permeability of samples were measured after oil and salt extraction. The brine with salinity of 20,000 mg/L was used in the experiment. The brine composition was: NaCl: $CaCl_2$:$MgCl_2 \cdot 6H_2O$＝7：0.6：0.4 mg/L. The degassed refined oil with viscosity of 23.2 cP at 20 deg C was used for displacement.

Table 1．The quantity and permeability range of core samples

Permeability，mD	1.11~1725		
	＜100	100~500	＞500
Quantity	31	34	32

In-situ Initial Water Saturation

The in-situ initial water saturation is obtained from Karl Fischer titration core analysis of the 293 core samples taken with full-closure coring technique using Water Based Mud from two wells of Shengli oil field (Figure 1). Two piece fresh adjacent core materials were taken, one piece was used to obtain a plug for k & phi determination, the other piece was used to obtained water saturation by extraction of alcohol. Water content in alcohol was determined by Karl Fischer titration. Average relative wettability index from 13 samples by Amott wettability evaluation is 0.328, which demonstrate wettability of core samples is water-wet.

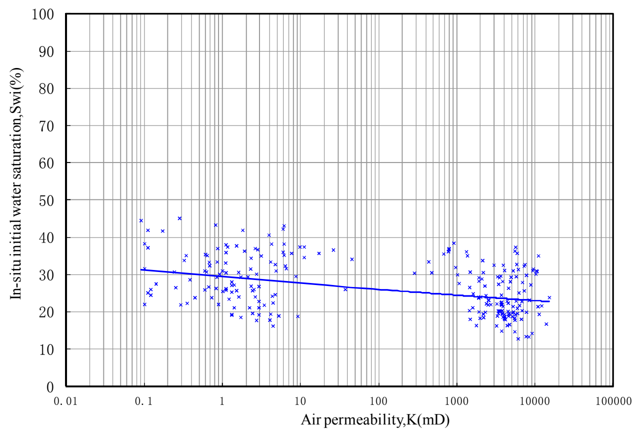

Figure 1. In-situ initial water saturation vs. permeability

Experimental Equipment

The equipment used for air-brine porous plate method consists of a pressure control system, a balance and a pressure vessel with a porous plate. The entry pressure of the porous plate is 200psi.

The equipment used in oil-brine dynamic displacement method is an oil-water relative permeability instrument (Core Laboratories). The flow rate range is from 0.001ml/min to 15.0ml/min and the maximum pore pressure is 9000psi.

The equipment for centrifugation method experiment is a BeckmanL8-60M/P high speed centrifuge that the maximum speed is 16,000rpm.

Experimental Procedures

Firstly, the air-brine porous plate method was used to establish the irreducible water saturation on batch samples, a micro-pipette is attached to the drain line from pressure vessel and monitored; equilibration was observed when movement of the meniscus stops. The maximum capillary pressure was 175psi; after salt leaching, the irreducible water was established with the oil-brine displacement method that the flooding rate was 0.1~3.0 ml/min; finally, the core sample was cleaned again and then established the irreducible water in absence of confining stress using centrifuge. The irreducible water saturation was calculated by average saturation method. The maximum speed was 12,000rpm, which is equal 60psi capillary pressure.

RESULTS AND DISCUSSION

The relationship between irreducible water saturation and permeability

Irreducible water saturation depends on the porosity and permeability of rocks, data on Figure 2 from three method shows that the irreducible water saturation decreases with the increasing of the air permeability.

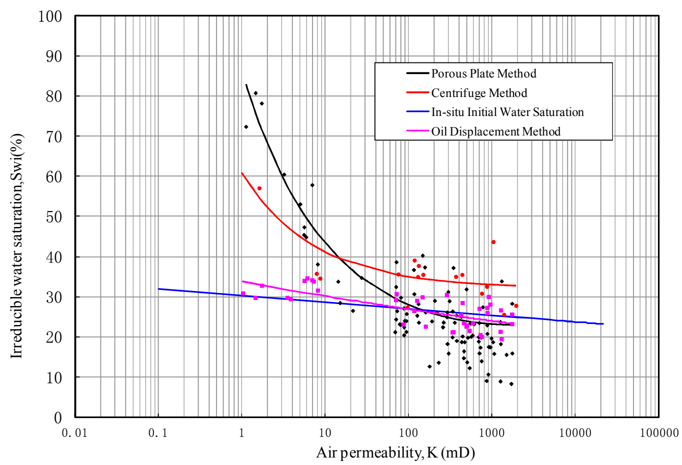

Figure 2. The comparison of the irreducible water saturation obtained by the three methods and in-situ initial water saturation vs. air permeability

The comparison of the three methods

Among the three methods, the porous plate technique produces a uniform saturation profile, multiple samples can be done in one run, but it is time consuming and limited by the porous plate entry pressure. Displacement technique is faster and easier to implement, it is convenient because the sample is mounted in the coreholder used later for the flooding process, but some time produces a non-uniform saturation profile. Centrifuge desaturation is very fast but is usually avoided because of a non-uniform profile.

All of these three irreducible water saturation data and in-situ initial water saturation data are shown in Figure 2. When the air permeability Ka>100 mD, the irreducible water saturation obtained by porous plate method and oil displacement method are both close to the in-situ initial irreducible water saturation. When Ka<100 mD, only the data from the oil displacement method is consistent with the in-situ initial water saturation data. The saturation of air-brine porous plate method is much higher than that of both displacement method and the in-situ initial water saturation, the deviation between the data from in-situ initial water saturation and air-brine porous plate method measurement increases as air permeability decreases. The irreducible water saturation obtained by the centrifugation method is over estimated for whole range of permeability with the discrepancy being much higher in the low permeability range than in the high permeability range. Table 2 shows the equivalent capillary pressure and interfacial tension data for each type of test, there is only 60psi maximum capillary pressure in the centrifuge test. Lack of adequate capillary pressure may have resulted in higher saturation than the in-situ initial water saturation, particularly for the low permeability sample.

Because air-water interfacial tension is larger than oil-water interfacial tension (table 2), the capillary pressure ratio in air-brine system and oil-brine system calculated with the formula $Pc=(2\sigma\cos\theta)/r$ is 1.7. Therefore higher pressure is needed to apply to air-brine system for low permeability core samples, but air-brine porous plate entry pressure is only 200psi.That is the reason why the deviation between the data from air-brine porous plate method and in-situ initial water saturation increases as air permeability decreases.

Table 2. Equivalent capillary pressure and interfacial tension data for each type of test

Test method	Fluid system	Contact angle, θ	Interfacial tension σ	Max. Pc(psi)	Equivalent oil-brine Pc(psi)
Air-water porous plate	Air-Brine	0	72	175	103
Oil-water porous plate	Oil-Brine	30	48	175	175
Centrifuge	Oil-Brine	30	48	60	60

Oil-brine porous plate method is recognized as the classical and effective technique to establish the irreducible water, and it is considered as a standard comparison test. In order to find out the reason that the irreducible water saturation in the low permeability core samples obtained through the air-brine porous plate method is over estimated, 5 samples were chosen to establish the irreducible water with oil-brine porous plate method. The results were shown in Table 3.

Table 3. The irreducible water saturation obtained from air-brine and oil-brine porous plate methods

Sample No.		G26A	J4B	112	1A	159
Air Permeability，mD		6.89	69.9	145.5	532	943
Irreducible water saturation，%	air-brine porous plate method	57.9	32.5	40.3	12.3	17.5
	oil-brine porous plate method	31.1	30.4	40.8	15.2	19.7
error，%		26.8	2.1	-0.5	-2.9	-2.2

We can see from table 2&3, comparing with oil-brine system, irreducible water saturation from air-brine plate system shows great deviation for low permeability samples because there is not enough capillary pressure. The maximum deviation is 26.8%. Application of porous plate with higher entry capillary pressure may help resolve this limitation.

CONCLUSION

(1) Irreducible water saturation is associated with permeability and to some degree with $(k/phi)^{0.5}$. It decreases with increasing of permeability or $(k/phi)^{0.5}$.

(2) The irreducible water saturation obtained by oil displacement method is close to the in-situ initial water saturation. So oil displacement technique is faster and easier way to set irreducible water saturation, it is convenient because the sample is mounted in the coreholder used later for the flooding process. However, capillary end-effect may produce a non-uniform saturation profile, thus, it could introduce significant uncertainty in determination of irreducible water saturation .

(3) The irreducible water saturation from air-brine porous plate technique is high for the low permeability samples because porous plate entry pressure limitation.

(4) In centrifuge test, higher saturation than in-situ initial water saturation was measured because of the absence of high centrifuge speed and associated higher equivalent capillary pressure. Therefore, the "irreducible water saturation" data could be misleading. Note that for calculation of capillary pressure – saturation curve, modeling such as Hassler Bruner or numerical simulation should be used to convert average saturation to end-face saturation data.

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