Much attention is now paid to the development of low permeable reservoirs. However, there is almost a dearth of literature on the study of relative permeabilities in rock samples with low permeability. Group J2S of QL Reservoir is characteristics of low porosity, low permeability and low crude oil viscosity.

Oil-water relative permeabilities of QL Reservoir have been measured at two different oil/water viscosity ratios by using unsteady-state method. The experimental results showed that the oil-water relative permeabilities change with the changing of oil/water viscosity ratio. It is explained that the oil-water relative permeabilities measured at oil/water viscosity ratio close to the oil/water viscosity ratio under reservoir condition coincide with the practical situation of QL Reservoir by comparing the injection-production ratio calculated from laboratory water flooding data with the practical one.

The irreducible water saturations in QL Reservoir rocks range from 27.7% to 35.8% and its average value is 31.5%. The water flooding residual oil saturations range from 11.6% to 21.7% and its average value is 14.8%. Most of the water relative permeabilities at residual oil saturations range from 0.23 to 0.50 and its average value is about 0.388. Oil-water 2-phase flowing limit ranges from 47.8% to 59.0% and its average value is about 53.7%. Moreover, the end water relative permeabilities are correlated with the air permeabilities of rock samples. That is, the bigger the air permeabilities of the rock samples, the higher the end water relative permeabilities.

INTRODUCTION

The development of a reservoir by water injection usually includes an oil-water 2-phase or an oil-gas-water 3-phase flowing in porous media(reservoir rock). The efficiency of development by water injection is closely related to the multi-phase flow in porous media which is dependent on rock permeability, pore structure, wettability, capillary pressure, interfacial tension, viscosity of fluid and relative permeability of each phase.

The basic idea of relative permeability is simple. However, the factors to affect relative permeability are very complex. Many literatures about relative permeability published now explain that it is very difficult to obtain really representative and true relative permeability data.

Data from Jennings[11], Donaldson et al[2] and other researchers[14] proved that the effect of reservoir rock
wettability on oil-water relative permeabilities was very large. Hence, it is necessary to restore the wettability of reservoir rock into the original state when the wettability is altered or there are no fresh-state core samples. After core samples are selected, the rock wettability may be the most important factor to affect behaviour of oil-water relative permeability. Just because of this reason, reservoir engineers often evaluate the preferred wettability of reservoir rocks according to the behaviour of oil-water relative permeability curve.

There are two types of viewpoints about the effects of oil/water viscosity ratio on oil-water relative permeabilities. Some researchers, for example, Leverett, Richardson, considered that there were little effects of oil/water viscosity ratio on oil-water relative permeability. But others considered that oil-water relative permeabilities were obviously affected by the ratio of oil/water viscosity and increased with the increase of the ratio. What said above is experimental result. One of the problems is that it is very difficult to ensure other factors constant when the effect of oil/water viscosity ratio on oil-water relative permeabilities is studied. The theoretical investigation by Kevin Li showed that the effect of oil/water viscosity ratio on relative permeabilities of non-wet phase is large.

There are also different opinions concerning the effect of temperature on relative permeability. The published data are contradictory. For example, Data from Edmonson indicate a strong temperature effect. However, results of Miller et al suggest no temperature effects. Again, data obtained by steady-state and unsteady-state methods are contradictory, with some studies showing significant difference(for example, Amaefule, Maini and Kevin Li) between two methods while other studies show agreement (for example, Johnson et al) between two methods.

QL Reservoir which was discovered recently is a large scale reservoir with very good quality of crude oil. Group J_2,S is the main oil group. Its average permeability is less than 50 md. This is a low permeable reservoir with the average clay content of 10.7%. In order to assist in numerical simulation and reservoir performance prediction, some core samples are selected from QL Reservoir and oil-water relative permeabilities of these core samples are measured by using ageing technique to restore rock wettability because there are no fresh-state core samples. The major methods for measuring oil-water relative permeabilities in laboratory are unsteady-state, steady-state, combination of unsteady-state and steady-state, centrifuge methods. Unsteady-state method has been used in this paper to measure oil-water relative permeabilities at ambient condition.

Two methods for the calculation of oil-water relative permeabilities from data obtained by unsteady-state method can be used. One is JBN method or its improved method. The other is automatic history matching method. The method for calculating oil-water relative permeabilities is the same as that in literature.

**EXPERIMENTAL EQUIPMENT AND PROCEDURES**

The diagram of the experimental equipment for measuring oil and water relative permeabilities by using unsteady-state method is shown in Fig. 1. The oil and water outputs at the outend of a core sample are measured by an oil-water separator during test with 0.025 ml errors of volume measurement. Differential pressure transducers are used to measure the differential pressure between two ends of a core sample with 0.4% F.S. error.

Porosities and permeabilities of core samples are measured after drilling, cutting, cleaning and dried at first. Then the core samples are saturated with the formation brine at high pressure of 12 Mpa after normal vacuum saturating. The core samples have been aged for one month in crude oil at reservoir temperature and pressure after the irreducible water saturations are set up by using oil displacement in order to restore the wettability of the crude oil-rock-brine system. Results of Cuiec showed that wettability equilibrium can sometimes be established at a shorter period. But Hiemeland et al demonstrated
that it need longer period of time to establish wettability equilibrium. It is determined to age one month for the restoration of wettability to be sufficient.

In order to study the effect of oil/water viscosity ratio on oil and water relative permeabilities, 17 core samples are selected from QL Reservoir and their oil-water relative permeabilities are measured with oil/water viscosity ratio 1.8 and 17.0 respectively.

Water flooding velocities during the oil-water relative permeability tests with two different oil/water viscosity ratio are the same and its LpV is larger than 1.0.

**SAMPLE SELECTION**

Porosities and permeabilities of QL Reservoir rocks are very low and range widely. For example, permeabilities of the east block range mainly from 2.15 to 50.0 md and the average permeability is about 20.6 md while permeabilities of the west block range from 6.4 to 411.8 md and the average permeability is about 257.7 md. The heterogeneity of QL Reservoir is characteristic of small difference between formations and large difference in formations. Therefore, the reservoir behaviour said above is considered when selecting core samples. 17 core samples are selected from the same group (JZS) of different wells in QL Reservoir and their porosities, permeabilities are listed in Table 1. Porosities of these core samples range from 10.3% to 20.7% and the average porosity is 14.1%. Permeabilities of these core samples range from 2.10 md to 216.0 md and the average permeability is 43.0 md. It can be seen from what said above that the porosities and permeabilities of these core samples can represent the practical situation of this reservoir to some extent.

Among the 17 core samples, 12 core samples are selected as parallel experimental samples which are divided into six groups. There are two core samples in each group. In Table 1, the core samples with symbol "LV" will be tested at the low oil/water viscosity ratio(1.8) and those with symbol "HV" will be tested at the high oil/water viscosity ratio(17.0).

Comparisons of porosities and permeabilities of core samples which are divided into six groups in Table 1 tested at low and high oil/water viscosity ratio respectively are shown in Fig.2 and Fig.3. It can be seen in Fig.2 and Fig.3 that most of the data points are located in the diagonal line, which shows that the porosities and permeabilities of parallel samples are almost the same.

The oil and water relative permeabilities of other five core samples in Table 1 are measured at low oil/water viscosity ratio(1.8).

**EXPERIMENTAL RESULTS**

The irreducible water saturations, residual oil saturations and the water end relative permeabilities(or water relative permeabilities at residual oil saturations) are listed in Table 2. Base permeability in the idea of relative permeability is defined as the effective permeability of oil phase at irreducible water saturation in this paper.

It can be seen in Table 2 that the irreducible water saturations in rocks of the group J2S in QL Reservoir range from 27.7% to 35.9% and the average irreducible water saturation is 32.7%. Three typical kinds of oil-water capillary pressure curves in QL Reservoir are shown in Fig.4. The irreducible water saturations in the three typical kinds of rocks are 25.2%, 35.0% and 43.2% respectively and their average value is about 34.5%, which shows that the irreducible water saturations in Table 2 are consistent with the property of irreducible water saturation in oil-water capillary pressure system.

Fig. 5 shows that the comparison of irreducible water saturations of six groups of parallel core samples. Most of the data points are located in or near the diagonal line, which shows that the irreducible water saturations of core samples tested at low oil/water viscosity ratio are the same as those tested at high oil/water viscosity ratio.

Comparison of the water flooding residual oil
THE OIL-WATER RELATIVE PERMEABILITY BEHAVIOUR OF A LOW PERMEABLE RESERVOIR

saturations at different oil/water viscosity ratio is shown in Fig.6. It can be seen in Fig.6 that the effect of oil/water viscosity ratio on water flooding residual oil saturations is not significant. Water flooding efficiency in laboratory can be calculated as follows:

\[ \eta_r = \frac{1 - S_{wc} - S_{or}}{1 - S_{wc}} \]  

Because Fig.5 suggests that the irreducible water saturations of six groups of core samples are almost the same and again Fig.6 shows that the residual oil saturations at two different oil/water viscosity ratios are almost the same, it is known from equation one that the effect of oil/water viscosity ratio on the water flooding efficiency is also not significant.

Fig. 7 shows the comparison of typical oil-water relative permeability curves measured from two different oil/water viscosity ratios. It is found that the effect of oil/water viscosity ratio on the oil and water relative permeabilities in low permeable core samples is significant. The higher the oil/water viscosity ratio, the lower the oil and water relative permeabilities. Comparison of water end relative permeabilities of all six groups of parallel core samples at different oil/water viscosity ratio is shown in Fig.8. It can be seen in Fig.8 that the water end relative permeabilities at high oil/water viscosity ratio are less than those at low oil/water viscosity ratio.

From what said above, oil and water relative permeabilities are dependent on oil/water viscosity ratio in sandstone core samples with low permeabilities. It will be discussed in which oil/water viscosity ratio oil and water relative permeabilities measured are more reasonable.

Injection-production ratio during oilfield development by water injection can be evaluated from oil and water relative permeabilities measured in laboratory. The development of QL Reservoir by water injection is not implemented yet. So it is impossible to evaluate the oil and water relative permeability data by using the practical information of water injection. However, group J2S of SS reservoir near QL Reservoir, only separated by a fault, was developed by water injection in 1991. Its sedimental and other reservoir properties are the same as those of QL Reservoir. SS and QL are actually two similar reservoirs in one oilfield. Therefore, it is reasonable to evaluate and analyse the oil and water relative permeabilities of QL Reservoir rocks by using practical information of water injection in SS reservoir.

There are 64 layers in 14 wells of group J2S of SS reservoir which have been perforated and the total perforated depth is about 502.68m. The perforated layers per well range from two to nine and the perforated depth per well ranges from 14.40 to 64.35m. The perforated layers and depth in a wide range have good representability.

The average water injectivity index per meter calculated with the well test information from 14 wells of group J2S in SS reservoir is:

\[ J_w = 0.0808 - 0.0940 \ m^3/d.Mpa.m \]  

And its average oil productivity index per meter is:

\[ J_o = 0.125 \ m^3/d.Mpa.m \]

The average injection-production ratio is calculated as:

\[ J_w/J_o = 0.6464 - 0.7250 \]

The method for calculated injection-production ratio from oil and water relative permeabilities is as follows:

\[ \frac{J_{we}}{J_{ow}} = \frac{K_w(S_{or})}{K_o(S_{wc})} \frac{\mu_o}{\mu_w} \]
Values of injection-production ratio calculated with oil and water relative permeabilities data by using equation (5) are listed in Table 3. The injection-production ratio with oil/water viscosity ratio of 1.8 and sample amount of six in Table 3 is the value of six parallel core samples. It can be seen in Table 3 that the injection-production ratio calculated from oil and water relative permeabilities measured at oil/water viscosity ratio (1.8) close to that in reservoir condition is much closer to the practical value of injection-production ratio of SS reservoir developed by water injection. However, the injection-production ratio calculated from oil and water relative permeabilities measured at high oil/water viscosity ratio is much higher than the practical value of SS reservoir, which shows that the oil and water relative permeabilities measured at simulated oil/water viscosity ratio is more representative and practical.

In the project designing of QL Reservoir development, the injection-production ratio has been decided as 0.5802–0.7015. For convenient, the value has been decided as 0.65 at last which is used to calculate the injectability of QL Reservoir. This shows that the reservoir engineers to design development program of QL Reservoir have made use of the oil and water relative permeabilities measured at simulated oil/water viscosity ratio at reservoir condition.

**OIL-WATER RELATIVE PERMEABILITY BEHAVIOUR OF QL RESERVOIR**

The oil-water relative permeability behaviour of QL Reservoir with low permeability will be discussed with data measured at the simulated oil/water viscosity ratio.

It is found in Table 2 that the irreducible water saturations of rocks in QL Reservoir (Group J1,S) range from 27.7% to 35.8% and its average value is about 31.5%. The residual oil saturations by water flooding range from 11.6% to 21.7% and its average value is about 14.8%. Most of the water end relative permeabilities range from 0.23 to 0.50 and its average value is about 0.388. The oil-water 2-phase flowing limits range from 47.8% to 59.0% and its average value is about 53.7%. It may be determined approximately from the oil-water relative permeability behaviour described above that the rock wettability of QL Reservoir is weakly water- wet/water-wet. Experimental results measured by Amott method also showed that the rock wettability of QL Reservoir is weakly water- wet/water-wet. This demonstrated again that the oil and water relative permeabilities measured at the simulated oil/water viscosity ratio in reservoir temperature and pressure are more practical in the aspect of wettability.

From what described above, although the porosities and permeabilities of QL Reservoir are very low, the water flooding residual oil saturations are not high and the oil-water 2-phase flowing limits are not narrow. This is because of two reasons as follows. One reason is that the viscosity of crude oil at reservoir condition is very low and the oil/water viscosity ratio is close to 1.0. This type of viscosity property is helpful to the decreasing of residual oil saturations. Another reason is that the rock wettability of QL Reservoir is weakly water-wet/water-wet which is also helpful to the decreasing of residual oil saturations by water flooding and the increasing of oil-water 2-phase limits.

Fig. 9 shows the relationship between water end relative permeabilities of QL Reservoir and air permeabilities of rock samples. The higher the air permeability, the larger the water end relative permeability of QL Reservoir. This demonstrated that water end relative permeabilities of QL Reservoir is affected significantly by rock permeabilities.

It is explained as follows that there is good relationship between water end relative permeabilities and air permeabilities. In general, the higher the rock permeability, the weaker the water wettability in one reservoir. And the weaker the water wettability, the larger the water end relative permeability obviously. It can be derived easily that the higher the rock permeability, the larger the water end relative permeability in one reservoir.

**CONCLUSIONS**

This work leads to the following conclusions which are considered relevant for experimental study on this
type of rock samples with low porosities and permeabilities in QL Reservoir:

1. The oil and water relative permeabilities measured at the simulated oil/water viscosity ratio in reservoir temperature and pressure are more reliable and practical. Hence, oil and water relative permeabilities should be measured at the simulated oil/water viscosity ratio in reservoir temperature and pressure for rock samples with low permeabilities.

2. The residual oil saturations by water flooding in QL Reservoir are lower relatively and its average value is only 14.8%. The oil-water 2-phase flowing limits are larger and its average value is about 53.7%. The water end relative permeabilities are not low and its average value is about 0.388. It may be predicted that the injectability of QL Reservoir with low permeability would not be low.

3. There is a good relationship between water end relative permeabilities and air permeabilities for rock samples of this reservoir. The higher the air permeability, the larger the water end relative permeability.

4. The oil and water relative permeabilities measured at high oil/water viscosity ratio are smaller than those measured at low oil/water viscosity ratio for rock samples with low permeabilities in QL reservoir.

ACKNOWLEDGEMENTS

The authors thank Zhubo Zhang, Yikuan Ren and Huirong Wang very much for conducting a large part work of the experimental work.

NOMENCLATURE

- \( \eta_W \) = Final Water Flooding Efficiency
- \( S_{wc} \) = Irreducible Water Saturation
- \( S_{or} \) = Residual Oil Saturation
- \( J_{wa} \) = Adsorption Water Index
- \( J_{wo} \) = Oil Production Index
- \( K_{wa}(S_{or}) \) = Water Relative Permeability at Residual Oil Saturation

\( \mu_o \) = Viscosity of Oil, mPa.s
\( \mu_w \) = Viscosity of Water, mPa.s

REFERENCES

Table 1. Basic Data of Core Samples

<table>
<thead>
<tr>
<th>Group No.</th>
<th>Sample No.</th>
<th>Porosity(%)</th>
<th>Air Perm.(md)</th>
<th>Description</th>
</tr>
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<td>12.5</td>
<td>25.7</td>
<td>LV</td>
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<td>HV</td>
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<td>69.8</td>
<td>LV</td>
</tr>
<tr>
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<td>70.0</td>
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<td>2.10</td>
<td>HV</td>
</tr>
<tr>
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<td>17.0</td>
<td>LV</td>
</tr>
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<td>10</td>
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<td>25.1</td>
<td>LV</td>
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<tr>
<td>11</td>
<td>L26-391(2)</td>
<td>13.8</td>
<td>21.7</td>
<td>LV</td>
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### Table 2. Water Flooding Experimental Results

<table>
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<tr>
<th>Group No.</th>
<th>Sample No.</th>
<th>$S_{aw}$(%)</th>
<th>$S_\alpha$(%)</th>
<th>$K_{rw}$/$S_\alpha$</th>
<th>Description</th>
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<td>0.29</td>
<td>LV</td>
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<td>L26-391(2)</td>
<td>35.8</td>
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### Table 3. Ratio of Injection-Production

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<tr>
<th>$\mu_o/\mu_w$</th>
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<th>1.8</th>
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<th>Practical Value</th>
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<td>$J_{aw}/J_{aw}$</td>
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<td>0.7017</td>
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