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Relative Permeabilities of Homogeneous and Heterogeneous Laminated Rock Samples under Hydrostatic and Triaxial Stresses

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Abstract. Production performance of a hydrocarbon-bearing reservoir is vital and largely controlled by certain reservoir rock and fluids intrinsic properties. Therefore, realistic measurements of reservoir rock properties under simulated in-situ stress-state are necessary. This work is aimed at investigating the integrated effect of rock geomechanics and fluid flow by measuring oil-water relative permeability of homogeneous and heterogeneously laminated rock samples at hydrostatic and triaxial stresses. Homogeneous samples show a trend of decreasing oil relative permeability and slight increase in water relative permeability as mean effective stress increases either with the increase of radial confining pressure at constant axial stress or with the increase of axial stress at constant radial confining pressure. The significant increase of axial stress way above the radial confining pressure tends to reverse the trend of oil relative permeability due to microcracks initiation.

Heterogeneous laminated samples with lamination parallel to flow direction show a decrease in oil relative permeability with no major effect in water relative permeability as axial stress increases up to the radial confining pressure. This is believed to be due to the increases of oil trapping. As radial confining pressure increases above the axial stress, oil relative permeability increases and no change was observed for water relative permeability. This behavior is attributed to the decrease in oil trapping due to the lamina close up with the increase of the radial confining pressure. When heterogeneous sample is subjected to constant low confining pressure and different increasing axial stresses above the confining pressure, an increase in oil relative permeability and minor change on water relative permeability was observed. This is believed to be due to the lamina opening with the increase of the axial stress overriding the radial confining pressure acting in the rock. In conclusion, it has been found that opposite consistent trends of relative permeability values can take place due to lamina opening and closure as a result of loading magnitude and orientation.

Introduction

The knowledge of comprehensive and integrated reservoir rocks and fluids properties is essential for optimum reservoirs development. Absolute and relative permeabilities, in specific, are properties of great importance for oil and gas reserve estimation and production planning. These properties are affected by many factors. Among these factors and by far the most essential are the degree of heterogeneities and the effect of in-situ stress state acting on the reservoir rocks. Several investigations have been conducted to explore the effect of in-situ stresses on absolute and relative permeabilities. These investigations were mostly conducted at hydrostatic stress condition, where all principle stresses are equal. Lately, several investigations were conducted to explore the effect of triaxial stress on absolute permeability but none, to our knowledge, exists on the effect of triaxial stress condition on water-oil relative permeabilities.

Effect of sample heterogeneities

Homogeneous core plugs have been traditionally chosen and used in relative permeability and capillary pressure measurements. However, naturally occurring porous media display a variety of heterogeneities and such heterogeneities can dramatically affect relative permeability. Corey and Rathjens (1956) were the first to study the effect of small-scale stratification on core plugs relative permeability measurements. They concluded that relative permeability is very much affected by flow direction and at a given saturation, when flow is parallel to bedding; relative permeability is greater in value than that obtained when flow is perpendicular to bedding. They attributed these effects to capillary differences caused by grain size differences. Later, Ehrilch (1971) used Corey-Rathjens observations to explain the relative permeability behavior of vuggy and fractured sample rocks. Huppler (1970) performed numerical simulation to investigate the effect of core heterogeneities on apparent relative permeability. He indicated that well distributed heterogeneities have little effect on water flood performance, but as it becomes channel-like, their influence becomes more pronounced.

Kortekaas (1985) conducted a small scale numerical simulation in a model representing a cross bedded water-wet reservoir. He concluded that ignoring small-scale heterogeneities could lead to erroneous recovery prediction. Jakobsen *et al.* (1994) conducted numerical simulation and indicated that stratification impact diminishes with the increase in capillary forces. This was stressed by Corbett *et al.* (1992) and Jones *et al.* (1993).

Honarpour *et al.* (1994) studied the effects of small-scale heterogeneities and anisotropy on the laboratory measured relative permeability and capillary pressure data. The results clearly showed the anisotropy of relative permeability and capillary pressure due to the presence of small-scale heterogeneities. In a second paper, Honarpour *et al.* (1995) conducted large-scale relative permeability measurements in a strongly water-wet cross-bedded core. The results point to the scale dependence of relative permeabilities and oil trapping due to capillary trapping in higher permeability lamina. These results have been confirmed later by Huang *et al.* (1995) using a laminated sandstone slab. Similarly, Kocberber and Collins (1990) simulated models of water-wet sandstone reservoirs containing small-scale heterogeneity. They concluded that small-scale heterogeneities dominated reservoir behavior and caused non-uniform drainage patterns in primary recovery as compared with conventionally developed models. Consequently, the measured relative permeability curves are moderately affected.

Crotti and Rosbaco (1998) concluded that flood efficiency parallel to the stratification is less than that perpendicular to stratification. Ataie-Ashtiani *et al.* (2002) showed that capillary pressure-saturation-relative permeability relationships are influenced in complex ways by boundary conditions and micro heterogeneities within a laboratory sample. Lemouzy *et al.* (1993) developed a scaling-up method to compute relative permeability and capillary pressure for simulation of heterogeneous reservoirs, and emphasized that relative permeability is a tensor at large scale and no longer a scalar value.

Effect of in-situ stress

Dynamic stress alteration during production or injection processes has a major effect on relative permeability curves. Many studies have been conducted to explore this effect. Fatt (1953) investigated gas-oil relative-permeability at simulated overburden pressures. He noticed no significant effect with the variation of overburden pressure. Similarly, Rex and Don (1972) reported small or nonexistent effect for low permeability cores.

In contrast, Ali *et al.* (1987) conducted unsteady state experiments on Berea sandstone cores subjected to net hydrostatic overburden pressure. They observed a decrease in oil relative permeability and a minor decrease in brine relative permeability with applied stress. They also noted an increase in end-point saturations (S_{wi} and S_{or}) with increasing pressure. Al-Quraishi and Jones (2003) observed a decrease in oil relative permeability and no significant changes in water relative permeability as confining pressure increases up to 8000 psi. Irreducible water saturation decreased while residual oil saturation increased with applied stress. Jones and Smart (2002) studied the changes in two-phase permeability of sandstone during deformation. They concluded that changes in permeability are dependent on the number of fluid phases present.

The analysis of the above-cited literature reveals that limited research works was conducted and contradicting conclusions were obtained in studying the sensitivity of relative permeability curves to applied stresses variation. The purpose of this investigation is to explore the effect of wide range of experimental triaxial in-situ stresses on two-phase's water-oil relative permeabilities. Furthermore, since rocks are frequently characterized by some degree of heterogeneities such as layering and lamination, combined effect of stress applied and rock heterogeneities presented by lamination parallel to fluid flow direction on relative permeabilities were investigated and compared to that of homogenous rocks under the same hydrostatic and triaxial stress conditions.

Experimental Set-up and Materials

The experimental set-up (Fig. 1) was built to integrate geomechanics and fluid flow mechanisms. It consists of a stiff loading frame, a servo-controlled confining pressure system and a vertically mounted Hoek cell. The cell provides the means of applying independent radial and axial stresses simulating horizontal and vertical in-situ stresses on the test sample. Confining pressure is delivered to the radial surface of the sample using a servo-controlled constant pressure pump. The vertical axial stress is applied to the sample ends using an external ram, via cylindrical end platens penetrated with 1/8-inch flow channels. During the course of the experiment, water or oil is pumped through the sample via the end platens using a constant rate positive displacement syringe pump.

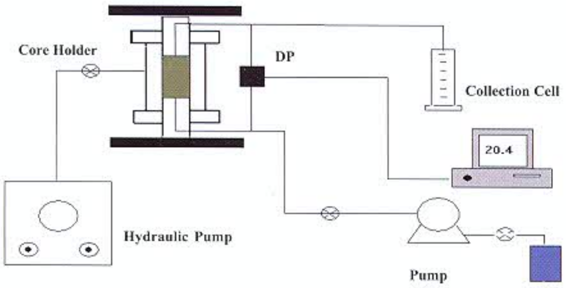

Fig. 1. Schematic of the experimental set-up used.

Fluids are flown through the rock sample using a network of 1/8-inch steel tubing and fittings. The network allows oil or brine to be pumped in either direction of the core. Pressure drop across the core sample under investigation was recorded via differential pressure transducer. All tests were conducted at ambient temperature and atmospheric pore pressure. Fluid effluents are collected at the outlet end in graduated glass tubes mounted in a timely controlled fraction collector.

Cores investigated were heterogeneous and homogenous sandstone samples 1.5 inches in diameter and 3 inches long. The heterogeneous samples are characterized with structured heterogeneities in the form of zero dip micro-scale lamination parallel to the flow direction visible to naked eye. All samples are strongly water wet as indicated by the contact angle measurements conducted on polished flat surface samples representing the core plugs used. Fluids used were tap water as aqueous phase (viscosity of 1 cp and density of 1.02 gm/cc) and Blandol mineral oil (viscosity of 18 cp and density of 0.845 gm/cc) as oleic phase.

Experimental Procedures and Basic Measurements

Failure criteria of the chosen samples were established using rock samples adjacent to those used in this study. The most simple and applicable failure criterion is the Mohr-Coulomb failure criterion. Evaluation of the criterion requires a series of triaxial compression tests using as many specimens as possible. Due to the limited number of samples, more conservative failure criterion was determined by conducting at least two unconfined compressive strength (USC) tests for each set of cores (Al-Awad, 2002).

Table 1 lists the mechanical properties of the tested rock samples. Accordingly, triaxial loadings used in this project were selected based on measured failure criteria shown in Fig. 2. Core samples chosen were first fired gradually to stabilize any clay minerals that may present. Samples were then weighed dry, evacuated and saturated under pressure. Wet weight was then measured and used to calculate the samples pore volumes and porosities. Samples porosity values were corrected considering the pore volume reduction due to the stresses applied at each experiment. Samples absolute permeabilities were measured using gas permeameter and corrected to liquid permeability at 400 psi hydrostatic radial confining pressure. Saturated rock sample under investigation was then loaded in the core holder with end platens hand-pressed against the sample ends. Low radial confining pressure was then applied to hold the sample and portion of the end platens within the sleeve. The core holder assembly was then placed in the loading frame and hydrostatic stresses of 400 psi were applied. Absolute permeability was remeasured at that hydrostatic condition to double check the measurement made with the gas permeameter. Good agreement was found between the two measurements. Table 2 lists the samples physical properties of porosity at atmospheric condition and permeability at hydrostatic confining pressure of 400 psi.

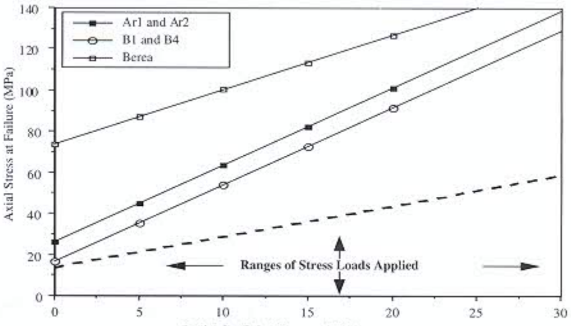

Fig. 2. Relationship between axial stress at failure and confining stress for samples used.

Table 1. Summary of Mechanical properties of the tested sandstones

Rock type	Unconfined Compressive Strength, psi (MPa)	Apparent Cohesion, psi (MPa)	Angle of Internal Friction (Degree)	Triaxial Stress Factor (Fraction)
Berea	10730 (74)	3321(22.9)	26.6	2.62
AR	2382 (16.43)	616(4.25)	35.3	3.73
B	2654 (18.3)	995(6.86)	35.2	3.72

Table 2. Physical rock properties of the tested samples

Sample	Porosity (Fraction)	Permeability @ 400 psi (md)
AR1	0.274	1500
AR2	0.229	244
Berea	0.220	750
B1	0.191	172
B4	0.184	179

The sample rock was then subjected to the stress load selected for the experimental run and drainage cycle was accomplished by injecting Blandol oil at a constant rate of 2 cc/min. The oil flood (drainage process) was continued until water production ceased. Initial water saturation was determined using material balance and oil effective permeability was calculated using Darcy's law.

Subsequent to the drainage cycle, the samples were subjected to water flood (imbibition process) at 2 cc/min until oil production ceased. Throughout the course of the water flooding process, pressure drop was recorded continuously across the core sample and production effluents were collected. Oil and water relative permeability were calculated using JBN unsteady state method with absolute permeability at the experimental condition of each run as a base. According to Crotti *et al.* (1998), the unsteady state method is more adequate than steady state since both lead to the same results for homogeneous medium, whereas steady state eliminates the influence of the porous medium heterogeneities.

At the end of each experiment, the core samples were cleaned with toluene in a Dean Stark extractor to double check the measurement of the residual fluids saturations (S_{wf} and S_{or}) and to prepare the samples for subsequent runs.

Results and Discussion

Sedimentary rocks exhibit stratification even on small core scale. This small-scale stratification is a major contributor to transport properties anisotropy. Thus, it is important to use representative rock samples rather than the homogenous ones. In addition, the transport properties are dynamic and may vary at different stress states (hydrostatic, triaxial, and true triaxial) caused by injection or withdrawal.

Since rocks exist in nature under unequal principle in-situ stresses, testing under triaxial stress conditions seems to be more realistic than that under hydrostatic condition. Therefore, homogeneous and heterogeneous laminated samples were investigated at different hydrostatic and triaxial stress conditions. Triaxial stress was applied by subjecting the rock samples to:

- Different axial stresses at constant radial confining pressure, or
- Different radial confining pressures at constant axial stress.

Table 3 lists the end point saturations (S_{wi} and S_{or}) and end point relative permeabilities (K_{ro} and K_{rw}) for the samples tested at the different applied stress conditions.

Homogeneous samples

To compare the effect of stress conditions (hydrostatic and triaxial) on relative permeability curves, three homogeneous samples (Ar2, Ar1 and Berea) were investigated. Sample Ar2 was subjected to four tests all at constant 580 psi radial confining pressure. Axial stress were increased in each test from the hydrostatic condition where axial stress equals the radial confining pressure in the first experiment to 870 psi in the second one and to 1160 psi in the third and finally to 1513 psi in the last experiment on this sample. Figure 3, a plot of relative permeability curves for the four experiments, indicates a significant decrease in oil relative permeability as the axial pressure increases from 580 to 870 psi. Less reduction has been noticed when the axial load was increased to 1160 psi. Opposite trend of increasing oil relative permeability was seen when the axial pressure was raised to 1513 psi. The trend of water relative permeability indicates a slight increase with increasing axial stress. The behavior of water and oil relative permeability curves is attributed to

Table 3. End point saturations and relative permeability values

Sample	CP, psi	σ_a, psi	K, md	S_{wi},	S_{or},	K_{ro}	K_{rw}
Ar1	580	580	1484.7	0.306	0.310	0.861	0.158
Ar1	1160	580	1361.0	0.278	0.329	0.902	0.163
Ar2	580	580	165.6	0.284	0.187	0.907	0.218
Ar2	580	870	160.1	0.290	0.332	0.913	0.208
Ar2	580	1160	153.4	0.316	0.389	0.855	0.219
Ar2	580	1531	147.7	0.304	0.335	0.915	0.236
Berea	1000	1000	525.0	0.284	0.330	0.788	0.062
Berea	1000	1914	409.4	0.280	0.308	0.966	0.059
B1	4000	1160	103.71	0.369	0.406	0.969	0.038
B1	4000	2320	99.22	0.357	0.359	0.980	0.036
B1	4000	4000	79.49	0.331	0.426	0.965	0.037
B1	1160	580	118.52	0.284	0.433	0.669	0.029
B1	2320	580	83.78	0.316	0.383	0.678	0.039
B4	580	580	231.93	0.330	0.446	0.457	0.029
B4	580	1160	170.37	0.347	0.251	0.782	0.071
B4	580	2320	155.26	0.354	0.270	0.786	0.064

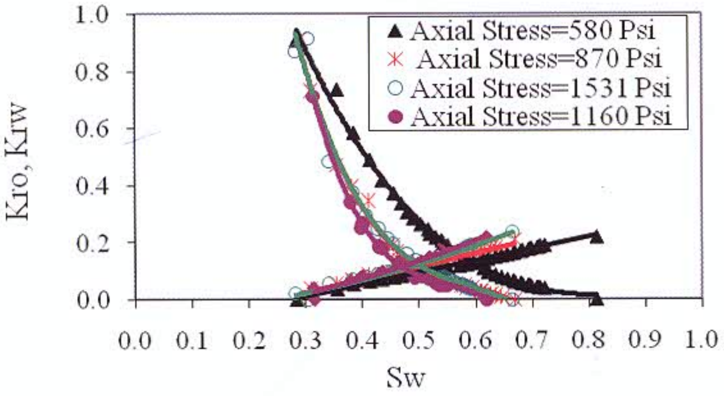

Fig. 3. Oil and water relative permeability of Ar2 homogeneous sample at different axial stresses at 580 psi confining stress.

the increase of mean effective stress as axial stress increases. Mean effective stress is defined as:

$$\sigma_{Mean} = 1/3(\sigma_a + 2\ CP)$$

The increase in mean stress caused the rock to compact. Consequently, pore geometry was altered and the fraction of larger pores was decreased mainly at the inlet and outlet ends of the core sample due to the increasing axial stress above the radial confining pressure in the first three experiments conducted on the sample rock. Since the rock is water wet and oil prefers to move into the larger pores, passageways available to oil became less and relative permeability to oil decreased. Rock sample is believed to experience some micro-cracks in the fourth experiment. Therefore, the fraction of larger pores increases causing oil relative permeability to increase. This is proved by the increase in both end point saturations (S_{wi} and S_{or}) as axial stress increases in the first three experiments and the later decreases in both end point saturations in the fourth experiment. The trend of decreasing oil relative permeability and slight increase on water relative permeability is consistent with previous investigations conducted on the effect of hydrostatic confining pressure on relative permeability curves (Ali *et al.*, 1987; Al-Quraishi and Jones, 2003).

Second homogenous but higher permeability sample (Berea) compared to Ar2 was investigated by subjecting it to two tests at constant confining pressure of 1000 psi and increasing axial pressure from hydrostatic level of 1000 psi to 1914 psi. Figure 4 is a plot of the relative permeability curves obtained for the two conducted experiments. It shows an increase in oil relative permeability and no change on water relative permeability as axial pressure is doubled. End point oil relative permeability also increases as axial stress increases. This behavior is similar to that obtained in the fourth experiment conducted on Ar2. This can again be attributed to the presence of micro cracks due to the increase in axial load two times greater than the confining radial pressure in the second experiment. This leads to pore geometry alteration and increase in overall rock pore size. This agrees well with the finding of Morgan and Gordan (1970) on the influence of pore geometry and the behavior of the bimodal pore system initiated with the increase of the axial load on relative permeability.

To study the effect of varying confining radial pressure at constant axial stress, homogenous sample Ar1 was investigated in two subsequent tests. The tests were conducted at constant axial stress of 580 psi and increasing radial confining pressure from hydrostatic level of 580 psi in the first run to 1160 psi in the second one. Figure 5 is a plot of the relative permeability curves of the two tests conducted. The trend indicates a slight decrease in oil relative permeability and an increase on water relative permeability as confining radial pressure increases. Compaction and changes in pore geometry caused by the increase of radial confining pressure, and hence the mean effective stress is the reason behind such trend. The reduction in oil relative permeability was much less than that observed on sample Ar1 when the axial stress was varied at constant radial load even though the mean load applied on sample Ar1 is much larger. This is attributed to the high permeability of sample Ar1 in addition to the uniform distribution of the stress load all over the sample circumference, which led to a lesser effect of mean effective stress on the rock sample characteristics. Irreducible water saturation (S_{wi}) tends to decrease while residual oil saturation (S_{or}) tends to increase as confining radial stress increases.

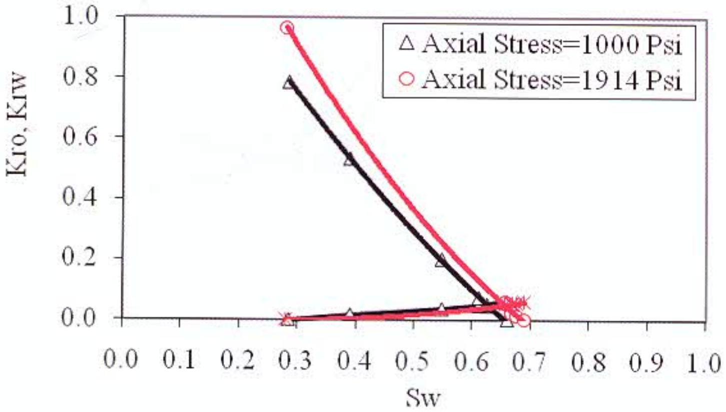

Fig. 4. Oil and water relative permeability of Berea homogeneous sample at different axial stresses at 1000 psi confining stress.

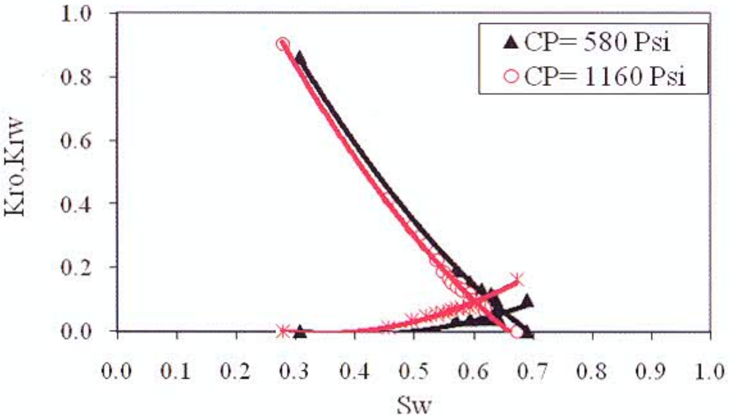

Fig. 5. Oil and water relative permeability of Ar1 homogeneous sample at different confining stresses at 580 psi axial stress.

Heterogeneous samples

To explore the combined effect of triaxial stress and heterogeneities on relative permeability curves, two samples (B1 and B4) characterized with visible lamination parallel to flow direction were used. Sample B1 was subjected to two experiments at two axial stresses of 2320 psi and 4000 psi. All were conducted at constant 4000 psi radial confining pressure. Figure 6 is a plot of the resulting relative permeability curves indicating a reduction in oil relative permeability and no major effect on water relative permeability as axial stress increases. Residual oil saturation (S_{or}) tends to increase and irreducible water saturation (S_{wi}) tends to decrease as axial stress increases. During capillary dominated imbibition, water moves into the lower permeability lamina while oil is trapped in the higher permeability lamina. Increasing the axial load to 4000 psi hydrostatic condition offset the effect of high confining radial pressure and help in opening the lamina and disturb the spatial distribution of high and low permeability regions, hence, increases the oil trapping and decreases the oil relative permeability and increases the residual oil saturation.

To investigate the effect of confining pressure at constant axial stress, B1 rock sample was again used and subjected to two different radial confining pressures of 1160 psi and 2320 psi at constant 580 psi axial stress. Figure 7 is a plot of the relative permeability curves for the two stress conditions. As radial confining pressure increases above the axial stress oil relative permeability increases, no change was observed for water relative permeability and S_{or} decreases and S_{wi} increases. This behavior is attributed to the lamina close up due to the increase of the confining pressure holding the sample radial face with weak axial load acting on the sample ends. The close up of the lamina decreases the oil trapping in the laminated rock body and this is proved by the reduction of residual oil saturation with the increase of the radial confining pressure. The plot indicates a linear dependence of relative permeability curves on saturation and low oil relative permeability values for the two experiments. These are distinctive relative permeability curves characteristics of laminated rocks.

Sample B4 is another laminated sample subjected to constant low radial confining pressure of 580 psi and three axial stresses of 580, 1160, and 2230 psi. Figure 8 presents the relative permeability curves of the three experiments. It indicates a slight increase in oil relative permeability with the increase of axial stress from 580 to 1160 Psi. However, significant decrease was observed with the increase of axial stress to 2320 psi. Little change was seen on water relative permeability. The major decrease in oil relative permeability is believed to be due to the lamina opening with the increase of the axial stress overriding the confining pressure acting on the radial surface of the rock. The lamina opening increases the oil trapping on the higher permeability strata and this is proved by the increase of S_{or} with the increase of the axial load.

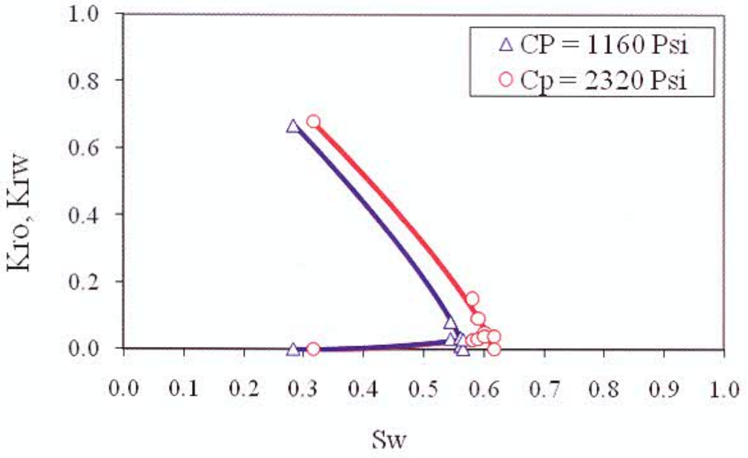

Fig. 6. Oil and water relative permeability of B1 laminated sample at different confining stresses at 580 psi axial stress.

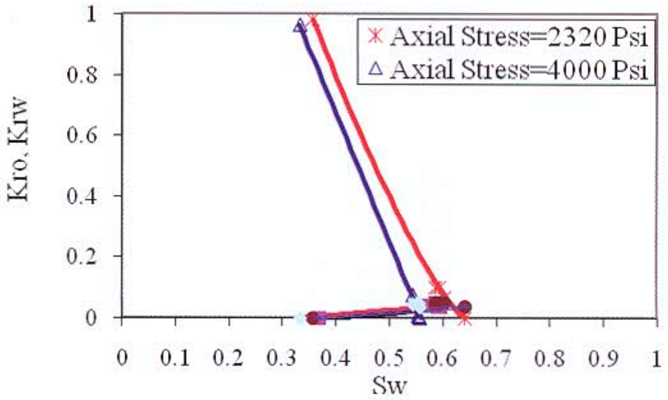

Fig. 7. Oil and water relative permeability of B1 laminated sample at different axial stresses at 4000 psi confining stress.

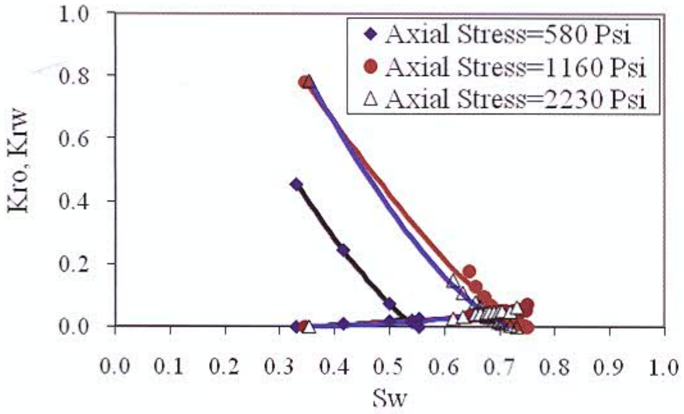

Fig. 8. Oil and water relative permeability of B4 laminated sample at different axial stresses at 580 psi confining stress.

Conclusions

Based on the analysis performed in this study, the following conclusions are made:

1. The trend of relative permeability for heterogeneous rocks is highly dependent on the applied loading stress type (hydrostatic or triaxial) during laboratory experiments.
2. Homogeneous rocks relative permeability is less sensitive to applied loading stress type during laboratory measurements and is highly affected by the applied mean stress.

For laminated rocks, the effect of applied loading stress type and rock orientation on relative permeability measurements are crucial.

Nomenclature

σ_{Mean} = Mean effective stress
σ_a = Axial stress
CP = Confining Pressure
S_{wi} = Initial water saturation
S_{or} = Residual oil saturation
K = Permeability
K_{ro} = Oil relative permeability
K_{rw} = Water elative permeability

References

Al-Awad, M. N. "Simple Correlation to Evaluate Mohr-Coulomb Failure Criterion using Uniaxial Compressive Strength." *Journal of King Saud University (Engineering Sciences)*, Vol. 14, No. (1), (2002), 137-145.

Ali, H. S.; Al-Marhoun, M. A.; Abu-Khamsin, S. A. and Celik, M. S. "The Effect of Overburden Pressure on Relative Permeability." SPE paper No. 15730 presented at the *SPE Middle East Oil Show* held in Manama, Bahrain, (March 7-10, 1987).

Al-Quraishi, A. and Colin, J. "Effect of Confining Stress on Relative Permeability." *Journal of Engineering*, Vol. 13, No. (1), (2003), 71-77.

Ataie-Ashtiani, B.; Hassanizadeh, S. M. and Celia, M. A. "Effects of Heterogeneities on Capillary Pressure-saturation-relative Permeability Relationships." *Journal of Contaminant Hydrology*, Vol. 56, (2002), 175-192.

Corbett, P. W. M.; Ringrose, P. S.; Jensen, J. L. and Sorbie, K. S. "Laminated Clastic Reservoirs: The Interplay of Capillary Pressure and Sedimentary Architecture." paper SPE 24699, presented at the *67th SPE Annual Technical Conference and Exhibition* held in Washington, D. C., (October 4-7, 1992).

Corey, A. T. and Rathjens, C. H. "Effect of Stratification on Relative Permeability." *JPT*, (December 1956), 69-71.

Crotti, M. A. and Rosbaco, J. A. "Relative Permeability Curves: The Influence of Flow Direction and Heterogeneities. Dependence of End Point Saturations on Displacement Mechanisms." paper SPE 39657 presented at the *1998 SPE/DOE Improved Oil Recovery Symposium* held in Tulsa, OK, U.S.A., (April 19-22, 1998).

Ehrilch, R. "Relative Permeability Characteristics of Vugular Cores: Their Measurement and Significance." paper SPE 3553 presented at the *46th SPE of AIME Fall Meeting*, New Orleans, LA, U.S.A., (October 3-6, 1971).

Fatt, I. "The Effect of Overburden Pressure on Relative Permeability." *Journal of the American Institute of Mechanical Engineers, Petroleum Transactions*, Vol. 198, (1953), 325-326.

Honarpour, M. M.; Cullick, A. S.; Saad, N. and Humphreys, N. V. "Effect of Rock Heterogeneity on Relative Permeability: Implications for Scale-up." SPE 029311 presented at the *SPE Asia Pacific Oil and Gas Conference* held in Kuala Lumpur, Malaysia, (March 20-22, 1995).

Honarpour, M. M.; Cullick, A. S.; Saad, N. and Humphreys, N.V. "Influence of Small-scale Rock Laminations on Core Plug Oil/Water Relative Permeability and Capillary Pressure." SPE 27968 presented at the *University of Tulsa Centennial Petroleum Engineering Symposium* held in Tulsa, OK, U.S.A., (August 29-31, 1994).

Huang, Y.; Ringrose, P. S. and Sorbie, K. S. "Capillary Trapping Mechanisms in Water-wet Laminated Rocks." *SPE Reservoir Engineering*, (November 1995), 287-292.

Huppler, J. D. "Numerical Investigation of the Effects of Core Heterogeneities on Water-flood Relative Permeabilities." SPE 2874 presented at the *SPE 45th Annual Fall Meeting* held in Houston, Texas, U.S.A., (October 4-7, 1970).

Jakobsen, S. R.; Ingsoy, P.; Braun, T.; Guo, Y. and Aga, M. "Assessing the Relative Permeability of Heterogeneous Reservoir Rock." SPE 28856 presented at the *European Petroleum Conference* held in London, U.K., (October 25-27, 1994).

Jones, A.; Doyle, J.; Jacobsen, T. and Kjonsvik, D. "Which Sub-seismic Heterogeneities Influence Waterflood Performance? A Case Study of Low Net-to-gross Fluvial Reservoir." *Proceedings of the 7th European IOR Symposium*, Moscow, Russia, (October 27-29, 1993), 35-46.

Jones, C. and Smart, B. G. D. "Stress Induced Changes in Two-phase Permeability." SPE/ISRM 78155 presented at the *SPE/IRM Rock Mechanics Conference* held in Irving, Texas, U.S.A., (October 20-23, 2002).

Kocberber, S. and Collins, R. E. "Impact of Reservoir Heterogeneity on Initial Distributions of Hydrocarbons." paper SPE 20547 presented at the *65th SPE Annual Technical Conference and Exhibition* held in New Orleans, LA, U.S.A., (September 23-26, 1990).

Kortekaas, T. F. M. "Water/Oil Displacement Characteristics in Cross Bedded Reservoir Zones." SPE 1212, *SPEJ*, (December 1985), 917-926.

Lemouzy, P. M.; Romeu, R. K. and Morelon, I. F. "A New Scaling-up Method to Compute Relative Permeability and Capillary Pressure for Simulation of Heterogeneous Reservoirs." SPE 26660 presented at the *SPE 68th Annual Technical Conference and Exhibition* held in Houston, Texas, U.S.A., (October 3-6, 1993).

Morgan, J. T. and Gordan, D. T. "Influence of Pore Geometry on Water-Oil Relative Permeability." *JPT*, (1970), 1199.

Thomas, R. D. and Ward, D. C. "Effect of Overburden Pressure and Water Saturation on Gas Permeability of Tight Sandstone Cores." *JPT*, Vol. 24, No. (2), (1972), 120-124.

النفاذية النسبية للصخور المتجانسة وغير المتجانسة (المرققة) المعرضة لإجهادات موضعية هيدروستاتيكية وثلاثية

عبدالرحمن بن علي القريشي[١] ، وعمر بن عبدالعزيز المسند[١] ، ومساعد بن ناصر العواد[٢]

[١] مركز البترول والغاز ، مدينة الملك عبدالعزيز للعلوم والتقنية ،
ص ب ٦٠٨٦ ، الرياض ١١٤٤٢ ، المملكة العربية السعودية
[٢] قسم هندسة البترول والغاز ، كلية الهندسة ، جامعة الملك سعود ،
ص ب ٨٠٠ ، الرياض ١١٤٢١ ، المملكة العربية السعودية

(قدم للنشر في ٢٠٠٨/١٠/١٥م ؛ وقبل للنشر في ٢٠٠٩/٣/٣٠م)

الكلمات المفتاحية: النفاذية النسبية ، عدم التجانس ، إجهاد موضعي ثلاثي.

ملخص البحث. يعتمد أداء إنتاج المكمن على خواص سوائل المكمن وصخوره ؛ ولذلك تجرى الاختبارات المعملية تحت إجهادات مشابهة لمثيلاتها المؤثرة فعلياً على الصخر. تم في هذه الدراسة قياس النفاذية النسبية للزيت والماء لعينات صخور متجانسة ومترققة (ترقق موازي لاتجاه السريان) تحت ضغوط هيدروستاتيكية أو ثلاثية مماثلة لتلك الواقعة على صخور المكامن. أظهرت العينات المتجانسة توجهاً لانخفاض نفاذية الزيت ، وارتفاعاً طفيفاً في نفاذية الماء مع ارتفاع الإجهاد الفعلي المتوسط ، سواءً بزيادة الضغط المحيط مع ثبات الإجهاد الرأسي أم بزيادة الإجهاد الرأسي عند ضغط أسطواني ثابت. إن زيادة الإجهاد الرأسي إلى درجة أكبر من الضغط المحيط أدى إلى عكس اتجاه التغير بسبب ظهور التشققات. إن تأثير الإجهاد ثلاثي المحاور على منحنى النفاذية النسبية بالنسبة للعينات الصخرية غير المتجانسة يبين انخفاضاً في نفاذية الزيت دون تأثير كبير على نفاذية الماء عند زيادة الإجهاد الرأسي من مستويات منخفضة وحتى الوصول إلى قيمة الضغط الأسطواني المحيط وذلك بسبب زيادة احتباس الزيت في الصخر. وكلما زاد الضغط الأسطواني المحيط متخطياً قيمة الإجهاد الرأسي زادت نفاذية الزيت دون أي تغيير في نفاذية الماء ، ويعزى ذلك إلى انغلاق الرقائق مما يقلل من احتباس الزيت مع زيادة الضغط الأسطواني المحيط. عندما عرضت عينات الصخور غير المتجانسة لضغط محيط منخفض وثابت ، وعدة زيادات في الإجهاد الرأسي أعلى من الضغط المحيط ، لوحظ ارتفاع في نفاذية الزيت ، وتغير ضئيل في نفاذية الماء. ويعتقد أن ذلك بسبب انفتاح الرقائق مع زيادة الإجهاد الرأسي. وفي الخلاصة ، فقد وجد أن هناك توجهان متعاكسان لقيم النفاذية النسبية ، وذلك بسبب انفتاح الرقائق وانغلاقها نتيجة لاتجاه التحميل وقيمته. ويستنتج من ذلك أن النفاذية النسبية للصخور تتأثر بعدم التجانس بحسب اتجاه الرقائق وحالة الإجهادات الواقعة على الصخر ونوع التحميل.