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Simulation of New Technique for Measuring Relative Permeability and Capillary Pressure at Capillary Dominated Flow

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طريقة جديدة لِمحاكاة قياس النفاذية النسبية والضغط الشُعيري

المبروك أحمد بن روين

تعتمد طريقة تمييز نوعية التبلّل للصخور المسامية على قياس النفاذية النسبية للصخور والضغط الشعيري في وقت واحد وتحت تأثير السريان الشعيري.

أكدت نتائج المحاكاة وتحت ظروف تبلل مختلفة إمكانية تطبيق هذه الطريقة الجديدة لتعيين نوع التبلل للصخور معملياً تحت ظروف خاصة.

Abstract: *A novel technique of characterizing wettability of porous media is based on simultaneous measurement of relative permeability and capillary pressure under capillary dominated flow. A simulation study was conducted under different wettability conditions and model results confirmed that the proposed scheme can be implemented in the laboratory.*

INTRODUCTION

The development of this new technique was based on recent network modeling study by McDougall and Sorbie[1,2]. They found that representing the relative permeability functions in the conventional way as a function of wetting phase saturation essentially "hides" the processes that are going on at the pore scale. The network predictions have suggested that, plotting oil relative permeability, Kro, as a function of the reciprocal of capillary pressure, $1/P_c$, enables the interpretation of the effects of pore scale physics. As a result of these findings, an experiment has been designed to measure relative permeability and capillary pressure simultaneously so that the proper plots can be generated. A schematic diagram of the apparatus is shown in Figure 1. The basic idea, in this new technique, is to carry out carefully controlled measurements under conditions of capillary equilibrium; this involves making such measurement with pressure regulation in each of the oil and water phases using the Back Pressure Regulators (BPR) system. The essential sequence of measurement is:

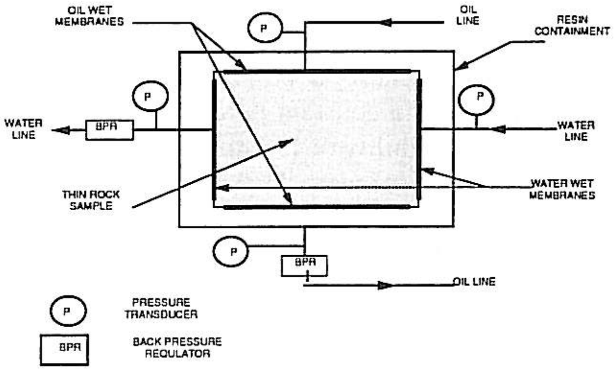

Fig. 1. Schematic diagram of the experiment

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(i) – Set the oil and water pressures on the separate BPRs, thus setting the capillary pressure, Pc.

(ii) – Flow the oil and water separately until the equilibrium are reached *i.e.* a steady-state fluid distribution in the small sample.

(iii) – Carry out the measurements of relative permeability at a given capillary pressure by setting the flows at appropriate levels, controlling the BPRs and measuring the pressure drops and flow rates.

A small size sample ensures that capillary equilibrium can be established quite rapidly so that many measurements can be made in a short period of time. In the work reported here, the main objective is to evaluate the proposed experimental approach numerically. This allows us to examine various procedures for the proposed experiments before trying to carry them out in the laboratory. In this study the modeling of the new technique was carried out using the Eclipse-100 black oil simulator.

MODEL DESCRIPTION

A numerical model was constructed using the Eclipse simulator to simulate the new experiment as proposed by McDougall and Sorbie[1,2]. The model layout is shown in Figure 2. It is a two-dimensional model (X-Y) composed of 100 grids, four of them non-active. The numbers of grids in both directions are set equal to 10 and have equal dimensions in both directions. The porous medium is represented by a two-dimensional square horizontal section and has dimensions of 0.8 cm by 0.8 cm and a thickness of 0.1 cm. this small section is necessary to achieve capillary equilibrium in a short period. The porous medium was assigned to a constant porosity of 20%, and absolute permeability of 100 mD. The wetting an non wetting phases were dead oil and water with identical density and viscosity of 1gm/cc and 1 cp. respectively. Each phase flow in one direction; independently of one another, *i.e.* they are not injected simultaneously from one side of the sample as it used to be in the other methods of measuring relative permeability. This will allow the potential drop of each phase measure independently.

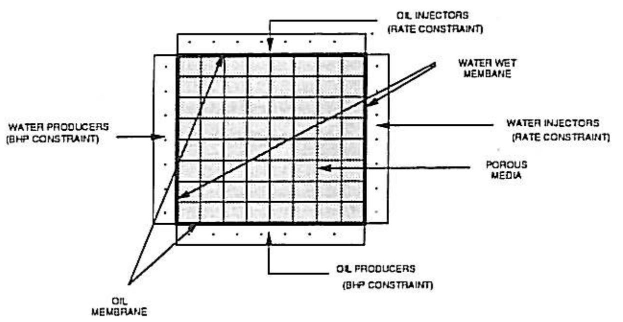

Fig. 2. Model layout

The injecting oil lines and water lines are represented by tiny horizontal wells that are in direct contact with the porous media through the semi-permeable membranes. The injection wells are controlled by rates and at each capillary equilibrium they are subjected to variable rates. Producing oil and water lines are also represented by horizontal wells and they are controlled by bottom hole pressures to represent the back pressure regulators. It is assumed here that by setting a back pressure on each line, the differences in the pressure between the oil lines and water lines will set the capillary pressure in the porous system.

Semi-permeable membranes are essential elements of the experimental set-up and were simulated using the concept of directional relative permeability. The main components of the input data are the capillary pressure and the relative permeability data which control the fluids distribution and their relative flow in the system. Table 1 gives the equations used to generate input data under different wettability conditions.

Table 1. Input capillary pressure and relative permeability data

Water-wet System:

$Krw = 0.30\ Se^3$
$Kro = 0.85\ (1-Se)^3$
$Pc\ = 3.0\ (\quad)^{0.5}\ (Se)$

Where

$Swc = 0.6 - 0.165\ \log\ (Kabs)$
$Swor = 0.7$

Oil-wet System:

$Krw=0.8\ Se^2$
$Kro=0.85\ (1-Se)^3$
$Pc=0.26038-5.652Sw+42.50Sw^2-148.44Sw^3+243.355Se^4-152.89Sw^5$

Where

$Swc=0.30$
$Swor=0.65$

Mixed-wet System:

$Krw=0.45\ Se^2$
$Kro=0.70\ (1-Se)^{2.75}$

- Capillary pressure for the imbibition curve: $Pc=15.78-112.47Sw+268.0Sw^2-213.33Sw^3$
- Capillary pressure for drainage curve: $Pc=0.220085-2.7945Sw+9.7049Sw^2-10.263Sw^3$

Where
$Swc=0.30$
$Swor=0.70$

$$Se=\frac{Sw-Swc}{Swor-Swc}$$

SIMULATION STRATEGY

At any stage of the simulation process, the outlet boundary conditions (represented by the bottom hole pressure of the oil and water producers) were set to impose a back pressure equivalent to a certain capillary pressure. Thus, for a fixed capillary pressure, (P_o-P_w), as steady-state saturation in the system can be reached.

Equilibrium conditions can be achieved by flowing both phases at low rates. When the pressure gradient of each phase is kept virtually unchanged across the system and the saturation distribution becomes uniform (for a homogeneous system), this indicates that equilibrium has been established in the system at that specific capillary pressure. The relative permeability of each phase can be measured independently at the equilibrium conditions by keeping the outlet boundary conditions fixed and gradually raising the flow rate of one of the phases until the pressure drop across the sample can be measured. After that, the flow rate is again gradually reduced until it returns to the initial (equilibrium) condition. This process can be repeated for the other phase. During this process, it is assumed that the saturation is uniform (for a homogeneous system) and maintained at equilibrium conditions fixing the capillary pressure.

If the water phase is to be allowed to imbibe into the system, the capillary pressure between the water phase and the oil phase should be reduced which can be done whether by decreasing the oil potential or by increasing the water potential.

RESULTS

The results from the simulation runs have shown that capillary equilibrium can be established which is characterized by uniform fluid saturation distribution in the system. Figure 3 shows the water phase saturation distribution at different capillary equilibrium for the water-wet system. Water saturation distribution at each equilibrium was within 1% differences over the whole system which is an acceptable tolerance for these types of experiments. The difference in

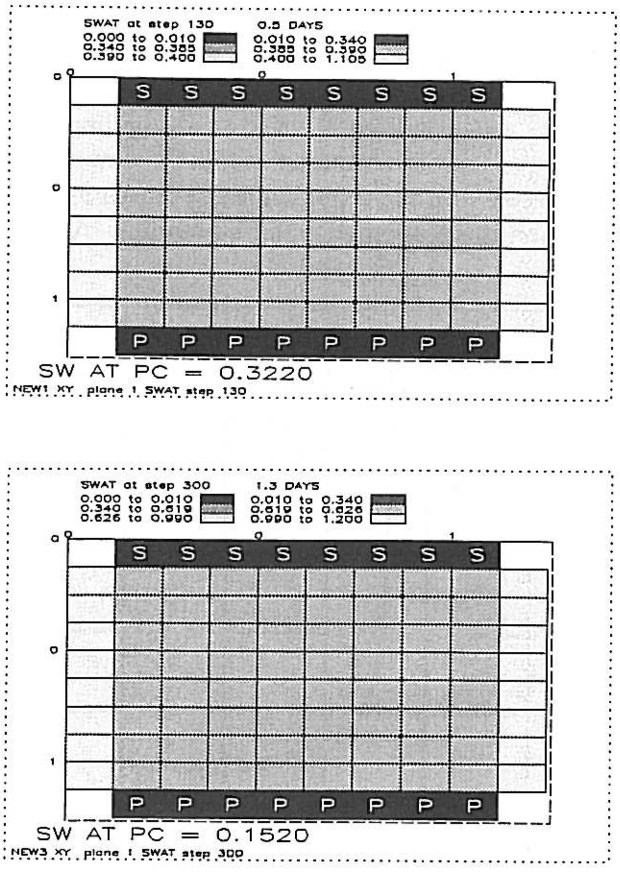

Fig. 3. Water-wet system

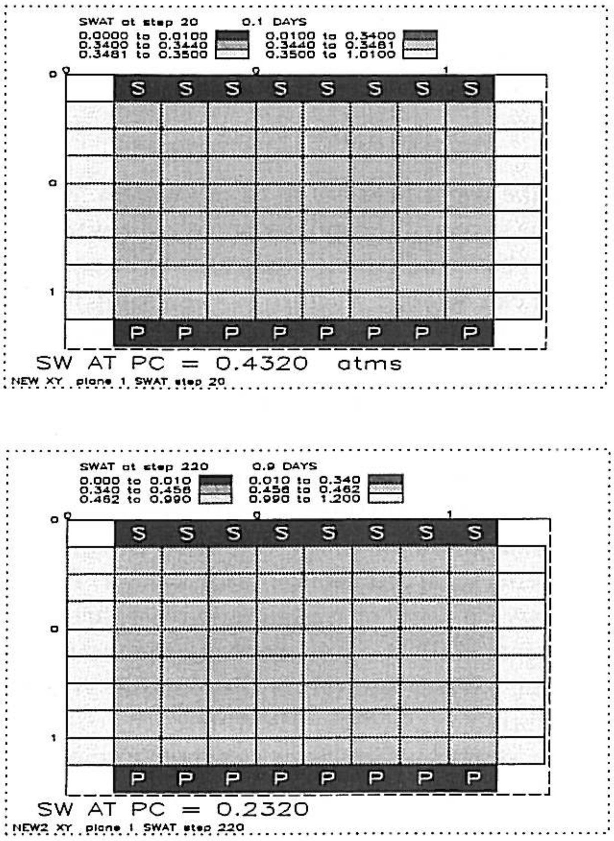

Fig. 3. Water-wet system

the pressure between the phases at the outlets was assumed to represent the capillary pressure in the system and it will be referred to as the imposed back pressure. The imposed capillary pressure was compared with the input capillary pressures as a function of he average water saturation. A very good match has been obtained for each wetting condition as shown in Figures 4,5,6.

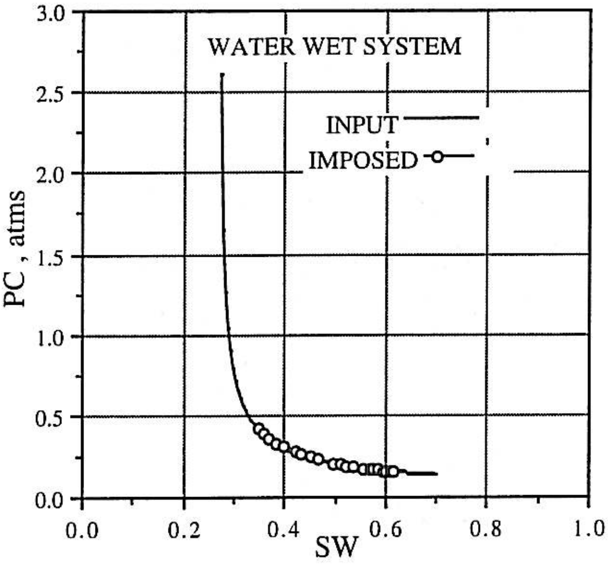

Fig. 4. Input *vs.* imposed capillary pressure

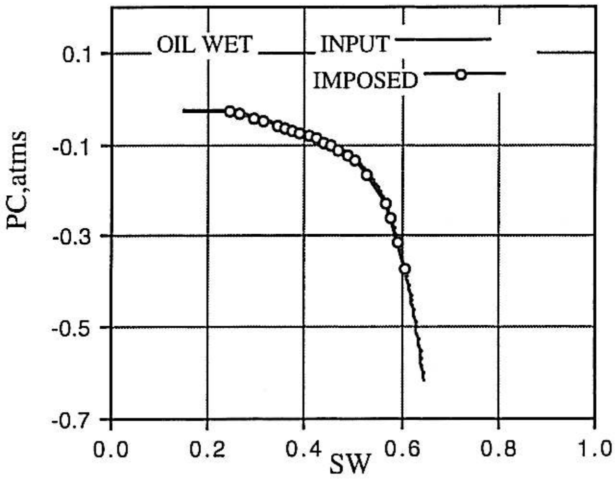

Fig. 5. Input *vs.* imposed capillary pressure

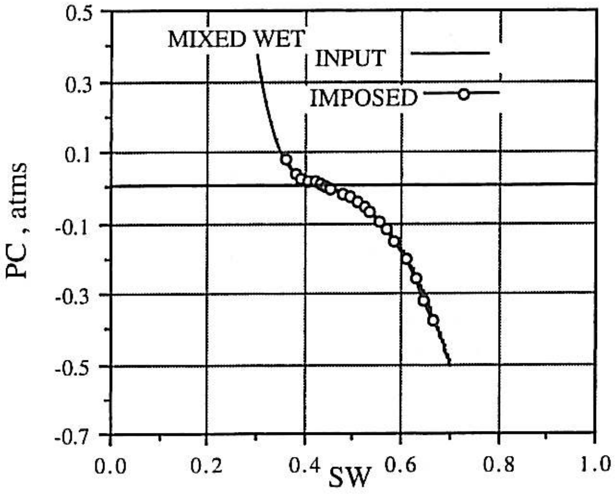

Fig. 6. Input *vs.* imposed capillary pressure

The model was also run to investigate the effect of the rising flow rate of one of the phases on the equilibrium condition. Figure 7 shows the effect of increasing oil rate on the saturation distribution for the water-wet system. First, the system is at an equilibrium then the rate is raised five times, at this stage the saturation distribution has been changed but within very small variations then the rate was increased 10 times and also a change in the saturation distribution has been observed but still within an acceptable range. Finally, the rate is reduced to its initial conditions (base case) where a complete re-establishment is obtained.

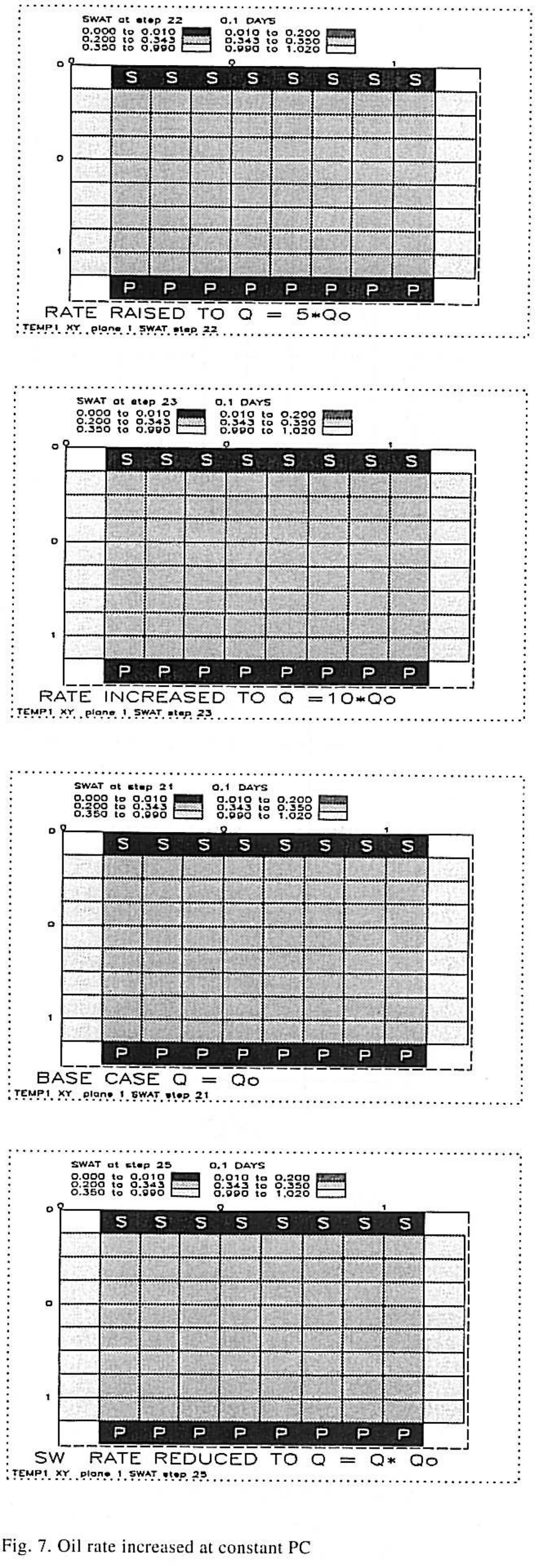

Fig. 7. Oil rate increased at constant PC

Darcy's law was used to calculate the relative permeability for each phase. These calculated relative permeabilities were compared with the input relative permeabilities (Figs. 8, 9, 10). All figures show a very good agreement that is achieved between the input and computed relative permeability data.

One of the advantages of using the simultaneous measurement of capillary pressure

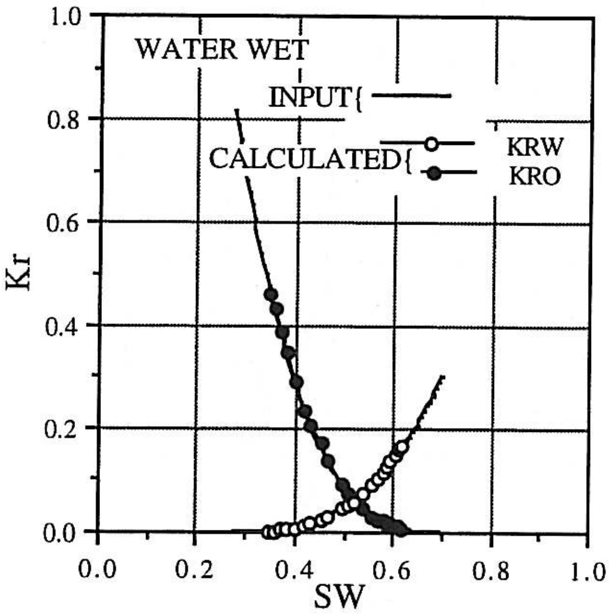

Fig. 8. Input *vs.* calculated relative permeabilities

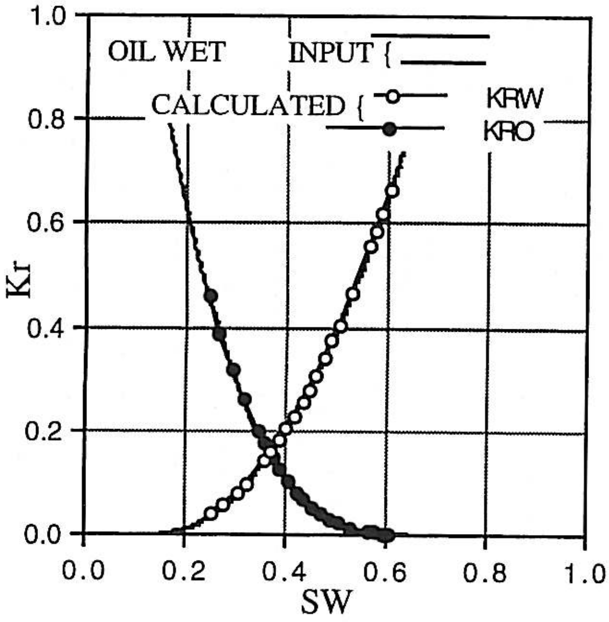

Fig. 9. Input *vs.* calculated relative permeabilities

and relative permeability is to use this data to plot the oil relative permeability as a function of he reciprocal of the capillary pressure to indicate the type of wettability in the system. Figures 11, 12, 13 show the plot between the inverse of the imposed capillary pressure with respect to the calculated relative permeabilities under different wettability conditions.

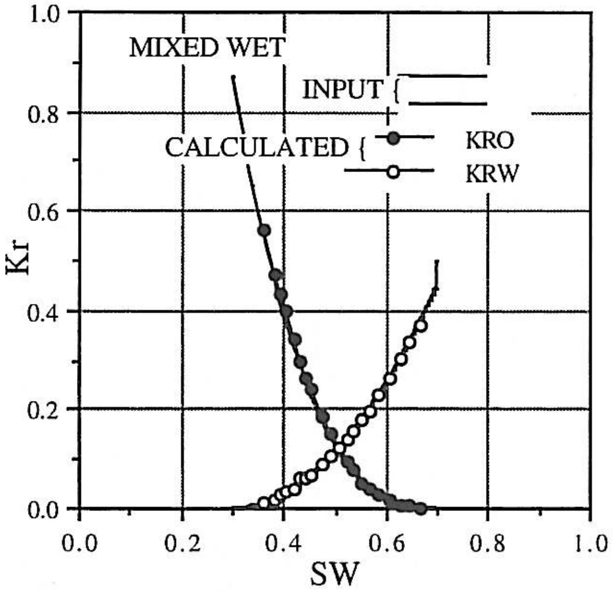

Fig. 10. Input *vs.* calculated relative permeabilities

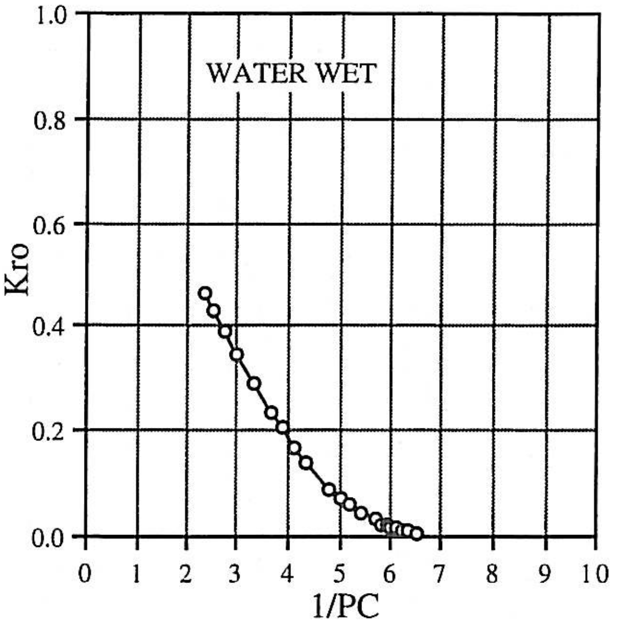

Fig. 11. 1/PC *vs.* Kro

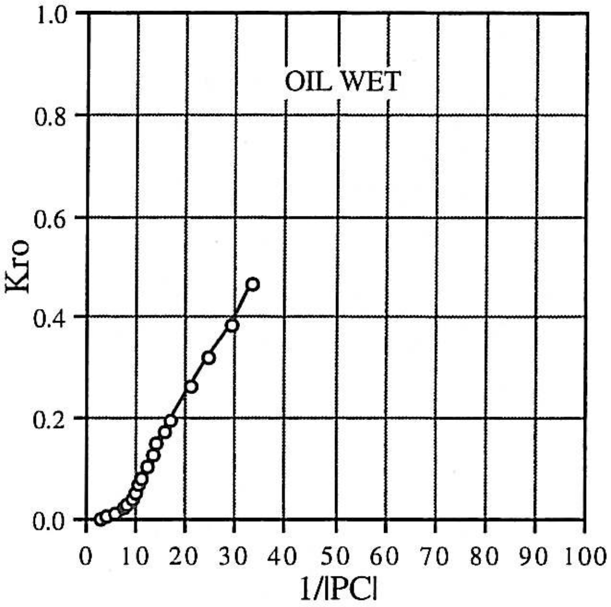

Fig. 12. 1/IPCI *vs.* Kro

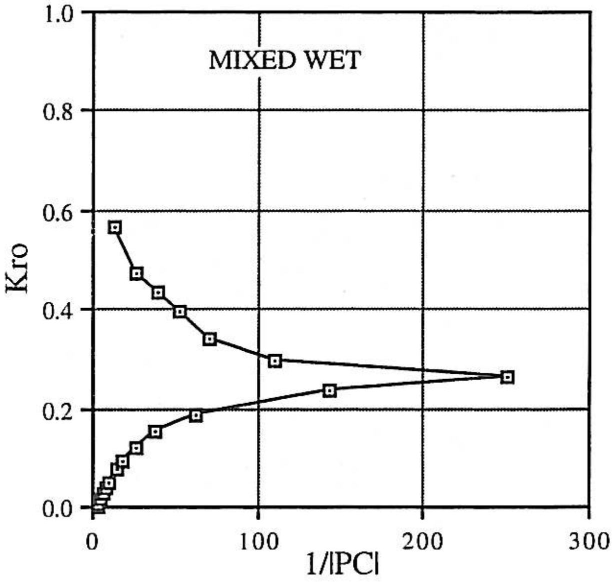

Fig. 13. 1/IPCI *vs.* Kro

DISCUSSIONS

In general, the model has been able to show clearly that capillary equilibrium can be established at dynamic conditions i.e. both phases can flow simultaneously while the saturations are held constant. Figure 3 shows the saturation distribution at different capillary pressure for the water-wet system. These rather featureless figures can be understood as follows: at Pc=0.432

(Atmospheres=6.65 psi) where the grey shading is for the saturation range 0.344 and 0.348; clearly, all the region is within this "contour" or shading. This is, in fact, the appropriate saturation at capillary equilibrium from the (input) capillary pressure curve. The other figures have been plotted in this way i.e. the shaded range closely brackets the expected saturation at capillary equilibrium.

The difference in the outlet boundary pressures impose a back pressure on the porous media equivalent to the capillary pressure between the phases. Figures 4, 5, 6 show an excellent agreement between the input capillary data. These indicate that, by measuring the difference in the pressure at the outlet, boundaries may enable us to measure the capillary pressure and to establish a constant equilibrium saturatio in the system. This concept may be well suited in small and thin samples, where the saturation gradients are small.

The model was also run to investigate the effect of rising the flow rate of one of the phases on the equilibrium condition. Figure 7 shows the results obtained for the water-wet system. First, the model was run at low rates for both phases and at fixed capillary pressure until equilibrium was established (the base case). The rate of one of the phase was then raised until the steady-rate conditions were achieved. After that, the rate is reduced to the base case where the same process is repeated for the other phase. It is this process of raising the flow rates that allows us to measure the corresponding relative permeabilities at the established capillary equilibrium. As soon as the rate of any phase is raised, while the back pressure is kept constant, a saturation gradient in the direction of the flow of that phase may be developed in the system. These saturation gradients were a result of an increase in the viscous force. If that force was controlled and carefully monitored just to make the pressure drop measurable, the differences in overall average of saturation in the porous media will be minimum and the system may be considered as if it is still in its equilibrium conditions. In order to sustain equilibrium conditions, the rates should be raised gradually until the pressure gradient across the sample for any phase reaches the level that can be measured (it must be greater than 0.01 psi). This procedure will avoid unnecessary rate increases that may cause high saturation gradient in the system.

Most of the results obtained under different wetting conditions show a slight difference in saturation distribution (less than 2% pore volume) which can be accepted as technical errors in the "experiment". In most of the steady-state methods, the average saturation agreed within 2% pore volume (McCaffery and Bennion[3], Honarpour *et al.*[4]).

The other interesting point from these processes is that the initial equilibrium conditions (base case) can be re-established after the rate is raised and the process can be repeated for the other phase. This condition enables the measurement of the relative permeability for both phases at fixed capillary condition and this is one of the most important tasks in this experiment.

According to the proposed experiment, the relative permeabilities should be measured simultaneously with the capillary pressure. The model has performed the above requirements by first establishing capillary equilibrium and then calculating the relative permeability of each phase using Darcy's law under steady-state condition. All the results were compared with the input relative permeability data as shown in Figures 8, 9, 10. Although the overall agreement is good, the simulation results show better agreement away from the end points. Near the end points, the viscous pressure gradients were high as a result of low relative permeability of one of the phases which cause high saturation gradient in the system.

One of the advantages of the new experiment is to detect the type of wettability from the plot of the reciprocal of the capillary pressure versus the oil relative permeability. The results obtained from the model outputs were used to check whether the trends that have been presented by McDougall and Sorbie[2] can be reproduced using this large scale model. Calculated oil relative permeabilities were plotted against the reciprocal of the capillary pressure as shown in Figures 11, 12, 13. The trend of the water-wet curve was identical to that predicted by network modeling for an imbibition process. For the oil-wet, the drainage process of the oil-wet system has not been presented by the network modeling and there is no comparison to be made, but it is believed that this trend is completely different from the water-wet system and can be used as a good indication of the type of wettability. The shape of the curve for the mixed-wet system is characterized by two trends. One represents the imbibition processes which lie in the positive section of the capillary pressure curve and the other represents the forced imbibition curve which lies in the negative side of the capillary pressure curve. The imbibition part of the mixed-wet system was identical to the ones predicted by the network model. The forced imbibition curve is identical to the trend of the drainage curve of the oil-wet system. Since the data used is not representative of actual cases, it is recommended to investigate the above trends with measured data under different wetting conditions.

The results have confirmed the possibility of carrying out the proposed experiment in the laboratory although a number of practical conditions may have to be investigated. In particular, the minimum rates that can be achieved practically. Model results have indicated that low rates are essential to establish capillary equilibrium. Those rates were ranging from high values as 0.1 cc/hr to low values as $1X10^{-4}$ cc/hr and depends mainly on the input petrophysical properties of the porous system. Low rates such as $4X10^{-3}$ cc/hr can be attainable in the laboratories (Kokkede and Boutkan[5]). It was found that increasing the number of wells representing the flow lines improves the intake rates into the system without distributing the capillary equilibrium. The model may be used as a good tool to determine the appropriate rate for the experiment if other relevant data are available. The mechanism on which the experiment has to be run was well simulated and procedures can be set for the experiment if the model is supplied with actual data. The semi-permeable membranes are an essential part of the experimental set-up and should be carefully selected to satisfy the boundary conditions.

CONCLUSIONS

A model was set up according to the proposed experimental scheme. The following conclusions were drawn from the simulation study:

1 - The results have confirmed the possibility of carrying out the proposed experiment in the laboratory although a number of practical conditions may have to be investigated.

2 - Relative permeability for oil and water phases can be measured at a fixed capillary pressure using the proposed scheme: i.e. by achieving capillary equilibrium and then raising the flow rates of the two phases separately. This technique will enable the representation of oil relative permeability as a function of reciprocal of capillary pressure that gives a good indication of what is going on at the pore-scale level.

3 - More studies are required at different wettability conditions in order to set-up a general trend for wettability characterization using actual data.

4 - Modeling the proposed experiment numerically is useful in that it may assist in establishing procedures for the experiment. Also, if such experiments are actually conducted, the model can be used to match the results.

5 - If such experiments prove to be practical, then a new technique may emerge for measuring relative permeabilities and capillary pressure simultaneously to detect the type of wettability in porous media.

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