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Overview of Three-Phase Relative Permeability Experimental Data

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مراجعة للمعلومات العملية للنفاذية النسبية ذات الأطوار الثلاثة

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تتطلب دراسات محاكاة أو تقييم المكامن النفطية معلومات للنفاذية النسبية ذات الأطوار الثلاثة التي يمكن الحصول عليها من القياسات المعملية أو بواسطة النماذج النظرية، وترجع بداية الدراسات المعملية إلى عام 1941 إلا أن الصعوبات الفنية التي واجهت معظم البحاث في قياسات النفاذية النسبية أدت إلى ندرة المعلومات في هذا المجال. وتقدم هذه الورقة مراجعة لمعظم نتائج التجارب التي تم نشرها وملخصاً لأهم الإستنتاجات التي تم التوصل إليها حتى تاريخ إعدادها.

Abstract: *Three-phase relative permeability data are required to run reservoir simulation studies or to evaluate reservoir performance. These data can be obtained from laboratory measurements or by theoretical models. Experimental studies have been carried out since 1941. The difficulties observed during the experimental procedures and calculations have limited the work conducted in this area. Only scattered amounts of published data are available in this subject.*

This paper gives an overview on the work done on experimental three phase relative permeability data, which presented in chronological order for the subject along with the main conclusions.

INTRODUCTION

Leverett and Lewis[1] were the first to publish results for three-phase relative permeability in unconsolidated sandstones in 1941. Unfortunately, only few experimental studies have been reported in the literature. Table 1 summarizes, in chronological order, most of the experiments results reported to date. In this brief ovreview, the main conclusions of the experimental results are presented.

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THREE-PHASE WATER RELATIVE PERMEABILITY

Several investigators[1,3,8,9,11,12,13,18] reported that in water-wet systems, the three-phase relative permeability to water depends mainly on the water saturation and the effect of saturation history on the water relative permeability is insignificant. Accordingly, two and three-phase water relative permeability are approximately the same at the same water saturation. Others[2,4,5,7,10] have found that three-phase water relative permeability is not just a function of it's own saturation but is dependent upon the saturation of all three phases.

Water isoperms, as reported by many investigators, are shown in figure 1. Water isoperms are either linear or concave toward 100% water apex. Linear isoperms indicate that the water relative permeability is a function of its own saturation while the concave water isoperms indicate higher water relative permeability when both gas and oil are present than in the presence of gas and oil alone. Linear isoperms are more likely to represent the water isoperms because water relative permeability does not depend on the saturation history in water-wet systems.

THREE-PHASE GAS RELATIVE PERMEABILITY

Leverett and Lewis[1] reported that the three-phase gas relative permeability is slightly less than

Table 1. Chronological listing of three-phase relative permeability experiments

Ref #	Date	Authors	Rock Propertis				Exp. type	Saturation Measures	Treat of	Treat of	Kr function			Isoperms		
			Rock type	Porosity %	k,mD	Wettability	Dynamic ss	Resistiviy	Hysteresi	End effect	Krw	Kro	Krg	Water	Oil	Gas
1	1941	Leveret	Uncons ss	42	5000-16000	...	Dynamic ss	Resistiviy	Ignored	Neglected	Sw	Sw,So,Sg	Sw,So,Sg	Linear	Concave	Convex
2	1951	Caudle	Cons ss	23	35	oil	Steady state	Vacum distill	Ignored	Neglected	Sw,So,Sg	Sw,So,Sg	Sw,So,Sg	Concave	Concave	Convex
3	1956	Corey et al	Berea ss	....	...	water	Steady state	Gravity	Diff Cores	Diaphragm	Sw	Sw,So,Sg	Sg	.....	Concave	Linear
4	1956	Reid	Uncons ss	35	3100	...	Steady state	Resist-Gama	Ignored	Mid cores	Sw,So,Sg	Sw,So,Sg	Sw,So,Sg	Concave	Convex	Concave
5	1962	Snell	Uncons ss	35	7100	water	Steady state	Rcl+Neutron	Revaluated	Mid cores	Sw,So,Sg	Sw,So,Sg	Sw,So,Sg	Concave	Convex	Convex
6	1966	Sarem	Berea ss	20	275	water	Unsteady	Volumetric	Ignored	Neglected	Sw	....	Sg	Linear	Linear	Linear
7	1966	Donald	Berea ss,ls	19-20	42.4-	water	Unsteady	Volumetric	Ignored	High rates	Sw,So,Sg	Sw,So,Sg	Sw,So,Sg	Concave	Concave	Convex
8	1967	Saraf	Boise ss	26	1450	water	Steady state	NMR	Diff Cores	Mid cores	Sw	Sw,So,Sg	Sg	...	Convex	Linear
9	1970	Schneinder	Torpedo ss	24	370	water	Steady state	Resist+Xray	Evaluated	Not discussed	Sw	Sw,So,Sg	Sw,So,Sg	Linear	Linear	...
10	1982	Vanspronsen	Berea ss	21.3-26	480-600	water	Steady state	Centrifuge	O/W imbib	High rates	Sw,So,Sg	Sw,So,Sg	.....	Concave	Concave	...
11	1982	Saraf et al	Berea ss	23	510-580	water	Steady state	M-balance	Not Discussed	Mid cores	Sw	Sw,So,Sg	Sg	Linear	Concave	Linear
12	1988	Oak et al	Berea ss	...	160-210	water	Steady state	X-ray	Not Discussed	Mid cores	Sw	Sw,So,Sg	Sw,So,Sg	Linear	Linear	Convex
13	1990	Oak	Berea ss	...	200-1000	water	Steady state	X-ray	Not Discussed	Not discussed	Sw	Sw,So,Sg	Sg	Linear	...	...
14	1990	Narahara	Berea ss	21.5	635-860	water-mixed	Unsteady	Centrifuge	Not Discussed	Comp-Cores	Sw	So	Sg	...	...	...
18	1990	Dria et al	Dolomite	20.2	24	water	Steady state	Tracer	Not Discussed	High rates	Sw	So	Sg	...	...	...
15	1991	Marek et al	LS	23.4	...	mixed	Steady state	Ct Scanner	Not Discussed	Not discussed	....	...	.....	...	Convex	...
23	1993	Kalaydjian	s.s	0.16-0.196	800-2300	water	Steady state	X-ray scan	Evaluated	semi-perm	....	....	...	....	...	....
24	1993	Baker et al	s.s	....	....	various	gravity drain	....	....	....	....	So+Sw	....	....	....	....
25	1994	Skauge et al	s.s	....	....	water	gravity drain	Gamma ray	....	....	....	....	....	....	....	....
26	1995	Eleri et al	s.s	18.2-22.5	234	water	Steady state	Gamma ray	....	Scaled	Sw	....	....	....	....	....
27	1995	Naylor et al	s.s	....	....	water	Unsteady	radioactive	....	....	....	So	....	....	....	....
28	1995	Goodyear	s.s	....	....	water	Unsteady		....	....	....	....	....	....	....	....
29	1996	Vizika	Sand packs	35	10000-14000	various	gravity drain	Ct Scanner	....	....	....	....	....	....	....	....
30	1996	Nordtvedt	Chalk	0.398	2.27	water	Unsteady	Ct Scanner	....	....	....	....	....	....	....	....
31	1998	Sahni et al	Sand packs	....	....	water	gravity drain	Ct Scanner	....	....	....	....	....	....	....	....
32	2000	Di carlo	Sand packs	....	....	various	gravity drain	Ct Scanner	Evaluated	....	....	....	....	....	....	....

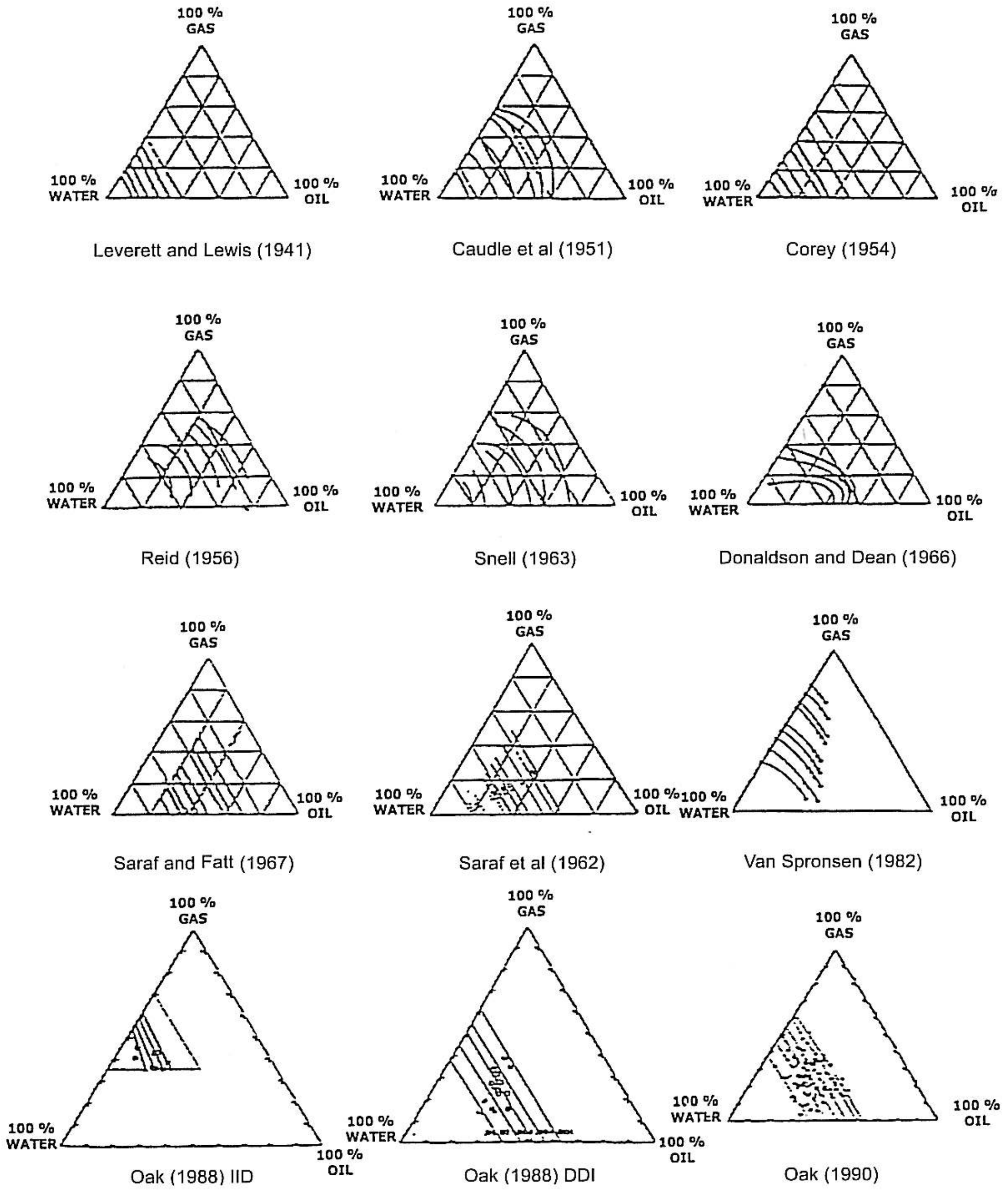

Fig. 1. A collection of water isoperms from the current literature.

what would correspond to the same gas saturation in two-phase flow. Saraf and Fatt[8] found that the three-phase gas relative permeability depends only on the total liquid saturation and is independent of oil and water saturations taken individually. Some investigators[3,6,14,18] found that three-phase gas relative permeability is a function of its own saturation only. Others[2,4,5,7,9] reported that gas relative permeability is dependent upon the saturation of all three phases.

Oak[13] and Saraf *et al*[11] reported that gas relative permeability depends mainly on gas saturation and saturation history of the gas phase. Both two-phase and three-phase relative permeability are approximately the same at the same saturation and saturation histories of the gas phase. Dicarlo *et al*[32] found that the gas relative permeability is smaller in an oil-wet medium than in a water-wet medium and explained their observations in terms of wetting spreading and pore scale configurations of fluids.

Gas isoperms from a variety of major studies are shown in figure 2. No definite trend can be observed because of errors associated with experimental measurements and dependence of gas relative permeability on the saturation history.

THREE-PHASE OIL RELATIVE PERMEABILITY

Leverett and Lewis[1] reported that oil relative permeability varies in a complex manner. Caudle

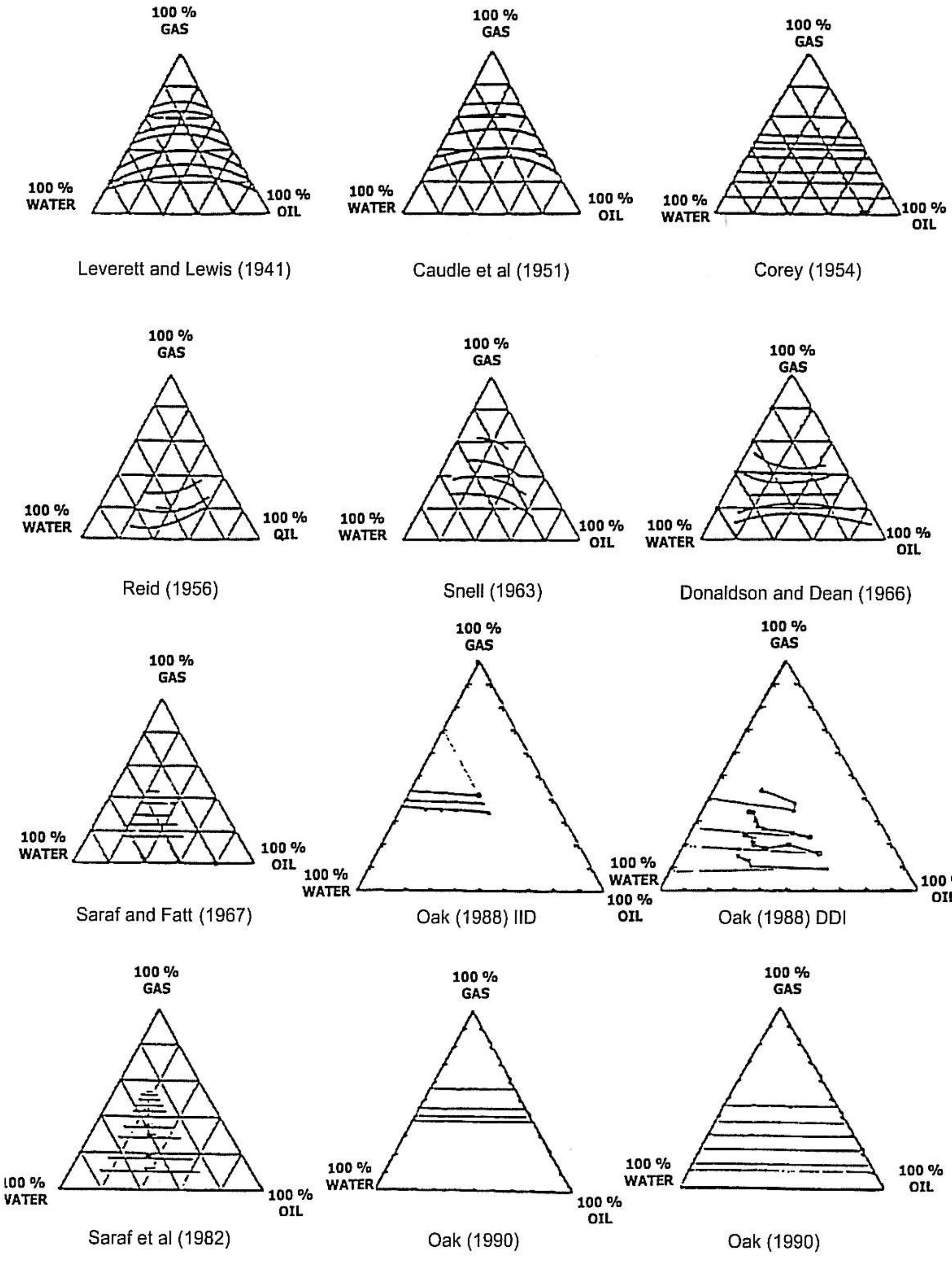

Fig. 2. A collection of gas isoperms from the current literature.

and Slobod[2] found that oil permeability is dependent on the saturation of all phases. Sarem [6] and Dria and Pope[18] found that oil relative permeability is a function of oil saturation only.

Other investigators[3,9,7,8,11,12,13] found that three-phase oil permeability varies not only with oil saturation but also with saturation of water and gas. The variation depends on saturation history.

Figure 3 shows oil isoperms from a number of studies. These results indicate that no general trend can be observed. The shape of theses isoperms are referred to as being concave or convex with respect to the 100 % oil saturation apex. More than half of the studies show a concave type of oil isoperms which indicates that, at high oil saturation, the oil permeability is higher when both gas and brine are present than in

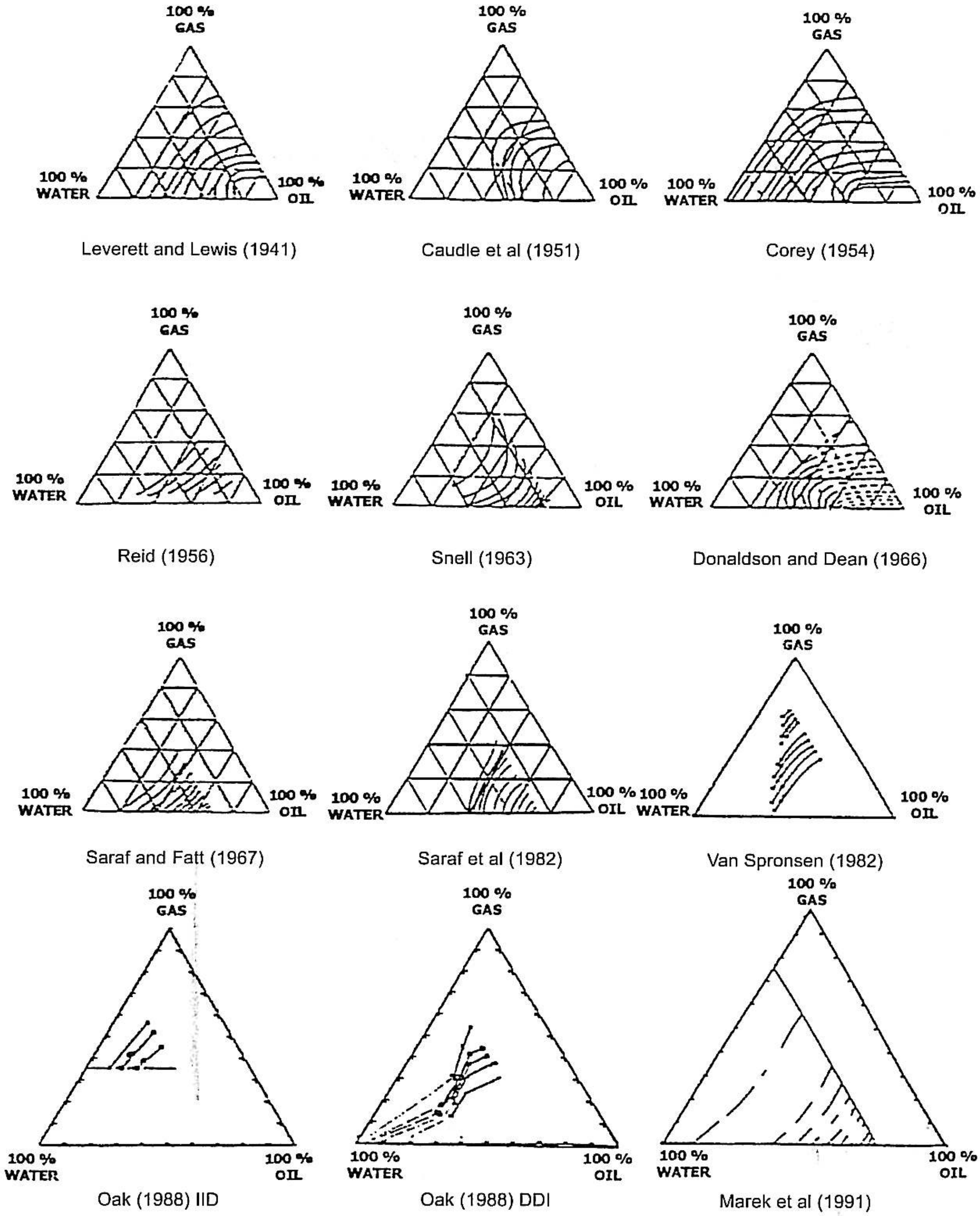

Fig. 3. A collection of oil isoperms from the current literature.

the presence of gas and brine alone. Saturation history affects the shape and the type of the oil isoperms.

Oak [13] found that more than half of the studies on the primary DDI* show convex type oil isoperms while the oil isoperms for secondary DDI and IDI are concave. Oil isoperms for unconsolidated sandstones are likely to be convex toward 100% oil apex.

FACTORS AFFECTING THREE-PHASE RELATIVE PERMEABILITY

1-Effect of Saturation History

Most experimental studies either have ignored or incompletely reported saturation history effect. Oak *et al* [12] have reported two cases of saturation histories . They found that in the primary DDI*, oil and gas relative permeability depend on three-phase saturations and in the primary IID, oil and gas relative permeability depend on their own saturation only. The water relative permeability is a function of water saturation only for both DDI and IID saturation histories.

Oak [13] studied six cases of saturation histories. He indicated that gas relative permeability depends upon the saturation history of the gas phase. The three-phase gas relative permeability was divided into two groups. In group 1, the gas saturation changes in increasing directions (drainage) as in the case of primary and secondary DDI's, DDI and IDI. In group 2, the gas saturation changes in decreasing directions, as in the case of IID, IDD, and DID. It was concluded that the effect of saturation history on the water permeability is insignificant and for gas and oil relative permeability it shows significant variations. As a result, oil and gas relative permeability varied with both their saturation and saturation histories.

2- Effect of Trapped Phases

The displacement of trapped oil by gas is a flow mechanism that occurs only in the three–phase flow system. Oak[13] postulated the following mechanism: If oil is present in a pore, the displacement by gas depends upon whether or not the oil is isolated .If oil is trapped and isolated by water, the displacement is hindered until the water trapping oil is displaced by gas .If the oil maintains continuous flow channels, the oil is immediately displaced by gas as the gas invades the same pore. Thus, the displacement of trapped oil by gas is one of the important events that result in the saturation history effect.

In the water-wet porous media, at a given oil saturation when the water saturation is high and the gas saturation is low, some oil is trapped by the water phase in dead end pores. This results in a lower oil permeability, but as the water saturation is decreased, this effect becomes less pronounced. In a predominately oil–gas system with only small amount of water present, oil (being wetting phase) is not trapped by the gas. Therefore, in the region where the water saturation is low and the gas saturation is high, oil permeability is high when compared to high water and low gas saturation eventhough the oil saturation is the same[8].

Narahara *et al*[14] found that gas-oil primary drainage relative permeability, measured with connate water present, are the same as those measured without connate water present for both water-wet and mixed-wet Berea sandstone provided that the water phase was immobile and the gas-oil relative permeability are expressed as function of total liquid saturation.

Kyte *et al*[16] and Holmgren and Morse[22] demonstrated that in the presence of a gas phase, the residual oil saturation is lower than in the absence of gas. The presence of a gas phase caused a decrease in the residual oil saturation in a water-wet media. It was believed that the ultimate residual oil saturation is trapped by water and that the gas phase, which in turn was trapped within the oil, occupied a portion of space which in the absence of gas would be occupied by oil. In the oil-wet media, the ultimate residual oil saturation is believed to be in the form of pendular rings around the contact points of the rock grains. The gas phase simply occupied space, which in the absence of gas would have been occupied by water. Hence, the trapped gas has no effect on the residual oil in oil-wet media.

Scheneider and Owens[9] found that for oil wet systems the presence of trapped gas affected only the water relative permeability because of the interference between the water and gas (non-wetting phase). Relative permeability to oil was not greatly affected by the presence of trapped gas saturation because oil is the wetting phase. For water-wet system, with trapped gas present, the highest oil

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* The notations DDI, IID, and DIC are used for simplicity to describe the saturations history. The letters indicate directional saturation changes of each fluid phase, in order of water, oil and gas, either decreasing, increasing or remains constant.

relative permeability values (at high oil saturation) fell below the oil relative permeability values obtained in the absence of gas saturation (zero gas saturation). The gas phase as the non-wetting phase with respect to oil had displaced oil from some of the larger flow channels. In the case of low oil saturation, the relative permeability to oil in the absence of gas saturation was lower than in the case of trapped gas present.

Saraf *et al*[11] reported that oil relative permeability was influenced by the direction of gas saturation change. Oil relative permeability was higher at a given oil saturation when gas saturation was decreasing than when gas saturation was increasing. This means simply that the trapping gas enables oil to flow more freely, or alternatively, since they occupy similar pore space. The achievement of gas mobility occurs at the expense of oil mobility. When a core was water flooded after gas flood, a higher ultimate recovery of oil was achieved. The gas seems to release part of the trapped oil allowing it to flow before the gas itself gets trapped in place of the oil.

3- Effect of Wettability:

Most experiments have been performed on uniform water-wet systems. In recent years, some measurements have been made in oil-wet, mixed-wet and fractionally-wet systems [14,15,17,24,29,33].

Oak *et al* [12] studied three-phase relative permeability in an intermediate-wet Berea sandstone and found that the water relative permeability was a function of water saturation only for water-wet media while in oil-wet and intermediate-wet media, the water relative permeability showed some hysteresis and was a function of two saturations. It was also found that the oil relative permeability was a function of two saturations and saturation history and the gas relative permeability was a function of gas saturation and appeared to be insensitive to wettability changes.

Di carlo *et al*[32] measured oil, water and gas relative permeability during three-phase gravity drainage on oil-wet, water-wet, mixed-wet and fractionally-wet sand packs. They found that under uniform wetting, the relative permeability of the most-wetting phase (water in a water-wet pack and oil in oil-wet pack) are similar. They also found that the relative permeability of intermediate-wet phase (oil in water-wet pack) are very different at low saturations. They observed that the gas relative permeability is smaller in oil-wet medium than in a water-wet medium at the same gas saturation.

4-Effect of Spreading:

The spreading coefficient of oil in water in presence of gas, denoted by S, is defined as:

$$S = \gamma_{wg} - (\gamma_{wo} - \gamma_{og})$$

Where γ = represents the interfacial tension between the phases.

When S is positive, the oil tends to form spreading films on the water subtrates thus favoring the hydraulic continuity of the oleic phase and leads to very low residual oil saturation. Kalaydjian *et al*[23] showed that both oil and gas relative permeability are lower under negative than under positive spreading conditions.

Vizika and Lombard[29] concluded that in water-wet and mixed-wet porous media oil relative permeability are higher for positive spreading conditions than for negative spreading conditions. In water-wet porous media, both oil and gas relative permeability are lower in the case of non-spreading and for low oil saturation. In oil-wet porous media, the same oil and gas relative permeability are obtained for both spreading and non-spreading cases.

LABORATORY CONDITIONS

Most of the experimens were carried out to improve the measurement techniques. The techniques used for measuring the relative permeability data ranged from resistivity measurement of fluid saturation to up -to-date technology of X-ray Computed Tomography (CT) scanning.

Most of the experiments were run under steady-state conditions and few were run under unsteady-state conditions. Steady-state methods proved to have broadest applicability and flexibility in controlling changes in the saturation of each of the three fluid phases in the system[9]. However, Unsteady-state methods are possibly the simplest and quickest methods of obtaining three–phase relative permeability data[6]. Steady-state three-phase relative permeability to both water and oil are similar to those obtained by unsteady-state methods. Schneider and Owens[9] found that steady state gas relative permeability are lower compared to unsteady-state values for increasing gas saturation, whereas the reverse is true for decreasing gas saturation (this may be related to the trapping of different amounts of gas in the two process).

Eleri *et al*[26] showed that more hysteresis is observed in the unsteady-state relative permeability curves than in the steady-state relative permeability curves. They also indicated that the unsteady-state relative permeability curves observed more oil-wet conditions than the steady-state relative permeability curves.

Berea sandstone has been used extensively in the experiments. The rock properties of the Berea sandstone are close in porosity values but not in absolute permeability values. Water-wet conditions are always considered for Berea sandstone. Few studies were conducted in carbonate rocks[15,18,23].

Air and N_2 are the most common gases used to represent the gas phase in three-phase relative permeability measurements because of their low interaction with other fluids. Dria and Pope [(18] showed that there are significant differences in results between the three-phase relative permeability measured when the gas is CO_2 and when the gas is N_2 or Air. All the experiments used refined hydrocarbon liquids and brine solutions to represent both the oil phase and the water phase. Eleri *et al* [26] concluded that extensive flushing of a restored core with refined oil may lead to a non- representative relative permeability data and should be, therefore, avoided. Use of ideal clean fluids rather than reservoir fluids may put some limitation on the use of experimental data to represent the reservoir conditions.

Experimental errors were reported in many experiments. Most of the errors are attributed to lack of consideration of the capillary end effect and hysteresis effect. Measurement of the data is always a problem, and most of the experimental work was targeted to improve the techniques of measurement rather than to study the phenomena of three -phase flow. The work of Leverett and Lewis [1] did not take into consideration the capillary end effect and hysteresis. Errors were also reported due to dead space in the cell and failure to reach equilibrium. Their work was considered incomplete.

Caudle and Slobod [2] used vacuum distillation for determining fluid saturations. This technique is very lengthy and time consuming. The authors described their work as incomplete. Fayers and Matthew[17] considered the results of Corey *et al*[3] incorrect because of uncertainties associated with non-uniform trapped water and the limited number of consistent results. There were possible errors in oil and gas saturation measurement when using Gamma-ray absorption due to differential absorption of Gamma rays by the oil and water phases.

The method proposed by Sarem[6] is simple and comparatively fast, but the assumptions that all relative permeability depend only on their saturations seem to be unrealistic and also neglecting capillary effect is a weak assumption.

Oak(13) reported that no data can be collected for high gas saturation because of an experimental limitation on the maximum gas injection rate.

All the experiments were run under different conditions and different measurement techniques in such a way that it becomes difficult to compare the results. A general standard of experimental procedures has not been set by the oil industry in order to make the studies of the three-phase relative permeability more compatible.

CONCLUSIONS

Based on this overview of the experimental work on three-phase relative permeability data, the following conclusions can be drawn:

1- Analysis of the experimental results indicates that there is no agreement on the qualitative or quantitative results obtained from the experiments. The discrepancy may be due to the different types of measurement techniques, different saturation histories, neglect of capillary end effect and hysteresis effect, and other experimental conditions.

2- The majority of the experiments in water-wet systems agree on the following points.
   - a- The three–phase water relative permeability depends on its saturation and does not depend on the saturation history.
   - b- The three-phase oil relative permeability behaves in a complex manner. It depends not only on its saturation but also in the other phase's saturation and on the saturation history.
   - c- The three-phase gas relative permeability depends on the oil, gas, and water saturation and may depend on the saturation history.

3- There are insufficient data for oil-wet systems. It is difficult to determine whether the oil, gas and water isoperms are significantly different from isoperms of water wet systems.

4- The effect of trapped oil and trapped gas on relative permeability has not been resolved.

5- Lack of experimental data have been reported for three-phase oil permeability at low oil saturation and for three-phase gas permeability at high gas saturation

6- More attention should be given to the saturation history for three-phase relative permeability studies. It is concluded from the latest experimental work that saturation history has an effect on the results of the relative permeability.

7- The complexity of experimental and calculation procedures for the three-phase relative permeability are primary reasons why published data in this area are limited.

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