Comparison of Calculated with Experimental Imbibition Relative Permeability

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ABSTRACT

Two-phase imbibition relative permeability was measured in an attempt to validate a method of calculating imbibition relative permeability. The stationary-liquid-phase method was used to measure several hysteresis loops for alundum and Berea sandstone samples. The method of calculating imbibition relative permeability is described, and calculated relative permeability curves are compared with measured curves. The calculated relative permeability is shown to be a reasonably good approximation of measured values if an adjustment is made to some necessary data. Due to the compressibility of gas, which is used as the nonwetting phase, a correction to the measured trapped gas saturation is necessary to make it agree with the critical gas saturation of the imbibition relative permeability curve.

INTRODUCTION

The existence of hysteresis in the relationship of relative permeability to saturation has been recognized for many years. Geffen et al.1 and Osoba et al.2 called attention to the occurrence of hysteresis and the importance of the direction of saturation change on the relative permeability-saturation relations. It is generally believed that relative permeability is a function of saturation alone for a given direction of saturation change, but that there is a distinct difference in relative permeability curves for saturation changes in different directions. The reservoir engineer should be aware of this hysteresis, and he should select the relative permeability curve which is appropriate for the recovery process of interest.

The directions of saturation change have been designated "drainage" and "imbibition" in reference to changes in the wetting-phase saturation. In a two-phase system, an increase in the wetting-phase saturation is referred to as imbibition, while a decrease in wetting-phase saturation is called drainage. The solution-gas-drive recovery mechanism is controlled by relative permeability to oil and gas in which the saturation of oil, the wetting phase, is decreasing. In waterflooding a water-wet reservoir rock, the saturation of water, the wetting phase, is increasing. These two sets of relative permeability curves, gas-oil and oil-water, do not have the same relationship to the wetting-phase saturation. This difference is not due to the difference in fluid properties, but is a result of the difference in direction of saturation change.

The flow properties of the drainage and imbibition systems differ because of the entrapment of the nonwetting phase during imbibition. As drainage occurs, the nonwetting phase occupies the most favorable flow channels. During imbibition, part of the nonwetting phase is bypassed by the increasing wetting phase, leaving a portion of the nonwetting phase in an immobile condition. This trapped part of the nonwetting-phase saturation does not contribute to the flow of that phase, and at a given saturation the relative permeability to the nonwetting phase is always less in the imbibition direction than in the drainage direction.

The concept that some of the nonwetting phase is mobile and some is immobile during a saturation change in the imbibition direction previously was used to develop equations for imbibition relative permeability.3 In this development, it was assumed that the amount of entrapment at any saturation can be obtained from the relationship between initial nonwetting-phase saturations established in the drainage direction and residual saturations after complete imbibition. The equations for imbibition relative permeability were not verified by laboratory measurements. The purpose of this report is to give the results of a laboratory study of imbibition relative permeability and to present a comparison of calculated relative permeability with relative permeability from laboratory measurements.

In two-phase systems, hysteresis is more prominent in the relative permeability to the nonwetting phase than in that to the wetting phase. The hysteresis in the wetting-phase relative permeability is believed to be very small, and thus difficult to distinguish from normal experimental error. For this reason, it
was decided that investigation of the nonwetting-
phase relative permeability would be sufficient to
check the validity of the calculation procedure. The
two-phase system of gas and oil was chosen for
investigation because of the simplicity of the
measurements involved and the certainty of
wettability tendencies. From generally accepted
relative permeability concepts, it is considered
that the gas-oil relative permeability curves are the
same as would be obtained from any other system
of two fluids, provided that one fluid is completely
wetting and the other nonwetting. Then, if the
calculation procedure is applicable to the gas-oil
system, it is considered valid for a water-wet
two-phase system of water and oil for the same
direction of saturation change.

CALCULATION OF
RELATIVE PERMEABILITY

Imbibition relative permeability to gas was
calculated using previously published equations.3
These equations were derived from established
theory of the dependence of relative permeability
on pore-size distribution. In the development of
these equations it was assumed that, during
imbibition, the nonwetting phase can be treated as
two separate saturations. It is considered that part
of the nonwetting phase is trapped and does not
contribute to flow, but that the mobile part of the
nonwetting phase can be used as the saturation of
the nonwetting fluid to be used in the calculation
of relative permeability. The mobile nonwetting-
phase saturation is calculated from the relation of
the residual nonwetting-phase saturation left after
imbibition starting from an initial nonwetting-phase
saturation established in the drainage direction.
Residual gas saturations from laboratory imbibition
tests were assumed to be the correct residual or
“critical” nonwetting-phase saturations of imbibition
relative permeability curves. This relationship
between initial and residual gas saturations is a
curve of characteristic shape which has been found
to be approximated by the equation

\[ \frac{1}{S_{rg}^{*}} - \frac{1}{S_{rg}} = C \]

where the constant C is a trapping characteristic of
the porous rock, and \( S_{rg}^{*} \) and \( S_{rg} \) are effective
residual and effective initial saturations, respectivley.
The effective saturations \( S_{rg}^{*} \) and \( S_{rg} \) are expressed as fractions of the pore volume excluding
the pore volume occupied by the irreducible wetting
phase. The effective saturations are related to the
ordinary saturations by the equations, \( S_{rg}^{*} = S_{gr}/(1
- S_{gr}) \) and \( S_{rg} = S_{gr}/(1-S_{gr}) \), where \( S_{gr} \) and \( S_{rg} \) are residual and initial gas saturations, respectivley, and \( S_{gr} \) is the irreducible oil saturation fractions of the pore volume.

Eq. 1 has been used to derive the equation for the
saturation of mobile gas during the imbibition cycle:

\[ S_{gF}^{*} = \frac{1}{2} \left[ S_{g}^{*} - S_{g}^{*} \right. \]

\[ + \frac{1}{C} (S_{g}^{*} - S_{g}^{*})^2 \right] \]

where \( S_{gF}^{*} \) is the effective mobile gas saturation
and \( S_{g}^{*} \) is the effective total gas saturation, including trapped gas. Relative permeability to gas,
\( k_{rg} \), for the imbibition direction of saturation change is calculated from

\[ k_{rg} = S_{gF}^{*2} \left[ 1 - (1-S_{gF}^{*})e^{-2} \right] \]

where \( \epsilon \) is a pore-size distribution factor. The
exponent, \( \epsilon \), is the same as the exponent of
saturation in the drainage wetting-phase relative
permeability equation of the Corey type: \( k_{ro} = S_{o}^{*q} \). Values of \( \epsilon \) and \( C \) to be used in the above equations
are empirically determined from the appropriate
laboratory data.

In calculating an imbibition gas relative
permeability curve, the point where imbibition
starts is selected. This is the maximum gas
saturation that has been established by drainage of
oil. After converting this saturation to the effective
saturation, Eq. 1 is used to find \( S_{g}^{*} \). For various
gas saturations, the mobile gas saturation, \( S_{gF}^{*} \),
is calculated from Eq. 2. The mobile gas saturation
is used in Eq. 3 to calculate \( k_{rg} \). Calculated values of \( k_{rg} \) are plotted against \( S_{gF}^{*} \) or \( S_{g}^{*} \) used in the
calculations.

EXPERIMENTAL METHODS

Cylindrical core samples approximately 1 in. in
diameter and 1½ in. in length were prepared for
testing. Two plug samples were cut from a block of
aluminum having a permeability of approximately 1
darcy and approximately 45 percent porosity. A
block of Berea sandstone outcrop was selected
which has a very uniform appearance with no
visible bedding planes. Four cylindrical samples
were cut from the Berea block; two were cut at
right angles to the other two to determine if the
sandstone was isotropic. Permeability of the Berea
samples was approximately 1 darcy and porosity
was approximately 23 percent.

The stationary-liquid method, which has been
described by Osoba et al.2 and Loomis and Crowell,4
was used to measure gas relative permeability.
Osoba et al.2 reported use of this method for
measuring gas relative permeability in the imbibition
direction as well as the normal application in the
drainage direction. In this method, gas flows
vertically upward under a pressure drop approxi-
mately equal to the gravity head of oil saturating
the core sample. Owing to this choice of pressure
drop, a capillary pressure gradient in the sample is
avoided. The plug samples were placed in a
Hassler-type holder for flow measurements, and
soap-film flowmeters were used to measure flow
rate. Dry nitrogen was used as the flowing gas.
Saturations were determined gravimetrically before and after each permeability measurement; and the average of these two saturations was the saturation associated with the relative permeability from the measurement.

At the beginning of each series of relative permeability determinations, the samples were saturated with Soltrol 130. Desaturation of the samples initially was by blotting with absorbent paper; but at low oil saturations blotting is less effective in removing oil from the samples and desaturation was mostly by evaporation. While allowing oil to evaporate from the samples, care was taken that evaporation did not occur too rapidly and that too large a saturation change did not take place between permeability measurements. These precautions were taken to keep the saturations of the samples as uniform as possible. In addition, several of the samples were desaturated by the centrifuge method. This first series of relative permeability measurements were determinations of the complete gas relative permeability curve with the saturation change in the drainage direction.

Several hysteresis loops for each sample were investigated. Permeability measurements were made with the saturation change in the drainage direction until a preselected saturation was reached. Then imbibition relative permeability to gas was measured for saturations between the preselected saturation and the saturation at which no more imbibition of oil occurs. Two procedures were used for changing saturations for imbibition relative permeability. In some cases the samples were allowed to imbibe small quantities of oil dropped on the samples to increase the oil saturation; at other times, the samples were allowed to imbibe oil until the maximum oil saturation was reached, and the samples were desaturated in the manner used for drainage relative permeability. This latter procedure is based on the reported observations that, after imbibition, relative permeability with saturation change in the drainage direction retraces the imbibition relative permeability curve until the previous minimum oil saturation is reached. In both procedures, saturation changes were taken in small steps to maintain a uniform saturation distribution through the samples. After a saturation change, samples were placed in a desiccator containing oil for a few minutes before the permeability tests. This was to prevent evaporation while allowing capillary forces to distribute saturations, eliminating any unequal saturation distribution that may have resulted from removal or addition of oil at the surface of the sample.

In addition to the relative permeability measurements, the relationship between initial gas saturation, established in the drainage direction, and the residual gas saturation after imbibition was investigated. The cylindrical samples used in relative permeability measurements were used in determining the residual-to-initial gas saturation relation. Saturations were changed by methods used in connection with the relative permeability measurements. A preselected saturation was established in the drainage direction. Then imbibition of oil was allowed until no more oil was imbibed. The saturation after imbibition was determined and this residual gas saturation was plotted vs the maximum gas saturation of the drainage cycle. All saturations were determined gravimetrically. After imbibition, the oil saturation was again decreased until a gas saturation larger than the previous maximum gas saturation was established, and another imbibition cycle was completed. This procedure was continued until the entire range of saturation was investigated.

**DISCUSSION OF RESULTS**

Results of the measurements of drainage relative permeability to gas were plotted against oil saturation as shown in Fig. 1 for alundum and in Fig. 2 for Berea sandstone. The scattering of data points is due to experimental error normally occurring in the measurement of relative permeability. The different methods of desaturation were observed to give equivalent results, and no distinction of methods was made in plotting the results. Data from all four Berea sandstone plug samples are shown in Fig. 2. Good agreement was obtained in results from samples cut in different directions, indicating that the block of Berea sandstone was uniform and isotropic. Figs. 1 and 2 contain relative permeability data for saturations between the previous maximum gas saturation and the saturation beginning the next imbibition cycle, as well as data of the continuous drainage curve. No difference is seen in the drainage relative permeability between hysteresis loops and the uninterrupted drainage curve.

The curves of Figs. 1 and 2 are trial-and-error fits of the equation proposed by Brooks and Corey,

\[ k_r = (1 - S_o)^2 (1 - S_w^c)^2 \]

In this equation, \( \epsilon \) is a pore-size distribution parameter and is related to the capillary pressure curve. For our purpose, the value of \( \epsilon \) may be taken as any number that gives a good approximation by the equation to the measured relative permeability data. Various values for \( S_{or} \) and \( \epsilon \) were used in calculating relative permeability curves. The curves giving the appearance of the best fit to data on the semilog plot were selected as representing the relationship of drainage relative permeability to saturation. The equation for relative permeability of the alundum samples (Fig. 1) has the residual oil value of 0.02 and the exponent, \( \epsilon \), equal to 3.2. These are realistic parameters for this synthetic porous material, because they represent an almost uniform pore size and a very small residual wetting-phase saturation. Drainage relative permeability (Fig. 2) of the Berea samples is represented by the equation having \( \epsilon = 3.0 \) and \( S_{or} = 0.19 \). The value of \( \epsilon \) is smaller than was expected, indicating uniform pore size. With a lower residual oil saturation, a more physically realistic value of \( \epsilon \) gives a good fit to the data except at
low oil saturations. However, the curve with \( \epsilon = 3.0 \) was taken as the equation of relative permeability in preference to the fit to a limited range of data, although a larger value of \( \epsilon \) may be physically justified.

Residual gas saturation left after imbibition of the wetting phase is shown plotted vs the initial gas saturation before imbibition in Figs. 3 (alundum) and 4 (Berea). The least-squares fit of Eq. 1 to the data of each plot was found by trial and error. A value of \( C \) for the alundum samples was found to be 4.617; \( C \) for the Berea sample was found to be 1.273. Some experimental error is apparent at low gas saturations with the Berea samples (Fig. 4) since the plotted data appear not to tend toward the origin. Results of the residual gas determinations were reproducible, and the source of the discrepancy could not be found.

Fig. 4 shows results of several series of tests using the different methods of desaturation previously discussed. The different methods establishing the initial gas saturations gave equivalent results. Also, results were the same when the samples were dried and resaturated after each imbibition cycle as they were when, after each imbibition, the next higher drainage gas saturation was established and the entire curve determined as a series of cycles.

Results of the imbibition relative permeability measurements are shown in Figs. 5 and 6. In these figures, part of the data plotted is from the imbibition direction of saturation change and part
is from saturation changes in the drainage direction following imbibition. The fact that both directions of saturation change give equivalent results verifies that imbibition relative permeability is reversible. This also indicates that the stationary-phase method of measuring imbibition relative permeability gives valid results since, if saturation distributions were not uniform, the effects of different saturation distributions would be seen from the two directions of changing saturations.

As in the drainage case, the various methods used to change saturations give results which are indistinguishable. The dashed curves of Figs. 5 and 6 are the drainage curves from Figs. 1 and 2, respectively. Fig. 5 shows the results of imbibition relative permeability measurements on the two alundum samples with maximum drainage gas saturations of approximately 0.45, 0.60 and 0.90. Results of the four Berea samples, Fig. 6, are for maximum drainage saturations of approximately 0.25, 0.35 and 0.80. With the exception of the data for the curve of Fig. 6 starting at a gas saturation of 0.80, the scatter of data indicates experimental error about the same as for the drainage relative permeability. The relative positions of the data trends with respect to the drainage curves are in agreement with the anticipated behavior of imbibition relative permeability.

Comparison of Fig. 5 with Fig. 3 and Fig. 6 with Fig. 4 reveals a discrepancy between the critical gas saturation of the imbibition relative permeability curves and the residual gas saturation after imbibition. Consider, for example, the middle imbibition curve of Fig. 5. Starting at an oil saturation of 0.40, the relative permeability to gas decreases steadily with an increase in oil saturation as an apparent residual gas saturation of approximately 0.30 is approached. At this saturation (oil saturation equal to 0.70), no flow was observed while attempting to measure permeability. Although no gas flow was apparent, the samples were capable of imbibing more oil until an oil saturation of approximately 0.84 was reached. The resulting gas saturation of 0.16 is in agreement with the residual gas saturation of Fig. 3 for an initial gas saturation of 0.60. Since no gas flow occurs after the first apparent residual or critical gas saturation is reached, it seems reasonable that a continuation of imbibition of oil must be accompanied by compression of trapped gas. While gas is flowing near atmospheric pressure, the oil phase must be at a pressure lower than atmospheric owing to capillary pressure. When the gas phase becomes discontinuous and no longer flows, continued imbibition of oil will terminate with pressure in the oil phase equal to atmospheric pressure, while pressure in the trapped gas will be increased to values determined by the interfacial tension and curvatures of the gas-oil interfaces. From these considerations, it is apparent that the residual gas saturations after imbibition as shown in Figs. 3 and 4 are not the critical gas saturations associated with the point on the relative permeability curve at which gas ceases to flow.

In the development of the relative permeability equations, the assumption was made that the
residual gas saturation after imbibition corresponds to the critical gas saturation of the imbibition relative permeability curve. This assumption appears to be incorrect when laboratory methods are used in which compression of the trapped gas is possible, and a modification of the procedure for calculating imbibition relative permeability is necessary.

The solid curves of Figs. 5 and 6 were calculated using Eq. 3 with $S_{gr}^*$ calculated from Eq. 2. In Eq. 2, a value of $C$ was used which is smaller than the value found experimentally. Using a smaller value for $C$, $S_{gr}$ from Eq. 1 is larger than indicated by the experimental relations shown in Figs. 3 and 4. The curves shown in Fig. 5 for imbibition relative permeability of the alundum samples were calculated using a value of 1.80 for $C$, which gives the relation between $S_{gr}^*$ and $S_{gi}$ shown by the dashed curve of Fig. 3. For Berea sandstone, a value of $C$ equal to 0.80 results in the relation of the dashed curve of Fig. 4 and the calculated imbibition relative permeability curves shown in Fig. 6.

While the selection of the appropriate value of $C$ is necessary to obtain a good fit to the experimental relative permeability data, it is significant that this value of $C$ gives agreement with all of the individual hysteresis loops for that porous material. This can be interpreted to mean that Eqs. 1 through 3 can be used to approximate imbibition relative permeability to gas, provided Eq. 1 gives the correct relationship for the residual values of the dynamic system.

In view of accepted relative permeability theory, we may consider the gas relative permeability obtained in this study to be equivalent to oil relative permeability that would be obtained from a strongly water-wet system of water and oil. The curve of imbibition relative permeability to oil starting at the irreducible water saturation (the curve commonly measured for use in waterflood calculations) can be found from the drainage (gas-oil) curve if a value of $S_{or}$ is known. Also, any of the intermediate imbibition oil relative permeability curves, which are associated with mobile connate water saturations, can be calculated using data from either the drainage curve or the major imbibition curve.

CONCLUSIONS

The different methods used to desaturate the porous materials and the different directions of saturation change while tracing the imbibition relative permeability curves give consistent results. This consistency indicates that the saturation distribution is sufficiently uniform, and that valid imbibition relative permeability to gas is obtained using the stationary-liquid-phase method.

Laboratory investigations of imbibition relative permeability to the nonwetting phase have verified fundamental behavior of relative permeability which has been reported previously and which was considered essential to the development of the equations being tested. It was observed that imbibition relative permeability to the nonwetting phase is reversible; that is, the drainage curve following imbibition retraces the imbibition curve until the previous maximum nonwetting-phase saturation is reached. Also, continuation of the drainage nonwetting-phase relative permeability curve above the previous maximum nonwetting-phase saturation follows the unique drainage curve which is not influenced by previous imbibition cycles.

The method for calculating imbibition relative permeability to the nonwetting phase of the two-phase system was found to be correct, fundamentally; but certain necessary data were found to be inadequate for use without correction. Laboratory methods used to find residual gas saturations after imbibition give a relationship between residual gas saturations and initial gas saturation that is not in agreement with the critical gas saturation of the measured imbibition relative permeability curve. This discrepancy is believed to be due to the compressibility of the trapped gas. If a correction is made to this residual gas relation so that one relative permeability hysteresis loop is matched, other hysteresis loops can be calculated correctly. From this observation, the conclusion is reached that if the correct residual nonwetting-phase saturation relation is available, the equations yield good approximations of the measured imbibition nonwetting-phase relative permeability.

NOMENCLATURE

$C$ = a trapping characteristic, constant for each sand
$k_{rg}$ = relative permeability to gas, fraction of absolute permeability
$k_{ro}$ = relative permeability to oil, fraction of absolute permeability
$S_{g}$ = gas saturation, fraction of pore space
$S_{gi}$ = initial gas saturation established by drainage, fraction of pore space
$S_{gr}$ = residual gas saturation after complete imbibition, fraction of pore space
$S_{g*}$ = residual effective gas saturation, fraction of effective pore space
$S_{gr}^*$ = $S_{g*}^*/(1 - S_{or})$ = effective gas saturation, fraction of effective pore space
$S_{gr}^*$ = $S_{g*}^*/(1 - S_{or})$ = initial effective gas saturation established in the drainage direction, fraction of effective pore space
$S_{g}^*$ = residual effective gas saturation after complete imbibition, fraction of effective pore space
$S_{g*}^*$ = mobile or "free" effective gas saturation, fraction of effective pore space
$S_{o*}$ = pore-size distribution factor, exponent in the equation for drainage wetting-phase relative permeability, $k_{ro} = S_{o*}^*$
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REFERENCES


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