# IMPACT OF DISPLACEMENT RATE ON RELATIVE PERMEABIILTY AND RESIDUAL SATURATION IN GAS-ASSISTED GRAVITY DRAINAGE PROCESS

B.Rostami[a,c], R.Kharrat[a], M.Pooladi-Darvish[b], S.Ghotbi[c], S.Samani[d]
a- Petroleum University of technology, Tehran Research Center, Iran
b- University of Calgary, Canada
c- Sharif University of Technology, Iran
d- Helmholtz-Centre, Leipzig-Halle, Germany

*This paper was prepared for presentation at the International Symposium of the Society of Core Analysts held in Abu Dhabi, UAE 29 October-2 November, 2008*

## ABSTRACT
Gas-oil displacement, when stabilized by gravity forces leads to high displacement efficiency, as manifested in high recovery factor associated with gas-cap drive and gravity-drainage. However, oil production rate by gravity drainage could be low, especially when permeability is low. In such cases, economic consideration may require increasing the displacement rate by increasing rate of gas supply (e.g. increasing injection rate). However, this increases the importance of viscous forces as compared with gravity force, which could influence displacement efficiently in a negative way. This paper addresses the impact of displacement rate on gas/oil relative permeability and remaining oil saturation for gravity-assisted gas injection processes. Experiments were conducted where oil was displaced from top to bottom by injecting gas at different rates. The results were analyzed in light of the relevant dimensionless groups.

The second contribution of this paper is an extension of Hagoort's method for determination of relative permeability, when oil displacement occurs by injection of gas from the top. Application of this method results in Corey type oil relative permeability without need for pressure data. To examine the validity of the relative permeability curves, these were used in a numerical model to predict oil production rate, and the results were compared with the experimental data.

Numerical experimentations indicated that at high displacement velocities, the results are not only a function of relative permeability to oil, but also that to gas. In these cases, the relative permeability to gas was determined by history matching. The use of the analytically-determined relative permeability to oil along with the history-matched relative permeability to gas reduced the non-uniqueness problem associated with backward modeling of two-phase flow experiments.
The results of this study indicate that the relative permeability varies with the balance between the gravity and viscous forces. A higher gas injection rate leads to a higher gas relative permeability and lower oil relative permeability. The remaining oil saturation was also found to be much higher for displacement rate above critical rate. This may be due to

loss of hydraulic connectivity of the oil phase, leading to oil trapping and bypassing. On the other had when capillary threshold height is large, it was found that part of the oil left behind by the capillary threshold height could be produced by increasing the gas pressure gradient. This may lead to a larger overall recovery, when the threshold height has a significant effect on the remaining oil saturation.

## INTRODUCTION

One of the important criteria in gas assisted gravity drainage mechanism is the injection and production rates. To find an optimum injection rate and to avoid unfavorable flood front movement, sensitivity analysis needs to be considered on gas injection rate. Generally, in vertical gas flood experiments the unfavorable mobility ratio is attempted to overcome by reducing the viscous force magnitude, by decreasing the injection rate. To accomplish this, the concept of maximum critical rate has been used to define the range of injection rates. The critical rate represents the injection rate in which the unfavorable gravity force effects are overcome by increased magnitude of viscous forces which is defined by Blackwell and Terry (1959) and Dumore (1946).

$$Q_c = (k\Delta\rho gA)/\Delta\mu \tag{1}$$

The rate applied is in most cases much higher than this gravity stable rate, therefore the effect of these high rates on oil prediction and saturation functions need to be considered. Clearly, gas-oil relative permeability is essential for performance prediction of reservoir with gas cap expansion or gas injection. Therefore, the accurate knowledge of relative permeabilities may lead us to better understanding of reservoir evaluation.

In gas assisted gravity drainage mechanism when the gas injection rate change from critical rate to higher rates the fluid flow characterization in reservoir could be changed. Therefore, a distinction should be made for modeling of each part of the reservoir. This difference can be distinguished through the gas/oil relative permeability curves. A comparison between the relative permeabilities determined from gravity dominant flow and gas flood experiments shows that the residual oil saturation is much higher and the oil relative permeability is lower for gas flood tests (Singh et al, 2001).

Usually, an estimate of relative permeability and residual oil saturation of a reservoir section is obtained by carrying out displacement experiments. These laboratory experiments include centrifuge displacements, unsteady state gas flood and steady state measurements for relative permeability quantification (Skauge et al, 1997). The centrifuge experiments represent conditions occurring during gravity dominated flow while unsteady state gas flood tests are conducted to simulate conditions occurring during high front velocity displacement (Singh et al, 2001).

Hirasaki et al (1995) believed that for centrifuge method Limitations include loss of information on the low saturation region that can not be gained from production data at low mobility ratio. Ali (1997) stated that “concerns remain regarding the replacement of centrifugal forces for unsteady state displacement process that are rate dependent". Firoozabadi and Aziz (1988) mentioned that steady state methods offer disadvantages, especially in the case of low permeable rocks where it is laborious to reach multiple steady states. Virnovskey (1995) believed that steady state techniques also require successive measurements for different total rates. Generally, for measuring gas/oil relative permeability all available techniques have their strength and weaknesses. Low viscosity of gas phase gives low differential pressure that contributes to inaccuracies in measurements.

In the method proposed here, the oil relative permeability is obtained by unsteady state displacement data using an analytical approach without need for pressure data. In this way the inaccuracy of low differential pressure has been removed. A previously measured capillary pressure versus saturation relationship is also needed for capillary dominated cases. The limitation of this method includes restricted shape, Corey type, for relative permeability curves. Skauge (1995) mentioned that some authors believed that a Corey representation is often used for case of comparison, thus the application of Corey type oil relative permeability to evaluate the rate effect on relative permeability curves can lead us to desirable answers.

## METHODOLOGY

In this section, the analytical approach and numerical models are briefly described. The validity of the proposed analytical model for determination of the relative permeability to oil is demonstrated. For high velocity experiments when the relative permeability to gas is important, after determination of the oil relative permeability by analytical methods, the gas relative permeability was obtained using history matching of the production data. In all cases, the oil relative permeability curve obtained from the analytical method was used as an input for numerical model and the agreement between experimental results and numerical data was checked. This methodology has been used for all cases at different gas velocity to show the effect of gas injection rate on residual oil saturations, relative permeabilities and oil recovery in consequence.

### Analytical Analysis

The basis of analytical model used here is that of Hagoort (1980). Hagoort introduced a backward methodology for determination of oil relative permeability from centrifugal data. He assumed that the capillary pressure is negligible and the gas phase has an infinite mobility. In forced gravity drainage mechanism with high gas velocity, the viscous force can have a large effect. In this circumstance, the assumption of infinite gas mobility used in Hagoort's model may not be valid. In this study, Hagoort's method is extended to cases where the viscous force is important and the gas mobility needs to be accounted for.

Formulation

Hagoort (1980) simplified the Buckley-Leverret solution by assuming negligible capillary pressure, infinite gas mobility and a Corey type oil relative permeability function. These assumptions yield the following equation for prediction of oil production.

$$N_p = 1 - (1 - \frac{1}{n})(\frac{1}{n\, k_{ro}^o\, t_D})^{\frac{1}{n-1}} \tag{2}$$

Where $k_{ro}^o$ is the curve-fitting parameter and exponent $n$ is the degree of curvature in the oil relative permeability. Note that Equation (2) is the forward solution for $N_p$, the backward solution requires the use of $N_p$ verses $t_D$ data in order to find $k_{ro}(s_{oe}^*)$.

Based on Equation (2), a plot of 1-$N_p$ verses $t_D$ on a log-log paper should be a straight line. Then the following equation can be used to calculate the value of Corey exponent from this straight line.

$$\frac{d\ln(1-N_p)}{d\ln t_D} = -(\frac{1}{n-1}) \tag{3}$$

This method can predict the oil relative permeability only for oil saturations that appears at the outflow end of the core. The relative permeabilities higher than shock front saturation can be found by interpolation. In Hagoort's method the amount of normalized shock front saturation has the following form.

$$s_{oe}^* = (\frac{1}{n\, k_{ro}^o t_D})^{\frac{1}{n-1}} \tag{4}$$

Using numerical experimentations we have observed that at high gas injection velocity, oil production at early time is affected by gas mobility. Therefore, the production data exactly after breakthrough time may not fully represent the oil mobility. Here it is suggested that when gas velocity is high, the straight line should be plotted some times after gas breakthrough to exclude the effect of gas mobility on oil production data. The numerical and experimental results given in the paper demonstrate that this modification could be easily applied graphically and the oil relative permeability exponent is estimated from the transient production data. As can be seen by the numerical experimentations, the early time production data is affected by gas relative permeability. However the gas relative permeability could not be determined; we estimated this parameter by history matching of the experimental production data.

## Numerical Simulation

A numerical model was developed for simulation, prediction and history matching of one-dimensional forced gravity drainage experiments. In this model gas enters from the top of an oil saturated column and oil is produced from the bottom of the model. The oil drainage is simulated and predicted by accounting for the gravity, capillary and viscous forces. The flow is assumed incompressible, and the connate water as modeled as part of the porous medium. The flow and mobility of the gas-phase was also accounted for.

## Verification of Proposed Method

In the following it is explained how a forward/backward loop was utilized to show the applicability of the proposed method. The forward numerical model was used to simulate oil production by incorporating an arbitrary relative permeability function, rock and fluid properties. Table 1 shows a sample of input data for a typical numerical run. The production data from the numerical model was then used in backward analytical model to obtain the relative permeability function. Figure 1 shows the oil production data on log-log scale and the position of straight line. As mentioned earlier, the position of the straight line is not exactly after gas breakthrough time. From the slope of this straight line, the Corey exponent can be estimated (see Equation 3). The oil relative permeability was determined and compared with the input function. Figure 2 shows the estimated oil relative permeability in comparison with the input function, suggesting a good agreement.

**Experiments**

The objectives of the experiments were to observe and quantify the gas-oil dynamic behavior and to verify and validate the proposed mathematical models. The experiments were performed in long cylindrical, sintered packs with a diameter of 3 and 4 cm and length of 60 and 120 cm, containing glass particles of 0.2-0.05 mm in diameter.

The tests were conducted under ambient laboratory temperature and the outlet face of the model was open to atmospheric pressure. Thus the gage pressure at the inlet gives the differential pressure during the displacements.

For each experiment, the apparatus was assembled, the model was placed in vertical gravity stable position and a leak test was performed by applying gas pressure and verifying that pressure was maintained for a period of time. Before start of any experiment, the packed model was first filled with $CO_2$, and vacuum-saturated with synthetic oil sample. Nitrogen was utilized as an injected fluid and n-decane as synthetic oil. Oil and gas production were also monitored continuously. The results are given in the following.

## RESULTS AND DISSCUSION

The experimental studies were categorized into two main sections. One category consists of what we shall call “gravity dominated” experiments where a high permeability porous medium and 120 cm long core holder was used. Under this condition the capillary threshold height plays a small role. The second category includes “capillary dominated experiments" where permeability was lower and a 60 cm core holder was used. As we shall see, in these tests the residual oil saturation and shape of relative permeability curves should be corrected against capillary end effect.

Different gas injection rates were used for each type of porous media to determine the effect of gas injection velocity on gas/oil relative permeability. Table 2 gives the key parameters for gas flood experiments. In this table the cores with similar texture, porosity, permeability, have been identified with different letters; the “a”, “b” and “c” sands exhibit permeability values of approximately 16, 9 and 3.5 Darcy. In each pair the comparison was performed between gravity dominated flow and gas flood displacements.

**Gravity Dominated Experiments**

To investigate the effect of gas injection velocity on two phase gas/oil relative permeability in gravity-assisted gas injection processes, six experiments were conducted into two different porous media at different gas injection velocity. The oil production data was used along with the backward-analytical model to find a Corey type oil relative permeability. Figure 3 shows a plot of $1-N_p$ versus $t_D$, the breakthrough time, and the position of straight line and the slope of that straight line which indicate the Corey exponent. For determination of residual oil saturation the experiments were continued until no more oil produced. The graphical method presented by Jones and Roszelle (1978) can be used to predict the final oil volume. This can help to ensure that the experimentally reported final oil production does actually represent the oil production at a very large throughput. The obtained relative permeability was then used along with the numerical model to predict the experimentally oil production. In Figure 4 experimental and simulated oil production profile, using the analytically determined oil relative permeability is compared for a typical core flood test.

The low rate gas flood tests were found to be mostly insensitive to gas relative permeability. However for high gas injection rate (greater than critical gravity drainage rate) the gas relative permeability was found to affect the early time production data. For these tests the gas relative permeability was determined by history matching of the early time production data. Figure 5 and Figure 6 show the effect of gas injection velocity on two phase relative permeability for two of porous media (“a” and “b”). The $Q_c$ in these figures and in Table 2 refers to critical rate, which is defined by equation 1.

As expected, for low gas injection rate around the critical rate, the oil relative permeability is high while the residual oil saturation is much higher for high gas injection rate above critical rate. As it was discussed earlier the capillary effect was ignored in this group of experiments. This was checked by calculating the capillary end effect number, $N_{c,end} = (P_{th} / \Delta P)$, which can be interpreted as the ratio of capillary force to viscous force at the macroscopic scale.

A distinction was clearly observed between relative permeabilities by process where density contrast and gravity control the flood front by those where gravitational forces play a less significant role in ultimate fluid distribution.

**Capillary Dominated Experiments**

In this category of experiments the length of a core holder was half of the previous model and the permeability of a porous media was significantly lower. According to the value of the capillary end effect the residual oil saturation and shape of relative permeability curve is affected by capillary effect. The retention of oil at the bottom of the porous media causes the estimated remaining oil saturation to be higher than the residual oil saturation. After determination of relative permeability using remaining oil saturation, the history matching gives us capillary corrected relative permeability and residual oil saturation.
The gas/oil relative permeability before (derived by modified Hagoort method) and after the capillary end effect correction is compared in Figure 7. A result of such a history

matching of typical experiment is shown in Figure 8. A comparison between oil relative permeability for different gas injection rate when capillary force is significant is shown in Figure 9.

As the flow rate increases, the oil recovery is expected to decrease due to the flood front instability, but it should also increase due to increase in capillary number (i.e. leading the partial displacement of the oil trapped by the capillary threshold). In our experimental studies the remaining oil saturation increased (oil recovery decreased) when gas velocity increased, the results showed that the capillary threshold height is partially produced. More experiments are required in various ranges of dimensionless numbers before any judgment about the effect of unstable gas injection tests on gas/oil relative permeability and ultimate oil recovery.

## CONCLUSIONS

The experimental study and analysis of the results presented in this paper indicated that:

The residual oil saturation is may be a function of gas velocity especially in high front velocity movement and the shape of relative permeability curve is dependent on viscous to gravity ratio.

The early time production data can be affected significantly in high-velocity gas displacement tests. The late time production data is mostly sensitive to capillary/gravity ratio.

As the flow rate increases, the residual oil saturation increase due to increase in front instability, but it is thought that partially decreases due to reduction of the oil trapped by the capillary threshold at the bottom of the porous medium.

A comparison of the relative permeability and residual oil saturation obtained from different gas flood experiments shows that separate saturation functions need to be considered depending upon the effective force in each part of the reservoir.

## NOMECLATURE

$g$ Gravitational constant

$k$ Absolute permeability of core

$k_{ro}$ Oil relative permeability

$k_{ro}^{o}$ Curve-fitting parameter

$L$ Length of core

$n$ Relative permeability exponent

$N_c$ Capillary number, ratio of viscous to capillary forces, $N_c = \dfrac{v_d . \mu_d}{\sigma}$

$N_{c,end}$ Capillary end effect number

$N_{gv}$ Gravity number, ratio of gravity to viscous forces, $N_{gv} = \dfrac{\Delta\rho_{(oil-gas)} g \left(\dfrac{k}{\phi}\right)}{\mu_o v_d}$

$N_p$ Produced oil (fraction)

$P_{th}$ Threshold capillary pressure

$Q_i$ Gas injection rate

$Q_c$ Critical rate or maximum gravity drainage rate

$s_{oe}^*$ Normalized oil saturation, $s_{oe}^* = (\frac{1}{n k_{ro}^o t_D})^{\frac{1}{n-1}}$

$s_{org}$ Residual oil saturation

$s_{wi}$ Irreducible water saturation

$t_D$ Dimensionless time

$v_d$ Displacing phase velocity

$\phi$ Core porosity

$\sigma$ Interfacial tension

$\Delta\rho$ Density difference of gas-oil

$\Delta\mu$ Viscosity difference of gas-oil

$\Delta P$ Imposed pressure differential

$\mu_d$ Displacing phase viscosity

## ACKNOWLEDGMENT

The authors gratefully acknowledge the laboratory assistance of PUT research center, H. Salimi, for his kindly assistant during laboratory working. Acknowledge is extended to H. Tabatabaei for his unconditional availability for technical comments during this study. We would also like to thank Tehran Petroleum Research Center for granting us the financial support.

## REFERENCES

Ali, J.K.: “Development in measurement and interpretation techniques in core flood tests to determine relative permeabilities” *SPE* 39016, Fifth Latin American and Caribbean Pet. Eng. Conf and Exhib, Rio de Janeiro, Brazil, (1997) 29 August- 2 September.

Blackwell, J.T., and Terry, M.W.: “Factors influencing the efficiency of miscible displacement, “*Trans AIME,* (1959) **216**, 1-8.

Dumore, J.M., “Stability consideration in downward miscible displacement,” *SPEJ,* (1964), 356-362.

Firoozabadi, A., Aziz, K.: “Relative permeability from centrifuge data,” *SPE* 15059, Proceeding of the 56th California regional meeting of the SPE, Okland, CA, (1988), 2-4 April.

Hagoort, J.: “Oil recovery by gravity drainage” *SPEJ,* (1980), 139-150.

Hirasaki, G.J., Rohan, J.H., Dudley, J.W.: “Interpretation of oil-water relative permeabilities from centrifuge experiments,” *SPE Adv. Techno,* (1995) **Ser 3 (1),** 66-75.

Jones, S.C., Roszelle, W.O.: “Graphical techniques for determining relative permeability from displacement experiments” *J. Pet. Tech*, (1978) 807-817.

Singh, M., Mani, V., Honarpour, M.M., Mohanty, K.K.: “Comparison of viscous and gravity dominated gas-oil relative permeabilities,” J. Pet. Sci & Tech, (2001) **30**, 67-81.

Skauge, A., Haskjold. G., Thorsen, T., Aarra, M.: “Accuracy of gas-oil relative permeability from two-phase flow experiments.” *SCA* 9707, International Symposium of the Society of Core Analysis, Calgary, Canada, (1997).

Skauge, A.: “Comparing core analysis data to field observations for gravity drainage gas injection,” *SCA* 9904, International symposium of the society of core analysis, Colorado, USA, (1999).

Virnovskey, G.A., Skjaevaland, S.M., Surdal, J., Ingsoy, P.: “Steady-state relative permeability measurements corrected form capillary effect,” *SPE* 30541, Proceeding of the SPE annual technical conference and exhibition, Dallas, TX, 22-25, (1995) October.

Table 1. Input data for numerical model

| **Parameter** | **Value (Unit)** |
|---|---|
| Density of oil | 740 (kg/m$^3$) |
| Viscosity of oil | 0.85 (cP) |
| Density of gas | 0.001 (kg/m$^3$) |
| Viscosity of gas | 0.02 (cP) |
| Intrinsic permeability | 3.7 (Darcy) |
| Porosity (fraction) | 0.38 |
| Length | 60 (cm) |
| Corey Relative permeability exponent ($n$) | 3 |
| Residual oil saturation, $s_{org}$ (fraction) | 0.1 |
| Connate water saturation, $s_{wi}$ (fraction) | 0 |
| Oil relative permeability end point ($k_{ro}^{o}$) | 1 |

Table 2. Key parameters for the selected pairs of gas flood experiments

| Core No | $\phi$ (fraction) | $L$ (cm) | $K$ (Darcy) | $Q_i$ (cc/min) | $N_c$ | $N_{gv}$ |
|---|---|---|---|---|---|---|
| 1a | 0.38 | 120 | 16.5 | 3.1 (0.5 $Q_c$) | 7.33E-08 | 2.0 |
| 2a | 0.375 | 120 | 15.8 | 8.0 (1.3 $Q_c$) | 1.89E-07 | 0.78 |
| 3a | 0.378 | 120 | 16 | 16.5 (2.6 $Q_c$) | 3.90E-07 | 0.38 |
| 1b | 0.365 | 120 | 8.8 | 5 (1.5 $Q_c$) | 1.18E-07 | 0.67 |
| 2b | 0.37 | 120 | 9 | 10 (3 ) | 2.36E-07 | 0.33 |
| 3b | 0.375 | 120 | 8.5 | 16 (5 ) | 3.78E-07 | 0.20 |
| 1c | 0.372 | 60 | 3.7 | 2 (0.9 ) | 2.65E-08 | 1.11 |
| 2c | 0.38 | 60 | 3.5 | 5.5 (2.5 ) | 7.30E-08 | 0.40 |
| 3c | 0.372 | 60 | 3.6 | 9.7 (4.2 ) | 1.29E-07 | 0.24 |

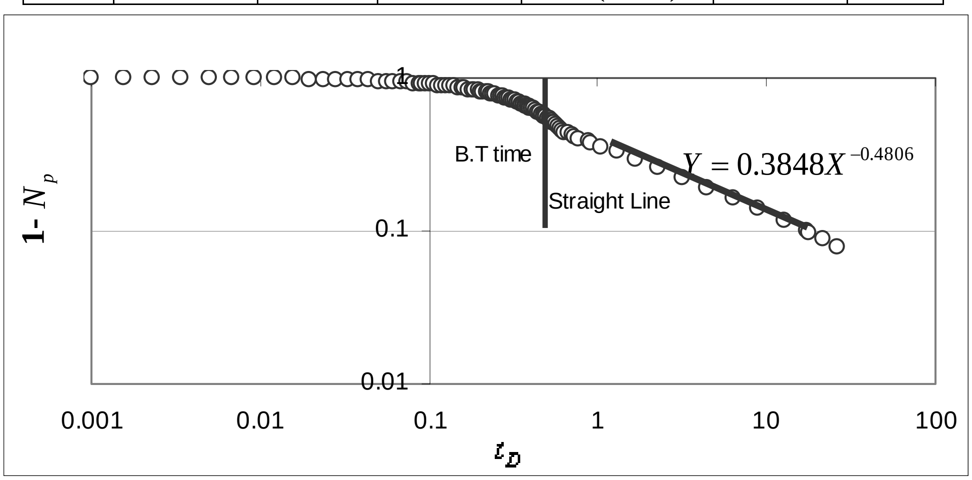


Figure 1. Backward analysis for a typical example

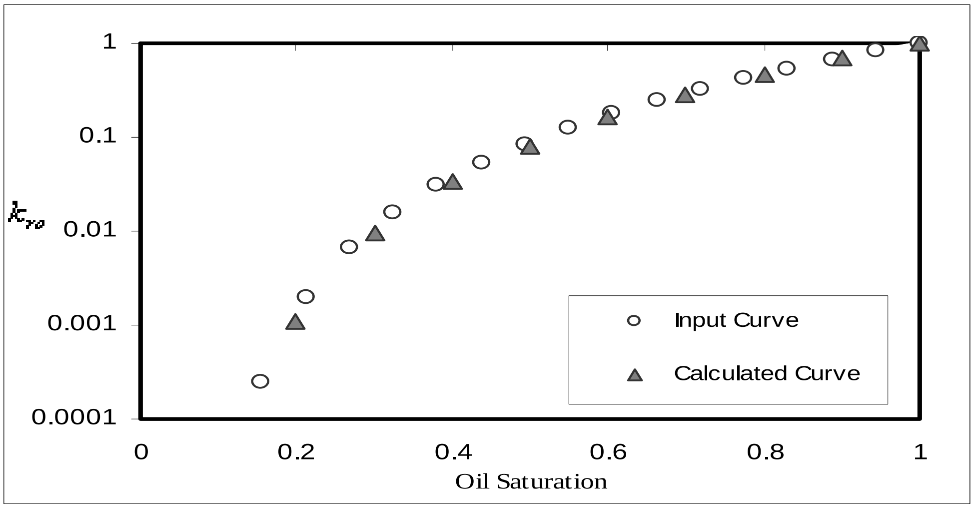


Figure 2. Comparison between pre-determined and calculated oil relative permeability curve

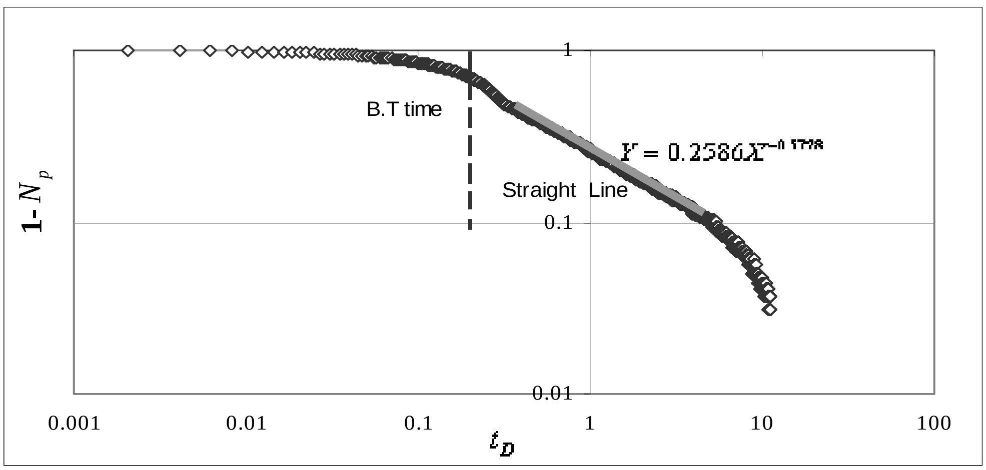


Figure 3. Analytical analysis of oil relative permeability for a typical core flood experiment

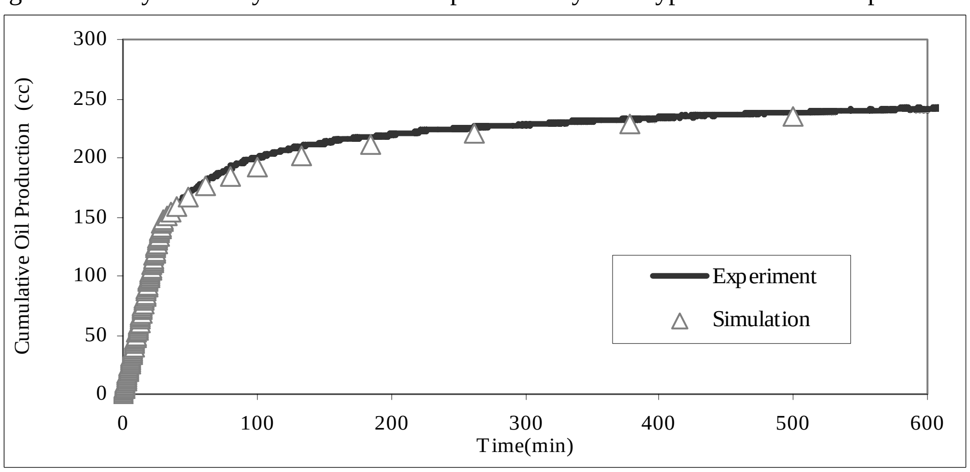


Figure 4. Experimental and simulated oil production profiles for a gravity dominated case

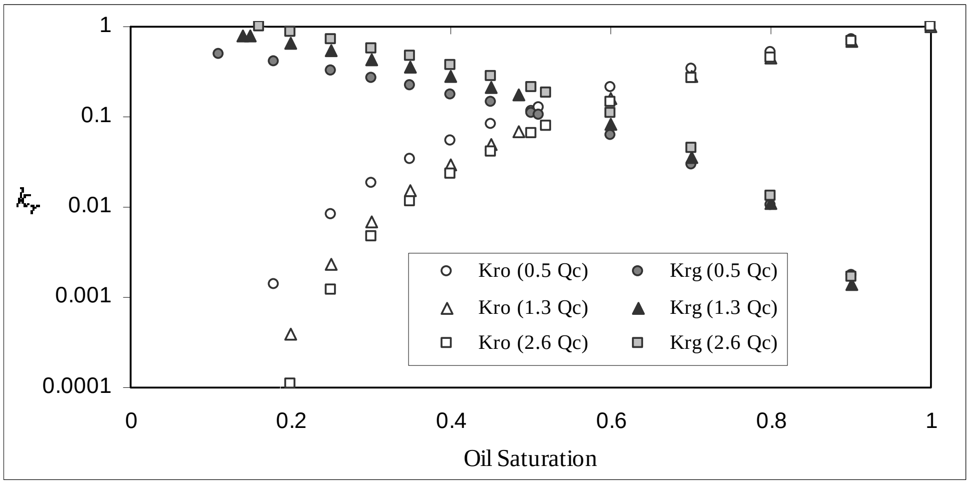


Figure 5. Comparison of gas/oil relative permeability for different gas injection rate (Porous media a)

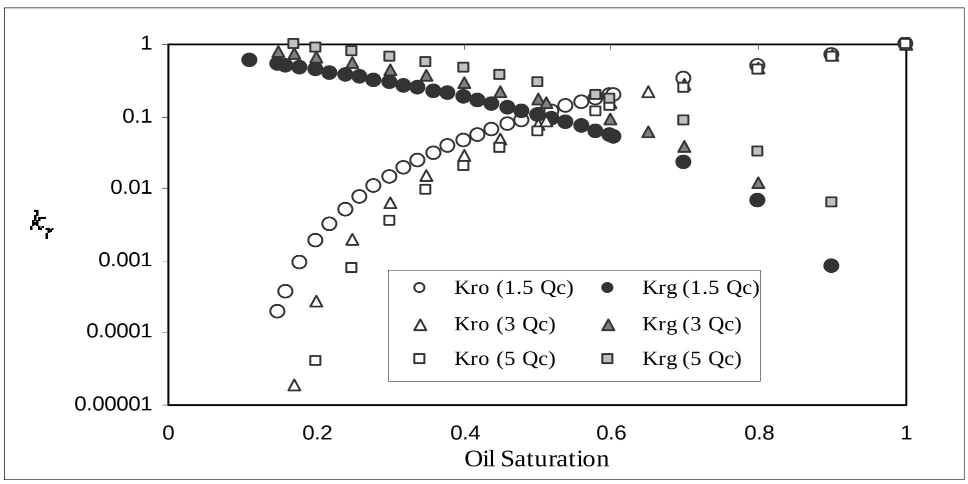


Figure 6. Comparison of gas/oil relative permeability for different gas injection rate (Porous media b)

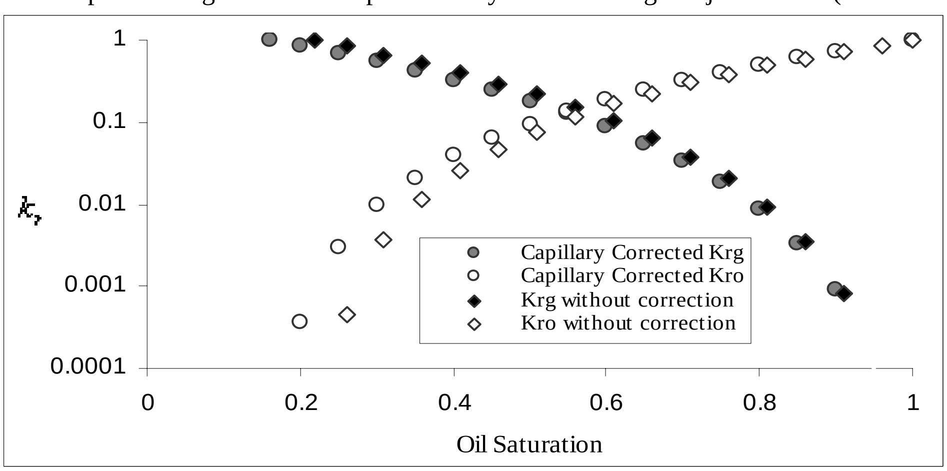


Figure 7. Gas-oil relative permeability of a gas flood test before and after capillary end effect correction

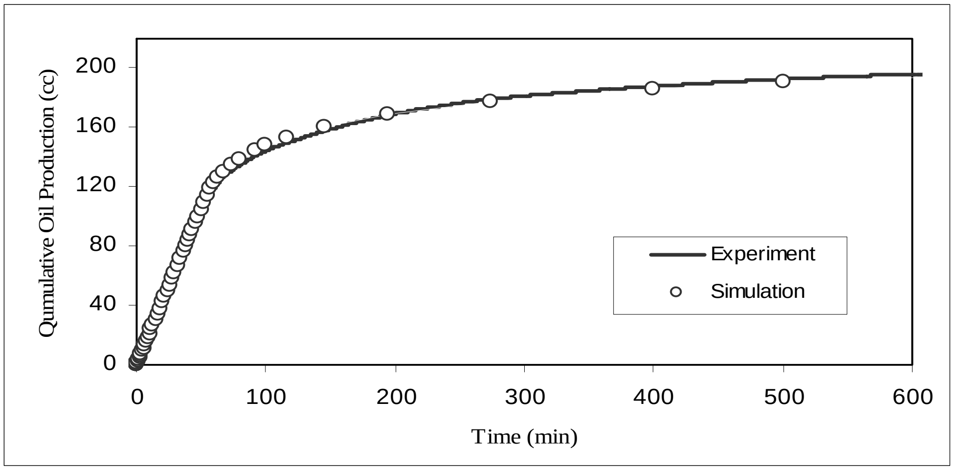


Figure 8. Experimental and simulated oil production profiles for a capillary dominated case

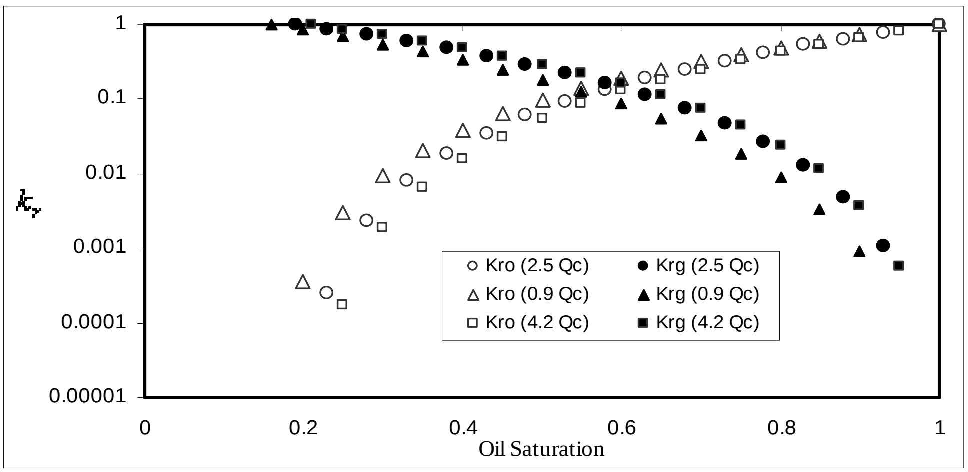


Figure 9. Gas/oil relative permeability for different gas injection rate (Porous media c)