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# The Relative Significance of Positive Coupling and Inertial Effects on Gas Condensate Relative Permeabilities at High Velocity

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## Abstract

The authors were the first to report that gas-condensate relative permeability will increase with increasing velocity. This positive rate effect, which was later confirmed by other investigators, was attributed to the coupling of the flow of the two phases and was referred to as the "positive coupling" effect. The observation was made in tests conducted at velocities where the effect of "inertia" was not significant. The objective of the latest study was to investigate the competition between the two effects of "negative inertia" and "positive coupling" on gas-condensate relative permeability at velocities up to one order of magnitude above the velocity boundary with significant inertia. The maximum tested velocity was 700 m/day, which was representative of the flow regime within fractions of a meter from the wellbore of a typical producer. The tests were conducted on different cores at various interfacial tension (IFT) values.

The results have shown that "inertia" was dominant in cores saturated with 100% gas at the tested conditions. However, as the condensate saturation increased, an improvement in relative permeability due to "positive coupling" was observed over the entire range of velocities at all values of IFT tested. This resulted in the generation of unique relative permeability curves, showing decreasing relative permeability with increasing velocity at low condensate saturations, and increasing relative permeability with increasing velocity at high condensate saturations. This trend was observed mainly for the gas phase. Previously published data had indicated that inertia reduced the gas relative permeability at high velocity.

The data has been used to develop empirical correlations, which relate the change of gas-condensate relative permeability to variations in fluid saturation, velocity and IFT.

## Introduction

In June 1994, the authors reported for the first time that the relative permeability of the gas phase in particular, and to a lesser extent the condensate phase, increased with increasing velocity when measuring relative permeability using condensing fluids in long cores [1]. This new phenomenon was referred to as the “positive coupling effect”, and was attributed to the coupling of the flow of the gas and condensate phases, based on the results of studies which had highlighted that gas and condensate can easily flow together in the same pore space [2,3]. Since this initial finding, interest in gas condensate relative permeability by other researchers has increased significantly [4,5,6,7,8,9,10,11,12], but few have reported the positive coupling effect using condensing fluids.

Over the period from 1994 to the present, the authors have published a series of papers reporting the data generated when using long cores containing condensing fluids to generate steady-state relative permeability curves [1,3,13,14,15,16,17]. The measurements were made over a range of IFT (interfacial tension) values covering 0.015 to 0.7mNm$^{-1}$, and at different velocities. Initial tests [1,3], were conducted using the technique of flashing the gas condensate fluid from above the dew-point pressure to the core pressure, to establish steady-state flow and measure relative permeability, a technique since adopted by others [11,12]. Subsequent measurements by the authors using the steady-state technique to measure the relative permeability confirmed the initial results [13,14,15,16,17]. A summary of the reported findings is given below;

1 The relative permeability of condensing fluids increased with increasing velocity, at conditions where the inertia was not significant for the dry gas (zero condensate saturation).
2. The positive coupling effect was not limited to one core type, but was observed for different lithologies and over a range of permeabilities, from 10 to 550 md.
3. Positive coupling was also observed when connate water was present in the cores. The gas relative permeability was observed not only to be a function of its own saturation, but that of the condensate phase too.
4. When the relative permeability was measured using unsteady-state procedures at the same test conditions as the steady-state tests, the observed positive coupling effect was minimal.

The objective of the latest study was to investigate the flow of gas condensate fluids in the wellbore region of gas condensate reservoirs, and in particular to investigate the effect that inertia would have on the relative permeability.

When the pressure in the vicinity of the reservoir around the wellbore falls below the dew-point in the retrograde region, the local condensate saturation will increase to support the gas-condensate inflow. Capillary forces will also increase with continued pressure reduction, and in conjunction with the increasing condensate saturation can have a significant detrimental effect on production by reducing the gas relative permeability. The highest velocities will occur in the wellbore region of producing wells, where the negative effect of inertia on flow is conventionally thought to significantly reduce the gas relative permeability with increasing velocity. It is therefore considered to be a distinct possibility that the combined effects of inertia and high IFT (increased viscous and capillary forces) in the wellbore region, may cancel the benefits of positive coupling, resulting in a reduction in relative permeability.

Simulations have however shown that the severity of the well impairment due to the effects of inertia at high velocity can be over predicted, if the benefits of positive coupling associated with condensing fluids is not taken into account [15]. There is however a lack of published laboratory relative permeability data available where measurements have been made at conditions where the velocity was high enough to make inertia significant. The absence of appropriate experimental data will be addressed in this study, where the results of high velocity steady-state core tests conducted using condensing fluids, will be reported. The maximum velocity used in the tests was one order of magnitude above the velocity with significant inertia, representing flow in the region of fractions of a meter from the wellbore of a typical North Sea producer. The generated relative permeability data clearly shows a change from an inertia dominated flow regime at low condensate saturations, to a regime where the positive coupling effect becomes dominant as the condensate saturation increases in the cores.

The generated laboratory data has been used to develop empirical correlations, which relate the change of gas-condensate relative permeability to variations in fluid saturation, velocity and IFT. The correlations account for both the positive coupling and the negative inertial effects. The positive coupling correlation relates the change in relative permeability to a change in the capillary number for the relevant curve, while the inertia correlation is based on the use of the two-phase inertial factor. The reliability of the developed correlations was tested using experimental data collected from more than ninety steady-state relative permeability tests conducted using several different cores. A preliminary version of the correlations has been incorporated in a major commercial compositional simulator.

The unique data generated highlights the competition which exists between forces governing production at the wellbore, and highlights the need to include the positive coupling effect in simulations to prevent underestimating the rate of production from gas condensate reservoirs.

## Experimental Procedure

**High pressure core facility.** A high pressure core facility was developed to allow steady-state relative permeability tests to be conducted to a high degree of accuracy [13]. Within the core facility, constant volumes of gas and condensate were stored in separate high pressure vessels and were circulated in a closed loop around the flow system, which increased the accuracy of fluid saturation measurements.

The pumps used to circulate the gas phase have a range in flow rate from 1 to 24000 cc/hour, with the fluid volumes displaced into the core being measured with a resolution of 0.01cc. The configuration of the pumps allows continual injection of gas through the core as the injection and receiving barrels automatically switch direction at the end of their stroke. The third barrel in the facility operates in a mode which ensures that there is a minimal spike in the differential pressure when switching occurs. In the tests reported, a differential pressure spike in the region of 0.0007 MPa would be expected if the total differential pressure across the core was in the region of 0.276 MPa. The condensate phase was circulated through the core using pumps with a maximum velocity which was in the region of 2000 cc/hour.

Fluid production from the core was measured at the test conditions in a high pressure sightglass situated at the core outlet to within an accuracy of ±0.1 cc. The differential pressure was measured using two high accuracy Quartzdyne quartz crystal transducers located at the inlet and outlet of the core, which provided stable differential pressure data to an accuracy of ± 0.0007 MPa, during the course of the tests. The values obtained from the differential pressure transducer, and subsequently used in the calculation of relative permeability, resulted in a maximum error which ranged from ±0.5% at low flow rates, to ±0.05% at the highest flow rates.

**Dry Gas Permeability Reduction : Beta Factor Calculation.** Each core sample tested was initially saturated with methane which was then injected through the core, with the gas flow rate being increased in increments from 100 to 10,000 cc/hour (on average a pore velocity of 7 to 700 m/day) to measure the gas permeability reduction associated with inertial flow. In general, it was observed that the gas permeability reduced when the flow rate was increased above 1000 cc/hour. The data was used to calculate the single phase gas beta factor of each core using :

$$\frac{M(P_1^{\,2}-P_2^{\,2})}{2zRT\mu L(W/A)}=\frac{W}{A\mu}\beta+\frac{1}{k} \tag{1}$$

**Single Phase Equilibrium Gas Permeability Reduction (CGR 0).** Prior to measuring the gas condensate relative permeability at each test conditions, the core was saturated with 100% single phase equilibrium gas at the required test pressure. The equilibrated gas was obtained by depleting the gas condensate fluid in the storage cells to the selected test pressure below the dew point. The individual phases were then mixed to equilibrate the fluids by flowing them together through the fluid bypass line at the test pressure, followed by separating the gas and condensate phases into their own storage cells. Each equilibrated phase was kept at a pressure above its saturation point to ensure lack of phase change. The equilibrium gas phase was then injected through the core to displace the methane, at a pressure well above the saturation pressure. When fully saturated with equilibrium gas, the core pressure was reduced to a pressure just above the saturation pressure.

Equilibrium gas was then injected into the core and the flow rate was increased in increments from 100 to 10,000 cc/hour, to measure the gas permeability reduction associated with inertial flow. This data was used as the gas permeability end-points at a condensate saturation of zero on the subsequently measured relative permeability curves. This enabled the relative permeability curves generated at high velocities using gas condensate fluids to be extrapolated back to the corresponding gas permeability at 100% gas saturation.

**Saturating the Core with Gas Condensate Fluid and Depletion.** The pressure in the core was then raised, and single phase gas condensate fluid, approximately 3.447 MPa above the dew point, was injected into the equilibrium gas saturated core. Two HCPV of gas condensate were injected and left for 24 hours, after which further gas condensate was injected until the differential pressure across the core was stable. To ensure that the gas condensate mixture in the core was of the correct composition, a sample of the produced gas from the core was collected in the sightglass at the core outlet. The sightglass was then isolated from the core, and the pressure reduced by constant composition expansion to ensure that the dew-point of the fluid and the measured liquid drop-out matched the previously measured PVT data. The sightglass was then filled with another sample of gas from the core which was above dew-point pressure.

The core was now at a stage when the planned experiment could begin, and commenced with the depletion of the core to the dew point. The depletion was controlled by retracting a pump connected to a gas piston vessel located within the core facility which was also connected to the sightglass and core. The pressure was depleted fairly rapidly, at a rate of approximately 0.069 MPa/minute, until 0.345 MPa above the dew point, where the rate of pressure reduction was decreased to 0.007 MPa /minute. When the dew point was reached, a condensate mist formed in the sightglass, resulting in condensate being deposited.

Using PVT data, the liquid dropout at any pressure below the dew-point was known, which enabled the condensate saturation in the core established by condensation during depletion to be calculated. The initial condensate saturation in the core varied between approximately 27 to 32 %, depending on the test pressure.

**Gas condensate relative permeability measurement.**
***Measurement of gas condensate steady-state points.*** When establishing steady-state flow, equilibrium gas and condensate were injected into the core at a selected CGR, until steady-state conditions were established. To provide data at lower condensate saturations, the initial CGR used in the tests was 0.005, which is the lowest possible CGR determined by the specification of the displacement pumps. At certain test conditions especially at low IFT, the low initial CGR could reduce the condensate saturation in the core at the initial steady-state conditions to a value lower than the saturation initially established by condensation. The condensate saturation in the core subsequently increased as the CGR was increased. Consequently, a process of drainage followed by imbibition of condensate could occur at the start of the tests. It has been demonstrated, however, that the hysterisis effect at the tested IFT range was minimal [13]

The fractional flow used in the tests ranged from a CGR of 0.005 to 0.4. An example of the flow conditions used in a test conducted at an IFT of 0.78 $mNm^{-1}$ is shown in Table 1. All flow rates used were converted to superficial pore velocities, calculated as,

$$\upsilon_s = \frac{q}{A\left[\phi(1 - Swi)\right]} \tag{2}$$

The relative significance of viscous to surface forces during injection has been described in terms of the capillary number for the gas phase, using;

$$N_c = \frac{\mu_g v_{sg}}{\sigma} \tag{3}$$

At each CGR, a number of steady-state relative permeability points were measured, covering the range of the velocities shown. During the test sequence the flow rate was increased in stages from a minimum total injection rate (gas + condensate) of 105cc/hour to a maximum rate of 10080 cc/hour. At the higher CGR's above 0.01, the steady-state points could not be measured at the highest velocities due to limitations in the maximum velocity achievable with the pumps circulating the condensate phase.

***Saturation calculation.*** At the start of each test sequence, the gas and condensate saturations in the core were known from PVT data. The initial volumes of gas and condensate in the flow system, (fluid storage cells, flow lines, and sightglass), were measured prior to the test commencing, to within an accuracy ±0.5 cc. After steady-state conditions were established, the core was isolated from the flow system, and any change in the condensate saturation in the core was calculated from the change in the total volume of condensate in the flow system between the beginning and the end of each test. The error in the condensate saturations reported for each steady-state relative permeability point has been calculated to be in the region of ± 0.35 to ± 0.75 %.

**Core properties.** Core properties such as permeability, porosity, weight and tracer profile were measured prior to and after all experiments. This procedure ensured that there was no variation in the flow characteristics of the core during the test, and that the core had been properly cleaned. The characteristics of the water-wet cores used in the tests are shown in Table 2. All cores were mounted horizontally and continually rotated through 360 degrees for the duration of the tests to minimise the influence of gravitational forces on the fluid distribution. Tracer analysis of the cores prior to the tests had indicated that they were homogeneous.

**Test fluid.** The gas condensate fluid used in the tests was a mixture of methane and normal butane, with a dew point of 12.89 MPa at a temperature of 37°C. The liquid drop-out curve of the fluid can be seen in Figure 1, and was measured in a PVT cell by constant composition expansion. A fluid with an initial high rate of liquid drop-out was selected, allowing a condensate saturation of up to 31% to be established in the core prior to the injection of gas and condensate. This was considered to be an important aspect of the tests, as previous studies had shown that it was necessary to establish the condensate saturation by condensation as opposed to injection [16]. An added attraction of the use of a binary fluid was that the physical properties of the gas and condensate phases would be constant at a given pressure and fixed temperature below the dew-point, regardless of the total fluid composition. Both gas and condensate fluids were kept in equilibrium with water for tests conducted where cores contained connate water.

**Results**

**Inertia versus Positive coupling at High Velocity.**

***Clashach Core.*** The combined effects of Inertia and positive coupling can be seen in Figure 2, for a Clashach sandstone core at an IFT of 0.78 mNm$^{-1}$. At a zero condensate saturation, when the single phase gas velocity was above 58.1 m/day, the gas permeability continually reduced with increasing velocity, due to inertia. As the condensate saturation increased and the positive coupling become active, the effect of velocity on relative permeability was reduced considerably, such that at a condensate saturation of approximately 30%, the effect was negligible, as the relative permeability curves measured at the various velocities converged at this saturation. As the condensate saturation increased above 30%, there was a “crossover”, and the effects of positive coupling become dominant over inertia. At these conditions, the gas relative permeability continually increased with increasing velocity, up to the maximum tested velocity of approximately 700 m/day.

The corresponding condensate relative permeability curves can be seen in Figure 3. The effect of inertia on the condensate relative permeability was minimal at lower condensate saturations, with the effects of positive coupling being observed when the condensate saturation increased above approximately 40 %.

For the velocities reported at the test conditions, the capillary number ranged from approximately 1.73 E-6 to 1.66 E-4.

***Berea Core.*** A similar trend was observed for the core tests conducted using the lower permeability Berea core at the same IFT value. The effects of inertia in this low permeabilty core reduced the gas relative permeability over a condensate saturation range from zero to the cross over saturation of approximately 40%, as can be seen in Figure 4. At a condensate saturation of approximately 45%, the percentage increase in gas relative permeability between the lowest velocity of 7.2 m/day to the highest velocity of 479.6 m/day was 60% due to the domination of positive coupling over the inertia. The dominance of positive coupling was again always observed even at the highest velocities used in this test, however the velocity range was lower than the Clashach core test reported in Figure 2, due to significant phase change encountered at high differential pressures, as will be discussed later.

Figure 5, shows the corresponding condensate relative permeability curves. As with the Clashach core (Figure 3), the effect of velocity on the condensate relative permeability was minimal at lower condensate saturations, with the dominance of positive coupling being observed when the condensate saturation increased above approximately 25%. For the velocities reported at the test conditions, the capillary number ranged from approximately 1.71 E-6 to 1.14 E-4.

When the corresponding gas relative permeability curves for the Clashach core were measured at lower IFT’s of 0.14 and 0.015 mNm$^{-1}$, the effect of inertia at lower condensate saturations was reduced considerably, and positive coupling was more pronounced at the lower IFT [14]. In these tests, it was observed that the gas relative permeability was particularly sensitive to IFT and velocity, with the condensate relative permeability being very similar, regardless of velocity or IFT.

The results reported were obtained when measuring the relative permeability using cores containing no connate water. As previously stated, one of the findings of the research project to date has been the fact that the gas relative permeability cannot be considered as a function of the gas saturation only, and that it varies depending on the magnitude of connate water saturation in the core [17]. The reported tests conducted using no connate water are however relevent, as the region around the wellbore may contain very little, if any, connate water if water vapourisation is occurring in the rocks in the wellbore vicinity.

***Texas Cream Core.*** High velocity relative permeability measurements for the lowest permeability core used in the test, a Texas Cream Limestone core, are shown in Figure 6. Up to condensate saturations of approximately 55%, the gas relative permeability curves are shown only for the initial four velocities, ranging from 6 to 48 m/day. When the velocity was increased above 48 m/day at condensate saturations below 55% (corresponding to CGR’s < 0.05), it was observed that the condensate saturation reduced significantly at a given

CGR. It was also observed that at these conditions, the length of time taken to establish steady-state flow was significantly longer compared to measurements made at higher CGR's.

During the measurement of relative permeability, the average core pressure was maintained at the selected test pressure (corresponding to the required IFT value), allowing the inlet core pressure to increase above and the outlet core pressure to decrease below the test pressure by an equal amount. The effect of increased differential pressure at higher velocities on the phase behaviour of the fluids was investigated, by employing a phase behaviour model. The simulations highlighted that at low CGR's, changes in the condensate saturation from the inlet to the outlet of the core could be as high as 58% at these conditions. Hence, reporting an average relative permeabilty-saturation data at such conditions was not justifiable. At higher CGR's above 0.05, the effect of variations in the CGR along the length of the core was greatly reduced, and was within acceptable limits up to the maximum tested velocity of 192 m/day shown in Figure 6, for the Texas Cream core. The reported values in Figure 6, cover only the reliable data where the saturation change within the core was small.

Note in Figure 6, that similar to the other two cores, the relative permeability curves converge (at a condensate saturation of 55%), and at higher saturations crossover to a regime where positive rate sensitivity is dominant, with the gas relative permeability increasing up to the maximum tested velocity of 192 m/day.

In the above tests, when phase behaviour problems occurred, they were easily detectable when using conventional relative permeability plots, as the condensate saturation was observed to reduce considerably. If, however, the data was plotted in the form of krg versus krg/krc, the effects of the variations in phase behaviour would be masked as the condensate saturation would not be measured. Consequently, there would be no indication that changes in phase behaviour were occurring along the length of the core, making the data invalid.

When generating gas condensate relative permeability data, the measurement of the condensate saturation is therefore a worthwhile procedure, as it can highlight potential phase behaviour problems encountered during the course of the tests. Saevareid [11], has reported gas condensate relative permeability data in the form of krg versus krg/krc, and commented that at ratios of krg/krc > 50, the measurement of relative permeability was a lengthy process. It was believed that this behaviour may have been due to the fact that steady-state conditions had not fully stabilised, or that relative permeability curves were fundamentally different when the krg/krc > 10. If the condensate saturation had been measured during the tests, phase behaviour problems may have been identified as the cause.

## Relative Permeability Correlations

The positive rate effect, which is due to the coupling of the gas and condensate phases, and the negative rate effect due to the inertial loss are two related phenomena of the complex multiphase flow in pores. Hence, it is appropriate to describe the flow behaviour in such a way to enable the combined effect to be estimated for engineering applications. However, to produce information readily applicable to existing commercial reservoir simulators, the two effects have been expressed by two separate mathematical expressions.

**Positive Rate Effect** The positive rate effect has been described by a correlation similar to that of Coats for the IFT effect, but using the capillary number as the controlling variable. The proposed correlation for each phase, similar to that of Coats, basically interpolates between the base relative permeability $k_{rb}$ at a low capillary number, $N_{cb}$, and the miscible relative permeability, $k_{rm}$:

$$k_r = Y\ k_{rb} + (1 - Y)\ k_{rm} \tag{4}$$

where the miscible relative permeabilities, $k_{rm}$, are given by Eqs.(4) and (5) for the gas and condensate phase, respectively

$$k_{rgm} = \left(\frac{k_w}{k}\right)\frac{S_g^* - X_g S_{grb}^*}{1 - X_g\ S_{grb}^*} \tag{5}$$

$$k_{rcm} = (k_w / k) S_c^* \tag{6}$$

Note that Eq.(5) results in zero critical condensate saturation. This behaviour has been observed experimentally at Heriot-Watt, and agrees with the fact that the condensate is the continuous phase throughout porous media. The scaling parameter for the residual gas is determined from,

$$X_g = \left( S_{gr}^* \big/ S_{grb}^* \right) = \left( S_{gr} \big/ S_{grb} \right) = 1 - e^{-m\left(\frac{N_{cb}}{N_c}\right)} \tag{7}$$

where the exponent m is a constant for each rock, and the capillary number is defined as:

$$N_c = \frac{\mu_g v_{sg}}{\sigma} \tag{8}$$

The scale function, Y, is represented by,

$$Y = \left(\frac{N_{cb}}{N_c}\right)^n \tag{9}$$

The exponent n depends on the rock and the phase saturation. The results for all the cores indicated that the exponent n for both gas and condensate correlations varied almost linearly with saturation. However, n can be treated independent of saturation with negligible effect on the reliability of the results.

**Non-Darcy effect** Measurement and evaluation of the non-Darcy effect for gas condensate systems is more demanding than that for a single phase gas, as the relative permeabilities of both phases depend on the flow rate, even at conditions where the conventional inertial effect is still insignificant.

The modified Darcy equation for each phase, including the inertial effect, can be written as,

$$\frac{\Delta P}{\Delta L} = \frac{\mu v_D}{k_{r(meas.)}k} = \frac{\mu v_D}{k_{r(Nc)}k} + \rho\beta v_D^2 \qquad (10)$$

where $k_{r(meas.)}$ and $k_{r(Nc)}$ are the measured relative permeability, which contains implicitly in its value the effect of inertia, and the calculated relative permeability form Eq(3), which includes only the coupling effect, respectively.

Hence, the two phase β-factor for gas can be determined as,

$$\beta_g = \frac{\mu_g A}{k\rho_g q_g}\left[\frac{1}{k_{rg(meas.)}} - \frac{1}{k_{rg(Nc)}}\right] \qquad (11)$$

or in a general form as:

$$k_{r(meas.)} = k_{r(Nc)}(1 + Re_\beta)^{-1} \qquad (12)$$

where the Reynolds number, $Re_\beta$, is defined as,

$$Re_\beta = \frac{\rho v_D k\beta}{\mu} \qquad (13)$$

**Results** On the basis of the above mentioned concept, the measured relative permeability values at low velocities where the inertial effect was considered insignificant were used to determine the exponents of the Nc correlation. The developed relation was then used in Eq(10) to estimate the β-factor at higher velocities. The implicit assumption is that the developed positive rate effect correlation is valid at high velocity conditions, where the measured data have not been used to develop the correlation.

A total of 5 sets of relative permeability data covering the inertial flow range were used to develop a correlation for the gas phase in the presence of mobile condensate. The variation of $\beta_g$ with condensate saturation and IFT is shown in Figure 7. Note that the gas phase inertial factor increases with increasing condensate saturation and IFT. The value of $\beta_g$ was also found to depend on velocity. Figure 8 shows the variation of $\beta_g$ with velocity at constant saturation and IFT for the Berea core. The inertial factor decreases with increasing velocity. Contrary results were also found for other tested cores. This could be attributed to the inadequacy of the method, which treats the two rate effects independently, or to the different characteristics of the cores. The inclusion of velocity in the inertial factor correlation did not improve the results, hence, the following correlation was developed to relate the gas inertial factor in the two-phase system ($\beta_g$) to that of single phase gas,

$$\beta_g = \beta S_g^{(-2.99-4422\sigma)} \qquad (14)$$

In the absence of experimental data on β, the dry gas inertial factor, its value can be estimated from the Geertsma correlation [10]:

$$\beta = 0.005k^{-0.5}\phi^{-5.5} \qquad (15)$$

The Geertsma [20] correlation for dry gas showed an average deviation of 68% in estimating β of all the tested cores in this laboratory.

Figures 9 and 10 compare $\beta_g$ as measured and predicted by the developed correlation for two different cores at IFT=0.78 mN/m, indicating acceptable results. A number of correlations for calculating the beta factor for two-phase systems have been proposed in literature [20-24]. They have been mostly either developed for gas-water or have been extended from single phase to two-phase systems without adequate information. It should be noted that neither of these correlations consider the positive coupling effect. Hence, their direct comparison with the correlation developed in this work, accounting for the positive coupling, is not justified. Figures 11 and 12 compare the values of beta factor calculated by ignoring the positive coupling effect, with those predicted by several correlations. Note that while some correlations hardly show any significant increase of beta factor with increasing condensate saturation, some highly over estimate the effect. In general, none of them are reliable.

## Conclusions

1. The effect of positive coupling was evident at high velocity and at high IFT for three different cores, with the gas relative permeability in particular increasing with increasing velocity at near wellbore flow rates.
2. "Cross over" relative permeability curves have been reported, which show a transition from inertia dominated relative permeability curves with increasing velocity at low condensate saturations corresponding to low CGR's, to conditions where the positive coupling effect was dominant as the condensate saturation and CGR increase.
3. The positive coupling effect continued to increase the relative permeability up to the highest tested velocity of almost 700 m/day at the highest tested IFT of 0.78 $mNm^{-1}$. A set of generalised relative permeability correlations accounting for both inertia and positive coupling effects have been developed.

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## Nomenclature

A = area
CGR = condensate to gas ratio (volume/volume at test conditions)
HCPV = hydrocarbon pore volume
k = permeability
$k_r$ = relative permeability
L = length
M = molecular weight of the gas
Nc = capillary number
P = pressure
q = volumetric flow rate
R = universal gas constant
$Re_\beta$ = Reynolds number
S = saturation
S* = HCPV saturation
T = temperature
W = mass flow rate
X = scaling function for residual gas saturation
Y = scaling function for relative permeability
z = compressibility factor
$\mu$ = viscosity
$\beta$ = Beta factor
$\upsilon_s$ = superficial fluid velocity
$\varphi$ = Porosity
$\mu$ =viscosity
$\rho$ = density
$\sigma$ = interfacial tension (IFT)

## Subscripts

B = base
g = gas
D = darcy
m =miscible
w = water
wi = initial water

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**TABLE 1 – MEASUREMENT SEQUENCE OF STEADY-STATE POINTS**
**Clashach core 0.78 mNm$^{-1}$**

| Test | Gas Flow Rate cchr$^{-1}$ | Condensate Flow Rate cchr$^{-1}$ | Total Flow Rate HCPVhour$^{-1}$ | Total Flow Rate Pore Velocity m/day$^{-1}$ | (Nc) Gas Capillary Number |
|---|---|---|---|---|---|
| 1 | 100 | 5 | 0.46 | 7.3 | 1.65E-06 |
| 2 | 200 | 10 | 0.92 | 14.5 | 3.29E-06 |
| 3 | 400 | 20 | 1.84 | 29.1 | 6.59E-06 |
| 4 | 800 | 40 | 3.68 | 58.1 | 1.32E-05 |
| 5 | 1600 | 80 | 7.36 | 116.2 | 2.64E-05 |
| 6 | 3200 | 160 | 14.72 | 232.4 | 5.27E-05 |
| 7 | 4800 | 240 | 22.10 | 348.8 | 7.91E-05 |
| 8 | 6400 | 320 | 29.44 | 465.1 | 1.05E-04 |
| 9 | 8000 | 400 | 36.80 | 581.4 | 1.32E-04 |
| 10 | 9600 | 480 | 44.15 | 697.7 | 1.58E-04 |

**TABLE 2 -- CORE PROPERTIES**

| Core | Lithology | Length cm | Diameter Cm | Porosity frac. | Permeability µm$^2$ | Swi % |
|---|---|---|---|---|---|---|
| Clashach | Sandstone | 66.0 | 4.98 | 0.175 | 0.546 | 0 |
| Texas Cream | Limestone | 75.0 | 4.99 | 0.209 | 0.009 | 0 |
| Berea | Sandstone | 63.9 | 5.08 | 0.185 | 0.109 | 0 |

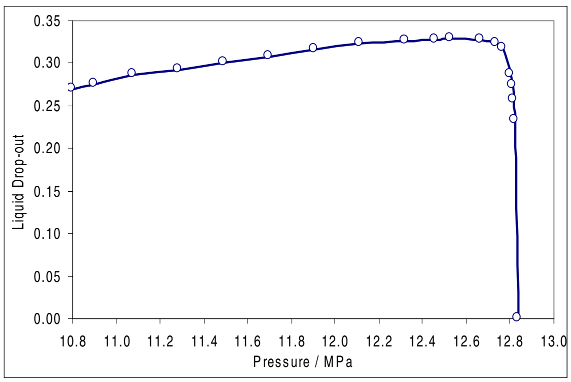


**Fig. 1—Liquid drop-out of binary methane n-butane Gas condensate fluid**

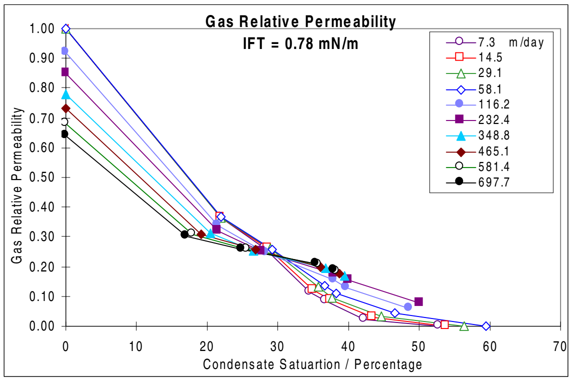


**Fig. 2—Clashach core gas relative permeability**

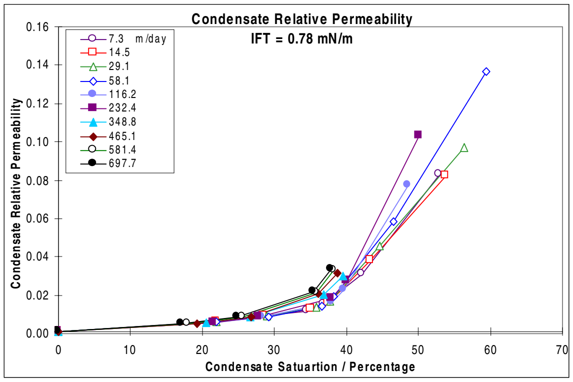


**Fig. 3—Clashach core condensate relative permeability**

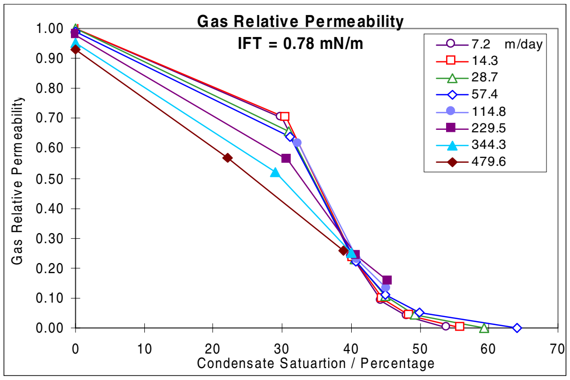


**Fig.4—Berea core gas relative permeability**

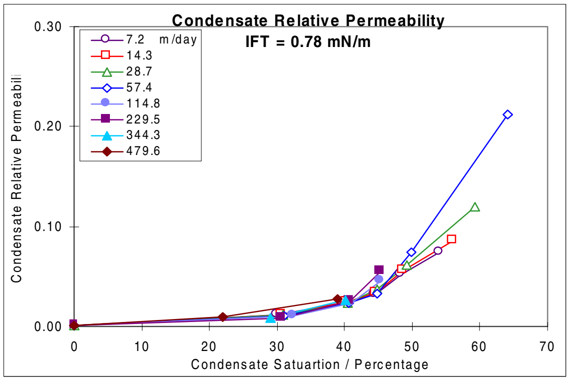


**Fig. 5—Berea core condensate relative permeability**

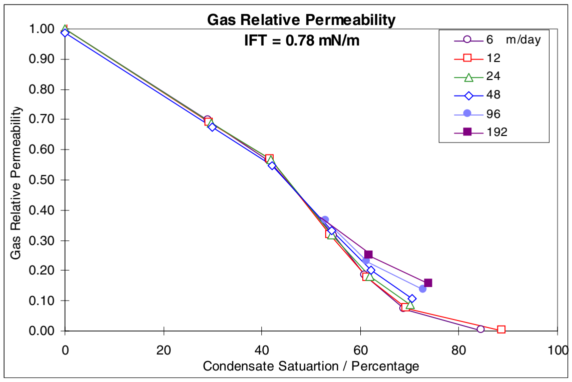


**Fig.6—Texas Cream core gas relative permeability**

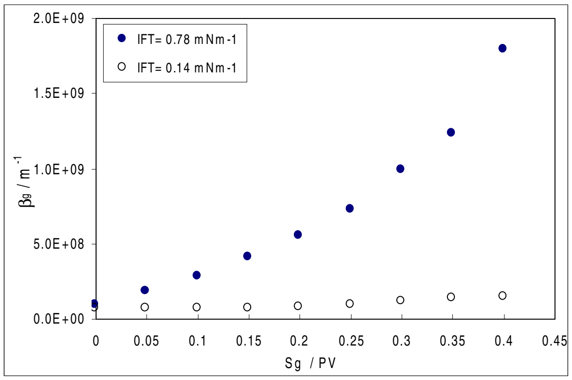


**Fig.7--Variation of $\beta_g$ with Condensate Saturation and IFT**

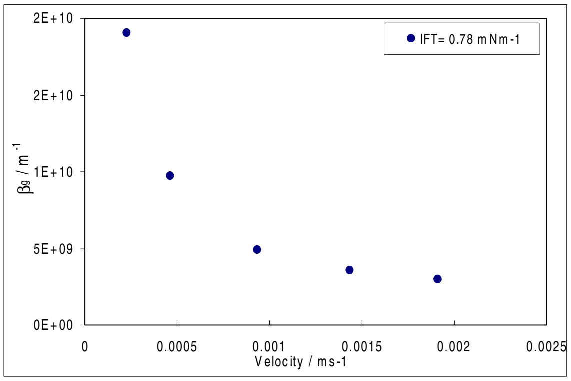


**Fig.8--Variation of $\beta_g$ with gas superficial velocity at $S_c$=0.40 PV IFT=0.78 mNm$^{-1}$, Berea core**

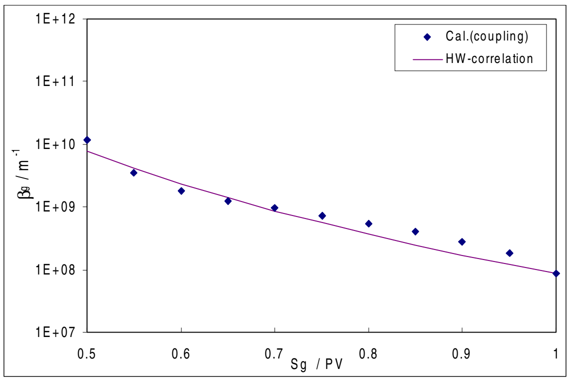


**Fig.9-- Comparison of $\beta_g$ as calculated with coupling and predicted by in-house correlation at Swi=0.0% and IFT of 0.78 mN/m, Clashach core**

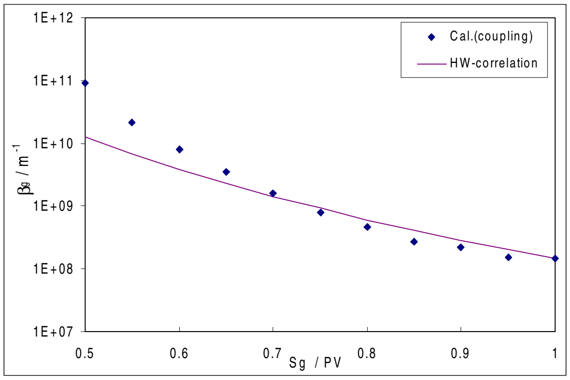


Fig.10— Comparison of $\beta_g$ as calculated with coupling and predicted by in-house correlation at Swi=0.0% and IFT of 0.78 mN/m, Berea Core.

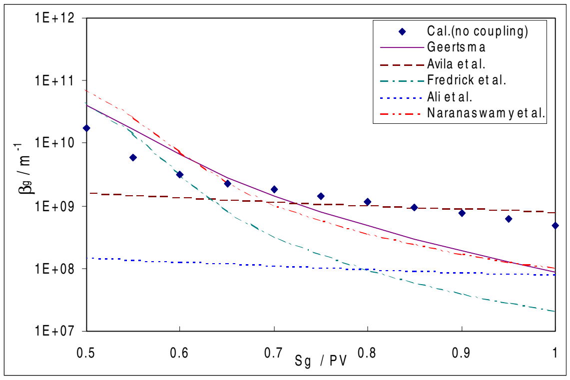


Fig 11--Comparisson of $\beta_g$ as calculated with no coupling and predicted by different correlations at Swi=0.0% and IFT of 0.78 mN/m, Clashach Core

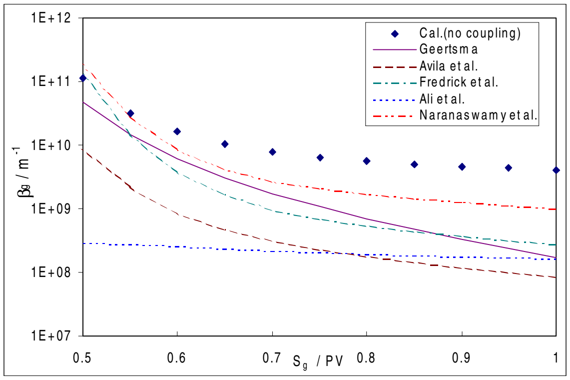


Fig 12--Comparisson of $\beta_g$ as calculated with no coupling and predicted by different correlations at Swi=0.0% and IFT of 0.78 mN/m, Berea Core