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A New Technique to Predict Relative Permeability for Two-Phase Gas/Oil System at Different Interfacial Tension

Latifa Al-Nuaimi, Omid Shahrokhi and Mehran Sohrabi, Centre for Enhanced Oil recovery and CO2 Solutions, Heriot-Watt University; Amir Jahanbakhsh, School of Engineering & Physical Sciences, Heriot-Watt University.*

Summary

Many physical factors are affecting relative permeability. These factors could be wettability, interfacial tension, and pore size distribution of the porous media. All these factors significantly change the shape of the relative permeability curve. The change of interfacial tension of flowing phases can considerably change flow characteristics especially in gas condensate reservoir or gas injection into wells with near miscible conditions.

Assuming that physical core properties and experiment conditions are constant, interfacial tension as the only variable would change relative permeabilities. Here our objective is to estimate relative permeability at lower interfacial tensions from immiscible relative permeability. We will also estimate the change of residual oil saturation with interfacial tensions.

In this paper, we have implemented Michaelis Menten Kinetics model to evaluate residual oil as a function of interfacial tension. Also, a new set of correlations was purposed to calculate gas and oil relative permeability at different IFT. The accuracy of the model is then assessed against experimental data available in literature and predictions of a default model in commercial simulators (Coat's model). Although the model needs fewer input data and it requires fewer calculations than Coat's model, it improved predictions.

Introduction

The effect of interfacial tension on oil recovery is well documented in the literature. In this paper, we will focus on modelling change of residual oil saturation to gas (S_{org}) and two-phase gas/oil relative permeability with interfacial tension (IFT).

Longeron (1980) examined the effect of IFT values on two-phase gas/oil relative permeability and residual oil saturation at high pressure and temperature. Interfacial tension between oil and gas was controlled by pressure and pre-equilibrated fluids (methanol/n-heptane) before each coreflood. They performed corefloods with IFTs ranging from 0.001 to 12.6 mN/m. They concluded that there is a relationship between IFT values and relative permeability and residual oil saturation. Below a critical IFT value of 0.04mN/m, the effect was more pronounced.

Asar and Handy (1988) performed two-phase steady state core flooding experiments by using binary hydrocarbon system (Methane/ Propane) to investigate the effect of IFT on gas/oil relative permeability. Interfacial tension was controlled in each experiment by changing pressure, IFT ranged between 0.03mN/m to 0.82 mN/m in their experiments. They reported that with IFT decrease; k_{rg} and k_{rog} became linear with S_{org} approaching zero

Henderson, Danesh et al. (1997) investigated the impact of flow rates and interfacial tension on relative permeability change for a condensate fluid pair. Their results showed an increase of relative permeability of fluids with increasing flow rates. They also observed relative permeability increase with interfacial tension reduction. They claimed the effect of interfacial tension on gas/oil system was more significant for condensate fluids.

Blom, Hagoort et al. (2000) investigated how interfacial tension and fluid flow rate affect two-phase relative permeability. They used methanol/n-hexane fluid pair in their study at low IFT range 0.31mN/m to 0.006 mN/m. When approaching lower IFTs, they observed linear relative permeability curve.

Al-Wahaibi, Grattoni et al. (2006) conducted two-phase flow experiments in drainage and imbibition saturation directions. They used Coat's model as well as Whitson and Fevange equation to predict their experimental results. Their experimental results showed residual oil decrease with IFT reduction. They also reported linear relative permeability curves at IFTs to zero.; They compared their results with predictions of Coat's model and concluded that the poor predictions of Coat's model are because of using one tuning parameter for both oil and gas. They reported that Whitson and Fevange model was more than Coats' model to predict their experimental results.

While two-phase investigations are abundant, there are few studies on the effect of IFT on three-phase flow. Cinar et al. (2005) conducted corefloods water-wet system to measure the three-phase relative permeability of an analogue G/O/W system with interfacial tensions of G/O at0.028 mN/m, 0.308 mN/m, and 2.297 mN/m. Their results showed that wetting phase relative permeability did not show any change with G/O IFT, while other two phases were significantly affected. (Cinar and Orr 2005).

Cinar, Marquez et al. (2007) extended their results by investigating the effect of wettability as well as interfacial tension on three-phase relative permeability. Pre-equilibrated fluids used in the experiments were mixtures of hexadecane, n-butanol and water. Their results indicated that relative permeability of water for the water-wet porous system was unchanged, while in oil-wet porous media water relative permeability declined with decreased IFT between gas and oil.

Coats (1980) purposed an equation to consider miscibility of gas and oil by considering oil compositions change. The model was aimed at predicting relative permeability and capillary pressure at different miscibility conditions. The model assumes gas and oil phases are in equilibrium at isothermal condition and diffusion is neglected. Coat's correlation is not based on a physical theory or experimental evidence. It describes the

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behaviour of fluids flowing under different interfacial tensions from a mathematical point of view. In the model, N is a single tuning parameter used for both gas and oil phase. The application of only one parameter methodology leads to errors in estimation, especially where oil and gas relative permeability shows different curvatures. Coats formula is widely adopted in commercial simulators like Eclipse and CMG. Equations 1 to 3 show Coat's model formulation:

$$k_{rg} = F_k k_{rg}^{imm} + (1 - F_k) k_{rg}^{misc} \qquad \text{Equation 1}$$

$$k_{ro} = F_k k_{ro}^{imm} + (1 - F_k) k_{ro}^{misc} \qquad \text{Equation 2}$$

$$F_k = min\left[1, (\frac{\sigma}{\sigma_0})^{1/N}\right] \qquad \text{Equation 3}$$

Theory and Method

In this section, we will discuss details modelling residual oil saturation as a function of IFT. Then formulation forpredicting two-phase gas/oil relative permeabilities at different IFTs based on a high IFT set of experimental data is presented.

Estimating residual oil saturation at different IFTs.

Different sets of two-phase experimental Gas/Oil relative permeabilities were employed to find a suitable correlation for predicting (S_{org}) as a function of IFT (Longeron 1980), (Asar and Handy 1988), (Al-Wahaibi, Grattoni et al. 2006). Then the predicted S_{org} would be used to estimate two-phase (oil/gas) relative permeability in this paper.

Published data were plotted (IFT versus S_{org}) to examine the effect of interfacial tension on residual oil saturation. The best type of equations to fit the experimental data was logarithmic equations. Figure 1 indicates a critical point for interfacial tension for each case study. At IFTs below this point, the Sorg is reduced significantly; the equation below fits this change;

$$S_{or}\ (IFT) = a * ln(IFT) + C \qquad \text{Equation 4}$$

It is important to note that at IFT=1; where predicted S_{org} equal C, the predicted value is not physically correct.

An alternative way of finding S_{org} is Michaelis Menten Kinetics (MMK) model. MMK model is used in biology to describe, the rate of enzymatic reactions (K(C)) by relating reaction rate to the concentration of the substrate (C). At K_n; the reaction is starting to transform from linear increase to a curvature reaching a plateau (K_{max}) (Keshet 1988).

$$K(C) = \frac{K_{max} C}{K_n + C} \qquad \text{Equation 5}$$

Equation (5) and figure (2) display MMK equation; the equation was adopted to estimate S_{org} as a function of IFT. Equation (6) was used to calculate residual oil saturation for the two-phase system (gas/oil). It calculates residual oil saturation as a function of IFT between gas and oil. Residual oil saturation at the immiscible condition ($Sor_{imm} IFT$) and critical IFT are used as input.

$$Sor(IFT) = \frac{Sor_{imm} IFT}{IFT_{critical} + IFT} \qquad \text{Equation 6}$$

K_n in MMK model is the point where enzyme reaction rate no longer linear. Several researchers have reported a critical IFT value below which gas and oil relative permeability increase with IFT is reduction is more significant. Figure (1) plots S_{org} versus IFT for different published experimental data. The figure indicates a critical change in S_{org}; we called this point the critical IFT. Below this critical interfacial tension, a sharp reduction in Sorg is observed. Above critical interfacial tension, the curve was almost constant.

Two techniques are suggested to estimate critical IFT. The first technique is found IFT value given $Sorg_{,immiscible}/2$. The second technique is guessing $IFT_{critical}$. For example, to guess $IFT_{critical}$ correctly for using (Longeron 1980) data;

$Sorg_{,\ immiscible}$ =0.35 at IFT=12.6 mN/m.

$$Sor(IFT) = \frac{0.35 \times 12.6}{IFT_{critical} + 12.6}$$

$IFT_{critical}$ is changed to get the difference between experimental $Sorg_{,\ immiscible}$ and calculated $Sorg_{,\ immiscible}$ by using equation (7) within 1% to 5% error. The calculation procedure is presented in figure (3), and results are summarized in Table (1).

Estimating gas/oil relative permeability at different IFT.

The purposed correlations were used to estimate relative permeability for gas/oil system at different IFT by using calculated Sorg which is predicted from MMK as input to new correlations. Performing experiments at different IFT is expensive and time-consuming. So suggested correlations aim at reducing uncertainty and errors of predicting interpolated relative permeability for gas/oil at different IFT; Purposed formula are as following:

$$kro\ (IFT,\ Sorg) = \llbracket [-(1 - Sorg,\ imm)] Sg + 1 \rrbracket^{Lo}, \text{ Equation 7}$$

$$krg\ (IFT,\ Sorg) = \llbracket Sg - Sgc,\ imm \rrbracket^{Lg}, \text{ Equation 8}$$

$$Lo\ (IFT,\ Sorg) = \text{Lo, ref} - [\text{Sorg, imm} - \text{Sorg (IFT)}], \text{ Equation 9}$$

$$Lg\ (IFT,\ Sorg) = \text{Lg, ref} - [\text{Sorg, imm} - \text{Sorg (IFT)}, \text{ Equation 10}$$

Equation (7) is utilized to compute oil relative permeability, by using L_o (oil reduction factor at IFT). Equation (8) is utilized to calculate gas relative permeability, by using L_g (gas reduction factor at IFT). L_o^{ref} and L_g^{ref} are tuning parameters which are calculated only once to match experimental immiscible k_{ro} and k_{rg}, respectively.

Procedure to obtain gas/oil relative permeability with varying IFT

As an example to evaluate new correlations (Longeron 1980) data is used. Initially, the objective is estimating k_{rg} and k_{ro} at IFT=0.065 mN/m. Inputs will be $Sorg_{,\ immiscible}$, Lo, Lg and Sorg (0.065).

Using equation (6) to find Sorg at 0.065.

$$Sor(0.065) = \frac{0.35 \times 0.065}{0.13 + 0.065} = 0.11$$

The gas and oil relative permeability curves, as well as saturations, are normalized. Then Lo_{ref} is tuned to match immiscible k_{ro} with r-squared fitting parameter closest to 1. (Lo_{ref} =4 with R^2=93.7%), and Lg_{ref} is tuned

(Lg_{ref} =1.9 with R^2=91.3%) to match immiscible k_{rg}. After that, L_o and L_g at IFT (0.065mN/m) are calculated [Lo (0.065)=3.87 and Lo (0.065)=1.77]. Finally, equation (8) and equation (8) are applied to predict oil relative permeability and gas relative permeability. Figure (5) is a comparison between the suggested method with predictions of Coat's method and table (1) list the prediction error of literature data by using these two methods.

Conclusions

Our suggested equation fitted experimental data reasonably. Results for each fluid pair indicated a critical IFT. The accuracy of the new correlations to predict k_{rg} and k_{rog} depend on the accuracy of critical IFT and input values; also compared to Coat's formula the purposed model improved the predictions. The new methodology is based on immiscible data to predict relative permeabilities at IFTs lower than immiscible corefloods. This methodology was evaluated by using two-phase gas/oil experimental data. However, potentially could be applied to W/O displacement during surfactant injection.The model could be extended to predict three-phase relative permeabilities.

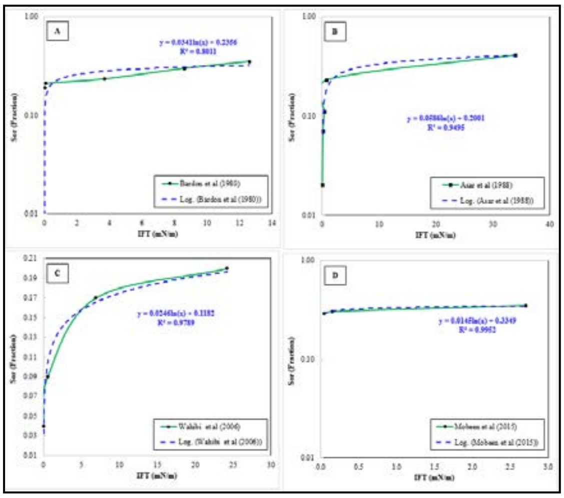

Figure 1: Semi-log plot for S_{or} versus IFT for different published data from A to D.

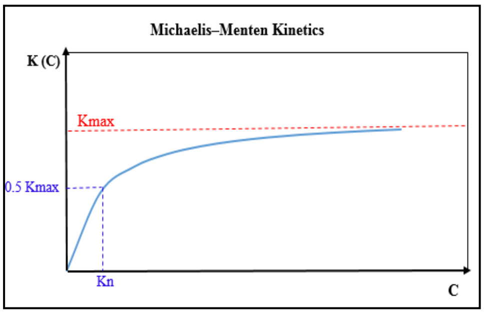

Figure 2: Michaelis Menten Kinetics Model

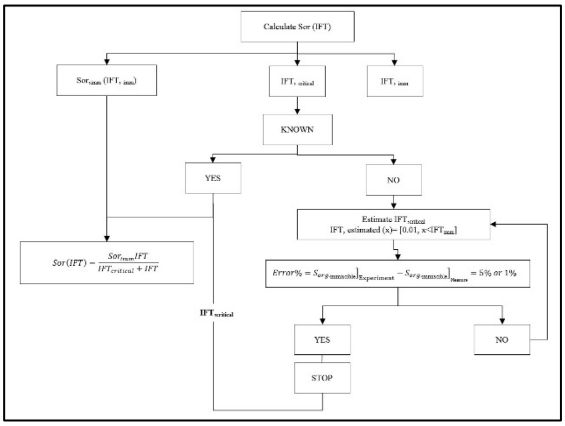

Figure 3: Flowchart to calculate $IFT_{critical}$ by setting error range between $Sorg_{,\ immiscible}$ experiment, and $Sorg_{,\ immiscible}$ calculated between 1% and 5%.

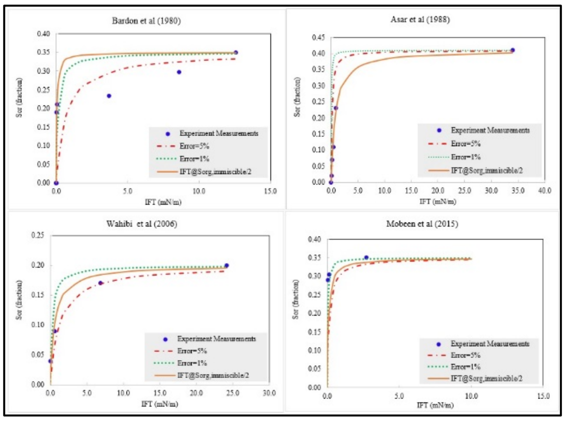

Figure 4: Comparison between experiments S_{org} vs IFT and by estimating $IFT_{critical}$. (Blue dotted curve indicates experimental data, green dashed curve indicates using $IFT_{critical}$ with 1%, red dashed line indicates 5% error and solid brown line indicates IFT at $Sorg_{,immiscible}/2$)

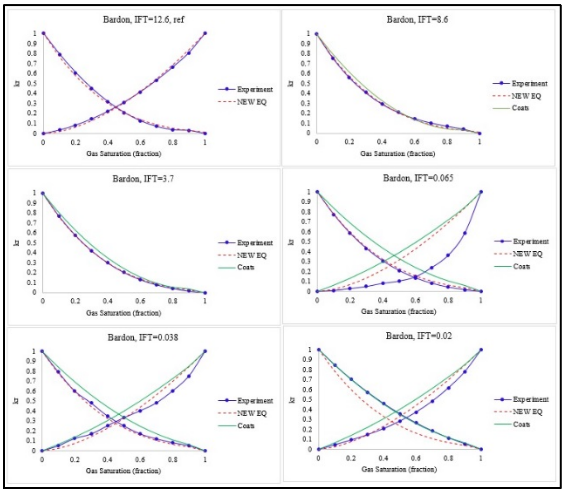

Figure 5: comparison between new methodology and Coat's prediction with laboratory tests at different IFT by using (Longeron 1980) data.

Table 1: Obtained critical IFT and error.

	$IFT_{Critical}$	Sorg Prediction Error (%)	
		MMK	Coats
(Longeron 1980)	0.13	39.8	28
(Asar and Handy 1988)	0.35	79.6	303
(Al-Wahaibi, Grattoni et al. 2006)	0.24	44.7	70

Table 2: Error compare between new method and Coats method.

	Gas/oil kr Prediction Error (%)	
	New method	Coats method
(Longeron 1980)	39.6	68.6
(Asar and Handy 1988)	71.6	75.2
(Al-Wahaibi, Grattoni et al. 2006)	45.4	34.2
Error Average	52.1	59.3

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