APPLYING MAK GAS-WATER RELATIVE PERMEABILITY CORRELATIONS TO PREDICT A GAS-CONDENSATE RELATIVE PERMEABILITY AND PRODUCTION PERFORMANCE (CASE STUDY)
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1.0 Abstract
An analytical correlation to describe relative permeability is extremely useful in the absence of laboratory measured data, or when a general representative fluid flow is required. Previously, experimental work has been done to develop new correlations to predict gas-water relative permeability (RP) data for various permeability and porosity media. The newly developed technique consists of quick laboratory measurements to measure end-point saturations and new correlations to predict gas-water relative permeability behaviour.

These differ from previous work because they honour the reservoir's rock and fluid properties – such as reservoir permeability, porosity, interfacial tension and gas density. The effectiveness and practicality of applying these new correlations to simulate laboratory measured gas-water relative permeability data (for various permeability and porosity cores) has been demonstrated in SPE 71523.

To conclude, as part of a doctoral dissertation, the correlations were tested on simulation models. The aims of this work segment were twofold:
1. To investigate the applicability of the newly developed analytical correlations to reservoir simulation and their impact on history matching and forecasting of reservoir production. No attempts were to be made to re-match the production history.
2. To investigate the effect of applying the correlations pre and post-upscaling of static reservoir model. This part of the investigation demonstrates that in situations where the upscaling of the static model has resulted in significant distortion of the K and ϕ relationship, application of Mulyadi-Amin-Kennaird (will be referred to as MAK throughout this paper) correlations, or similar, would be erroneous.

The new correlations were used to generate several sets of gas-water relative permeability data to replace the corresponding history-matched relative permeability data in the pre-upscaled and a post-upscaled producing gas-condensate reservoir models. The implications of the new correlations were assessed from the model's historical and forecasted reservoir production performance.

The results of the specific cases investigated demonstrated that while the new correlations did not significantly affect the history-matched period, it did have significant impact on the forecasted production profiles and ultimate recovery. Although these are not unexpected, the differences were significant enough to warrant attention; in particular the manner in which such correlations are used to populate dynamic models.

2.0 Introduction
The importance of core analysis measurements for determination of residual gas saturation has long been recognised and experimental work has been conducted to investigate water displacement and entrapment of gas. Geffen et al measured residual gas saturation (Sgr) of 15 to 50 percent pore space for various porous media. Work on carbonate formations by Keelan and Pugh revealed trapped gas saturations from 23 to 69 percent of pore space.

Relative permeability is defined as the ability of one phase to flow through a medium in the presence of another and, as such, it is a mathematical abstract. Therefore, the accurate determination of end-point saturations, such as initial wetting saturation and residual non-wetting saturation, are key to any reservoir model. In the case of a gas-water system, these are initial water saturation (Swi) and residual gas saturation (Sgr). Given the range of possible Sgr in the various types of formations, it is imperative that a common best technique is used to provide consistency in the method and comparison of Sgr measurements. However, there was a lack of a commonly accepted laboratory method for quantitative
determination of residual gas saturation. Consequently, there is uncertainty in estimating producible reserves for gas reservoirs under strong water drive with subsequent economic implications.

To address the issue, a study was conducted to test the accuracy of the commonly used Special-Core-Analysis (SCAL) techniques used for measuring residual gas saturation (Sgr). These include Steady-State displacement, Co-current Imbibition, Centrifuge (decane-brine) and Counter-Current Imbibition. In the study, experiments were conducted on various consolidated homogeneous sandstone core samples with permeability ranging from 1 mD to 3,500 mD. Circumstantial evidence found in the experiments suggested that Steady-state displacement and Co-current Imbibition are the most representative techniques for measuring Sgr. However, Steady-state displacement is the preferred method because it measures both Sgr and gas-water relative permeability data. Consequently, it is more time consuming and expensive.

To minimize the reliance on lengthy and expensive laboratory tests such as Steady-State Displacement, a new technique was proposed which consists of a quick experimental measurement of the end-points (Swi and Sgr) and analytical correlations to determine the gas-water relative permeability behaviour.

The newly developed correlations are derived from Corey’s equations for gas-oil systems. However, they differ from previously developed correlations because they account for the unique physical properties of the system such as gas permeability (Ka), porosity (φ), interfacial tension (σ) and gas density (ρg). These newly developed correlations, named as Mulyadi-Amin-Kennaird (MAK), correlations are shown in equations (1) to (7).

\[
\alpha = \frac{2b'(Sgr)^2}{\alpha' + 1.20287b - 0.8117} \\
\alpha' = -0.0455 \ln(Ka) - 10.544 \phi^2 + 10.263 \rho_g - 0.0326 \phi \\
a' = -9 \times 10^{-5} Ka - 9.034 \phi^2 + 1.6758 \phi + 3.0779 \\
b' = -72.092 Swi^2 + (38.0845 - 0.0343 \ln(Ka)) Swi + 0.0098 \sigma - 2.633 \\
c' = 1.20287 \cdot b^{-0.8117}
\]

Previous work has also shown that the newly developed correlations are accurate and reliable for simulating gas-water relative permeability data for various water-driven gas reservoirs.

As MAK correlations are capable of simulating the two-phase flow of water and gas in a core plug scale, the next stage of the study is to test the ability of the correlations to simulate the overall gas-water reservoir fluid behaviour using reservoir simulation. In this study, the accuracy of MAK correlations in predicting the gas-water fluid behavior was investigated by comparing simulated and actual fluid production.

3.0 Case Study Background

The purpose of the reservoir simulation studies was to investigate the effect of the MAK correlations on production performance of water-driven gas reservoir. However, in this case study, the application of MAK correlations was extended to a gas condensate system to demonstrate its applicability in more generalised 3-phase flow (gas/water/oil) systems.
Although MAK correlations do not cater for oil relative permeability calculations, this paper will demonstrate that the correlations’ application can be readily extended from dry gas systems to gas condensate systems.

4.0 Model Assumptions

4.1 Two-Phase System

In the studied water-driven gas condensate field, the issue of mobile condensate in the reservoir needs to be considered. Previously, a study was conducted to address the possibility of 3-phase flow in the reservoir and concluded that, with gas recycling and pressure maintenance above the dew point, condensate drop out is not an issue. Only at the end of recycling and reverting to depletion-drive can condensate form in the reservoir; by which time most of the condensate would have been stripped and dry gas mixing would have further depressed the dew point, again making mobile condensate an unlikely issue. Therefore, it is assumed that the active phases are gas and water.

However, two hydrocarbon pseudo-components were used to model a gas-condensate system to cater for the possibility of condensate drop out; hence, requiring gas-oil and water-oil relative permeability data. In this case, MAK correlations were implemented to generate gas and water relative permeability data in gas-oil and water-oil systems. Meanwhile, the oil relative permeability data were generated by Corey’s equations.

4.2 Formation Properties

In the reservoir model, each permeability class is assigned an average Swi, determined by capillary-pressure saturation curves. Meanwhile, residual gas saturation (Sgr) as a function of initial water saturation was developed from extensive experimental work using Counter-current Imbibition. Furthermore, several correlations were also developed to derive residual oil saturation in the presence of water (Sorw) and residual oil saturation in the presence of gas (Sorg). These equations are given below:

\[
S_{gr} = 0.5(1-S_{wc}) \text{ or } 0.01(4.8747\ln(S_{wc}^{100})+14.209) \tag{8}
\]
\[
S_{orw} = (S_{gr}+0.16) \text{ or } 0.9(1-S_{wc}) \tag{9}
\]
\[
S_{org} = 0.1 \text{ or } 0.25(1-S_{wc}) \tag{10}
\]

5.0 Modifying MAK correlations for Gas-Condensate Systems

In their current form, MAK correlations do not account for the presence of oil. Although the reservoir is assumed to be a 2-phase flow of water and gas, gas-oil and water-oil relative permeability data are still required in the reservoir model to reflect the effect of oil on water and gas relative permeabilities during condensate dropout. Therefore, MAK correlations are modified to transform them from a two-phase gas-water to a three-phase gas-water-oil system. The assumptions used in transforming the equations are:

- Water (w) is the wetting phase, gas (g) is the non-wetting phase and oil (o) is the intermediate phase.
- The relative permeability of oil, water and gas are considered as a function of its own saturation i.e. 
  \[K_w = K_w(S_w)\text{ and } K_g = K_g(S_g)\].

Using the assumptions above, the individual gas and water equations in MAK correlations were modified to account for oil in water-oil and gas-oil relative permeabilities.

5.1 Modifying Water Relative Permeability Equation

In a water-oil system, core flooding experiments are conducted in the presence of oil (So, max) and Swi. However, as the original MAK equation for water relative permeability is already expressed as a function of water saturation, no modifications were necessary to transform it to a water-oil system. Hence, the water equation for water-oil system is given in equation (1).

5.2 Modifying Gas Relative Permeability Equation
In the gas-oil system, the experiment is initially performed in the presence of Swi and Sgr while surrounded by the maximum oil saturation (So,max). Then, gas is injected at incremental stages to reduce the oil saturation to give the residual oil saturation at the presence of gas (Sorg).

As the original gas equation in MAK correlations was expressed in terms of water saturation (Sw), the first modification required is to express Sw in terms of gas saturation (Sg). Sw can be rewritten as 1-Sg and therefore, the gas relative permeability equation (2) still for a gas-water system can be rewritten as:

$$K_{rg} = \left[ 1 - \left( \frac{1 - Sg}{1 - Swi} \right) \right]^b \left[ 1 - \left( \frac{1 - Swi}{1 - Sgr} \right) \right]^c$$

(11)

However, in a 3-phase flow for gas-oil system, the initial saturation present is not only limited to Swi; Sorg is also present. Therefore, for a 3-phase flow, the gas relative permeability in equation (11) for gas-oil system should be rewritten as:

$$K_{rg} = \left[ 1 - \left( \frac{1 - Sg - Sorg}{1 - Swi - Sgr - Sorg} \right) \right]^b \left[ 1 - \left( \frac{1 - Swi - Sorg}{1 - Swi} \right) \right]^c$$

(12)

6.0 Reservoir Simulation Study

The purpose of the simulation study is to compare the impact of the MAK correlations on the production performance of reservoir simulation models based on established Corey and Land correlations. Unlike the latter correlations, the MAK correlations will consider the reservoir’s formation properties eg. Ka, φ and Swi and will be assigned based on reservoir properties and on a cell-by-cell basis. The investigation began by replacing the gas and water permeability data from a history-matched reservoir model with relative permeability data generated by the transformed MAK correlations. Then, simulations were performed to investigate the effect of the change in relative permeability models.

In this case study, a hypothetical reservoir model was used. Two cases were tested for the investigation into the effect of the implementation of MAK correlations in reservoir simulation models: pre-upscaled and post-upscaled.

1. In the post-upscaled case, the dynamic model was derived from a geological modeling package (containing the raw interpretation data from core analysis, seismic, log etc) and then upscaled using an upscaled package. During this process, the permeability and porosity properties of individual cells have been averaged to yield the upscaled properties of the simulation blocks of the dynamic model.

2. In the pre-upscaled model, the dynamic model was built on the framework of the geological structure and the K and φ relationship was retained in the simulation blocks. It is obvious (as in post-upscaled model) that once the K and φ relationship is destroyed by upsampling, then the application of the MAK correlations, which depends on the integrity of such a relationship, would be erroneous.

In both cases, the effect of the MAK correlations will be examined in terms of timing of the water breakthrough and gas, water and condensate production.

6.1 Up-scaled Reservoir Model Application

In the upscaled reservoir application of MAK correlations, 2 cases are presented in this paper. In the first case, the minimum subdivision of permeability and porosity classes was used. The second case highlights the importance choosing the correct experimental methodology to measure residual gas saturation.

6.1.1 Case Study 1

The X field permeability distribution ranges from 2 to 2,000 mD. In the model, this range is subdivided into 11 different sets of permeability classes as shown in Table 1. Each of the permeability class is
assigned average formation properties – Swi, Sorg, Sorw and Sgr – and a set of water-oil and gas-oil relative permeability tables.

The history match resulting from MAK correlations is shown in Figure 1. The figure demonstrates that changing out the relative permeability model to MAK correlations did not significantly alter the history-match. A slight mismatch did occur between the simulated and actual rate of water production, whilst the timing of water breakthrough and its fluctuation trends were similar to the actual profile.

Since the only slight mismatch occurred for the water profile and timing of water breakthrough, production forecasts were performed without further history matching. The resultant rate and cumulative productions are shown in Figure 2 and Figure 3 respectively. The main differences between the original and MAK correlated forecasts are higher sustained gas and condensate rate for the latter. Furthermore, MAK correlations predicted a lower rate of water production. The differences are attributed to higher gas and lower water relative permeabilities calculated by MAK correlations for the majority of sands with permeability between 2 and 2,000 mD. Examples of the differences between the original and new water-oil and gas-oil relative permeability data are shown in Figure 4 and 5, respectively.

Figure 3 also demonstrate that MAK correlations have also provided more stability during simulation, enabling further forecast beyond year 7. This can be attributed to voiding out those low porosity and extremely high permeability blocks, which caused numerical instability in the original (reference) model.

6.1.2 Case Study 2
In this case study, a sensitivity analysis is performed on the effect of end-point saturation on production rates and the ultimate recovery. As described previously, Swi is determined by capillary-pressure-saturation curve. Meanwhile, Sgr is determined from the minimum value between Land correlations and Sgr’s rule-of-thumb in equation (8).

The difference between the experiment and correlated Swi and Sgr is shown in Figure 6 and 7. As shown, the modelled Swi and Sgr, expressed as a function of permeability, differ significantly to the experimental data. The difference in Sgr was due to the methodology used to determine it. In the original model, Sgr was measured by Counter-current Imbibition tests. However, the new model contained Sgr measured by Co-Current Imbibition test. The difference in the experimental methodology has implications on the accuracy of the measured Sgr as explained in SPE 64710.

Consequently, new sets of corresponding Sorg, Sorw, gas-oil and water-oil relative permeability data were regenerated based on the experimental Sgr and Swi.

The resultant simulated historical rate of production is shown in Figure 8. The figure showed that MAK correlations and the experimental end-point saturations achieved a history-match between actual and simulated condensate and gas rate of production. However, the simulated water breakthrough is delayed and its rate is lower than actual. Furthermore, MAK predicted higher sustained gas rate during the mid-life of the field.

The overall cumulative recovery of gas, water and condensate is shown in Figure 9. The main differences between the original and MAK forecast are that MAK predicted lower water production and slightly higher condensate production. This is due to lower experimental Swi and MAK correlated water relative permeability in water-oil system. However, MAK correlations have not produced different cumulative gas production because of the compensating effect between the lower experimental Sgr, and higher calculated gas relative permeability.

6.2 Pre Up-scaled Reservoir Model Application
The purpose of this last case study is to investigate the application of MAK correlations in the pre-upscaled reservoir model whereby the model still contains the raw interpretation from seismic, log and core data. This would be used as a direct comparison of the appropriate application of MAK correlations in the pre-upscaled and post-upscaled stage of reservoir modeling.

6.2.1 Case Study 3
In this case, experimental end-point saturations Swi and Sgr were used to determined Sorg and Sorw. Meanwhile, the gas-oil and water-oil relative permeability data were calculated by MAK correlations. Furthermore, the number of permeability and porosity clustering were increased from 11 sets of tables to 48 sets of gas-oil and water-oil production as shown in Table 2 and 3.
As this field has no production history, the comparison study was based on production forecasts. The overall resultant cumulative production rate of water, gas and condensate is shown in Figure 10 and 11. MAK correlations predict significantly (some 43 percent) less water compared to the original forecast. Consequently, higher gas and condensate rate of production in the early life of the field.

7.0 Discussions
In these case studies, it is demonstrated that:
1. While MAK correlations did not affect the history matched period of a dynamic model (unfortunately an upscaled model, but with crucial production history for comparison), the production forecasts were significantly different from the reference runs, in particular in the water production. The reduction in water production is due to the difference in curvature of the water relative permeability curve.
2. It should be noted that the application of the MAK or similar correlations, which depends on the integrity of K and φ relationship, on a cell-by-cell basis, for an upscaled model is inappropriate. Nevertheless, this investigation was carried out to demonstrate the impact of the new correlations.

During the post-upscaled application of MAK correlations, several instability problems occurred. The instability was found to be due to the possible extreme combinations of high permeability and low porosity resulting from upscaling in some of the simulation blocks and they were duly voided out, hence, the distortion of the genuine relationship between the formation permeability and porosity. The differences in the K and φ relationship inside the pre-upscaled and post-upscaled models are shown in Figure 12, 13, 14 and 15.

Figure 12 is a 3-D plot counting the number of cells, for cases 1 & 2, with the various combinations of permeability and porosity in the post-upscaled reservoir model. It clearly demonstrates how upscaling may severely distort the unique K and φ relationship in the formation. As shown, upscaling implies the existence of extreme combinations of high permeability and porosity; for example, a 4,000-mD rock with a porosity of 0.01 %. Figure 13 further demonstrates the distortion of the K and φ relationship compared to data obtained from core plugs from single or multiple gas reservoirs.

Figure 14 is a similar 3-D plot counting the number of cells, for case3, with the various combinations of permeability and porosity in the pre-upscaled reservoir model. It shows that the pre-upscaled reservoir model did not contain such extreme combinations of permeability and porosity that can result from the upscaling process. Although the model may contain multiple K and φ relationships, Figure 15, which is a log (K) versus φ plot of Figure 14, demonstrates the two porosity/permeability trends used in the simulation model.

Instability problems may also occur for extremely tight reservoirs (less than 1 mD) or highly permeable reservoirs (greater than5,000 mD) because the correlations are based on experimental measurements on cores with permeabilities between 1 mD and 3,515 mD. However, numerical instability is most likely to be caused by the combination of low porosity (low volume) and high permeability (high flux) as counted in Figure 12.

8.0 Conclusions
The fundamental assumption of MAK correlations is the preservation of the physical relationship between permeability and porosity.

MAK correlations are best applied in the pre up-scaled stage of reservoir modeling whereby the physical relationship between permeability and porosity still exists, as in the formation itself.
1. Accurate determination of end-point saturations is also required simultaneously with MAK correlations application. Therefore, it is suggested that all end-point saturations are determined by Co-current Imbibition and a relationship is developed between each end-point saturation especially Swi and Sgr.

2. MAK correlations enhanced the description of the dynamic reservoir models because it minimized the necessity to use averaged formation properties; it enables further refinement of the permeability and porosity clustering. It can be applied on a voxel-by-voxel basis before upscaling to generate dynamic models.
3. MAK correlations are limited to reservoirs with permeabilities between 1 mD and 3,515 mD.
4. Although MAK correlations were developed based on laboratory measurements for gas-water systems, it has been demonstrated that they can be readily extended to gas condensate systems to estimate the flow behaviour of gas and water for 3-phase flow.

References

Nomenclature
\[ \sigma = \text{interfacial tension (gas-water), dynes/cm} \]
\[ \Delta \rho = \text{gas-water density difference, g/cc} \]
\[ \rho = \text{gas density, g/cc} \]
\[ K_r = \text{relative permeability, fraction} \]
\[ K_a = \text{absolute gas permeability, mD} \]
\[ S = \text{saturation, fraction} \]
\[ \phi = \text{porosity, fraction} \]

Subscripts
w = water
g = gas
i = initial
r = residual
orw = oil in reference to water
org = oil in reference to gas

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Table 1 – Permeability Clustering

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Table 2 – Increasing permeability clustering

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Table 3 – Increasing Porosity Clustering
Figure 1 – Comparison between Actual Historical and Simulated Production Rate of Gas, Water and Condensate Using MAK correlations.

Figure 2 – Comparison between Original and New Forecasts for the Production of Gas, Water and Condensate Using MAK correlations.
Figure 3 – Comparison between Original and New Forecasts for Gas, Water and Condensate using MAK correlations.

Figure 4 – Example of the Difference between the Original and MAK Calculated Relative Permeability Curve for Water-Oil System with A Permeability Range Between 100 to 500 mD.
Figure 5 – Example of the Difference between the Original and MAK Calculated Relative Permeability Curve for Gas-Oil System with a Permeability Range Between 100 to 500 mD.

Figure 6 – Comparison of Swi Estimation in the Original Model and New Model Using Experimental Data.
Figure 7 – Comparison of Sgr Estimation Using Land Correlations and Rule-of-Thumb in the Original Model and Experimental Data in the New Model.

Figure 8 – Comparison between Original and New Forecast on Gas, Water and Condensate Using MAK correlations and Experimental Swi and Sgr From Co-Current Imbibition rather than Counter-current Imbibition.
Figure 9 – Comparison between Original and New Forecasted Ultimate Recovery Using MAK correlations and Experimental Swi and Sgr From Co-Current Imbibition rather than Counter-current Imbibition.

Figure 10 – Comparison between Original and New Forecast for the Production Rate of Gas, Water and Condensate for the Pre-Upscaled Reservoir Model.
Figure 11 – Comparison between Original and New Forecast for Ultimate Recovery of Gas, Water and Condensate for the Pre-Upscaled Reservoir Model.

Figure 12 – 3-D Plot of Cell Count Containing the Various Combinations of Permeability and Porosity in the Post-Upscaled Reservoir Model.
Figure 13 – Distortion of Permeability and Porosity Relationship in Upscaled Reservoir Model Compared to That of Core Plugs From A Single and Multiple Gas Reservoirs.

\[ K = 0.043 \times \exp(0.3847 \times \Phi \times 100) \times \text{mdarcy} \]

Figure 14 – 3-D Plot of Cell Count Containing the Various Combinations of Permeability and Porosity in the Pre-Upscaled Reservoir Model.
Figure 15 – Preservation of Permeability and Porosity Relationship in the Pre-Upscaled Reservoir Model

Two linear trends

Log (Permeability)

Porosity