ABSTRACT

Water-oil relative permeability information of hydrocarbon reservoir rocks plays important roles in various modeling activities related to reservoir modeling and production forecast. The imbibition relative permeability scheme - the process of concern in this study – affects many dynamic processes in reservoir. Water flooding and water encroachment form aquifer to oil zone in the reservoir are two examples which representation in reservoir model requires the data. This study uses the standard Corey relative permeability model as a tool to study and model imbibition relative permeability behaviour of some reservoir rocks in Indonesia. Laboratory data from as many as 340 rock samples - sandstones and limestones - of various permeability and wettability from various oil fields in Indonesia is used. Activities in the modeling has pointed out the need to introduce two new empirical factors that relate to rock wettability and non-wetting flow hindrance to the model. The two factors appear to have significantly improved the ability of the model to agree and match to the measured data. The modeling also produces suggested values of the factors for rock groups based on rock wettability type and strength, as well as on permeability categories. Comparison between modeling results before and after modification has shown significant improvement in validity of output.

Keywords: Imbibition water-oil relative permeabilities, wettability, oil trapping, model improvement
I. INTRODUCTION

Fluid movements in porous and permeable rocks are largely governed by a petrophysical property referred to as the relative permeability. This includes fluid movements in hydrocarbon reservoirs, be them sandstones, limestones, or others. Different rocks with their different pore features and fluid-rock, as well as fluid-fluid, interactions tend to have different characteristics of relative permeability. These different characteristics are further influenced by relative volumes of the reservoir fluids and saturation history in the form of drainage process - e.g. the encroachment of non-wetting gas from gas cap into oil zone - and imbibition process, in which displacement by the wetting formation brine from aquifer on the oil phase in the reservoir is one of the examples. Detailed discussion on the factors and their interaction in micro scales can be found in references such as Blunt (2017). Different relative permeability shapes and end-points caused by all these factors determine exploitation path and recovery factors in the hydrocarbon production from the reservoirs.

One of the most affecting factors that shape the relative permeability characteristics is wetting tendency of reservoir rocks by reservoir liquids, i.e. water or/oil, or universally known as wettability. The importance of this rock property on relative permeability has been acknowledged and therefore been studied in depths accordingly. As early as late 1920s had the petroleum industry acknowledged the importance of wettability on multiphase flow (Fatt & Klikoff, 1959), and since then an abundant volume of study results has been reported on the issue. Some researchers in their various laboratory studies (e.g. Schneider & Owens, 1970; Owens & Archer, 1971; Donaldson & Thomas, 1971; Morrow et al, 1973; McCaffery & Benion, 1974; Wang, F.H.L., 1988; and Chang et al, 1997) revealed that rock wettability types have strong influence on relative permeability characteristics while others also did similar studies for the same objective through wider angle of views and more varied observation tools (e.g. Amaefule & Handy, 1982; Heaviside et al, 1987; Jadhunandan & Morrow, 1995; Pedrera et al, 2002; Masalmeh, 2003; Rao et al, 2006; Cinar et al, 2007; Zhao et al, 2010; and Falode & Manuel, 2014). In conjunction with the laboratory works efforts have also been spent to improve our further understanding on the issue through theoretical/modeling works (e.g. Heiba et al, 1983; Bradford et al, 1997; Huang et al, 1997; Oren & Bakke, 2003; Nguyen et al, 2005; and Gharbi & Blunt, 2012).

The issue of establishing a relatively simple relative permeability model for practical application in various activities using dynamic flow models is always actual. A relatively simple but reliable model is always desired. With regard to that aim a series of studies have been performed on laboratory-derived imbibition water-oil relative permeability and wettability data of a large set of sandstone and limestone core samples obtained from various reservoirs in Indonesia. Attempts have been made to apply existing relative permeability model – the Brooks-Corey model in this case – on the data. A series of disagreements has been readily observed from the model’s application on the data which is notably due to influence of rock wettability. This paper presents the attempt to introduce modified parameters on the model, which in the end to provide a better imbibition three-phase relative permeability model that takes into account rock wettability strength.

II. METHODOLOGY

A. Relative permeability model

Relative permeability has long been recognised as a reservoir petrophysical property that governs movements of reservoir fluids – usually two or three – under reservoir condition. This emphasizes its importance in the attempts to understand and model reservoir’s fluid flow mechanisms in their relation to hydrocarbon production. Although laboratory direct measurement in core laboratory has been established as the standard method for obtaining the data but, nevertheless, models (i.e. mathematical models) are always required both as a means for the purpose of understanding over the mechanism and as a means for overcoming data scarcity.

Early researchers such as in A.T. Corey in 1954 established oil-gas relative permeability based on Burdine’s variation in pore sizes and fluid saturation distribution model. Later the model was expanded in Corey et al (1956) and Brooks & Corey (1964). Other approaches in modeling relative permeability have also been taken such as the flexible LET approach (e.g. Lomeland & Ebeltoft, 2013; and Lomeland, 2018), empirical (e.g. Honarpour et al, 1982), and pattern recognition (e.g. Guler et al, 2003). In this work, however, the classic Corey three-phase relative permeability model is used to analyse the relative permeability data due to its relative simplicity.
Imbibition process is a condition in which the non-wetting phase fluid - usually taken as hydrocarbon - is displaced by the wetting-phase fluid (i.e. water). This process is usually made to represent conditions in reservoirs such as aquifer water encroachment to oil/gas zone or displacement of water on oil in waterflood. As the imbibition process is explained and presented in Standing (1975), the wetting-phase relative permeability ($K_{rw}$) for imbibition process - which is essentially the same for drainage process (i.e. not affected by saturation direction) is expressed in the form of

$$K_{rw} = (S_w^*)^{2+3\lambda}$$ \hspace{1cm} (1)

with $S_w^*$ is normalized water saturation of

$$S_w^* = \frac{(S_w - S_{wbr})}{(1 - S_{wbr})}$$

and $S_w$ and $S_{wbr}$ water saturation at one point during wetting-phase saturation process and irreducible water saturation, respectively. Lambda ($\lambda$) in Equation (1) is defined as ‘pore distribution index’, a parameter that describes the complexity of the pore system. It has positive dimensionless values of which the smaller the values the more complex the pore configuration of a rock (i.e. more varied pore sizes). Standing (1975) suggested values of between 0.5 and 4 for sandstones and limestones, which were later in this study proved not to be entirely accurate.

Unlike in drainage scheme, in imbibition displacement the concept by Corey puts that during the saturation process some of the non-wetting phase - oil in this case - is trapped in larger pores, while the smaller pores remain fully water saturated, hence does not contribute to oil relative permeability at some water saturation values. In regard to the imbibition displacement, Land (1968) found relationship between normalized initial and residual oil saturations ($S_{oi}^*$ and $S_{or}^*$, respectively) as

$$\frac{1}{S_{or}^*} - \frac{1}{S_{oi}^*} = C$$ \hspace{1cm} (2)

with

$$S_{oi}^* = \frac{S_{oi}}{(1 - S_{wbr})}$$ \hspace{1cm} and \hspace{1cm} $$S_{or}^* = \frac{S_{or}}{(1 - S_{wbr})}$$

While $C$ is accordingly denoted as ‘trapping constant’. The $C$ constant can theoretically be determined from laboratory fluid displacement test, even though Standing proposed the use of values between 1 and 3. The $C$ constant is regarded important since it controls the shape of the non-wetting phase curve. In this study, the values of $C$ are not calculated but are chosen within the range of 1-3.

For the non-wetting (i.e. oil) relative permeability, $K_{ro}$, Corey established that provided it is governed solely by the free oil phase saturation (normalized, $S_{or}^*$) - the oil volume that is not trapped by incoming water in the larger pores - then it can be expressed as

$$K_{ro} = K_{or}^0 (S_{or}^*)^2 \left[1 - (1 - S_{or}^*)^{2+3\lambda}\right]$$ \hspace{1cm} (3)

with $K_{or}^0$ represents a normalization factor that converts oil relative permeability from basing on intrinsic rock permeability (represented by air permeability, $K_{air}^0$) to basing on oil maximum effective permeability ($K_{or} @ S_{wbr}$). The two permeability values for producing the ratio are available in any imbibition relative permeability laboratory measurement, and since the ratio is closely linked to irreducible water saturation ($S_{wbr}$) correlation between the two is to be established for model application purposes carried out in this study.

As presented in Standing (1975) the concept of ‘free oil saturation’ is imaginary in nature, and therefore it is approximated through the use of

for every $S_{or}^*$ in equation (4), which in turn can be estimated using

$$S_{or}^* = \frac{1}{2} \left[ \left( S_{oi}^* - S_{or}^* \right) + \sqrt{\left( S_{oi}^* - S_{or}^* \right)^2 + \frac{4}{C} \left( S_{oi}^* - S_{or}^* \right) } \right]$$ \hspace{1cm} (4)

In this study, equations (1) and (3) are applied to model the water-oil imbibition relative permeabilities

$$S_{or}^* = \frac{S_{oi}^*}{CS_{oi}^* + 1}$$ \hspace{1cm} (5)

obtained from laboratory measurements on the sandstone and limestone core samples. A correlation of $K_{ro}^0$ vs $S_{wbr}$ is to be established, and it was originally planned to determine the most representative $\lambda$ values for the reservoir rocks examined.

**B. Relative permeability and wettability data**

For laboratory imbibition relative permeability measurements, two huge sets of data have been used.
The first set consists of water-wet core samples of various wettability strengths (170 sandstones and 29 limestones) whereas the second set is made up by 141 oil-wet and mixed-wet samples (121 sandstones and 20 limestones) of various wettability strengths. The one and 1.5 inch-diameter core samples have been drawn from oil reservoirs through 61 oil wells in 38 oil fields located in seven productive sedimentary basins mostly in Western Indonesia. The mostly Tertiary sandstone and limestone reservoir rocks encompass various types, flow facies, and depositional environments. They also represent the wide arbitrary ranges of permeability, from poor-fair permeability (from around one mD to roughly 150 mD), moderate/good permeability (roughly from around 150 to 400-500 mD), and high permeability (>500 mD). The lowest permeability measured through air permeability measurement is 1.1 mD and the highest being 13,185 mD. Table 1 presents summary of wells with quantity of core samples drawn from and Table 2 exhibits some examples of core basic data.

### Table 1
Sources of core samples

<table>
<thead>
<tr>
<th>Sandstone [Field (number of core samples)]</th>
<th>Limestone [Field (number of core samples)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Balam South (5), Batang (9), Bekasap (10), Bunyu (4), Cemara Timur (11), Duri (24), Jirak (7), Kataling Timur (4), Kotabatak (12), Krap South (4), Lirik (11), Minas (28), Mlandong (13), Ogai (2), P Pakam Timur (4), P Tabuan Barat (10), Petani (17), Petapahan (31), Pondok Tengah (5), Pusako (7), Rantau (16), Tanjung (40), Tanjung Tiga (5), Talang Jimar (11)</td>
<td>ASDJ (9), Ginaya (4), GTR (3), Karangdewa (4), Pondok Tengah (1), Prabumenang (4), Senoro (8), Tambun (16)</td>
</tr>
<tr>
<td>Total: 24 fields, 291 core plugs</td>
<td>Total: 8 fields, 49 core plugs</td>
</tr>
</tbody>
</table>

### Table 2
Examples of basic data for sandstone and limestone core samples used in the study

<table>
<thead>
<tr>
<th>Field</th>
<th>Well</th>
<th>Plug No.</th>
<th>Porosity (%)</th>
<th>Permeability (mD)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tanjung</td>
<td>TJ-158</td>
<td>3</td>
<td>18.9</td>
<td>246</td>
<td>SS; Gry, fr, fg - og, sb-md, p sd, dis-carb, s/ic, bick min</td>
</tr>
<tr>
<td>Kataling Timur</td>
<td>KT-142</td>
<td>9H</td>
<td>19</td>
<td>16.8</td>
<td>SS; L.Bm-brm, med.hd, ft-fu, rd, w.srd, qz, tr.ang, fliky.carb, tr.kao, thin laim shale</td>
</tr>
<tr>
<td>Petani</td>
<td>PT-138</td>
<td>44B</td>
<td>21.2</td>
<td>6.2</td>
<td>SS; Gy, hd, vxf, abrmd, mod-w srd, qzg, sili mica, sili carb flks, silyarg</td>
</tr>
<tr>
<td>Bekasap</td>
<td>BKS-154</td>
<td>15</td>
<td>25.7</td>
<td>3610</td>
<td>SS; L.Bm, hd, ft-gran (6mm), sb.sand, sili.mica, clay/lays, congl</td>
</tr>
<tr>
<td>Pusako</td>
<td>PSK-37</td>
<td>1</td>
<td>26.3</td>
<td>75.4</td>
<td>SS; Gy, med.hd, fu-nl, rd, w.srd, qz, sili arg. trglu</td>
</tr>
<tr>
<td>Tambun</td>
<td>TBN-08</td>
<td>9</td>
<td>15.5</td>
<td>34.3</td>
<td>LS; Packstr, crnm, vhd, coral, l.foram, fiss fragm, pp-mott vugs, nat fract</td>
</tr>
<tr>
<td>Prabumenang</td>
<td>PMN-06</td>
<td>11A</td>
<td>12.7</td>
<td>126</td>
<td>LS; Bindst, dk-gy, hrd, F-C, sb-ang-md, sili vug, dru cdt, pyt, algae, Sty</td>
</tr>
<tr>
<td>Karangdewa</td>
<td>KRD-02</td>
<td>9B</td>
<td>16</td>
<td>10.3</td>
<td>LS; Bindst, Wh-Lt, Hard, Vogor, Rnd-Slb rd, Coral</td>
</tr>
<tr>
<td>Senoro</td>
<td>SN-05</td>
<td>40</td>
<td>29.4</td>
<td>72</td>
<td>LS; Gmsst, wh-flt-bm, bioturb (brck, trail, mlk, cast, bra), lam, Inse, Peloid, M-grm, gm-sprrd, cstk, qzt</td>
</tr>
</tbody>
</table>

The imbibition water-oil relative permeability measurements have been overwhelmingly performed using unsteady-state flow relative permeability method (~94%) while the remainders were carried out using steady-state flow relative permeability and centrifuge methods. Typically, in conducting an unsteady-state imbibition relative permeability test, the cleaned core sample is saturated with synthetic brine under vaccumed condition for the most appropriate time. In the relative permeability measurement itself the sample is then flushed with synthetic oil - in most tests under ambient condition - until irreducible brine saturation is reached. Viscosities of the synthetic oil were arranged following viscosities of the oil in reservoir condition and brine’s salt contents was arranged following actual formation brine. During the imbibition displacement tests volumes of brine and oil are taken at selected intervals, hence facilitating the determination of effective permeability. Using predetermined air permeability or effective permeability...
at respective maximum saturations relative permeabilities to both water and oil are determined for selected water saturations. Table 3 presents an example of results from an imbibition unsteady-state relative permeability measurement.

Rock wettability measurements are performed on fresh core plug samples prior to core cleaning and relative permeability measurements, or alternatively, the wettability tests are made using plug samples from locations adjacent to the plug samples assigned for the relative permeability measurements. The standard Amott method has exclusively been used for determination of wettability. Briefly, the method is based on spontaneous imbibition and forced displacement of oil and water out of tested core plug(s). Through the process two indexes are produced, the oil wet index ($I_o$) and water wet index ($I_w$), with

$$I_o = \frac{V_{wi}}{V_{wd}} \quad \text{and} \quad I_w = \frac{V_{oi}}{V_{od}}$$

whereas $V_{wi}$ and $V_{wd}$ are volume of displaced water resulted from slow imbibition process and volume of displaced water (including $V_{oi}$) yielded through the forced displacement by oil following the imbibition process, respectively. The step is followed on the now oil saturated sample with irreducible water saturation by a succession of oil displacements using water imbibition and forced displacement resulting in $V_{oi}$ and $V_{od}$ respectively. See Amot (1959) for more details regarding the method.

For wettability determination, Amott-Harvey index (AI) that is defined as

$$AI = I_w - I_o$$

is used, of which values of between -1 and -0.3, between -0.3 and 0, 0, between 0 and 0.3, and between 0.3 and 1 are defined as oil wet, weak oil wet, neutral, weak water wet, and water wet. In this study, AI values of zero, or around zero, as results of roughly equal water and oil inces are termed 'mixed

<table>
<thead>
<tr>
<th>Well: TJG-145</th>
<th>Depth, m: xx 7.83</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample No.:</td>
<td>8</td>
</tr>
<tr>
<td>Air permeability, mD:</td>
<td>53</td>
</tr>
<tr>
<td>Ko @ Swirr, mD:</td>
<td>17.4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Water saturation (percent pore space)</th>
<th>W-O relative permeability ratio</th>
<th>Relative permeability to water((^*)), fraction</th>
<th>Relative permeability to oil((^*)), fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>27.09</td>
<td>-</td>
<td>0</td>
<td>0.3281</td>
</tr>
<tr>
<td>30.25</td>
<td>0.0036</td>
<td>0.0008</td>
<td>0.2188</td>
</tr>
<tr>
<td>32.5</td>
<td>0.0097</td>
<td>0.0016</td>
<td>0.1622</td>
</tr>
<tr>
<td>34.53</td>
<td>0.0224</td>
<td>0.0026</td>
<td>0.1148</td>
</tr>
<tr>
<td>37.32</td>
<td>0.0621</td>
<td>0.0043</td>
<td>0.0691</td>
</tr>
<tr>
<td>39.18</td>
<td>0.1289</td>
<td>0.0065</td>
<td>0.0501</td>
</tr>
<tr>
<td>41.7</td>
<td>0.2757</td>
<td>0.009</td>
<td>0.0326</td>
</tr>
<tr>
<td>43.33</td>
<td>0.5072</td>
<td>0.012</td>
<td>0.0236</td>
</tr>
<tr>
<td>46.65</td>
<td>1.5253</td>
<td>0.019</td>
<td>0.0125</td>
</tr>
<tr>
<td>48.5</td>
<td>2.8379</td>
<td>0.023</td>
<td>0.0081</td>
</tr>
<tr>
<td>50.8</td>
<td>6.2411</td>
<td>0.03</td>
<td>0.0048</td>
</tr>
<tr>
<td>52.51</td>
<td>11.518</td>
<td>0.037</td>
<td>0.0032</td>
</tr>
<tr>
<td>54.41</td>
<td>23.5659</td>
<td>0.047</td>
<td>0.002</td>
</tr>
<tr>
<td>56.08</td>
<td>46.5788</td>
<td>0.056</td>
<td>0.0012</td>
</tr>
<tr>
<td>57.8</td>
<td>98.3477</td>
<td>0.068</td>
<td>0.0007</td>
</tr>
<tr>
<td>58.99</td>
<td>215.3288</td>
<td>0.08</td>
<td>0.0004</td>
</tr>
<tr>
<td>59.62</td>
<td>426.1076</td>
<td>0.087</td>
<td>0.0002</td>
</tr>
<tr>
<td>60.26</td>
<td>1002.2</td>
<td>0.1002</td>
<td>0.0001</td>
</tr>
<tr>
<td>62.04</td>
<td>0.1206</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

(* relative to air permeability)
wettability’. Tables 4 presents some examples of wettability tests.

III. RESULTS AND DISCUSSION

A. $K'_p$ versus $S_{wirr}$ correlations

In Equation (3), the permeability ratio of $K'_p$ used for conversion is obtained from ratio between oil effective permeability at irreducible water saturation ($K_{o@S_{wirr}}$) and air permeability ($K_{air}$). The data is available for each plug sample, and plot between the ratio and irreducible water saturation was made. Attempts were initially made to plot the entire data population but the resulting data scatter has led to no solid conclusions and reliable correlation(s) over relationship between the two parameters. Divisions were made following rock wettability and permeability classification have resulted in correlations between the two parameters become more apparent. Results are presented on Figures 1 through 4.

On Figures 1 through 4, it was obvious that some degree of data scatters are also observed. However, since the maximum value of $K'_p$ is unity at $S_{wirr}$ value of zero correlation curves are therefore observable. This results in presence of dual curves for each division. Following permeability classification of ‘poor-fair’ ($K < 150$ mD) and ‘moderate-high’ ($K > 150$ mD) - the ranges of classification appears to be effective enough to produce distinctive trends - the water wet rock samples yield

$$K'_p = 1 - 0.25 * S_{wirr} - 5.5 * (S_{wirr})^2 (7)$$

for the lower curve with suggested range of $S_{wirr}$ validity of 0.20 – 0.40, and

$$K'_p = 1 - 0.01 * S_{wirr} - 2.5 * (S_{wirr})^2 (8)$$

for the upper curve with suggested range of validity of 0.25 - 0.55, both are for the ‘poor-fair’ permeability group (Figure 1). For the ‘moderate-high’
permeability group, the corresponding correlations for the lower and upper curves are respectively (Figure 2)

\[ K_r^o = 1.05 - 3.87 \times S_{wirr} , \]  
(9)

(for range of 0.15 – 0.3)

and

\[ K_r^o = 1 - 0.05 \times S_{wirr} - 7.2 \times (S_{wirr})^2 \]  
(10)

(for range of 0.07 – 0.25)

For the oil-wet/mixed wet rocks similar correlations are also obtained. For the low-fair permeability rocks the correlations (Figure 3) are

\[ K_r^o = 1 - 0.1 \times S_{wirr} - 3.8 \times (S_{wirr})^2 , \]  
(11)

(for range of 0.26 – 0.45)

and

\[ K_r^o = 1 - 0.05 \times S_{wirr} - 10.1 \times (S_{wirr})^2 , \]  
(12)

(for range of 0.2 – 0.3)

Whereas for the moderate-high permeability rocks the corresponding correlations (Figure 4) are

\[ K_r^o = 1.0 - 3.25 \times S_{wirr} , \]  
(13)

(for range of 0.15 – 0.3)

and

\[ K_r^o = 1 - 0.05 \times S_{wirr} - 10.1 \times (S_{wirr})^2 , \]  
(14)

(for range of 0.08 – 0.22)

All equations in Equations (7) through (14) have been obtained through polynomial regression that is in combination with visual fitting and a series of trial-and-error in which all curves are set to lead to equal to unity (Figures (1) through (4)).

Although presented in the form of \( K_r^o \) vs \( S_{wirr} \) correlations the irreducible water saturation as the intended input parameter for determining \( S_{wirr} \) is strongly influenced by the intrinsic permeability
of the rocks. For practical purposes, permeability - 
S_wirr correlations are therefore required, and references 
such as Widarsono (2016) can be of use.

One of the most immediate question regarding the 
use of Equations (7) through (14) is the overlapping 
nature of equations for each permeability category. 
For a certain S_wirr value two correlations may be ready 
for use. For instance, for a S_wirr value of 0.3 in the 
category of poor-fair permeability water wet rocks 
two correlations are usable, the ‘lower’ correlation of 
equation (7) (S_wirr validity range of 0.28 - 0.55) and 
the ‘upper’ correlation of equation (8) (S_wirr validity 
range of 0.23 – 0.36). Which one is to be used?.

Conceptually, correlations between S_wirr and K_wirr have 
to go through K_wirr equals to unity at zero S_wirr, assuming 
that the K_wirr can truly represent the rock’s permeability. 
This leads to presence of two correlations for 
each category in the form of upper* and ‘lower’ 
correlations, which in turn leads to the S_wirr overlapping. 
Through examining the data that makes the 
correlations of the data plots presented on Figures (1) 
through (4) it must be accepted that there are some 
ambiguities in the determination of the permeability 
ratio (used for converting K_w data from K_wirr domain to 
K_o/S_wirr domain) from irreducible water saturation. 

Table 5 presents overlapping S_wirr range for each 
category and the percentages of samples that belong 
to either the ‘upper’ or ‘lower’ correlations. From the 
investigation the problem does not appear to be over-
whelming since firstly, ‘lower’ correlation (Equation 
7) seems to prevail for the water poor-fair permeability 
water wet rocks with 83.3%, and secondly, from the oth-
er three categories with almost fifty-fifty percentages 
the two oil wet/neutral/mixed categories show 
relatively narrow S_wirr overlapping which means 
that most S_wirr values for the two correlations do not 
overlap, even though some overlapping S_wirr values 
are still there. These all leave the moderate-high 
water wet category as the remaining problem with its 
relatively wide S_wirr overlapping range of 0.15 - 0.25.

## Table 4

Examples of wettability test results

<table>
<thead>
<tr>
<th>Field</th>
<th>Well</th>
<th>Plug</th>
<th>Lithology</th>
<th>Water wet index (J_w)</th>
<th>Oil wet index (J_o)</th>
<th>Amott-Harvey index</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tanjung</td>
<td>TJ-158</td>
<td>2W</td>
<td>sandstone</td>
<td>0.4401</td>
<td>0.1212</td>
<td>0.3189</td>
<td>water wet</td>
</tr>
<tr>
<td>Ketalting Timur</td>
<td>KT-142</td>
<td>9B</td>
<td>sandstone</td>
<td>0.4571</td>
<td>0.3448</td>
<td>0.1123</td>
<td>weak water wet</td>
</tr>
<tr>
<td>Petani</td>
<td>PTN-38</td>
<td>32W</td>
<td>sandstone</td>
<td>0.4472</td>
<td>0.9429</td>
<td>-0.4957</td>
<td>oil wet</td>
</tr>
<tr>
<td>Bekasap</td>
<td>BKS-154</td>
<td>15A</td>
<td>sandstone</td>
<td>0.1059</td>
<td>0.2296</td>
<td>-0.1236</td>
<td>weak oil wet</td>
</tr>
<tr>
<td>Pusako</td>
<td>PSK-37</td>
<td>1A</td>
<td>sandstone</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>neutral</td>
</tr>
<tr>
<td>Tambun</td>
<td>TBN-08</td>
<td>9A</td>
<td>limestone</td>
<td>0.0417</td>
<td>0.2687</td>
<td>-0.227</td>
<td>weak oil wet</td>
</tr>
<tr>
<td>Prabumening</td>
<td>PMN-06</td>
<td>16A</td>
<td>limestone</td>
<td>0.614</td>
<td>0</td>
<td>0.614</td>
<td>water wet</td>
</tr>
<tr>
<td>Karangdewa</td>
<td>KRD-02</td>
<td>9B</td>
<td>limestone</td>
<td>0.4294</td>
<td>0.1905</td>
<td>0.2389</td>
<td>weak water wet</td>
</tr>
<tr>
<td>Senoro</td>
<td>SN-05</td>
<td>40A</td>
<td>limestone</td>
<td>0.0108</td>
<td>0</td>
<td>0.0108</td>
<td>neutral</td>
</tr>
</tbody>
</table>

## Table 5

Overlapping irreducible water saturation (S_wirr) values for each group with percentages 
of samples belonging to ‘upper’ and ‘lower’ K vs S_wirr correlations

<table>
<thead>
<tr>
<th>Wettability Category</th>
<th>Overlapping S_wirr range (%)</th>
<th>‘Upper’ curve (%)</th>
<th>‘Lower’ curve (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water wet</td>
<td>0.25 – 0.40</td>
<td>16.7</td>
<td>83.3</td>
</tr>
<tr>
<td>Oil wet/neutral/mixed</td>
<td>0.15 – 0.25</td>
<td>45.1</td>
<td>54.9</td>
</tr>
<tr>
<td>Oil wet/neutral/mixed</td>
<td>0.26 – 0.30</td>
<td>52.9</td>
<td>47.1</td>
</tr>
<tr>
<td></td>
<td>0.15 – 0.22</td>
<td>45.2</td>
<td>54.8</td>
</tr>
</tbody>
</table>
1. Imbibition Water-Oil Relative Permeability: Introduction of Wettability Strength for Enhancing Model Robustness (Widarsono, B.)

Three examples of agreement between observed and calculated water and oil relative permeabilities; (a) good agreement for both $K_r$ (sandstone, oil wet, $K=2,008$ mD), (b) failed match for $K_w$ curve (sandstone, water wet, $K=9.3$ mD), and (c) failed match for $K_o$ curve (sandstone, neutral, $K=15.4$ mD). Combination between cases (b) and (c) also occur.

Figure 5

Plot between Ammot-Harvey index versus $K_w@S_w$. The rock water wetness is divided into three groups; weak water wet ($I_o=0.0-0.2$), medium water wet ($I_o=0.2-0.6$), and strong water wet ($I_o=0.6-1.0$).

Figure 6
| Wettability | Permeability | Wettability | C | λ | x | y |
|-------------|--------------|-------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|             | Category(1)  | Strength(2) | Range | Avg | Suggested | Range | Avg | Suggested | Suggested | Range | Avg | Suggested |
| Water wet   | Moderate-high (sandstone) | weak | 0.7-2.0 | 1.3 | 1.0-1.5 | 0.8-5.0 | 2.5 | 1.0-2.5 | 1.5 | 1.0-8.0 | 2.8 | 1.5-3.0 |
|             |              | medium | 0.9-2.0 | 1.6 | 1.4-1.8 | 0.4-7.0 | 1.5 | 0.8-1.2 | 2 | 0.7-9.0 | 5.7 | 7.0-8.0 |
|             |              | strong | 1.4-2.8 | 1.9 | 1.5-2.0 | 2.0-6.0 | 3.9 | 3.0-4.0 | 3 | 1.0-9.0 | 5.2 | 5.0-7.0 |
|             | Poor-fair (sandstone) | weak | 0.6-2.9 | 1.8 | 1.5-2.0 | 0.5-6.0 | 2.3 | 1.0-2.5 | 1.5 | 1.0-8.0 | 5.4 | 4.0-6.0 |
|             |              | medium | 0.7-5.2 | 1.9 | 1.0-2.0 | 0.1-10.0 | 1.8 | 2.0-4.0 | 2 | 1.0-15.0 | 4.6 | 3.0-6.0 |
|             |              | strong | 0.8-1.9 | 1.2 | 1.0-1.5 | 0.5-5.0 | 1.8 | 1.0-2.0 | 3 | 1.0-15.0 | 7.8 | 6.0-8.0 |
|             | Poor-fair (limestone) | weak | 0.9-2.2 | 1.7 | 1.5-2.0 | 0.7-15 | 1.1 | 1.0-15 | 1.5 | 3.0-10.0 | 6 | 5.0-6.0 |
|             |              | medium | 0.8-3.1 | 1.5 | 1.5-2.0 | 0.5-10.0 | 3.3 | 2.0-4.0 | 2 | 1.0-6.0 | 4 | 3.0-4.0 |
|             |              | strong | 1.2-2.8 | 2 | 2.0-3.0 | 1.5-4.0 | 2.8 | 2.0-3.0 | 3 | 2.0-4.0 | 3 | 2.0-3.0 |
|             | Neutral/mixed(6) | weak | 0.5-3.0 | 1.9 | 1.0-2.0 | 0.4-4.0 | 1.3 | 1.0-2.0 | 1.5 | 1.0-14.0 | 6.3 | 4.0-8.0 |
|             |              | medium | 0.8-3.3 | 1.6 | 1.5-2.5 | 0.7-20.0 | 2.6 | 1.0-2.0 | 1.5 | 0.9-9.0 | 4.7 | 3.0-6.0 |
|             |              | strong | 2.3-2.4 | 2.3 | 2.3 | 1.2-8.0 | 4.6 | 2.0-3.0 | 1.5 | 1.0-3.0 | 2 | 2 |
| Oil wet/neutral/mixed | Moderate-high (sandstone) | weak | 0.5-3.0 | 1.9 | 1.0-2.0 | 0.4-4.0 | 1.3 | 1.0-2.0 | 1.5 | 1.0-20.0 | 8.5 | 6.0-9.0 |
|             |              | medium | 0.9-1.2 | 1 | 0.9-2.2 | 1.5 | 1.3-1.8 | 1.5 | 6.0-15.0 | 8.7 | 8.0-10.0 |
|             |              | Strong(5) | - | 2.2 | 2.2 | - | 0.5 | 0.5 | 1.5 | - | 9 | 9 |
|             | Poor-fair (limestone) | neutral/mixed(6) | 1.6-1.7 | 1.6 | 1.6 | 0.9-1.6 | 1.1 | 1.0-1.5 | 1.5 | 3.0-4.0 | 3.3 | 3.5 |
|             |              | weak | 1.6-1.7 | 1.6 | 1.6 | 0.9-1.6 | 1.1 | 1.0-1.5 | 1.5 | 3.0-4.0 | 3.3 | 3.5 |
|             |              | medium | 1.5-1.8 | 1.7 | 1.8 | 0.8-6.0 | 3.6 | 2.0-4.0 | 1.5 | 2.0-8.0 | 4 | 4.0-6.0 |
|             |              | strong | 0.8-2.1 | 1.8 | 1.9 | 0.7-6.0 | 2.8 | 2.0-4.0 | 1.5 | 1.0-12.0 | 4.7 | 3.0-6.0 |

Table 6
Summary of C, λ, x, and y factors including suggested values for each wettability and rock permeability groups
This all overlapping $S_{wir}$ problem may actually be solved by avoiding the use of $S_{wir}$ values within the overlapping ranges. The nearest value to the overlapping $S_{wir}$ may be used to represent them. However, since the overlapping $S_{wir}$ range of the moderate-high permeability water wet rocks are relatively wide, hence this approach should be adopted with caution in order to minimize invalid results.

### B. Application and modification of model

Application of equations (1) through (5) on the laboratory imbibition relative permeability data presents the pore distribution index or lambda ($\lambda$) as the variable for achieving agreement between calculated and observed relative permeability values. Initially, apart from the imbibition relative permeability to water ($K_w$) in equation (1), a modified imbibition relative permeability to oil ($K_o$) in the form of

$$K_o = K^{\mu} \left[ \frac{(S_{wir})^{-1}}{S_{wir}} + S_{wir} \right] \left[ 1 - (1 - S_{wir}^{2+}) \frac{\lambda}{2} \right] \frac{\lambda}{2} \right)$$

has also been applied. As explained in Standing (1975), Equation (15) is actually a modification of Equation (3) which takes into account an additional parameter named ‘wetting-phase saturation parameter’ or $S_m$. This parameter has no physical significance and it serves as a controlling factor on the shape of the $K_o$ curve, steeper for values greater than unity and left-shifted for values lower than it. The introduction of $S_m$ appears to have come through a series of graphical trials.

Using equations (1) through (5) - as well as by utilizing Equation (15) - calculations have been performed to match the laboratory-derived relative permeability data through the use of varied $\lambda$ and $S_m$ parameters. Results of model calculations have shown that some of the calculated effective permeability values (at certain wetting phase saturation values) show good agreement to their corresponding observed values but others show insufficient agreements hence suggesting the model’s shortcoming. Figure 5 depicts examples for three cases; case (a) showing good agreement, case (b) representing failed $K_w$ match, and case (c) depicting mismatched $K_o$ curves. For some failures in $K_w$ match gaps between calculated and observed values appear to be fairly related to water wettability strength, with stronger water wetness tends to widen the gap. On the other hand, no effects
Example of recalculation using the modified Krw and Kro equations. Presented are the same Kr data sets of figure 5: (a) sandstone, oil wet: \(C=1.6, \lambda=1.3, x=1.5, \) and \(y=5\); (b) sandstone, water wet: \(C=1, \lambda=4, x=2, \) and \(y=3\); and (c) sandstone, neutral: \(C=1.5, \lambda=1, x=1.5 \) and \(y=9\).
appear to be shown by rock wettability variation with the \( K_{ro} \) mismatches suggesting that they are most probably caused by disruption to oil-phase mobility caused by combination of different rock pore configurations, water-oil interfacial tension, water-oil mobility ratio, and tendency of oil phase trapping by the incoming water.

Investigation over the relation between water wetness and \( K_{ro} \) mismatch had led to an attempt to plot between Amott-Harvey index (equation (6)) and \( K_{ro} @ S_{or} \) representing the gap between calculated and observed \( K_{ro} \) values. As the index is roughly divided into weak water wet (\( I_o = 0 – 0.2 \)), medium water wet (\( I_o = 0.2 – 0.6 \)), and strong water wet (\( I_o = 0.6 – 1 \)) then cluster analysis on the plot shown on Figure 6 present that strong water wetness tends to widen the \( K_{ro} \) gap (i.e. leads to higher \( K_{ro} @ S_{or} \)). The occurrence on Figure 6 suggests that water wetness strength should have a special effect on the \( K_{ro} \) path. Provided that Corey model is based on variation in pore size and that of water resides in smaller pores - the more complicated the pore configuration the more water tends to stick to the rock’s wall - then the water wetness should have something to affect the \( \lambda \).

Through trials it was found eventually that the equation (1) has to be modified into

\[
K_{rw} = S_{w}^{x} \cdot \frac{2 + x \lambda}{\pi} \tag{16}
\]

in order to obtain the most optimum fit, with replacing ‘3’ to serve as an influencing parameter that represent water wettability strength. Abundant trials using various values of \( x \) appeared to converge into a set of values of

- \( x = 3.0 \) for strong water wet rocks
- \( x = 2.0 \) for medium water wet rocks,
- \( x = 1.5 \) for weak water wet rocks, neutral/mixed, and oil wet rocks.

The empirical parameter of \( x \) may therefore be termed something like ‘water wettability factor’.

In a series of attempts to solve the problem of \( K_{ro} \) curve mismatch on Figure 5(c), similar plots have been made between Amott-Harvey Index and effective oil saturation (\( S_{or}^* \)). Figures (7) and (8) present the plots for water wet and neutral/mixed/oil wet rocks, respectively. Cluster analyses on the data show that roughly remains within the same value ranges of \( S_{or}^* = 0.15 - 0.4 \) for water wet rocks, and \( S_{or}^* = 0.2 - 0.5 \) for neutral/mixed/oil wet rocks.

suggesting that in general wettability strength does not affect amount of trapped oil during water displacements, even though the \( S_{or}^* \) range for the neutral/mixed/oil wet rocks show slightly higher value range. This difference in the \( S_{or}^* \) range may logically be attributed to the oil wettability effect, but since the \( K_{ro} \) curves mismatch take place in both wettability groups, it could be nonetheless seen that it is not the oil wettability that affect the mismatch, and the \( S_{or}^* \) factor in Equation (15) appears to be unable to satisfactorily solve the problem. In a way similar to the modification of Equation (1), Equation (3) is modified to become

\[
K_{ro} = K_{ro}^0 \left( S_{or}^* \right)^2 \left[ 1 - \left( 1 - S_{or}^* \right)^{2+\lambda} \right] \tag{17}
\]

with \( y \) as the additional parameter that serves as a magnifying factor to the pore size variation factor (\( \lambda \)) in ‘partially immobilizing the oil’ for a water saturation value during water displacement. The \( y \) factor seems to vary for different permeability grouping and wettability types. Table 5 presents a summary of ranges, average, and suggested values for \( C, \lambda, x, \) and \( y \) factors as the results of calculations and matchings using Equations (16) and (17).

The summary of parameters presented in Table 6 covers the range of values that are used in obtaining acceptable curve matching, average values, and suggested values for use in form of ranges as well as a single value in cases of either high certainty or limited data from very limited number of rock samples. Suggested values in form of value ranges are picked up to cover the most representative values and to cover as many values as possible. (It is also worth noting that value ranges do not always cover average values since they do not always lie amongst the most representative values). Variations within the value ranges may serve as sources of sensitivity tests in the attempt to obtain the most applicable and representative relative permeability curves in any practical reservoir modeling works. Considering the higher certainty provided by \( x \) as well as fairly high certainty provided by \( C \) and \( \lambda \), therefore the least certain parameter is the \( y \), which picking requires caution.
C. Recalculations and suggested $C$, $\lambda$, $x$, and $y$ values

Examples of the recalculations of the calculated relative permeabilities data are presented on Figure 9, the same samples that are presented on on Figure 5. The three relative permeability sets now appear to show fine agreements between observed and calculated relative permeabilities resulting from the use of chosen $C$, $\lambda$, $x$, and $y$ values in Equations (16) and (17). In general, in order to obtain good match between observed and calculated values all individual set of $K_w$ data has their own respective set of $C$, $\lambda$, $x$, and $y$ values. However, as presented in Table 6, for practical purposes ‘average’ and ‘suggested’ values are available for use, from which average values may be used as first guess whereas the suggested ranges of values may serve as flexibility for fiddling the calculated $K_{rw}$ and $K_{ro}$ curves provided sources of validation have become available.

In using Equations (16) and (17), and $C$, $\lambda$, $x$, and $y$ factors in Table 6 one has to carefully choose the most suitable value(s). Upon having information regarding wettability and permeability (K) of his/her reservoir rocks one may determine irreducible water saturation ($S_{wi}$) – various literatures present how to determine this parameter, including from K vs $S_{wi}$ correlations such as in Widarsono (2016) – to produce saturation related values ($S_w$, $S_o$, $S_{wi}$, and $S_{or}$) required by Equations (16) and (17). Using the two equations – with $K_w^o$ values obtained from equations (7) through (14) – for any predetermined water saturation ($S_w$) $C$, $\lambda$, $x$, and $y$ values are required. The most ready factor is the $x$, which is determined by the rock’s wettability, after which average values may be used as the opening values for the $C$, $\lambda$, $x$, and $y$. As mentioned earlier, since is in general having wider ranges of values it therefore serves as the most uncertain parameter. Accordingly, greater caution has to be observed for its choice.

IV. CONCLUSIONS

In this study, data from hundreds of reservoir rocks-both sandstones and limestones – have been used for testing the modified Corey imbibition water-oil relative permeability model. A couple of new empirical parameters have been introduced to take into account the rock wettability strength into the model. Eventually, a set of main conclusions have been drawn from the results:

The introduction of ‘water wettability factor’ ($x$) and ‘non-wetting phase slowing factor’ ($y$) have enriched the Corey model into a relative permeability model that is not dependent only on pore size distribution and fluid saturation but also on rock wettability and other interfacial tension related factors such as non-wetting phase trapping and slowing. Although the two parameters are fully empirical in nature but they appear to work well to enhance the model robustness.

As the results of application of the modified model on the measured relative permeability data, a set of ‘trapping constant’ ($C$), ‘pore distribution index’ ($\lambda$), $x$, and $y$ values have been resulted for all rock wettability types and strength, as well as for poor-fair and moderate-high permeability categories. The values are in the form of both average and suggested range, using which both robustness and flexibility of the model produce the most realistic and realistic relative permeability curves are maintained.

The use of permeability ratio of $K_w^o$ for converting the oil relative permeability curves from air permeability domain to oil effective permeability at irreducible saturation ($S_{wi}$) still leave a problem, especially for the moderate-high permeability water wet rocks. This problem occurs for certain irreducible water saturation values for which two correlations are usable, the ‘upper’ and ‘lower’ correlations. This ‘overlapping’ $S_{wi}$ problem could be solved by avoiding the use of overlapping irreducible values for determining $K_w^o$ even though this may still be a problem for the moderate-high permeability water wet rocks that have wide range of overlapping $S_{wi}$. Caution has to be taken for determining the most representative $K_w^o$.

The modified Corey water-oil imbibition relative permeability model is easily usable to produce the needed realtive permeability curves upon acknowledging wettability index, permeability, and estimated – or through assignment of values – irreducible water saturation of a permeable rock. For a set of predetermined water saturation values the needed relative permeability curves can be easily produced with assistance of the suggested $C$, $\lambda$, $x$, and $y$ values. Use of other sources of information related to fluid flow in reservoir may enhance the curves’ validity.

Application of the modified model is indeed conducted on Tertiary reservoir rocks in Indonesia, and the resulting $C$, $\lambda$, $x$, and $y$ values are related to that. However, what matters to the use of the modified model is simply information about rock’s permeability and wettability type/strength. Therefore, factors such as geographical position and geological history are not related to any validity concern for the use of the model.
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REFERENCES


