SCIENTIFIC CONTRIBUTIONS OIL AND GAS
Vol. 42, Number 1, April 2019: 1 of 5

RESEARCH AND DEVELOPMENT CENTRE FOR OIL & GAS TECHNOLOGY LEMIGAS

Journal Homepage:http://www.journal.lemigas.esdm.go.id, E-mail: jurnal.lemigas@esdm.go.id
ISSN: 2089-3361, e-ISSN: 2541-0520

IMBIBITION WATER-OIL RELATIVE PERMEABILITY: INTRODUCTION OF WETTABILITY STRENGTH FOR ENHANCING MODEL ROBUSTNESS

(*Permeabilitas Relatif Air - Minyak Imbibisi: Faktor Kekuatan Wettabilitas untuk Memperbaiki Kemampuan Model*)

Bambang Widarsono

"LEMIGAS" R & D Centre for Oil and Gas Technology
Jl. Ciledug Raya, Kav. 109, Cipulir, Kebayoran Lama, P.O. Box 1089/JKT, Jakarta Selatan 12230 INDONESIA
Tromol Pos: 6022/KBYB-Jakarta 12120, Telephone: 62-21-7394422, Faxsimile: 62-21-7246150
E-mail: bambang.widarsono@esdm.go.id

First Registered on March 14th 2019; Received after Correction on April, 5th 2019
Publication Approval on: April, 30th 2019

ABSTRAK

Informasi tentang permeabilitas air - minyak dari batuan reservoar memainkan peranan yang penting dalam kegiatan pemodelan yang berhubungan dengan pemodelan reservoar dan peramalan produksi. Permeabilitas relatif dalam skema imbibisi - skema yang merupakan tema dari tulisan ini - berpengaruh besar atas berbagai proses dinamis di reservoar. Proses injeksi air dan masuknya air dari akuifer ke reservoar merupakan dua contoh yang membutuhkan data tersebut. Studi ini menggunakan model permeabilitas relatif Corey sebagai model permeabilitas relatif imbibisi yang digunakan. Data laboratorium dari 340 percontoh - batupasir dan batugamping- dengan berbagai permeabilitas dan wetabilitas yang diambil dari berbagai lapangan minyak di Indonesia digunakan. Kegiatan pemodelan yang dilakukan menunjukkan perlunya untuk menambahkan dua faktor empiris yang berhubungan dengan wetabilitas batuan dan hambatan diluar pembasahan ke dalam model. Peran kedua faktor tersebut dalam model senyara nyata meningkatkan kemampuan dari model, dan nilai-nilai yang dianggap paling baik untuk kedua faktor juga dihasilkan sesuai dengan jenis wetabilitas dan kategori permeabilitas batuan. Perbandingan antara hasil pemodelan sebelum dan sesudah modifikasi menunjukkan perbaikan dalam validitas dari keluaran.

Kata Kunci: *Permeabilitas relatif air - minyak, wetabilitas, minyak terperangkap, perbaikan model*

ABSTRACT

Water-oil relative permeabilty 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 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/and 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; Øren & 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. is not affected by saturation direction) is expressed in the form of

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

with S_w^* is normalized water saturation of

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

and S_w and S_{wirr} water saturation at one point during wetting-phase saturation process and ir-reducible water saturation, respectively. Lambda (λ) 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

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

with

$$S_{oi}^* = \frac{S_{oi}}{(1-S_{wirr})} \text{ and } S_{or}^* = \frac{S_{or}}{(1-S_{wirr})},$$

While C is accordingly denoted as 'trapping constant'. The C constant can theoreticaly 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 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_{oF}^*) - the oil volume that is not trapped by incoming water in the larger pores - then it can be expressed as

$$K_{ro} = K_r^o (S_{oF}^*)^2 \left[1 - (1 - S_{oF}^*)^{\frac{2+\lambda}{\lambda}}\right] \quad (3)$$

with K_r^o represents a normalization factor that converts oil relative permeability from basing on intrinsic rock permeabilty (represented by air permeability, K_{air}) to basing on oil maximum effective permeability ($K_o@S_{wirr}$). The two permeability values for producing the ratio are available in any imbibition relative permeability laboratory measurement, and since the ratio is closeley linked to irreducible water saturation (S_{wirr}) 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

$$S_{oF}^* = \frac{1}{2}\left[(S_o^* - S_{or}^*) + \sqrt{(S_o^* - S_{or}^*)^2 + \frac{4}{C}(S_o^* - S_{or}^*)}\right] \quad (4)$$

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

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

obtained from laboratory measurements on the sandstone and limestone core samples. A correlation of K_r^o vs S_{wirr} is to be established, and it was originally planned to determine the most representative λ 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.

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 pre-determined air permeability or effective permeability

Table 1
Sources of core samples

Sandstone [Field (number of core samples)]	Limestone [Field (number of core samples)]
Balam South (5), Batang (9), Bekasap (10), Bunyu (4), Cemara timur (11), Duri (24), Jirak (7), Ketaling Timur (4), Kotabatak (12), Kra South (4), Lirik (11), Minas (29), Mlandong (13), Ogan (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)	ASDJ (9), Ginaya (4), GTR (3), Karangdewa (4), Pondok Tengah (1), Prabumenang (4), Senoro (8), Tambun (16)
Total: 24 fields, 291 core plugs	Total: 8 fields, 49 core plugs

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

Field	Well	Plug No.	Porosity (%)	Permeability (mD)	Description
Tanjung	TJ-158	3	18.9	246	SS; Gry, fri, fg - cg, sb rnd, p srtd, diss carb, s lc, blck min
Ketaling Timur	KT-142	9H	19	16.8	SS; Lt.brn-brn, med.hd, fL-fU, rnd, w.srtd, qz, tr.arg, flky.carb, tr.kao, thin.lam shale
Petani	PT-138	44B	21.2	6.2	SS: Gy, hd, vfg, sbrnd, mod-w srtd, qtz, sli mica, sli carb flks, silty/arg
Bekasap	BKS-154	15	25.7	3610	SS; Lt.Brn, hd, f-gran (6mm), sb.ang, ply.srtd, sli.mica, clay.lams, congl
Pusako	PSK-37	1	26.3	75.4	SS; Gy, med.hd, fu-mL, rnd, w.srtd, qz, sli.arg, tr.glu
Tambun	TBN-08	9	15.5	34.3	LS; Packstn, crm, vhd, coral, l.foram, foss fragm, pp-mott vugs, nat fract
Prabumenang	PMN-06	11A	12.7	126	LS; Bndst, dk-gy, hrd, F-C, sb.ang-rnd, sli vug, dru clct, pyr, algae, Sty
Karangdewa	KRD-02	9B	16	10.3	LS; Bndst, Wh-Lt, Hard, Vcgr, Rnd-Sb.rnd, Coral
Senoro	SN-05	40	29.4	72	LS; Grnst, wh-lt.brn, bioturb (trck, trail, mld, cast, brw), lam, lnse, Peloid, M-grn, grn spprtd, calc, qtz

Table 3
An example of imbibition unsteady-state water-oil relative permeability measurement

Well:	TJG-145	Depth, m:	xx7.83
Sample No.:	8	Porosity, percent:	27.9
Air permeability, mD:	53	Swirr, percent :	27.1
Ko @ Swirr, mD:	17.4		

Water saturation (percent pore space)	W-O relative permeability ratio	Relative permeability to water(*), fraction	Relative permeability to oil(*), fraction
27.09	-	0	0.3281
30.25	0.0038	0.0008	0.2188
32.5	0.0097	0.0016	0.1622
34.53	0.0224	0.0026	0.1148
37.32	0.0621	0.0043	0.0691
39.18	0.1289	0.0065	0.0501
41.7	0.2757	0.009	0.0326
43.33	0.5072	0.012	0.0236
46.65	1.5253	0.019	0.0125
48.5	2.8379	0.023	0.0081
50.8	6.2411	0.03	0.0048
52.51	11.518	0.037	0.0032
54.41	23.5659	0.047	0.002
56.08	46.5788	0.056	0.0012
57.8	98.3477	0.068	0.0007
58.99	215.3288	0.08	0.0004
59.62	426.1076	0.087	0.0002
60.26	1002.2	0.1002	0.0001
62.04		0.1206	0

(*) relative to air 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

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

whereas V_{wi} and V_{wd} are volume of displaced water resulted from slow imbibition process and volume of displaced water (includingV_{wi}) 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

$$AI = I_w - I_o \tag{6}$$

is used, of which values of between -1and -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 wettability'. Tables 4 presents some examples of wettability tests.

III. RESULTS AND DISCUSSION

A. K_r^o versus S_{wirr} correlations

In Equation (3), the permeability ratio of K_r^o 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_r^o 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

$$K_r^o = 1 - 0.25 * S_{wirr} - 5.5 * (S_{wirr})^2 \quad (7)$$

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

$$K_r^o = 1 - 0.01 * S_{wirr} - 2.5 * (S_{wirr})^2 \quad (8)$$

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'

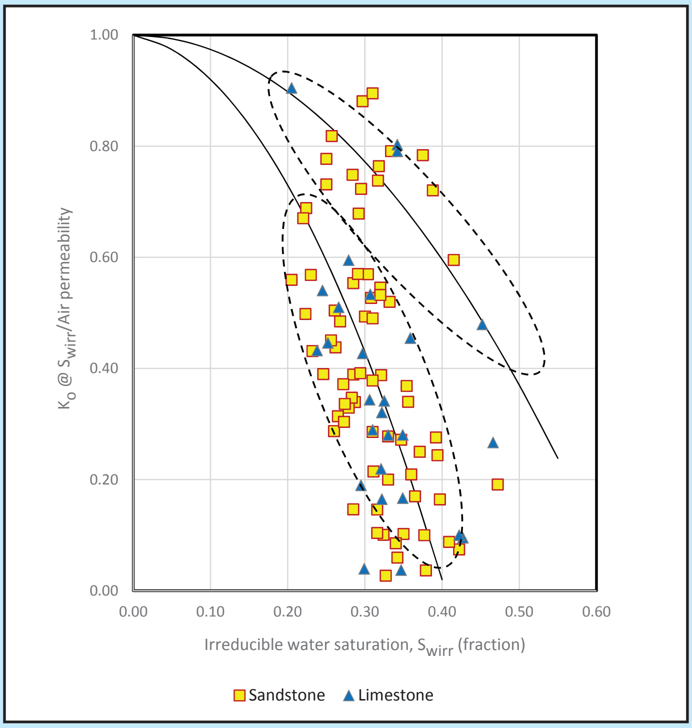

Figure 1
K^r vs S_{wirr} correlations for water-wet sandstones and limestones with poor-fair permeability (roughly from 1 through 150 mD). The upper and lower curves are suggested for approximate S_{wirr} ranges of 0.25-0.55 and 0.20-0.40, respectively.

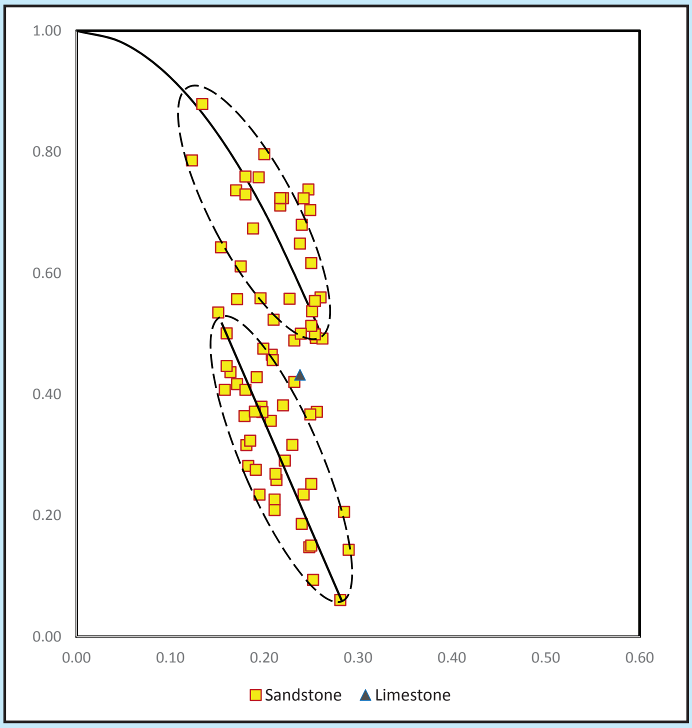

Figure 2
K^r_o vs S_{wirr} correlations for water-wet sandstones and limestones with moderate-high permeability (roughly >150 mD). The upper and lower curves are suggested for S_{wirr} ranges of approximately 0.07-0.25 and 0.15-0.30, respectively.

permeability group, the corresponding correlations for the lower and upper curves are respectively (Figure 2)

$$K_r^o = 1.05 - 3.87 * S_{wirr} \,, \qquad (9)$$

(for range of 0.15 – 0.3)

and

$$K_r^o = 1 - 0.05 * S_{wirr} - 7.2 * (S_{wirr})^2 \qquad (10)$$

(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

$$K_r^o = 1 - 0.1 * S_{wirr} - 3.8 * (S_{wirr})^2, \quad (11)$$

(for range of 0.26 – 0.45)

and

$$K_r^o = 1 - 0.05 * S_{wirr} - 10.1 * (S_{wirr})^2, \quad (12)$$

(for range of 0.2 – 0.3)

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

$$K_r^o = 1.0 - 3.25 * S_{wirr}, \qquad (13)$$

(for range of 0.15 – 0.3)

and

$$K_r^o = 1 - 0.05 * S_{wirr} - 10.1 * (S_{wirr})^2, \quad (14)$$

(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

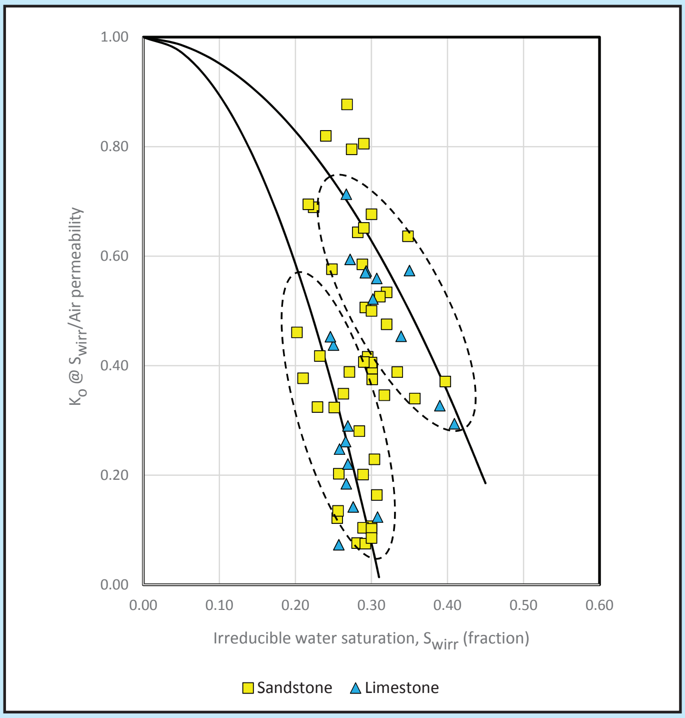

Figure 3
K_r^o vs S_{wirr} correlations for oil-wet/mixed-wet sandstones and limestones with poor-fair permeability (roughly from 1 through 150 mD). The upper and lower curves are suggested for S_{wirr} approximate ranges of 0.26-0.45 and 0.20-0.30, respectively.

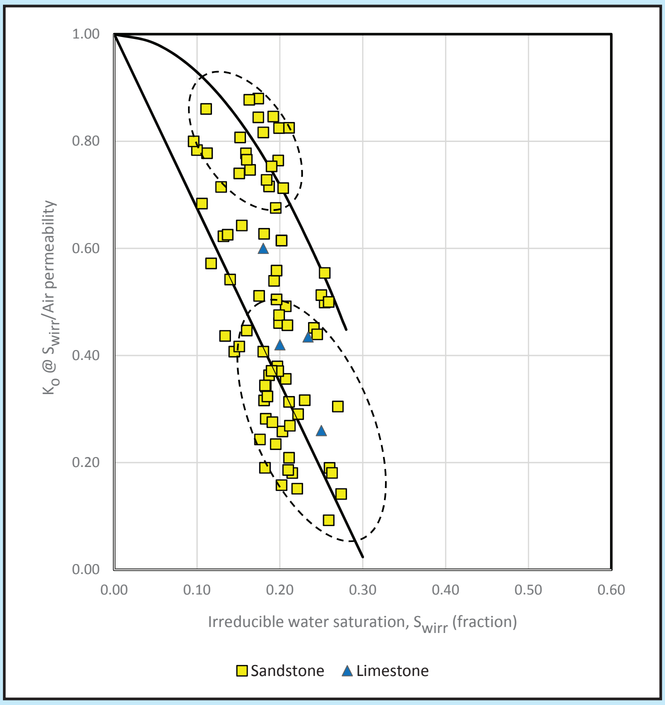

Figure 4
K_r^o vs S_{wirr} correlations for oil-wet/mixed-wet sandstones and limestones with moderatehigh permeability (roughly >150 mD). The upper and lower curves are suggested for S_{wirr} ranges of approximately 0.008-0.22 and 0.15-0.30, respectively.

Table 4
Examples of wettability test results

Field	Well	Plug	Lithology	Water wet index (I_w	Oil wet index (I_o)	Amott-Harvey index	Description
Tanjung	TJ-158	2W	sandstone	0.4401	0.1212	0.3189	water wet
Ketaling Timur	KT-142	9B	sandstone	0.4571	0.3448	0.1123	weak water wet
Petani	PTN-38	32W	sandstone	0.4472	0.9429	-0.4957	oil wet
Bekasap	BKS-154	15A	sandstone	0.1059	0.2295	-0.1236	weak oil wet
Pusako	PSK-37	1A	sandstone	0	0	0	neutral
Tambun	TBN-08	9A	limestone	0.0417	0.2687	-0.227	weak oil wet
Prabumenang	PMN-06	16A	limestone	0.614	0	0.614	water wet
Karangdewa	KRD-02	9B	limestone	0.4294	0.1905	0.2389	weak water wet
Senoro	SN-05	40A	limestone	0.0108	0	0.0108	≈neutral

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 y

Wettability	Permeability Category	S_{wirr} overlapping (fraction)	‘Upper’ curve (%)	‘Lower’ curve (%)
Water wet	poor-fair	0.25 – 0.40	16.7	83.3
	moderate-high	0.15 – 0.25	45.1	54.9
Oil wet/ neutral/mixed	Poor-fair	0.26 – 0.30	52.9	47.1
	moderate-high	0.15 – 0.22	45.2	54.8

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 K_r^o and S_{wirr} have to go through K_r^o equals to unity at zero S_{wirr}, assuming that the K_{air} can truly represent the rock’s permeability. This leads to presence of two correlations for each category in the form of úpper’ 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_r data from K_{air} 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 overwhelming 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 other 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.

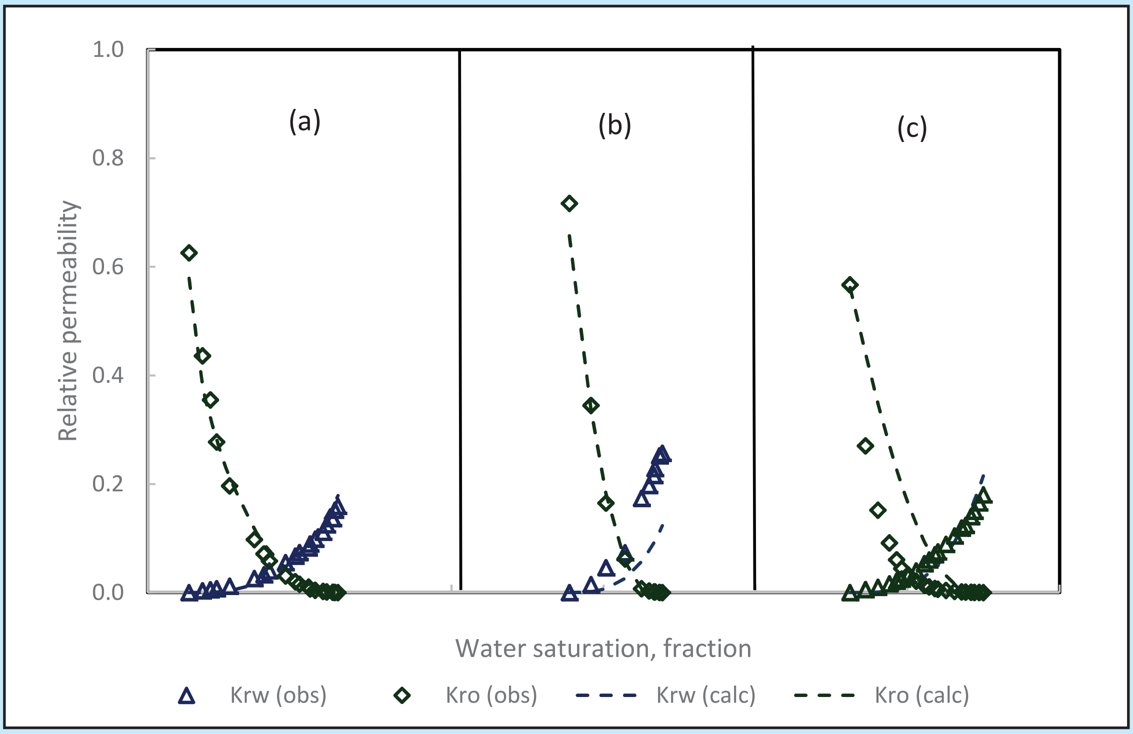

Figure 5
Three examples of agreement between observed and calculated water and oil relative permeabilities; (a) good agreement for both K_r (sandstone, oil wet, K= 2,008 mD), (b) failed match for K_{rw} curve (sandstone, water wet, K= 9.3 mD), and (c) failed match for K_{ro} curve (sandstone, neutral, K= 15.4 mD). Combination between cases (b) and (c) also occur.

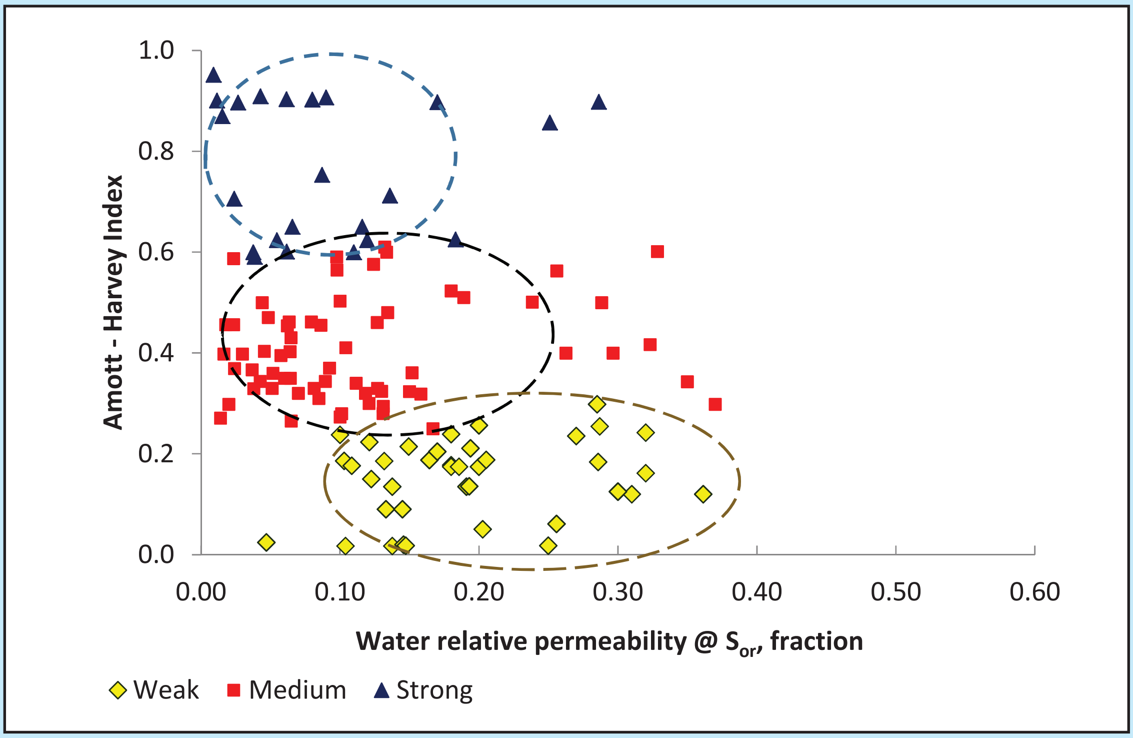

Figure 6
Plot between Ammot-Harvey index versus K_{rw}@S_{or}. The rock water wetness is devided into three groups; weak water wet (I_o =0.0-0.2), medium water wet (I_o= 0.2-0.6), and strong water wet (I_o = 0.6-1.0)

Wettability	Permeability Category[1]	Wettability Strength[2]	*C* Range	*C* Avg	*C* Suggested	*λ* Range	*λ* Avg	*λ* Suggested	x^{-3} Suggested	*y* Range	*y* Avg	*y* Suggested
		weak	0.7-2.0	1.3	1.0-1.5	0.6-5.0	2.5	1.0-2.5	1.5	1.0-8.0	2.8	1.5-3.0
	Moderate- high (sandstone)	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
		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
Water wet	Poor-fair (sandstone)	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
		weak	0.9-2.2	1.7	1.5-2.0	0.7-1.5	1.1	1.0-1.5	1.5	3.0-10.0	6	5.0-6.0
	Poor-fair (limestone)	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[4]	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
	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	1.0-14.0	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
		neutral/mixed[4]	0.8-2.7	1.5	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
Oil wet/	Poor-fair (sandstone)	weak	0.8-2.7	1.5	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
neutral/		medium	0.9-1.2	1	1	0.9-2.2	1.5	1.3-1.8	1.5	6.0-15.0	8.7	8.0-10.0
mixed		Strong[5]	-	2.2	2.2	-	0.5	0.5	1.5	-	9	9
		neutral/mixed[4]	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
	Poor-fair (limestone)	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_{wirr} problem may actually be solved by avoiding the use of S_{wirr} values within the overlapping ranges. The nearest value to the overlapping S_{wirr} may be used to represent them. However, since the ovelapping S_{wirr} 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 (λ) as the variable for achieving agreement between calculated and observed relative permeability values. Initially, apart from the imbibition relative permeability to water (K_{rw}) in equation (1), a modified imbibition relative permeability to oil (K_{ro}) in the form of

$$K_{ro} = K_r^o \left[\frac{(S_m-1)}{S_m-S_{wirr}} + S_{oF}^* * \frac{(1-S_{wirr})}{(S_m-S_{wirr})}\right]^2 \left[1-(1-S_{oF}^*)^{\frac{2+\lambda}{\lambda}}\right] \quad (15)$$

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_{ro} 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 λ 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_{rw} match, and case (c) depicting mismatched K_{ro} curves. For some failures in K_{rw} 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

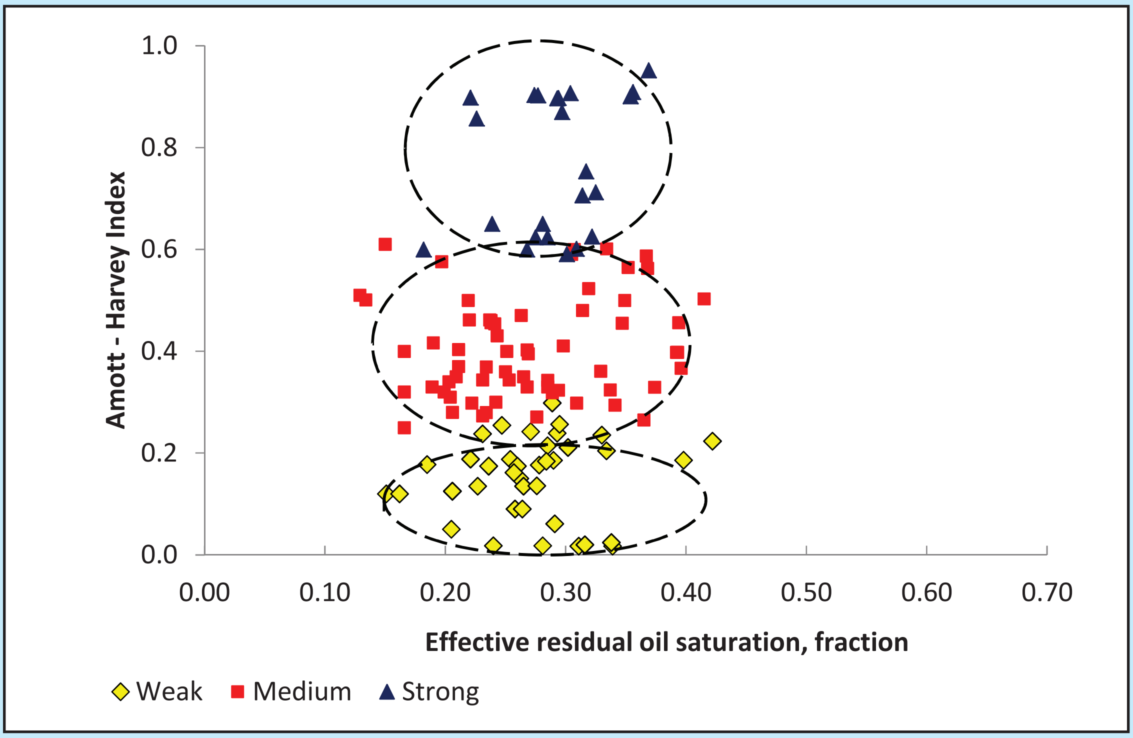

Figure 7
Plot between Ammot-Harvey index versus effective rediual oil saturation for water wet rocks. The rock water wetness is devided into three groups, weak water wet (I_o=0.0-0.2), medium water wet (I_o=0.2-0.6), and strong water wet (I_o=0.6-1.0).

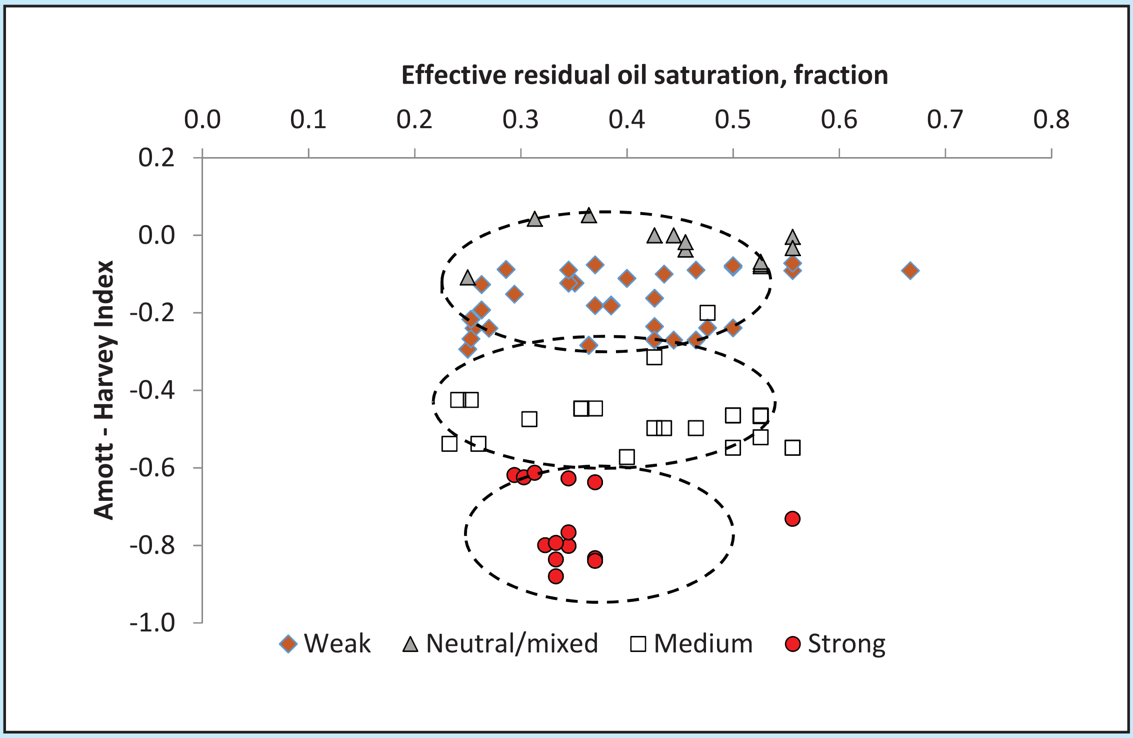

Figure 8

Plot between Ammot-Harvey index versus effective residual oil saturation for neutral/mixed/oil wet rocks. The rock wettability is devided into four groups, neutral/mixed wet (I_o= -0.1-0.0), weak oil wet (I_o= -0.2-0.0)), medium oil wet (I_o= -0.6-(-0.2)), and strong oil wet (I_o=-1.0-(-0.6)).

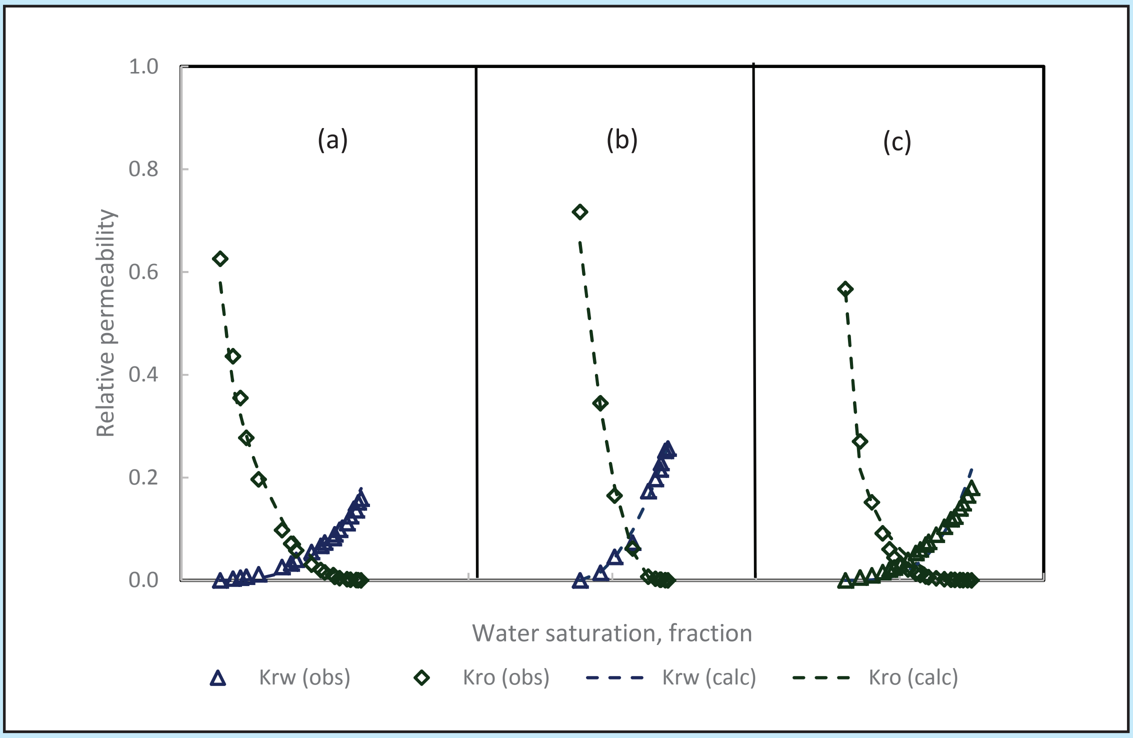

Figure 9

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, λ=1.3, x=1.5, and y=5; (b) sandstone, water wet: C=1, λ=4, x=2, and y=3; and (c) sandstone, neutral: *C*=1.5, λ=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_{rw} mismatch had led to an attempt to plot bettwen Amott-Harvey index (equation (6)) and $K_{rw}@S_{or}$ representing the gap between calculated and observed K_{rw} values. As the index is roughly devided 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_{rw} gap (i.e. leads to higher $K_{rw}@S_{or}$). The occurence on Figure 6 suggests that water wetness strength should have a special effect on the K_{rw} 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 λ. Through trials it was found eventualy that the equation (1) has to be modified into

$$K_{rw} = (S_w^*)^{\frac{2+x\lambda}{\lambda}} \quad (16)$$

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 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 serries 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 neural/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.

S_{or}^*

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 nonetheles seen that it is not the oil wettability that affect the mismatch, and the S_m factor in Equation (15) appears to be unable to satisfactorilly solve the problem. In a way similar to the modification of Equation (1), Equation (3) is modified to become

$$K_{ro} = K_r^o (S_{oF}^*)^2 \left[1 - (1 - S_{oF}^*)^{\frac{2+\lambda}{y\lambda}}\right] \quad (17)$$

with *y* as the additional parameter that serves as a magnifying factor to the pore size variation factor (λ) 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*, λ, *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 λ, therefore the least certain parameter is the *y*, which picking requires caution.

C. Recalculations and suggested *C*, λ, *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*, λ, *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_r data has their own respective set of *C*, λ, *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*, λ, *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_{wirr}) – various literatures present how to determine this parameter, including from K vs S_{wirr} correlations such as in Widarsono (2016) – to produce saturation related values (S_{oi}, S_{or}, S^*_{oi} , and S^*_{or}) required by Equations (16) and (17). Using the two equations – with K^o_r values obtained from equations (7) through (14) – for any predetermined water saturation (S_w) *C*, λ, *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*, λ, *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' (λ), *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^o_r for converting the oil relative permeability curves from air permeability domain to oil effective permeability at irreducible saturation (S_{wirr}) 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_{wirr} problem could be solved by avoiding the use of overpaping irreducible values for determining K^o_r , even though this may still be a problem for the moderate-high permeabilty water wet rocks that have wide range of overlapping S_{wirr} . Caution has to be taken for determining the most representative K^o_r .

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*, λ, *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*, λ, *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 geographycal position and geological history are not related to any validity concern for the use of the model.

ACKNOWLEDGMENTS

The author wishes to express his grattitude and apreciation to the Indonesian national Research and Development Center for Oil and Gas Technology PPPTMGB "LEMIGAS" for granting permission for the use of all the needed data required by this study.

REFERENCES

Amaefule, J.O & **Handy, L.L**. (1982) The effect of interfacial tensions on relative oil/water permeabilities of consolidated porous media. SPE Paper 9783 – PA, https://doi.org/10.2118/9783-PA.

Amott, E. (1959) Observations relationg to wettability of porous rocks. *Trans.* AIME, vol. 219, pp: 156 – 162.

Baker, L.E. (1988) Three-phase relative permeability correlations. SPE Paper 17369, presented at the SPE/DOE Enhanced Oil Recovery Symposium held at Tulsa – Oklahoma, 17-20 April.

Blunt, M.J. (2017) Multiphase flow in permeable media – A pore-scale perspective. Cambridge University Press, Cambridge CB2 8BS – UK, ISBN: 9781107093461, p: 475.

Bradford, S.A., Abriola, L.M., & **Leij, F.J**. (1997) Wettability effects on two- and three-fluid relative permeabilities. *Journal of Contaminant Hydrology,* 28 (1997), 171 – 191.

Brooks, R.H. & **Corey, A.T.** (1964) Hydraulic properties of porous media. *Hydrology Papers*, Colorado State University – Fort Colins, Colorado, p: 37.

Chang, Y.C., Mohanty, K.K., Huang, D.D., & **Honarpour, M.M.** (1997) The impact of wettability and core-scale heterogeneity on relative permeability. *Journal of Petroleum Science and Engineering* vol. 18 issues 1-2, July, pp: 1 – 19, https://doi.org/10.1016/S0920-4105(97)00006-5.

Cinar, Y., Marquez, S. & **Orr, F.M.** (2007) Effect of IFT variation and wettability on three-phase relative permeability. SPE Paper 90372–PA, https://doi.org/10.2118/90572-PA

Corey, A.T. (1954) The interrelation between gas and oil relative permeabilities. *Producers Monthly*, November, pp: 38 – 41.

Corey, A.T.; Rathjens, C.H., Henderson, J.H. & **Wyllie, M.R.J.** (1956) Three-phase relative permeability. *Journal of Petroleum Technology*, Technical Note 375, November, pp: 63 – 65.

Donaldson, E.C. & **Thomas, R.D.** (1971) Microscopic observation of oil displacement in water-wet and oil-wet systems. SPE Paper 3555 – MS, https: //doi.org/10.2118/ 3555-MS.

Falode, O. & **manuel, E.** (2014) Wettability effects on capillary pressure, relative permeability, and irreducible water saturation using porous plate. *Journal of Petroleum Engineering,* Article ID 465418, http://dx.doi.org/10.1155/2014/465418.

Gharbi, O. & **Blunt, M.J**. (2012) The impact of wettability and connectivity on relative permeability in carbonates: A pore network modeling analysis. *Water Resources Research*, volume 48 issue 12, December, https://doi.org/10.1029/ 2012WR011877

Goda, H.M. & **Behrenbruch, P.** (2004) Using a modified Brooks-Corey model to study oil-water relative permeability for diverse pore structures. SPE Paper 88538, presented at the SPE Asia Pacific Conference & Exhibition held in Perth – Australia, 18-20 October.

Guler, B., Eterkin, T. & **Grader, A.S.** (2003) An artificial neural network based relative permeability predictor. *Journal of Canadian Petroleum Technology*, Vol. 42 issue 04, April, https://doi.org/10.2118/03-04-02.

Heaviside, J., Brown, C.E. & **Gamble, I.J.A**. (1987) Relative permeability for intermediate wettability reservoirs. SPE Paper 16968-MS, https://doi.org/10.2118/16968-MS.

Heiba, A.A., Davis, H.T. & **Scriven, L.E**. (1983) Effect of wettability on two-phase relative permeability and capillary pressure. SPE Paper 12172-MS, presented at the SPE Annual Conference and Exhibition 5-8 October, San Fransisco – California, https://doi.org/10.2118/12172-MS.

H**onarpour, M., Koederitz, L.F.** & **Herbert Harvey, A.** (1982) Empirical equations for estimating two-phase relative permeability in consolidated rock. SPE Paper 9966-PA, *Journal of Petroleum Technology*, Vol. 34 issue 12, December, https://doi.org/10.2118/9966-PA.

Huang, D.D., Honarpour, M.M. & **Al-Hussainy, R.** (1997) An improved model for relative permeability and capillary pressure incorporating wettability. Paper SCA – 9718, presented at the SCA International Symposium, Calgary – Canada, September 7-10.

Jadhunandan, P.P. & **Morrow, N.R.** (1995) Effect of wettability on waterflood recovery for crude-oil/brine/rock systems. SPE Paper 22597-PA, https://doi.org/10.2118/ 22597-PA.

Land, C.S. (1968) Calculation of imbibition relative permeability for two- and three phase flow from rock properties. *Society of Petroleum Engineers Journal*, Vol. 8 issue 02, June, https://doi.org/10.2118/1942-PA.

Lomeland, F. & **Ebeltoft, E.** (2013) Versatile three-phase correlations for relative permeability and capillary pressure. SCA 2013-034, presented at the International Symposium of the Society of Core Analysts held in Napa Valley – California, 16-19 September.

Lomeland, F. (2018) Overview of the LET family of versatile correlations for flow functions. SCA 2018-056, presented at the International Symposium of the Society of Core Analysts held in Trondheim – Norway, 27 – 30 August.

Masalmeh, S.K. (2003) The effect of wettability heterogeneity on capillary pressure and relative permeability. *Journal of Petroleum Science and Engineering* vol. 39 issues 3-4, September, pp: 399 – 408, https://doi.org/10.1016/S0920-4105(03)00078-0.

McCaffery, F.G. & **Bennion, D.W**. (1974) The effect of wettability on two-phase relative permeability. *The Journal of Canadian Petroleum Technology*, October – December, pp: 42 – 53.

Morrow, N.R., Cram, P.J. & **McCaffery, F.G** (1973) Displacement studies in dolomite with wettability control by octanoid acid. SPE Paper 3993 – PA, https://doi.org/10.2118/3993-PA.

Nguyen, V.H., Sheppard, A.P., Knackstedt, M.A. & **Pinczewski, W.V.** (2005) The effects of displacement rate and wettability on imbibition relative permeability. SPE Paper 95953-MS, presented at the 2005 SPE Annual Technical Conference and Exhibition held in Dallas, Texas, U.S.A., 9 – 12 October, https://doi.org/10.2118/ 95953-MS.

Øren, P-E. & **Bakke, S**. (2003) Reconstruction of Berea sandstone and pore-scale modeling of wettability effect. *Journal of Petroleum Science and Engineering* vol. 39 issues 3-4, September, pp: 177 – 199, https: // doi:10.1016/S0920-4105(03)00062-7.

Owens, W.W. & **Archer, D.L.** (1971) The effect of rock wettability on oil-water relative permeability relationships. SPE Paper 3034-PA, https://doi.org/10.2118/3034-PA.

Pedrera, B., Bertin, H., Hamon, G. & **Augustin, A.** (2002) Wettability effect on relative permeability during a gravity drainage. SPE Paper 77542-MS, https://doi.org/10.2118/77542-MS.

Rao, D.N., Ayirala, S.C., Abe, A.A. & **Xu, W**. (2006) Impacts of low-cost dilute surfactants on wettability and relative permeability. SPE Paper 99609-MS, https://doi.org/10.2118/99609-MS.

Schneider, F.N. & **Owens, W.W**. (1970) Sandstones and carbonates two- and three-phase relative permeability characteristics. SPE Paper 2445-PA, https://doi.org/10.2118/2445-PA.

Wang, F.H.L. (1988) Effect of wettability alteration on water/oil relative permeability, dispersion, and flowable saturation in porous media. SPE Paper 15019-PA, https://doi.org/10.2118/15019-PA.

Widarsono, B. (2016) Petrophysical Characteristics of Some Indonesian reservoir Rocks. LIPI Press, ISBN 978-979-840-0, pp: 257.

Zhao, X., Blunt, M.J. & **Yao, J.** (2010) Pore scale modeling: effects of wettability on waterflood oil recovery. *Journal of Petroleum Science and Engineering* vol. 71 issues 3-4, April, pp: 169 – 178, https://doi.org/10.1016/j.petrol.2010.01.011.