ESTIMATION OF WATER SATURATION IN CARBONATE RESERVOIRS WITHOUT RESISTIVITY LOG DATA. PART I: THEORY AND EXISTING MODEL

by

Bambang Widarsono, Heru Atmoko, Ridwan, and Kosasih

ABSTRACT

This paper presents an observation over a suggested approach for establishing water saturation model that is specifically designed without the need of resistivity log data. One of the main strength of the approach is that the resulting water saturation model can be specifically established for local or specific use only. This is true since the approach can be applied using carbonate rocks that are obtained locally or from specific areas. Another important conclusion is that this approach can also be applied for any carbonate rock classification as long as the classification can clearly group carbonate rocks into groups with distinctive petrophysical properties. This paper – first part of two – presents theory and rock classification that underlines the approach, as well as procedure and the existing models available.

Key words: carbonate rocks, classification, water saturation model, capillary pressure

I. INTRODUCTION

Water saturation as one of the most important data for estimating hydrocarbon acumulation needs to be determined reliably. However, in cases that are characterized by high level of heterogeneity, such as in carbonate reservoirs, transisition zones and capilary network above water table are influential in determining fluid saturation throughout the reservoirs.

Capilary pressure, which is basically an interaction between fluids and rocks, is very much influenced by pore configuration, pore throat dimension, wettability, and interfacial tensions both fluid – fluid and fluid – rock. It is understandable therefore that carbonate reservoirs with their usual high level heterogeneity – meaning varried pore configuration and dimension – have their water saturation distribution very much determined by variation in capillary pressure.

Developments in conventional log analysis have demonstrated that most of water saturation models are dedicated to petrophysical evaluations in sandstone reservoirs. These models usually differ among each others with regard to clay distribution and other correction-related additions on the classic Archie model. Not much has been devoted to carbonate reservoirs, since it is commonly assumed that carbonate rocks are clay-free and therefore Archie model sufices. This gross simplification may prove wrong since Archie model was actually derived for sands and sandstones.

One important aspect that is often neglected, even though very well realized, about carbonate reservoirs in log analysis is their heterogeneity and complexity. Additionally, conventional log analysis that relies solely on resistivity log may record and reflect whatever fluid saturation nearby wellbore but in case of highly heterogeneous rocks, in which mud invasion may vary considerably from shallow to very deep, fluid saturation distribution may not reflect the true condition in the reservoir. It is in this light that an alternative approach – free from mud invasion effect – is needed.

Apart from complexity and mud invasion issues, it is often in Indonesia to find cases in which no resistivity logs available (or if available, of old vintage with its low reliability) for old wells. This becomes a problem when in the wake of high oil prices old oil fields have again come into center of attention. This requires an alternative method that does not rely on availability of resistivity log data.

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In relation to complexity in carbonate reservoir rocks, Lucia (1983) has classified carbonate reservoir rocks into three groups based on their hydraulic quality. Using these three classes he generated empirical relationships between water saturation (S_w), porosity, and heights (h) above free water level for each class. Thi Lucia model was generated using core data taken from Illinois and West Texas – USA, which is not neccessarilly valid for Indonesian carbonate rocks. Efforts have to be spent to generate ones that are valid for Indonesian cases. It is therefore the purpose of this paper – first part of two – to present results of an effort to establish the models. This first part presents theoretical considerations and existing models, whereas the second part later on will cover data inventory, modeling/ formulating, and validity testing.

II. CLASSIFICATION OF CARBONATE ROCKS

Classification of carbonate rocks is in general based on genetical aspects that are related to grain size and fabric. Such classification has been suggested by various workers including Dunham (1962), Choquette and Pray (1970), and more recently Lucia (1983).

Dunham (1962) established a stratified classification starting from the top by recognising “crystalline“ and “non-crystalline“, dividing the “non-crystalline“ into “components bound“ and components not bound“, dividing further the “components not bound“ into “containing mud“ and not, down to division of the rocks classified as “containing mud“ into “mud dominated“ and “grain dominated“. These definitions, based clearly on rock fabric, classify carbonate rocks into rocks types of crystalline, boundstone, grainstone, packstone, wackstone, and mudstone. See Figure 1 for the classification.

In a manner differently, Lucia (1983) stressed the importance of rock petrophysical properties, especially porosity and permeability, in the defining of rock groups. He showed that mouldic and intra-particles porosities differ significantly from inter-particle and intercrystalline porosities. In brief, Lucia’s classification for carbonate rocks includes three groups: a) rocks with interparticle porosity, b) rocks with interparticle porosity as background mass + vugs are mostly unconnected, and c) type (b) rocks but with connected vugs (touching vugs). Figures 2 and 3 present illustrative pictures for the three groups. The two figures also show that Dunham classification serves only as classification of ‘background masses’ to the vugs in the Lucia classification.

This porosity-derived classification has come into its relevance when it is related to rocks permeability. Lucia showed that the three groups may have members overlaping in permability magnitudes but the three groups can be distinguished from their three different porosity – permeability relationships. Most of type (a) rocks are characterized by relatively low permeability while most of type (b) rocks show higher permeability and type (c) rocks in general show permeability higher than permeability of the two other rock types. These three distinct groups were then classified, referring to their permeability trends, as Class – 1, Class – 2, and Class – 3 representing type (c), type (b), and type (c) rocks, repectively.

<table>
<tr><td colspan="5">Depositional textures recognizable</td><td rowspan="5">Depositional textures not recognizable</td></tr>
<tr><td colspan="4">Original components not bound together during deposition</td><td rowspan="4">Original components were bound together</td></tr>
<tr><td colspan="3">Contains mud
(Clay and fine silt-size carbonate)</td><td rowspan="3"></td></tr>
<tr><td colspan="2">Mud supported</td><td>Grain supported</td></tr>
<tr><td>Less than 10% grains</td><td>More than 10% grains</td><td></td></tr>
<tr><td>Mudstone</td><td>Wackstone</td><td>Packstone</td><td>Grainstone</td><td>Boundstone</td><td>Crystalline</td></tr>
</table>

Figure 1
Dunham classification

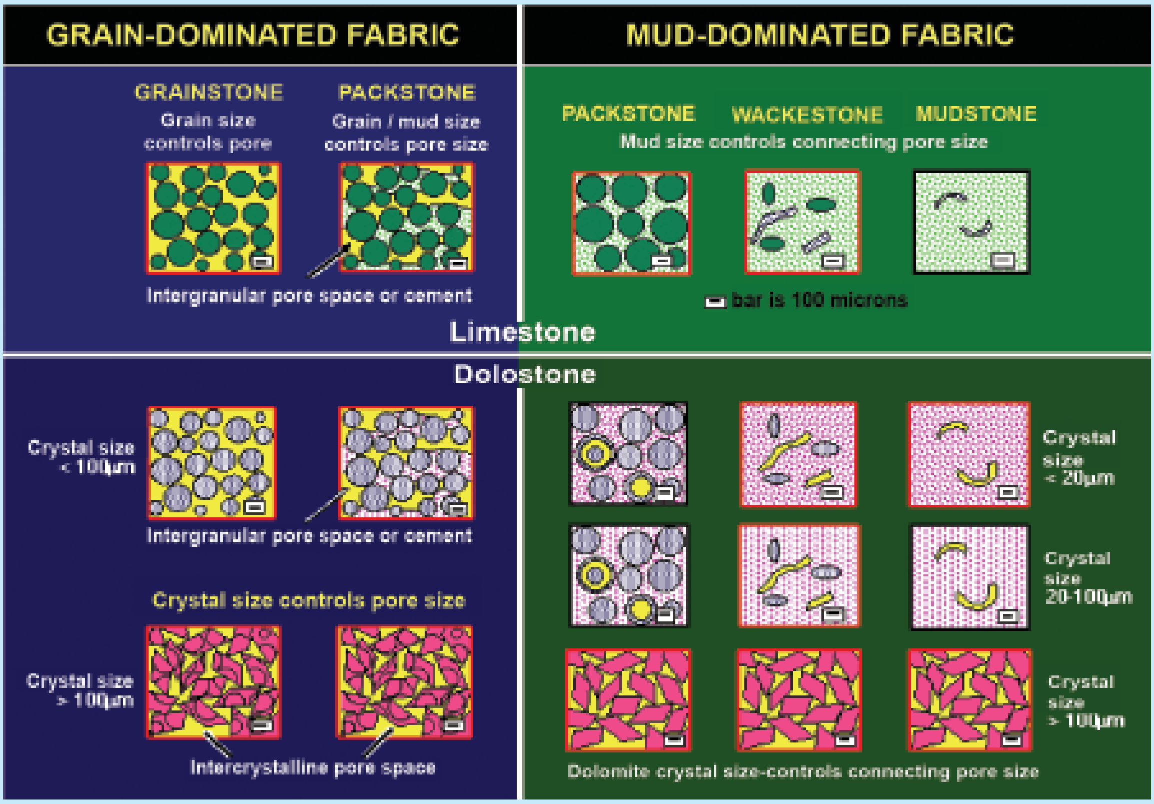

Figure 2
Luclassification, inter-crystalline

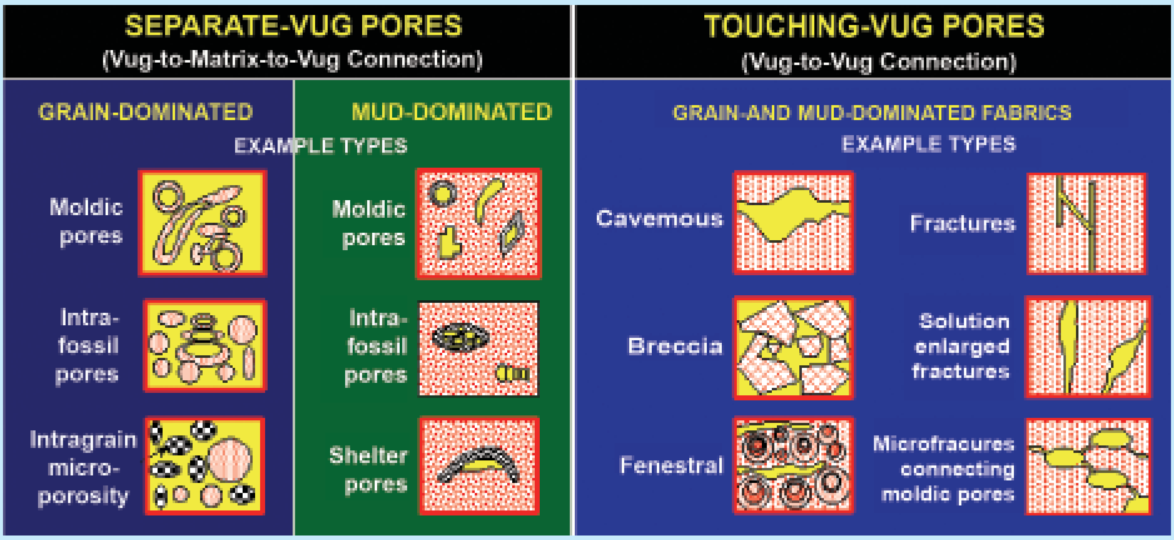

Figure 3
Lucia classification, vuggy

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III. CAPILLARY PRESSURE AND WATER SATURATION

Capillary presure is defined as pressure difference between wetting phase and non-wetting phase fluids under immiscible and static conditions. Capillary pressure reflects interactions between fluids and rocks, and is controlled by pore geometry, interfacial tension, and wettability. In a simple way, capillary pressure of a capillary pipe is expressed in the form of:

$$P_C = \frac{2\sigma\cos\theta}{r} \qquad (1)$$

where

σ= interfacial tension,

θ = contact angle (related to wettability and solid-fluid interactions), and

r = capillary radius (related to porosity and permeability)

Equation (1) is also used for describing capillary pressure that prevails in the rock pores and the justification comes from analoging the pore system in the rock with a bundle of capillary tubes. The tubes diameter(s) are then considered as representing the pore throat sizes. Capillary pressure behaviour of a given rock is normally measured in laboratory, and upon its use for real reservoir applications the capillary pressure data is converted using (Amyx, 1960).

$$P_c(res) = P_c(lab)\frac{(c\ \cos\theta)res}{(\sigma\cos\theta)lab} \qquad (2)$$

Where the subscribes of *res* and *lab* represent reservoir and laboratory conditions, respectively. Table 1 presents some interfacial tension and contact angle data normally used for the conversion.

Pressure gradient for oil and water in reservoir is influenced by the fluid's density difference. This difference in density controls buoyancy forces and in general controls water saturation distribution above free water level (FWL). This is described, after conversion to field unit, through

$$P_c = \frac{h(\rho_w - \rho_o)}{144} \qquad (3)$$

with P_c in psi, density in lbm/ft^3, and height above FWL (h) in ft.

The distribution of water saturation above FWL can be related to height above FWL under conditions of: 1) hydrocarbon and water pressures are equal at FWL, 2) hydrocarbon and water have to be continuously in contact above FWL, and 3) system is under static equilibrium.

Under the conditions presented above, water saturation decreases gradually from FWL to a level at which the water saturation reaches as low as *irreducible water saturation* (S_{wirr}) and the hydrocarbon saturation reaches its highest level (S_{hc} = 1 - S_{wirr}). This level is called water oil contact (WOC) for oil-water system and gas water contact (GWC) for gas-water system. The interval above FWL within which the gradual decrease in water saturation, acompanied by gradual increase in hydrocarbon saturation, is called the *transition zone*. Thickness of this transition zone (i.e. thickness between FWL and WOC/GWC) is dependent on the capillary behaviour of the system. The transition zone above FWL is regarded important especially in relatively thin reser-

Table 1
Interfacial tension and contact angle data for some fluid systems

Wetting phase	Non wetting phase	Condition	Contact angle	IFT (dyne/cm)
Brine	Oil	Reservoir	30	30
Brine	Oil	Laboratory	30	48
Brine	Gas	Laboratory	0	72
Brine	Gas	Reservoir	0	50
Oil	Gas	Reservoir	0	4
Gas	Mercur	Laboratory	140	480

voir with large capillary forces. In this case the whole reservoir column is within this transition zone and interval(s) with $S_w = S_{wirr}$ is simply non-existent. It is in this case that estimation of water saturation using the concept of capillary force is at its utmost relevance and importance.

IV. LUCIA'S CONCEPT FOR WATER SATURATION MODEL

Sequentially, Lucia's concept of water saturation modeling can be described in the following steps:

1. Classify all samples available into the three classes, namely Class – 1, Class – 2, Class – 3.
2. Establish porosity – permeability correlation for each class.
3. Referring to the samples' membership to the three classes, groupping capillary pressure data (P_c vs. S_w) into the three classes is made. Theoretically, capillary behaviour of the three classes will be different from each other due to difference in pore system.
4. Conversion of all capillary pressures data from laboratory condition to reservoir condition.
5. Average (normalize) capillary pressure curves in each class using Leverette method (Amyx, 1960) of

$$J(S_w) = \frac{P_c}{\sigma \cos\theta}\sqrt{\frac{k}{\phi}} \tag{4}$$

or with substituting Equation (3), Equation (4) becomes

$$J(S_w) = \frac{h}{144}(\rho_1 - \rho_2)\sqrt{\frac{k}{\phi}} \tag{5}$$

where

$J(S_w)$ = J-Function,

k = permeability, and

$ø$ = porosity.

Note that subscripts *1* and *2* represent heavier and lighter fluids, respectively.

6. Plot $J(S_w)$ versus S_w for each capillary curve data. Perform regression analysis using either Power Law or Exponential series in order to obtain averaged $J(S_w)$ versus S_w curve for each class.
7. Combine the averaged $J(S_w)$ versus S_w with Equation (5).
8. Incorporate porosity – permeability correlations resulted from step (2) to produce water saturation model as a function of height (h) above FWL and porosity (ϕ), $S_w = f(h, \phi)$.

Using this approach Lucia (1995) produced

$$K = \left(43.35\times10^{8}\right)\times\phi^{8.537} \tag{6}$$

$$S_w = 0.02219\times h^{-0.316}\times\phi^{-1.745} \tag{7}$$

for Class 1 rocks,

$$K = \left(2.04\times10^{6}\right)\times\phi^{6.38} \tag{8}$$

$$S_w = 0.1404\times h^{-0.407}\times\phi^{-1.44} \tag{9}$$

for Class 2 rocks, and

$$K = \left(2.884\times10^{3}\right)\times\phi^{4.275} \tag{10}$$

$$S_w = 0.611\times h^{-0.505}\times\phi^{-1.21} \tag{11}$$

for Class 3 rocks.

V. DISCUSSION

According to Lucia (1995) the three saturation models presented above was basically developed following three steps. First, mercury capillary pressure curves were converted to reservoir height using generic values such as ones preseted in Table 1. (Actually Lucia used interfacial tension, contact angle, and water density of 480 dynes/cm, 140°, and 1.04 for laboratory condition and 28 dynes/cm, 44°, and 0.88 for reservoir condition, respectively.) Second, wetting phase saturation from capillary pressure curves are plotted against porosity for several reservoir heights. Third, lines of equal reservoir height are drawn assuming equal slopes resulting in a relationship between intercepts and reservoir height. By substituting this relationship into the porosity versus wetting phase saturation, Equations (7), (9), and (11) were established.

According to the authors of this paper, the above description of steps can better be explained following the procedure mentioned earlier. First, conversion of capillary pressure data from laboratory to reservoir conditions. Second, establishment of porosity – permeability correlations for the three rock classes. Third, plot between J-function ($J(S_w)$) and water saturation. Correlations between averaged $J(S_w)$ and water saturation for the three classes are established. Fourth, substitution of porosity – permeability relationships into Equation (5). Fifth, substitution of J(S_w) - water saturation relationships into Equation (5). Through some mathematical rearrangement relationships among water saturation, reservoir height, and porosity are established. Formulation using Indonesian carbonate rocks data will be presented in the second part of this paper.

The water saturation modeling approach shown by Lucia suggests that unique models can be established for specific reservoir/rock types. This characteristics of modeling further suggests that the modeling can be applied on other kind of rock classification as long as it produces differences in porosity – permeability and capillary pressure characteristics. This is certainly in accordance with the very purpose of reservoir characterization for reservoir modeling itself, in which distribution of reservoir rock propertiies is based on rock facies classification and its distribution. The water saturation modeling approach suggested by Lucia can therefore be regarded as a powerful tool to be integrated into the conventional reservoir characterization method.

VI. CONCLUSIONS

From the observation on rock classification and water saturation modeling suggested by Lucia, some conclusions can be drawn.

- Lucia has suggested a method for establishing water saturation model that takes into consideration local aspects such as specific pore structures and wettability.
- Considering its basic use, J-function averaging method can be used to refine distinction in rock characteristics between the rock classes.
- In theory, the suggested method can be used for classification else than Lucia classification, as long as the classification produces differences in porosity – permeability and capillary pressure characteristics.

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