An Alternative Approach for Estimating Water Saturation in Indonesian Carbonate Reservoirs

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 strengths 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.

STUDI LABORATORIUM UNTUK REAKTIVASI LAPANGAN-X DENGAN INJEKSI KIMIA

ACIDIZING IN ESP WELLS:
AN EFFICIENT PRODUCTION OPTIMIZATION

Kebergantungan Pada Migas:
Kebijakan Pemerintah RI Yang Cinta Kemudahan

Optimization Of Super Light Weight Completion Fluids Using Fractional Factorial Design

Underbalanced perforation is widely known as one of the best techniques to increase hydrocarbon flow. Numerous researchers have proved that the resulting production increases is due to the surge of hydrocarbon that eliminates permeability damage around the perforation tunnel. In order to achieve the underbalance condition downhole, super light weight fluids needs to be formulated. The formulated fluid has lower density compared to the existing fluid in the market. In this research, optimization formulation of super light weight completion fluids was conducted based on experimental design software.

Tracer Test Evaluation on Core Flooding
Pertama-tama ijinkan segenap pengurus IATMI-Pusat periode 2008-2010 mengucapkan Selamat Hari Ulang Tahun Kemerdekaan Republik Indonesia yang ke 64 tahun, semoga Bangsa Indonesia bisa menjadi bangsa yang besar dan sejahtera. Dalam suasana menyambut datangnya bulan Suci Ramadhan, tidak lupa segenap jajarannya pengurus IATMI periode 2008-2010 mengucapkan selamat menunaikan ibadah puasa Ramadhan 1430H.

Pada ulang tahun yang ke-64 ini, Bangsa Indonesia mendapatkan salah satu hadiah yang sangat berharga yaitu ternyata tingkat pertumbuhan ekonomi berkisar antara 3.5 % - 4.5 % dalam situasi krisis keuangan Global, dimana bangsa lain pertumbuhannya malah ke arah negative. Bangsa Indonesia menemani pertumbuhan ekonomi nomor tiga di asia, dibawah negara Cina dan India. Hadiah ini adalah buah kerja yang luar biasa oleh semua komponen bangsa dan menjadi suatu optimisme bangsa ke depan.

Pada Saat penerbitan JTMGB yang pertama di bulan April 2009, harga minyak NYMEX di NYSE berkisar di harga $45 - $50 /Bbl, di bulan Agustus ini sudah mulai menanjak ke harga diatas $70/bbl dengan kenaikan rata-rata mendekati 50 %. Kenaikan harga minyak ini tentunya bagi Industri Migas sangat berdampak banyak, salah satunya adanya kesempatan untuk melakukan lebih banyak riset, eksplorasi dan penerapan teknologi yang lebih mutakhir. Kegiatan ini diharapkan dapat meningkatkan nilai lebih bagi kegiatan migas di Indonesia, terutama dalam kenaikan cadangan, kenaikan produksi migas dan biaya yang lebih efektif.


Jajaran team JTMGB juga mengucapkan terima kasih kepada Bapak Widjajono P yang sudah berkenan memberikan sumbangan artikel bagi IATMI mengenai arah kebijakan negara, Kebergantungan pada Migas: Kebijakan Pemerintah RI yang cinta kemudahan.

Semoga tulisan-tulisan kalangan perminyakan Indonesia ini semakin menambah sumbangsih bagi negara tercinta.

Salam dan Terima kasih

Redaksi
Introduction

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

Capillary 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 varied 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 suffices. 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.

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. The Lucia model was generated using core data taken from Illinois and West Texas – USA, which is not necessarily valid for Indonesian carbonate rocks. Efforts have to be

Abstrak

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.

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

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oleh
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PPPTMGB “LEMIGAS”
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.

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 overlapping in permeability 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, respectively.

Capillary pressure and water saturation

Capillary pressure 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:

$$P_c = \frac{2 \sigma \cos \theta}{r}$$  \hspace{1cm} (1)

where

$\sigma = \text{interfacial tension}$,
$\theta = \text{contact angle (related to wettability and solid-fluid interactions)}$, and
$r = \text{capillary radius (related to porosity and permeability)}$

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)

$$P_{c_{\text{res}}} = P_{c_{\text{lab}}} \left( \frac{\sigma \cos \theta_{\text{res}}}{\sigma \cos \theta_{\text{lab}}} \right)$$  \hspace{1cm} (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

$$P_c = \frac{h(\rho_o - \rho_w)}{144}$$  \hspace{1cm} (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, accompanied 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 reservoir 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.

**Lucia water saturation model**

Following Lucia’s concept of water saturation modeling (Lucia, 1995) presented

$$K = \left(43.35 \times 10^9\right) \times \phi^{0.537}$$

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

for Class 1 rocks,

$$K = \left(2.04 \times 10^5\right) \times \phi^{0.38}$$

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

for Class 2 rocks, and

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

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

for Class 3 rocks.

**Model for Indonesian Reservoirs**

**Core Data**

As many as 407 limestone plugs taken from fields in Indonesia, mostly from West Java and South Sumatera, were used in the study. Table 2 lists the regional origins of the core samples. Data for each sample consists of porosity, permeability, grain density, fluid saturation, visual description, and type/classification. Capillary pressure data for the study was provided by special core analysis laboratory (SCAL) data from seven wells among the fields. Table 3 presents an example of capillary data taken Sukamandi field’s plug samples.

Apart from the basic and capillary pressure data, other core-derived data was also prepared for the purpose of validity test on the new formula. The data is log suites, resistivity (a, m, and n), drill-stem test (DST), and water analysis result taken from a well in a West Java field. Table 4 summarizes the primary data availability for the model validity check. Other auxiliary data was also prepared consisting of petrographic and scanning electron microscope (SEM) data. This visual data was used for confirming aspects such as lithology model and pore configuration type.

**Classification of the Rock Samples**

In classifying the rock samples, analyses were performed in order to interpret the rocks’ characteristics with regards to their facies, class, petrophysical properties, diagenesis, and depositional environment. The rock samples were in general interpreted as to belong to wackestone, packstone, and grainstone classes.

Briefly, the rock samples involved in this study are generally characterized by some typical features. Wackestones are usually of fine to coarse-grained skeletal wackestones dominated by coral fragments, planktons, echinoderms, bryozoans, and ostracods (Figure 4). This poorly to moderately sorted limestone is made of 40% to 65% carbonate mud. As in accordance with the Lucia classification, this rock is classified among Class 3 rocks.

Packstones of the studied samples are characterized by their medium to coarse skeletal materials consisting of larger fossils of coral, bryozoans, and echinoderms with irregular appearance of red algae and bivalves (Figure 5). Smaller fossils are also present represented by benthonic foraminifera such as Amohistegina sp, Lepidocyclina sp, and Miogypsina sp. This kind of rocks are classified into Class 2 in the Lucia classification.

The rock samples that were classified as grainstone are characterized by their poor grain...
sortation and presence of large amount of skeletal material such as larger coral fragments and foraminifers (Figure 6). Other skeletal material that are usually present are bryozoa, bivalves, gastropods, and other calcareous benthonic foraminifers. These rocks are categorized among Class 1 rocks in accordance with Lucia classification. Some boundstones among the studied samples are also classified into this class.

**Formulation of The New Models**

**Selection of capillary pressure data**

First step in the formulation is to select capillary pressure data in accordance with the rock samples that have been classified into Class 1, Class 2, and Class 3. As discussed previously these three classes are represented grainstones (and boundstones), packstones, and wackestones, respectively. Figures 7 through 10 present the capillary pressure data for the four rock types. All capillary curves have been converted into reservoir condition following the method presented in Widarsono et al. (2008).

The capillary pressure curves shown in Figures 7 through 10 have apparently differences in the pore configuration. This is, at least, shown by the difference in irreducible water saturation ($S_{irr}$) values. The wackestones, having the expectedly lowest permeability, are represented by a range of $S_{irr}$ values of 30% - 70%, packstones by 25% - 55%, graistones by 23% - 37%, and bounstones by 25% - 35%.

As the second step, correlations were made between water saturation and capillary pressure averaging (power law) and normalization among the capillary pressure curves using the J-function (JF) approach to yield

- Class 1:  $JF = 0.71S_w^{-3.8774}$ with $R^2 = 0.8372$
- Class 2:  $JF = 0.3606S_w^{-5.3589}$ with $R^2 = 0.8081$
- Class 3:  $JF = 0.653S_w^{-4.9542}$ with $R^2 = 0.968$

**Porosity vs. Permeability correlation**

Following the classification of the rock samples into three classes, porosity – permeability relationships were determined through plotting porosity and permeability data belonging to each class. Figure 8 shows the plots and correlations for the three classes. As exhibited by the plots, no sharp correlations are visible even though there are clear correlations between porosity and permeability. However, scatters are also obvious implying that there could be overlapped domains among the rock types. Some wackestones could be part of Class 2 while some packstones could also be part of Class 3 rocks. Nevertheless, porosity ($\phi$) – permeability ($k$) relationships for the three classes have been found as follows

- Class 1:  $k = 0.07021\phi^{2.2923}$  \(10\)
- Class 2:  $k = 0.000925\phi^{3.1744}$  \(11\)
- Class 3:  $k = 0.0000509\phi^{3.527}$  \(12\)

**Formulation of new water saturation models**

By combining the J-function form of Equation (3) of

\[
J(F) = \frac{h}{144}(\rho_1 - \rho_2)\sqrt{\frac{k}{\phi}}
\]

where $\rho_1$ and $\rho_2$ are densities of heavier and lighter fluids, with Equations (1) through (3) water saturation ($S_w$) models - see Atmoko (2007) for complete derivation – water saturation equations of

\[
S_w = 1.25472h^{-0.25759}\phi^{-0.03815}
\]

for Class 1 rocks,  \(14\)

\[
S_w = 1.55178h^{-0.1866}\phi^{-0.02442}
\]

for Class 2 rocks, and  \(15\)

\[
S_w = 2.4350h^{-0.20185}\phi^{-0.03592}
\]

for Class 3 rocks are derived, with $h$ is height above free water level at which capillary pressure is zero. From Equations 14 through 16 it is clear that the new water saturation models are functions of, beside porosity, height above free water level. This implies that the models are suitable for cases in which reservoirs of concern are at their initial condition. The models simply estimate water saturation vertical distribution, depending on the porosity (i.e.
permeability), up to positions above which water saturation values are simply the irreducible water saturation. At any other conditions that have involved flows as the results of production operations these models are simply not valid.

Model Validity Test

For validity test on the newly proposed water saturation models, log data from two wells in a West Jawa field was used. A complete set of standard log data (gamma ray, spontaneous potential, resistivity, neutron, density, acoustic, and caliper) was available for the analysis.

In term of rock quality, the field’s structure can be divided into two parts; the upper 30-meter of poor to fair quality rocks and the better and thicker lower parts with average thickness of 120 meters. Porosity estimation using the most suitable method has yielded average porosity values of 14% and 22% for the upper and lower parts, respectively.

Information from petrographic (thin section) and scanning electron microscope (SEM) has shown that the upper interval is generally made of bioclastic packstones with intercrystalline porosity, dolomite crystals, and secondary porosities caused by dissolution and fracturing. In general, this interval can be classified as having Class 2 rocks. For the lower interval no laboratory data was available but from the log analysis it appears that the interval is made of rocks belonging to Class 1.

In the log analysis for the two wells (WJ-X1 and WJ-X2) used in the model validity test, porosity was estimated using neutron-density log cross-plot. Considering that the lithology in general is carbonate water saturation was estimated using Archie water saturation model with input data as listed in Table 3. Results of porosity and water saturation estimation are presented in Table 5.

Water saturation (Archie) estimates appear to be in reasonably good conformity with well test and capillary pressure data. For instance, water saturation estimate for WJ-X1 well’s Lower zone (Class 1 rocks) is 33.15%. This zone was tested and yielded gas and water at 7 MMSCFD and 89 BWPD, respectively. When this data is confronted to potential irreducible water saturation ($S_{water}$) range of 23% - 37% (Figures 9 and 10 combined) the water saturation estimate seems to be a bit too optimistic.

However, when it is considered that Class 1 rocks are characterized by ‘touching vugs’ (Figure 12), which could result in very high porosity and permeability, then the more likely $S_{water}$ values should take the lower side of the range. $S_{water}$ values of 25% - 30% are likely to conform well with the well test data.

For the Lower zone of WJ-X2 well, the water saturation (Archie) estimate is 31.3% with corresponding well test data of $Q_g = 3.5$ MMSCFD with no water production. The absence of produced water means that the water saturation in that zone is equal to irreducible water saturation or $S_{water} = S_w = 31.3\%$. Comparing this estimate to the corresponding analysis of WJ-X1’s Lower zone above, one can speculate that even though both Lower zones are of Class 1 rocks the WJ-X1’s Lower zone is likely to have higher permeability than the WJ-X2’s Lower zone. This is supported by the fact that the tested gas production rate of WJ-X2’s Lower zone is only half of the WJ-X1’s tested gas production rate.

For the two wells’ Upper zones (Class 2 rocks) the water saturation (Archie) estimates are around 46% - 48%. No firm justification for the $S_w$ estimates, but since the $S_w$ estimates for the Lower zones have been well justified using the well test and $S_{water}$ data then it can safely be assumed that the estimates for the Upper zones are also justified.

After the application of Archie models for the two wells is well justified estimation using the new models, as well as the Lucia models, were performed. Water saturation estimation using the original Lucia models (Equations 5, 7, and 9) appear to yield very optimistic (i.e. low) estimates (see Table 6). For the Lower zones in the two wells the $S_w$ estimates are around 8% - 10%. Comparing to the 23% - 37% irreducible water saturation range for Class 1 rocks, the $S_w$ estimates are far too low. Similarly to the Lower zones, $S_w$ estimates for the Upper zones may also be considered too optimistic.

Application of the newly formulated models (i.e. the ‘new’ models) has proved encouraging. Tests on Class 1 and Class 2 rocks resulted in $S_w$ estimates that are very close to the estimates produced using Archie model. Considering the validity that has been shown by the Archie model, this means that the new models have proved themselves to be valid also, at least for Class 1 and Class 2 rocks. No validity test has been made on Class 3 rock since, understandably, no data were of primary importance for such low flow-quality rocks. Nevertheless, such test should also be performed in the future whenever the needed data has become available or been made available. With the establishment of the new models, an alternative way for determining water saturation data in carbonate reservoirs has been proposed.

Conclusions

From the study, some primary conclusions have been drawn:

- An alternative method for estimating water saturation in carbonate reservoirs has been validated proposed to be used.
Water saturation estimation for carbonate reservoirs can now be performed in cases where there is no reliable resistivity log data and absence of laboratory-derived resistivity data.

The new models are valid at least for use on Class 1 and Class 2 rocks. Validity test on Class 3 rocks has to be performed in the future.

Lucia models tend to produce too optimistic (i.e. too low) water saturation estimates for, at least, the reservoir rocks used in this study.

The new models are valid for Indonesian carbonate reservoirs, even though further application and tests using core samples from other carbonate reservoirs are suggested.

References


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

<table>
<thead>
<tr>
<th>Wetting Phase</th>
<th>Non wetting Phase</th>
<th>Condition</th>
<th>Contact Angle</th>
<th>IFT (dyn/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brine</td>
<td>Oil</td>
<td>Reservoir</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Brine</td>
<td>Oil</td>
<td>Laboratory</td>
<td>30</td>
<td>48</td>
</tr>
<tr>
<td>Brine</td>
<td>Gas</td>
<td>Laboratory</td>
<td>0</td>
<td>50</td>
</tr>
<tr>
<td>Brine</td>
<td>Gas</td>
<td>Reservoir</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>Oil</td>
<td>Gas</td>
<td>Reservoir</td>
<td>140</td>
<td>480</td>
</tr>
<tr>
<td>Gas</td>
<td>Mercury</td>
<td>Laboratory</td>
<td></td>
<td></td>
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</tbody>
</table>

**Table 2** Regional origins of the core samples

<table>
<thead>
<tr>
<th>Sedimentary Basin</th>
<th>Formation</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>North Sumatera</td>
<td></td>
<td>15%</td>
</tr>
<tr>
<td>South Sumatera</td>
<td>Baturaja</td>
<td>35%</td>
</tr>
<tr>
<td>West Java</td>
<td>Parigi, Cibulakan</td>
<td>35%</td>
</tr>
<tr>
<td>East Java</td>
<td></td>
<td>10%</td>
</tr>
<tr>
<td>Papua</td>
<td>Kais</td>
<td>5%</td>
</tr>
</tbody>
</table>
Table 3 Capillary pressure data for West Java limestone samples

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Depth (Meters)</th>
<th>Permeability (Mili-Darcies)</th>
<th>Porosity (Per Cent)</th>
<th>Brine Saturation, Per Cent Pore Space</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Well: SKD-02</td>
<td>23</td>
<td>7.54</td>
<td>19.98</td>
<td>83.971</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>5.39</td>
<td>16.77</td>
<td>88.724</td>
</tr>
<tr>
<td></td>
<td>22</td>
<td>2.67</td>
<td>12.92</td>
<td>89.901</td>
</tr>
<tr>
<td></td>
<td>17</td>
<td>2.58</td>
<td>7.63</td>
<td>90.118</td>
</tr>
</tbody>
</table>

Table 4 Summary of data to be used in model validity test

<table>
<thead>
<tr>
<th>Formation</th>
<th>Laboratory Measurement</th>
<th>Vsh</th>
<th>Porosity</th>
<th>Sw</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parigi</td>
<td></td>
<td></td>
<td>GR-log</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>N-D</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Archie</td>
<td></td>
</tr>
</tbody>
</table>

Table 5 Results of log analysis for WJ-X1 and WJ-X2 wells

<table>
<thead>
<tr>
<th>Well</th>
<th>Zone</th>
<th>Class</th>
<th>Porosity, %</th>
<th>Sw (Archie), %</th>
<th>Well Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>WJ-X1</td>
<td>Upper</td>
<td>2</td>
<td>13.89</td>
<td>48.16</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>Lower</td>
<td>1</td>
<td>22.06</td>
<td>33.15</td>
<td>Qg=7MMSCFD, Qw=89 BPWD</td>
</tr>
<tr>
<td>WJ-X2</td>
<td>Upper</td>
<td>2</td>
<td>14.15</td>
<td>46.72</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>Lower</td>
<td>1</td>
<td>22.67</td>
<td>31.3</td>
<td>Qg=3.5 MMSCFD</td>
</tr>
</tbody>
</table>

Table 6 Comparison between results of conventional log analysis (Archie), Lucia models, and the new models

<table>
<thead>
<tr>
<th>Well</th>
<th>Zone</th>
<th>Class</th>
<th>Por, %</th>
<th>Sw (Archie), %</th>
<th>Sw (new), %</th>
<th>Sw (Lucia), %</th>
<th>Well Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>WJ-X1</td>
<td>Upper</td>
<td>2</td>
<td>13.89</td>
<td>48.16</td>
<td>50.36</td>
<td>38.34</td>
<td>N/A</td>
</tr>
<tr>
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<td>35.67</td>
<td>10.53</td>
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<td>46.72</td>
<td>46.19</td>
<td>31.10</td>
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<tr>
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<td>31.3</td>
<td>31.56</td>
<td>8.84</td>
<td>Qg=3.5 MMSCFD</td>
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</table>
### Table: Depositional Textures Recognizable

<table>
<thead>
<tr>
<th>Depositional Textures Recognizable</th>
<th>Depositional Textures Not Recognizable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contains mud (Clay and fine silt-size carbonate)</td>
<td></td>
</tr>
<tr>
<td>Mud supported</td>
<td>Grain supported</td>
</tr>
<tr>
<td>Less than 10% grains</td>
<td>More than 10% grains</td>
</tr>
</tbody>
</table>

**Figure 1** Dunham classification.

---

**Figure 2** Lucia classification, inter-crystalline.

---

**Figure 3** Lucia classification, vuggy.
Figure 4 A thin section showing an example of wackestone among the rock samples under study

Figure 5 A thin section showing an example of packstone among the rock samples under study
Figure 6 A thin section showing an example of grainstone among the rock samples under study

Figure 7 Capillary pressure curves for wackestone samples
Figure 8 Capillary pressure curves for packstone samples

Figure 9 Capillary pressure curves for grainstone samples
Figure 10 Capillary pressure curves for boundstone samples

Figure 11 Porosity – permeability correlations for the three classes
Figure 12 A thin section showing vugs that are connected to form ‘touching vugs’ porosity and permeability system
STUDI LABORATORIUM UNTUK REAKTIVASI LAPANGAN-X DENGAN INJEKSI KIMIA

oleh
Hestuti Eni, Suwartiningsih, Sugihardjo
PPPTMGB “LEMIGAS”

Abstrak

Studi laboratorium untuk penentuan rancangan fluida injeksi kimia diperlukan sebelum implementasinya di lapangan minyak. Untuk mereaktivasi suatu lapangan minyak tua (lapangan-X) telah dilakukan serangkaian studi yang meliputi beberapa tahap pekerjaan, seperti screening surfaktan, screening polimer, pencampuran surfaktan-polimer dan core flooding.

Screening surfaktan dilakukan untuk memastikan kandidat surfaktan yang digunakan cocok (compatible) dengan air formasi. Dalam penelitian ini, screening dilakukan terhadap 4 jenis surfaktan, yaitu S-F1, S-F2, S-A1, S-A2. Pada masing-masing surfaktan dilakukan serangkaian uji. Rangkaian uji tersebut adalah uji kompatibilitas, pengukuran IFT (interfacial tension), uji kestabilan terhadap panas, uji filtrasi dan uji adsorpsi. Dari keempat jenis surfaktan, diambil 2 jenis surfaktan yang terbaik untuk dilakukan uji pencampuran dengan polimer.

Screening polimer dilakukan terhadap 3 jenis polimer, yaitu P-MA, P-MB dan P-MC. Polimer diperlukan untuk memperbaiki mobilitas rasio selama pendesakan. Dalam penelitian ini, screening dilakukan terhadap 3 jenis polimer, yaitu P-MA, P-MB dan P-MC. Selain screening polimer, pada ketiga jenis polimer juga dilakukan serangkaian uji laboratorium setelah dicampur dengan 2 jenis surfaktan yang terbaik untuk dilakukan uji pencampuran.

Dari hasil screening terhadap surfaktan dan polimer, campuran surfaktan S-A2 dan polimer P-MC menunjukkan performa terbaik. Oleh karena itu, core flooding dilakukan menggunakan campuran kedua-duanya. Recovery minyak hasil core flooding menunjukkan kenaikan yang cukup signifikan, hampir mencapai 25% OOIP.

Kata kunci : kompatibilitas, IFT, thermal stability, filtrasi, rheologi, injeksi (core flooding)

Pendahuluan


Ada beberapa teknologi pengurasan tahap lanjut (EOR) yang sudah dikembangkan para peneliti, disamping penemuan-penemuan baru yang terus berlanjut seperti injeksi mikroba dan fibroseismik yang masih terus dikembangkan. Beberapa teknologi pengurasan terhadap lapangan minyak tua yang sudah dikembangkan meliputi beberapa jenis, yaitu: injeksi gas, injeksi panas, injeksi kimia, dan beberapa kombinasi darinya seperti WAG (water alternating gas), foam dan sebagainya.

Injeksi kimia merupakan teknologi EOR yang sangat menjanjikan, terutama pada lapangan-lapangan dangkal yang tidak mungkin dilakukan injeksi gas CO2 atau N2 karena tekanan rekahnya yang rendah. Data-data lapangan membuktikan inefisiensi injeksi kimia sebagai cara efektif untuk me-recover minyak yang masih tersisa. Hasil evaluasi penelitian laboratorium secara mendetail juga mendukung kelayakan injeksi kimia. Apalagi, chemical yang
digunakan sekarang ini terbukti mampu bekerja lebih efektif pada konsentrasi 10 kali lipat lebih rendah dibanding chemical hasil penemuan terdahulu. Tentu saja ini menjadi hal yang penting karena berarti chemical cost menjadi lebih rendah.

Injeksi kimia dilakukan dengan menginjeksikan chemical seperti surfaktan, polimer dan alkali baik secara sendiri, gabungan atau berkelanjutan pada sumur-sumur tua yang diyakini masih mengandung minyak potensial. Material tersebut menyebabkan perubahan pada interaksi batuan dengan fluida dan meningkatkan recovery factor meningkat pada daerah kontak reservoir.

Sebelum implementasi injeksi kimia dilaksanakan di lapangan, perlu dilakukan beberapa tahap studi laboratorium. Pada penelitian ini, chemical yang digunakan adalah gabungan surfaktan dan polimer. Oleh karena itu, tahapan studi yang dilakukan adalah screening surfaktan, screening polimer, pencampuran surfaktan dan polimer, dan yang terakhir dilakukan untuk mengetahui seberapa besar kinerja chemical yang digunakan adalah core flooding.

Sampel fluida dan batuan berasal dari Lapangan-X dengan viskositas minyak 4,20 cP dan temperature reservoir 85 °C.

SCREENING SURFAKTAN

Surfaktan adalah senyawa organik yang dalam molekunya memiliki sedikitnya satu gugus hidrofilik dan satu gugus hidrofobik dimana apabila ditambahkan ke suatu cairan pada konsentrasi rendah, dapat merubah karakteristik tegangan permukaan dan antarmuka cairan tersebut.

Untuk meningkatkan recovery minyak secara optimum, sejumlah uji terhadap surfaktan dilakukan di laboratorium seperti uji kompatibilitas, uji pengukuran IFT, uji kestabilan terhadap panas, uji filtrasi dan uji adsorpsi sebelum implementasi injeksi surfaktan di lapangan. Screening dilakukan pada empat jenis surfaktan, yaitu : S-F1, S-F2, S-A1 dan S-A2.

**Uji Kompatibilitas**

Uji kompatibilitas merupakan uji screening paling awal untuk mengetahui apakah suatu jenis surfaktan compatible dengan air formasi dari reservoar terentu.

Keempat jenis surfaktan tersebut dilarutkan dalam air formasi dengan konsentrasi 0,1%, 0,2% dan 0,3%. Kemudian masing-masing larutan dimasukkan dalam tabung, dan dilakukan pengamatan tiap waktu tertentu. Hasil lengkap tertera pada Tabel 1.


**Uji Tegangan Antarmuka**

Tegangan antar muka antara minyak/air dengan mikroemulsi merupakan salah satu parameter utama dalam EOR. Pengukuran nilai tegangan antarmuka menggunakan alat Spinning Drop Tensiometer pada suhu sekitar 60°C. Indikasi dari kinerja surfaktan adalah menurunnya tegangan antarmuka minyak-air, semakin rendah semakin baik. Nilai IFT yang sekarang ini diyakini bagus agar surfaktan disebut layak untuk diinjeksikan adalah sekitar 10-3 Dyne/cm.

Hasil pengukuran tegangan antarmuka untuk ketiga jenis surfaktan tertera pada Tabel 2. Berdasarkan selurow hasil pengukuran tegangan antar muka menunjukkan surfaktan S-A2 dengan konsentrasi 0.3% mempunyai harga IFT yang paling kecil yaitu sebesar 3.46.10-3 Dyne/cm.

**Uji Thermal Stability**

Uji thermal stability dilakukan untuk mengetahui ketahanan surfaktan terhadap panas. Surfactant yang bagus, kinerjanya akan tetap stabil oleh pengaruh panas.

Uji ini dilakukan dengan cara memasukkan larutan pada botol borosilikat yang tertutup rapat kemudian diletakkan pada oven pada temperatur reservoir, yaitu 85°C. Tiap waktu tertentu dilakukan pengamatan dan pengukuran IFT. Diharapkan hasil pengukuran IFT stabil yang berarti surfaktan tidak rusak oleh panas. Hasil pengukuran ditunjukkan pada Tabel 3 dan hasil pengukuran IFT pada Tabel 4.


Pada pengukuran IFT sebagai rangkaian uji thermal stability untuk semua jenis surfaktan terlihat bahwa surfaktan S-F2 dan S-A2 lebih stabil dibanding yang lain. Namun demikian, seperti telah dijelaskan sebelumnya, bahwa nilai IFT yang
dianggap bagus adalah pada kisaran 10-3 Dyne/cm. Jadi, surfaktan S-F2 dianggap kurang bagus.

Uji Filtrasi

Uji filtrasi dilakukan dengan melewatkan 500 ml larutan surfaktan melalui membran saring ukuran 0,22 mikron dengan diberi tekanan. Setiap 50 ml larutan surfaktan yang melewati kertas saring, dicatat waktunya. Kemudian dibuat grafik volume (ml) versus waktu (detik).

Semua larutan surfaktan, kecuali S-F2 menunjukkan garis lurus (Gambar 2), yang berarti laju alir konstan yang mengindikasikan tidak adanya penyumbatan pada saat melewati membran saring. Hasil ini harus dipenuhi agar suatu jenis surfaktan dinyatakan layak untuk diinjeksi ke dalam batuan.

Uji Adsorpsi


Hasil uji adsorpsi baik statik maupun dinamik ditampilkan pada Tabel 5. Pada surfaktan S-F2 tidak dilakukan uji adsorpsi karena dari serangkaian uji sebelumnya, surfaktan ini menunjukkan performance yang kurang bagus. Surfaktan S-A2 menunjukkan adsorpsi terkecil dibanding lainnya.

Dari semua uji yang sudah dilakukan terhadap surfaktan, surfaktan S-F1 dan S-A2 dianggap lebih bagus dibanding lainnya dan pada keduanya akan dilakukan uji lebih lanjut dengan dicampur polimer.

SCREENING POLIMER

Selain surfaktan, polimer juga diperlukan untuk proses chemical flooding, yaitu sebagai fluida pendorong minyak untuk memperbaiki mobilitas rasio. Pada kajian ini, beberapa uji screening seperti rheologi polimer, uji thermal stability, uji filtrasi dan uji adsorpsi dilakukan terhadap 3 (tiga) jenis polimer, yaitu P-MA, P-MB dan P-MC.

Rheologi Polimer

Uji rheologi polimer bertujuan untuk menentukan konsentrasi polimer yang optimal untuk core flooding, yaitu konsentrasi dimana viskositas larutan polimer sedikit lebih tinggi di atas minyak, sehingga proses pendesakan minyak menjadi efektif.

Injeksi larutan polimer sebagai salah satu metode EOR dimaksudkan untuk menghindari fingering yang kadang terjadi pada injeksi air. Fingering terjadi karena viskositas air sebagai fluida pendesak lebih rendah dibanding fluida minyak yang didesak. Efektifitas penyapuan dapat ditingkatkan dengan penambahan polimer ke dalam air injeksi agar mobilitas air injeksi mengecil.

Pada ketiga jenis polimer dibuat larutan masing-masing dengan konsentrasi 800, 1000, 1500, dan 2500 ppm. Pengukuran viskositas dilakukan pada suhu reservoar, yaitu 85°C dan shear rate 7 s-1. Diasumsikan fluida dalam reservoar mengalir pada shear rate tersebut.

Hasil pengukuran viskositas ditampilkan pada Tabel 6. Pertimbangan dalam menentukan konsentrasi optimum polimer selain harus lebih tinggi dari viskositas minyak, juga harus diperhatikan cost dari polimer itu sendiri, yang tentunya semakin tinggi konsentrasi, semakin tinggi pula cost polimer.

Uji Thermal Stability

Salah satu faktor yang mempengaruhi efektivitas larutan polimer selama mengalir dalam media berpori adalah degradasi polimer, yaitu terputusnya rantai molekul polimer menjadi unit-unit yang lebih kecil. Ini merupakan fenomena kehilangan berat molekul polimer yang tentunya akan menyebabkan pengurangan viskositas.

Salah satu jenis degradasi polimer adalah degradasi thermal yang disebabkan oleh suhu yang tinggi. Oleh sebab itu, dalam kajian ini, perlu dilakukan uji thermal stability. Uji ini dilakukan untuk mengetahui kestabilan viskositas larutan polimer, jika dipanaskan sampai pada suhu tertentu, dalam hal ini suhu reservoar.

Untuk uji ini, diambil data harga viskositas polimer sebelum dan sesudah dipanaskan (Tabel 7). Terlihat bahwa polimer P-MA dan P-MC cukup stabil dengan penurunan viskositas sekitar 5%, yang berarti masih masuk dalam batas toleransi, yaitu 20%.

Uji Filtrasi

Penurunan harga permeabilitas batuan dapat terjadi selama uji core flooding dengan menggunakan larutan polimer. Untuk menganalisisi kejadian tersebut, dilakukan uji filtrasi. Uji dilakukan dengan menggunakan kertas saring (membran) berukuran 3 mikron, yaitu dengan cara mencatat waktu yang diperlukan untuk melewatakan sejumlah fluida melalui kertas saring tersebut.

Gambar 3 adalah plot volume terhadap waktu hasil uji filtrasi ketiga jenis polimer. Surfactan P-MB membentuk garis melengkung yang mengindikasikan adanya penyumbatan pada kertas saring sehingga laju alir menjadi tidak konstan.
Uji Adsorpsi
Sebagai mana surfaktan, pada polimer juga dilakukan uji adsorpsi untuk mengetahui seberapa jauh chemical loss pada saat berinteraksi dengan batuan. Tentunya diharapkan hasilnya adalah serendah mungkin. Pada Tabel 8 terlihat bahwa adsorpsi yang terjadi pada polimer P-MA dan P-MC cukup rendah untuk kedua jenis batuan.

PENCAMPURAN SURFAKTAN-POLIMER (SP)
Untuk mengoptimalkan recovery minyak, polimer ditambahkan pada surfaktan. 2 jenis surfaktan yang lolos screening adalah S-F1 dan S-A2. Pada kedua polimer dilakukan uji adsorpsi dengan 3 jenis polimer. Surfactant masing-masing dengan konsentrasi 0,3% dan polimer masing-masing 1000 ppm.

Uji Kompatibilitas
Hasil Uji kompatibilitas campuran surfaktan-polimer (SP) ditunjukkan pada Tabel 9. Pada pencampuran semua jenis polimer dengan surfaktan S-F1, terbentuk larutan milky (warna susu) dan terbentuk gumpalan di atas. Sedangkan pencampuran polimer dengan surfaktan S-A2 menunjukkan warna jernih dari hari pertama sampai pengamatan berakhir (Gambar 4).

Uji Tegangan Antarmuka
Pada dasarnya, pencampuran dengan polimer tidak mempengaruhi hasil pengukuran IFT. Hasil menunjukkan hampir semua sistem mempunyai nilai IFT 10-3 Dyne/cm, kecuali larutan surfaktan S-F1 dicampur dengan polimer P-MA (Tabel 10).

Uji Rheologi
Tabel 11 memperlihatkan viskositas larutan polimer setelah dicampur dengan surfaktan. Secara umum, viskositas polimer akan menurun setelah dicampur dengan surfaktan.

Uji Thermal Stability

Gambar 5 adalah contoh larutan dalam uji thermal stability.

Uji Filtrasi
Hasil uji filtrasi ditunjukkan pada Gambar 6. Hampir semua larutan membentuk garis lurus, kecuali sampuran surfaktan S-F1 dan P-MB yang cenderung melengkung.

CORE FLOODING
Dari semua uji screening, campuran surfaktan S-A2 dan polimer P-MC menunjukkan performance terbaik, karenanya, campuran ini dipilih untuk diinjeksi pada batuan dengan konsentrasi surfaktan 0,3% dan polimer 1000 ppm sebagai slug utama. Selain itu, untuk lebih mengoptimalkan penyapuan, setelah slug utama juga diinjeksi polimer P-MC 800 ppm. Pemilihan konsentrasi tersebut karena mempunyai viskositas relatif di atas slug utama sebagai fluida yang akan didorong.

Uji core flood dilakukan pada native core dengan volume main slug 0,3 PV dan volume polimer pendorong 0,2 PV. Recovery factor dari minyak yang dihasilkan adalah sekitar 23.5%. Hasil secara lengkap ditunjukkan pada Gambar 7.

KESIMPULAN
Berdasarkan kajian yang telah dilakukan maka dapat disimpulkan:
1. Dari 4 jenis surfaktan yang telah discreening, surfaktan S-A2 dengan konsentrasi 0,3% menunjukkan performance terbaik pada hampir semua uji screening.
2. Campuran surfaktan S-A2 0,3% dan Polimer P-MC 1000 ppm menghasilkan IFT dan viskositas yang optimal, karenanya terpilih sebagai slug utama untuk uji core flooding.
3. Untuk lebih mengoptimalkan penyapuan, setelah slug utama juga diinjeksi polimer P-MC 800 ppm yang mempunyai viskositas relatif di atas slug utama sebagai fluida yang akan didorong.
4. Recovery factor hasil core flooding dengan 0,3 PV slug utama dan 0,2 PV polimer pendorong menggunakan native core mencapai 25%.

DAFTAR PUSTAKA
1. www.migas.go.id
2. www.oil-chem.com
Tabel 1. Hasil Uji Kompatibilitas Surfactan

<table>
<thead>
<tr>
<th>Jenis Surfactan</th>
<th>Konsentrasi</th>
<th>Hasil Pengamatan Hari ke-</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>S-F1</td>
<td></td>
<td>warna susu</td>
</tr>
<tr>
<td></td>
<td>0.10%</td>
<td>keruh</td>
</tr>
<tr>
<td></td>
<td>0.20%</td>
<td>keruh</td>
</tr>
<tr>
<td></td>
<td>0.30%</td>
<td>keruh</td>
</tr>
<tr>
<td>S-F2</td>
<td></td>
<td>jernih</td>
</tr>
<tr>
<td></td>
<td>0.10%</td>
<td>keruh</td>
</tr>
<tr>
<td></td>
<td>0.20%</td>
<td>keruh</td>
</tr>
<tr>
<td></td>
<td>0.30%</td>
<td>keruh</td>
</tr>
<tr>
<td>S-A1</td>
<td></td>
<td>seperti kabut</td>
</tr>
<tr>
<td></td>
<td>0.10%</td>
<td>keruh</td>
</tr>
<tr>
<td></td>
<td>0.20%</td>
<td>keruh</td>
</tr>
<tr>
<td></td>
<td>0.30%</td>
<td>keruh</td>
</tr>
<tr>
<td>S-A2</td>
<td></td>
<td>jernih</td>
</tr>
<tr>
<td></td>
<td>0.10%</td>
<td>keruh</td>
</tr>
<tr>
<td></td>
<td>0.20%</td>
<td>keruh</td>
</tr>
<tr>
<td></td>
<td>0.30%</td>
<td>keruh</td>
</tr>
</tbody>
</table>

Tabel 2. Hasil Pengukuran Tegangan Antarmuka Surfactan

<table>
<thead>
<tr>
<th>Surfaktan</th>
<th>Konsentrasi</th>
<th>IFT Dyne/cm</th>
</tr>
</thead>
<tbody>
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<td>S-F1</td>
<td>0.10%</td>
<td>1.14E-02</td>
</tr>
<tr>
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<td>0.20%</td>
<td>9.91E-03</td>
</tr>
<tr>
<td></td>
<td>0.30%</td>
<td>8.75E-03</td>
</tr>
<tr>
<td>S-F2</td>
<td>0.10%</td>
<td>1.45E-01</td>
</tr>
<tr>
<td></td>
<td>0.20%</td>
<td>1.31E-01</td>
</tr>
<tr>
<td></td>
<td>0.30%</td>
<td>1.75E-01</td>
</tr>
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<td>S-A1</td>
<td>0.10%</td>
<td>3.45E-01</td>
</tr>
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<td>0.20%</td>
<td>7.31E-02</td>
</tr>
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<td>S-A2</td>
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<td>6.31E-03</td>
</tr>
<tr>
<td></td>
<td>0.30%</td>
<td>3.46E-03</td>
</tr>
</tbody>
</table>

Tabel 3. Hasil Uji Ketahanan terhadap Panas pada Surfactan

<table>
<thead>
<tr>
<th>Surfaktan</th>
<th>Konsentrasi</th>
<th>Hasil Pengamatan Hari ke-</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>S-F1</td>
<td></td>
<td>warna susu, agak coklat, keruh</td>
</tr>
<tr>
<td></td>
<td>0.10%</td>
<td>keruh</td>
</tr>
<tr>
<td></td>
<td>0.20%</td>
<td>keruh</td>
</tr>
<tr>
<td></td>
<td>0.30%</td>
<td>keruh</td>
</tr>
<tr>
<td>S-F2</td>
<td></td>
<td>jernih</td>
</tr>
<tr>
<td></td>
<td>0.10%</td>
<td>keruh</td>
</tr>
<tr>
<td></td>
<td>0.20%</td>
<td>keruh</td>
</tr>
<tr>
<td></td>
<td>0.30%</td>
<td>keruh</td>
</tr>
<tr>
<td>S-A1</td>
<td></td>
<td>seperti kabut</td>
</tr>
<tr>
<td></td>
<td>0.10%</td>
<td>keruh</td>
</tr>
<tr>
<td></td>
<td>0.20%</td>
<td>keruh</td>
</tr>
<tr>
<td></td>
<td>0.30%</td>
<td>keruh</td>
</tr>
<tr>
<td>S-A2</td>
<td></td>
<td>jernih</td>
</tr>
<tr>
<td></td>
<td>0.10%</td>
<td>keruh</td>
</tr>
<tr>
<td></td>
<td>0.20%</td>
<td>keruh</td>
</tr>
<tr>
<td></td>
<td>0.30%</td>
<td>keruh</td>
</tr>
</tbody>
</table>
Tabel 4. Hasil Pengukuran IFT pada Uji Ketahanan terhadap Panas

<table>
<thead>
<tr>
<th>Surfactan</th>
<th>Konsentrasi</th>
<th>Hasil Pengamatan IFT (Dyne/cm) Hari ke-</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1</td>
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<tr>
<td>S-F1</td>
<td>0,10%</td>
<td>4.53E-02</td>
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<td></td>
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</tr>
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<td></td>
<td>0,30%</td>
<td>6.39E-03</td>
</tr>
<tr>
<td>S-F2</td>
<td>0,10%</td>
<td>2.05E-01</td>
</tr>
<tr>
<td></td>
<td>0,20%</td>
<td>2.14E-01</td>
</tr>
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<td></td>
<td>0,30%</td>
<td>3.89E-01</td>
</tr>
<tr>
<td>S-A1</td>
<td>0,10%</td>
<td>1.46E-02</td>
</tr>
<tr>
<td></td>
<td>0,20%</td>
<td>2.71E-02</td>
</tr>
<tr>
<td></td>
<td>0,30%</td>
<td>1.13E-02</td>
</tr>
<tr>
<td>S-A2</td>
<td>0,10%</td>
<td>5.98E-03</td>
</tr>
<tr>
<td></td>
<td>0,20%</td>
<td>8.31E-03</td>
</tr>
<tr>
<td></td>
<td>0,30%</td>
<td>2.71E-03</td>
</tr>
</tbody>
</table>

Tabel 5. Hasil uji Adsorpsi surfaktan

<table>
<thead>
<tr>
<th>Surfactan</th>
<th>Adsorpsi (μg/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Statik</td>
</tr>
<tr>
<td>S-F1</td>
<td>1487.07</td>
</tr>
<tr>
<td>S-A1</td>
<td>4208.18</td>
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<tr>
<td>S-A2</td>
<td>1200.03</td>
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Tabel 6. Viskositas polimer pada suhu reservoir dan shear rate 7 s⁻¹

<table>
<thead>
<tr>
<th>Polimer</th>
<th>Konsentrasi</th>
<th>Viskositas @ Tres, 7 s⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ppm</td>
<td>cP</td>
</tr>
<tr>
<td>P-MA</td>
<td>800</td>
<td>2.89</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>4.25</td>
</tr>
<tr>
<td></td>
<td>1500</td>
<td>7.63</td>
</tr>
<tr>
<td></td>
<td>2500</td>
<td>21.39</td>
</tr>
<tr>
<td>P-MB</td>
<td>800</td>
<td>8.3</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>5.72</td>
</tr>
<tr>
<td></td>
<td>1500</td>
<td>9.27</td>
</tr>
<tr>
<td></td>
<td>2500</td>
<td>45.80</td>
</tr>
<tr>
<td>P-MC</td>
<td>800</td>
<td>5.79</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>6.88</td>
</tr>
<tr>
<td></td>
<td>1500</td>
<td>9.61</td>
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<tr>
<td></td>
<td>2500</td>
<td>29.92</td>
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</table>

Tabel 7. Uji Thermal Stability polimer

<table>
<thead>
<tr>
<th>Polimer</th>
<th>Konsentrasi</th>
<th>Viscositas @ Tres, 7 s⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ppm</td>
<td>hari ke-0</td>
</tr>
<tr>
<td>P-MA</td>
<td>1000</td>
<td>4.25</td>
</tr>
<tr>
<td>P-MB</td>
<td>1000</td>
<td>5.72</td>
</tr>
<tr>
<td>P-MC</td>
<td>1000</td>
<td>6.88</td>
</tr>
</tbody>
</table>
### Tabel 8. Hasil Uji Adsorpsi Polimer

<table>
<thead>
<tr>
<th>Polimer</th>
<th>Konsentrasi (ppm)</th>
<th>Adsorpsi (µgr/gr) Batuan I</th>
<th>Adsorpsi (µgr/gr) Batuan II</th>
</tr>
</thead>
<tbody>
<tr>
<td>P-MA</td>
<td>1000</td>
<td>585,752</td>
<td>391,862</td>
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<tr>
<td></td>
<td>1500</td>
<td>558,668</td>
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<tr>
<td></td>
<td>2500</td>
<td>604,724</td>
<td>370,058</td>
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<tr>
<td>P-MB</td>
<td>1000</td>
<td>801,794</td>
<td>505,94</td>
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<tr>
<td></td>
<td>1500</td>
<td>861,914</td>
<td>497,324</td>
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<td></td>
<td>2500</td>
<td>1001,222</td>
<td>536,606</td>
</tr>
<tr>
<td>P-MC</td>
<td>1000</td>
<td>104,222</td>
<td>468,596</td>
</tr>
<tr>
<td></td>
<td>1500</td>
<td>79,298</td>
<td>413,204</td>
</tr>
<tr>
<td></td>
<td>2500</td>
<td>100,346</td>
<td>426,122</td>
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### Tabel 9. Hasil Uji Kompatibilitas Surfaktan – Polimer (SP)

<table>
<thead>
<tr>
<th>Surfaktan</th>
<th>Polimer</th>
<th>Hasil Pengamatan Hari ke-</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
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<tr>
<td></td>
<td></td>
<td></td>
<td>0</td>
<td>1</td>
<td>7</td>
<td>14</td>
</tr>
<tr>
<td>S-F1</td>
<td>P-MA</td>
<td>warna susu (milky)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>P-MB</td>
<td>milky, gumpalan di atas</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>P-MC</td>
<td>light milky, lebih banyak gumpalan di atas</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S-A2</td>
<td>P-MA</td>
<td>jernih</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>P-MB</td>
<td>jernih</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>P-MC</td>
<td>jernih</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Tabel 10. Hasil Pengukuran Tegangan Antarmuka Surfaktan – Polimer (SP)

<table>
<thead>
<tr>
<th>Surfaktan</th>
<th>Polimer</th>
<th>IFT (Dyne/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-F1</td>
<td>P-MA</td>
<td>5.72E-02</td>
</tr>
<tr>
<td></td>
<td>P-MB</td>
<td>7.21E-03</td>
</tr>
<tr>
<td></td>
<td>P-MC</td>
<td>4.58E-03</td>
</tr>
<tr>
<td>S-A2</td>
<td>P-MA</td>
<td>7.13E-03</td>
</tr>
<tr>
<td></td>
<td>P-MB</td>
<td>8.20E-03</td>
</tr>
<tr>
<td></td>
<td>P-MC</td>
<td>4.29E-03</td>
</tr>
</tbody>
</table>

### Tabel 11. Hasil Pengukuran Viskositas Surfaktan – Polimer (SP)

<table>
<thead>
<tr>
<th>Surfaktan</th>
<th>Polimer</th>
<th>Viscosity @ Tres, 7 s⁻¹ (cP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-F1</td>
<td>P-MA</td>
<td>3.97</td>
</tr>
<tr>
<td></td>
<td>P-MB</td>
<td>4.44</td>
</tr>
<tr>
<td></td>
<td>P-MC</td>
<td>5.31</td>
</tr>
<tr>
<td>S-A2</td>
<td>P-MA</td>
<td>4.02</td>
</tr>
<tr>
<td></td>
<td>P-MB</td>
<td>5.25</td>
</tr>
<tr>
<td></td>
<td>P-MC</td>
<td>5.45</td>
</tr>
</tbody>
</table>
Tabel 12. Hasil Pengamatan Uji Thermal Stability Surfaktan – Polimer (SP)

| Surfaktan | Polimer | Hasil Pengamatan Hari ke-
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>S-F1</td>
<td>P-MA</td>
<td>warna susu (milky)</td>
</tr>
<tr>
<td></td>
<td>P-MB</td>
<td>light milky, gumpalan di atas</td>
</tr>
<tr>
<td></td>
<td>P-MC</td>
<td>milky, sedikit gumpalan</td>
</tr>
<tr>
<td>S-A2</td>
<td>P-MA</td>
<td>jernih</td>
</tr>
<tr>
<td></td>
<td>P-MB</td>
<td>jernih</td>
</tr>
<tr>
<td></td>
<td>P-MC</td>
<td>jernih</td>
</tr>
</tbody>
</table>

Tabel 13. Hasil Pengukuran IFT pada Uji Thermal Stability Surfaktan – Polimer (SP)

| Surfaktan | Polimer | Pangukuran IFT (Dyn/cm) hari ke-
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>S-F1</td>
<td>P-MA</td>
<td>5.72E-02</td>
</tr>
<tr>
<td></td>
<td>P-MB</td>
<td>7.21E-03</td>
</tr>
<tr>
<td></td>
<td>P-MC</td>
<td>4.58E-03</td>
</tr>
<tr>
<td>S-A2</td>
<td>P-MA</td>
<td>7.13E-03</td>
</tr>
<tr>
<td></td>
<td>P-MB</td>
<td>8.03E-03</td>
</tr>
<tr>
<td></td>
<td>P-MC</td>
<td>4.29E-03</td>
</tr>
</tbody>
</table>

Tabel 14. Hasil Pengukuran Viskositas pada Uji Thermal Stability Surfaktan – Polimer (SP)

<table>
<thead>
<tr>
<th>Surfaktan</th>
<th>Polimer</th>
<th>Viscositas (cP) @ Tres, 7 s⁻¹</th>
<th>Penurunan Viskositas</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>hari ke-0</td>
<td>hari ke-60</td>
<td>%</td>
</tr>
<tr>
<td>S-F1</td>
<td>P-MA</td>
<td>3.97</td>
<td>3.78</td>
</tr>
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<td>P-MB</td>
<td>4.44</td>
<td>3.16</td>
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<td></td>
<td>P-MC</td>
<td>5.31</td>
<td>4.88</td>
</tr>
<tr>
<td>S-A2</td>
<td>P-MA</td>
<td>4.02</td>
<td>3.74</td>
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<td></td>
<td>P-MB</td>
<td>5.25</td>
<td>3.49</td>
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<tr>
<td></td>
<td>P-MC</td>
<td>5.45</td>
<td>5.26</td>
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</table>

Gambar 1. Hasil Uji Kompatibilitas Surfaktan S-F1 dan S-F2 Hari Ke-1
Gambar 2. Uji Filtrasi surfaktan

Gambar 3. Uji Filtrasi Polimer

Gambar 4. Uji Kompatibilitas Surfaktan-Polimer
Gambar 5. Pengamatan uji thermal stability campuran Surfactan – Polimer (SP)

Gambar 6. Uji Filtrasi campuran Surfactan – Polimer (SP)

Gambar 7. Hasil Core Flood pada Native Core
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IATMI 2009
ITB, BANDUNG 2 - 5 DESEMBER 2009

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Ikatan Ahli Teknik Perminyakan Indonesia

Departemen Energi dan Sumber Daya Mineral
Direktorat Jenderal Minyak dan Gas Bumi

BPMGAS

Institut Teknologi Bandung
ACIDIZING IN ESP WELLS: AN EFFICIENT PRODUCTION OPTIMIZATION

oleh
Noke Fajar Prakoso, Dendy Wicaksana
Medco E&P Indonesia

Abstrak

Many electric submersible pumps (ESPs) are being installed in Kaji Semoga Field, South Sumatra, Indonesia (operator: Medco E&P Indonesia) to change the artificial lift method from gas lift. This is being implemented in accordance with the water-flood project and is also due to decreasing produced gas. Until now, 15 ESPs have been installed and are running. After ESP installation, three wells suffered influx impairment, so oil production did not meet the target. Therefore stimulations were needed to restore the influx. In this case, the stimulations were in the form of acidizing to Baturaja carbonate formation.

Acidizing without pulling ESP out of hole has been done in three ESP wells in Kaji Semoga Field. 15% HCl was pumped thru annulus to solve the formation damage problem, which was suspected to have been caused by workover fluid quality and also loss circulation material (LCM). The results were good: influx improved, the oil gain was more than 400 BOPD, and also costs of up to USD 35,000 per job were saved, since these jobs did not need the use of a rig. As per November 2008 (3 months), the three ESPs are still running in good condition. This shows that the acidizing job without pulling the ESPs out of hole does not have any negative effect on the pumps since the techniques are implemented.

This paper presents well performance analysis, acid risk analysis, acid recipe, acidizing technique, and cost justification. These three success stories can be implemented as best practice in other similar cases.

Introduction

Kaji-Semoga Field is in Rimau Block, South Sumatera, Indonesia. Oil was found and production commenced in 1997.

There are around 350 wells, which consist of oil producers and water injection wells. Most wells are gas lifted and deviated in a cluster system. Each cluster consists of 3 to 15 wells, either producers or injectors.

This field produces oil from 3 formations: Telisa Sandstone (TLS), Baturaja Carbonate (BRF), and Talang Akar Sandstone (TAF). Most oil is produced from BRF, since it has the largest hydrocarbon reserve among all. Its porosity ranges from 13 to 20% and matrix permeability ranges from 20-150 md. Its productivity index (PI) is between 0.5 to 8 bfpd/psi. The depth is between 3000 to 4000 ft. The oil is relatively light, 38 degrees of API. Average field properties are: 82% water cut and GOR 700 scf/stb. Currently the BRF pressure is about 800 psig.

The water-flood project has been carried into this formation in order to maintain the pressure and to sweep the oil. It has been observed that the associated gas is declining while the water cut is increasing. Medco E&P Indonesia has therefore conducted studies on artificial lifts to replace existing gas lift, since make-up gas for gas lift compressors has declined and gas lift cannot create maximum drawdown for the current conditions. The studies recommend changing from gas lift to electric submersible pump (ESP). More than 50% of gas lifted wells will be changed to ESP wells. At the moment 15 ESPs are running.

ESP Installation, Influx Impairment and Rejuvenation

In 2006, Medco started to convert 15 gas lifted wells to ESP, with different optimum pump ranges. Unfortunately, three of them, KS-38, KS-57 and KS-63, suffered influx impairment.

KS-38

ESP was installed in KS-38 on March 12, 2008. Everything was as normal during installation,
but after the well was put on production the rate did not meet the target. On the contrary, the rate was lower than when gas lift was used (see Figure 1). From pump intake pressure (PIP) and rate data converted to inflow performance relationship (IPR, see Figure 2), it was suspected that there was influx impairment. It may have been caused by unfiltered killing fluid in ESP installation job and incompatible killing fluid to formation fluid. Therefore acid wash was conducted in this well. The result was very satisfying, since after acidizing the oil production increased 472 BOPD (see Figure 1).

KS-57

ESP was installed in KS-57 on May 14, 2008. This well produces oil from 2 perforation intervals in BRF (flow unit 1 and 2). During installation loss circulation occurred, so the LCM was pumped into the formation to stop loss circulation. But after it was produced, the same thing happened. Production dropped (see Figure 3). It was suspected that this formation damage happened because LCM did not work properly in the formation, since killing fluid loss circulation happened at one well. After mechanical well service was completed and the well was produced, the rate did not meet the design rate or pump range performance because of influx impairment. It was suspected the sealing of LCM which invaded the formation did not break perfectly and Influx impairment happened as shown in its IPR (see Figure 4). Then it was acidized. After acid wash the rate was better than before, but still lower than when it was gas lifted. The damage may still exist in the formation.

KS-63

ESP was installed in KS-63 on May 10, 2008. Everything was as normal during installation, but after the well was put on production, the rate was lower than when it was gas lifted (see Figure 5). From its IPR as shown in Figure 6, it is known that there was influx impairment, and therefore acid wash was conducted. After acid wash the rate was better than before, but still lower than when gas lift was used. The damage may still exist in the formation.

Economics

There were two options for performing the acidizing job: to follow the common procedure at a high cost, or to try the lower cost alternative. The common procedure at a high cost is that prior to the acidizing job the ESP must be pulled out of the hole, while the lower cost alternative means acidizing without pulling ESP out of hole at all. After several discussions and careful consideration, Medco decided to do rig-less acidizing in order to study and to find the most efficient way to do acidizing in ESP wells. Cost savings per job reached USD 35,000. A cost comparison between both options is presented in Table 1.

Acid Recipe

The rig-less acid washing in the ESP wells used 15% HCl, which is similar to common acid washing in this formation. Table 2 shows volume calculation of acid & formation water to be injected thru annulus.

Risk Analysis and Acidizing Techniques

Formation damage in carbonate could be solved by acid stimulation. The main problem of acid in ESP well was damaging pump stages (impeller & diffuser), but this problem was mitigated by minimizing acid exposure time to ESP down hole equipment. Some negative effects which may have occurred as the impact of contacting with acid were:

1. Electrical short at down-hole cable.
2. Damage on bag type protector.
3. Damage on other parts, such as seals, bearings, impellers & diffusers.

To minimize the risks, a sequence of jobs should be performed in order to achieve the objective (see Figure 7):

1. Prepare acid pumping equipment.
   a. Acid pump combo
   b. Water tank
   c. Square tank for return fluid
2. Ensure that the ESP is running.
3. Hold a pre-job safety/operations meeting and review job procedures and safety issues.
4. Rig up acid pump and connect to annulus.
5. Pressure test to maximum wellhead working pressure (2000 psig) and hold for 10 minutes.
6. Bleed off pressure to 0 psig and open the flow line.
7. Ensure the ESP is running
8. Open casing valve, kill well thru annulus with 78 bbls (filled up volume of 5½” casing, 3280 ft deep of well) 8.4 ppg of salt water. Pump in killing fluid until it is circulated to the surface to ensure wellbore is fulfilled with killing fluid.
9. Shut off ESP, close tubing valve at surface to trap killing fluid in the annulus and tubing, then perform injectivity test thru annulus.
10. Prepare 125 gallons (3 bbls) of 15% acid, open casing valve, spot 3 bbls 15% acid thru annulus, followed by 49 bbls 8.4 ppg of formation water (pump pressure = 500 psig and 2 bpm rate of injection)
11. Stop pumping killing fluid thru annulus while 15% acid placement in formation (soak 15% acid for 30 minutes)
12. Open tubing valve and start up ESP to flush out acid mixture from the annulus until all acid comes out to the surface and cleans up well.
13. Measure the pH of return fluid from tubing. Once the acid is returned, switch return line to square tank
14. Keep monitoring the return pH. Once all the acid has already returned, indicated by normal return pH, switch return back to production line.
15. Close annulus valve.
16. Neutralize the spent acid with caustic soda.
17. Rig down acidizing equipment
18. End job.

The question is: how reliable are the pump stages after exposure to acid, and what is the pump’s acid tolerance level? The standard pump stage material supplied is ni-resist alloy. The vendor specified there should be a limit of 4 hours maximum exposure with 15% acid threshold. Based on this allowance, it was decided to soak acid thru the annulus to the formation without needing a rig. This is because the pump does not need a lengthy exposure to acid, and our technique achieve less than 15 minutes of pump exposure, and acid placement for 30 minutes into formation. Then, the acid is pumped out thru tubing to the surface and the well is cleaned up.

Conclusion and Recommendation
After reviewing the results of this job, the authors have reached the following conclusions:
1. Rig-less acidizing in KS-38 ESP well was successful. This technique can be implemented in other wells.
2. Rig-less acidizing in KS-57 and KS-63 wells can be considered successful because of influx improvements as shown on their IPR, although they have not been fully recovered. The authors recommend that rig-less acidizing should be repeated with a larger acid volume, especially in KS-57.

Acknowledgement
The authors would like to thank Mr. Anwas Tanuwijaya in addition to the Petroleum Engineering Division and Rimau Asset of Medco E&P Indonesia.

References

Figure 1 Production Performance KS-38
Figure 2 IPR Curve KS-38 (B)

Figure 3 Production Performance KS-57
Figure 4 IPR Curve KS-57

Figure 5 Production Performance KS-63
Table 1 Cost Comparison

<table>
<thead>
<tr>
<th>Job</th>
<th>Cost for Rigless Acidizing (USD)</th>
<th>Cost for Acidizing with POOH ESP</th>
<th>Cost saving (USD)</th>
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<tbody>
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<td>Acidizing</td>
<td>5,200</td>
<td>+/- 30,000</td>
<td>+/- 40,000</td>
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Table 2 Acid Recipe and Acid Volume Calculation

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<th>15% Acid Recipe</th>
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<tr>
<td>a. 32% Raw HCl</td>
<td>= 442</td>
<td>gal/Mgal</td>
<td></td>
</tr>
<tr>
<td>b. AS-7</td>
<td>= 5</td>
<td>gal/Mgal</td>
<td></td>
</tr>
<tr>
<td>c. HAI-404</td>
<td>= 5</td>
<td>gal/Mgal</td>
<td></td>
</tr>
<tr>
<td>d. Losurf-259</td>
<td>= 5</td>
<td>gal/Mgal</td>
<td></td>
</tr>
<tr>
<td>e. Musol E</td>
<td>= 50</td>
<td>gal/Mgal</td>
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</table>

Volume Calculation

<table>
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</tr>
</thead>
<tbody>
<tr>
<td>a. ID 5 1/2&quot; Casing Size</td>
<td>= 4.95</td>
<td>inch</td>
<td></td>
</tr>
<tr>
<td>b. OD 2 7/8&quot; tubing</td>
<td>= 2.875</td>
<td>inch</td>
<td></td>
</tr>
<tr>
<td>c. Perforation</td>
<td>= 3198</td>
<td>-</td>
<td>3242</td>
</tr>
<tr>
<td>d. Bridge Plug Depth</td>
<td>= 3280</td>
<td>ft</td>
<td></td>
</tr>
<tr>
<td>e. Downhole Equipment Depth</td>
<td>= 3099</td>
<td>ft</td>
<td></td>
</tr>
<tr>
<td>f. Total volume of killing fluid</td>
<td>= 78</td>
<td>bbls</td>
<td></td>
</tr>
<tr>
<td>g. Total volume of 15% Acid</td>
<td>= 2</td>
<td>bbls</td>
<td></td>
</tr>
<tr>
<td>h. (1 bbl additional volume)</td>
<td>= 3</td>
<td>bbls</td>
<td></td>
</tr>
<tr>
<td>i. Total volume of flush killing fluid (to flush cut acid &amp; clean well)</td>
<td>= 49</td>
<td>bbls</td>
<td></td>
</tr>
</tbody>
</table>
Figure 7 Job Sequences of Rigless Acidizing in ESP Wells

Legend:
- Acid
- Salt Water
- Formation Fluid
- Gas
IATMI WORKSHOP
Cadangan Minyak & Gas Bumi Nasional
Yogyakarta, 15-17 Oktober 2009

- definisi, metode, estimasi & standart cadangan migas nasional
- strategi pengembangan lapangan migas

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“Someday, you will have to choose between what is right and what is easy” yang artinya: suatu hari nanti kau harus memilih di antara apa yang benar dan apa yang mudah...

Selain kutipan kata-kata Yasadipura (kakek Ranggawarsita) dalam buku pujangga Jawa klasik tsb. (1873):

“Waniya ing gampang, wediya ing pakewuh, sabarang nora tumeka.”, yang artinya: sukaiah kemudahan, takutlah kesulitan, insya’Allah tidak ada yang diperoleh.

Persoalan energi dan bangsa tidak bisa hanya diselesaikan oleh Pemerintah sendiri, apalagi pemerintah terpilih saat ini yang dipersepsikan sangat-sangat hati-hati dalam memutuskan segala sesuatu. Negara yang baik membantu yang adilnya Pemimpin, amalnya Pengusaha, ilmunya Akademisi (Ulama) serta kesabaran, kemandirian dan keperdulian Masyarakat.
Migas dan energi penting untuk pembangunan di Indonesia, sehingga permasalahannya perlu dipahami oleh para pemangku kepentingan (stakeholders)-nya yaitu Pemerintah, Pengusaha, Akademi dan Anggota masyarakat lain. Buku Widjajono tampaknya berusaha untuk menjelaskan agar para pemangku kepentingan lebih memahami permasalahan dan analisis kebijakan migas dan energi di Indonesia sehingga diharapkan bisa dipilih kebijakan energi yang lebih tepat dan penanganan permasalahan energi dengan lebih baik. Untuk lebih memahami permasalahan, ditambahkan teori-teori penduduk baik dari teknokonomi maupun analisis kebijakan.

Dalam pandangan Widjajono (2009), ada beberapa anggapan yang keliru mengenai migas dan energi, diantaranya:

1. Indonesia adalah Negara yang kaya minyak, padahal tidak. Kita lebih banyak memiliki energi lain seperti batubara, gas, CBM (Coal Bed Methane), panas bumi, air, BBN (Bahan Bakar Nabati) dan sebagainya,
2. harga BBM (Bahan Bakar Minyak) harus murah sekali tanpa berpikir bahwa hal ini menyebabkan terkurasnya dana Pemerintah untuk subsidi harga BBM, ketergantungan kita kepada BBM yang makin lama makin besar serta makin sulitnya energi lain berkembang,
3. investor akan datang dengan sendirinya tanpa perlu kita bersikap terlalu 'ramah' dan usahakan memberikan iklim investasi yang lebih baik,
4. peningkatan kemampuan Nasional akan terjadi dengan sendirinya tanpa keberpihakan Pemerintah.

Menurut Prof. Widjajono yang juga anggota Dewan Energi Nasional ini, kita tidak perlu memberlakukan harga pasar apabila harga BBM tinggi. Yang perlu diberlakukan adalah sebaiknya kita tidak menerapkan harga BBM yang lebih rendah dari biaya (ditambah keuntungan) pengembangan energi lain. Misal BBN (Bahan Bakar Nabati, untuk minyak jarak dan ketela sebesar Rp 5500/liter) atau tidak menerapkan harga listrik lebih rendah dari harga rata-rata listrik panasbumi (sebesar 8 sen dollar AS /kwh) dengan demikian BBN dan panasbumi akan berkembang.

Kita tidak perlu mengikuti harga BBM di pasar bebas atau mengenakan pajak untuk BBM sehingga harapannya bisa diatas dua kali lipat harga pasar seperti berlaku dikebanyakan negara-negara lain. Walaupun demikian, kita tidak bisa mengikuti harga BBM murah di negara-negara yang produksi minyaknya berlimpah. Perlu disadari bahwa walaupun kita menghasilkan minyak 953 ribu barel per hari dan mengakses 370 ribu barel per hari, kita juga mengimpor minyak mentah sebesar 318 ribu barel/hari dan BBM sebesar 411 ribu barel/hari (Ditjen Migas, 2007). Cadangan terbukti minyak kita hanya 4,4 milyar barel atau 0,4 % dunia. Sebagai net importer minyak yang tidak memiliki cadangan terbukti minyak yang banyak, kita tidak bijaksana apabila mengikuti harga BBM murah di Negara-negara yang produksi minyaknya melimpah.

Apabila kita harus menerapkan harga politik (subsidi), maka seharusnya kita tidak hanya mensubsidi harga BBM baik untuk non listrik dan listrik tetapi juga harus mensubsidi harga energi alternatif. Dengan demikian energi alternatif akan berkembang sehingga kita bisa mengurangi impor minyak dan BBM. Apalagi kebutuhan energi kita makin lama makin besar dengan peningkatan kesejahteraan.

Untuk mereka yang kurang mampu perlu diberikan subsidi untuk pemakaian LPG (Liquefied Petroleum Gas) dan gas kota untuk memasak, transportasi umum (di kota-kota besar sebaiknya menggunakan BBG) dan listrik 450 watt untuk pemakaian tertentu (kalau boros maka ‘pemborosannya’ – berdasarkan ukuran intensitas konsumsi energi - tidak perlu disubsidi). Pengurangan subsidi harga akan meningkatkan dana untuk subsidi langsung (kesejahteraan rakyat) dan depletion premium.

Menurut Widjajono, mengundang investor adalah iberat mengundang pelanggan untuk mengunjungi rumah makan. Rumah makan hanya akan laku apabila pelanggannya tahu, makanannya enak, hargaanya bersaing, pelayanannya dan lingkungannya baik. Perlu informasi yang baik, sistem fiskal dan regulasi yang menarik, birokrasi dan birokrasi yang mendukung, koordinasi antar sektor dan antar pusat-daerah untuk menarik investor baik asing maupun domestik di sektor energi.

Peningkatan Kemampuan Nasional akan terjadi apabila pemerintah mampu keberpihakan kepentingan misalnya untuk kontrak-kontrak yang sudah habis maka pengelolaannya diutamakan untuk pekerjaan nasional diperhatikan dengan kehati-hatian.

Untuk memperbaiki iklim investasi dan meningkatkan kemampuan nasional di bidang energi perlu diperhatikan bahwa untuk penentuan energi yang untuk migas diperkirakan sekitar 10 persen dari equity to be split (revenue dikurangi recovery cost). Dana tersebut digunakan untuk meningkatkan kualitas informasi bagi penawaran konsesi-konsesi baru, untuk meningkatkan kemampuan sumber daya manusia dan penelitian, untuk mempersiapkan infrastruktur pendukung migas serta untuk pengembangan energi terbarukan dan energi perdesaan. Peningkatan...
Menjadi Anggota OPEC?; Belajar dari Pak Ibnu, Musibah Lusi (Lumpur Sidoarjo), Masukan dari Pemangku Kepentingan dan Pakar serta Belajar dari Petronas/Malaysia, Bekas Murid Pertamina. Dalam membahas Kebijakan Migas serta pembahasan tentang Peningkatan Produksi, Investasi dan Kemampuan Nasional Hulu Migas serta Kontrak Kerja Sama, Institusi dan Iklim Investasi Migas di Indonesia dan Pertamina dan Elnusa Baru, Widjajono cukup terinci juga sampai penyajian perhitungan dan rumus-rumus teknokonomi tak terlewatkan pula.

Tentang Energi Terbarukan dan Pembangunan Berkelanjutan


Karena terus-menerus BBM mendapatkan subsidi, energi alternatif menjadi sulit bersaing. Hal itu terbukti pada energi panas bumi, yang selama 20 tahun terakhir tidak mampu berkembang dan menyaiingi BBM, karena secara keekonomian selalu kalah oleh BBM yang disubsidi.

Disamping rendahnya harga BBM (insentif untuk pemakaian BBM), tidak adanya insentif untuk pengembangan energi alternatif menyebabkan krisis energi dewasa ini. Sebagai contoh, PLN dulu selalu berdalih “least cost” kalau mau membeli gas atau panasbumi, sehingga mereka selalu membandingkannya (net back) dengan batubara. Akibatnya, pengembangan gas (lapangan kecil dan menengah) dan panasbumi macet karena hanya mau dibeli dibawah 5 sen per KWh, sedangkan biayanya diatas 7 sen per KWh. Padahal, akibat tidak cukupnya pasokan listrik PLN maka untuk menutupinya PLN menggunakan BBM yang sekaranburg biayanya 15-30 sen per KWh (tergantung harga minyak). Hal ini yang menyebabkan kenapa...
subsidi BBM untuk listrik pada APBN_P 2008 sebesar 60,3 trilyun rupiah.

Contoh lain adalah bagaimana jarak (biodiesel) dan ketela (bioethanol) bisa berkembang apabila harga BBM masih Rp 4.500 / liter. Untuk memproduksikan satu liter BBN dibutuhkan paling tidak 5 kg jarak atau ketela yang jika petani meminta harga Rp800,-/kg sehingga bahan mentahnya saja sudah Rp 4.000 per liter BBM, belum proses dan transportasinya. Usaha biodiesel dan bioethanol baru menguntungkan apabila dijual Rp 5.500 per liter. Insentif untuk pengembangan energi alternatif lebih bermanfaat daripada subsidi harga BBM yang terlalu mahal dan menyebabkan pemakaian BBM yang boros.

Perlu dicatat bahwa cadangan terbukti minyak Indonesia (4,4 milyar barel pada akhir 2007) hanya 0,4% cadangan terbukti minyak dunia, cadangan gas 1,7% cadangan terbukti gas dunia, cadangan terbukti batubara 0,5% cadangan terbukti batubara dunia dan potensi panasbumi Indonesia diperkirakan 40% potensi panasbumi dunia.\(^1\) Potensi energi nasional 2006 diperlihatkan pada Tabel 1.

### Tabel 1 Potensi Energi Nasional 2006

<table>
<thead>
<tr>
<th>ENERGI FOSIL</th>
<th>SUMBER DAYA</th>
<th>CADANGAN (Proven-Possible)</th>
<th>PRODUKSI (per Tahun)</th>
<th>RASIO CAD/PROD (tanpa eksporlasi) Tahun</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minyak Bumi</td>
<td>86,9 miliar barel</td>
<td>9,1 miliar barel</td>
<td>365 juta barel</td>
<td>25</td>
</tr>
<tr>
<td>Gas Bumi</td>
<td>384,7 TSCF</td>
<td>187 TSCF</td>
<td>2,77 TSCF</td>
<td>68</td>
</tr>
<tr>
<td>Batubara</td>
<td>90,5 miliar ton</td>
<td>18,7 miliar ton</td>
<td>170 juta ton</td>
<td>110</td>
</tr>
<tr>
<td>Coal Bed Methane (CBM)</td>
<td>453 TSCF</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>ENERGI NON FOSIL</td>
<td>SUMBER DAYA</td>
<td>SETARA</td>
<td>KAPASITAS TERPASANG</td>
<td></td>
</tr>
<tr>
<td>Tenaga</td>
<td>845,0 juta SBM</td>
<td>75,67 GW</td>
<td>4,2 GW</td>
<td></td>
</tr>
<tr>
<td>Panas Bumi</td>
<td>219,0 juta SBM</td>
<td>27,00 GW</td>
<td>0,8GW</td>
<td></td>
</tr>
<tr>
<td>Mini/Micro Hydro</td>
<td>0,45 GW</td>
<td>0,45 GW</td>
<td>0,648 GW</td>
<td></td>
</tr>
<tr>
<td>Biomass</td>
<td>49,81 GW</td>
<td>49,81 GW</td>
<td>0,3 GW</td>
<td></td>
</tr>
<tr>
<td>Tenaga Surya</td>
<td>-</td>
<td>4,80 kWh/m²/day</td>
<td>0,008 kWh</td>
<td></td>
</tr>
<tr>
<td>Tenaga Angin</td>
<td>9,29 GW</td>
<td>9,29 GW</td>
<td>0,0005 kWh</td>
<td></td>
</tr>
<tr>
<td>Uranium (Nuclear)</td>
<td>24,112 ton*</td>
<td>11 tahun</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*) Hanya di Kalimantan - West Kalimantan

**Sumber ESDM 2007**

Nasib serupa juga dialami sumber energi alternatif lain yang masih dalam taraf pengembangan, seperti BBN, matahari, angin, dan mikrohidro. Sumber-sumber alternatif itu tak akan bisa sejajar atau meningkat mengejar penggunaan BBM, selama kebijakan pemerintah masih berpihak pada BBM.

Kini sebetulnya saat yang tepat untuk memindahkan subsidi dari BBM ke energi alternatif. Dengan demikian, dalam kurun 5-10 tahun ke depan, ketahanan energi nasional dapat terjamin, karena energi alternatif yang melimpah ruah di bumi Nusantara dapat berperan dengan nyata.

Apabila pemerintah memiliki keinginan yang kuat menata energi nasional di masa yang akan datang, seyogyanya BBM dilepaskan dari subsidi, dan mengikuti harga pasar yang berlaku. Biaya subsidi yang sudah ada di APBN selanjutnya dialihkan untuk mensubsidi energi alternatif (ingan potensi Panas Bumi kita 40% atau terbesar di dunia sedang pemanfaatannya baru 0,4%), sehingga bisnis dan industri energi alternatif tumbuh dengan sendirinya karena secara keekonomian menjadi atraktif. Dampak lanjutannya, kesadaran masyarakat sedikit demi sedikit akan terpola untuk mengurangi energi dari BBM, beralih ke energi alternatif.

Mengacu studi JICA 2007, harga panasbumi untuk 55 MW dengan IRR 15%, apabila dikenakan bea masuk, PPN impor dan PPh impor adalah 8,68 sen dolar AS per kWh. Apabila bea masuk dihapuskan dan PPN impor dan PPh impor ditanggung pemerintah adalah 8,09 sen dolar AS per kWh. Apabila pemerintah mengandalkan batubara dan gas, untuk memenuhi kenaikan produksi listrik sebesar 5% atau lebih di masa depan serta menggantikan pemakaian BBM tahun 2007 sebesar 23,571 GWh atau 23,6 x 10⁹ kWh dengan panasbumi maka pemerintah dapat menghemat 23,6 x 10⁹ kWh x US$(0,26-0,08) /kWh x Rp. 9300 /US$ atau Rp 39,5 trilyun per tahun. Untuk itu dibutuhkan penambahan pembangkit listrik panasbumi hanya sekitar 3000 MW.

Menurut Prof. Widjajono, masyarakat saat ini sebaiknya dibuat lebih banyak belajar hemat belanja energi dan memahami kenyataan bahwa harga bensin premium terbaik adalah tetap di kisaran Rp 5.500 per liter. Karena, bersamaan dengan itu, energi alternatif yang melimpah ruah di Nusantara ini akan termanfaatkan.
Kita juga jangan membiarkan PLN untuk *melanjutkan* praktek monopsoninya dan *melanjutkan* impor BBMnya dengan harga tinggi (15-30 sen dolar AS / Kwh) demi puluhan pembangkit konvensionalnya, sambil tetap *melanjutkan* pemaksaan harga beli listrik murah (kurang dari 6 sen dolar AS/Kwh) dari Pembangkit Tenaga Listrik Panas Bumi lokal (PLTP, yang mengoperasikan energi terbarukan, berkelanjutan, bersih lingkungan, mendapat hadiah lingkungan internasional, meraih PROPER 'Gold' dari Kementrian KLH dsb.).

Seperti kata Yasadipura yang dikutip cucunya: pujangga Ranggawarsita, jika kita *lanjutkan sikap suka kemudahan, takut kesulitan, insya‘allah takkan ada yang diperoleh*, demi tanah air kita tercinta....

(Penulis : Prijo Hutomo, praktisi di industri energi alternatif yang tengah belajar dan berusaha keras memahami praktek-praktek manajemen keberlanjutan energi di Indonesia; dan Prof. Zulkifli Husin, Ketua Program Doktor Ekonomi Bidang 'Sustainable Development' di Universitas Trisakti, Jakarta, Indonesia).
Introduction

In the upstream oil and gas industry, perforation is referred to small holes made at the portion of the production casing which connects to the production zone. This connection provide path for hydrocarbon to flow from the reservoir up to the surface. It has been proven in the literatures that during perforation operation, rock around the perforation tunnel will be squeezed and compacted as the perforation bullets enter the formation (Behrmann et al., 1996; Jilani et al. 2002; Smith et al. 1997). This process can result “low-permeability crushed zone” as the primary cause of wellbore damage. In order to minimize this damage, underbalanced perforating should be considered (Jan et al. 2007; King et al. 1986).

Underbalanced perforating is a perforation conducted when wellbore pressure is lower than the reservoir pressure (King et al. 1986). It is generally regarded as one of the best methods of creating open and undamaged perforations. The benefits of underbalanced perforation extend far beyond a producer’s ability to utilize previously hard-to-harvest oil and gas. In addition, it also helps to minimize damage to under-pressurized hydrocarbon pools or formations prone to lost circulation; increased drilling rates have been observed with certain rock types; bit life may be extended; reduced chip holdown occurs, allowing the bit to continuously cut new rock which is then swept away by the drilling fluid; and, oftentimes, well stimulation can be eliminated, further protecting damage-prone formations (Wong and Arco 2003).

It has been reported that an underbalanced perforation condition could be achieved by formulating a stable fluid with non-damaging chemical properties that would have a significantly lower density which called as completion fluid (Jan et al. 2007; Wong and Arco 2003). Jan et al. in 2003 had successfully formulate a super light weight completion fluid which consist of Shell Sarapar 147 synthetic oil [Shell MDS (M)], 3M™ Glass Bubbles as a density reducing agent and an appropriate rheology control agent. The measured density of the formulated completion fluids is around 5.0 ppg. The measured value is much lower than the existing completion fluids in the market which is around 7.57 ppg. Field test has also shown the increase of production rate after perforation job was conducted with fluids based on the optimized formulation from laboratory (Jan et al. 2007).

In order to optimize the formulation, it is necessary to perform critical parameters optimization. Such parameters include the amount of rheology controlling agent, amount of additive, speed of mixing, and mixing time. Fractional factorial experimental design was used to evaluate the significance the variables, as well as their interactions (Morgan 1991).
Materials and Methods

2.1 Materials
To formulate the super light weight completion fluids, synthetic oil based completion fluids were used. The completion fluids are Shell Sarapar 147 synthetic oil [Shell MDS (M)]. 3M<sup>TM</sup> Glass Bubbles (HGS) were used as a density reducing agent. Homogenizing agent was used as a rheology controlling agent in order to suspend the glass bubbles in homogenous slurry, and additive was used to increase the stability. For the determination of density, a 25 ml pichemeter was used. The rheological measurements were conducted by a HAAKE VT 550 shear rate controlled-viscometer (Gebruder Haake GmbH, Karlsruhe, Germany). For the slurry mixing, disperser T25 (IKA LABORTECHNIK, Germany) was used.

2.2 Formulation of super light weight completion fluids
To formulate super light weight completion fluids, firstly, 65 % w/w of completion fluids was mixed manually with additive. The amount of additive was optimized from 1 % w/w until 10 % w/w. Secondly, 35 % w/w of glass bubbles was mixed with the homogenizing agent. The amount of homogenizing agent was optimized from 1 % w/w until 4 % w/w. The solution of the completion fluids and additive was placed under homogenizer, and the powder mixture (glass bubbles and homogenizing agent) was added slowly into the solution. The slurry was agitated at various speeds and mixing time. Finally, other variables of response such as density, plastic viscosity, and stability were also determined.

2.3 Experimental Design
Since a full factorial design is introduced to the experimental design with k factors, there would be 2<sup>k</sup> experimental runs. However, as we discuss earlier, it is not necessary to investigate the whole 2<sup>k</sup> experimental runs. In a two level half fractional factorial design experimental, each factor was assigned as two levels: low (-1.000) and high (1.000). If k factor are considered, there will be 2<sup>k-1</sup> measurements in order to perform the analysis. In order to gain the accuracy, at least one replicate must be conducted. Into the bargain, it is necessary to conduct at least one central point measurement in order to test for quadratic term within the low-to-high range (Abdul-wahab & Abdo 2007). Therefore, the total number of test is given as:

\[ N = r2^{k-1} + C \] (1)

Where N represents the total number of test, r is the number of replicates, and C represents the number of center-point measurements. The aims of this optimization are to get the minimum density of the slurry in order to perform underbalanced perforation condition, to gain the stability of the fluid, and to minimize the viscosity.

In this research 4 critical factors of formulating super light weight completion fluids, k = 5, i.e. A (amount of homogenizing agent), B (amount of additive), C (speed of mixing), and D (time of mixing) were investigated. The coded level for these factors is given in table 1. Since two tests are made for each combination (r = 2) to estimate for the pure error, and three center-point measurement are conducted in the analysis (C = 3) to estimate curvature in the model, it was resulted in a total N = 19 experimental measurements based on equation 1. Table 2 represents the experimental design using fractional factorial design which used in this research, the extra experimental measurements (center-point measurements) were collected at mid-level (coded as zero). Experiments were randomized to maximize the effects of unexplained variability in the observed responses, due to extraneous factors.

The statistical software was used in order to model building, experimental design, and data analysis. The effect of each factors and their interactions were considered to three parameters, i.e. density of the slurry, plastic viscosity, and stability.

Results and Discussions

3.1 Response Analysis
The software was used in the statistical analysis investigation. Using this software, half-normal plot in which the ranks of the absolute value of various effects were measured. Figure 1 shows the half normal-normal plot for density as the response variable. Based on figure 1, the factor that lie along the line are negligible and the rest of the factors and their cross interaction are significant. In figure 1, it can be seen that speed of mixing (C), time of mixing (D), the interaction between the
amount of homogenizing agent and amount of additive \((AB)\), and the interaction between amount of homogenizing agent and time of mixing \((AD)\) are significant to the density of slurry. The effects of the factor are calculated by averaging the responses of each factor at the plus levels and subtracting the average at the minus levels for the same factor (Abdul-Wahab & Abdo 2007).

Similar analysis for the significant factors and their interaction was also conducted to other responses, i.e. plastic viscosity and stability. Figure 2 and 3 show the half-normal plot for those two responses respectively. Based on figure 2, there are 6 terms as the significant factor for the effects, i.e. speed of mixing \((C)\), the interaction between amount of homogenizing agent and time of mixing \((AD)\), the interaction between amount of homogenizing agent and speed of mixing \((AC)\), time of mixing \((D)\), amount of homogenizing agent \((A)\), and amount of additive \((B)\). Afterwards, based on figure 3 the significant terms are amount of homogenizing agent \((A)\), amount of additive \((B)\), the interaction between amount of homogenizing agent and additive \((AB)\), the interaction between amount of homogenizing agent and speed of mixing \((AC)\), the interaction between amount of homogenizing agent and time of mixing \((AD)\), and speed of mixing \((C)\).

Before the conclusion from the analysis of variance was adopted, the adequacy of the underlying model should be checked by examination of residual. The normal probability plot is a graphical technique for assessing whether or not a data set is approximately normally distributed. Figure 4 presents a normal probability plot of the residual for density, plastic viscosity, and stability respectively.

Figure 4(a) and 4(b) indicate that the model was adequate and it is also normally distributed for those three responses. However based on figure 4(c), the model for stability does not seem to be normally distributed. It is proved by the data doesn’t resemble to the straight line. Hence, it is necessary to check another transformation that could have been applied using Box-Cox plot.

3.2 Box-Cox Transformation

Normal plot of residual for stability indicates that the model doesn’t seem to be normally distributed. Hence, it is necessary to conduct the Box-Cox transformation check. Figure 5 shows the Box-Cox plot for stability. It is recommended to used square root transformation \((\text{Lambda} = 0.5)\) with \(k = 0.2\).

3.3 Residual Analysis

In order to check on the equality of variance, residual versus predicted plot was investigated. Figure 7 shows the residual versus predicted plot for density. From this figure, it seems that the equality of variance is not violated. The same indication also obtained at the rest of responses (plastic viscosity and stability).

3.4 Regression Analysis

Using the software, it is possible to develop the model equation in order to predict the outcome depending on the level for each factor. This equation called the coded equation since the +1 and -1 values are used to represent high and low levels, respectively. In inverse, if the actual values are used, there would be actual equation. Equation 2, 3, and 4 show the coded equation for density, plastic viscosity, and stability respectively. \(R^2\) value for those model was very high, i.e. 0.9589 for density (equation 2), 0.9727 for plastic viscosity (equation 3), and 0.9920 for stability (equation 4).

\[
\text{Density} = 4.68 + 0.046 * A - 0.027 * B + 0.29 * C + 0.17 * D + 0.15 * A * B - 8.558E-003 * A * C - 0.10 * A * D
\]

\[
\text{plastic viscosity} = 487.38 + 57.16 * A - 51.53 * B - 240.51 * C - 61.37 * D - 14.06 * A * B - 61.88 * A * C + 119.41 * A * D
\]

\[
\sqrt{\text{stability} + 0.2} = 1.64 + 1.03 * A + 0.81 * B + 0.10 * C + 0.049 * D + 0.65 * A * B + 0.26 * A * C - 0.11 * A * D
\]

3.5 Optimal Design

In order to get the best condition for formulating super light completion fluids, a fractional factorial experimental design tests were investigated. Figure 8 shows ramps of various as the solution to the optimization job. It was obtained that 4% w/w of homogenizing agent, 10% w/w of additive and mixed at 14276.11 rpm during 1 hour as the best condition with the desirability = 0.710. The software also provides the optimal design in different desirability factors. Table 3 presents the alternative solution for optimal design at other desirability.

Conclusion

In order to get underbalanced condition in the borehole during perforation job, low density of the slurry, low viscosity and higher stability should be important. A fractional factorial design was develop for optimizing super light completion fluids. The result have shown that speed of mixing \((C)\), time of mixing \((D)\), the interaction between the amount of homogenizing agent and amount of additive \((AB)\), and the interaction between amount of homogenizing agent and time of mixing \((AD)\) are...
significant to the density of slurry. Then, for the plastic viscosity, the significant terms are speed of mixing ($C$), the interaction between amount of homogenizing agent and time of mixing ($AD$), the interaction between amount of homogenizing agent and speed of mixing ($AC$), time of mixing ($D$), amount of homogenizing agent ($A$), and amount of additive ($B$). And finally, for stability, the terms are amount of homogenizing agent ($A$), amount of additive ($B$), the interaction between amount of homogenizing agent and additive ($AB$), the interaction between amount of homogenizing agent and speed of mixing ($AC$), the interaction between amount of homogenizing agent and time of mixing ($AD$), and speed of mixing ($C$).

The model was tested for its adequacy using normal plot residual and found that the assumption of normality and independency are not violated except for stability. Then, Box-Cox transformation have suggested square root transformation ($\lambda = 0.5$) with $k = 0.2$. $R^2$ value was very high, that suggesting that model accounted for most of the variability. The optimal solution with specified desirability was calculated using the software and presented. The selected solution is 4% w/w of homogenizing agent, 10% w/w of additive and mixed at 14276.11 rpm during 1 hour as the best condition with the desirability = 0.710.

References
Figure 1 Half-normal plot of density

Figure 2 Half-normal plot of plastic viscosity.
Figure 3 Half-normal plot of stability.

Figure 4 Normal plot of residual for the responses; (a) for density, (b) for plastic viscosity, (c) for stability.
Figure 5 Box-Cox plot for stability.

Figure 6 Normal plot of for stability after Box Cox transformation.
Figure 7 Residual versus predicted plot for density.

Design-Expert® Software
density
Color points by value of
density:
5.5218
4.2001

Residuals vs. Predicted

Internally Studentized Residuals

4.24 4.22 4.2 5.00 5.37

Predicted

Desirability = 0.710

Figure 8 Ramps for various factors.
Table 1. Code levels for independent factors used in the experimental design

<table>
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<tr>
<th>Factors</th>
<th>Symbols</th>
<th>Coded Level</th>
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<tbody>
<tr>
<td>Amount of homogenizing agent (% w/w)</td>
<td>A</td>
<td>Low (-1)</td>
</tr>
<tr>
<td>Amount of additive (% w/w)</td>
<td>B</td>
<td>High (1)</td>
</tr>
<tr>
<td>Speed of Mixing (rpm)</td>
<td>C</td>
<td></td>
</tr>
<tr>
<td>Time of Mixing (Hours)</td>
<td>D</td>
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Table 2. Experimental design used in fractional factorial design studies by using for independent variables and three dependent variables

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<tr>
<th>Experiments</th>
<th>Coded Level</th>
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Table 3. Optimal Solution

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<tr>
<th>Solution Number</th>
<th>Amount of Homogenizing agent</th>
<th>Amount of Additive</th>
<th>Speed of Mixing</th>
<th>Time of Mixing</th>
<th>Density</th>
<th>Plastic Viscosity</th>
<th>Stability</th>
<th>Desirability</th>
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<tr>
<td>1*</td>
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<td>10.00*</td>
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<td>4.7876*</td>
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<td>0.710139*</td>
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<td>406.92*</td>
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<td>20189.31</td>
<td>1.00</td>
<td>4.9454*</td>
<td>239.87*</td>
<td>4.421*</td>
<td>0.695289*</td>
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<td>4.7255*</td>
<td>530.19*</td>
<td>4.070*</td>
<td>0.688201*</td>
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<td>4.8061*</td>
<td>489.61*</td>
<td>4.122*</td>
<td>0.67526*</td>
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<td>10.00</td>
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<td>22813.98</td>
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<td>4.8364*</td>
<td>259.663</td>
<td>2.211*</td>
<td>0.540831*</td>
</tr>
</tbody>
</table>

* selected solution
Tracer Test Evaluation on Core Flooding

oleh
Utomo Pratama, Usman Pasarai, Sugihardjo
PPPTMGB “LEMIGAS”

Abstrak

The implemented and success or failure of an EOR process are always affected by reservoir geologic heterogeneities which causes fluids movement in reservoir is very non uniform. Factors of this type, unless properly identified and understood before the start of EOR process, will likely cause a project failure.

Core flooding as the model of small scale of fluids movements in reservoir undergoes similar circumstances. Tracer test was performed prior oilflood to characterize the core. On this experiment, lithium solution was selected as tracer solution to be then injected into core at constant rate, 4 ft/day. Afterwards, the effluent collected by Gilson sample collector in each tube for further d its concentration using Atomic Absorption Spectrometry (AAS).

Lithium concentration reported in some extent and subsequently analyzed by employing method of temporal moments. This method provides numerical calculation to estimate effective core pore volume (PV). Weighing method made also use to compare the PV with aforementioned method and the results were comparable. Furthermore, response curves were able to determine core heterogeneities and set up.

Introduction

Success of secondary and tertiary oil recovery projects targeting the remaining oil in mature or partially depleted reservoirs strongly depends on adequate description of reservoir heterogeneity. Process that are well-understood in a laboratory environment and properly designed for the reservoir may fail when implemented in the reservoir because of inadequate description of reservoir. Reports such failures are numerous in petroleum engineering literature. A number of procedures exist that can be used before implementation of an EOR process in attempt to describe the reservoir geology. One of these procedures is tracer test.

Tracer technology plays an important role in improving the reservoir characterization before the application of EOR methods by providing qualitative information on reservoir compartmentalization, preferential flow paths to improve understanding of fluid movement in the reservoir, stratification, and heterogeneities distribution. Basically, tracer is chemicals that can be added to fluids in small concentrations and used to follows their movement without affecting their physical properties. It also can be used as an effective tool to detect and estimate of remaining oil saturation using two different types of tracers. The two tracer types are differentiated into the conservative (ideal) tracer and the partitioning tracer. The ideal tracers do not have solubility in other substances, at this case is oil or by definition they do not interact with the rock or other fluid phases present. Thus when ideals are injected in reservoir, they will flow only in the water phase adopting the velocity of this phase. Some examples that can be used as ideal tracer are iso-propyl alcohol (IPA), bromide and lithium.

In contrast, partitioning tracers are soluble in liquid hydrocarbon as well as water or gas phases. The molecules of the partitioning tracers are moving back and forth between the water and oil phase, because they have high partition coefficient (absorb into the rock) which is determine the tracer solubility in other phases. Consequently, when a pulse of aqueous solution containing a suite of partitioning tracers is injected into an oil reservoir, the tracer will continuously partition into and out of the oil phase contacted by aqueous solution (injected gas). Hence the molecules of partitioning tracers are flowing with the water velocity when they are in the water phase and oil velocity when they are in oil phase. Thus, partitioning tracers propagate more slowly in an oil reservoir than conservative tracers. This retardation of the partitioning tracer is analogue to chromatographic separation where this mechanism is utilized to estimate oil saturation in the reservoir. Several examples from this type of tracers are n-butanol, rhodamine, and propanol.
Tracer test is necessary to be performed in core flooding experiment when we are deeply concern with core properties and validation seeking. Besides, describes the heterogeneity within core including its connectivity, another advantage is leak indicator in core set up. Moreover, we could obtain effective pore volume swept by the tracer.

This paper will describe the results of tracer test on several core flooding succinctly including how to use the method of temporal moment analysis from tracer response curve data to estimate effective core pore volume. A quick look observation on response curve to reflect core heterogeneity and experimental set up was also presented concisely.

**Tracer Interpretations data method**

A host of tracer analysis methods consider the temporal behavior of tracers. The methods were originally developed for closed reactor vessel, but have been applied to more general conditions of open boundaries, characterization fractured media under continuous reinjection and estimates flow geometry. The methods have rigorous mathematical basis. The methods and application mentioned above are all based on analysis of tracer residence times. The mean residence time or first temporal moment, is the most useful single property derived from tracer test, although other properties have been used as well. Levenspiel\(^{10}\) shows the total pore volume swept by the tracer can be determined from its residence time.

The method of temporal moments is a very simple, fast and robust method to estimate swept pore volume and remaining oil saturation. As explained earlier, to calculate remaining oil saturation we need two different types of tracer where the ideal tracer behaves as the reference tracer and the partitioning tracer as the partitioned one. Because of the presence of oil, partitioning tracers are retarded compound to the non-partitioning. However, this paper aims merely on effective pore volume estimate.

Effective pore volume can be estimated using one tracer that swept by tracer. The pore volume was determined from tracer mean residence time which required steps are summarized as follows:
- Normalize the tracer history
- Extrapolate the history to late time
- Calculate mean residence time and swept volume

Although this method provides some advantages but it is necessary to inform that moment analysis is a general method, and one that suffers from few limitations. Assumed conditions essentially state that the flow field is steady and tracers moves with bulk fluid flow such that the information obtained from the analysis is general applicable. These conditions can be stated as follows:

1. Steady state injection and extraction
2. The tracer is ideal and conservative

**Experiment Procedure**

Several tracer tests were conducted by using high pressurized core cell with low dead volume. The experiment used both standard and native sandstone core that condition set to reservoir state (table 1). The core was prepared to contain residual oil saturation using standard procedure by altering flow of brine and crude oil. The experiment configuration is illustrated in figure 1.

When residual oil saturation had been established, core was flooded with synthetic brine at constant flow rate, 4 ft/day. During this period, a small volume of tracer was injected into the flowing water phase close to the core inlet. On this experiment Lithium (Li\(^+\)), which dissolved in LiCl solution, was selected as conventional tracer. The solution had been designed 100 ppm Li\(^+\) ion. Waterflood resumed at stable flow rate until the tracer chemical was eluted through the core plug, thus the majority of the injected tracer mass could be recovered.

The Aliquots of 5 ml of the effluent were continuously collected by Gilson sample collector fraction close to the outlet of the backpressure regulator valve. Then each sample fractions were analyzed for its content of Li by atomic absorption spectrometry (AAS).

**Results**

Each sample concentration was plotted versus its volume, as depicted in figure 2. The calculation of effective swept pore volume will be determined from temporal moment method. The first step is normalizing the concentration history by dividing measured Li\(^+\) concentration to total Li\(^+\) injected concentration.

Tracer response curves should be complete in terms of outflow measured concentration in order to estimate effective pore volume precisely, because much of the information is contained in the tails of the response curve. Unfortunately, the tracer response curve is often incomplete either due to dilution of the tracer concentration below detectable limit of apparatus or some other reasons. Therefore to overcome this difficulty is with extrapolating the history to long time. The tracer response curve can be extrapolated with an exponential function provided the derivation of the test is sufficient to establish this decline.

The first moment of the tracer response curves was obtained by dividing the data into two parts. The first part represents the data from zero to the time \(t_b\) where time becomes exponential, and the
second covers the exponential part in which it goes from \( t_b \) to infinity.

After time \( t_b \), the tracer response is assumed to follow an exponential decline given by:

\[
C = C_b e^{-\left(\frac{t-t_b}{a}\right)}
\]

Where \( 1/a \) is slope of the straight line when the tracer response curves are plotted in semi-log scale and \( C_b \) is the tracer concentration at time \( t_b \) when curve becomes exponential. The extrapolated curve is seen in figure 3.

The mean residence time, or first temporal moment, of tracer is determined directly from the normalized and extrapolated tracer history as:

\[
t^{*} = \frac{\int_{0}^{t^{*}} Cdt + \frac{b}{a} e^{-at_b}(1 + at_b)}{\int_{0}^{t^{*}} Cdt + \frac{b}{a} e^{-at_b}}
\]

The constants \( a, b \) and \( t_b \) are determined by curve-fitting late time tracer data in spreadsheet. Pore volume estimates follow directly from the mean residence time as describe from the equation below:

\[
V_p = \frac{m}{M_{inj}} q_{inj} t^{*}
\]

Then each data was tabulated and plotted against cumulative volume as shown in figure 4. The effective pore volume calculation from temporal moments and weighing method is 118.14 cc and 115.23 cc respectively. There is a fair difference between the estimation of effective pore volume using temporal moments and weighing method.

Core heterogeneity is reflected from two peaks which formed in tracer response curve. These peaks mean the core was stratified into different flow paths (Fig. 5). Another case depicted in Figure 6 shows scattered and varying noise in response curve that may indicate the leakage occurred during the flooding due to imperfect core set up particularly in core holder sleeve.

Conclusions

1. Effective pore volume estimates from temporal moments and weighing method are 118.14 cc and 115.23 cc respectively

2. Tracer test provides helpful tools to improve core characterization by providing qualitative information on preferential flow, stratification, core connectivity, heterogeneities distribution and apparatus set up.

3. Method of First Temporal Moment Analysis is simpler and faster to interpret tracer response curve.

4. Tracer test possible to be used as initial assessment to core before proceeding core flooding. Hence, it will save times and cost in experimental.

Nomenclature

- \( C \) = tracer concentration, ppm
- \( q \) = flow rate, cc/min
- \( M \) = total tracer injected, cc

References

1. Tang, J.S.,“extended brigham model for remaining oil saturation measurement by partitioning tracer test”, SPE 84874.
8. Abidin, Z., “Teknologi Perunut Untuk Manajemen Reservoir Minyak bumi (EOR)”, Pusat Teknologi Aplikasi Isotop dan radiasi, BATAN.
Figure 1. Core flooding scheme for Tracer Test

Table 1. General Experimental Data

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</tr>
<tr>
<td>Core diameter</td>
<td>3.8 cm</td>
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<tr>
<td>Pore volume</td>
<td>115.23 cc</td>
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<tr>
<td>Porosity</td>
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<tr>
<td>Flow rate</td>
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<td>Velocity</td>
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<td>Synthetic brine</td>
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<tr>
<td>Volume of tracer injected</td>
<td>24.36 cc</td>
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Figure 2. Tracer Response Curve

Figure 3. Li Extrapolated Curve
Figure 4. Pore Volume Estimation Curve

Figure 5. Core Heterogeneity Response Curve
Figure 6. Leakage on Core Holder Set up Response Curve