Prediction of Saraline-based super lightweight completion fluid densities at elevated pressures and temperatures

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ABSTRACT

This paper presents a concise investigation of the density of Saraline-based super lightweight completion fluid (SLWCF) at elevated temperatures and pressures. Fluid density was measured at temperatures and pressure ranging from 313.15 K to 393.15 K, and 0.1 MPa to 25 MPa, respectively. In this work, the experimental data were fitted to the Tait-like equation and the generated results were statistically evaluated. Based on the results, it suggests that the Tait-like equation is able to satisfactorily predict the relationship between the density of the fluids as a function of pressure and temperature. The results also showed that the predicted density values are very close to the actual data with very low deviation. The predicted density values based on the Tait-like equation are also in good agreement with the regressed model results. This confirmed the reliability and accuracy of density prediction using the Tait-like equation. Furthermore, it was also found that the Tait-like equation gives better density predictions for Saraline-based SLWCF than Sarapar-based SLWCF.

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1. Introduction

It is widely known that one of the popular completion practices to establish clean and undamaged perforation tunnels between wellbore and reservoir rock via underbalanced perforation (King et al., 1986; Halleck and Deo, 1989; Tariq, 1990; Behrmann, 1996; Bakker et al., 2003; Badrul et al., 2009). In underbalanced perforation, perforation tunnel is perforated at which the wellbore pressure is kept lower than the reservoir pressure (Bakker et al., 2003; Viera et al., 2007). According to literatures, it has been proven that wells perforated underbalanced lead to higher oil production (Regalbuto and Riggs, 1968; Halleck and Deo, 1989; Behrmann, 1996; Walton, 2000). The increment of oil production is due to the ability of underbalanced perforation in minimizing perforation-induced formation damage, which leads to cleaner production tunnels.

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In underbalanced perforation, surge flow phenomenon is considered as the main reason for the improvement of hydrocarbon recovery. Here, a flow of reservoir fluid surges into the wellbore due to dynamic forces, differential pressure and drag between wellbore and reservoir rock immediately after the detonation of the perforation gun. (Walton, 2000; Bahrami et al., 2009). As a result, this surge flow erodes and removes debris and crushed rock grains created during the detonation resulting in a clean perforation hole (Bartusiak et al., 1997; Halleck, 1997). Fig. 1 illustrates the improvement from under underbalanced perforation condition compared to balanced condition in which the former clearly produces wider and cleaner perforation tunnels.

Generally, underbalanced condition could be achieved through several ways. One of the simplest and most widely used approaches is by using low to very low density completion fluids (Millhone, 1983). Traditionally, gas-based compressible fluid mixtures, such as air-, gas-, mist-, or natural gas-based completion fluids have been used to maintain an underbalanced condition during perforation (Al-Riyamy, 2000). Underbalanced condition can also be achieved using the gas cushion technique which is applied with the gun jump technique (Badrul et al., 2009;
Zazovsky et al., 2007).

Recently, underbalanced condition can also be achieved via Perforating Ultimate Reservoir Exploitation (PURE) perforating system. A technique which was developed by Schlumberger (Johnson et al., 2003; Brooks et al., 2003). In this method, the transient underbalance of the well was used and optimized without applying the equivalent static initial underbalance, which occurs instantaneously after the creation of the perforation cavity (Behrmann et al., 2002). To improve the performance and ensure clean perforation, this system is strengthened with a new deep-penetrating shaped charge, the Schlumberger Powerjet Omega (Bruyere et al., 2006). However, the use of the aforementioned procedures is not always attractive since they require additional work, time, special equipment, cost and safety considerations (Khalil et al., 2010a, 2010b). For example, the utilization of compressible gas-based completion fluid is usually not preferred due to its high processing cost, special high pressure equipment and extra safety concern. Therefore, utilization of non-compressible completion fluid that has low- to very low-density to ensure the underbalanced condition is desired.

In our previous works, we have successfully developed a new type of completion fluid for underbalanced perforation referred to as Super Lightweight Completion Fluid (SLWCF) (Badrul et al., 2009). The application of SLWCF in perforation process is considered as one of the simplest means to achieve an underbalanced condition due to its nearly incompressible and low density properties resulting in low hydrostatic pressure inside the wellbore. In addition, the application of SLWCF does not require additional work, equipment, or special treatment. Based on the field test in well BKC-18 of Bunga Raya field located at a joint-development area between Malaysia and Vietnam, at the center of Block PM3 CAA, the well was perforated through the application of SLWCF. The well produced approximately an additional 1000 barrels of oil daily compared to the production of a neighboring well with similar properties but perforated with conventional completion fluid (Badrul et al., 2009). Here, SLWCF was formulated using Sarapar oil as the continuous phase (Khalil et al., 2010a, 2010b, 2011, 2012, 2013). However, the fluid can also be formulated using Saraline oil (Muhammad and Raman, 2011). It is known that Saraline oil is suitable for application as base oil for deepwater exploration activities due to its low viscosity, low pour point and relatively high flash point properties (Teow et al., 2001). Recently, the study on the rheological properties of Saraline-based SLWCF has also been reported (Amir et al., 2015).

As mentioned earlier, the density of completion fluid plays a key role in ensuring underbalanced condition during perforation. In general, the density of oil-based fluids remains constant inside the wellbore since the volume shrinkage due to pressure increment and the volume expansion due to temperature compensate each other (Demirdal and Cunha, 2009). This is because the volume shrinkage due to pressure increment seems to be compensated by the volume expansion with temperature rises. However, this is not always the case for synthetic based fluids like Sarapar and Saraline oils (Demirdal and Cunha, 2009). When synthetic fluids are compressed under pressure and expand with temperature, their downhole densities are usually different from their surface densities. Therefore, a study on the relationship of borehole fluids densities as a function of subsurface conditions is crucial.

In the literatures, studies on the relationship between fluid’s density as a function of pressure and temperature have been widely reported. However, they are only limited to water- and oil-based fluids. For instance, McMordie et al. (1982) studied density change with pressure and temperature in water- and oil-based drilling fluids. They observed that the density of oil-based drilling fluid seems to be more dependent on pressure and temperature compared to water-based drilling fluid. In another report, Sorelle et al. (1982) presented a mathematical model to predict the downhole densities of diesel and water-based muds. However, the mathematical model only determines density changes with depth, a factor that is not under consideration in our study. Furthermore, Kutasi (1988) also proposed an exponential function to describe the empirical relationship between the density of drilling mud and surface and downhole conditions. The results showed that the density of the drilling fluid decreases with temperature because of thermal expansion and it increases with pressure due to compressibility.

Later, Babu (1993) conducted a study on a model used to represent the measured data for water mud during deep well drilling. Kårstad and Aadnøy (1998) also developed a mathematical model to evaluate the density behavior of drilling fluid. It was assumed that the initial temperature and pressure conditions ($p_{0}, T_{0}$) are equal to surface conditions ($p_{s}, T_{s}$). However, the assumption may not hold when the surface temperature is very high.
or very low. More recent study related to the density behavior of upstream petroleum mud is the investigation by Demirdal and Cunha (2009). They investigated the density behavior of two commonly used Olefin-based drilling fluids under high pressure and high temperature conditions. They concluded that synthetic-based drilling fluid is more sensitive to pressure and temperature compared to the other types of drilling fluid. They also suggested that the modeling of density as a function of temperature and pressure is crucial to accurately determine the pressure under both static and dynamic conditions.

Owing to its importance, experimental measurement and prediction of Saraline-based SLWCF densities at elevated pressure and temperature is conducted in this study. Here, the densities of the fluid were measured at temperatures ranging from 313.15 K to 393.15 K and pressures ranging from 0.1 MPa and 25 MPa to mimic the reservoir condition during perforation process. In this work, Tait-like equation was used for experimental data modeling to establish a reliable mathematical tool in the prediction of density at wide range of pressure and temperature. Furthermore, a generalized regression equation reported by Chhetri and Watts (2012) was also applied to validate the reliability and accuracy of the density prediction using the Tait-like equation.

2. Materials and method

2.1. Materials

Shell Saraline 185V synthetic oil (Shell Middle Distillate Synthesis, Kuala Lumpur) was used as the continuous phase in Saraline-based SLWCF formulation. Saraline oil is prepared from natural gas; hence it does not contain aromatic hydrocarbons, sulfur compounds, or amines. The density of Saraline oil is 0.778 g/cm³ (6.49 lbm/gal) (Shell MDS, 2014). 3 M glass bubbles (HGS4000) (3 M, St. Paul, Minnesota, USA) was used as a density-reducing agent. Bentonite clay and suitable emulsifier (Somi Oiltools Berhad, Kuala Lumpur, Malaysia) were used to improve fluid stability.

2.2. Formulation of Saraline-based SLWCF

In this study, Saraline-based SLWCF was prepared by mixing 60 wt% of Saraline and 40 wt% of glass bubbles. To improve the stability of the fluid, 3 wt% of clay and 9 wt% of emulsifier were added. The mixture was then agitated using an IKA T25 digital ultra-turrax disperser at 6000 rpm for an hour. The prepared fluids were then placed in a sealed-cap container for further tests.

2.3. Density measurement

The Saraline-based SLWCF density was measured using a Anton Paar DMA model (Anton Paar GmbH, Ostfildern, Germany) high-pressure vibrating tube density meter equipped with DMA 4500 as the evaluation unit. A high-pressure volumetric hand-pump (model HPT1, rating: 10,000 psi; Si Pressure Instruments Ltd., Birmingham, UK) equipped with a GE Druck DPI 104 manometer was used to pressurize and introduce the sample into the density meter. A peristaltic pump (Masterflex Model 77800-50, Cole Parmer Instrumental Company) was used to inject the sample into the system. Finally, a digital pressure transducer (Swagelok S Model transducer, rating: 0-8,000 psi) was used to monitor the pressure during the measurement. The uncertainty of the pressure was estimated at about 0.5% of the real pressure. The experiment was conducted at various temperatures and pressures ranging from 313.15 to 393.15 K and 0.1 to 25 MPa, respectively. The schematic diagram of the experimental setup is shown in Fig. 2.

2.4. Data analysis and evaluation

In this study, The experimental densities of Saraline-based SLWCF were fitted to the Tait-like equation Eq. (1). Data analysis and model fitting analysis were carried out using commercial statistical software, the SAS Enterprise Guide Software version 5.1 (SAS Institute, Cary, NC, USA). The calculation of the Tait-like equation parameters and the absolute average deviation (AAD), the maximum deviation (DMAX), the average deviation (bias), and the standard deviation values were also calculated.

$$\rho(T, P) = \frac{\rho_0(T)}{1 - C \ln \left( \frac{B(P) + P}{B(P) + 0.1} \right)}$$  (1)

where $\rho_0(T)$ is the temperature dependence of the density at 0.1 MPa expressed as

$$\rho_0(T) = A_0 + A_1 T + A_2 T^2 + A_3 T^3$$  (2)

Parameter C is assumed to be temperature independent, and $B(T)$ is given by the following polynomial function

$$B(T) = B_0 + B_1 T + B_2 T^2$$  (3)

In addition, regression analysis was also performed to verify the accuracy of the Tait-like equation results. Here, a mathematical model Eq. (4) proposed by Chhetri and Watts (2012) was used on the regression analysis.

Density ($\rho$) = $c - a \times T + b \times P$  (4)

where $c$ is a constant, $a$ is the temperature coefficient, $T$ is the temperature in K, $b$ is the pressure coefficient and $P$ is the pressure in MPa.

Using this regression model, the experimental density data of Saraline-based SLWCF, over the temperature and pressure range of interest, were fitted to the model using a commercial statistical toolbox on Matlab R2013A. A linear relationship was plotted to calculate the coefficients and statistical parameters. Then, the deviation of each values from the regressed model were compared to Tait-like equation. Then the accuracy of the predicted values using Tait-like equation was determined.
3. Results and discussion

3.1. Densities of Saraline-based SLWCF

To mimic the reservoir condition during perforation process, measurement of the density values of Saraline-based SLWCF was performed at temperatures and pressure ranging from 313.15 K to 393.15 K and 0.1 MPa to 25 MPa, respectively. The result of the measurement is presented in Table 1. Fig. 3 shows the variation of Saraline-based SLWCF densities as a function of temperature at various pressures. Based on the result, it is apparent that the density is inversely proportional to temperature and directly proportional to pressure, in a linear fashion. The reduction of fluid density with temperature is believed due to the increase of fluid volume with temperature through the reduction of the intermolecular force in the fluid. As a result, when mass is kept constant, thermal energy eventually decreases the density of the fluid under isobaric conditions. Similar result is also reported by Demirdal and Cunha (2009) on their study on the density of the Linear Alpha Olefin (LAO)-Based-Oil. In their result, it is found that the density of LAO-Based-Oil is more sensitive to temperature changes compared to the other fluids. Furthermore, it is also observed that Saraline-based SLWCF is more compressible at higher temperature (Fig. 3). However Saraline-based SLWCF seems to exhibit a small increment in density at room temperature when the pressure is increased.

Fig. 4 shows the density of Saraline-based SLWCF as a function of pressure at various temperatures. Based on the result, it is clear that the density is increasing with pressure under isothermal condition. Like any other types of synthetic oil fluids in oil and gas application, it is known that the increment of pressure under isothermal conditions seems to decrease the volume of the fluid. This is due to the compression of intermolecular space in the fluid while the mass is kept constant. As the result, the density is increased. However, it is also found that the effect of pressure on the fluid density is considered not very significant comparatively to the other types of synthetic oil-based fluids. This may be due to the high content of glass bubbles in Saraline-based SLWCF. It is believed that glass bubbles can keep the fluid to be less compressible and more resistance to pressure.

3.2. Model Fitting

In the present work, two fitting methods were used to correlate the density of Saraline-based SLWCF as a function of temperature and pressure. First, the measured density values were fitted to Tait-like equations Eq. (1). Tait-like equation has widely and successfully been used to correlate the relationship of density with a wide range of pressures, typically less than 100 kbar (145,000 psi). In this study, experimental data obtained from density measurements (Table 1) were fitted to the Tait-like equation and its parameters were calculated. To determine the efficiency of the fitting process, several statistical parameters such as absolute average deviation (AAD), the maximum deviation (DMAX), the average deviation (bias), and the standard deviation σ, were calculated using the following equations:

\[
AAD = \frac{100}{N} \sum_{i=1}^{N} \frac{\rho_{i}^{\text{exp}} - \rho_{i}^{\text{calc}}}{\rho_{i}^{\text{exp}}} \tag{5}
\]

\[
DMAX = \max \left( \frac{100}{N} \sum_{i=1}^{N} \frac{\rho_{i}^{\text{exp}} - \rho_{i}^{\text{calc}}}{\rho_{i}^{\text{exp}}} \right) \tag{6}
\]

\[
bias = \frac{100}{N} \sum_{i=1}^{N} \frac{\rho_{i}^{\text{exp}} - \rho_{i}^{\text{calc}}}{\rho_{i}^{\text{exp}}} \tag{7}
\]

Table 1

<table>
<thead>
<tr>
<th>Pressure (MPa)</th>
<th>Temperature (K)</th>
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<tbody>
<tr>
<td>0.1</td>
<td>313.15</td>
</tr>
<tr>
<td>1</td>
<td>333.15</td>
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<tr>
<td>5</td>
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<tr>
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<td>333.15</td>
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<tr>
<td>25</td>
<td>333.15</td>
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</tbody>
</table>

*Experimental density (g/cm²) values for Saraline-based SLWCF as a function of temperature and pressure.*
The eight calculated Tait-like equation parameters and statistical fitting parameters, i.e. AAD, DMAX, bias, and standard deviation (σ) are given in Table 2. Based on the statistical calculation and the value of statistical parameters, it is found that the Tait-like equation provides an excellent ability to describe the correlation between fluid’s density as a function of temperature and pressure. Results show that the standard deviation (σ) and absolute average deviation (AAD) are very small (0.002 g/cm³ and 0.2949%), suggesting that the predicted value is very close to the real value. This is also supported by the low value of the measurement uncertainty (bias: −0.0008%). Hence, the Tait-like equation could be used satisfactorily in predicting the effects of temperature and pressure on Saraline-based SLWCF density.

Tait-like equation is shown in Fig. 6. The data suggests that the Tait-like equation is able to give a reliable performance. It seems to perform satisfactorily in predicting the experimental data. This is due to the low deviation range, which is in the range of ± 0.6%. The value was confirmed by the maximum deviation (DMAX) in Table 2, which is 0.5982%.

To confirm the reliability and accuracy of the density prediction using the Tait-like equation, a generalized regression equation from Chhetri and Watts (2012) was applied. The generalized regression model is presented as Eq. (5). To assess the suitability of the generalized regression model, the experimental data fitting outcome using this model was analyzed. The results of the regression constant, together with the corresponding calculated model and statistical parameters, such as $R^2$, the sum of square error (SSE), and the root mean square error (RMSE) are summarized in Table 3. Based on the results, the regressed plot gives a very high $R^2$ and adjusted $R^2$ value (0.9788 and 0.9778) and very low SSE and RMSE values (0.0002873 and 0.002615). High $R^2$ and adjusted $R^2$ values, and low SSE and RMSE values indicate good and satisfactory prediction. Because of the good fitting performance, this regression model is appropriate as comparative model for Tait-like equation.

![Fig. 5. Comparison of the Saraline-based SLWCF experimental density values and calculated density values using Tait-like equation at 393.15 K.](Image)

![Fig. 6. Deviation between the measured and calculated Saraline based SLWCF densities.](Image)

### Table 2

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Calculated value</th>
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<tr>
<td>$A_0$, g cm⁻³</td>
<td>−3.3066</td>
</tr>
<tr>
<td>$A_1$, g cm⁻³ K⁻¹</td>
<td>$3.37 \times 10^{-2}$</td>
</tr>
<tr>
<td>$A_2$, g cm⁻³ K⁻²</td>
<td>$-1.0 \times 10^{-4}$</td>
</tr>
<tr>
<td>$A_3$, g cm⁻³ K⁻³</td>
<td>$9.076 \times 10^{-8}$</td>
</tr>
<tr>
<td>$C$</td>
<td>$9.941 \times 10^1$</td>
</tr>
<tr>
<td>$B_0$, MPa</td>
<td>$-8.603 \times 10^2$</td>
</tr>
<tr>
<td>$B_1$, MPa K⁻¹</td>
<td>$3.046 \times 10^1$</td>
</tr>
<tr>
<td>$B_2$, MPa K⁻²</td>
<td>$-4.79526$</td>
</tr>
<tr>
<td>AAD, %</td>
<td>2.949 \times 10^{-1}</td>
</tr>
<tr>
<td>DMAX, %</td>
<td>5.982 \times 10^{-1}</td>
</tr>
<tr>
<td>Bias, %</td>
<td>$-8.48 \times 10^{-4}$</td>
</tr>
<tr>
<td>Standard Deviation (σ), g cm⁻³</td>
<td>$2.393 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

where $N$ is the number of experimental data points and $m$ is the number of calculated parameters.

Fig. 5 presents a comparison of the Saraline-based SLWCF experimental density values and the calculated density values using the Tait-like equation at 393.15 K. From the results, it can be seen that all of the points are very close to the straight line. This suggests that the Tait-like equation is appropriate for the prediction of the density of Saraline-based SLWCF. Furthermore, the deviations between the experimental and predicted values were also considered. The deviation (D) is calculated by comparing the density value calculated using Tait-like equation and its corresponding real data $(D=100 \times (1-\rho \text{ Experimental} / \rho \text{ Predicted}))$. The deviation between the measured fluid densities and calculated from the

$$
\sigma = \sqrt{\frac{\sum_{i=1}^{N} (\rho_i^{\text{exp}} - \rho_i^{\text{calc}})^2}{N - m}}
$$


### Table 3

<table>
<thead>
<tr>
<th>Parameters</th>
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<tr>
<td>$a$</td>
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</tr>
<tr>
<td>$b$</td>
<td>0.00151</td>
</tr>
<tr>
<td>$c$</td>
<td>0.6942</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.9788</td>
</tr>
<tr>
<td>Adjusted $R^2$</td>
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</tr>
<tr>
<td>RMSE</td>
<td>0.002615</td>
</tr>
<tr>
<td>SSE</td>
<td>0.0002873</td>
</tr>
</tbody>
</table>
3.3. Comparison with Sarapar-based SLWCF

The experimental and prediction data of Saraline-based fluid was further compared to Sarapar-based fluid. Figs. 8 and 9 show the comparison of density for the two fluids at various temperatures and pressures. In general, the densities of Saraline-based SLWCF were found to be lower than Sarapar-based SLWCF, regardless of the temperatures and pressures. This is due to the higher concentration of glass bubbles in Saraline-based SLWCF formulation which leads to the lower density compared to Sarapar-based SLWCF. Lower density of Saraline-based SLWCF tend to remain throughout various temperatures and pressures. At low temperatures and pressures, the rate of density change of both fluids is almost identical. However, density of Saraline-based fluid tends to decrease more significantly than of Sarapar based SLWCF. The density of Saraline-based SLWCF tends to be more sensitive to temperature.

In contrast, at higher pressures, the density of Sarapar-based SLWCF seems to increase more than the density of Saraline-based SLWCF. This is because of the higher concentration of glass bubbles in Saraline-based SLWCF. Higher glass bubble content leads the Saraline-based SLWCF to be less compressible. Thus it may compensate for compression at higher pressures. This minimizes glass bubble breakage and maintains the lower density change in Saraline-based SLWCF.

Fig. 10 presents a comparison between the two SLWCF in terms of prediction value using the Tait-like equation. The results show that the predicted values of Saraline-based SLWCF are in good agreement with the experimental data compared to Sarapar-based SLWCF. The calculated deviation for Saraline-based SLWCF is very near to 0 compared to Sarapar-based SLWCF. This suggests that the Tait-like equation gives a better prediction of density for Saraline-based SLWCF than Sarapar-based SLWCF.

4. Conclusions

A study on the prediction of Saraline-based SLWCF densities at elevated temperatures and pressures was conducted in this work. Experimental data for Saraline-based SLWCF densities were fitted to Tait-like equation and used for density forecast at wide range of pressure and temperature. Based on the results, the following conclusions are reached:

1. The density of Saraline-based SLWCF is inversely correlated with temperature at isobaric condition but positively correlated with pressure at isothermal condition, both in the linear fashion.
2. Statistical evaluations suggest that Tait-like equation was able to accurately predict the density values of Saraline-based SLWCF at wide range of pressure and temperature.
3. The goodness of Tait-like equation is comparable with the goodness of regressed model. The comparative accuracy value between two equations was found to be up to 99%.
4. The density of Saraline-based SLWCF was found to be more sensitive to temperature rather than pressure while the density...
of Saraline-based SLWCF was more prone to the effect of pressure than temperature.

5. Tait-like equation provides better predictions for Saraline-based SLWCF densities than Sarapar-based SLWCF.

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