Rheological Properties of Super Light Weight Completion Fluid for Perforation with Underbalanced

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Abstract

In enhancing flow of hydrocarbon from the reservoir to wellbore, small passages referred to as perforation tunnels are made. Historical data showed that one can increase the efficiency of the fluid flow if the perforation process was conducted underbalanced, i.e., when the wellbore pressure is lower than the formation. It is believed that the post shot surge flow of formation fluid is responsible for creating a clean and undamaged perforation tunnels. One way to ensure underbalanced condition during perforation is thru formulating a non-traditional completion fluid, which has significantly lower density than the completion fluid currently in the market. Field test has showed at least a thousand barrel of additional oil per day could be produced when perforation was completed underbalanced with the formulated super light weight fluid. This paper presents an experimental study on the rheological behavior of the super light weight completion fluid. Viscosity values of the super light weight completion fluid were measured at various temperatures, ranging from 25 °C to 85 °C. Data of the experimental results were fitted to various rheological models, namely Newton, Bingham, Casson-De-Weale, Herschel-Bulkley, and Mizhari-Berk. The rheological behavior of the super light weight completion fluid was best fitted with Mizhari-Berk equation. In addition, the effect of temperature on viscosity was also evaluated using Arrhenius-type equation. The dependency of fluid viscosity to temperature is best described by Arrhenius model since the calculated R-square is relatively high. The estimated value of the activation energy of the superlight weight completion fluid is 3.5533 kcal.mol$^{-1}$.

Introduction

During well perforation as high velocity shaped charge come makes its way into the formation, it will alter the rock properties near to perforation tunnel$^{1,2}$. It results in damage of perforation tunnel$^{1,3}$. This damage is the main contribution
factor for the reduction of hydrocarbon production. The damage is the results of plugged perforation tunnels by charge debris, crushed zone, and shock-damaged rock along the path of jet\textsuperscript{4,5}. Apparently, to ensure successful well completion operation, it is desirable to reduce or eliminate the perforation damage.

Researcher has showed that the damaged zone created by invasion of shaped charge usually extends about 1 centimeter into the rock with about 20 percent or more of permeability reduction\textsuperscript{6}. One of the best ways to minimize the damage in and around perforation tunnel is thru underbalanced perforation tunnels\textsuperscript{3,6,7}. This could be achieved by designing a stable fluid with non-damaging chemical properties that would have a significantly low density. Pressure in the wellbore is a function of gravity, density of fluid in the wellbore and depth of the reservoir\textsuperscript{8}. The relation is given by equation 1. Apparently, one could have desired pressures thru manipulating the value of density of fluid in the wellbore.

\[
\text{Pressure (psi)} = 0.052 \times \text{Density (ppg)} \times \text{Depth (feet)} \quad (1)
\]

Currently, the existing completion fluid in the market has a density in the order of 6.6 ppg\textsuperscript{9}. This leads to its limited application especially in depleted reservoirs where pressure is typically low. In 2007, Badrul et al. has successfully engineered a stable and safe completion fluid with a density much lower than the existing completion fluid in the market. It was achieved by mixing Shell Sarapar 147 synthetic oil [Shell MDS (M)] and 3M\textsuperscript{TM} Glass Bubbles with appropriate stabilizing and homogenizing agents. Glass bubble is a very light material with extremely low density value of 0.017 ppg\textsuperscript{7}. The measured density value of glass bubble mixed fluid is around 4.80 ppg. Similar fluids as prepared in the lab was mixed in the field to perforate BKC-18, an oil well at Bunga Raya filed located in a joint development area between Malaysia and Vietnam, in the middle of block PM3 CAA. About 72 barrels of light glass bubble mixed completion fluids was pumped downhole. The result is very promising. The well shows a marked increase of hydrocarbon production of about 1000 additional barrel of oil per day\textsuperscript{7}.

The formulated superlight weight completion fluid is considered as a basic formulation. Further studies are required to characterize and better understand the properties of the formulated fluid. One of the important parameters includes the effect of temperature on the rheological properties of the fluid. This is due to the fact that temperature variations exist as fluid travels from the surface to the reservoir. Data of the fluid rheological properties as a function of temperatures will be essential for contractors in the field to handle the fluid.

This study presents a laboratory works to investigate the effect of temperature on the flow properties of the super light weight completion fluids. For common fluids they could easily represented or described by existing model i.e., Newtonian, Bingham and etc\textsuperscript{10}. However, for fluids with high viscosity, their properties usually cannot be represented by simple model such as Newtonian or Bingham\textsuperscript{11,12,13}. Thus, a more complex model is required. In this study, few rheological models were fitted to the experimental data. The fitted models are Newtonian, Bingham, Cassson, Ostwald-De-Weale, Herschel-Bulkley, and Mizhari-Berk. They are given in equation 2 thru 7.

\[
\tau = \mu(\gamma) \quad (2)
\]

\[
\tau = \tau_0 + \eta_\gamma \gamma \quad (3)
\]

\[
\frac{\rho^{0.5}}{\tau^{0.5}} = k_{OC} + k_{CY} \gamma^{0.5} \quad (4)
\]

\[
\tau = k(\gamma)^n \quad (5)
\]

\[
\tau = \tau_0 + k(\gamma)^n \quad (6)
\]

\[
\frac{\rho^{0.5}}{\tau^{0.5}} = k_{OM} + k_{MY} \gamma^{0.5} \quad (7)
\]

In this study, not only the best model that describes the flow properties of the fluid was optimized. It is also possible to investigate the fluid behavior by calculating the values of $n$. For a Newtonian fluid, $n = 1$. If $n < 1$, the fluid is called pseudoplastic; and if $n > 1$, the fluid is dilatant\textsuperscript{11,13,14}.

In order to assess the dependency of the rheological behavior for the super light weight completion fluids on
temperature, an exponential relationship was hypothesized and Arrhenius equation was fitted to the experimental data.\textsuperscript{15,16} Falcone \textit{et al.} (2007) stated that high activation energy value indicates strong dependency of viscosity on temperature.\textsuperscript{17} Arrhenius model for the viscosity dependence on temperature is given in equation 8.

$$\eta_a = \eta_0 \exp \left( \frac{E_a}{RT} \right)$$ (8)

\textbf{Materials and Methods}

\textit{1. Materials}

In the formulation of a super light weight completion fluids, a synthetic oil based completion fluids, Shell Sarapar 147 synthetic oil [Shell MDS (M)] was used. Hollow glass bubbles, 3MTM Glass Bubbles was used as a density reducing agent. In addition, homogenizing agent was used as rheology controlling agent to suspend the glass bubbles in homogenous slurry, and additive was used to increase the final fluid stability. Measurement of density was made from a 25 ml pycnometer. Fluid viscosity was measured using HAAKE VT 550 shear rate controlled-viscometer (Gebruder Haake GmbH, Karlsruhe, Germany). Fluids were mixed using a disperser T25 (IKA LABORTECHNIK, Germany). For model building and statistical analysis, a statistical software named Sigmaplot release 10.0 was used.

\textit{2. Formulation of super light weight completion fluids.}

In the formulation of super light weight completion fluids 65% w/w of completion fluids was mixed manually with 10% w/w of additive. Secondly, 35% w/w of glass bubbles was mixed manually with 4% w/w of homogenizing agent. 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 solution then mixed at 15000 rpm as long as an hour. The final fluid then placed into sample container, thus its density then was measured using pycnometer.

\textit{3. Rheological characterization}

The rheological properties of super light weight completion fluid were measured using a rotational viscometer equipped with MV2 P ST spindle (Haake model VT 550). The measurement was carried out by measuring the shear stress with varying the shear rate ranging from 2.639 to 264 s\textsuperscript{-1}. The measurements were made at eight different temperatures, i.e. 25, 35, 45, 55, 65, 75, 80 and 85 °C. Experiments were repeated as much as five repetitions to gain the accuracy. The averages and standard deviations of the measured data were estimated for each temperature studied.

\textit{4. Calculation of flow behavior parameters}

As much as six models, i.e. Newton, Bingham, Casson, Ostwald-De-Weale, Herschel-Bulkley, and Mizhari-Berk were fitted to the rheological data obtained for the super light weight completion fluid. For the rheological behavior dependence on the temperature, an Arrhenius’s law (equation 8) was fitted to the experimental data. The statistical software named Sigmaplot release 10.0 was used for the calculation. Parameters of the models were calculated together with their confidence intervals by using Levenberg-Marquardt algorithm. In addition, in this case, the goodness of fit was evaluated by mean of $R^2$, ANOVA results, and sum of square error (SSE).

\textbf{Results and Discussions}

In oil and gas upstream industry, once the drilling process has reached the reservoir rock, a completion fluid is pumped down into the wellbore to complete the well completion process.\textsuperscript{8} One of the important roles of super light weight completion fluid in well completion process is to control and/or manipulate the wellbore pressure so that it can show an underbalance condition during perforation process. However, due to this pumping process, the main consideration of designing a completion fluid should be
taken into account of its rheological properties.

A series of investigations for flow behavior of super light weight completion fluid are introduced in this study. The relationship between shear stress and shear stress were examined in order to optimize the rheological properties of the sample. Table 1 shows the measured shear stress for the super light weight completion fluids at different shear stress which generated by the viscometer.

Based on experimental data from table 1, the models of Newton, Bingham, Casson, Ostwald-De-Weale, Herschel-Bulkley, and Mizhari-Berk as lies in equation 2-7 were fitted with the experimental data. Figure 1 shows the result of fitting curve for the super light weight completion fluid according to the model tested.

In this study, the models fitting of rheological behavior for the super light weight completion fluid was carried out using Levenberg-Marquadt algorithm. The Levenberg-Marquardt (LM) algorithm is an interactive technique that locates the minimum of a multivariate function that is expressed as the sum of squares of non-linear real-valued functions. Table 2 shows the fitted parameters for the models tested for the super light weight completion fluid.

According to the test, based on Figure 1 and Table 2, the rheological behavior of super light weight completion fluid was best fitted with Mizhari-Berk equation. The R-Square value indicates that the model of Mizhari-Berk is the highest and the lowest of Sum of Square Error as well. This model was developed by Mizhari and Berk (1972), who found that it was appropriate for concentrated orange juice. This model was a modification of the model of Casson which was constructed to assess the rheological behavior of pigment-oil suspensions. The calculated n index value for this model shows that the super light weight completion fluids flow behavior seems to follow a typical pseudoplastic behavior. The constant of $k_{OM}$ was interpreted as a function of shape and interaction of the particles, giving rise to the yield stress, and $k_M$ is a function of the dispersing medium. This is true since in the super light weight completion fluid, glass bubbles act as a dispersing particle inside the slurry.

As in the model-fitting test that the slurry shows a pseudoplastic behavior, figure 2 shows the plot of apparent viscosity as a function of shear rate proved that the viscosity decreases with increasing rate of shear. The same property of this fluid is found in certain complex solutions, such as ketchup, whipped cream, blood, paint, and nail polish. It is also a common property of polymer solutions and molten polymers. Pseudoplasticity can be demonstrated by the manner in which shaking a bottle of ketchup causes the contents to undergo an unpredictable change in viscosity. In figure 2, the apparent viscosity of the slurry seems to decrease dramatically in low shear rate, and gradually reached a constant viscosity when the shear rate was being increased up to 100 s$^{-1}$.

The effect of temperature seems also to be responsible on the decrement of fluid viscosity. Based on figure 2, the apparent viscosity of the super light weight completion fluids decreases as the temperature increase. Hence, in order to understand the dependency of the fluid viscosity on the effect of temperature, an Arrhenius's law is used to assess this property. Table 3 shows the result of the Arrhenius equation fitting to the viscosity of the super light weight completion fluids. Based on the result, the determination coefficient is quite satisfactory. The calculated activation energy, $E_a$, is measured by plotting $\ln \eta_a$ (ordinate) versus $1/T$ (abscissa), and multiplying the slope with R (gas constant = 1.978 x 10$^{-3}$ kcal mol$^{-1}$ K$^{-1}$). It is commonly known that a high activation energy value indicates that the viscosity is highly dependent on the temperature. Figure 3 shows the plot for temperature effect on viscosity of the super light weight completion fluids.

### Conclusion

During the well completion process, a super light weight completion fluid need to be pumped down to the
wellbore in order to maintain the wellbore pressure to make sure underbalance perforation. Due to this pumping process, the rheological behavior of the super lightweight completion fluids were investigated in this study. A series of investigation on experimental data fitting to the flow models, i.e. Newton, Bingham, Casson, Ostwald-De-Weale, Herschel-Bulkley, and Mizhari-Berk was conducted. The result shows that the flow properties of super lightweight completion fluid was best described using the Mizhari-Berk equation. This is due to the presence of glass bubble as the dispersion particle in the slurry. Besides, based on the Mizhari-Berk model, it is proved that the fluids seem to follow the pseudoplastic behavior since the value of the fluid behavior indicator ($n$) is lower than 1. In addition, the effect of temperature to the fluid viscosity was also being investigated. The dependency of fluid viscosity to the temperature is well described using the Arrhenius model since the calculated $R$-square is quite high. The calculated activation energy for the super lightweight completion fluid is 3.5533 kcal mol$^{-1}$. This result allows the use of the model to predict how the rheological fluid behavior behaves as a function of temperature during well completion process inside the wellbore.

References
15. Khalil KE, Ramakrishna P, Nanjundaswamy AM, Patwardhan MV
Figure 1. Fitting curves for the flow properties of super light weight completion fluids according to (a) Newton, (b) Bingham, (c) Casson, (d) Ostwald-De-Weale, (e) Herschel-Bulkley, and (f) Mizhari-Berk.
Figure 2. Plot of apparent viscosity as a function of shear rate at different temperatures

Figure 3. The Arrhenius model to the viscosity as a function of temperature data of the super light weight completion fluid
Table 1 Measured shear stress of super light weight completion fluid at different shear rate at 25 °C

<table>
<thead>
<tr>
<th>Shear rate (s^{-1})</th>
<th>Shear stress (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.639</td>
<td>3.179 ± 0.087</td>
</tr>
<tr>
<td>5.279</td>
<td>4.699 ± 0.137</td>
</tr>
<tr>
<td>26.4</td>
<td>11.962 ± 0.663</td>
</tr>
<tr>
<td>52.71</td>
<td>17.508 ± 0.317</td>
</tr>
<tr>
<td>79.28</td>
<td>22.972 ± 0.652</td>
</tr>
<tr>
<td>88.17</td>
<td>23.756 ± 0.415</td>
</tr>
<tr>
<td>158.3</td>
<td>38.148 ± 0.857</td>
</tr>
<tr>
<td>176</td>
<td>41.532 ± 1.363</td>
</tr>
<tr>
<td>264</td>
<td>57.258 ± 0.871</td>
</tr>
</tbody>
</table>

Table 2. Rheological parameters of the super light weight completion fluids by fitting the experimental data to the models at 25 °C

<table>
<thead>
<tr>
<th>Model</th>
<th>R-Square</th>
<th>Sum of Square Error (SSE)</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Newton ( (\tau = \mu(\gamma)) )</td>
<td>0.99231</td>
<td>129.7494</td>
<td>( \mu = 0.2348 )</td>
</tr>
<tr>
<td>Bingham ( (\tau = \tau_0 + \eta_\gamma) )</td>
<td>0.99231</td>
<td>20.0447</td>
<td>( \tau_0 = 5.2867 ) ( \eta_\gamma = 0.2034 )</td>
</tr>
<tr>
<td>Casson ( (\tau^{0.5} = k_{OC} + k_C\gamma^{0.5}) )</td>
<td>0.99912</td>
<td>2.3081</td>
<td>( k_{OC} = 1.3652 ) ( k_C = 0.3821 )</td>
</tr>
<tr>
<td>Ostwald-De-Weale ( (\tau = k(\gamma)^n) )</td>
<td>0.99707</td>
<td>9.761</td>
<td>( k = 0.9612 ) ( n = 0.7298 )</td>
</tr>
<tr>
<td>Herschel-Bulkley ( (\tau = \tau_0 + k(\gamma)^n) )</td>
<td>0.99887</td>
<td>2.9543</td>
<td>( \tau_0 = 2.5149 ) ( k = 0.5727 ) ( n = 0.8168 )</td>
</tr>
<tr>
<td>Mizhari-Berk ( (\tau^{0.5} = k_{OM} + k_M\gamma^{nM}) )</td>
<td>0.99920</td>
<td>2.0789</td>
<td>( k_{OM} = 1.221 ) ( k_M = 0.4376 ) ( n_M = 0.4794 )</td>
</tr>
</tbody>
</table>