Viscosity prediction model optimization for Saraline-based super lightweight completion fluid at high pressure and temperature

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Abstract: Investigation and analysis of the viscosity variation of Saraline-based super lightweight completion fluid (SLWCF) at high pressure and temperature were reported, and the viscosity prediction model was optimized. Viscosity measurements were carried out at temperature and pressure ranging from 298.15 K to 373.15 K, and 0.10 MPa to 4.48 MPa respectively. The data analysis reveals that the reduction of viscosity as a function of temperature may be divided into two regions, i.e. significant viscosity reduction at low temperature and fairly slow viscosity reduction at high temperature; the viscosity of Saraline-based SLWCF is less affected by the changes of pressure. The experimental data were fitted to four different viscosity-temperature-pressure models. The results show that, the modified Mehrotra and Svrcek’s and Ghaderi’s models are able to satisfactorily predict the viscosity value and measured value and describe the viscosity property at high pressure and temperature. The comparison with the Sarapar-based SLWCF reveals that the viscosity of Sarapar-based SLWCF is more affected by temperature than the Saraline-based SLWCF; pressure seems to have negligible effect on Saraline-based SLWCF viscosity; the modified Mehrotra and Svrcek’s and Ghaderi’s models are able to give more reliable viscosity predictions for Saraline-based SLWCF than for Sarapar-based SLWCF.

Key words: high pressure and temperature; viscosity prediction; super lightweight completion fluid; Saraline synthetic oil; underbalanced perforation

Introduction

In the case of cased oil wells, perforation tunnels created during perforation job are the only passages that allow hydrocarbon to flow towards the wellbore. However, the formation damage induced by perforation is one of the reasons for production decline[1-3]. The underbalanced perforation can minimize the perforation induced formation damage. And it refers to perforation job conducted when wellbore pressure is maintained lower than reservoir pressure prior to gun detonation[4-6]. And in order to meet underbalanced requirement, it is necessary to use low-extra low density completion fluid[7-9].

Based on previous researches, we have successfully developed a new type of completion fluid for underbalanced perforation application, i.e., Saraline-based Super Lightweight Completion Fluid (SLWCF) with density value of approximately 0.60 g/cm³. This completion fluid has been successfully applied to Well BKC-18 by cleaning perforation tunnels effectively to increase oil production significantly. Well BKC-18 is a well of Bunga Raya field located at a joint-development area between Malaysia and Vietnam[6]. Given such promising potential application, further studies on SLWCF’s physical properties (such as density and viscosity) are highly recommended, especially at reservoir conditions. It is shown that Saraline-based SLWCF flow behavior can be satisfactorily described by using two types of models, namely Sisko and Mizrahi-Berk models. However, these predictions are only limited at considerably low temperature and ambient pressure[10]. In its real application, however, SLWCF is always
subjected to extreme reservoir conditions, which may alter the fluid behavior.

The investigation on the fluid properties of Saraline-based SLWCF at reservoir conditions, i.e. high pressure and high temperature (HPHT) is presented in this paper. Viscosities of Saraline-based SLWCF were measured at various temperature and pressure. The experimental data obtained from these measurements were then fitted to four different types of viscosity-temperature-pressure models. And then, the prediction model suitable for HPHT viscosity of Saraline based SLWCF was optimized by means of statistical analysis approach.

1. Research method

Fig. 1 summarizes the research idea and method.

1.1. Material preparation

To formulate Saraline-based SLWCF, Shell Saraline 185V synthetic oil (Shell Middle Distillate Synthesis, Kuala Lumpur) was used as the continuous phase. Saraline oil is derived 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). 3M glass bubbles (HGS4000) (3M, St. Paul, Minnesota, USA) were used as a density-reducing agent. Bentonite clay and suitable emulsifier were used to improve fluid stability.

1.2. Formulation of Saraline-based SLWCF

In this study, Saraline-based SLWCF was prepared based on our previous works⁹⁻¹¹. The fluid was prepared by mixing 60% of Saraline synthetic oil and 40% of glass bubbles. To improve the stability of the fluid, 3% of clay and 9% of emulsifier were added. The mixture was then agitated by using IKA T25 digital high-speed disperser at 6 000 r/min for one hour. The readily prepared fluids were then placed in a sealed-cap container for further tests.

1.3. Viscosity measurement

Saraline-based SLWCF viscosity at high pressure and high temperature (HPHT) conditions was measured by using an HPHT NI Rheometer FANN 75 (Nordman Instruments, Inc., Houston, Texas, USA). After the equipment was set up, approximately 100 ml of the sample were injected through the sample port. The experiment was carried out at temperature and pressure ranging from 298.15 K to 373.15 K and 0.1 to 4.48 MPa (14.5 to 650 psi) respectively. Test sample pressures and temperatures were varied by fluid pressurization and electric heater, respectively. Measurements were carried out at two different speeds, specifically 600 r/min and 300 r/min for each pressure and temperature. Measurements were conducted at least 3 times for each speed, before an average value was obtained. To obtain the viscosity, the reading angle at 600 r/min was subtracted from the reading angle at 300 r/min and the result was divided by 1 000 for unit conversion from cP to Pa·s.

1.4. Data analysis and model fitting

The measured viscosity data of Saraline-based SLWCF were fitted to four different viscosity-temperature-pressure models. The four models are the Mehrotra and Svrcek’s equation⁰¹² (Equation (1)), modified Mehrotra and Svrcek’s equation⁰¹³ (Equation (2)), Ghaderi’s equation⁰¹⁴ (Equation (3)) and Gold et al.’s modulus equation⁰¹⁵ (Equation (4)).

\[
\ln \mu = \exp (A_1 + A_2 \ln T + A_3 \rho) 
\]

\[
\ln \mu = A + B \ln T + C \rho 
\]

\[
\mu = \exp \left( B_1 + \frac{B_2 \rho}{\ln \rho} + \frac{B_3}{T} \right) 
\]

\[
\mu = \mu_0 \exp \left( \frac{p}{a_1 + a_2 T + (b_1 + b_2 T) \rho} \right) 
\]

Data analysis and model fitting were carried out by using the software Matlab. Based on the data fitting, each of the calculated equation’s parameters is generated and its ability to describe the relationship of viscosity function of pressure and temperature was statistically evaluated with Matlab. Several statistical parameters such as Sum of Square Error (SSE), and Root Mean Square Error (RMSE), R-squared and adjusted R-squared are calculated for model optimization.

1.5. Validation

To validate the prediction of SLWCF viscosity, the fitting results were evaluated by measuring the average absolute percentage deviation (AAPD), standard error (σ) and deviation (D) between the experimental values measured in the laboratory and the predicted values calculated by using the equa-
The formulas for these parameters are expressed as follows:

\[
AAPD = \frac{100}{n} \sum_{i=1}^{n} \left(1 - \frac{\mu_{\text{exp}}}{\mu_{\text{cal}}}\right)
\]

(5)

\[
\sigma = \frac{100}{n} \sum_{i=1}^{n} \left(\frac{\mu_{\text{exp}} - \mu_{\text{cal}}}{\Delta \mu}\right)^2
\]

(6)

\[
D = 100 \left(1 - \frac{\mu_{\text{exp}}}{\mu_{\text{cal}}}\right)
\]

(7)

2. Result and discussion

2.1. Measured viscosities of Saraline-based SLWCF

Measurements of Saraline-based SLWCF viscosities were performed at temperatures and pressures between 298.15 K and 373.15 K and 0.1 MPa and 4.48 MPa, respectively. Table 1 shows the experimental viscosity data measured in the laboratory.

<table>
<thead>
<tr>
<th>Temperature/K</th>
<th>Pressure/MPa</th>
<th>Viscosity/(Pa·s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>298.15</td>
<td>0.10</td>
<td>0.125 13</td>
</tr>
<tr>
<td></td>
<td>1.34</td>
<td>0.122 42</td>
</tr>
<tr>
<td></td>
<td>2.06</td>
<td>0.121 52</td>
</tr>
<tr>
<td></td>
<td>2.75</td>
<td>0.120 19</td>
</tr>
<tr>
<td></td>
<td>4.48</td>
<td>0.119 69</td>
</tr>
<tr>
<td>313.15</td>
<td>0.10</td>
<td>0.116 76</td>
</tr>
<tr>
<td></td>
<td>1.34</td>
<td>0.108 03</td>
</tr>
<tr>
<td></td>
<td>2.06</td>
<td>0.107 93</td>
</tr>
<tr>
<td></td>
<td>2.75</td>
<td>0.105 63</td>
</tr>
<tr>
<td></td>
<td>4.48</td>
<td>0.103 82</td>
</tr>
<tr>
<td>323.15</td>
<td>0.10</td>
<td>0.102 38</td>
</tr>
<tr>
<td></td>
<td>1.34</td>
<td>0.097 03</td>
</tr>
<tr>
<td></td>
<td>2.06</td>
<td>0.093 25</td>
</tr>
<tr>
<td></td>
<td>2.75</td>
<td>0.091 70</td>
</tr>
<tr>
<td></td>
<td>4.48</td>
<td>0.090 37</td>
</tr>
<tr>
<td>343.15</td>
<td>0.10</td>
<td>0.066 92</td>
</tr>
<tr>
<td></td>
<td>1.34</td>
<td>0.065 65</td>
</tr>
<tr>
<td></td>
<td>2.06</td>
<td>0.064 58</td>
</tr>
<tr>
<td></td>
<td>2.75</td>
<td>0.062 30</td>
</tr>
<tr>
<td></td>
<td>4.48</td>
<td>0.061 15</td>
</tr>
<tr>
<td>353.15</td>
<td>0.10</td>
<td>0.066 05</td>
</tr>
<tr>
<td></td>
<td>1.34</td>
<td>0.063 95</td>
</tr>
<tr>
<td></td>
<td>2.06</td>
<td>0.060 23</td>
</tr>
<tr>
<td></td>
<td>2.75</td>
<td>0.059 85</td>
</tr>
<tr>
<td></td>
<td>4.48</td>
<td>0.057 77</td>
</tr>
<tr>
<td>373.15</td>
<td>0.10</td>
<td>0.054 55</td>
</tr>
<tr>
<td></td>
<td>1.34</td>
<td>0.052 90</td>
</tr>
<tr>
<td></td>
<td>2.06</td>
<td>0.052 40</td>
</tr>
<tr>
<td></td>
<td>2.75</td>
<td>0.051 92</td>
</tr>
<tr>
<td></td>
<td>4.48</td>
<td>0.050 05</td>
</tr>
</tbody>
</table>

Based on the data, it can be seen that the reduction of viscosity may be divided into two regions, i.e., significant viscosity reduction at low temperature (298.15 K to 343.15 K) and fairly slow viscosity reduction at high temperature (343.15 K to 373.15 K). This is mainly due to the effect of temperature on the intermolecular interaction since thermal energy weakens the intermolecular forces\(^{[16]}\). As a result, the molecules are able to move easily and the viscosity is reduced. When the temperature is further increased, the viscosity change seems to be negligible, for flocculation phenomenon tends to emerge at high temperature. It is a process where small dispersing particles such as clays, glass bubbles or polymers tends to agglomerate and precipitate to form a fragile structure called floc\(^{[17-18]}\), which prevents the reduction of viscosity. The high concentration of solid (e.g. glass bubbles) in completion fluid leads to higher probability of the flocculation phenomenon in the completion fluid. Furthermore, it is also observed that the viscosity of SLWCF is less affected by the changes of pressure and the effect is almost negligible. This might be due to the high concentration of glass bubbles that increases the fluid resistance to pressure and causes the fluid to become less compressible.

2.2. Model fitting result

The results of the data fitting along with the calculated model and statistical parameters are summarized in Table 2. And the following information is indicated from Table 2.

First, the original Mehrotra and Svreck along with Gold et al.’s modulus equation gave a poor prediction for Saraline-based fluids. These two models gave negative R-squared and adjusted R-squared. Moreover, the fitting of these two models also seems to give greater fitting errors. It is shown that neither of them may be suitable to represent the viscosity-temperature-pressure relationship of Saraline-based SLWCF. This phenomenon might be due to the nature of SLWCF viscosity. The Mehrotra and Svreck’s equation was originally developed for an investigation of the effects of pressure and temperature on the viscosity of compressed Cold Lake bitumen in Canada. It could describe the significant decline of bitumen viscosity with the change of temperature. And in the same temperature interval, the viscosity decline rate of Saraline-based SLWCF is much lower than that of Canada bitumen\(^{[19]}\). Gold et al.’s modulus equation was originally used to model the viscosity-temperature-pressure relationship of synthetic mineral lubricants. The model is accommodating lubricant characteristics (such as compressibility and rapid viscosity change under high pressure), which are not observed in Saraline-based SLWCF.

Second, the modified Mehrotra and Svreck’s equation is well fitted with significantly high \(R^2\) and adjusted \(R^2\) values (0.968 4 and 0.966 0, respectively), and very low calculated SSE and RMSE.

And third, good prediction can also be obtained by using Ghaderi’s model. Based on calculation, the model gave a considerably high value of \(R^2\) and adjusted \(R^2\) (0.965 4 and
Table 2. Calculated model’s coefficients and statistical parameters of Saraline-based SLWCF

<table>
<thead>
<tr>
<th>Viscosity model</th>
<th>Parameters</th>
<th>R-squared</th>
<th>Adjusted R-squared</th>
<th>SSE</th>
<th>RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gold et al.’s modulus</td>
<td>$a_1 = 0.998$, $a_2 = 11.63$, $b_1 = 1.027$, $b_2 = 20.17$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modified Mehrotra and Svrcek</td>
<td>$A = 20.14$, $B = -3.894$, $C = -0.001 877$</td>
<td>0.968 4</td>
<td>0.966 0</td>
<td>0.000 649 0</td>
<td>0.004 903 0</td>
</tr>
<tr>
<td>Ghaderi</td>
<td>$B_1 = -12.68$, $B_2 = -0.013 12$, $B_3 = 5 378$, $B_4 = -658500$</td>
<td>0.965 4</td>
<td>0.961 4</td>
<td>0.000 709 3</td>
<td>0.005 223</td>
</tr>
</tbody>
</table>

Fig. 2. Comparison of the Saraline-based SLWCF experimental and calculated viscosity values by using modified Mehrotra and Svrcek’s and Ghaderi’s equations.

2.3. Validation

Average absolute percentage deviation (AAPD) and standard error ($\sigma$) for modified Mehrotra and Svrcek’s and Ghaderi’s models are presented in Table 3. It is shown that the statistical error parameters for both modified Mehrotra and Svrcek’s and Ghaderi’s equation were very low, and they could predict about 95% of viscosity data with AAPD less than 6%.

Fig. 2 exhibits the comparison between the experimental viscosity data of the Saraline-based SLWCF and the calculated values obtained from modified Mehrotra and Svrcek’s and Ghaderi’s equations. Obviously, they are higher in term of prediction accuracy.

Figs. 3 and 4 show the deviation between the experimental viscosity values and the one predicted by modified Mehrotra and Svrcek’s and Ghaderi’s models. Based on the result, it is clear that the data fitting using both equations is considered good and acceptable since almost all prediction points fall at low deviation range, which mostly is in the range of ±10%.

2.4. Comparison with Sarapar-based SLWCF

Viscosity behavior comparison between Saraline-based SLWCF and Sarapar-based SLWCF was made since Sarapar and Saraline are the most common base oil used in the upstream oil and gas operations nowadays. Either of them has different physical and chemical properties, which may affect the properties of the completion fluid. For example, Saraline is more suitable in deepwater applications, while Sarapar is preferred in high pressure high temperature (HPHT) wells but it is limited for the shallow water.

Fig. 5 shows the viscosity-temperature relationships of Saraline- and Sarapar-based SLWCF at various temperatures and pressures. It is shown that the viscosity of Sarapar-based SLWCF is almost doubled the viscosity of the Saraline-based SLWCF at the same temperature and pressure, for the clay concentration of Sarapar-based SLWCF is higher (The optimum clay content in Sarapar-based SLWCF is 4% [20]). In SLWCF formulation, clay acts as viscosifier. It is also shown...
that temperature seems to have more effect on the viscosity of the Sarapar-based SLWCF than that of Saraline-based SLWCF. The viscosity of Sarapar-based SLWCF increases gradually with pressure while the effect of pressure on Saraline-based SLWCF’s viscosity is negligible. This might be because the optimum glass bubbles loading for Saraline-based SLWCF is 40% while the optimum loading for Sarapar-based SLWCF is only 35%. High content of glass bubbles causes the overall fluid slurry to become more incompressible and be able to withstand higher pressure.

Fig. 6. shows the statistical comparison of experimental values and the predicted values by using the modified Mehrotra and Svrcek’s equation between Saraline- and Sarapar-based SLWCF. And Fig. 7 shows the statistical comparison of experimental values and the predicted values by using the Ghaderi’s equation between Saraline- and Sarapar-based SLWCF. Based on both equations, it is clear that the calculated deviation for Saraline-based SLWCF is lower than that of Sarapar-based SLWCF. This suggests that both models may provide a better viscosity prediction for Saraline-based SLWCF than Sarapar-based SLWCF at various temperatures and pressures.

3. Conclusions

The viscosity of Saraline-based SLWCF at high temperature and high pressure has been measured. It is found that the viscosity of Saraline-based SLWCF is more sensitive to temperature than to pressure.

From the model fitting and validation, the modified Mehrotra and Svrcek’s and Ghaderi’s equations are able to describe viscosity behavior of Saraline-based SLWCF over a wide range temperature and pressure. The predicted and calculated viscosity values by using both equations show a good agreement with the experimental data.

From the comparison study, it is also observed that the viscosity of Saraline-based SLWCF is less affected by temperature than that of Sarapar-based SLWCF. Moreover, pressure seems to have negligible effect on Saraline-based SLWCF viscosity. Both the modified Mehrotra and Svrcek’s and Ghaderi’s equations gave a better prediction for Saraline-based SLWCF than that of Sarapar-based SLWCF.

The study in this paper is beneficial and useful for operators and contractors to determine operational parameters (such as the required pump horsepower) to ensure the completion fluid could be pumped safely as planned.

Nomenclature

AAPD—average absolute percentage deviation, %;
\( a_1, a_2, b_1, b_2, A_1, A_2, A_3, A_4, B_1, B_2, B_3, B_4 \)—model fitting coefficient;
D—deviation, %;
n—number of data point;
p—pressure, MPa;
\( \Delta \mu \)—difference between maximum and minimum measured viscosity, Pa·s;
T—temperature, K;
\( \mu \)—viscosity, Pa·s;
\( \mu_0 \)—viscosity at atmosphere, 0.14 Pa·s\(^{10}\);
\( \mu_{\text{exp}} \)—predicted viscosity by using the model, Pa·s;
\( \mu_{\text{exp}} \)—experimental viscosity in laboratory, Pa·s;
\( \sigma \)—standard error, %.

References


