Calculate Viscosity of Crude Oil by Redwood Viscometer

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ABSTRACT

The viscosity plays a very important role in a variety of interesting engineering problems involving fluid flow in porous media and reservoir simulation. Generally oil viscosity can be obtained in two ways, either by carrying out experimental measurements or estimated by a proper model. Due to the high expenses, and time wasting, literature models were applied to measure viscosity of crude oils. Whenever laboratory data obtained were made to find a best-fit correlation due to the demand for mathematical equation of fluid flow for reservoir simulation. This study has been done based on data received from Iraqi’s oil fields, consists of fifteen experimental points of oil viscosity at known temperature. In this work; several correlations have been presented in the literature [Beggs & Robinson (1975), Petrovsky and farshad (1995), Egbogah-Jacks (1990), Glaso’s (1980), Beal’s (1946), Kartoadmjo & Schmidt (1991), Labedi (1992)] used for predicting the viscosity of crude oil. Statistical analysis in terms of absolute deviation percent (% AD), and the absolute average deviations percent (% AAD) are used to subject the evaluation of the viscosity correlations. A correlation appeared to have the minimum average absolute error (2.477 %) is selected to be the best formula adopted in this study. This correlation has been developed for prediction of dead oil viscosity. Validity and accuracy of this correlation has been confirmed by comparing the obtained results of this correlation and other ones with experimental data for Iraqi oil samples. Checking the results of this correlation shows that the obtained results of Iraqi oil viscosities in this work are in agreement with experimental data compared with other correlations.

Keywords: fluid flow, viscosity correlation, absolute deviation, absolute average deviations, dead oil viscosity, Iraqi oil viscosities.

INTRODUCTION

Crude oil viscosity is an important physical property that controls and influences the flow of oil through porous media and pipes. The viscosity, in general, is defined as the internal resistance of the fluid to flow. The oil viscosity is a strong function of the temperature, pressure, oil gravity, gas gravity, gas Solubility. Whenever possible, oil viscosity should be determined by laboratory measurement at reservoir temperature and pressure. The viscosity is usually reported is standard pvt analyses. If such laboratory data are available, engineers may refer to published correlations, which usually vary in complexity and accuracy depending upon the available data on the crude oil. Depending on the pressure, the viscosity of crude oils can be classified into three categories[1]: dead oil viscosity, µod, saturated oil viscosity, µob, and under saturated oil viscosity, µo.

Estimation of the oil viscosity at pressure equal to or blow the bubble point pressure is a two-step procedure: Firstly calculate the viscosity of the oil without dissolved gas (dead oil) µod, at the reservoir temperature and the second step is adjust the dead oil viscosity to account for the effect of the gas solubility at the pressure of interest. At pressure greater than the bubble point pressure of the crude oil, another adjustment step, i.e.step3,should be made to the bubble point oil viscosity µob, to account for the compression and the degree of under-saturation in the reservoir. A brief description of several correlations that are widely used in estimating the oil viscosity in the above three steps is given below:

Models can be classified into three different categories:

1. Theoretical models
2. Semi-theoretical models
3. Empirical models

The theoretical models are mainly used for calculating viscosities of pure component and their mixtures Empirical models are mainly described in terms of correlations[2].Semi theoretical models for viscosity prediction have provided blend between theoretical and correlative models[3].Semi theoretical models are derived from theoretical framework,
but involve parameters experimentally determined. Empirical methods include a wide variety of equation used throughout the industry involving constants calculated from experimental data. There are several empirical correlations used to calculate the oil viscosity based on frequently available hydrocarbon system parameter, such as temperature, pressure, oil gravity, gas gravity, and gas solubility.

**Dead-oil viscosity correlation:**

For empirical correlations, the dead oil viscosity is determined first. The dead oil is defined at atmospheric pressure and at any fixed system temperature without dissolved gas. This dead oil viscosity then is corrected for the system pressure condition. Normally dead oil viscosity is determined in the laboratory [4]. The dead oil viscosity correlations are:

**Beal’s correlation:**

From a total of 753 values for dead oil viscosity between 100-220°F, Beal (1946) developed graphical correlation for determining the viscosity of the dead oil as a function of temperature and the API gravity of the crude [5]

\[
\mu_{od} = (0.32 + 1.8 \times 10^{-0.7})^{(\frac{360}{T+200})} a
\]

where,

\[a = 10^{0.43 + \frac{8.33}{API}}\]

\[\mu_{od}: \text{Dead oil viscosity at 1 atm pressure and temperature, } T \text{ in } ^{\circ}\text{F}\]

**Beggs and Robinson correlation:**

Beggs and Robinson (1975) developed an empirical correlation for determining the viscosity of crude oil [6]. It is based on 460 dead oil viscosity measurements and can be expressed as

\[
\mu_{od} = 10^\beta (x - 1)
\]

\[\beta = \log(3.0324 - 0.02023x^{API}) - \log(T - 1.163)\]

**Glaso’s Correlation:**

Glaso (1980) proposed a generalized mathematical relationship for computing the dead oil viscosity the relationship was developed from experimental measurements on 26 crude oil sample [7]. the correlation has the following form:

\[
\mu_{od} = (3.141 \times 10^{10}) \cdot (T - 460 - 3.444) \cdot \log(API) \cdot a
\]

\[a = 10^{0.313 \log(T - 460 - 36.447)}\]

**Kartoamodjo and Schmidt’s Correlation:**

In its empirical form, this correlation [8] is a combination of the three correlation; they are Beal’s correlation [5], standing’s correlation [9], and Beggs and Robinson’s correlation [6]; it can be expressed as:

\[
\mu_{od} = (16 \times 10^8) [T^2 \cdot (-2.8177) \cdot \log(API)^{5.756 \log(T) - 26.9718}]
\]

**MODIFIED KARTOAMODJO CORRELATION (MEDIUM OILS):**

\[
\mu_{od} = 220.15 \times 10^{0.9 \cdot T^2 \cdot (-3.556) \cdot \log(API)^{2.5428 \cdot \log(T) - 45.7874}}
\]

**EGBOGAH-JACKS CORRELATION:**

\[
\mu_{od} = 10^{0.10 \cdot [-1.7095 + \frac{389.45}{API + 131.5}] + [-1.2943 + \frac{135.585}{API + 131.5}] \cdot \log((T - 32) \cdot 10^5)}
\]

**MODIFIED EGOBOGAH-JACKS CORRELATION (EXTRA-HEAVY OILS):**

\[
\mu_{od} = 10^{0.10 \cdot [1.90296 - 0.012619 \times API - 0.61748 \times \log(T)]}
\]

**MODIFIED EGOBOGAH-JACKS CORRELATION (HEAVY OILS):**

\[
\mu_{od} = 10^{0.10 \cdot [2.06492 - 0.0179 \times API - 0.70226 \times \log(T)]}
\]

**LABEDI CORRELATION:**

\[
\mu_{od} = 10^{0.9 \cdot 2.224 \times \log(4.7013 \times T \cdot 0.6739)}
\]

**PETROSKY & FARSHAD CORRELATION:**

\[
\mu_{od} = 2.3511 \times 10^7 \times T^{-2.10255} \times (\log(API)^{4.59388 \times \log(T) - 22.82792})
\]

**CORRELATION FROM LITERATURE:**

\[
\mu_{od} = 10^{0.8 \cdot [4.9563 - 0.00480T]} \times \frac{T^{3.57} \cdot 14.29}{API}^{2.7962}
\]
SATURATED CRUDE OIL VISCOSITY CORRELATIONS:

The reservoir oil viscosity depends on the solution-gas content. Oil viscosity decreases with rising pressure as the solution gas increases, up to the bubble point pressure. There are few empirical correlations to determine the viscosity of saturated or under saturated crude oil systems.

BEGGS AND ROBINSON CORRELATION:

This correlation is based on 2073 saturated oil viscosity measurements [6]. The empirical form of this equation is:

\[
\mu_{ob} = (10.715 (Rs + 100)^{0.515}) \mu_{od} \quad (17)
\]

Where,

\[
b = 5.44 (Rs + 150)^{(-0.338)} \quad (18)
\]

This correlation was developed from these ranges of data:

- Pressure = 132 to 5.265 psia
- Temperature = 70 to 295°F
- Oil gravity = 16 to 58°API
- Gas solubility = 20 to 2070 scf/STB

KARTOATMODJO AND SCHMIDT'S CORRELATION:

This correlation recommends the following correction of the dead-oil viscosity presented in equations below to determine the live-oil viscosity [8].

\[
\mu_{ob} = -0.06821 + 0.9824 F + 0.0004034 F^2 \quad (19)
\]

where :

\[
F = (0.2001 + 0.8428 \times 10^{-0.000845Rs}) \times \mu_{ob}^{0.43} \times 0.5165y \quad (20)
\]

Y = \frac{10^x}{0.0008Rs} \quad (21)

CHEW & CONNALLY CORRELATION: [14]

\[
\mu_{ob} = a \times (\mu_{ob})^b \quad (22)
\]

Where :

\[
a = 0.20 + 0.80 \times 10^{-0.00081 x Rs} \quad (23)
\]

\[
b = 0.43 + 0.57 \times 10^{-0.00072 x Rs} \quad (24)
\]

LABEDI CORRELATION: [12]

\[
\mu_{ob} = \frac{102.344 - 0.03542xAPI \times \log(0.6447)}{\rho b^{0.426}} \quad (25)
\]

KAHN ET AL CORRELATION: [15]

\[
\mu_{ob} = \frac{0.09 x (5G gas)^{0.5}}{Rs x \left(\frac{144.5}{459.67}\right) \times \left[1 - \left(\frac{141.5}{API + 131.5}\right)\right]} \quad (26)
\]

KARTOATMODJO CORRELATION:

\[
\mu_{ob} = -0.06821 + 0.9824 F + 0.0004034 x F^2 \quad (27)
\]

Where :

\[
F = [0.2001 + 0.8428 \times 10^{-0.000845Rs}] \times \mu_{ob}^{0.43} \times 0.5165 \times 10^{-0.00081 x Rs} \quad (28)
\]

UNDER SATURATED OIL-VISCOSITY CORRELATIONS:

Above the bubble-point pressure, rising pressure increases the viscosity of oil because of its compressibility; that is when the pressure increases then the oil molecules become closer from each other and then the internal friction of oil increases, so the viscosity increases because it is a measure of the internal friction

KAHN'S CORRELATION:

From 1500 experimental viscosity data point on Saudi Arabian crude oil systems, the following equation was developed with a reported absolute average relative error of 2% [15].

\[
\mu_{ob} = \frac{\mu_{ob}^{0.43} \times \left(\frac{1}{\rho b}\right)}{\left(1 + \frac{1}{\rho b}\right)} \quad (29)
\]

BEAL CORRELATION: [5]

\[
\mu_0 = \mu_{ob} + 0.001 \times (p - p_b) \times (0.024 \times \mu_{ob}^{-1.6} + 0.038 \times \mu_{ob}^{0.56}) \quad (30)
\]
VASQUEZ AND BEGGS’S CORRELATION:

The following correlation was proposed to determine crude oil viscosity above the bubble point pressure using the viscosity at the bubble point pressure.[16]

\[ \mu_o = \mu_{ob} m \left( \frac{p}{p_b} \right)^m \]  
(31)

Where,

\[ m = 2.6 \times 10^{1.87} \times 10^a \]  
(32)

\[ a = - (3.9 \times 10^{-5}) \times p - 5 \]  
(33)

This correlation is based on data in the following ranges:
- Pressure = 141 to 9,515 Pisa
- Gas solubility = 90.3 to 2.199 scf/ STB
- Viscosity = 0.1177 to 148 cp
- Gas specific gravity = 0.511 to 1.351
- Oil gravity = 15.3 to 59.5° API

KARTOATMODJO AND SCHMIDT’S CORRELATION:

This correlation allow correlation the saturated crude oil viscosity at the bubble-point, \( \mu_{ob} \), based on equation for under saturated pressure, \( p \).

\[ \mu_o = 1.0008 \times \mu_{ob} + 0.001127(p - p_b) \times (-0.006517 \times \mu_{ab}^{1.8148} + 0.038 \times \mu_{ab}^{1.59}) \]  
(34)

VISCOSITY Mesurement:

Viscosity measurements at different temperatures were performed by using Capillary viscometer. The selection of type and size of viscometer depend on the type and density of oil stocks. The Capillary tube viscometer was placed in a water bath type Koehler, which was capable of maintaining the temperature within ±0.1°C of the selected temperature. The viscosity of all crudes was measured at five different temperature, 22, 30, 40, 50 and 60°C. Kinematic viscosity was calculated from the measured flow time (t) and the viscometer calibration constant by the equation (35).

\[ v = k \times t \]  
(35)

Where:
- \( v \): Is the kinematic viscosity in cst.
- \( k \): Is the calibration constant of the viscometer in cst/s.
- \( t \): Is the flow time in second.

EXPERIMENTAL PROCEDURE

1. A certain amount of each crude oil sample was poured in to a breaker then transferred to the viscometer.
2. The viscometer which containing the crude oil is inserted in the water bath at the required temperature.
3. The pump was used to raise the level of the crude oil to the starting mark on the left hand limp of the viscometer, another finger is used to close the other limp to avoid the flow of the crude oil due to air.
4. The finger is removed to allow his flow of crude oil down the capillary at that point, the time at which the crude oil flow down is taken and recorded.
5. This process is repeated for the various crude oils and at different temperature.
6. The viscosity then is obtained by multiplying the constant of the viscometer by the time obtained

Fig. (1): (Kinematic viscosity measurement apparatus & capillary viscometer) experimental DATA
Three Iraqi crude oil of different API gravities were selected for this study, as given in tables (1). Type (A) was kirkuk crude of (23.3)API gravity, type(B) was kirkuk crude of (29.3)API gravity and type (C) was jamboor crude of (37) API gravity.

Table (1): properties of Iraqi crude oils

<table>
<thead>
<tr>
<th>Specification</th>
<th>Type A</th>
<th>Type B</th>
<th>Type C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sp.gr.at 15.6°C(60°F)</td>
<td>0.914</td>
<td>0.88</td>
<td>0.84</td>
</tr>
<tr>
<td>API gravity</td>
<td>23.3</td>
<td>29.3</td>
<td>37</td>
</tr>
</tbody>
</table>

Data have been provided from three reservoirs, tape A, type B, type C. Details of these data are listed in table (2,3).

Table (2): Experimental data of three oil sample viscosities

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Type (A) Kirkuk crude oil data</th>
<th>Type (B) Kirkuk crude oil data</th>
<th>Type (C) Kirkuk crude oil data</th>
</tr>
</thead>
<tbody>
<tr>
<td>-------------</td>
<td>----------</td>
<td>--------------------------</td>
<td>-----------------</td>
</tr>
<tr>
<td>22</td>
<td>71.6</td>
<td>67.6</td>
<td>61.786</td>
</tr>
<tr>
<td>30</td>
<td>86</td>
<td>45.3</td>
<td>41.404</td>
</tr>
<tr>
<td>40</td>
<td>104</td>
<td>29.3</td>
<td>26.780</td>
</tr>
<tr>
<td>50</td>
<td>122</td>
<td>19.98</td>
<td>18.261</td>
</tr>
<tr>
<td>60</td>
<td>140</td>
<td>14.4</td>
<td>13.161</td>
</tr>
</tbody>
</table>

The viscosities are measured in centistokes. To obtain the viscosity in centi-poise, the viscosity in centistokes is multiplied by the fluid density (g/cm³).

**VISCOSITY TEMPERATURE RELATIONSHIP**

Plotting the experimental data yields Fig.(2) in which viscosity versus temperature has been drawn for the three samples. While Fig(3) shows how viscosity changes according to API gravity and Fig(4) we shows the relationship between dead oil viscosity against calculated oil viscosity.
Table (3): properties of Iraqi crude oils VS. Temperature

<table>
<thead>
<tr>
<th>Kirkuk crude oil</th>
<th>Temp.(°C)</th>
<th>Viscosity(c time (sec))</th>
</tr>
</thead>
<tbody>
<tr>
<td>sp. gr = 0.914</td>
<td>22</td>
<td>67.6</td>
</tr>
<tr>
<td>API = 23.3°</td>
<td>30</td>
<td>45.3</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>29.3</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>19.98</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>14.4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Kirkuk crude oil</th>
<th>Temp.(°C)</th>
<th>Viscosity(c time (sec))</th>
</tr>
</thead>
<tbody>
<tr>
<td>sp. gr = 0.88</td>
<td>22</td>
<td>27.6</td>
</tr>
<tr>
<td>API = 29.3°</td>
<td>30</td>
<td>20.6</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>14.7</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>10.3</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>6.3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Jamhoor crude oil</th>
<th>Temp.(°C)</th>
<th>Viscosity(c time (sec))</th>
</tr>
</thead>
<tbody>
<tr>
<td>sp. gr = 0.842</td>
<td>22</td>
<td>7.6</td>
</tr>
<tr>
<td>API = 37°</td>
<td>30</td>
<td>5.6</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>4.2</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>3.4</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>2.9</td>
</tr>
</tbody>
</table>

Fig. (3): Dynamic viscosity Vs. API gravity

Fig. (4): dead oil viscosity are plotted against calculated oil viscosity

THE RESULTS

The most popular empirical models presently used in petroleum engineering calculations for predicting dead oil viscosity (gas-free crude or stock tank) are those developed by Beal, Beggs and Robinson, and Glaso. Beal’s model was developed from crude oil data from California, Beggs and Robinson’s model was developed from the crude oils of an unknown location, whereas Glaso’s model from crude oils in the North Sea. Recently, Labedi and Kartoatmodjo and Schmidt presented other empirical models for estimating dead crude oil viscosity for African crudes and using data bank respectively.
All of these models have expressed dead oil viscosity as a function of both oil API gravity and reservoir temperature (T). When these correlations were applied to data collected considerable errors and scatter were observed. The error percentage for all published dead crude oil models are measured. The average relative error (ARE), absolute average relative error (AARE) are defined as below:

\[
ARE = \frac{1}{N} \sum_{i=1}^{N} \frac{|x_{\text{experimental}}(i) - x_{\text{calculated}}(i)|}{x_{\text{experimental}}(i)} \times 100
\]

Where \( i \) is the sample number and \( N \) is the total number of samples which is three. Twenty four correlations were used in this work, to estimate the viscosity of dead oil, some of these correlation are shown below Fig (5, 6, 7, 8):

**Fig (5):** Beal & Robinson and Glaso correlations

**Fig (6):** Kartoadmodjo and MODIFIED KARTOADMODJO Correlation
### Fig (7): Egbogah- Jacks & Modified Egbogah-jacks and Modified Egbogah-Jacks correlation

<table>
<thead>
<tr>
<th>API</th>
<th>T in °F</th>
<th>Exp. μ (CP)</th>
<th>Parameters</th>
</tr>
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<tr>
<td>23.3</td>
<td>71.6</td>
<td>61.7664</td>
<td>Egbojah-Jacks</td>
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<tr>
<td>23.3</td>
<td>86</td>
<td>41.4042</td>
<td>Modified Egbojah-Jacks (Extra Heavy Oils)</td>
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<tr>
<td>23.3</td>
<td>104</td>
<td>26.7802</td>
<td>Modified Egbojah-Jacks (Heavy Oils)</td>
</tr>
<tr>
<td>23.3</td>
<td>122</td>
<td>18.2167</td>
<td>Parameters</td>
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<tr>
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<tr>
<td>71.6</td>
<td>24.288</td>
<td>21.748029</td>
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<tr>
<td>86</td>
<td>14.1025</td>
<td>21.975249</td>
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<tr>
<td>104</td>
<td>12.3936</td>
<td>20.920943</td>
<td>0.118994</td>
</tr>
<tr>
<td>122</td>
<td>9.592</td>
<td>21.911627</td>
<td>0.119651</td>
</tr>
<tr>
<td>140</td>
<td>7.304</td>
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<td>6.3992</td>
<td>2.4327081</td>
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<tr>
<td>86</td>
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<tr>
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</tr>
<tr>
<td>122</td>
<td>2.8523</td>
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<td>0.137076</td>
</tr>
<tr>
<td>140</td>
<td>2.4413</td>
<td>2.3427081</td>
<td>0.137076</td>
</tr>
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</table>

Average Absolute Percent Error: 10.07529

### Fig (8): Labedi & Petrosky-Farshad correlation

<table>
<thead>
<tr>
<th>API</th>
<th>T in °F</th>
<th>Exp. μ (CP)</th>
<th>Parameters</th>
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<td>12.86021</td>
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<tr>
<td>140</td>
<td>2.4413</td>
<td>2.3427081</td>
<td>12.917416</td>
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</table>

Average Absolute Percent Error: 12.86021
CONCLUSIONS

In this work, ten correlations were used to estimate the viscosity of dead oil and define the effect of change of temperature on dead oil viscosity. The accuracy of each correlation for dead oil viscosity calculation was checked with experimental data. All the dead oil correlations were modified through introducing tuning parameters to improve their accuracy for Iraqi dead oil. The performance of the tuned correlations was found to better predict the data where the APE and AAPE decreases. The selected formula was Beal’s correlation because it has minimum AAE (2.477 %). By the comparison of experimental values of viscosity with predicted ones, it is obvious that the new correlation provides results in good agreement with experimental values. Input parameters for this correlation are oil API gravity, reservoir temperature and pressure, which are easily measured in oil fields.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbols</th>
<th>Description</th>
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<tr>
<td>T</td>
<td>Temperature</td>
<td>°F</td>
</tr>
<tr>
<td>API</td>
<td>Gravity of oil at 60°F</td>
<td>°API</td>
</tr>
<tr>
<td>P</td>
<td>Reservoir Pressure</td>
<td>psia</td>
</tr>
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REFERENCES


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