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The Oil Viscosity Correlations: A Simulation Approach

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Over the years, different authors have proposed many oil viscosity correlations for various crude oil mixtures (dead, saturated, or undersaturated) from all over the world. Authors tend to support their own correlations, which are developed for specific sets of hydrocarbon mixtures. When tested on other data sets, however, they do not perform as anticipated. The authors considered a total of 13 undersaturated correlations for a sharp review from a simulation perspective. They came to the conclusion of supporting the use of undersaturated viscosity correlations that use the exponential parameterized pressure differential form. Thus a new fine tuning parameter, which sets a sound basis for local data sets to be accounted for, has been proposed.

Keywords: correlation, dead, saturated, simulation, undersaturated, viscosity

1. INTRODUCTION

During the course of black-oil or compositional reservoir simulation, the task of calculating crude oil viscosity is required at each pressure step. This task is accomplished by a three-stage process, which starts with the estimation of dead oil (gas-free) viscosity at atmospheric pressure and reservoir temperature. The dead oil viscosity is taken as input for the estimation of the gas-saturated crude oil viscosity, which, in turn, is taken as input for the estimation of undersaturated crude oil viscosity at reservoir pressure.

Crude oil viscosity is affected by the oil composition (specific gravity and characterization factor), solution gas/oil ratio, system temperature and pressure. In this study, we do consider the undersaturated oil viscosity correlations for revision from a simulation perspective. We do support the approach of using local correlations if available as opposed to global correlations. In addition, correlations that are flexible to account for local data sets are preferable over others.

2. DEAD OIL VISCOSITY CORRELATIONS

Many correlations were proposed to estimate viscosity of dead oils at atmospheric pressure and reservoir temperatures. Naji (2010) presented a detailed revision of the most widely accepted correlations. Correlations that utilize the Watson characterization factor for characterizing crude oils, however, show stable viscosity predictions over a wide range of prevailing temperature. Twu (1985) and Bergman and Sutton (2007a) correlations are examples of such correlations. The

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detailed procedure of both correlations has been presented by Naji (2010). Their general form is given by

$$\mu_{od} = \gamma_{oT} v_{oT}, \quad (1)$$

where γ_{oT} and v_{oT} are the crude oil specific gravity and kinematic viscosity as affected by the temperature T , respectively.

3. SATURATED OIL VISCOSITY CORRELATIONS

Most saturated oil viscosity correlations adopt the scheme presented by Chew and Connally (1959). They observed that when plotting log of the saturated oil viscosity, $\log(\mu_{ob})$, versus log of the dead oil viscosity, $\log(\mu_{od})$, the plot results in a linear relationship described by

$$\log(\mu_{ob}) = \log(A) + B \log(\mu_{od}), \quad (2)$$

where A is the intercept and B is the slop of the line. From the definition and properties of exponential and logarithmic functions, the previous equation is written as

$$\log(\mu_{ob}) = \log(A) + \log(\mu_{od}^B), \quad (3)$$

which can be written as

$$\log(\mu_{ob}) = \log(A\mu_{od}^B), \quad (4)$$

which takes this final form:

$$\mu_{ob} = A\mu_{od}^B. \quad (5)$$

A and B are expressed in terms of the solution gas/oil ratio, R_{so} , of the crude oil. A detailed revision of such correlations was given by Bergman and Sutton (2007b).

4. UNDERSATURATED OIL VISCOSITY CORRELATIONS

In this study, a total of 13 undersaturated oil viscosity correlations were considered for review. Table 1 summarizes those correlations alphabetically along with their defining equations. All correlations use viscosity at the bubble-point pressure, μ_{ob} , as the common correlating parameter. A plot of the log of viscosity ratio, $\ln(\frac{\mu_o}{\mu_{ob}})$ versus pressure differential, $(p - p_b)$, results in a linear relationship expressed by

$$\ln\left(\frac{\mu_o}{\mu_{ob}}\right) = \alpha(p - p_b), \quad (6)$$

where α is the slope of the line. Rearranging and solving for undersaturated oil viscosity, the previous equation takes the final form as

$$\mu_o = \mu_{ob} e^{\alpha(p - p_b)}. \quad (7)$$

The fit to experimental data may be satisfied via fine tuning the term. Many researchers have proposed different expressions for α . Kouzel (1965) has proposed this expression:

$$\alpha = 5.50318 \times 10^{-5} + 3.77163 \times 10^{-5} \mu_{ob}^{0.278}. \quad (8)$$

TABLE 1
Defining Equations of the Undersaturated Oil Viscosity Correlations

#	Reference	Correlation
1	Abdul-Majeed et al. (1990)	$\mu_o = \mu_{ob} + 1000 \times 10^{[X-5.2106+1.11 \log [6.894757(P-P_b)]]}$ $X = 1.9311 - 0.89941(\ln R_{sb}) - 0.001194\gamma_{API}^2 + 0.0092545\gamma_{API}(\ln R_{sb})$
2	Al-Khafaji et al. (1987)	$\mu_o = \mu_{ob} + 10^{[X+1.11 \log [0.07031(P-P_b)]]}$ $X = -0.3806 - 0.1845\gamma_{API} + 0.004034\gamma_{API}^2 - 3.716 \times 10^{-5}\gamma_{API}^3$
3	Almehaideb (1997)	$\mu_o = \mu_{ob} \left(\frac{P}{P_b} \right)^{(0.134819+1.94345 \times 10^{-4} R_{sb}-1.93106 \times 10^{-9} R_{sb}^2)}$
4	Beal (1946)	$\mu_o = \mu_{ob} + [0.001(P - P_b)](0.024\mu_{ob}^{1.6} + 0.038\mu_{ob}^{0.56})$
5	Bergman and Sutton (2006)	$\mu_o = \mu_{ob} e^{\alpha(P-P_b)\beta}$ $\alpha = 6.5698 \times 10^{-6} \ln(\mu_{ob})^2 - 1.48211 \times 10^{-5} \ln(\mu_{ob}) + 2.27877 \times 10^{-4}$ $\beta = 2.24623 \times 10^{-2} \ln(\mu_{ob}) + 0.873204$
6	Dindoruk and Christman (2004)	$\mu_o = \mu_{ob} + a_6(P - P_b)10^X$ $X = a_1 + a_2 \log(\mu_{ob}) + a_3 \log(R_{sb}) + a_4\mu_{ob} \log(R_{sb}) + a_5(P - P_b)$ Where: $a_1 = 0.776644115$ $a_4 = 0.009147711$ $a_2 = 0.987658646$ $a_5 = -0.000019111$ $a_3 = -0.190564677$ $a_6 = 0.000063340$
7	Kartoatmodjo and Schmidt (1991)	$\mu_o = 1.00081\mu_{ob} + 1.127 \times 10^{-3}(P - P_b)(-6.517 \times 10^{-3}\mu_{ob}^{1.8148} + 0.038\mu_{ob}^{1.59})$
8	Khan et al. (1987)	$\mu_o = \mu_{ob} e^{9.6 \times 10^{-5}(P-P_b)}$
9	Kouzel (1965)	$\mu_o = \mu_{ob} e^{\alpha(P-P_b)}$ $\alpha = 5.50318 \times 10^{-5} + 3.77163 \times 10^{-5}\mu_{ob}^{0.278}$
10	Kouzel (1997)	$\mu_o = \mu_{ob} e^{\alpha(P-P_b)}$ $\alpha = 2/34974 \times 10^{-5} + 9.30705 \times 10^{-5}\mu_{ob}^{0.181}$
11	Orbey and Sandler (1993)	$\mu_o = \mu_{ob} e^{\alpha(P-P_b)}$ $\alpha = 6.76 \times 10^{-5}$ for paraffinic hydrocarbons $\alpha = 7.24 \times 10^{-5}$ for alkyl-benzenes and cyclic hydrocarbons $\alpha = 6.89 \times 10^{-5}$ for average
12	Petrosky (1990)	$\mu_o = \mu_{ob} + 1.3449 \times 10^{-3}(P - P_b)10^{X_2}$ $X_2 = -1.0146 + 1.3322X_1 - 0.4876X_1^2 - 1.15036X_1^3$ $X_1 = \log(\mu_{ob})$
13	The present study	$\mu_o = \mu_{ob} e^{\alpha(P-P_b)}$ $\alpha = 6.265 \times 10^{-5} e^{\left[\frac{7.141 \times 10^{-4}(P-P_b)^{938}}{\mu_{ob} + 4.347 \times 10^{-3}(P-P_b) - 79.1} \right]}$
14	Vazquez and Beggs (1976)	$\mu_o = \mu_{ob} \left(\frac{P}{P_b} \right)^{[2.6P^{1.187} 10^{(-3.9 \times 10^{-5} P - 5)}]}$

Khan et al. (1987) set α to a constant value of $9.6 \times 10^{-5} \text{psi}^{-1}$ for Saudi crude oils. Orbey and Sandler (1993) set α to a constant value of $6.76 \times 10^{-5} \text{psi}^{-1}$ for paraffinic hydrocarbons and $7.24 \times 10^{-5} \text{psi}^{-1}$ for alkyl-benzenes and cyclic hydrocarbons. Kouzel (1997) updated the original Kouzel (1965) expression to the following:

$$\alpha = -2.34864 \times 10^{-5} + 9.30705 \times 10^{-5} \mu_{ob}^{-.181}. \quad (9)$$

Bergman and Sutton (2006) have inserted an exponent, β , to the pressure differential to account for the slight downward curvature observed at higher pressure differentials. They expressed Eq. (7) as follows:

$$\mu_o = \mu_{ob} e^{\alpha(P-P_b)\beta}, \quad (10)$$

where α and β are given in terms of μ_{ob} as follows:

$$\alpha = 6.5698 \times 10^{-7} \ln(\mu_{ob})^2 - 1.48211 \times 10^{-5} \ln(\mu_{ob}) + 2.27877 \times 10^{-4} \quad (11)$$

$$\beta = 2.24623 \times 10^{-2} \ln(\mu_{ob}) + 0.873204. \quad (12)$$

In this study, we started with the definition of the formation volume factor of undersaturated crude oils; which is written as

$$B_o = B_{ob} e^{-C_o(P-P_b)}, \quad (13)$$

where C_o is the isothermal oil compressibility. Standing (1947) proposed the following correlation for C_o :

$$C_o = 10^{-6} e^{\left[\frac{\rho_{ob} + 4.347 \times 10^{-3}(P-P_b) - 79.1}{7.141 \times 10^{-4}(P-P_b) - 12.938} \right]}. \quad (14)$$

After testing many variations of Eq. (14) on Eq. (7), the following equation for α is found to be the best form that minimizes the deviation from the experimentally measured data:

$$\alpha = 6.265 \times 10^{-5} e^{\left[\frac{7.141 \times 10^{-4}(P-P_b) - 12.938}{\rho_{ob} + 4.347 \times 10^{-3}(P-P_b) - 79.1} \right]}. \quad (15)$$

This equation was found to perform better than all existing correlations presented in this study with the investigated data sets. It represents, however, a starting point for researchers to fine tune it based on their local data sets. The only term in the equation that needs fine tuning is the constant number 6.265×10^{-5} . It may be changed to satisfy the best fit with local data sets. In the absence of experimental data, however, the parameter presented here is of great help.

Two data sets were used to check the performance of correlations along with the new proposed parameter. Figures 1 and 2 are plots of crude oil viscosity versus pressure for correlations of exponential form only. Those correlations were used to generate the undersaturated viscosity. For the dead and saturated viscosity, Khan et al. (1987) correlation was used. The average error (AE) and average absolute error (AAE) indicators are used to check the accuracy of viscosity predictions in this study. As it can be seen from the plots, the proposed value of α matches excellent with maximum AE of -0.977 , maximum AAE of 0.977 , and maximum standard deviation (STDEV) of 0.713 for all correlations.

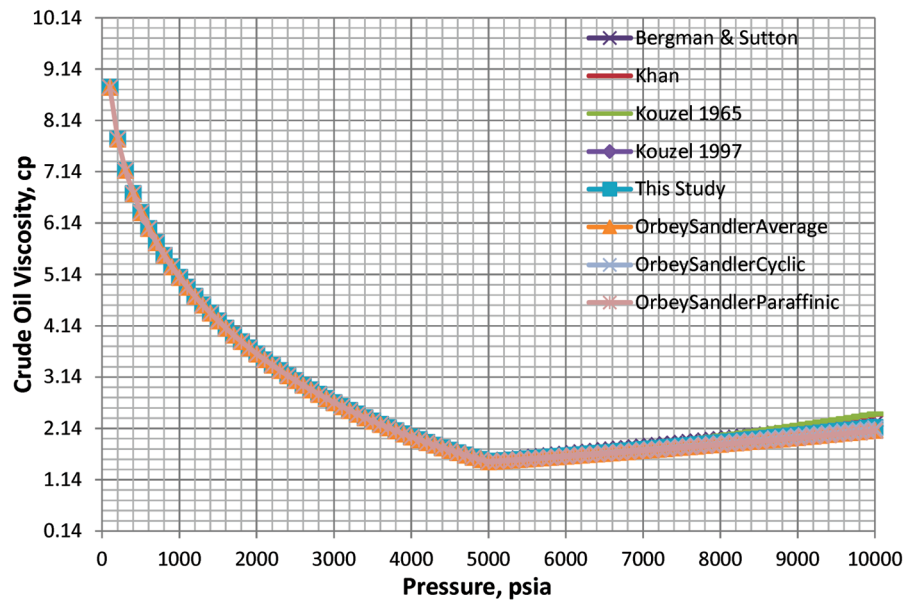


FIGURE 1 Plot of crude oil viscosity versus pressure for the various correlations (Dindoruk and Christman, 2004, Oil A). (color figure available online)

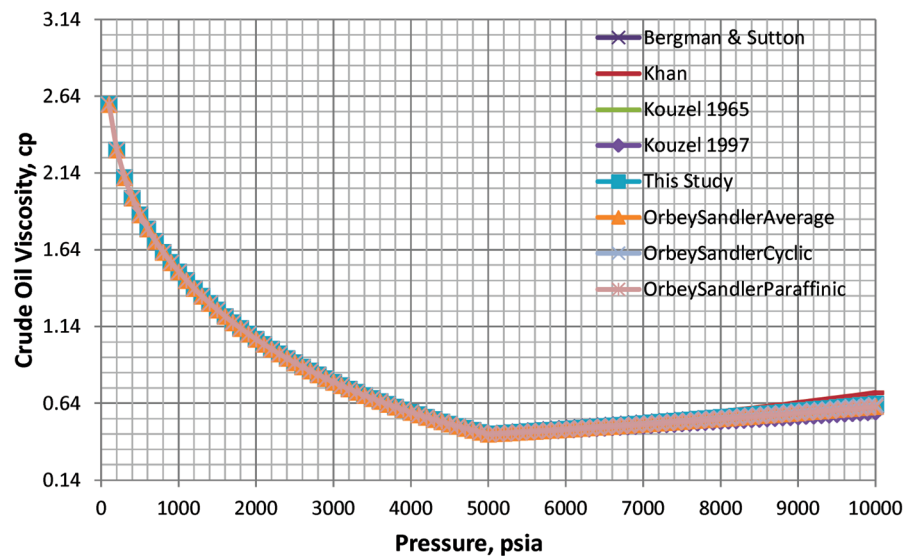


FIGURE 2 Plot of crude oil viscosity versus pressure for the various correlations (Dindoruk and Christman, 2004, Oil B). (color figure available online)

TABLE 2
Dindoruk and Christman (2004) Experimental Input Data Used for
Generating Crude Oil Viscosity for the Various Correlations

<i>Parameter</i>	<i>Oil A</i>	<i>Oil B</i>
$T, ^\circ F$	160	230
$\gamma_g, (air = 1)$	0.7310	0.7072
$^\circ API$	27.4	33.3
$P_b, psia$	5,000	5,000
$R_{sb}, scf/STB$	813	1,049
$T_{sep}, ^\circ F$	68	60
$p_{sep}, psia$	114.7	114.7

5. INPUT DATA

Table 2 presents the experimental input data of two oil samples that were presented by Dindoruk and Christman (2004). The two samples were used to generate the crude oil viscosities for all correlations considered in this study.

6. CONCLUSIONS

1. Two dead oil viscosity correlations that utilize the Watson characterization factor for characterizing crude oils, are recommended. Namely, Twu (1985) and Bergman and Sutton (2007a). These correlations account for crude oil character and tend to give more accurate dead oil viscosity predictions.
2. The saturated oil viscosity correlations, that adopt the scheme proposed by Chew and Connally (1959), are reliable in their viscosity predictions and flexible to account for local data sets.
3. Many correlations were proposed for the evaluation of undersaturated oil viscosity. The set of exponential correlations with pressure differential is reliable and easy to apply. The pressure exponent, α , however, should be fine tuned to mach experimental data.
4. A new expression has been proposed for the α term. We do recommend that the constant term of the pressure exponent, α , be fine tuned to match the experimentally measured data. In the absence of experimental data, however, the α term presented here suffices.
5. Two experimentally generated data sets were used to test all viscosity correlations. The proposed value of matches excellent with maximum AE of -0.977 , maximum AAE of 0.977 and maximum STDEV of 0.713 for all correlations.
6. At higher pressures, all correlations tend to give close predictions for crude oils with API gravity less than $35^\circ API$. For high gravity crude oils, greater than $35^\circ API$, correlations tend to give slightly divergent predictions.

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NOMENCLATURE

AE	average error, %
AAE	average absolute error, %
STDEV	standard deviation
API	oil specific gravity in API units, °API
B_o	oil formation volume factor, bbl/STB
P	current system pressure, psia
P_b	oil bubble point pressure, psia
P_{sep}	separator pressure, psia
R_{sb}	solution gas/oil ratio at the bubble-point pressure, SCF/STB
R_{so}	solution gas/oil ratio at current pressure P, SCF/STB
T	system temperature, °F
T_{sep}	separator temperature, °F
γ_o	oil specific gravity
γ_g	gas specific gravity
μ_o	undersaturated oil viscosity, cp
μ_{ob}	saturated oil viscosity, cp
μ_{od}	dead oil viscosity, cp
ν_o	kinematic oil viscosity, cp
ρ_o	oil density, lb
ρ_g	gas density, lb