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A Rigorous Yet Simple Dead Oil Viscosity Correlation

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A rigorous yet simple correlation for the estimation of dead oil viscosity is proposed. The new correlation requires oil API gravity and system temperature as the only correlation parameters. It calculates the Watson characterization factor as a function of oil API gravity. Hence, the paraffinicity or character of the crude oil is implicitly taken into account. The new correlation was checked against other correlations for a full spectrum of oil API gravities and system temperatures. It performed exceptionally good thus eliminating the lengthy and complex calculation procedure of other correlations.

Keywords: correlation, dead oil, phase behavior, simulation, viscosity

1. INTRODUCTION

During the course of reservoir simulation, the task of calculating dead oil viscosity is required at the initialization stage or whenever oil composition changes. Many correlations were proposed to estimate viscosity of the dead oils at atmospheric pressures and reservoir temperatures. Most common correlations, however, require the dead oil API gravity and reservoir temperature as the only correlating parameters (Naji, 2011). Beal (1946) suggested the following correlation:

$$\mu_{od} = \left(0.32 + \frac{1.8 \times 10^7}{API^{4.5a}}\right)\left(\frac{360}{T + 200}\right)^X \tag{1}$$

$$X = 10^{(0.43 + \frac{8.3a}{API})}. \tag{2}$$

Beggs and Robinson (1975) suggested this correlation:

$$\mu_{od} = 10^X - 1, \tag{3}$$

$$X = 10^{(3.032a - 0.02023API)} T^{-1.16a}. \tag{4}$$

Glasø (1980) suggested the following correlation:

$$\mu_{od} = 3.141 \times 10^{10} T^{-3.44*} (\log(API))^X, \tag{5}$$

$$X = 10.313 \log(T) - 36.447. \tag{6}$$

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Egbogah and Ng (1990) suggested the following correlation:

$$\mu_{od} = 10^{X} - 1, \tag{7}$$

$$X = 10^{1.865a - 0.02508aAPI - 0.56441\log(T)}. \tag{8}$$

Al-Khafaji et al. (1987) suggested this correlation:

$$\mu_{od} = \frac{N}{D}, \tag{9}$$

$$N = 10^{(4.956a - 0.00488T)}, \tag{10}$$

$$D = \left(API + \frac{T}{30} - 14.29\right)^{2.709}. \tag{11}$$

Petrosky (1990) suggested the following correlation:

$$\mu_{od} = A \times B, \tag{12}$$

$$A = 2.3511 \times 10^{7} T^{-2.1025s}, \tag{13}$$

$$B = [\log(API)]^{(4.5938a\log(T) - 22.82792)}. \tag{14}$$

Kartoatmodjo and Schmidt (1994) suggested this correlation:

$$\mu_{od} = A \times B, \tag{15}$$

$$A = 1.6 \times 10^{9} T^{02.8177}, \tag{16}$$

$$B = [\log(API)]^{5.7526\log(T) - 26.9718}. \tag{17}$$

Dindoruk and Christman (2004) have suggested a correlation that requires bubblepoint pressure and solution gas/oil ratio at the bubblepoint pressure as extra parameters. Their correlation is given by

$$\mu_{od} = \frac{a_3 T^{a_4} (\log(API))^{A}}{a_5 p_b^{a_6} + c_7 R_{3b}^{a_8}}, \tag{18}$$

$$A = a_1 \log(T) + a_2, \tag{19}$$

$$a_1 = 14.505357625, \tag{20}$$

$$a_2 = -44.868655416, \tag{21}$$

$$a_3 = 9.36579e9, \tag{22}$$

$$a_4 = -4.194017808, \tag{23}$$

$$a_5 = -3.1461171e - 9, \tag{24}$$

$$a_6 = 1.517652716, \tag{25}$$

$$a_7 = 0.010433654, \tag{26}$$

$$a_8 = -0.00077688. \tag{27}$$

The previous correlations are only few of many excellent correlations found in the literature. The main drawback of such correlations, however, is that they ignore the paraffinicity or character of the crude oil.

Correlations that utilize the Watson characterization factor for defining the paraffinicity or character of the crude oil have been proposed. Those correlations show stable viscosity predictions over a wide range of prevailing temperature. Such correlations were not extensively used by the industry due to their lengthy and complex procedure. Twu (1985) proposed a correlation that requires the dead oil API gravity, reservoir temperature, and Watson characterization factor. Bergman and Sutton (2007) revised Twu coefficients and proposed new regression equations for the kinematic viscosity at the reference temperatures of 100°F and 210°F. Twu' (1985) and Bergman and Sutton' (2007) procedure may be summarized as follows:

$$\mu_{od} = \gamma_{oT} \upsilon_{oT}, \tag{28}$$

where γ_{oT} is the crude oil specific gravity as affected by the temperature T and is given by

$$\gamma_{oT} = 0.999012 \gamma_{o6o} VCF_T, \tag{29}$$

γ_{o6o} is the crude oil specific gravity (γ_o) at 60°F.

VCF_T is the crude oil volume correction factor with a base temperature of 60°F:

$$VCF_T = E^{[-\alpha_{6e} \Delta T(1+0.8\alpha_{6a} \Delta T)]}, \tag{30}$$

α_{60} is the thermal expansion coefficient with a base temperature of 60°F:

$$\alpha_{6o} - \frac{K_0 + K_1 \gamma_{o6o}}{\gamma_{o6o}^2}. \tag{31}$$

The coefficients K_0 and K_1 are given for each liquid of interest. The ASTM D1250-80 (2002) code provides values for both pure components and generalized crude oils, which were updated by Bergman and Sutton (2007) for pure components as

$$K_0 = 3.4175 \times 10^{-4}, \tag{32}$$

$$K_1 = -4.542 \times 10^{-5}. \tag{33}$$

Whereas for the generalized crude oils, the updated values are given by:

$$K_0 = 2.5042 \times 10^{-4}, \tag{34}$$

$$K_1 = 8.3020 \times 10^{-5}. \tag{35}$$

$\Delta T = T - 60$ is the temperature difference between base and current temperatures.

υ_{oT} is the crude oil kinematic viscosity as affected by the temperature T. It is evaluated as follows:

$$\upsilon_{oT} = \psi - e^{\chi}. \tag{36}$$

Other parameters are given by

$$\chi = -0.7487 - 3.295\psi + 0.6119\psi^2 - 0.3193\psi^3, \tag{37}$$

$$\psi = (Z_T - 0.7), \tag{38}$$

$$Z_T = e^{\Gamma}, \tag{39}$$

$$\Gamma = e^{H}, \tag{40}$$

$$H = \ln[\ln(Z_{100})] + B[\ln(T_{Abs}) - \ln(559.67)], \tag{41}$$

$$B = \frac{\ln[\ln(Z_{210})] - \ln[\ln(Z_{100})]}{\ln(669.67) - \ln(559.67)}, \tag{42}$$

$$T_{Abs} = T + 459.67, \tag{43}$$

$$Z_{100} = (v_{100} + 0.7) + e^{[-1.47-1.84(v_{100})-0.51(v_{100})^2]}, \tag{44}$$

$$Z_{210} = (v_{210} + 0.7) + e^{[-1.47-1.84(v_{210})-0.51(v_{210})^2]}. \tag{45}$$

Twu (1985) adopted the following expressions for calculating kinematic viscosities of the crude oil at the two reference temperatures of 100°F and 210°F:

$$v_{100} = e^{ln(v_1+\frac{450}{T_b})(\frac{1+2f_1}{1-2f_1})^2} - \frac{450}{T_b}, \tag{46}$$

$$v_{210} = e^{ln(v_2+\frac{450}{T_b})(\frac{1+2f_2}{1-2f_2})^2} - \frac{450}{T_b}, \tag{47}$$

$$v_1 = e^{0.801621+1.37179\ln(v_2)}, \tag{48}$$

$$v_2 = e^{4.73227-27.0975\alpha+49.4491\alpha^2-50.4706\alpha^4} + 1.5, \tag{49}$$

$$f_1 = 1.33932\xi\Delta\gamma_o - 21.1141\frac{(\Delta\gamma_o)^2}{\sqrt{T_b}}, \tag{50}$$

$$f_2 = \xi\Delta\gamma_o - 21.1141\frac{(\Delta\gamma_o)^2}{\sqrt{T_b}}, \tag{51}$$

$$\xi = \left|1.99873 - \frac{56.7394}{\sqrt{T_b}}\right|. \tag{52}$$

Using nonlinear regression techniques on various forms from Twu (1985), Bergman and Sutton (2007) updated those expressions to minimize the error in the calculated dead oil viscosity. The final resulting equations are given by

$$v_{100} = e^{ln(v_1 + \frac{232.442}{T_b})(\frac{1+2f_1}{1-2f_1})^2} - \frac{232.442}{T_b}, \tag{53}$$

$$v_{210} = e^{ln(v_2 + \frac{232.442}{T_b})(\frac{1+2f_2}{1-2f_2})^2} - \frac{232.442}{T_b}, \tag{54}$$

$$v_1 = e^{0.701254+1.38359\ln(v_2)+0.103604[\ln(v_2)]^2}, \tag{55}$$

$$v_2 = e^{2.40219-9.59688\alpha+3.45656\alpha^2-143.632\alpha^4} + 0.152995, \tag{56}$$

$$f_1 = 0.980633\xi\Delta\gamma_o - 47.6033\frac{(\Delta\gamma_o)^2}{\sqrt{T_b}}, \tag{57}$$

$$f_2 = \xi\Delta\gamma_o - 47.6033\frac{(\Delta\gamma_o)^2}{\sqrt{T_b}}, \tag{58}$$

$$\xi = \left|2.68316 - \frac{62.0863}{\sqrt{T_b}}\right|. \tag{59}$$

Other parameters are given by

$$\Delta\gamma_o = \gamma_o - \gamma_o^o, \tag{60}$$

$$\gamma_o^o = 0.843593 - 0.128624\alpha - 3.36159\alpha^3 - 13749.5\alpha^{12}, \tag{61}$$

$$\alpha = 1 - \tau, \tag{62}$$

$$\tau = 0.533272 + 1.91017 \times 10^{-4} T_b + 7.79681 \times 10^{-8} T_b^2 - 2.84376 \times 10^{-11} T_b^1 + 9.59468 \times 10^{27} T_b^{-1a}. \tag{63}$$

This concludes the correlation of Twu (1985) and its update by Bergman and Sutton (2007). Note, however, that the procedure is lengthy, complex, and requires the boiling point as an extra parameter.

2. THE NEW CORRELATION

In this study, the dead oil viscosity correlation developed by Twu (1985) and its later update by Bergman and Sutton (2007) were used to generate viscosities, as a function of temperature, for API gravities in the range 15–75 at a step size of 5° API. Additionally, viscosities were generated as a function of API gravity, for temperatures in the range 50–700 at a step size of 10°F. Nonlinear regression methods were applied to all data sets of the generated viscosities. The following final

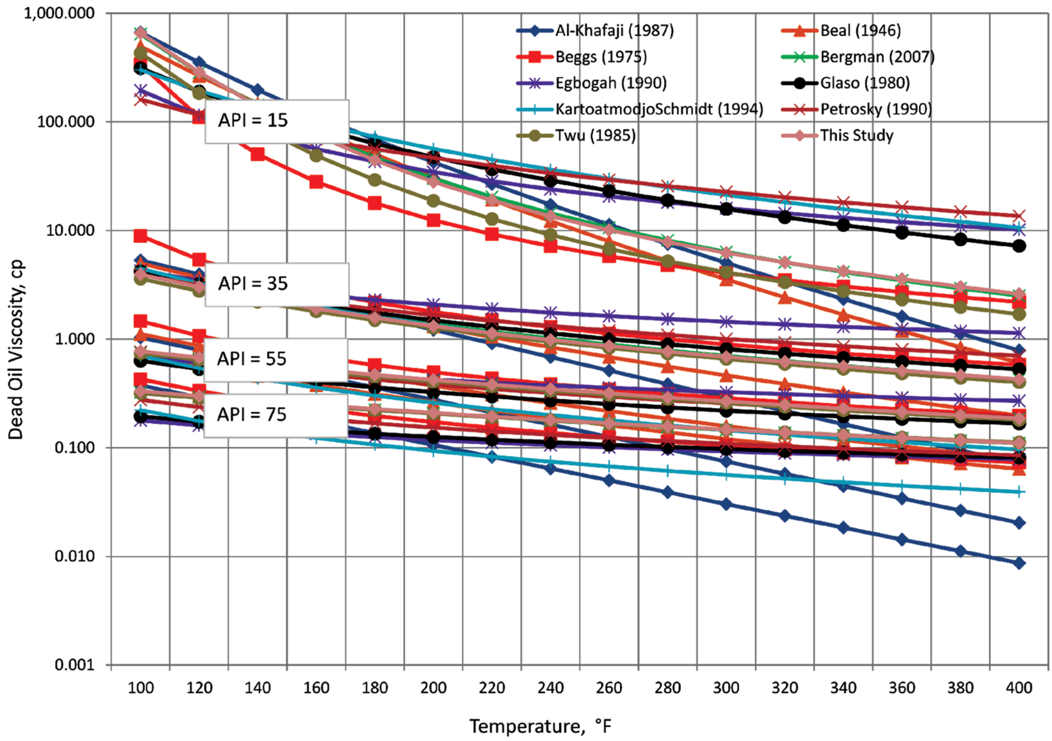

FIGURE 1 Plot of dead oil viscosity versus temperature for the various correlations and four sets of API gravities: 15°, 35°, 55°, and 75° API. (color figure available online)

resulting equations were obtained:

$$\mu_{od} = e^X, \tag{64}$$

$$X = a_o + a_1 API + a_2 API^2 + a_3 API^3 + a_4 API^4, \tag{65}$$

$$a_0 = 32.33430 - 2.087709 \times 10^{-1} T + 6.3561 \times 10^{-4} T^2$$
$$- \; 9.503757 \times 10^{-7} T^2 + 5.495131 \times 10^{-10} T^4, \tag{66}$$

$$a_1 = -1.856230 + 1.154522 \times 10^{-2} T - 3.438567 \times 10^{-5} T^1$$
$$+ \; 5.062298 \times 10^{-2} T^2 - 2.927572 \times 10^{-11} T^4, \tag{67}$$

$$a_2 = 4.429566 \times 10^{-2} - 2.679795 \times 10^{-4} T + 7.636526 \times 10^{-7} T^2$$
$$- \; 1.110438 \times 10^{-9} T^3 + 6.483044 \times 10^{-10} T^4, \tag{68}$$

$$a_2 = -5.036133 \times 10^{-4} + 2.938302 \times 10^{-6} T = 8.082334 \times 10^{-9} T^2$$
$$+ \; 1.174944 \times 10^{-11} T^2 - 6.988541 \times 10^{-15} T^4, \tag{69}$$

$$a_4 = 2.202543 \times 10^{-6} - 1.252737 \times 10^{-8} T + 3.375388 \times 10^{-11} T^2$$
$$- \; 4.955252 \times 10^{-14} T^3 + 3.011429 \times 10^{-17} T^4. \tag{70}$$

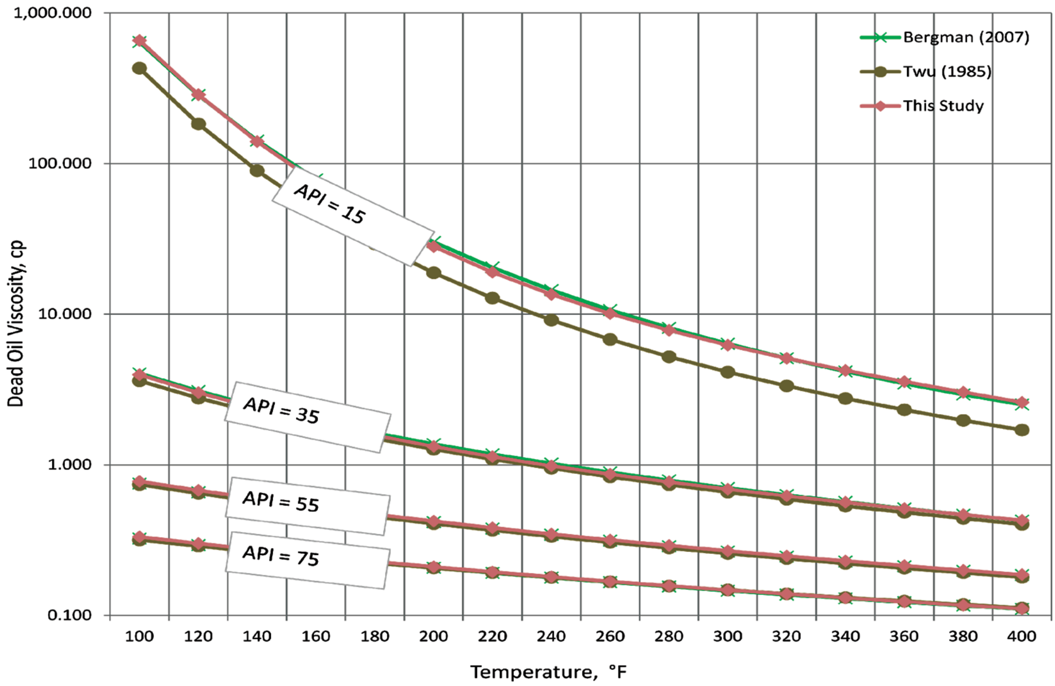

FIGURE 2 Plot of dead oil viscosity for this study and Twu (1985) and Bergman and Sutton (2007) versus temperature for the various sets of API gravities. (color figure available online)

3. RESULTS AND DISCUSSIONS

All dead oil viscosity correlations considered in this study require oil API gravity and system temperature as the only input. Dindoruk and Schmidt (2004) correlation, however, requires bubblepoint pressure and solution gas/oil ratio at the bubblepoint pressure as extra parameters. Therefore, for brevity, this correlation was excluded from the comparisons made in this study. To cover the full spectrum of oil API gravities and system temperatures, dead oil viscosities were generated for API gravities in the range 15–75 and for temperature values in the range 50 to 700°F.

Figure 1 is a plot of the calculated dead oil viscosity versus temperature for the various correlations and for four sets of API gravities 15, 35, 55, and 75. Note how the correlation of this study matches well with Bergman and Sutton (2007) correlation, which is an update to Twu (1985) correlation (see Figure 2). Similarly, Figure 3 is a plot of the dead oil viscosity versus oil API gravity for the various correlations and for four sets of system temperatures, 100, 300, 500, and 700°F. The correlation of this study also matches well with Bergman and Sutton (2007) correlation (see Figure 4).

4. CONCLUSIONS

The dead oil viscosity correlations fall into two categories: the first category requires oil API gravity and system temperature as the only input parameters. This category, however, ignores the paraffinicity or character of the crude oil, which may render it as the least accurate. The second category requires the Watson characterization factor as an extra parameter. Correlations in this

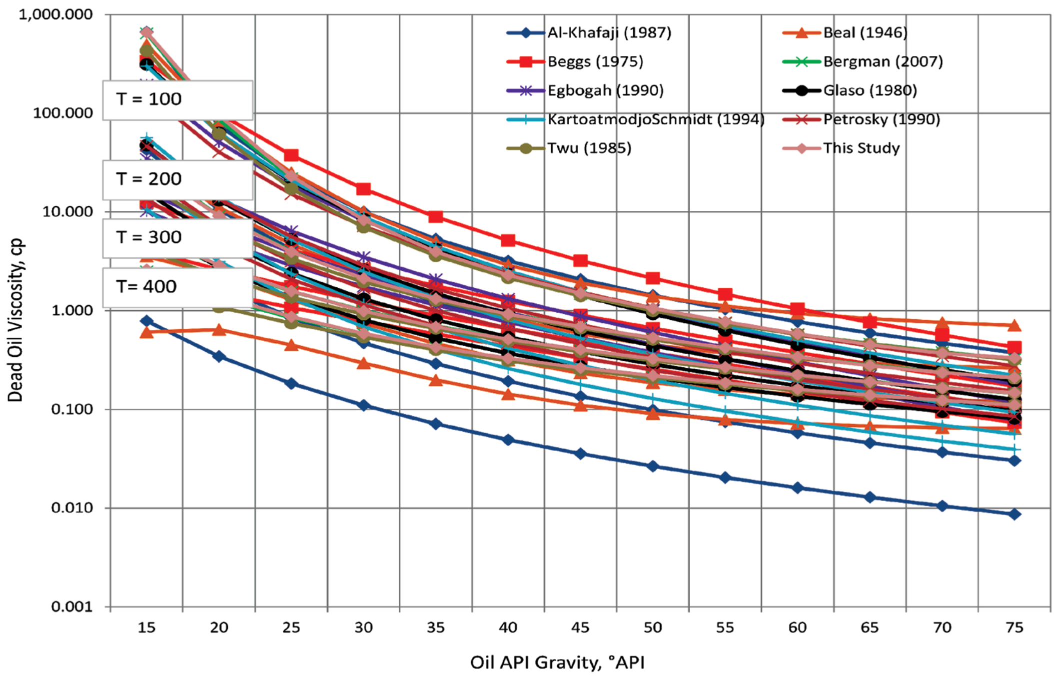

FIGURE 3 Plot of dead oil viscosity versus oil API gravity for the various correlations and four sets of temperatures: 100, 200, 300, and 400°F. (color figure available online)

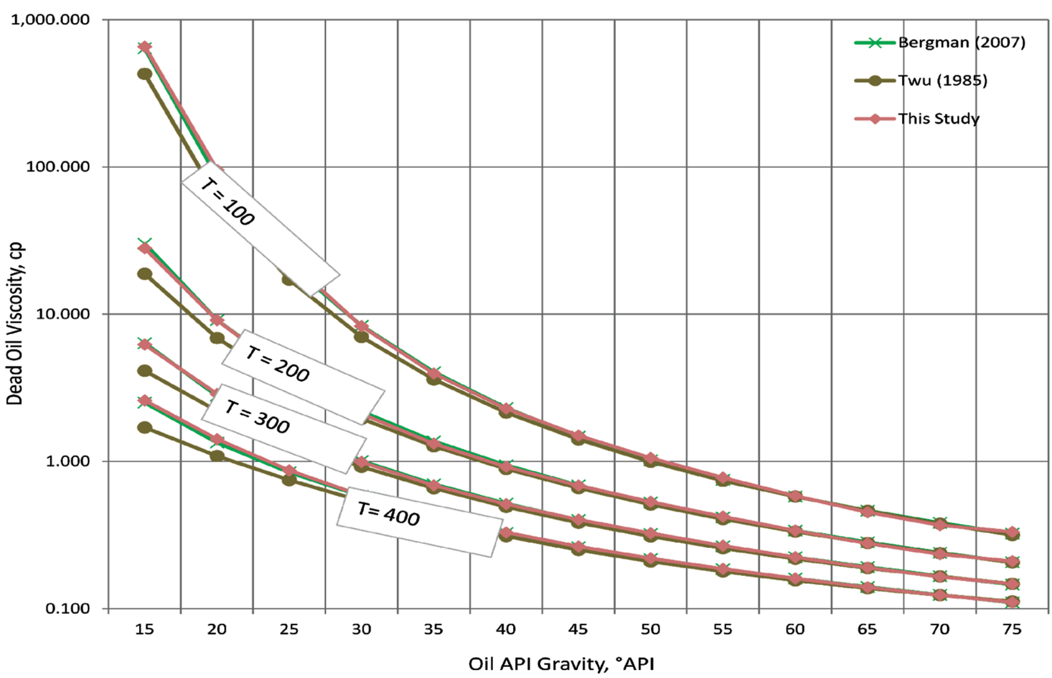

FIGURE 4 Plot of dead oil viscosity for this study and Twu (1985) and Bergman and Sutton (2007) versus oil API gravities for the various temperatures. (color figure available online)

category were ignored due to their lengthy and complex procedure. However, such correlations show stable viscosity predictions over a wide range of prevailing temperature.

A new dead oil viscosity correlation, that considers oil paraffinicity, has been proposed. The correlation requires oil API gravity and system temperature as the only correlating parameters. It implicitly calculates the Watson characterization factor as a function of oil API gravity. Hence the paraffinicity or character of the crude oil is implicitly accounted for. The new correlation is simple and straightforward compared to other correlations of the same category. It is also rigorous in the sense that it matches excellent with the predictions of other correlations with maximum average error of 0.0328 and maximum average absolute error of 0.0328. In conclusion, the new correlation eliminates the lengthy and complex procedure of both Twu (1985) and Bergman and Sutton (2007) correlations. It offers researchers a simple and straightforward method of generating dead oil viscosities.

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NOMENCLATURE

AE average error, $\% = \dfrac{100}{N}\sum_{i=1}^{N}\dfrac{X_{i_{calc}} - X_{i_{meas}}}{X_{i_{meas}}}$

AAE average absolute error, $\% = \dfrac{100}{N}\sum_{i=1}^{N}\left|\dfrac{X_{i_{calc}} - X_{i_{meas}}}{X_{i_{meas}}}\right|$

STDEV	standard deviation $= \sqrt{\dfrac{\sum_{i=1}^{N}(X_i - \overline{X})^2}{N-1}}$
AP!	oil specific gravity in API units, °API
P	current system pressure, psia
P_b	oil bubble point pressure, psia
R_{sb}	solution gas/oil ratio at the bubble-point pressure, SCF/STB
T	system temperature, °F
μ_{od}	dead oil viscosity, cp