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NEW VISCOSITY CORRELATIONS FOR DEAD CRUDE OILS

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Abstract

Based on a non-linear regression method, using relatively a large set of experimental data, new comprehensive correlations for prediction of viscosity of the Iranian heavy and light dead crude oils have been developed. The new models correlate viscosity, °API gravity and temperature for a quite wide range, i.e. 2-570 cP for viscosity and 17-45 for °API gravity. Absolute average deviation (%AAD) of 19.5% and 15.3% are achieved for the heavy (°API=17~28) and light (°API=28~45) crude oils, respectively. A comparison with previous works reveals good prediction ability of the new correlations for the Iranian dead crude oils.

Key words**:** Heavy crude oil; Reservoir; Petroleum; Transport property; Kinematic viscosity; Live oil.

1. Introduction

The evaluation of viscosity of dead crude oil is an important step in the design of various operations in oilfield and refineries. Therefore, viscosity of crude oil, which is pressure and temperature dependent, must be evaluated for both reservoir engineering and operation design. The variation in viscosity with temperature and pressure change is usually predicted empirically.

Despite the importance of viscosity in engineering design, our understanding of such property is inferior to that of equilibrium properties. There are difficulties in obtaining reliable viscosity measurements, especially for live oil, which is, a very important property that should be precisely evaluated for reservoir simulation. However, this property can easily be evaluated using dead oil viscosity.

The viscosity of crude oil varies depending on its origin, type and the nature of its chemical composition, particularly the polar components, for which intermolecular interactions can occur. For example, there is a gradation of viscosity among light, heavy and extra heavy cruds oils, and bitumen. For this reason, developing a comprehensive model of viscosity to include different regions of the world seems to be an impossible task.

There are a number of correlations for predicting crude oil viscosity. These correlations can be categorized into three main groups: dead oil viscosity (μ_{od}), bubble point viscosity (μ_{ob}) and below saturation oil viscosity (μ_b). In general, the correlations utilize oil density and temperature to determine μ_{od}. Beal's correlation was developed in 1946 using data obtained from California crude oil [1]. It is still widely used throughout the oil industry and is considered to be fairly accurate. Beggs and Robinson in 1975 [2]; Glasø in1980 [3]; Labedi in 1992 [4]; Kartoamodjo & Schmidt in 1994 [5]; and Petrosky & Farshad in 1995 [6] developed their correlations for different types of crude oils. Elsharkawy and Alikhan in 1999 [7] have also presented other empirical correlations for estimating dead crude oil viscosity of Middle East crude.

Recently, Naseri et al. in 2005 [8] have developed a correlation for prediction of the Iranian dead oil viscosity.

Brief information for some of the above-mentioned correlations, is presented in table (1). Most of them have expressed dead oil viscosity μ_{od} as a function of both oil °API gravity and temperature. However, in 1990 Egbogah and Ng [9] improved Beggs and Robinson's correlation by adding pour point temperature as a new parameter, but it is neither reported in any usual PVT report nor measured in the field. Mehrotra and Svrcek in 1988 [10] presented a one–parameter viscosity equation for bitumen. This equation was later extended by Mehrotra in 1991 [11] to predict the viscosity of light and medium hydrocarbons. This parameter is evaluated from molar mass, normal boiling point, critical temperature, and acentric factor of components, which are not available for most crude.

Several other empirical and semi-empirical correlations have also been developed from corresponding state equation, e.g. Johnson and Mehrotra in 1987 [12]. Although, these corresponding state correlations involve numerous computations and utilize fluid composition as input variables, their prediction ability of dead oil viscosity is relatively poor.

Table 1. Data used for dead crude oil viscosity correlation

Correlations	Beal	Beggs & Robinson	Glasø	Labedi	Schmidt & Kartomodjo	Elsharkawy & Alikhan	Naseri & et. al.
Year	1946	1975	1980	1992	1994	1999	2005
Source of data	US	Unknown	North sea	Africa	Unknown	Middle East	Iran
°API	10-52	16-58	20-48	32-48	14.4-59	20-48	17-44
Temperature, F	100-220	70-295	50-300	100-306	80-320	100-300	105-295
Viscosity, cP	0.8-188	NA	0.6-39	0.6-4.8	0.5-596	0.6-33.7	0.75-54

Application of dead oil viscosity correlations to crude oils from different sources results in huge errors. These deviations are attributed to the difference in asphaltenic, paraffinic and/or mixed nature of the oils. The aim of this work is to develop comprehensive dead oil viscosity correlations for off-shore and on-shore Iranian crude oils with respect to their nature, which can reliably be employed by reservoir engineers for evaluating live oil viscosity as well as by chemical engineers for design of oilfield and refinery processes.

2. Materials and Methods

A large reliable set of 438 Iranian off and on-shore dead crude oil viscosities was collected in Crude Oil Evaluation department at RIPI over last eight years. These data are meticulously selected from a data set of 473 points. Standard test method of ASTM D-445 was used for kinematic viscosity measurements. All crude oil viscosities were measured at temperatures 10, 20, and 40 °C. ASTM D-5002 method was utilized to measure density and relative density of crude oils.

With respect to °API gravity, data were divided into two major groups. The first group included 85 Iranian heavy crude oil (°API=17 to 28) data-points and the second one contained 353 Iranian light crude oil (°API=28 to 45) data-points. Each data set is also divided into training and test subsets. Randomly, 17 and 43 data points are selected for test subsets of heavy and light crude oil data sets, respectively. Summery information of the data sets is presented in Table 2. The supplied data contain more than one set of viscosity data for each crude oil, providing information for the effect of temperature.

Absolute average deviation (AAD) and root mean square error (RMSE) are used to compare and evaluate the prediction ability of correlations, which are defined as below:

$$\%\mathrm{AAD} = \frac{\sum_{i}^{n} \frac{\left| y_i^{\exp} - y_i^{pred} \right|}{y_i^{\exp}}}{n} \times 100 \quad (1) \qquad \mathrm{RMSE} = \sqrt{\frac{\sum_{i}^{n} \left(y_i^{\exp} - y_i^{pred} \right)^2}{n}} \quad (2)$$

Where n is the number of data points, $y_i^{\exp}$ is the viscosity obtained experimentally and y_i^{pred} is predicted viscosity.

Table 2. Data used for this work

Number of data	440
Temperature, °C	10, 20, 40
°API	17-45
Dead oil viscosity	2-570

Non-linear regression is used for correlating viscosity with °API gravity and temperature by means of training data set. The developed correlations are validated with test data set. Matlab codes (*m*-files) are developed for the mentioned routines.

3. Results and Discussion

The measured viscosities were expressed in centistokes rather than centipoises. To obtain viscosity in centipoises, multiply viscosity in centistokes is by the fluid density (g/cm^3). Fluid densities have been estimated using Standing and Katz method [13] and then viscosities were adjusted accordingly. Knowing the nature of dead crude oils, i.e. composition ranging from light to heavy hydrocarbons, it is not unreasonable to assume that there is not much of light hydrocarbon vaporization at low temperature. Therefore, the °API gravity of the dead crude oil can be assumed to remain near constant at the temperatures studied. Density of crude oil as a function of pressure and temperature can be expressed by the following relationship:

$$\rho = \rho_{sc} + \Delta\rho_P - \Delta\rho_T \tag{3}$$

where ρ is crude oil density (lb/ft^3) at *P* (pressure) and *T* (temperature), ρ_{sc} is crude oil density at standard condition, $\Delta\rho_p$ is density correction for compressibility of oils and $\Delta\rho_T$ is density correction for thermal expansion of oils. Density corrections for compressibility and thermal expansion can be estimated according to Standing's relationships [14]:

$$\Delta\rho_P = [0.167 + (16.181)10^{-0.0425\,\rho_{sc}}](\frac{p}{1000}) \tag{4}$$

$$\begin{aligned}\Delta\rho_T = {} & [0.0133 + 152.4(\rho_{sc} + \Delta\rho_P)^{-2.45}]\times(T-520) - [8.1(10^{-6}) - 90.0622)\times \\ & 10^{-0.764(\rho_{sc}+\Delta\rho_P)}](T-520)^2\end{aligned} \tag{5}$$

where *T* is in °R.

Original data-set, including 473 viscosity data points at three temperatures, is refined for eliminating unreliable data points. It is found that viscosity of dead crude oils, at constant temperature, can be exponentially correlated with ºAPI gravity. Therefore, leverage analysis is examined to discard 35 unreliable data points, which strongly influence each individual correlation, i.e. correlation at constant temperature.

At first, attempt was made to develop a unified model for the entire range of dead crude oil density. Viscosity data were plotted versus ºAPI gravity for each temperature. These plots were found reasonably well fitted by an equation of the form:

$$\mu_{od} = a \times b^{API} + \ln(\sqrt{API}) \tag{6}$$

Coefficients *a* and *b* were regressed against temperature and the following equations were derived:

$$a = -27.698 \times T^2 + 14800.142 \times T - 191095.258 \qquad b = 0.00012 \times T^2 - 0.07068 \times T + 11.24910$$

where *T* is temperature in ^{o}K. Equation (6) shows almost a good agreement with the experimental data. %AAD and RMSE of it for the test data-set are %20.0 and 16.5, respectively, which are comparable with the results of training data, i.e. %21.6 and 14.5 for %AAD and RMSE, respectively. That means, equation (6) is a generalized correlation and is not over-fitted to the data-points. A comparison of the result of this work with some other previous correlations is presented in Table 3. %AAD, RMSE, and regression coefficient (r^2) are used to compare the prediction ability of different models. Table 3 reveals the superiority of the new model, though, %AAD of two models, i.e. Beal [1] and Glasø [3], are lower than this model. This could not be, however, purely attributed to the accuracy of the models in the entire range of oil gravity, since their RMSE and regression coefficients are not as good. The contradiction may be clarified by referring to Fig. 1, which compares the scatter diagrams of this work with Beal's correlation.

This figure shows that the results of Beal's correlation are accurate for viscosities less than about 20 cP (Figs. 1.a and 1.b) which covers 318 data points of the whole data-set, but, its prediction ability for dead crude oil of higher viscosity is weak (Figs. 1.c and 1.d).

Table 3. Comparison of this work with some others correlation (heavy and light)

	This work	Beal (1946)	Naseri et al. (2005)	Kartoatmodjo (1994)	Modified Kartoatmodjo	Glasø (1980)
RMSE	14.8	25.5	46.1	27.3	27.5	69.0
%AAD	21.6	18.9	24.7	17.1	49.1	14.8
r^2	0.954	0.864	0.554	0.844	0.841	0.873

To develop more accurate correlations, it might be useful to discriminate between heavy and light crude oils, since their rheological behavior is quite different. Therefore, two separate equations are derived for heavy (°API less than 28) and light (°API higher than 28) dead crude oils. A simple correlation for heavy oil is found as follow:

$$\mu_{od} = a \times API^{b} \tag{7}$$

where *a* and *b* are temperature dependent parameters which are calculated by means of the following equations:

$$a = -5.9836 \times 10^{7} T^{2} + 3.511 \times 10^{10} T - 5.2145 \times 10^{12}$$

$$b = 0.00418T^{2} - 2.50406T + 368.78706$$

For light dead crude oils the following correlation is found best fitted to the experimental data:

$$\mu_{od} = a \times \frac{e^{(b/API)}}{API} \tag{8}$$

Where

$$a = 0.00735T^{2} - 4.3175T + 641.3572$$

$$b = -1.51T + 568.84$$

The statistical data for training and test data-sets of both correlations are presented in Table 4, which shows that prediction ability for test data-set is comparable with those of training data-set. In other words, the correlations are not over-fitted to the experimental data.

Table (4): Statistical results of heavy and light dead crude oil viscosity correlations for test and training data (Eqs. 7 and 8)

	Heavy dead crude oil		Light dead crude oil	
	Training	Test	Training	Test
%AAD	26.3	12.0	15.4	14.4
RMSE	47.3	13.3	2.43	2.41
r^2	0.930		0.920	

A statistical result of a comparison between the developed correlations with the well-known Beal's correlation and also Naseri et al.'s correlation, which is specially developed for Iranian crude oils, is presented in Table 5. It is clearly shown that, discriminating crude oils to heavy and light categories, and then using new correlations can provide more reliable results. Referring to the scatter diagrams in Fig. 2, predictability of different correlations can also be compared. It is clear that the correlation of this work can reliably predict viscosity of light oils as well as heavy oils (Fig. 2-a), where, Naseri, et al. and Glasø's correlations (Fig. 2-b and 2-c) completely fail to do so for heavy dead crude oils. The results of Beal's, Kartoatmodjo's and modified Kartoatmodjo's correlations are fairly good, however, for heavy oils, they are not as reliable.

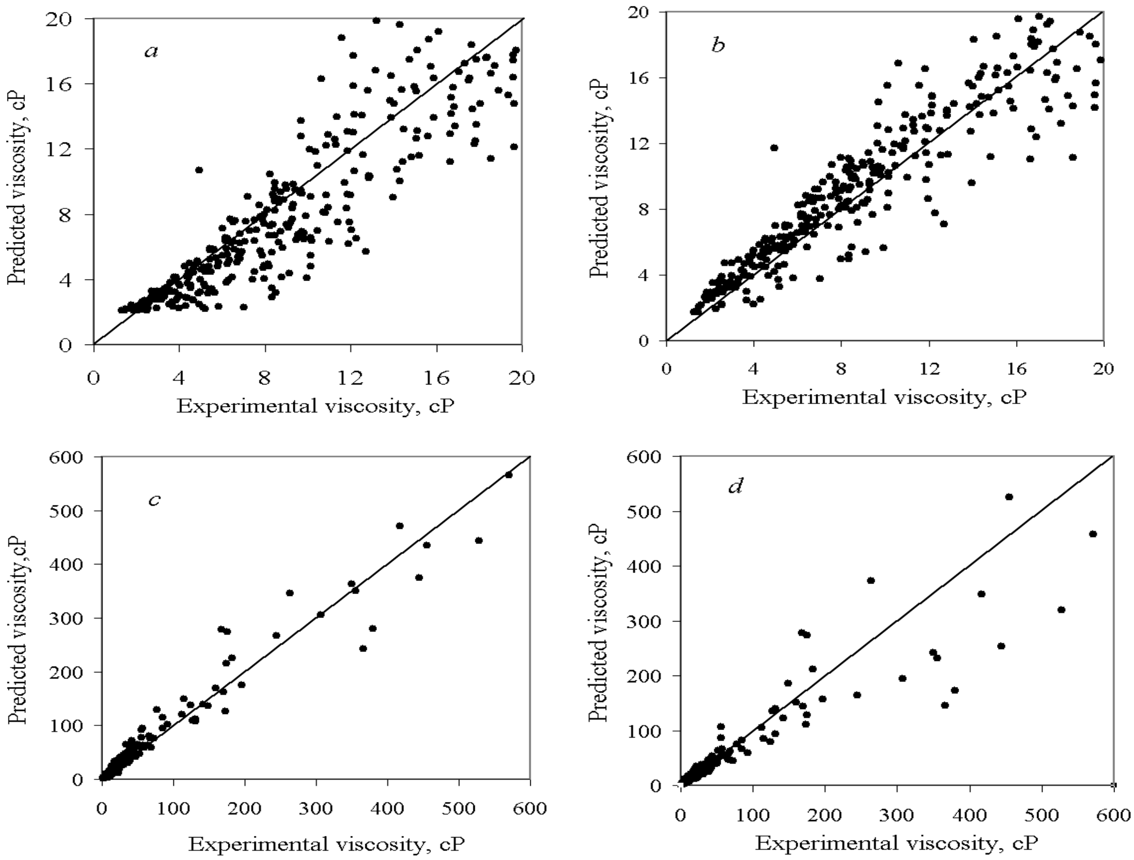

Fig. 1: Scatter diagrams of viscosity prediction from equation 6 (a & c) and Beal's correlation (b & d)

Table (5): Comparison of the new correlations with Beal and Naseri et al.'s correlations

	This work		Beal		Naseri et al.	
	Heavy	Light	Heavy	Light	Heavy	Light
%AAD	21.6	15.3	23.8	17.8	38.5	21.4
RMSE	34.2	2.43	57.6	2.81	104.6	2.95
r^2	0.930	0.920	0.801	0.892	0.343	0.881

4. Conclusion

Three different correlation of viscosity are developed for dead crude oil based on 438 data points. Many of reported viscosity correlations for dead crude oils, are set up for light and medium crude oils. These data are mainly used in reservoir engineering, for live oil viscosity estimation. These correlations are suitably applicable for prediction of light and fairly heavy dead crude oils at elevated temperatures (around reservoir temperature), but they fail at low (ambient) temperatures, especially for heavy crude oils, when accurate results are needed, e.g. transportation processes. Results in Table 3 and Fig. 2 prove this fact. The main aim of this work was to develop a reliable viscosity estimation method for Iranian crude oils. However, it is found that developing a comprehensive viscosity correlation for entire range of viscosity is not achievable by means of a few limited oil parameters such as gravity and temperature. Different oil constituents such as resinous and asphaltenic compounds in heavy crude oils could cause this limitation, since they make the fluid to be a non-Newtonian fluid, i.e. pesudo-plastic. Therefore, two distinct correlations are presented for heavy and light dead crude oils (equations (7) and (8)).

It should be noted that although, Naseri et al.'s correlation has been specially developed for Iranian crude oils, the range of viscosities has been limited to 0.75-54 cP which makes viscosity estimation for of light and heavy oils at ambient temperature highly unreliable.

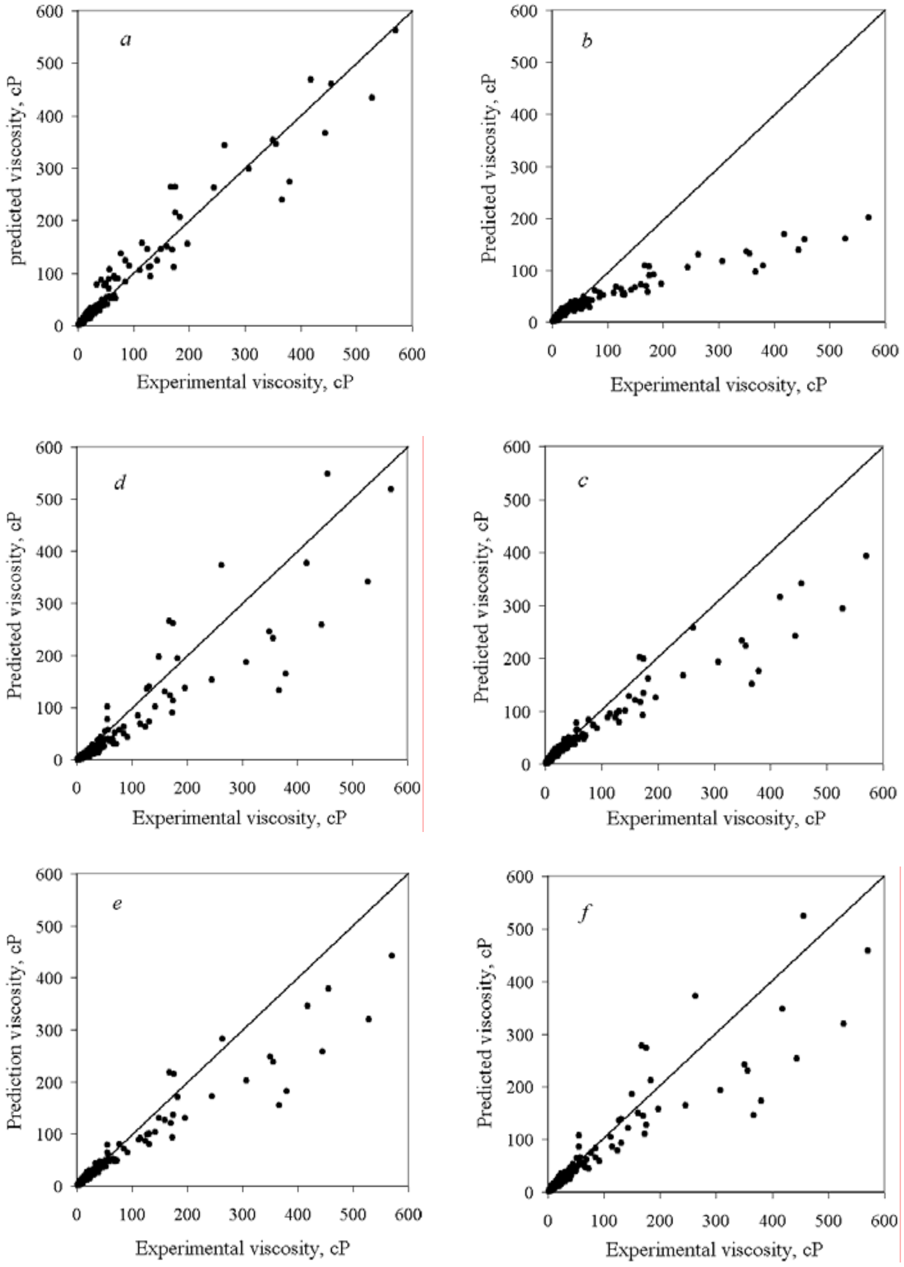

Fig. 2: Scatter diagrams, a) this work, b) Naseri et al., c) Glasø, d) Beal, e) Kartoatmodjo, and f) modified Kartoatmodjo.

Appendix: Viscosity Correlations

Beal :

$$\mu_{od} = \left(0.32 + \frac{1.8\times10^7}{^\circ\mathrm{API}^{4.53}}\right)\left(\frac{360}{T+200}\right)^a$$

$$a = anti\log\left(0.43 + \frac{8.33}{^\circ\mathrm{API}}\right) \quad \text{(A1)}$$

Glasø:

$$\mu_{od} = \left(3.141\times10^{10}\right)\times T^{-3.444}\times\left(\log{}^\circ\mathrm{API}\right)^{[10.313\times(\log T)-36.447]} \quad \text{(A2)}$$

Kartoatmodjo:

$$\mu_{od} = 16\times10^8\times T^{(-2.8177)}\times\left[\log\left(^\circ\mathrm{API}\right)\right]^{(5.7526\times\log(T)-26.9718)} \quad \text{(A3)}$$

Modified Kartoatmodjo:

$$\mu_{od} = 220.15\times10^9\times T^{(-3.5560)}\left[\log(^\circ\mathrm{API})\right]^{(12.5428\times\log(T)-45.7874)} \quad \text{(A4)}$$

Naseri et al.

$$\mu_{od} = anti\ \log(11.2699 - 4.298\log(^\circ\mathrm{API}) - 2.052\log(T)) \quad \text{(A5)}$$

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