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A New Correlation for Prediction of the Kinematic Viscosity of Crude Oil Fractions as a Function of Temperature, API Gravity, and 50% Boiling-Point Temperature

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A new kinematic viscosity–temperature correlation for liquid petroleum fractions has been developed to represent the experimental data for a wide range of temperatures (100 to 400°F, 37.8 to 204.4°C). The only characterization properties required for estimation are the API gravity and the 50% boiling-point temperature (T_b). Fitting parameters have been evaluated for 156 experimental data points from 12 true boiling-point fractions of Arab heavy, Arab medium, and Arab Berri (extralight) crude oils with boiling ranges from 200 to 850°F (93.3 to 454.4°C) and also for 102 data points of 34 other world crude oil fractions. In addition, fitting parameters have also been evaluated for both Arabian and other world crude-oil fractions. The proposed correlation fits the kinematic viscosity data with an overall average relative error of 2.75% for the 12 Arabian crude-oil fractions and 4.46% for the 34 other world fractions. The fitting correlation when used for all available experimental data gives an overall average error of only 3.5%.

KEY WORDS: correlation; crude oil fractions, kinematic viscosity.

1. INTRODUCTION

Knowledge of viscosity plays an important role in a variety of engineering problems involving fluid flow and momentum transfer. The viscosity behavior of crude oils is qualitatively similar to that of pure liquids. Oils are known to become less viscous as temperature increases, but no theory

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has yet been formulated to predict precisely the variation in viscosity of liquids with temperature.

Petroleum is a complex mixture consisting mainly of hydrocarbons and contains minor quantities of sulfur, nitrogen, oxygen, and metals. The physical and chemical characteristics of crude oils, and the yields and properties of products or fractions made from them, vary considerably and are dependent on the concentration of the various types of hydrocarbons and the minor constituents. Furthermore, analysis in terms of individual components is not practical, which makes the theoretical development of predictive procedures extremely difficult.

Watson et al. [1] presented plots of experimental kinematic viscosity data as a function of the API gravity data and the Watson characterization factor, *K*. The API Technical Data Book [2] replaced these figures with a nomograph for given values of the API gravity and the Watson characterization factor. The kinematic viscosity is given at 100 and 210°F (37.8 and 98.9°C). This has proven to be useful over the years and is at present accepted as an industrywide standard for estimating viscosities of light to moderately heavy oils. In view of the limited experimental kinematic viscosity–temperature data available for crude oils and petroleum fractions, it has not been possible to establish the general reliability of predictions made by this method for the wide variation in properties characteristic of crude oils and petroleum fractions. Abbott et al. [3] reduced the API nomograph to equations with reasonable accuracy but these were found to be subject to singularities [4]. Because of this shortcoming, the correlation cannot be extrapolated into the region where no experimental data are available.

The alternative approach is to develop reliable generalized correlations based on the experimental kinematic viscosity data for a wide range of temperature. The literature contains reports of various proposed forms of viscosity–temperature functions for liquids. Types that have received considerable attention are the exponential and double-exponential forms. Amin and Maddox [5] carried out extensive research work on a correlative procedure for predicting the viscosity of petroleum fractions. They used several modifications of Eyring's [6] equation, and the one which best correlated the viscosity data was found to be of the following form:

$$\nu = Ae^{B/T} \tag{1}$$

where ν is the kinematic viscosity ($1\ \text{cSt} = 10^{-6}\ \text{m}^2 \cdot \text{s}^{-1}$), T is the absolute temperature (in K), and A and B are constants. Numerous attempts were made to relate the constants A and B with characterization properties of the true boiling-point fractions. The properties considered include API gravity, 50% boiling point, molecular weights, and Watson characterization factor. The parameter B was best correlated by the following expression:

$$B = e^{5.471 + 0.00342 T_b} \tag{2}$$

where T_b is the 50% boiling-point (K). This correlation predicts B with an overall absolute average error of 1.8%. A maximum error of 5.52% was estimated for the high-boiling fractions (650–850°F, 343.3–454.4°C) of Arab medium crude oils [7]. It may be noted that B is a function only of the 50% boiling point. The parameter A in Eq. (1) was correlated with the API gravity, 50% boiling-point (T_b), and parameter B by the following expression:

$$A = -0.0339(\mathrm{API})^{0.188} + 0.241(T_b/T) \tag{3}$$

Equation (3) predicts A for the 12 fractions of the Arabian crude oils with an overall absolute average error of 7%. The numeric values of the parameters A and B are given elsewhere [7]. Substitution of Eqs. (2) and (3) into Eq. (1) gives the generalized kinematic viscosity–temperature correlation proposed by Beg et al. [7].

In 1995, Mehrotra [8] used a double-logarithmic relationship developed earlier [9] to fit the kinematic viscosity of crude oils including the 12 Arabian crude-oil fractions. It should be noted that in his work Mehrotra [8] used two parameters to fit the kinematic viscosity vs temperature for each oil fraction at some specific API gravity and 50% boiling-point temperature. A review of some other empirical formulas used for prediction of kinematic viscosity of oil fractions is given in Ref. 10, and a more recent review is given in Ref. 11.

In this work a new correlation that relates kinematic viscosity, temperature, API gravity, and 50% boiling-point for crude-oil fractions has been proposed. This correlation can be used for reliable predictions of the kinematic viscosity–temperature behavior of Arabian as well as other world crude-oil fractions over a wide range of temperature, API gravity, and 50% boiling-point temperature.

2. DEVELOPMENT OF THE NEW VISCOSITY–TEMPERATURE CORRELATION

The development of the generalized correlation is based on Eq. (1), using the kinematic viscosity–temperature data from the 12 fractions of

Arabian crude oils and the 34 other world crude oils. The data cover a wide boiling range among the fractions (200–850°F, 93.3–454.4°C). The proposed correlation is of the form

$$v = a(\mathrm{API})^b\,(T_b/T)^c\,e^{(dT_b+e)/T} \tag{4}$$

where a, b, c, d, and e are fitting parameters. The multilinear regression technique has been used to evaluate the above parameters as follows. Equation (4) can be converted to a linear form by taking the logarithm of both sides of the equation.

$$\ln v = \ln a + b\ln(\mathrm{API}) + c\ln(T_b/T) + d(T_b/T) + e/T \tag{5}$$

The optimized values for the fitting parameters are given in Table I for the 12 Arabian crude-oil fractions (156 data point), for the 34 other world crude-oil fractions (102 data points), and for both groups of data together (258 data points). The coefficient of determination, R^2, and the overall average of the absolute relative error, AARE, are also given in Table I. The units used for T and T_b in Eqs. (4) and (5) are kelvins. If degrees Rankine are to be used for T and T_b, then the same values of the parameters given in Table I can be used except parameter e, which should be multiplied by 1.8. The coefficient of determination, R^2, is defined as

$$R^2 = \sum (v_{i,\,\mathrm{exp}} - v_{\mathrm{avg}})^2 \Big/ \sum (v_{i,\,\mathrm{pred}} - v_{\mathrm{avg}})^2 \tag{6}$$

and the AARE is defined as

$$\mathrm{AARE} = \sum (|v_{i,\,\mathrm{exp}} - v_{i,\,\mathrm{cal}}| / v_{i,\,\mathrm{exp}})/\text{number of data points} \tag{7}$$

Table I. Values of the Optimized Fitting Parameters in Eq. (5), Coefficient of Determination (R^2), and Overall Average of the Absolute Relative Error (AARE)

Crude oil	ln a	b	c	d	e	R^2	AARE (%)
Arabian (156 data points)	−5.747613	−0.896755	−7.681342	7.414199	429.58085	0.998	2.75
Others (102 data points)	−5.623956	−0.552109	−5.955556	6.584445	150.06343	0.986	4.46
All (258 data points)	−6.489436	−0.614916	−7.285711	7.448011	251.94553	0.996	3.40

3. TESTING OF THE NEW VISCOSITY–TEMPERATURE CORRELATION

The accuracy of predictions made by means of the proposed correlation has been estimated by comparing the predicted values of the kinematic viscosity for all the fractions of the Arabian crude oils considered with the corresponding experimental data. Table II lists the average and overall average of the absolute relative error (AARE) involved in prediction for each set of data of the 12 fractions of the three Arabian crude oils.

As shown in Table II, the proposed correlation has been found to fit the data for the low-boiling (200–400°F, 93.3–204.4°C), medium-boiling

Table II. Average and Overall Average of the Absolute Relative Error (AARE) for Arabian Crude Oil Fractions

					AARE (%)			
Crude oil	M	T_b, °F (°C)	API gravity	Temp. Range °F (°C)	API method	Beg et al.	Mehrotra	This work
Arab Berri	5	300 (148.9)	56.00	104–176 (40–80)	7.4	3.8	0.55	0.78
	15	450 (232.2)	43.80	104–356 (40–180)	4.9	1.1	1.19	2.99
	15	575 (301.6)	36.39	104–356 (40–180)	5.2	2.1	1.12	3.62
	17	750 (398.9)	27.79	104–392 (40–200)	32.3	21.2	1.08	2.22
Overall AARE					14.1	8.2	1.00	2.71
Arab medium	5	300 (148.9)	54.17	104–176 (40–80)	6.2	4.8	0.68	0.63
	15	450 (232.2)	43.28	104–356 (40–180)	5.3	1.1	1.08	3.11
	15	575 (301.6)	35.48	104–356 (40–180)	21.7	4.6	0.78	3.56
	17	750 (398.9)	25.67	104–392 (40–200)	29.6	12.3	0.88	2.56
Overall AARE					18.0	6.1	0.86	2.82
Arab heavy	5	300 (148.9)	55.97	104–176 (40–80)	6.2	5.0	0.22	1.00
	15	450 (232.2)	43.13	104–356 (40–180)	4.6	2.6	0.94	3.37
	15	575 (301.6)	34.77	104–356 (40–180)	19.2	3.1	0.71	2.68
	17	750 (398.9)	25.42	104–392 (40–200)	30.0	14.0	0.98	2.66
Overall AARE					17.2	6.7	0.71	2.71
Overall AARE for 156 data points					17.5	7.2	0.92	2.75

(400–650°F, 204.4–343.3°C), and high-boiling (650–850°F, 343.3–454.4°C) Arabian oil fractions, with an overall AARE of about 2.71, 2.82, and 2.71%, respectively. This is compared to 14.1, 18.0, and 17.2% for the API method and 8.2, 6.1, and 6.7% for the Beg et al. method [7]. Also, the proposed correlation fits all the Arabian crude-oil fractions with almost the same accuracy, compared to the relatively high errors involved in the other methods when dealing with high-boiling fractions. It is also clear from Table II that the proposed correlation fits the 156 experimental data points for the 12 Arabian crude-oil fractions (200–850°F, 93.3–454.4°C) with an overall absolute error of 2.75%, compared to 17.5% for the API method and 7.2% for the Beg et al. correlation [7].

In the same way, the proposed correlation has been applied (with new fitting parameters; see Table I) to other available world crude-oil fractions [1]. Table III shows a comparison of the proposed correlation results with the API method and the Beg et al. correlation [7]. The proposed correlation gives an overall absolute average error of 4.46% for 102 experimental data points of viscosity for 34 other world crude-oil fractions. The corresponding overall AARE is 19.1% for the API method and 7.4% for the Beg et al. correlation [7]. It may be concluded therefore that the proposed correlation, which requires only two characterization properties (i.e., the API gravity and the 50% boiling-point temperature) provides a more accurate means of predicting kinematic viscosity–temperature behavior of undefined petroleum fractions. Of the 14 sets of data studied for the worldwide crudes, the present correlation is superior to the Beg et al. correlation [7] for 10 sets of these data, while the Beg et al. correlation gives better predictions for the other 4 sets of data. These sets are for Iranian, Stabilized Arabian, Light Valley, and Waxy crude fractions, as shown in Table III.

The maximum AARE for the Arabian crude fractions was 17% for this work, compared with 38.7% for the Beg et al. correlation [7] and 66.5% for the API method. Also, of the 156 data points, only 4 points give AARE $>10\%$, compared to 36 data points for the Beg et al. work and 94 data points for the API method.

Naturally it is expected that a two-parameter fit for each oil fraction at some specific API gravity and 50% boiling-point temperature would give better results than a general five-parameter correlation used for the 12 Arabian oil fractions independent of their API gravity or their 50% boiling-point temperature. This is the case for Mehrotra's work [8] compared to this work. Table II shows that the AARE in Mehrotra's work is about 0.92%, compared to 2.77% for this work. But when a generalized formula, including the 50% boiling-point temperature, is tried in Mehrotra's work, the AARE becomes 2.53%, compared to 2.77% for this work.

Table III. Average and Overall Average of the Absolute Relative Error (AARE) for the 34 Other World Crude Oil Fractions

Crude oil type	M	T_b, °F (°C)	API gravity	Temp. Range °F (°C)	AARE (%) API method	Beg et al.	This work
California (USA)	3	279.5 (137.5)	49.49	104–212 (40–100)	10.0	11.0	2.84
	3	324.5 (162.5)	44.30	104–212 (40–100)	13.9	12.6	1.23
	3	369.5 (187.5)	41.50	104–212 (40–100)	20.1	39.0	0.58
Overall AARE					14.7	20.9	1.55
Oklahoma (USA)	3	279.5 (137.5)	55.20	104–212 (40–100)	6.1	7.7	1.78
	3	369.5 (187.5)	46.31	104–212 (40–100)	9.3	3.8	0.985
	3	459.5 (237.5)	39.41	104–212 (40–100)	47.8	3.3	4.64
Overall AARE					21.1	4.9	2.47
Pennsylvania (USA)	3	279.5 (137.5)	58.20	104–212 (40–100)	3.9	9.6	2.67
	3	369.5 (187.5)	51.60	104–212 (40–100)	7.6	8.5	5.01
	3	459.5 (237.5)	46.00	104–212 (40–100)	13.5	13.7	10.58
Overall AARE					8.3	10.6	6.09
Wyoming (USA)	3	279.5 (137.5)	53.71	104–212 (40–100)	7.9	9.6	1.87
	3	369.5 (187.5)	47.21	104–212 (40–100)	11.1	6.8	2.85
	3	459.5 (237.5)	40.60	104–212 (40–100)	12.2	7.3	4.63
Overall AARE					10.4	7.9	3.12
Minas (Sumatra)	2	182 (83.3)	71.50	100–130 (37.8–54.4)	16.2	10.5	2.11
	2	301 (149.4)	56.40	100–130 (37.8–54.4)	19.0	6.1	2.23
	3	412 (211.1)	48.60	100–210 (37.8–98.9)	17.3	4.0	1.68
	3	511 (266.1)	41.21	100–210 (37.8–98.9)	22.9	3.1	5.84
	3	590 (310.0)	39.11	100–210 (37.8–98.9)	39.7	5.1	3.17
Overall AARE					23.8	5.4	3.14
Iranian Export	2	194 (90.0)	65.30	100–130 (37.8–54.4)	5.7	11.5	1.11
	3	275 (135.0)	55.45	100–210 (37.8–98.9)	43.2	2.4	5.77
	3	353 (178.3)	49.79	100–210 (37.8–98.9)	63.4	2.6	8.45
	3	434 (223.3)	45.11	100–210 (37.8–98.9)	17.9	1.9	5.57
Overall AARE					35.0	3.9	5.60

Table III. *(Continued)*

Crude oil type	M	T_b, °F (°C)	API gravity	Temp. Range °F (°C)	AARE (%) API method	Beg et al.	This work
Stabilized Arabian	2	245 (118.3)	61.91	100–130 (37.8–54.4)	18.1	5.6	0.54
	3	319 (159.4)	52.89	100–210 (37.8–98.9)	45.3	1.3	6.77
	3	385 (196.1)	47.91	100–210 (37.8–98.9)	39.6	0.9	3.27
Overall AARE					36.4	2.2	3.90
Midway Special	2	212 (100)	57.29	100–130 (37.8–54.4)	11.4	18.4	9.47
	3	354 (178.9)	39.29	100–210 (37.8–98.9)	10.7	4.7	1.97
	3	473 (245.0)	31.11	100–210 (37.8–98.9)	17.7	7.7	10.51
Overall AARE					13.5	9.3	7.05
Boscan	2	360 (182.2)	42.31	100–130 (37.8–54.4)	13.5	6.9	2.07
	3	476 (246.7)	31.91	100–210 (37.8–98.9)	4.7	4.9	1.72
	3	554 (290.0)	27.79	100–210 (37.8–98.9)	13.4	12.2	9.08
Overall AARE					10.1	8.1	4.57
Safania (Saudi Arabia)	2	291 (143.9)	58.31	100–130 (37.8–54.4)	3.6	18.8	15.34
	3	394 (201.1)	48.80	100–210 (37.8–98.9)	21.3	5.0	1.35
Overall AARE					14.2	10.5	6.95
Light Valley	2	319 (159.4)	47.50	100–130 (37.8–54.4)	3.4	3.9	6.82
	2	415 (212.8)	37.50	100–210 (37.8–98.9)	17.1	1.6	4.54
	3	487 (252.8)	31.20	100–210 (37.8–98.9)	24.1	1.5	1.95
Overall AARE					16.2	2.2	4.08
Waxy	2	256 (124.4)	54.09	100–130 (37.8–54.4)	16.1	0.8	6.43
	2	329 (165.0)	46.60	100–130 (37.8–54.4)	13.1	2.9	8.04
	2	423 (217.2)	40.10	100–130 (37.8–54.4)	18.1	3.9	8.49
Overall AARE					15.8	2.5	7.65
Overall average for 102 data points					19.1	7.4	4.46

For the 34 other world fractions, the maximum AARE was 18.6% for this work, compared with 44.7% for the Beg et al. results and 94.4% for the API method. Also, of the 102 data points, only 8 points give an AARE >10%, compared to 25 data points for the Beg et al. work and 77 data points for the API method.

Finally, when the fitting parameters for all crude-oil fractions are used (see last row in Table I), the overall AARE for the 258 data points is 3.5%, with an overall AARE of 2.71% for the 12 Arabian crude fractions and 4.62% for the 34 other world fractions.

4. CONCLUSIONS

A new kinematic viscosity–temperature correlation has been developed for liquid petroleum fractions in the boiling range 200–850°F (93.3–454.4°C), based on a modified form of the Eyring equation and using a combination of the power and exponential forms. For kinematic viscosity predictions, the proposed correlation uses only two characterization properties of the oil fractions (i.e., the API gravity and the 50% boiling-point temperature, T_b). Fitting parameters have been evaluated for available kinematic viscosity vs temperature experimental data.

The correlation has been tested for twelve fractions of three Arabian crude oil fractions over a wide range of temperature from about 100 to 400°F (37.8 to 204.4°C). The correlation, in this case, gives an overall average relative error of 2.75% for 156 viscosity measurements, compared with 17.5% given by the API method and 7.2% for the Beg et al. correlation. Furthermore, the proposed correlation fits the data for 102 experimental points of kinematic viscosity data of 34 other world crude oil fractions with an overall average relative error of 4.46%, compared to 19.1% for the API method and 7.4% for the Beg et al. correlation. The fitting parameters have also been evaluated for both Arabian and other world crude oil fractions. The fitting correlation in this case gives an overall average error of only 3.5%.

NOMENCLATURE

AARE	Average of the absolute relative error
A, B	Constants in Eyring's kinematic viscosity correlation
API	American Petroleum Institute gravity (API = 141.5/SG − 131.5)
a, b, c, d, e	Fitting parameters in Eqs. (4) and (5)
IBP	Initial boiling point
K	Watson characterization factor ($= T_b^{0.33}$/SG, T_b in °R)
M	Number of data points in a given set of data

R^2	Coefficient of determination
SG	Specific gravity at 60°F (288.71 K)
TBP	true boiling point
T	Temperature
T_b	50% boiling-point temperature
ν	Kinematic viscosity ($1\ \mathrm{cSt} = 10^{-6}\ \mathrm{m^2 \cdot s^{-1}}$)

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