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Viscosity Reduction of Heavy Crude Oil by Dilution Methods: New Correlations for the Prediction of the Kinematic Viscosity of Blends

Saeed Mohammadi[1], Mohammad Amin Sobati[2*], and Mohammad Taghi Sadeghi[3]

[1] M.S. Student, School of Chemical Engineering, Iran University of Science and Technology, Tehran, Iran
[2] Assistant Professor, School of Chemical Engineering, Iran University of Science and Technology, Tehran, Iran
[3] Associate Professor, School of Chemical Engineering, Iran University of Science and Technology, Tehran, Iran

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Abstract

Dilution is one of the various existing methods in reducing heavy crude oil viscosity. In this method, heavy crude oil is mixed with a solvent or lighter oil in order to achieve a certain viscosity. Thus, precise mixing rules are needed to estimate the viscosity of blend. In this work, new empirical models are developed for the calculation of the kinematic viscosity of crude oil and diluent blends. Genetic algorithm (GA) is utilized to determine the parameters of the proposed models. 850 data points on the viscosity of blends (i.e. 717 weight fraction-based data and 133 volume fraction-based data) were obtained from the literature. The prediction result for the volume fraction-based model in terms of the absolute average relative deviation (AARD (%)) was 8.73. The AARD values of the binary and ternary blends of the weight fraction-based model (AARD %) were 7.30 and 10.15 respectively. The proposed correlations were compared with other available correlations in the literature such as Koval, Chevron, Parkash, Maxwell, Wallace and Henry, and Cragoe. The comparison results confirm the better prediction accuracy of the newly proposed correlations.

Keywords: Heavy Crude Oil, Kinematic Viscosity, Blending, Genetic Algorithm, Binary Blend

1. Introduction

The increasing global demand for energy as well as the reduction of conventional crude oil resources has made the heavy crude oil as one of the future hydrocarbon resources. Heavy crude oils are more viscous in comparison with the conventional crude oils (Eskin et al., 2011).

One of the major difficulties in the pipeline transportation of heavy crude oils is their very high viscosity. In addition, the mobility of heavy crude oils in reservoirs is also very low, making their production economically unfeasible. Therefore, the viscosity reduction is necessary for the production, transportation, and pumping of heavy crude oils.

* Corresponding Author:
Email: sobati@iust.ac.ir

There are many different methods available such as heating, the oil-in-water emulsion, and dilution for viscosity reduction of heavy crude oils (Saniere et al., 2004). Viscosity decreases rapidly with an increase in the temperature. Therefore, the heating method is one of the interesting ways to improve the flow properties of heavy crude oils. However, there are some technical difficulties for designing pipelines based on the heating method such as thermal expansion of the pipelines, the number of required heating stations, and heat losses (Saniere et al., 2004). Moreover, Ahmed (Ahmed, 2013) stated that the heat treatment can result in the changes of the colloidal structure of crude oil and worsen its rheological properties. In the emulsion method, a dispersion of stable droplets of heavy crude oil in water is formed, which results in a significant decrease in the viscosity of heavy crude oil/water emulsion. Major technical difficulties of this method are the demulsification of crude oil/water emulsion and water recovery and recycling (Saniere et al., 2004). One of the effective methods for the transport of heavy crude oil is mixing it with less viscous solvents such as gas condensate, naphtha, kerosene, and light crudes. This method prevents an increase in the pressure drop, and it reduces the cost of pumping; it also helps the downstream processes such as desalting and dehydration (Aburto et al., 2009).

In this method, heavy crude oil is mixed with a solvent or diluent in order to achieve a certain viscosity. Thus, the viscosity of a crude oil blend depends on the mass or volume fraction and viscosity of each component of the blend. The accurate prediction of the blend viscosity is a challenge, and, in this context, various mixing rules have been proposed in the literature in order to predict the blend viscosity. From the thermodynamic point of view, the mixing rules can be classified as follows (Centeno et al., 2011):

- Pure mixing rules (Arrhenius (Arrhenius, 1887); Bingham (Bingham, 1914); Kendall and Monroe (Kendall & Monroe, 1917); Reid (Reid et al., 1987); Chirinos (Miadonye et al., 2000); Koval (Koval, 1963)).
- Mixing rules based on viscosity blending index (Parkash (Parkash, 2003); Cragoe (Cragoe, 1933); Refutas Baird (Baird IV, 1989); Maxwell (Maxwell, 1950); Wallace and Henry (Wallace & Henry, 1987); Chevron (Riazi, 2005); Al-Maamari and Vatani (Al-Maamari & Vatani, 2015)).
- Mixing rules with additional parameters (Walther (Walther, 1931); Latour (Miadonye et al., 2000); Lederer (Lederer, 1933); Shu (Shu, 1984); Ishikawa (Ishikawa, 1958); Lobe (Lobe, 1973); Barrufet and Setiadarma (Barrufet & Setiadarma, 2003); Panchenkov (Panchenkov, 1950); Reik (Reik, 1955); Al-Besharah et al. (Al-Besharah et al., 1989); Shan-peng et al. (Shan-peng et al., 2007)).
- Mixing rules with a binary interaction parameter (Van der Wyk (Van der Wyk, 1936); Grunberg and Nissan (Grunberg & Nissan, 1949); Tamura and Kurata (Tamura & Kurata, 1952)).
- Mixing rules with an excess function (Ratcliff and Khan (Ratcliff & Khan, 1971); Wedlake and Ratcliff (Wedlake & Ratcliff, 1973)).

In the abovementioned mixing rules, the blend viscosity is a function of the volume or weight fraction and the viscosity of each component involved in the blend. A number of additional parameters are also added to some mixing rules in order to improve the prediction accuracy. Moreover, a part of mixing rules is provided to predict dynamic viscosity, and the other part is applied to the prediction of kinematic viscosity. It should be noted that the prediction of kinematic viscosity is focused in the present work.

In this study, new empirical correlations for viscosity blending index are developed. We tried to provide simple mixing rules with a low number of parameters covering the wide range of kinematic viscosity at higher prediction accuracy in comparison with the available correlations. Genetic algorithm technique was used to determine the parameters of the proposed model. In the current work, the binary blend data points are used to develop the correlations. Furthermore, the data points of ternary blends are also used to evaluate the prediction capability of the proposed correlations. The prediction results are also compared with some correlations available in the literature.

2. Available mixing rules for the prediction of the viscosity of crude oil blends

As mentioned in the previous section, there are several mixing rule models in the literature for the prediction of the kinematic viscosity of crude oil blends. These mixing rules can be classified into two categories, namely weight fraction-based mixing rule models and volume fraction-based ones.

2.1. Available weight fraction-based viscosity models

Table 1 lists the weight fraction-based mixing rule models available in the literature. It should be noted that the mixing rules mentioned in Table 1 are based on the weight fraction and the kinematic viscosity of each component involved in the blend.

Table 1

Weight fraction-based models for the prediction of the viscosity of crude oil blends.

Model name	Model	
Chirinos **(Miadonye et al., 2000)**	$\log\log(\nu_{mix}+0.7) = w_A \log\log(\nu_A+0.7) + w_B \log\log(\nu_B+0.7)$	(1)
Refutas **(Baird IV, 1989)**	$VBI_i = 10.975 + 14.534 \ln\ln(\nu_i+0.8)$	(2a)
	$VBI_\beta = w_A VBI_A + w_B VBI_B$	(2b)
	$\nu_{mix} = \exp\left(\exp\left(\frac{VBI_\beta - 10.975}{14.534}\right)\right) - 0.8$	(2c)
Latour **(Miadonye et al., 2000)**	$\nu = \exp(\exp(a(1-w_B^n) + \ln\nu_B - 1))$	(3a)
	$a = \ln(\ln\nu_A - \ln\nu_B + 1)$	(3b)
	$n = \frac{\nu_B}{0.9029\nu_B + 0.1351}$	(3c)
Wallace & Henry **(Wallace & Henry, 1987)**	$\nu_{mix} = 0.01\exp(\frac{1}{I_{WH}})$	(4a)
	$I_{WH} = w_A I_{WH_A} + w_B I_{WH_B}$	(4b)(4c)
	$I_{WH_i} = \frac{1}{\ln(\frac{\nu_i}{0.01})}$	
Cragoe **(Cragoe, 1933)**	$\nu_{mix} = 0.0005\exp(\frac{1000\ln(20)}{I_{Cr}})$	(5a)
	$I_{Cr} = w_A I_{Cr_A} + w_B I_{Cr_B}$	(5b)(5c)
	$I_{Cr_i} = \frac{1000\ln(20)}{\ln(\frac{\nu_i}{0.0005})}$	

2.2. Available volume fraction-based viscosity models

Table 2 tabulates the volume fraction based mixing rule models available in the literature. It should be noted that the mixing rules mentioned in Table 2 are based on the volume fraction and the kinematic viscosity of each component involved in the blend.

Table 2

Volume fraction-based models for the prediction of the viscosity of crude oil blends.

Model name	Model	
Koval (Koval, 1963)	$\nu_{mix}{}^{-0.25} = x_A \nu_A^{-0.25} + x_B \nu_B^{-0.25}$	(6)
Parkash (Parkash, 2003)	$\nu_{mix} = \exp\left(\exp\left(\frac{VBI_\beta + 157.43}{376.38}\right)\right) - 0.93425$	(7a)(7b)
	$VBI_\beta = x_A\,(VBI)_A + x_B\,(VBI)_B$	(7c)
	$VBI_i = -157.43 + 376.38 lnln(\nu_i + 0.93425)$	
Maxwell (Maxwell, 1950)	$\nu_{mix} = \exp\left(\exp\left(\frac{VBI_\beta - 59.58959}{-21.8373}\right)\right) - 0.8$	(8a)(8b)
	$VBI_\beta = x_A\,(VBI)_A + x_B\,(VBI)_B$	(8c)
	$VBI_i = 59.58959 - 21.8373 lnln(\nu_i + 0.8)$	
Chevron (Riazi, 2005)	$VBI_i = \frac{\log \nu_i}{3 + \log \nu_i}$	(9a)
	$VBI_\beta = x_A\,(VBI)_A + x_B\,(VBI)_B$	(9b)
	$\nu_{mix} = antilog\left(\frac{3VBI_\beta}{1 - VBI_\beta}\right)$	(9c)

3. Data set

850 data points on the kinematic viscosity of crude oil blends were obtained from the related literature. 717 data points on kinematic viscosity (i.e. 584 points on binary blends and 133 points on ternary blends) are based on weight fraction. 133 data points on the kinematic viscosity of binary blends are based on the volume fraction.

The present experimental data set covers wide ranges of kinematic viscosities (i.e. 3.66-4272.39 cSt for volume fraction-based data, and 1.73-15323.38 cSt for weight fraction-based data). Table 3 presents the detailed specifications of the present data set.

Table 3

Detailed specifications of the applied data set.

References	Mixture component		Kinematic viscosity range (cSt)		wt.% based	vol.% based
	Heavy	Diluent	Heavy component	Light component		
(Faris et al., 2015)	Heavy crude oil	Toluene & naphtha	394-574.75	0.571-0.588	√	
(Motahhari et al., 2011)	Live & dead bitumen	Condensate	9.91-156862.74	0.185-0.554	√	
(Rahmes & Nelson, 1948)	Heavy sample oil	Light sample oil	3.58-516.9	2.719-312.1	√	
(Al-Maamari & Vatani, 2015)	Heavy Omani sample oil	Light Omani sample oil	13.19-1157.02	6.67-13.19	√	
(Díaz et al., 1996)	Heavy sample oil	Light sample oil	10.66-496.99	4.44-95.01	√	
(Al-Besharah et al., 1987)	Heavy sample oil	Light sample oil	24.98-2470	4.85-189.1	√	
(Doust et al., 2015)	Residue fuel oil	Acetonitrile	485.07-4981.34	0.412-0.522		√
(Centeno et al., 2011)	3 sample oils	Desulfurized diesel	40-165860	3.1-6		√

It should be noted that about 80% of total data points of blends were randomly selected to develop the models, and the remaining data points (i.e. 20% of the total data points) were used for model validation. More details regarding the applied data set can be found in the supplementary materials.

4. Methodology of the present study

In the present study, several potential correlations are first proposed by the inspiration from the available correlations in the literature. It is worth mentioning that our examined models are in the category of mixing rules based on viscosity blending index from the thermodynamic point of view. The examined correlation forms are listed in Table 4.

Table 4

Some of the models examined for the prediction of the kinematic viscosity of blends.

Try number	Model	Data type
I	$IX_i = \frac{a_1 \ln(\ln(\nu_i + a_2))}{a_3 + \ln(\ln(\nu_i + a_1))}$ $IX = \sum_{i=1}^{n} w_i IX_i$	Weight fraction data

Try number	Model	Data type
II	$\nu_{mix} = \exp\left(\exp\left(\frac{a_3 IX}{a_1 - IX}\right)\right) - a_2$ $IX_i = a_1 + a_2 \ln(\ln(\nu_i + a_3))$ $C = a_4 \ln(\nu_1 \nu_2) + a_5$ $IX = \sum_{i=1}^{n} w_i IX_i + C w_1 w_2$ $\nu_{mix} = \exp\left(\exp\left(\frac{IX - a_1}{a_2}\right)\right) - a_3$	Weight fraction data
III	$IX_i = \frac{a_1}{\ln(\frac{\nu_i}{a_2})}$ $C = \sum_{i \neq j} \ln(\frac{\nu_j}{\nu_i})$ i = 1: n j viscous component $IX = \sum_{i=1}^{n} w_i IX_i + a_3 C$ $\nu_{mix} = a_2 \exp(^{a_1}/_{IX})$	Weight fraction data
IV	$IV_i = \frac{a_1}{\log(\frac{\nu_i}{a_2})}$ $IV = IV_1 x_1 + IV_2 x_2 + a(3) \log(\frac{\nu_1}{\nu_2})$ $\nu_{mix} = a_2 \text{ antilog}(\frac{a_1}{IV})$	Volume fraction data
V	$IV_i = \frac{a_1}{\ln(a_2 \nu_i)}$ $IV = IV_1 x_1 + IV_2 x_2 + x_1 x_2 IV_1 IV_2$ $\nu_{mix} = a_3 \exp(\frac{a_4}{IV})$	Volume fraction data
VI	$IV_i = \ln(\ln(\nu_i + a_1)$ $C = a_2 \ln(\nu_A \nu_B)$ $IV = I_{V_A} x_A + I_{V_B} x_B + C x_A x_B$ $\nu_{mix} = \exp(\exp(IV)) - a_1$	Volume fraction data

Then, the model parameters were determined by the genetic algorithm (GA) through the minimization of the prediction error.

Genetic algorithm (GA) is an optimization algorithm with wide applications. In the present work, average absolute relative deviation (AARD) (Equation 10) is considered as the fitness function in the GA algorithm. The flowchart of the calculation procedure based on GA is depicted in Figure 1.

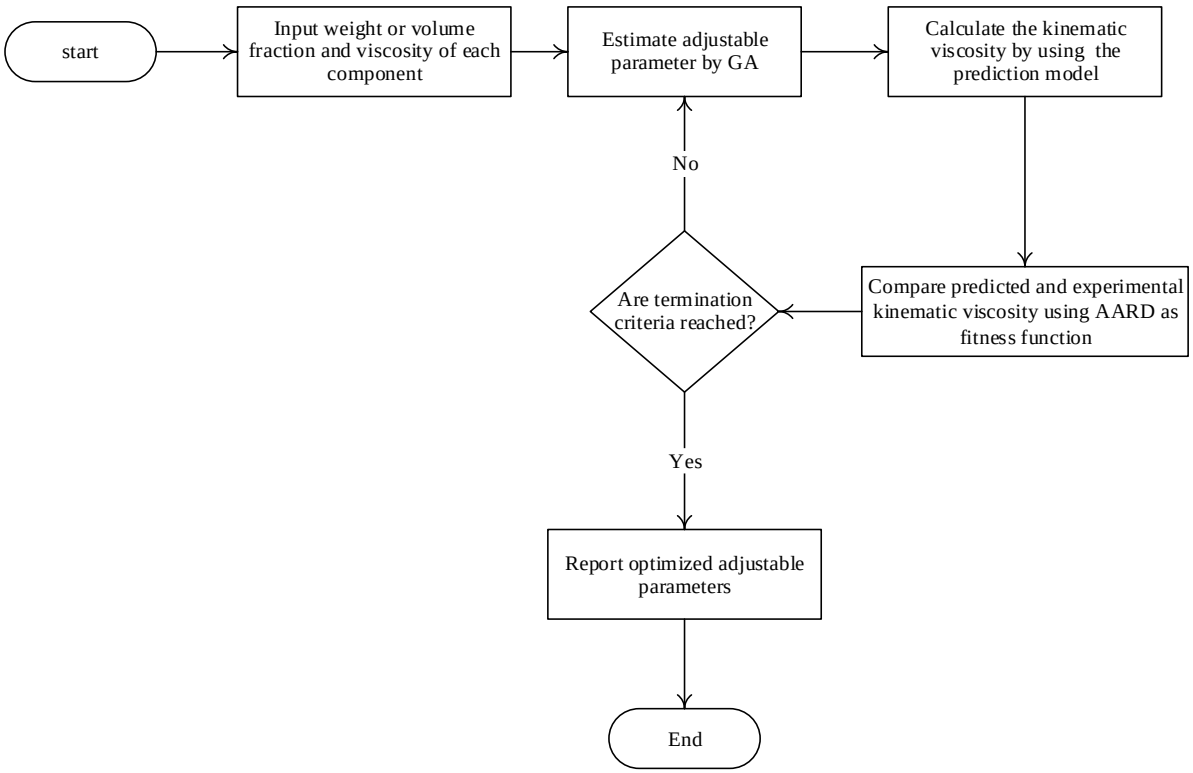


Figure 1

Flow chart of the development of new models using genetic algorithm.

$$\text{=Objective function: AARD (\%)} = \left(\sum_{i=1}^{n} \frac{1}{n} \left| \frac{v_i^{exp.} - v_i^{cal.}}{v_i^{exp.}} \right| \right) \times 100 \quad (10)$$

As can be seen in Figure 1, GA selects preliminary values for the different parameters of the model at first. Then, the kinematic viscosity of the blend is calculated using these parameters. Afterwards, the fitness function, i.e. AARD, is calculated considering the predicted and experimental blend viscosity. To do so, the genetic algorithm was implemented several times to achieve the optimum value for the model constants. Then, if the value of AARD was not in the desired range, a new correlation form should be examined by following the procedure again.

The significant parameters of the genetic algorithm applied to the development of the correlation for kinematic viscosity are tabulated in Table 5.

Table 5

Parameters of the genetic algorithm applied to the development of the correlations.

Genetic algorithm parameters	
Population size	50
Scaling function	Rank
Selection function	Roulette
Mutation function	Gaussian
Crossover function	Two point

5. Results and discussion

Some statistical criteria such as average absolute relative deviation (AARD), root-mean-square deviation (RMSD), and coefficient of determination (R^2) were used to evaluate the developed models.

5.1. Development of the weight fraction-based kinematic viscosity model

Models I, II, and III proposed in Table 4 were matched to the experimental data using GA, and the model parameters were determined. Table 6 presents the results of the fitting procedure for each model in terms of different statistical criteria.

Table 6

Statistical analysis of different examined models.

Model No.	R^2		AARD (%)		RMSD	
	Train	Test	Train	Test	Train	Test
I	0.936	0.955	15.03	14.65	279.8	369.07
II	0.723	0.814	8.40	11.38	2003.34	3255.05
III	0.984	0.998	7.20	7.70	224.47	389.95
IV	0.93	0.86	18.73	18.81	170.65	65.81
V	0.975	0.965	13.65	12.55	103.21	33.91
VI	0.987	0.989	8.67	8.94	75.705	31.204

As can be seen in Table 6, model III shows the best performance in comparison with the other examined models for the weight fraction-based data. The optimized model parameters are as follows: a_1=831.839, a_2=0.011, a_3=0.2; hence, the developed model is given by:

$$IX_i = \frac{831.839}{\ln\left(\frac{\nu_i}{0.011}\right)} \tag{11a}$$

For binary blend: $$C = \ln\left(\frac{\nu_j}{\nu_i}\right) \tag{11b}$$

For ternary blend: $$C = \ln\left(\frac{\nu_j}{\nu_i}\right) + \ln\left(\frac{\nu_j}{\nu_k}\right) \tag{11c}$$

where, j stands for the most viscous component in the blend.

$$IX = \sum_{i=1}^{n} w_i IX_i + 0.2C \tag{11d}$$

$$\nu_{mix} = 0.011 \exp\left(\frac{831.839}{IX}\right) \tag{11e}$$

Table 7 shows the statistical analysis of the available and the newly proposed models for the prediction of kinematic viscosity of binary blends.

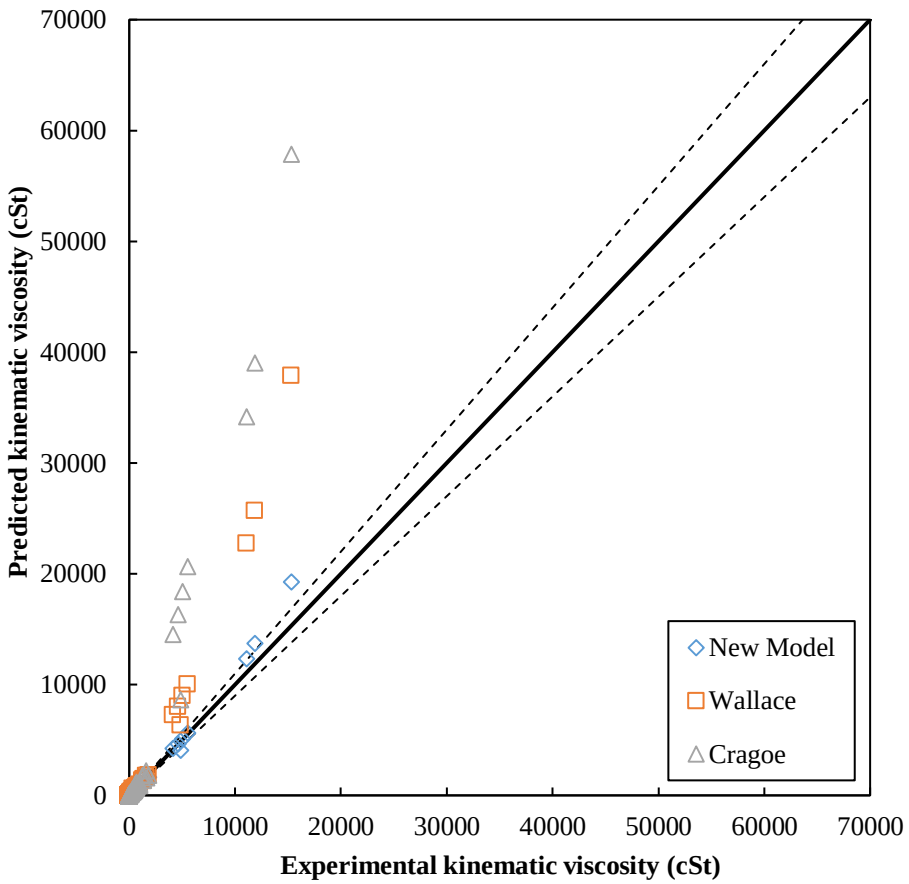
Table 7

Prediction capability of new weight fraction-based model for binary blends in comparison with the other available models.

	Train data		**Test data**	
	RMSD	AARD (%)	RMSD	AARD (%)
Wallace& Henry	1409.10	7.72	2354.26	8.30
Cragoe	2954.11	19.32	4516.69	18.72
New model	224.47	7.20	389.95	7.70

As can be observed, the application of the new GA-based model proposed in this work leads to the minimum AARD in comparison with the available models in the literature. As shown in Table 7, the AARD of the new model is close to the model of Wallace and Henry, but the application of the new model significantly reduces the RMSD. Figures 2 and 3 confirm this claim. It should also be noted that some available mixing rules such as Chirinos, Refutas, and Latour were not examined because these models cannot predict the viscosity of the blend in the range of our data set and support a smaller range of kinematic viscosities.

a)



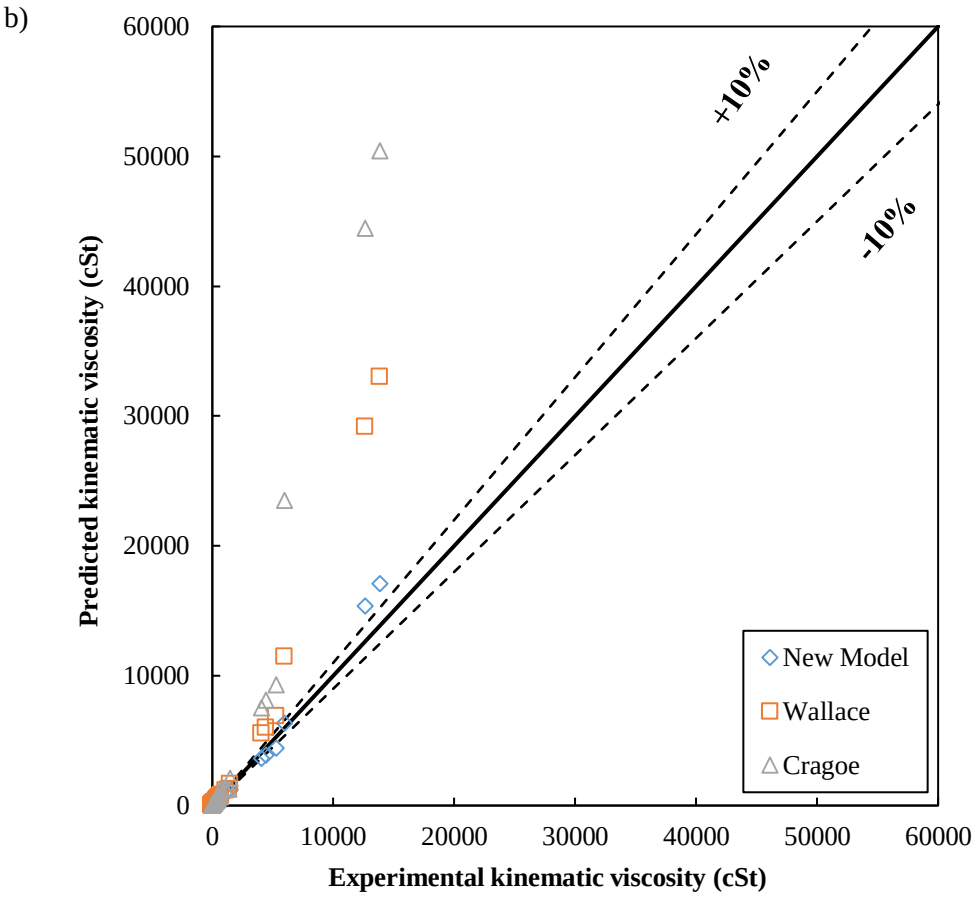


Figure 2

Comparison between the experimental and predicted weight fraction-based kinematic viscosity for binary blends a) the training data and b) the test data.

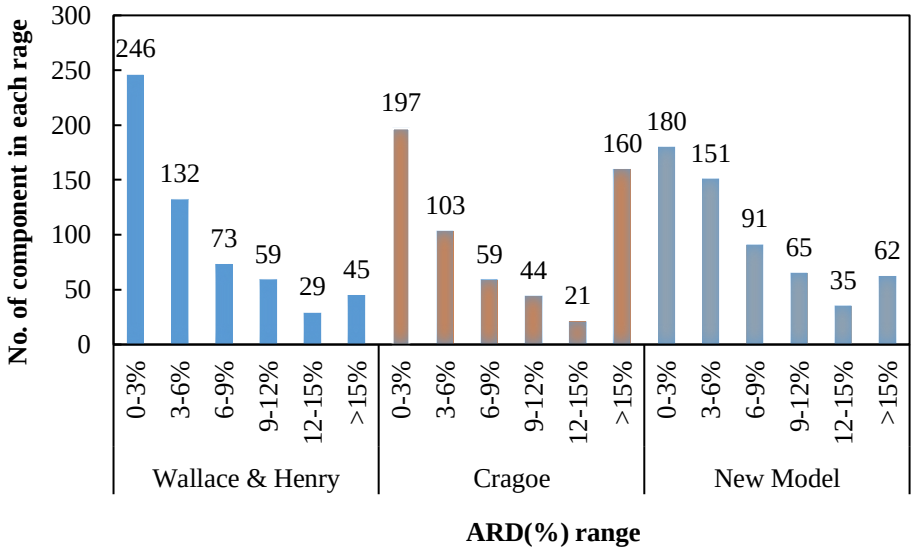


Figure 3

The absolute relative deviation (ARD (%)) of the proposed weight fraction-based model for the prediction of the kinematic viscosity of binary blends; ARD (%) is defined as: $\left|{(\nu_{exp.} - \nu_{cal.})}/{\nu_{exp}}\right| \times 100.$

In Table 8, the results of the comprehensive analysis of the prediction capability of the proposed models applied to different experimental data are summarized.

Table 8

Comprehensive analysis of the new weight fraction-based models applied to different classes of data.

Reference	Mixture component	Mixture type	Prediction error		Description
			Minimum ARD (%)	Maximum ARD (%)	
(Faris et al., 2015)	Heavy crude oil/Toluene & naphtha	B	0.08	40.2	
(Motahhari et al., 2011)	Live & dead bitumen/Condensate	B	0.34	28.85	
(Rahmes & Nelson, 1948)	17 samples of crude oil	B	0.01	13.56	Sample oils API gravity range: 12.3-31.8
(Díaz et al., 1996)	3 sample oils (L, M, and H)	B	0.11	13.57	Density at 20 °C ($g.cm^{-3}$) Sample L: 0.8616 Sample M: 0.8809 Sample H: 0.9911
		T	2.025	22.21	
(Al-Maamari & Vatani, 2015)	3 sample oils (L, M, and H)	B	0.76	58.04	Density at 20 °C ($g.cm^{-3}$) Sample L: 0.830 Sample M: 0.854 Sample H: 0.940
(Al-Besharah et al., 1987)	3 sample oils (L, M, and H)	B	0.011	65.98	Density at 15 °C ($g.cm^{-3}$) Sample L: 0.8445 Sample M: 0.9059 Sample H: 0.9667
		T	0.15	49.95	

B: Binary mixture T: Ternary mixture

As seen, the application of the new models leads to smaller prediction errors for the blend of live and dead bitumen with gas condensate and the blend of the different samples of crude oil with various specific gravity values.

5.2. Development of volume fraction-based viscosity model

Models IV, V, and VI proposed in Table 4 were matched to the experimental data using GA, and the model parameters were determined. Table 6 summarizes the results of the fitting procedure for each model in terms of different statistical criteria.

According to Table 6, model VI provides the best performance in comparison with the other examined models for the volume fraction-based data. The optimized model parameters are as follows: a_1=0.623 and a_2=0.042; hence, the developed model is described by:

$$IV_i = \ln\left(\ln\left(\nu_i + 0.623\right)\right) \tag{12a}$$

$$C = 0.042 \ln\left(\nu_1 \nu_2\right) \tag{12b}$$

$$IV = IV_1 x_1 + IV_2 x_2 + C x_1 \mathrm{x}_2 \tag{12c}$$

$$\nu_{mix} = \exp\left(\exp\left(IV\right)\right) - 0.623 \tag{12d}$$

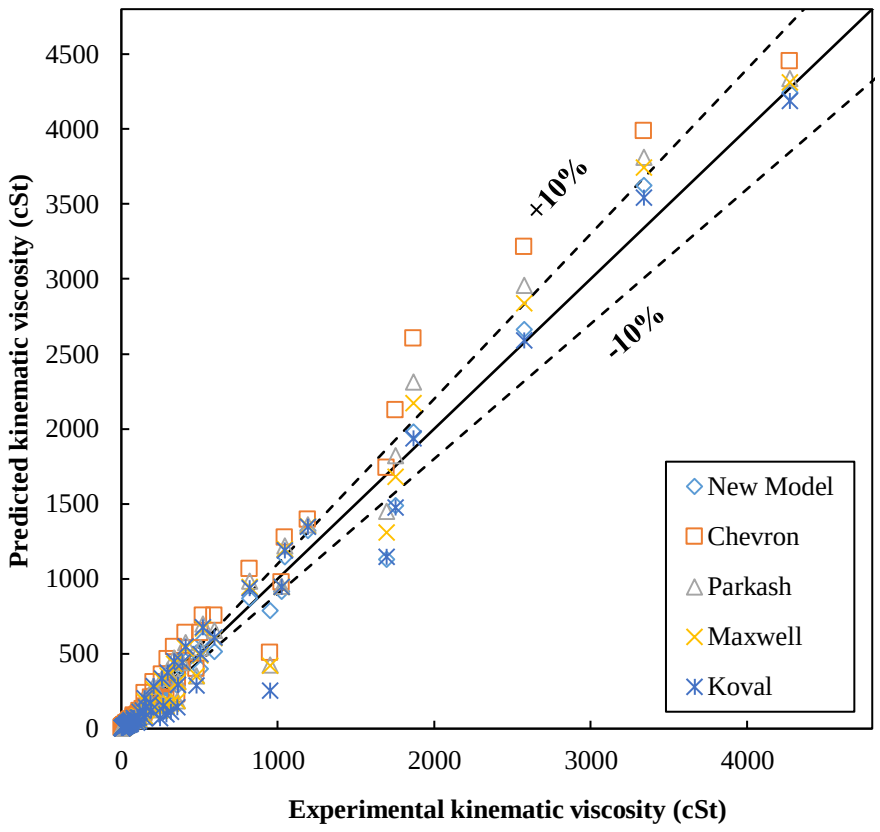
The published models introduced in Table 2 were used for calculating the viscosity of crude oil blends.

Table 9

Prediction capability of the new volume fraction-based model for binary blends in comparison with the other available models.

	Train data		Test data	
	RMSD	AARD (%)	RMSD	AARD (%)
Koval	111.63	19.88	51.59	19.10
Chevron	138.84	14.00	105.48	14.95
Parkash	96.76	17.51	109.63	18.24
Maxwell	85.596	17.47	107.7	17.93
New model	75.705	8.67	31.204	8.94

a)



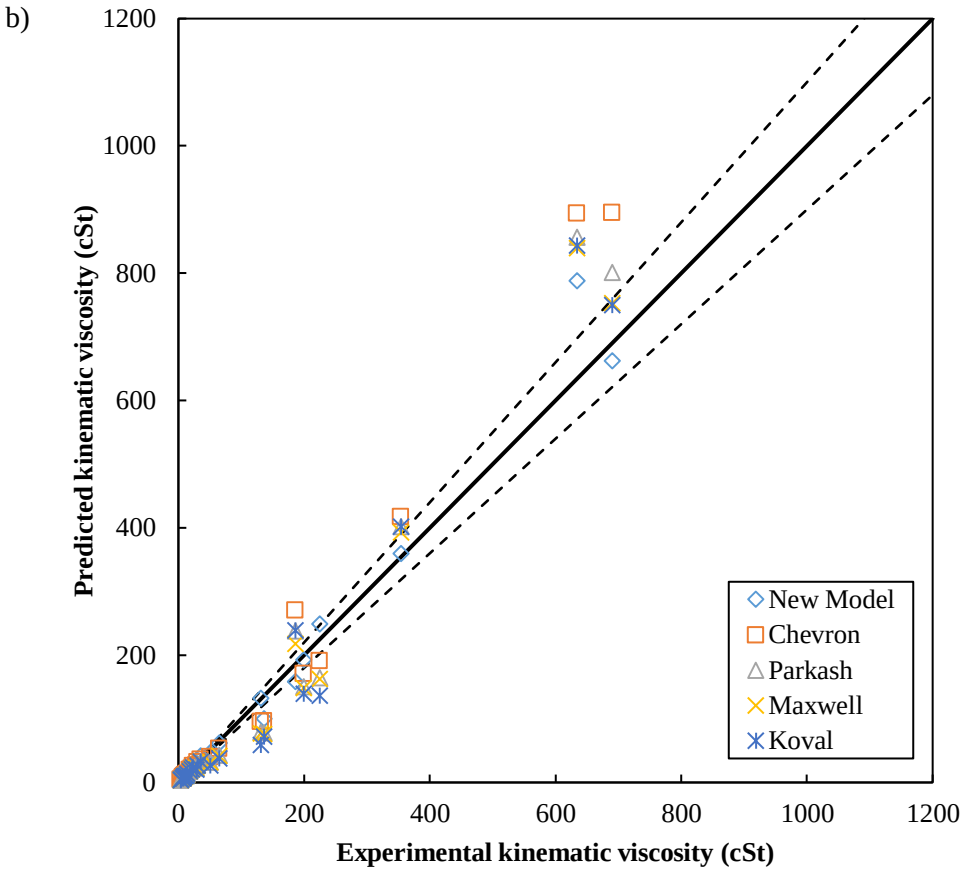


Figure 4

Comparison between the experimental and the predicted volume fraction-based kinematic viscosity for binary blends a) the training data and b) the test data.

As can be inferred from Table 9 and Figure 4, the application of the new GA-based model proposed in this work leads to the minimum AARD in comparison with the available models in the literature; Figure 5 also confirms this claim.

The statistical parameters of these models are presented in Table 9; it is seen that for the volume fraction-based models, Chevron model with AARD≅14% is the best available model in the literature. However, AARD for the new proposed model is significantly smaller in comparison with the other examined models.

In Table 10, the results of the comprehensive analysis of the prediction capability of the proposed models applied to the different experimental data are tabulated.

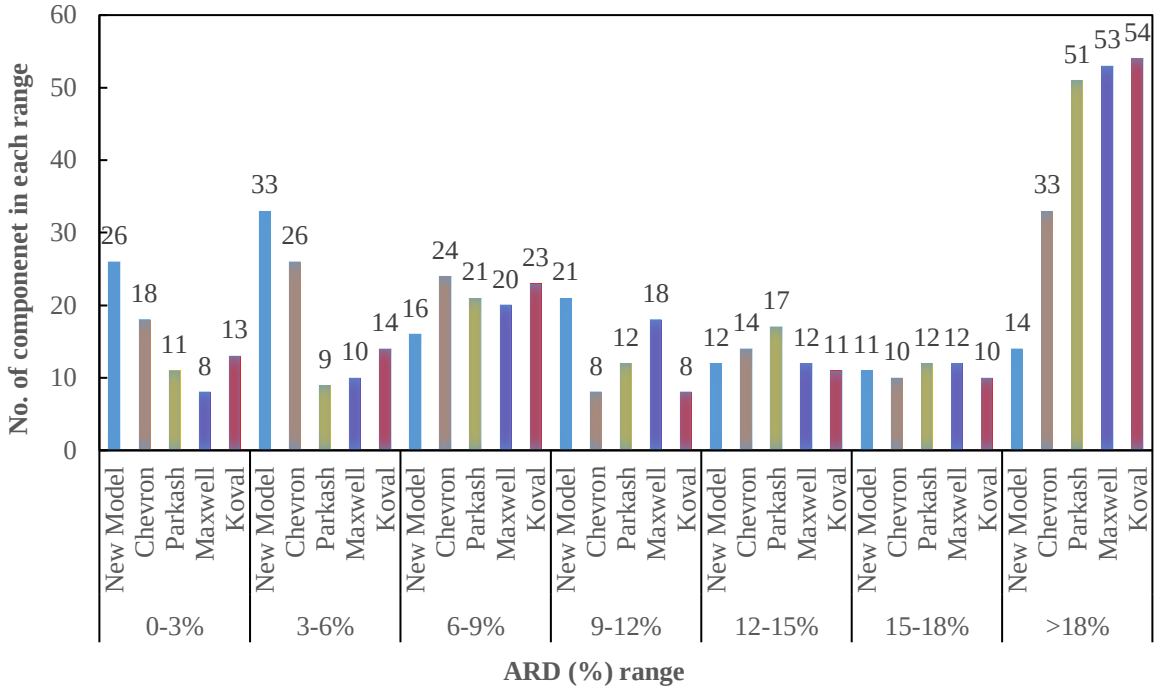


Figure 5

The absolute relative deviation (ARD (%)) of the proposed volume fraction-based model for the prediction of the kinematic viscosity of binary blends; ARD (%) is defined as: $\left|{(\nu_{exp.} - \nu_{cal.})}/{\nu_{exp}}\right| \times 100$.

Table 10

Comprehensive analysis of the new volume fraction-based models applied to different classes of data.

Reference	Mixture component	Mixture type	Prediction error		
			Minimum ARD (%)	AARD (%)	Maximum ARD (%)
(Doust et al., 2015)	Residue fuel oil /Acetonitrile	B	0.07	10.26	33.43
(Centeno et al., 2011)	3 sample oils (L, M, H)/Desulfurized diesel	B	0.006	8.39	26.55

B: Binary mixture

As can be seen, the prediction errors are in the same range for both parts of the experimental data indifferent references.

6. External validation for weight fraction-based new model

The experimental data on the kinematic viscosity of ternary blends are used for model external validation. Figure 6 illustrates the prediction of the newly developed model in comparison with the prediction of the other available models for weight fraction-based data.

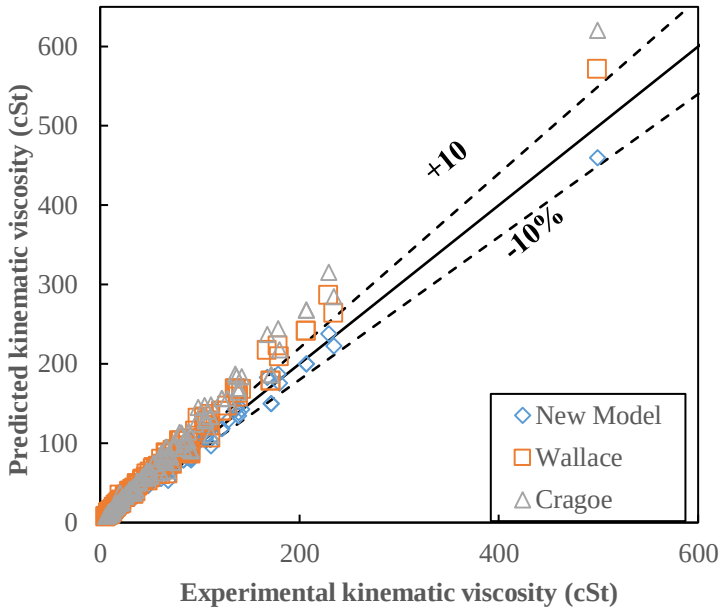


Figure 6

Comparison between the experimental and the predicted weight fraction-based kinematic viscosity of ternary blends as external validation data.

It is clear that the prediction capability of the present model is better in comparison with the other available models. Figure 7 and Table 11 also confirm this claim.

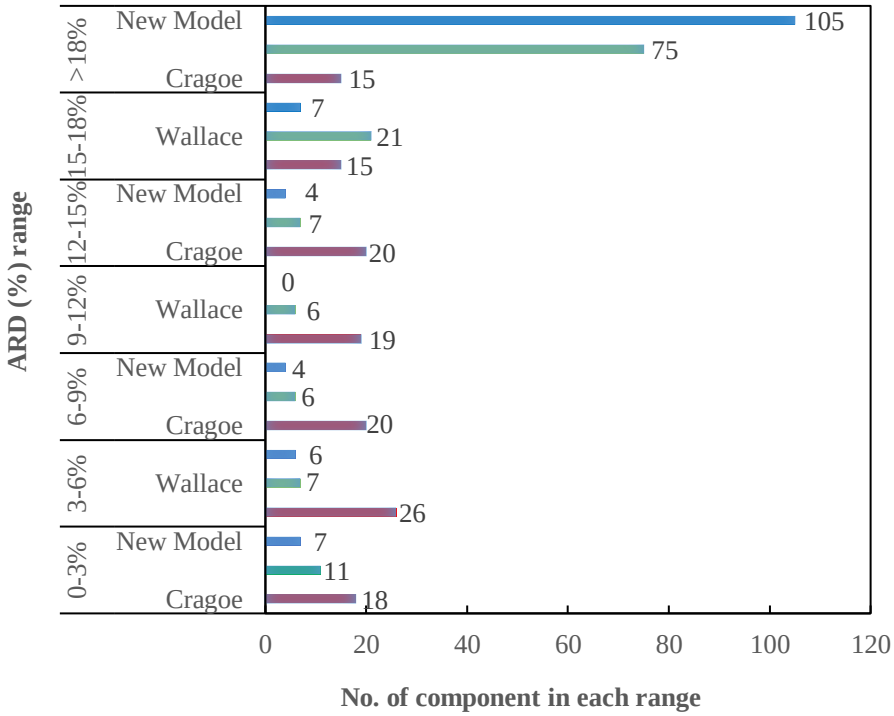


Figure 7

The absolute relative deviation (ARD (%)) of the proposed weight fraction-based model for the prediction of the kinematic viscosity of ternary blends; ARD (%) is defined as: $\left|{(\nu_{exp.}-\nu_{cal.})}/{\nu_{exp}}\right| \times 100$.

Table 11

Prediction capability of the new weight fraction-based model for ternary blends in comparison with the other available models.

	RMSD	AARD (%)
Wallace& Henry	15.84	19.34
Cragoe	24.35	26.62
New model	6.897	10.15

7. Conclusions

In the current paper, new correlations were developed for estimating the viscosity of crude oil blends with diluents. The adjustable parameters of the proposed models were calculated based on a genetic algorithm method. The proposed correlations are simple and easy to apply. The comparison between the estimation of the new correlations and the other correlations available in the literature demonstrates a good estimation capability in a wide range of kinematic viscosity values. The new model can be employed to estimate the weight and volume fraction-based kinematic viscosity of crude oil blends at higher accuracy in comparison with the other models available in the literature. The application of different machine learning methods such as artificial neural network (ANN), support vector regression (SVR), and gene expression programming (GEP) to the development of models predicting blend viscosity can be suggested as a good subject for future studies.

Supplementary data

There are two supplementary Microsoft Excel spreadsheets containing the detailed information on our data points as well as the predicted viscosity using the proposed models and the correlations available in the literature.

Nomenclature

API	API gravity
VBI_i	Viscosity blending index component *i*
VBI_β	Viscosity blending index of the blend
ν	Kinematic viscosity (cSt)
w	Weight fraction
x	Volume fraction

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