An Investigation on the Viscosity Reduction of Iranian Heavy Crude Oil through Dilution Method

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ABSTRACT: *An increase in the global energy demand and also the shortage of conventional crude oil resources have led to an increase in the attention to unconventional crude oil resources. However, unconventional crude oils need additional processes which make their production and refining costly. Therefore, some techniques including heating, dilution, or creating oil in water emulsions have been proposed to solve this problem. In the present study, the dilution method has been investigated to reduce the viscosity of heavy Iranian crude oil produced in the Nowrouz field which has a viscosity of 608 mPa.s and API of 19.5 at 25°C. After a preliminary diluent selection, the examined diluents were kerosene, diesel, and toluene in the range of 5-30% v/v in 25°C. It was found that using toluene at 30% v/v reduces the viscosity of crude oil/diluent blend up to 97% in comparison with initial crude oil. To predict the viscosity of crude oil/diluent blend, simple mixing rules and mixing rules based on the viscosity blending index have been examined. It was found that the prediction accuracy for the crude oil/toluene blends was not satisfactory. Koval, Maxwell, and Almaamari mixing rules showed the best results for predicting the viscosity of blends using kerosene and diesel diluents.*

KEYWORDS: *Heavy crude oil; Viscosity reduction; Dilution; Prediction; Mixing rules.*

INTRODUCTION

The increase in the global demand for crude oil has not been stopped in the last years [1]. However, conventional oil resources are limited. A few solutions to meet this growing demand are proposed, including the production from unconventional resources such as shale gas, shale oil, and heavy crude oil. Heavy crude oil resources have a good potential to meet the future demand for petroleum products [2].

Comparing to the conventional light oil resources, the capacity of unconventional crude oil resources is double. However, the capital expenditure (CAPEX) and the energy required for production is twice. The reason is their high viscosity which leads to low mobility. Also, the presence of several components such as asphaltenes, heavy metals, and sulfur compounds makes production, transportation, and refining more difficult. The presence of asphaltenes can lead to the clogging of transportation pipelines. Also, the separation of sulfur and metal-containing compounds needs additional processing units which increases the refining cost. [3]

Pipeline transportation is a conventional method for transporting the crude oil from the oil production fields to the refineries. However, the pipeline transportation of heavy crude oil without viscosity reduction is a challenge due to the considerable pumping power required

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to overcome the high pressure drop[4]. Specific physical properties of heavy crude oils such as higher values of density and viscosity, and worse fluidity[5] lead to higher pressure drop. For economic pipeline transportation, the viscosity of fluids should be lower than 400 mPa.s[6].

Many studies have been conducted to facilitate the pipeline transportation of heavy crude oil. These studies can be classified into three main categories including partial upgrading, friction reduction, and viscosity reduction. For the viscosity reduction of crude oil, different solutions have been proposed such as emulsification, heating, dilution with lighter components, and adding chemicals[3]. One of the simple methods is dilution of heavy crude oil with a suitable diluent. Dilution method does not requires any additional equipment or increment in the capacity of the existing equipment for the separation of water unlike to the emulsification method. Besides, there is no need for heating and energy consumption in the dilution method unlike to the heating method. Different diluents have been used for this purpose. The summary of the related studies is presented in Table 1.

Gas condensates were used to decrease the viscosity of produced crude oils in Canada. By adding 14% of gas condensate, a viscosity reduction of about 90% can be achieved for heavy crude oils[14]. However, the gas condensates are not good diluents for asphaltene and their use can lead to the pipeline fouling [9]. *Faris et al.*[8] have reported 67% viscosity reduction of Iraqi crude oil through adding 7% of toluene and naphtha. Alcohols and their mixture with other polar diluents can also decrease the crude oil viscosity [6]. According to *Affan* [6], 63% viscosity reduction of Arabian heavy oil could be achieved by adding 30% v/v of toluene, methanol, and ethanol. *Doust et al.* [3] reduced the viscosity of Residual Fuel Oil (RFO) from 4940 cSt to 2679 cSt by adding 5% acetonitrile as diluent. Also, some studies are conducted by adding condensate to the crude oil. *Motahhari et al.* [12] have reported the viscosity reduction of Alberta bitumen from 4000 mPa.s to 10 mPa.s by adding 30% of condensate.

87% viscosity reduction of heavy Kuwaiti crude oil was reported by Alomair[1] by the addition of kerosene, diesel, and light oil as diluent. *Mortazavi-Manesh*[11] has added n-heptane, toluene, and butanone to the Maya crude oil and reduced its viscosity from 14 Pa.s to 1 Pa.s. *Gateau et al.*[15] added naphtha and its mixture with 2-butanol to the Venezuelan heavy crude oil and reduced its viscosity from 500 to 1 mPa.s. In some studies, the effect of diluents such as toluene, and xylene is evaluated [11, 16, 17]. *Homayuni et al.* [7] have studied the effect of naphtha, light crude, and kerosene addition to the viscosity reduction of Soroush and Nowrouz heavy crude oil. According to their report, 75% viscosity reduction of the crude oil can be achieved through dilution method.

Asphaltene concentration is an important parameter affecting the viscosity of the crude oil. *Gateau et al.*[15] measured the viscosity of crude oil in different concentration of asphaltene. According to their report, the change in the viscosity versus asphaltene concentration is less pronounced in the concentration lower than the critical concentration (i.e., 10 % wt. which is called dilute system) in comparison with the concentration range beyond the critical concentration (which is called semi-dilute system). It should be noted that in the dilute system, the asphaltene particles are independent from each other and the viscosity is relatively low. While, in semi-dilute system, the asphaltene particles entangle. This entanglement leads to a dramatic increase in the viscosity of the heavy crude oils.

It should be noted that the main part of previous studies has been carried out in batch mode. However, *Doust et al.*[3], *Motahhari et al.* [12] and *Kariznovi et al.*[18] have evaluated different setups for continuous flow experiments.

In summary, the majority of the previous works is devoted to very viscous crude oils and residues with viscosities higher than 4000 mPa.s. In this kind of crude oil, even adding small amount of diluents leads to a considerable decrease in the viscosity of blend. Since the viscosity of Iranian and Iraqi heavy crude oils are in the range of 600-1600 mPa.s, more studies seems to be required for these crude oils.

Also, regarding the Iranian heavy crude oil, only *Homayouni et al.*[7] have studied the viscosity reduction by adding the kerosene, light crude oil, and naphtha. As a result, few reports are available for the Iranian heavy crude oil. Therefore, in the present study, the effect of addition of different diluents to the viscosity reduction of Nowrouz crude oil as a representative of Iranian heavy crude oils was investigated. Moreover, several available mixing rules for the prediction of the viscosity of crude oil/diluent blends were examined.

Table 1: Some studies on the viscosity reduction of heavy crude oil using diluents.

Oil	Initial viscosity (mPa.s)	Temperature (°C)	diluents	Amount of diluent (% wt)	Max. Viscosity reduction	Reference
Heavy Kuwaiti crude oil (HO)	4,000	25	Kerosene, Diesel, and LCO	20	88	*Alomair et al.* [1]
Maya crude oil	14,000	25	n-heptane, toluene, butane	20	93	*Mortazavi-Manesh* and *Shaw* [11]
Alberta bitumen, condensate, diluted bitumen	4,000	25	condensate	30	99	*Motahhari et al.* [12]
Mukhaizna crude oil	15000	20	kerosene	20	98	*Yaghi* and *Bemani*[13]
Soroosh & Nowrouz crude oils	832 608	25	Naphtha, light crude, and kerosene	0-30 **	75	*Homayuni et al.* [7]
Residue Fuel Oil	4940 *	20	Acetonitrile	0 – 5 **	45	*Doust et al.* [3]
Iraqi crude oil	580 *	27	Toluene, Naphtha	7	66	*Faris et al.* [8]

** viscosity in cSt, ** Concentration in v/v %*

EXPERIMENTAL SECTION

Materials

Iranian crude oil produced in Nowrouz field was selected as the base heavy crude oil. Six diluents including the diesel, kerosene, ethanol, toluene, acetonitrile, and dimethylformamide (DMF) were examined for the viscosity reduction of the crude oil. Kerosene, diesel, ethanol, DMF, acetonitrile, and toluene were supplied from Tehran oil refining company (Iran), Bandar-Abbas oil refining company (Iran), Zanjan Kimia Alcohol (Iran), Merck (Germany), DUXAN (South Korea), and Halal Pouyan Arak (Iran), respectively.

Experimental methods

Density of samples are measured based on ASTM D4052 in 15°C. Then, densities at 25°C are calculated using ASTM D1250. Viscosities of crude oil, kerosene, diesel, and toluene are measured based on ISO 3219. The properties of the examined diluents are mentioned in the Table 2.

Also, the distillation profiles of crude oil, kerosene, and diesel were measured according to ASTM D86. The distillation profile of the examined crude oil was also tested in the vacuum conditions according to the ASTM D1160. The results are presented in Table 3.

The crude oil was diluted with different concentration of the diluents (0%, 5%, 10%, 15%, 20%, 25%, 30% v/v). Rheometry test was carried out using Anton Paar MCR 300 rheometer with Coaxial cylinder measuring system (CC-27) and Double-gap measuring system (DG-26.7) measuring systems. The rheometer was calibrated by silicon oil to prevent the spindle inertia effect. Also, water circulation was applied to maintain the constant temperature (25 ºC) to avoid the viscous heating effect.

DG 26.7 spindle was used to measure the viscosity of fluids below 10 mPa.s. Moreover, CC27 was used for measuring the viscosity of the fluids beyond this limit. Anton paar DM35N was used for measuring the kinematic viscosity. Also, Setavis manufactured by Stanhope-Seta was used for measuring the kinematic viscosity.

Asphaltene concentration was determined according to ASTM D6560. In this regard, the samples were washed with n-heptane and then passed through a filter paper. After drying the filter paper, the asphaltene mass was calculated by subtracting the filter paper mass from the total mass of the residue.

Selection of diluents

For selecting the appropriate diluent, different diluents were examined by preparing 20% v/v mixtures with crude oil. Ethanol, acetonitrile, DMF, diesel, kerosene, and toluene were used in this stage. The three diluents with the best results, were selected for further evaluations.

Sample preparation

For preparation of each sample, the crude oil was mixed for 5 min, firstly. Then, 20 mL of crude oil and the required amount of diluent were mixed at 1200 rpm with

Table 2: Physical properties of the examined diluents.

	Test Method	Ethanol	DMF	Acetonitrile	Toluene
Density (kg/m^3)	ASTM D4052	789	948	786	859
Viscosity, (mPa.s)	ASTM D445	1.1	0.92	0.343	2.9

Table 3: Specifications of the crude oil, kerosene, and diesel.

Property	Crude Oil		Kerosene	Diesel
Density (kg/m^3)	937		797	821
API Gravity	19.5		46	40.9
Viscosity, (mPa.s)	608		2.4	5.2
Asphaltene concentration (% wt)	16		-	-
Distillation range (°C)	ASTM D86	ASTM D1160	ASTM D86	ASTM D86
Initial Boiling Point (I.B.P)	70	-	155	168
5%	134	136	175	188
10%	180	182	183	201
20%	271	265	190	224
30%	337	342	197	245
40%	376	380	203	265
50%	398	388	208	286
60%	400	395	214	299
70%	>400	410	221	313
80%	-	>410	228	327
90%	-	-	238	346
95%	-	-	247	359
FBP	-	-	276	379

a magnetic stirrer (IKA C-Mag HS 7) for 5 min, in 25°C. Then, the samples were kept for one day in order to provide enough time for eliminating the possible air bubbles added to the samples during the mixing. Afterwards, the samples were tested for the rheometry and also the density measurement.

RESULTS AND DISCUSSION

Crude oil rheometry

The result of crude oil rheometry test is shown in the Fig. 1. From 0.1 s^{-1} to 100 $s^{-1,}$ the fluid shows Newtonian behavior (i.e., the viscosity is approximately constant). For evaluating the repeatability of test results, the test was carried out two times for the crude oil. Both measurements are shown in Fig. 1. Coefficient of variation (C.V. %) for the experiments was 3.0.

In this study, we have focused on the Newtonian behavior of the crude oil and its viscosity reduction by adding the diluents. The average viscosity in the Newtonian zone is used for comparison of the effect of addition of different diluents on the viscosity reduction.

It should be also noted that the asphaltene concentration in the Nowrouz crude oil is 16% wt. It is higher than the critical concentration of asphaltene which is 10%. Therefore, it seems that the addition of diluents and subsequent decrease in the asphaltene concentration, can decrease the viscosity of the blend, considerably.

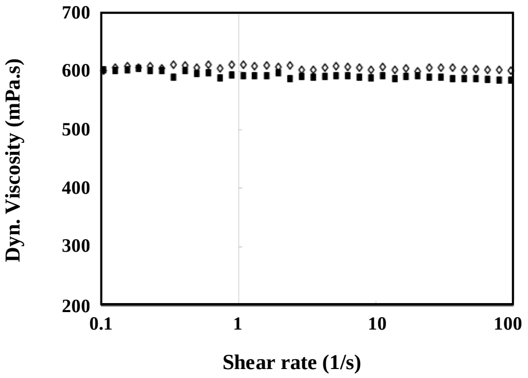

Fig. 1: Rheometry results of the Nowrouz crude oil (test 1: ◊, test 2 :■).

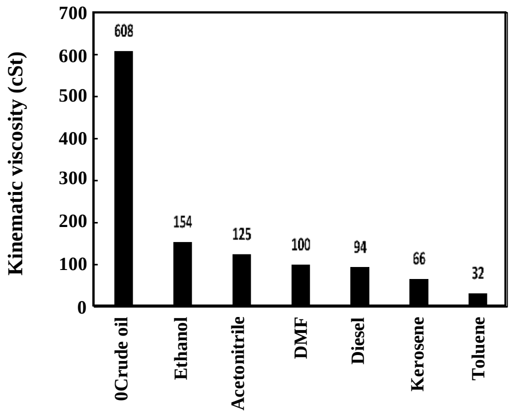

Fig. 2: The effect of addition of different diluents (with 20 % v/v) on the viscosity of the crude oil and diluent blend at 25°C.

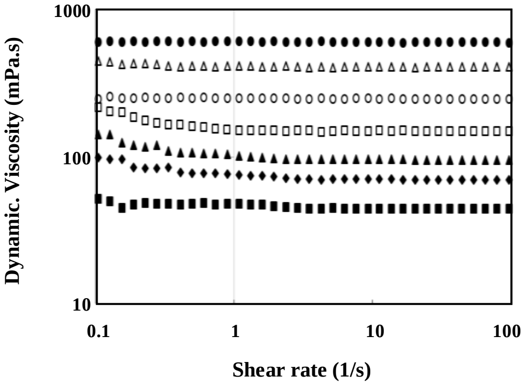

Fig. 3: Rheometry test for the crude oil samples diluted with kerosene in different concentrations at 25°C. (Crude oil: ●, kerosene 5%: Δ, kerosene 10%:○, kerosene 15%:□, kerosene 20%:▲, kerosene 25%:♦, kerosene 30%:■)

Preliminary diluent Selection

For selecting the appropriate diluents, different diluents were screened by preparing 20% v/v mixture with crude oil. Ethanol, acetonitrile, DMF, diesel, kerosene, and toluene were examined at this stage. The kinematic viscosity of the blends is shown in the Fig. 2.

As can be observed, the reduction in the viscosity of the blend is more pronounced in case of using toluene, kerosene, and diesel. Therefore, these diluents were selected for further investigations.

The results of rheometry tests for crude oil/diluent blends

In Figs. 3 to 5, the effect of addition of different diluents to the results of rheometry tests are shown.

As can be observed, the dynamic viscosity of the blend decreases by an increase in the diluent concentration. The difference for toluene is more pronounced in comparison with kerosene and diesel.

Effect of diluent addition on the blend viscosity

It should be noted that the average values of viscosity in the Newtonian zone were reported as the viscosity of the crude oil/ diluent blend for comparison of the effect of addition of different diluents. Fig. 6 shows the viscosity of different crude oil/diluent blends in the diluent concentration range of 0% to 30% v/v.

The diluent concentration range is selected between 5-30% v/v. because, in high concentration of diluent, the addition of diluents was not so effective in the viscosity reduction comparing to the lower concentration. This claim was proved by comparing the slope of the viscosity change versus the diluent concentration between 5 %v/v and 30% v/v (See Fig. 6).

As can be observed in Fig. 6, the viscosity decreases with an increase in the diluent concentration. It should be noted that adding the diluents limits the entanglement of asphaltene particles which results in the viscosity reduction. This could be enhanced by increasing the interactions between the diluent and the polar compounds of the crude oil (mainly the asphaltenes) and breaking the asphaltene/asphaltene interactions [19].

Also, the slope of the viscosity change decreases with an increase in the diluent concentration (see Fig. 6). The asphaltene concentration in the Nowrouz crude oil is 16%, which is higher than the asphaltene critical concentration. Therefore, as discussed in the introduction section, adding

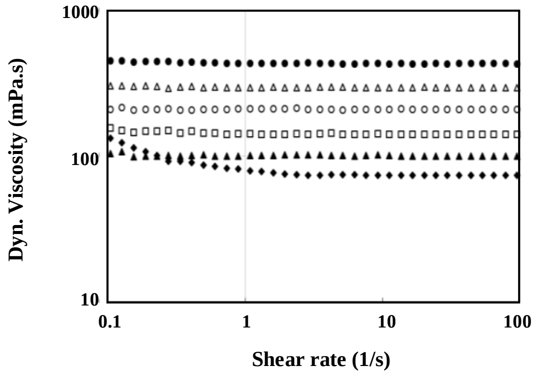

Fig. 4: Rheometry test for the crude oil samples diluted with diesel in different concentrations at 25°C (Crude oil: ●, diesel 5%:Δ, diesel 10%:○, diesel 15%:□, diesel 20%:▲, diesel 25%:♦, diesel 30%:■).

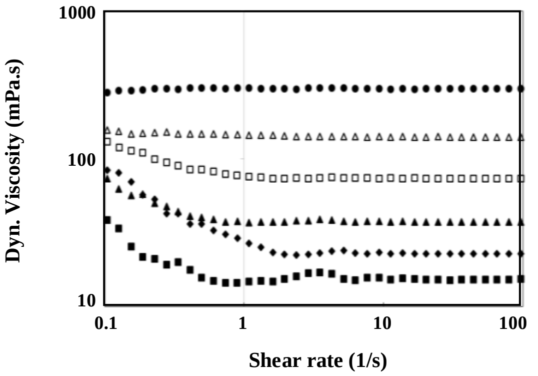

Fig. 5: Rheometry test for the crude oil samples diluted with toluene in different concentrations at 25°C. (Crude oil: ●, toluene 5%:Δ, toluene 10%:○, toluene 15%:□, toluene 20%: ▲, toluene 25%:♦, toluene 30%:■).

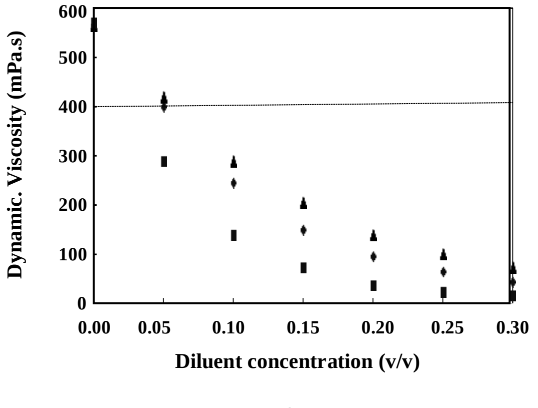

Fig. 6: The dynamic viscosity of the crude oil/diluent blend versus diluent concentration at 25°C (kerosene: ♦, diesel: ▲, toluene: ■) (Note: 400 mPa.s is the maximum allowable viscosity for the pipeline transportation).

more diluent in semi-diluted system reduces the viscosity dramatically. As asphaltene concentration decreases to the range of dilute system, the slope of the viscosity versus diluent concentration decreases.

As can be observed, the addition of toluene could decrease the dynamic viscosity of the crude oil blend more effectively in comparison with kerosene and diesel. As an example, in the concentration of 10% v/v of the diluents, toluene decreased the viscosity up to 140 mPa.s in comparison with 290 and 246 mPa.s for kerosene and diesel, respectively. In other words, the viscosity reduction by adding 10% of diluent, is 75% for toluene in comparison with 57% and 49% for kerosene and diesel, respectively. The superiority of toluene over kerosene and diesel may be attributed to the interaction of toluene as an aromatic compound with polar groups of the asphaltene components resulting in the dispersion of asphaltene agglomerates and subsequent reduction in the crude oil viscosity.

However, adding pure toluene may not be good idea for decreasing the crude oil viscosity because of its high costs. The combination of toluene with other cheaper diluents may be a good idea for further investigations.

The viscosity reduction can be defined as follows:

$$\text{Viscosity Reduction\%} = \frac{\text{crude oil viscosity} - \text{blend viscosity}}{\text{crude oil viscosity}} \times 100 \quad (1)$$

Fig. 7 shows the viscosity reduction as a function of diluent concentration for different diluents. As can be observed, toluene shows the best performance for viscosity reduction. The addition of toluene to the crude oil in 20% concentration leads to 93% viscosity reduction in comparison with 83% and 75% for kerosene and diesel in the same concentration, respectively.

Houmayouni et al. [7] reported 66% viscosity reduction of Nowrouz heavy crude oil by kerosene addition. In the present study, 83 % viscosity reduction is achieved by addition of kerosene in the same concentration. This difference may be attributed to the difference between the composition of the crude oil samples. For example, the asphaltene concentration in the sample examined by *Houmayouni et al.* is about 10% wt in comparison with 16% wt for the present crude oil sample.

Yaghi and *Bemani* [13] reported the reduction of viscosity of heavy crude oil from 15000 mPa.s to 250 mPa.s (i.e., 98% reduction) by adding kerosene in 20% concentration. In the present study, the viscosity of Nowrouz crude oil is decreased from 608 mPa.s to 96 mPa.s by adding kerosene in 20% concentration. The higher values of viscosity reduction in *Yaghi* and *Bemani* research can be attributed to the higher initial viscosity of their examined heavy crude oil as well as the difference between the compositions of the examined crude oil samples.

Alomair et al. [1] reported a decrease in the viscosity of Kuwaiti heavy crude oil from 4000 mPa.s to 300 mPa.s (i.e., 92% viscosity reduction) through the addition of diesel in 20% w/w concentration. In the present study, the viscosity of Nowrouz crude oil is decreased from 608 mPa.s to 140 mPa.s (i.e., 77% viscosity reduction) through the addition of diesel in 20% v/v concentration.

Faris et al. [8] reported 72% viscosity reduction of Iraqi heavy crude oil with initial viscosity of 590 mPa.s by adding toluene in the concentration of 10% wt. In the present study, 75% viscosity reduction is achieved using the same amount of toluene as diluent.

These differences between the present work and other available reports can be attributed to the diversity of the examined crude oils in terms of physical properties and composition.

As mentioned earlier, the maximum acceptable viscosity for economic pipeline transportation is reported as 400 mPa.s [5]. To calculate the minimum required amount of each diluent to achieve 400 mPa.s, the trend of viscosity of the blend with diluent concentration was fitted by several correlations. Table 4 shows the best fitted correlations for different diluents.

In these correlations, x is the volume fraction of diluent in the blend. By the application of the fitted correlations, it has been found that the viscosity of 400 mPa.s can be achieved for the blends of crude oil with 2.8% v/v of toluene, 4.3% v/v of kerosene, and 5.3% v/v of diesel.

Effect of diluent addition on the blend density

The effect of diluent addition on the density of the blends has been also investigated. Fig. 8 shows the densities of crude oil/diluent blends for different diluents in different concentrations.

As expected, adding diluents decreases the density of the crude oil blend. This can be attributed to the lower density of the diluents in comparison with the density of the crude oil. In addition, the trend of density change with the concentration is almost linear due to approximate linear correlation between the densities of component and the density of blend.

Prediction of the viscosity of the crude oil/diluent blend

Simple mixing rules and the mixing rules with the viscosity blending index were examined for the prediction of the viscosity of crude oil/diluent blends. The simple mixing rules were *Arrhenius* [20], *Bingham* [21], *Kendal Monroe* [22], *Cragoe* [23], *Reid* [24], *Chirinos* [25], and *Koval* [26]. Mixing rules with viscosity blending index were *Refutas* [27], *Chevron* [27], *Wallace* and *Henry* [28], *Maxwell* [29] , *Parkash* [30], and *Almaamari* [31].

For comparing the mixing rules, the Average Absolute Relative Deviation (AARD, %) was used:

$$\mathrm{AARD,\%} = \frac{1}{N}\sum_{i=1}^{N}\left|\frac{\mu_i^{exp}-\mu_i^{cal}}{\mu_i^{exp}}\right|\times 100 \qquad (5)$$

Where μ_i^{exp}, $\mu_i^{cal.}$, N are the experimental dynamic viscosity, the predicted dynamic viscosity, and the number of experimental data, respectively.

Simple mixing rules

Table 5 shows simple mixing rules which were evaluated in this study.

Fig. 9 shows the AARD values for the prediction of the viscosities of the crude oil/diluent blends with simple mixing rules.

As can be observed, there are very large prediction errors for the blends containing toluene. Regarding the blends containing kerosene and diesel as diluents, the application of simple mixing rules, except for Koval, leads to considerable prediction errors (i.e., AARD higher than 25%). Therefore, it can be concluded that the simple mixing rules have a limited capability in the prediction of the viscosity of heavy crude oil/diluent blends.

Mixing rules with viscosity blending index

Table 6 shows mixing rules with viscosity blending index which were evaluated in this study.

It should be noted that V_i, w_i, $\boldsymbol{\nu_i}$, and $\boldsymbol{\mu_i}$ are the volume fraction of i-th component of blend, the weight fraction of i-th component of blend, the kinematic viscosity of i-th component of blend, and the dynamic viscosity of i-th component of the blend, respectively.

Table 5: The examined simple mixing rules.

Model Name	Equation	Ref	No.
Arrhenius	$\log \mu = V_A \log \mu_A + V_B \log \mu_B$	[20]	(6)
Bingham	$\mu^{-1} = V_A \mu_A^{-1} + V_B \mu_B^{-1}$	[21]	(7)
Kendal Monroe	$\mu^{1/3} = w_A \mu_A^{1/3} + w_B \mu_B^{1/3}$	[22]	(8)
linear	$\mu = V_A \mu_A + V_B \mu_B$	[32]	(9)
Cragoe	$\mu = 0.0005\, exp\left(\frac{1000 ln(20)}{I_{cr}}\right)$ $I_{cr} = w_A I_{cr_A} + w_B I_{cr_B}$ $I_{cr_i} = \frac{1000 ln(20)}{ln(\frac{\mu_i}{0.0005})}$	[23]	(10)
Reid	$\nu = \frac{(V_A + V_B)\nu_A \nu_B}{V_A \nu_A + V_B \nu_B}$	[24]	(11)
Chirinios	$\log \log(\nu + 0.8) = w_A \log \log(\nu_A + 0.8) + w_B \log \log(\nu_B + 0.8)$	[25]	(12)
Koval	$\mu^{-0.25} = V_A \mu_A^{-0.25} + V_B \mu_B^{-0.25}$	[26]	(13)

Table 6: The examined mixing rules with the viscosity blending index.

Model Name		Ref.	Equation
Refutas	$\nu = exp\, exp \frac{I_R - 10.975}{14.534} - 0.8$ $I_R = w_A I_{R_A} + w_B I_{R_B}$ $I_{R_i} = 10.975 + 14.534\, ln\, ln(\nu_i + 0.8)$	[27]	(14)
Chevron	$\mu = 10^{(\frac{3I_c}{1-I_c})}$ $I_C = V_A I_{C_A} + V_B I_{C_B}$ $I_{C_i} = \frac{\log \mu_i}{3 + \log \mu_i}$	[27]	(15)
Wallace and Henry	$\mu = 0.01\, exp\left(\frac{1}{I_{WH}}\right)$ $I_{WH} = w_A I_{WH_A} + w_B I_{WH_B}$ $I_{WH_i} = \frac{1}{ln \frac{\mu_i}{0.01}}$	[28]	(16)
Maxwell	$\mu = exp\, exp \frac{I_M - 59.58959}{-21.8373} - 0.8$ $I_M = V_A I_{M_A} + V_B I_{M_B}$ $I_{M_i} = 59.58959 - 21.8373\, ln\, ln(\mu_i + 0.8)$	[29]	(17)
Parkash	$\mu = exp\, exp \frac{I_p + 157.43}{376.38} - 0.93425$ $I_p = V_A I_{p_A} + V_B I_{p_B}$ $I_{p_i} = -157.43 + 376.38\, ln\, ln(\mu_i + 0.93425)$	[30]	(18)
Almaamari	$\mu = exp\, exp \frac{VBI + 0.8944}{1.7637} - 1.2641$ $VBI = V_A VBI_A + V_B VBI_B$ $VBI_i = 1.7637\, ln\, ln(\mu_i + 1.2641) - 0.8944$	[31]	(19)
Mohammadi III	$IX_i = \frac{831.839}{ln(\frac{\nu_i}{0.011})}$ $C = ln(\frac{\nu_j}{\nu_i})$ $IX = w_A IX_A + w_B IX_B + 0.2C$ $\nu = 0.011 exp(\frac{831.839}{IX})$	[33]	(20)
Mohammadi IV	$IV_i = ln(ln(\nu_i + 0.623))$ $C = 0.042\, ln(\nu_i \nu_j)$ $IV = IV_A x_A + IV_B x_B + C x_A x_B$ $\nu = exp(exp(IV)) - 0.623$	[33]	(21)

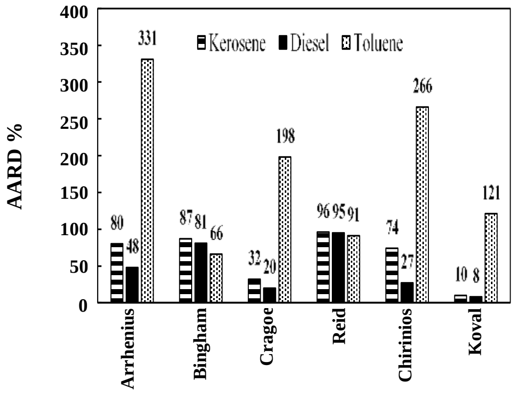

Fig. 9: AARD values for the prediction of the viscosities of the crude oil/diluent blends using simple mixing rules.

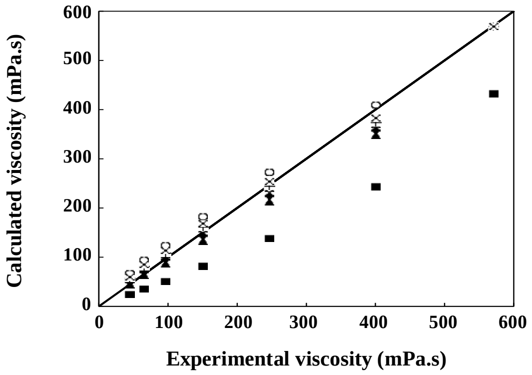

Fig. 10: Comparison of the experimental and predicated viscosity of crude oil diluted with kerosene using the mixing rules with viscosity blending index (Chevron :Δ, Refutas: ○, Maxwell:▲, Al-maamari:♦, Parakash:■, Wallace-Henry: ◊, Mohammadi III: + , Mohammadi VI: ×).

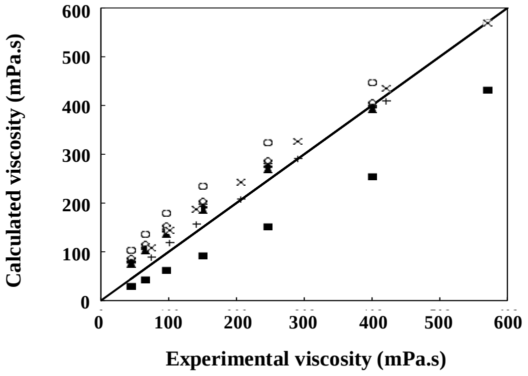

Fig. 11: Comparison of the experimental and predicated viscosity of crude oil diluted with diesel using the mixing rules with viscosity blending index (Chevron :Δ, Refutas: ○, Maxwell:▲, al-Maamari:♦, Parakash:■, Wallace-Henry: ◊, Mohammadi III: + , Mohammadi VI: ×).

Figs. 10 and 11 show the predicted and experimental viscosities of the crude oil diluted with kerosene, and diesel, respectively.

Regardless of toluene, there are some mixing rules with viscosity blending index which could predict the viscosity of the blend, satisfactorily.

Fig. 12 shows the AARD values of mixing rules based on the viscosity blending index.

As can be observed, Almaamari and Maxwell can predict the viscosity of crude oil/diluent blend, satisfactorily (i.e., AARD lower than 10 %).

Although the application of mixing rules based on the viscosity blending index shows reasonable predictions for the blend of crude oil with kerosene and diesel, but none of the mentioned mixing rules in Tables 5 and 6 could predict the viscosity of heavy crude oil/toluene blend. It should be noted that the mentioned mixing rules consider the viscosity, the density, and the concentrations of the components composing the blend. These specifications for the applied diluents are not very different, but toluene reduces the viscosity of blends more effective in comparison with kerosene and diesel. In other words, the mechanism of toluene for the viscosity reduction of heavy crude oil cannot be taken into account considering the mentioned parameters.

CONCLUSIONS

In the present study, the viscosity reduction of a heavy Iranian crude oil sample (produced in Nowrouz field) was investigated through the dilution method. The effect of the addition of three different diluents including kerosene, diesel, and toluene in different concentration (5%-30% v/v) was studied. Comparing different examined diluents, it was found that toluene can reduce the viscosity of blends more effectively. The superiority of toluene over kerosene and diesel may be attributed to the interaction of toluene as an aromatic compound with polar groups of the asphaltene components.

The addition of toluene in the concentration of 30% can reduce the initial viscosity of crude oil from 608 to 17 mPa.s. It was also tried to predict the viscosity of the crude oil/diluent blends with different mixing rules. It was found that the available mixing rules are not capable to predict the viscosity of blends containing toluene. Besides, the simple mixing rules have a limited capability for the prediction of the viscosity of crude oil/diluent blends.

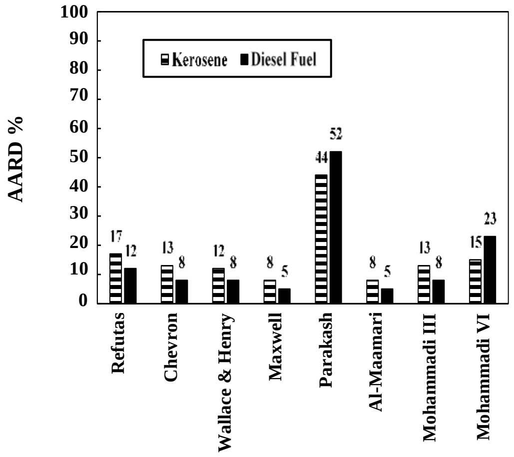

Fig. 12: AARD values for the prediction of viscosity of the crude oil/diluent blends using the mixing rules with viscosity blending index.

Therefore, it can be concluded that the prediction of the viscosity of crude oil/light diluent blend is a challenge that can be considered an attractive subject for future studies. Also, the mechanism of toluene diluent for viscosity reduction and developing a suitable mixing rule for the toluene containing blends can be also studied in the next researches.

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