Petroleum and Coal

Article **Open Access**

A Current Viscosity of Different Egyptian Crude Oils: Measurements and Modeling Over a certain Range of Temperature and Pressure

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Received August 16, 2016; Accepted November 15, 2016

Abstract

Viscosity is an important characteristic of crude oil. The value and changing of viscosity have essential significance for all events in the transportation pipeline of crude oil. The viscosity of crude oil is chan-ged with temperature and pressure and chemical composition of crude. In analyzing the determination of crude oil viscosity operations, it is usual to use only the temperature dependence of viscosity while the influence of pressure is neglected. Therefore the principal objective of this paper is to obtain an exact model that can successfully predict this important fluid property covering a wide range of tem-peratures and pressures. Moreover, in this paper, a mathematical model of changing the current visco-sity of Egyptian crude oils with changing of temperature and pressure is determined. A total of 6 oil samples of different API gravities ranging from 13.4 to 40.4 is tested. Viscosity is measured in the temperature range from 20 to 150°C, and pressure ranges from 14.7 to 132.3 psi. These measu-rements are determined by using the process viscometer apparatus. The comparison between the experi-mental data and the predicted values indicate that the proposed model successfully predict the experi-mental data with an average absolute relative error of less than 3 % and correlation coefficients (R^2) of 0.991. It is observed that it is impossible to generalize a correlation for the crude oil viscosity using only API and temperature because the pressure dependence of viscosity cannot be neglected.

Keywords: current viscosity; viscometer apparatus; crude oils; mathematical; correlation.

1. Introduction

Crude oil viscosity is an important physical property that controls and influences the flow of oil through porous media and pipes [1]. The viscosity, in general, is defined as an internal resistance of the fluid to flow .The evaluation of viscosity of crude oil is an important step in the design of various operations in oilfield and refineries. Therefore, the 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 changes 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. Measuring the viscosity of the dead oil is easier using empirical correlations at temperatures other than the reservoir temperatures. These dead oil measurements can be used as the starting point for live oil viscosity predictions [2]. The diffi-culty and high costs of viscosity measurements at reservoir conditions are the main reasons for the lack of such data. Additionally, the viscosity is an important guideline for numerical simula-tions to determine the economics of the enhanced oil recovery (EOR) project and the success or failure of a given EOR scheme. Consequently, a correlation

must estimate these values under diffe-rent temperatures and pressures. The viscosity of crude oil depends on many factors, such as the source of chemical composition [3] . Therefore, developing a comprehensive model of viscosity to include different regions of the world seems to be a very challenging task [4]. Beal created a chart that described the viscosities of 655 dead oil samples at 38°C, representing 492 oil fields around the world and covering viscosities ranging from 0.8 to 155 cP, gravities ranging from 10.1 to 52.5 API and temperatures from 38 to 105°C. In addition, [5] developed an empirical correlation to predict the viscosity of dead oil with 3588 data points from 661 dead oil samples that covered gravities ranging from14.4 to 58.9 API, viscosities ranging from 0.5 to 682 cP, and temperatures ranging from 75 to 320°F. Labedi also correlated the dead oil viscosity in the range of 0.66 to 4.79 cP and gravity in the range from 32.2 to48.0 API as a function of API gravity and temperature covering the range from 38 to 152°C using 91 data points [6].

Several correlations for predicting dead oil viscosity are available in the literature reviews and some of these models are discussed in this paper, such as the Beggs and Robinson [7] model for temperatures ranging from 21 to 146°C and El Sharkawy and Alikhan [8] model based on crude oil samples from the Middle East for temperatures ranging from 38 to 150°C. Naseri *et al*. [9] presented a model for temperatures ranging from 40 to146°C. Other authors suggest that the variation in compositions is why correlating the viscosity of heavy crude with high accuracy is impro-bable claimed that Beal, Beggs, and Robinson equations are more accurate than previous efforts, which might have been true for this tight viscosity range; however, large errors are observed when this model is applied outside of these temperatures, viscosity or API ranges. Darko Knežević *et al.* [10] are developed a mathematical model of a new correlation of dynamic viscosity as a function of temperature and pressure for lubricating oils. In this work viscosity of Egyptian crude oils with API ranges from 13.4 to 40.4 are measured experimentally over a wide range of temperature and pressures, and a mathematical model has been developed.

2. Experimental work

The dynamic viscosity, μ of 6 dead crude oil samples in a temperature range from 20 to 140°C and pressure range from 14.7 to 132.3 psi is determined using a process viscometer apparatus. The process viscometer consists of two components, the electronic device for control and eva-luation and the measuring head. For the measuring head, the core of the process viscometer is an oscillating quartz sensor that is subjected to dampening by the viscous properties of the surrounding liquid. The type of the sensor is SiO_2 of cylindrical shape with small dimensions. The quartz viscometer's microprocessor contains powerful extrapolation algorithm of the temperature dependent density of the liquid, resulting from a mathematical and physical analysis of the system [11]. Optionally the viscometer can be supplied with a high-pressure sample container, which can be used to measure the viscosity of pressurized samples up to 100 bars (1450 psi) at a maximum tem-perature of 150°C (300°F) as shown in Fig.1.

Fig.1. The process viscometer apparatus

Moreover, the steps for how to use this apparatus are illustrated in Fig.2. These steps are expre-ssed as the following:

1. The sample is filled into the pressure cell (1)
2. Inside the pressure cell, a crude oil level of 100ml is marked (10)
3. The formation of a vortex due to a stirrer with (200 r/m) found so recommended to fill in some more fluid (~103ml).
4. The sensor head is screwed into the closure head from the below using a suitable copper gasket (3).
5. Before closing the unit, please place the O-ring seal (2) in the notch on the inner side.
6. A location bolt (4) shows the correct orientation of the flanged lid; please make sure that the pin enters the corresponding bore (5).
7. After closing the unit, use the 8 screws (6) to close and fix the pressure cell.
8. To improve the temperature regulation, a customized insulation jacket (11) can be supplied.
9. The needle valve (7) is used to pressurize the unit. The pressure inside the unit is displayed on the pressure gauge (8).
10. For safety reasons an overpressure valve (9) is part of the unit.

Fig. 2. Steps of measurements in the process viscometer apparatus

According to the density extrapolation of the samples the process viscometer need to intro-duce thermal expansion factor (α) which calculated from the following equation(1):

$$\rho_t = \rho_{15} - \alpha(t_f - t_{15}) \quad (1)$$

where: ρ_t = the density of the crude oil at final temperature in Kg/m^3; ρ_{15}=the density of the crude oil at 15.5°C; α= thermal expansion coefficient; t_f= temperature of crude oil at final tempe-rature; t_{15}= temperature of the crude oil at 15.5°C.

Every crude oil gravity has certain (α) introduced at the beginning of process measurements. The measurements based on time step as you prefer,(ex.: every 15 sec). Also, magnetic stirrer is used in samples at 200 revolutions per minute (r/m) (current measurements). After recording the reading of runs from the apparatus, the Figures between the viscosities versus temperatures are plotted. Table1 describes the data used for these runs. Hence, when talking about chemical compo-sition of the crude oil taking into consideration

(specific gravity and characterrization factor) The Watson factor is related to the average boiling point and API gravity of the crude oil through the following relation [12]

$$K_W = \left(\frac{131.5 + API}{141.5}\right)(T_b)1/3$$

In the category of correlations utilizing the Watson characterization factor, we follow the procedure of Twu [13] for the estimation of dead oil viscosity; which can be summarized as follows:

$$\mu_{od} = \gamma_{oT}\nu_T$$

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

$$\gamma_{oT} = 0.999012\gamma_{o\,60}VCF_T$$

$\gamma_{o\,60}$ is the crude oil specific gravity (γo) at 60°F; VCF_T is the crude oil volume correction factor with a base temperature of 60°F.

$$VCF_T = e^{[-\alpha_{60}\Delta T(1+0.8\alpha_{60}\Delta T)]}$$

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

$$\alpha_{60} = \frac{K_o + K_1\gamma_{o\,60}}{\gamma_{0\,60}^2}$$

At the quartz process viscometer apparatus, the thermal expansion coefficient α_{60} is an essential input parameter for each run and the density of (g/cm^3) which equals the specific gravity of the crude oil at 60°F. Hence, the apparatus automatically apply this rule in its calculations for the current viscosity in experimental data. So, the composition is talking into consideration in the recent model, and its calculations and the parameters (constants) of the recent model have directly indicated the composition.

Table 1.Description of data used with samples

Variable	Range
ºAPI	13.4 to 40.4
Temperature (ºC)	20 to140
Pressure (psi)	14.7 to 132.3
Density (g/cm3)	808.8 to 975.6
Thermal expansion factor (α)	0.65 to 0.7
Revolution / minute (r/m)	200

3. Results and discussion

3.1. Proposed model

The experimental data of the viscosity of 6 dead oil samples with different API values are measured in the temperature range of 20 to 150°C and pressure range of 14.7 to 132.3 Psi. The ASTM indicates that dead oil viscosity is labeled according to its standard API at 15.5 °C. This value is the first parameter of any model, and the second parameter is the value of the measured tempe-rature [14-15]. According to literature reviews, most of the models are based on, sometimes two parameters, the API, and temperature to calculate the viscosity**.** In most cases, the API parameter has no physical meaning [16] .Therefore, another parameter is used with temperature, such as pressure. The goal is to create a model in the following formats for the viscosity prediction:

μ_{od} α(T, P), (2)

where μ_{od} the viscosity of the dead oil in cP is; T is the temperature in °C and$P$ is the pressure in psi.

Before developing the new viscosity model, understanding the relationship between the input and output variables is essential; specifically, identifying which parameters are insignificant and can be eliminated from the final model and the parameters that are highly correlated with the output. Consequently, the dead oil viscosity (μ_{od}) is considered to be a

function of the value of tempe-rature (T) and pressure (P). As shown in plotting the data yields Fig.3. It illustrates how viscosity changes according to temperature and pressure changes. This Figure illustrates the behavior of viscosity at different ranges of temperatures and pressures with different API. As illustrated in Fig. 3 the viscosity decreasing by increasing temperature and when measuring the viscosity at different pressures are observed that the value of viscosity increased by increasing the pressure at certain API. More addition, due to the samples of crude oils are prepared from different Egyptian companies fields so there are a difference in composition. Fig.4. illustrates the relationship between current viscosity and frequency (the frequency is a parameter given by the quartz viscometer apparatus) for every run at (0,3,6,9 bar) and 200 r/m. Additionally, it shows decreasing in current viscosity with increasing the frequency of the fluid. Moreover, Reynolds Number is calculated at tempe-rature intervals (50,100,150)°C from the following relation to know the type of flow [17].

$$NRe = D\,N\,\rho\,/\mu \quad (3)$$

where: D is the inside diameter of the crude cylinder in the quartz process viscometer; N = the agitator speed (rph); ρ = the denisty of the crude given by the apparatus; μ= the viscosity of the crude oil. The NRe > 10,000 the flow is turbulent.

3.2. Assessment of the proposed viscosity models

After multiple regression analysis of all the experimental viscosity data, and using many forms for a viscosity equations as a function of pressure and temperature, the results represent that the following functional form is set to be presented the data in this work and give us correlation coefficients (R^2) up to 0.99 as follow:

$$\mu(P,T) = a e^{\left[\frac{b}{(T-c)}\right]} e^{[P/(a_1 + a_2\,T)]} \quad (4)$$

where: μ is the dynamic viscosity of cp; T is the temperature in °C; P is the pressure in psi and (a, b, c,a1,a2) are constants (unknown parameters).

The model can predict the dead oil viscosity data with an average absolute error of 0.3 % and R^2 of 0.991.The values are evaluated and tested using different techniques. One of the main challenges in this study is that most of the existing models in the literature are limited to certain ranges of temperature ,API value, but this study determines the current viscosity at different ranges not only for temperatures but also for different pressures .Table 2 shows the values for (a, b, c, a1, a2) for each run of the data set.

Table2. The values of modeling parameters at different pressure and API

Parameters (directly indicate composition)	Values of parameters at different pressures (Psi)				ºAPI
	14.7	44.1	88.2	132.2	
a	1.007	0.000212	6.475	2.717	
b	-20.38	4.405	102.7	115.7	
c	-1.897	-0.6139	-9.704	-5.272	13.4
a_1	1.469	-10.28	-2241	-4769	
a_2	0.04793	1.491	239	483.6	
a	0.9112	0.9423	0.0293	1.006	
b	0.142	3.759	0.00852	-4349	
c	-376.3	-1105	26.11	0.7489	39.6
a_1	5.301	11.57	14.35	0.4612	
a_2	0.0538	0.2569	0.0488	0.24	
a	0.3132	0.0043	0.00165	0.00603	
b	65.56	-0.00346	-0.00128	302.1	
c	-5.811	26.1	25.45	-139.7	31.01
a_1	-7.439	5.511	9.61	24.52	
a_2	5.435	0.0324	0.0583	0.1663	

Parameters (directly indicate composition)	Values of parameters at different pressures (Psi)				ºAPI
	14.7	44.1	88.2	132.2	
a	0.00017	0.0044	511.6	4.585	
b	0.7921	26.34	161.8	1395	
c	0.6613	57.57	63.64	239.4	33.02
a_1	0.8194	9.282	-17.72	-10.79	
a_2	0.0576	0.0796	-0.1206	2.401	
a	$1.08e^{-06}$	0.00323	0.07038	$3.335e^{-6}$	
b	-0.0124	-2.86	125.6	0.00297	
c	26.97	19.82	-6.978	21.67	40.04
a_1	1.078	4.876	625	9.934	
a_2	0.002261	0.05478	22.28	0.0183	
a	0.05061	0.07867	0.03676	$1.213e^{-07}$	
b	-34.77	-89.97	-86.09	-28.9	
c	4.174	2.507	8.988	13.2	32.38
a_1	-0.1303	-0.208	-2.118	5.831	
a_2	0.1268	0.2811	0.4903	0.05881	

To check the ability of the proposed viscosity model to present all experimental data, cross plots of the measured and predicted viscosity values are used .The results are in good agreement, with the average absolute relative error and standard division comparing with a previous work as shown in Table 3 for the previous studies and Table 4 for this work.

Table 3. Average absolute relative error and standard deviation of previous model

References	Average absolute relative error % (AARE %)	Standard deviation% (SD %)
Beal **[4]**	31.6	37.3
Beggs and Robinson **[7]**	21.2	28.0
Glaso **[?]**	27.4	31.9
Labedi **[6]**	29.7	42.6
Kartoatmodjo and Shmidt **[5]**	33.1	37.25
Ibrahim Ashour **[2]**	19.2	25.8
Osama Alomair **[14]**	8	203.7

In addition Table 4 gives the results of proposed correlations and for prediction of the dead oil viscosity .The absolute average relative error(AARE %) and the standard deviation (SD) tests are performed between the calculated and the measured values using the following expression:

$$AARE\% = \left|\frac{(measured - calculated)}{measured}\right| * 100 \quad (5)$$

$$SD = \frac{1}{1-N}\sqrt{\sum_{i=1}^{N}\left(\left|\frac{measured - calculated}{measured}\right| - AARE\right)2} \quad (6)$$

where: *i* is the sample number; and *N* is the total number of samples.

The proposed model shows the lowest average absolute error, and standard deviations relative to the others. The graphical approach in Fig. 5 shows the behavior of a new model according to the experimental and calculated values .The new model (Fig.5) provides the best prediction without any scattering between the experimental data and the model measured value, and thus the new model presents a relatively high value of R^2.Fig.6 consists of plots for 6 values of API (13.4, 31.01, 32.38, 33.02, 39.6, 40.4) API.

Table 4. Accuracy of Egyptian crude oil model for estimating viscosity of recent study

API	Pressure (psi)	Average Absolute Relative Error (AARE%)	(Standard Deviation) SD %	R^2
13.4	14.7	0.056	0.00452	0.9739
	44.1	0.144	0.937	0.9186
	88.2	0.1756	0.474	0.8867
	132.3	0.1037	0.856	0.9180
31.01	14.7	0.0792	0.0023	0.8860
	44.1	0.030	0.0388	0.9862
	88.2	0.0078	0.00569	0.9881
	132.3	0.0199	0.0302	0.9798
32.38	14.7	0.0772	0.3135	0.9138
	44.1	0.116	0.4587	0.8327
	88.2	0.1377	0.177	0.9007
	132.3	0.0826	0.5554	0.9910
33.02	14.7	0.0557	0.725	0.9784
	44.1	0.3047	4.36	0.9285
	88.2	0.0787	1.127	0.9665
	132.3	0.1876	2.502	0.9207
39.6	14.7	$8.117e^{-05}$	0.00019	0.9787
	44.1	$4.948e^{-05}$	$1.95e^{-05}$	0.9897
	88.2	0.00068	0.000652	0.9879
	132.3	0.00632	0.00998	0.9844
40.4	14.7	0.00451	0.00134	0.9304
	44.1	0.00804	0.00763	0.9876
	88.2	0.0413	0.0213	0.9744
	132.3	0.0315	0.0917	0.9522

4. Conclusion

Although oils of widely varying compositions can have the same gravity, considerable errors may be introduced when the viscosities of heavy oils are estimated from general viscosity trends and the API gravity. This current viscosity model is a function of different temperatures (T), different pressures (P) and taking into consideration the composition of crude oil which are more valuable and simple to use.

One of the main challenges in this study is that most of the existing models in the literature are limited to determine the dynamic viscosity at certain ranges of temperature, and API values, of dead oils from the reservoirs of many countries, but impossible to find any similarity between this study and previous one because all measurements are current viscosity not only, dynamic viscosity, the crude oil is in continues motion during the runs in the apparatus (200 r/m) and the temperature increasing gradually without any control on it up to 150°Cand the apparatus take the reading automatically with time step every. but also, the pressure range used is chosen to unique the pressure inside the pipe line which the fluid(crude oil) is transferred across. So, this process is simulated to the reality.

The assessment of the agreement between the experimental current viscosity data and the predicted values indicates that the new model successfully represents the experimental data with an average absolute relative error of less than 3 % and coefficients of determination R^2 of 0.99 to 0.94 at different temperatures and pressures. From statistical analysis, the proposed model is demonstrated as one of the best models in comparison with other models published in the literature. The overall results show that it is not an easy task to generalize a dead oil viscosity model along with the pressure and temperature as an input for these models. Therefore, this new model shows it is easy to use different temperatures and pressures to conclude current viscosity, provide good accuracy and precise over a wide range of oil gravities, and could be used to predict better outcomes in future works.

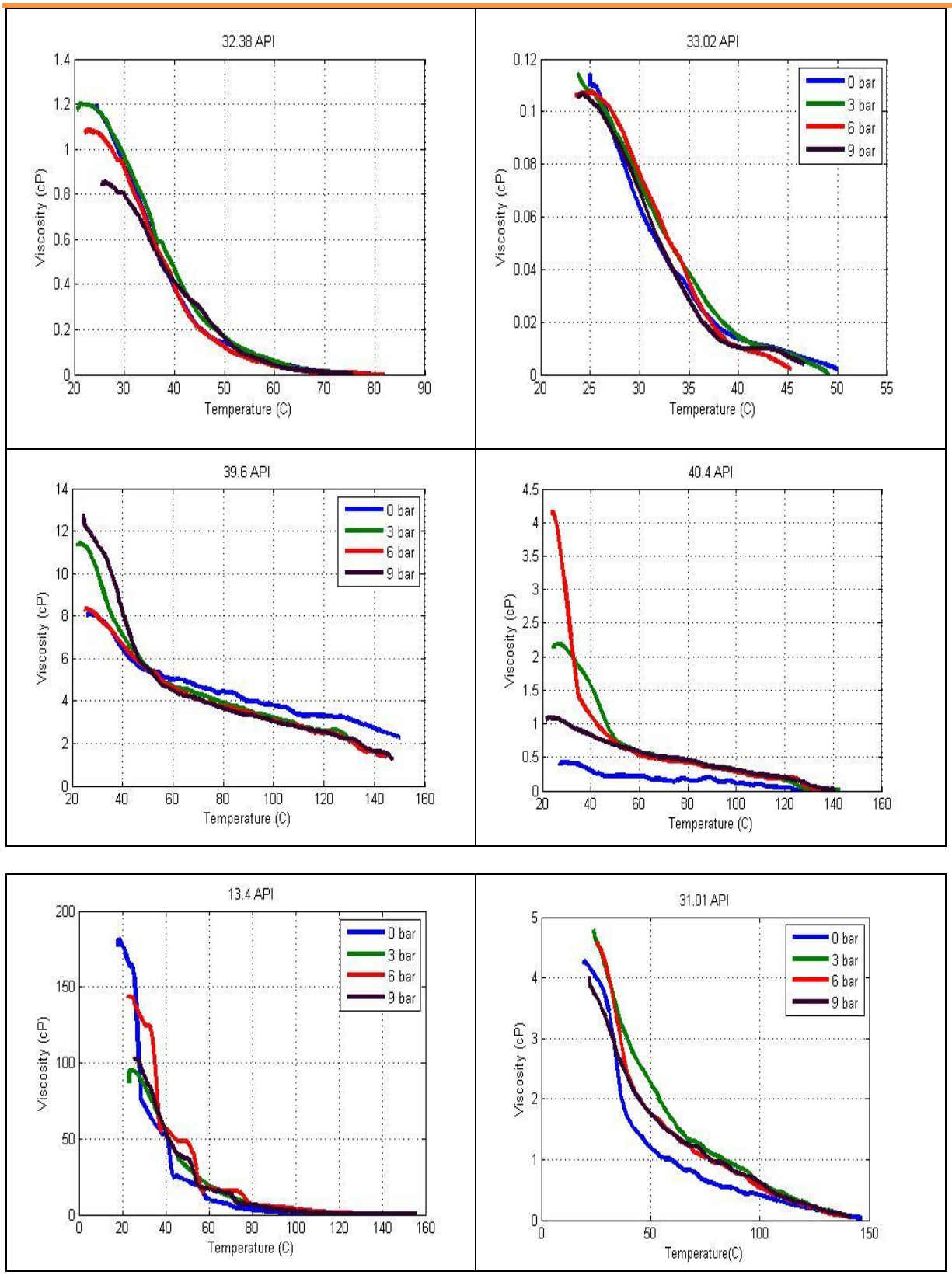

Figure 3. Experimental data of different Egyptian crude oil samples viscosities at different tempera-tures and pressures

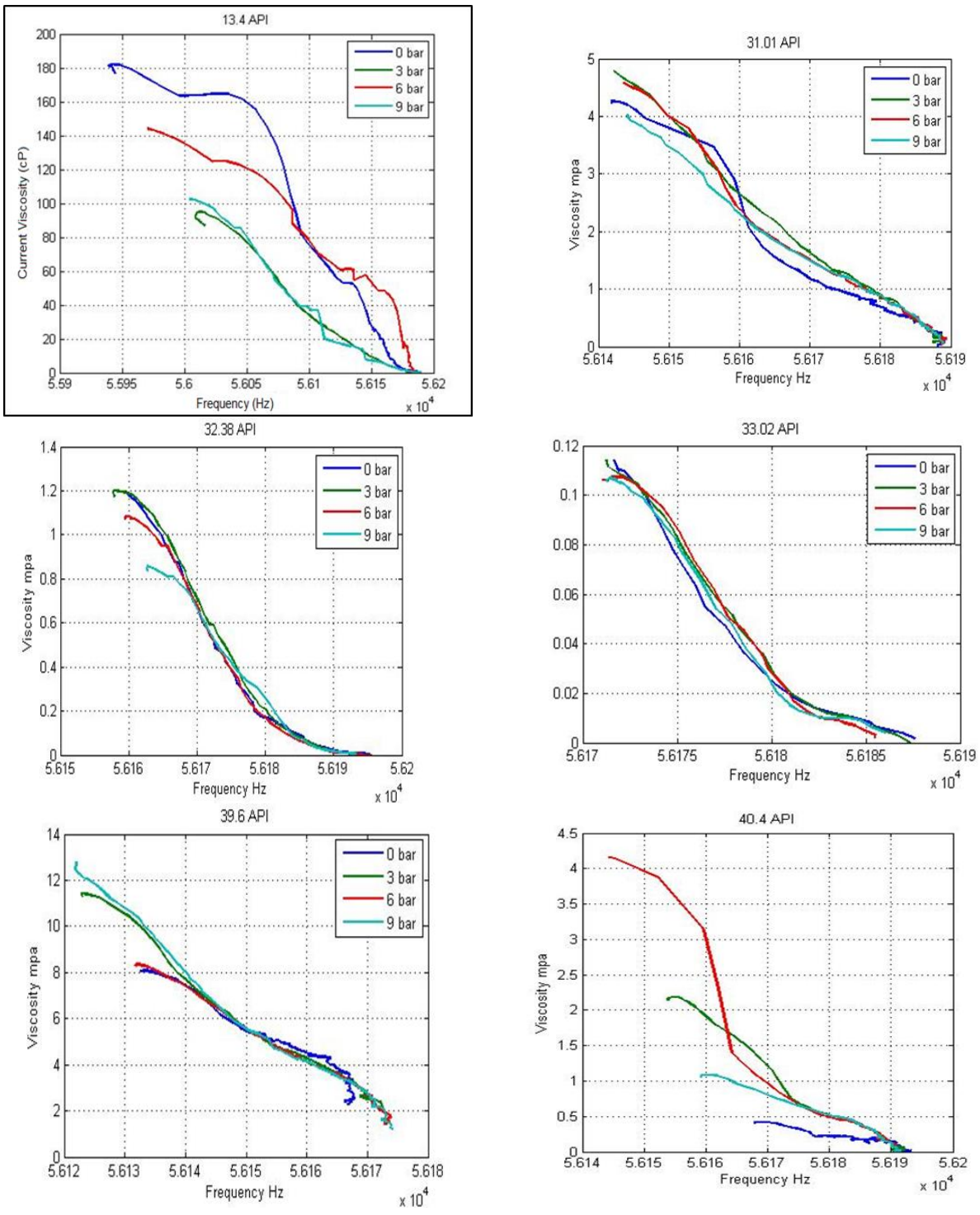

Figure.5. The relation between frequency vs. viscosity at certain temperatures

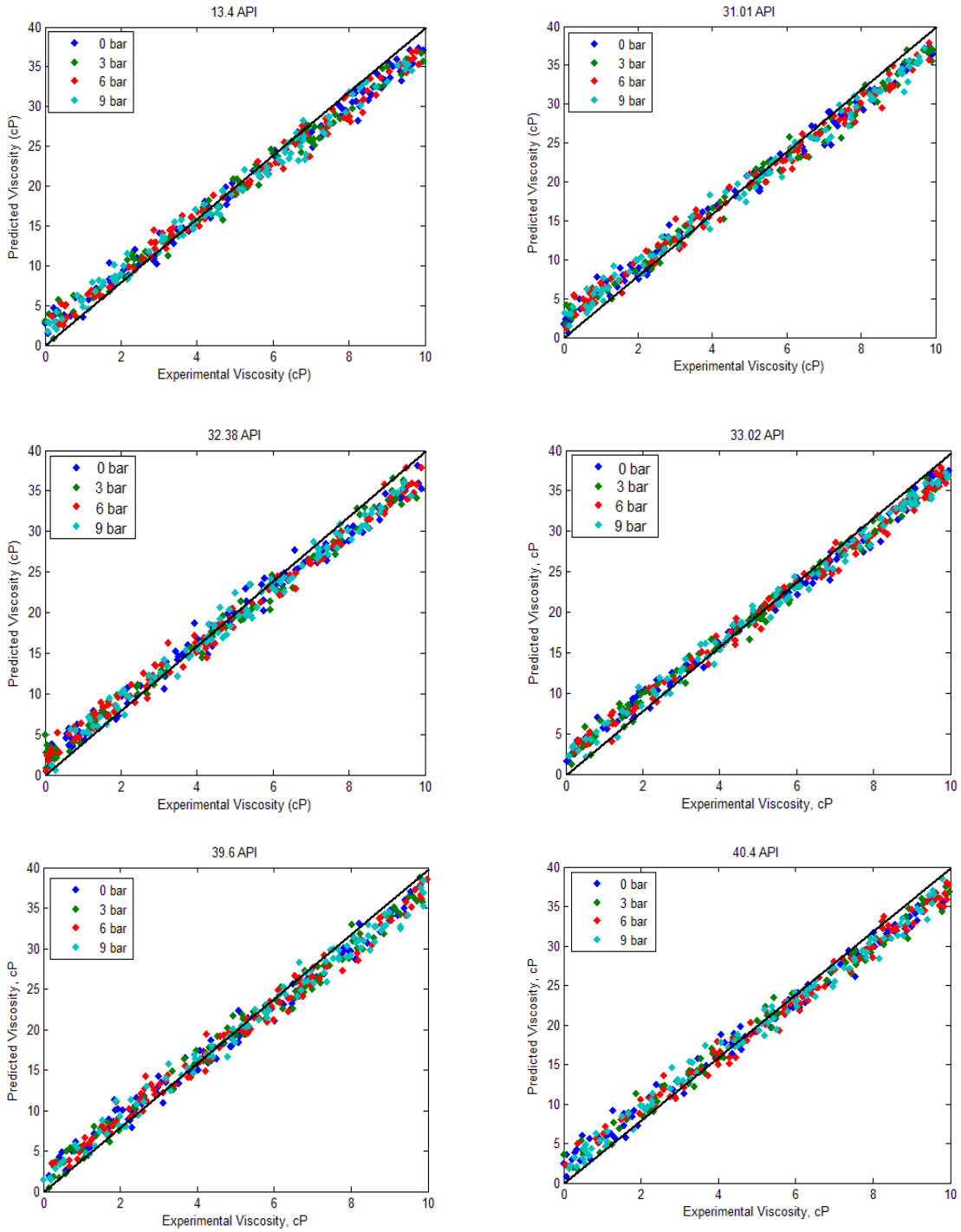

Figure 6. Deviation of experimental current viscosity data from predictive values using the new model for

5. References

[1] Ahrabi F, Ashcroft SJ, Shearn RB (1987) High-pressure volumetric phase composition and viscosity data for a the North Sea crude oil and NGL mixtures. Chem.Eng Res 67: 329–334.

[2] Al-Rawahi N, Vakili-Nejad G, Ashour I and Fatemi A. A New Correlation for Prediction of Viscosities of Omani Fahud-Field Crude Oils
Chapter 12 published 7 Nov 2012 in Advances in Modeling of Fluid Dynamics
DOI:10.5772/47813.

[3] Sattarin M, Modarresi H, Bayat M, Teymori M (2007) New viscosity correlations for dead crude oils. Pet Coal 49:33–39.

[4] Beal, C.: Trans, AIME, 165, 1946, p.94-112.

[5] Kartoatmodjo F, Schmidt Z. Oil & Gas J. 4, 1994, p. 51-55.

[6] Labedi R. J. Pet. Sci. Eng. 8 .1992 ,p. 221 – 234.

[7] Beggs HD, Robinson JF. J. Pet. Tech., Sept. 1975, p. 1140-1141.

[8] Elsharkawy AM, Alikhan AA. Fuel, 78, 1999, p.891-903.

[9] Naseri A, Nikazar M, Mousavi Dehghani SA. J. of Pet. Sci. Eng. 47, 2005, p.163-174.

[10] Knežević D, Savić V. Mathematical modeling of changing of dynamic viscosity, as a function of temperature and pressure, of mineral oils for hydraulic systems FACTA UNIVERSITATIS 2006, Series: Mechanical Engineering 4(1):27-34.

[11] F5 Technologie GmbH ImBüchenorte 3 D-31515 Wunstorf, Germany E-mail: info@f5-tech.de , http://www.f5-tech.de

[12] Hassan SN. The Dead Oil Viscosity Correlations A C-Sharp Simulation Approach JKAU: Eng. Sci., 22(2): 61-87.

[13] Twu CH. Internally Consistent Correlation for Predicting Liquid Viscosities of Petroleum Fractions, Ind. Eng. Chem. Process Des. Dev. 34 (4): 1287-1293(1985).

[14] Alomair O, Jumaa M, Alkoriem A.. J Petrol Explor Prod Technol (2016) 6: 253.

[15] Mehrotra AK. Ind. Eng. Chem. Res., 30, 1991, p.1367-1372.

[16] Standing MB (1947) A pressure-volume-temperature correlation for mixtures of California oils and gasses. Drill Prod Pract, American Petroleum Institute, New York, 275–284.

[17] Pietranski JF. 2012. Mechanical Agitator Power Requirements for liquid batches. (PDH online Course K103 , 2 PDH) http://www.pdhonline.com/.

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