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Viscosity Correlation for Non-Newtonian Waxy Oils

T.F. AL-FARISS, A.H. FAKEEHA,
I.S. AL-MUTAZ and A.M. AL-SHAMRANI
Chemical Engineering Department, College of Engineering,
King Saud University, Riyadh, Saudi Arabia.

ABSTRACT. Rheological characteristics of six types of waxy oils were measured with rotational co-axial cylinder viscometer at different temperatures of 282, 285, 288, 291, 294 and 297K.

A modified form of Eyring equation relating viscosity, temperature, and shear rate is proposed as

$$\mu = A \ e^{B/T} \ \dot{\gamma}^C$$

The correlation was developed using superposition approach.

Experimental data show that rheological behavior of waxy oil change from a Newtonian fluid into non-Newtonian fluid at lower temperatures and at higher wax content.

The modified correlation has been found to fit the experimental data adequately.

1. Introduction

The pumping power of non-Newtonian fluid (crude oil) and the function and working durability of lubricant oil depend on their viscosity which is strongly depend on the temperature.

Many studies have described the behavior of crude oils as shear-thinning with or without a yield stress[1-5]. The rheological behavior of crude oils can be well described by applying the power-law model[6].

Apparently there is no single theory for the precise prediction of the change in liquid viscosity with temperature. Eyring[7] developed an approximate theory, for the rough estimation of liquid viscosity as a function of temperature. This theory is based on the physical properties of the liquid. Amin and Maddox[8] reviewed the common correlations used for the prediction of liquid viscosity. These are summarized in Table 1.

TABLE 1. Correlation for viscosity prediction of liquids[8].

Date	Investigator	Relationship
1913	De Guzman	$d\ln\phi / dT = W/RT^2$
1916	Arrhenius	$d\ln \mu v^{1/3} / dT = K/T^2$
1923	Raman	$\mu_1 = \mu v e^{(E2-E1)/RT}$
1925	Fulcher	$\ln\mu = A + B/(T+C)$
1926	Dunn	$\mu = A e^{Q/RT}$
1926	Frenkel	$\mu = CTe^{U/RT}$
1930	Madge	$\mu = A e^{BT}/(T-C)$
1930	Andrade	$\mu V^{1/3} = A e^{B/TV}$
1933	Silverman	$\mu = (A/\sqrt{T})\, e^{(B/T \cdot CT)}$
1936	Eyring	$\mu = (Nh/V)\, e^{(\Delta E/RT)}$
	Modified forms of Erying equation	$\mu = A e^{B/T}$
		$= (A/V) e^{BT} b/T$
1952	Litovitz	$\ln\mu = A + a/RT^3$
1955	Cornelissen and Girifalco	$\mu = e^{B + A/T}$
		$\ln\mu = C + B/T + A/T^2$
1971	Agrawal and Thodes	$\mu + k = \alpha e^{m/T_r}$
1972	Valzen	$\ln\mu = B[1/T - 1/T_o]$

None of the above researchers have proposed an equation describing the viscosity of certain types of crude oils, which exhibit shear-thinning behavior as function of temperature and shear rate.

The objective of this study is to developed a simple relationship for the prediction of viscosity as a function of temperature and shear rate, which is suitable for specific waxy crude oils.

2. Experiment

The viscometer used to measure the shear stress and shear rate of the fluids tested was a rotating bob type coaxial cylinder viscometer (HAAKE Rotovisco Model RV-12). The outer stationary cylinder (cup) is surrounded by a temperature controlled water jacket. Inside the cup, there is an inner cylinder (bob) of smaller diameter which rotates to shear the material in the gap between the cup and bob. There are many possible combinations of the size and type of bobs and cups for this instrument. The set of NV cup and bob was chosen because it has the biggest surface area of any sensor system, and hence the greats sensitivity. A schematic diagram of the experimental set up is shown in Fig. 1 and more details about this apparatus are given in Al-Fariss[6].

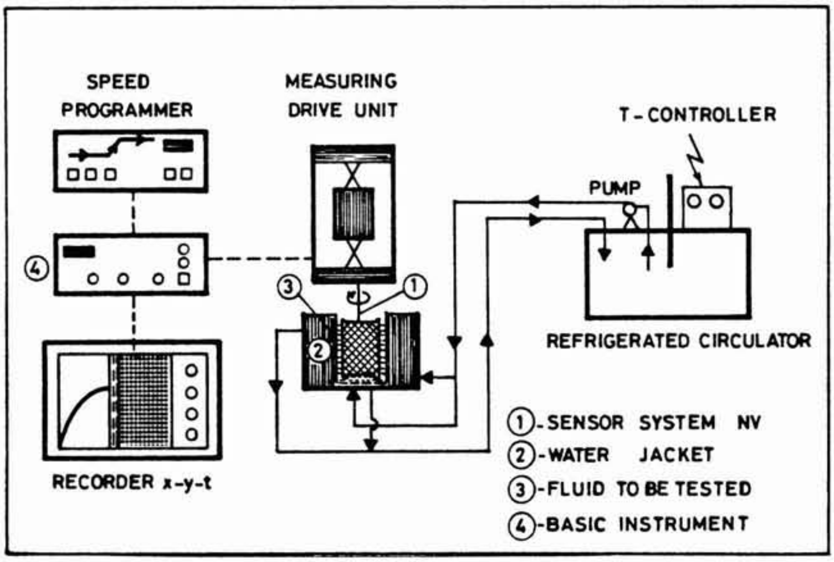

FIG. 1. A schematic diagram of the experimental set up.

3. Tested Materials

Six types of waxy oil were tested. The different waxy oil were prepared by choosing three kinds of base oil from Riyadh refinery (700) with different wax melting points 316,322 and 333 K. Two wax content were used for each of the above base oil, 3 and 6 wt%. The viscosity measurement for each of base oil were performed at 282, 285, 288, 291, 294 and 297 K.

4. Results and Discussion

Many well known correlations are available in the literature for viscosity prediction of liquid as summarized in Table 1. None of these correlations includes the effect of shear rates. Al-Fariss[9] modified Eyring equation to account for the effect of shear rate by including the term ($\dot{\gamma}^C$), *i.e.*, the combination between Newtonian behavior represented by the Eyring form of equation and the non-Newtonian behavior represented by the power-law model. The modified equation take the form.

$$\mu = A \ e^{B/T} \ \dot{\gamma}^C$$

The correlation was developed by using superposition approach, detail found in Al-Fariss[9]. A total of 180 experimental measurement for the viscosity of six types of waxy oils were measured with rotational co-axial cylinder viscometer at different temperatures (282, 285, 288, 291, 294 and 297 K).

The coefficients of the proposed equation are given in Table 2 and the experimental measurements of viscosity and its deviation from the viscosity calculated from the proposed equation at different shear rate are shown in Tables 3-8. The maximum absolute error obtained in all the 180 points was 37.3% and the overall absolute error was 8.5%. The shear rate effect on the viscosity is shown in Fig. 2-7. These figures illustrate the variation of viscosity with shear rate for different temperatures and solid lines represent the proposed equation. It is clear from Table 2 that the values of the constant C are higher for higher wax content, *i.e.*, 3% wax oils are close to Newtonian fluid, while 6% wax oils showed more non-Newtonian behavior. This means that the last term ($\dot{\gamma}^C$) in the proposed equation is working as a correction factor for the non-Newtonian behavior.

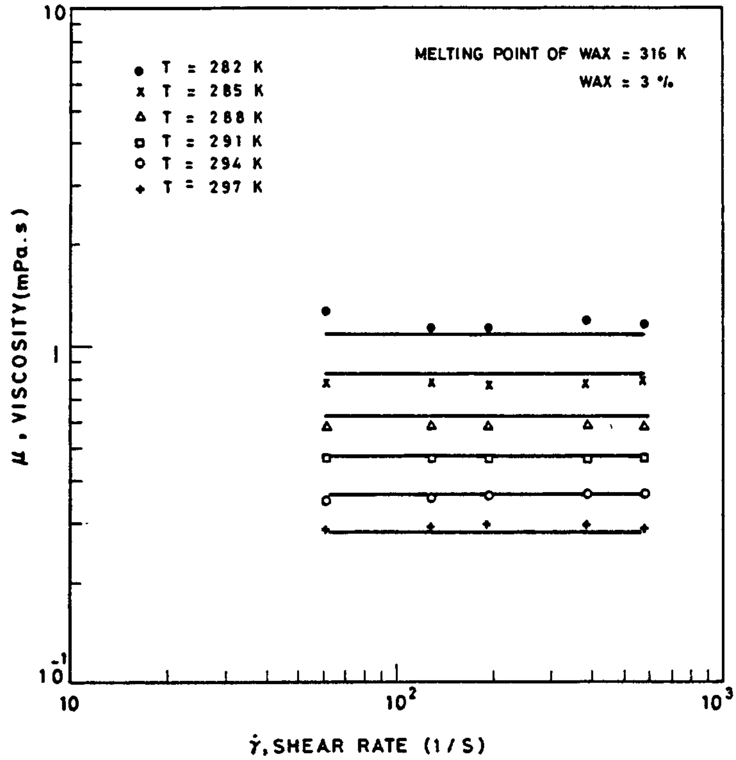

FIG. 2. Effect of temperature on the viscosity of waxy base oil (700) with 3% wax content and wax melting point of 316 K.

TABLE 2. Data for the constants A, B and C of the proposed corrrelation for Saudi waxy base oil (700).

Wax melting point K	Wax concentration wt%	A	B	C
316	3	0.2925×10^{-11}	751.79	- 0.0027
316	6	0.1275×10^{-14}	9826.53	- 0.0471
322	3	0.2506×10^{-13}	8923.77	- 0.0010
322	6	0.2691×10^{-15}	10669.89	- 0.2284
333	3	0.7319×10^{-10}	6770.42	- 0.0467
333	6	0.1800×10^{-13}	9259.93	- 0.0564

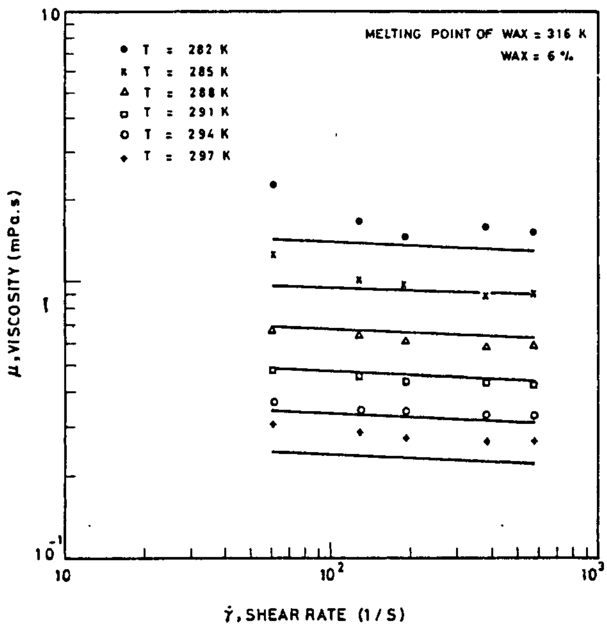

FIG. 3. Effect of temperature on the viscosity of waxy base oil (700) with 6% wax content and wax melting point of 316 K.

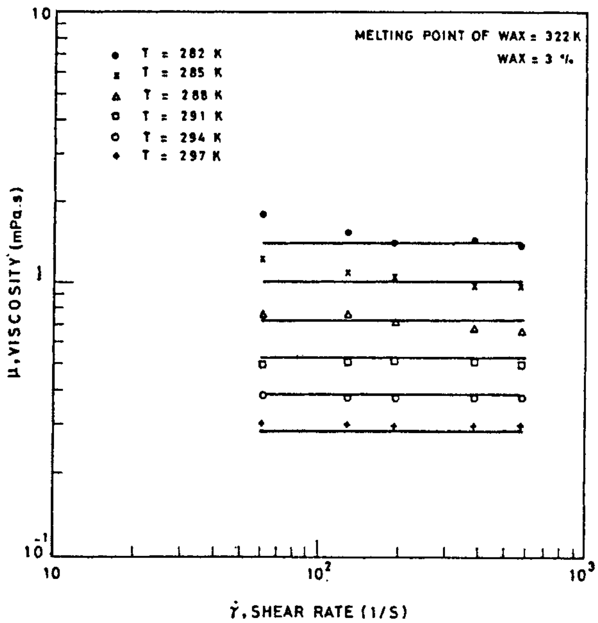

FIG. 4. Effect of temperature on the viscosity of waxy base oil (700) with 3% wax content and wax melting point of 322 K.

TABLE 3. Deviation between experimental and calculated viscosity of waxy base oil (700) that has wax M.P. of 316 and wax concentration of 3 wt %.

Wax M.P. K	Wax conc. wt %	T, K	γ – range (s^{-1})	μ_{exp} range (m pascal s)	% Min. error	% Max. error	% Avg. error
316	3	297	64.14 – 577.26	0.2878 – 0.2900	1.8	5.4	3.80
		294	64.14 – 577.26	0.3519 – 0.3697	0.6	4.0	1.79
		291	64.14 – 577.26	0.4665 – 0.4693	1.3	2.6	1.70
		288	64.14 – 577.26	0.5928 – 0.5872	4.4	5.6	5.10
		285	46.14 – 577.26	0.7800 – 0.7880	4.6	6.5	5.50
		282	64.14 – 577.26	1.1600 – 1.2700	4.8	14.6	8.10

TABLE 4. Deviation between experimental and calculated viscosity of waxy base oil (700) that has wax M.P. of 316 and wax concentration of 6 wt %.

Wax M.P. K	Wax conc. wt %	T, K	γ – range (s^{-1})	μ_{exp} range (m pascal s)	% Min. error	% Max. error	% Avg. error
316	6	297	64.14 – 577.26	0.3087 – 0.2662	14.95	20.58	17.13
		294	64.14 – 577.26	0.3704 – 0.3366	3.82	7.24	5.54
		291	64.14 – 577.26	0.4754 – 0.4253	2.02	6.05	3.78
		288	64.14 – 577.26	0.6791 – 0.5900	1.51	8.03	4.87
		285	46.14 –577.26	1.2473 – 0.8900	0.03	20.84	6.82
		282	64.14 – 577.26	2.2721 – 1.5200	7.41	37.29	19.08

TABLE 5. Deviation between experimental and calculated viscosity of waxy base oil (700) that has wax M.P. of 322 and wax concentration of 3 wt %.

Wax M.P. K	Wax conc. wt %	T, K	γ – range (s^{-1})	μ_{exp} range (m pascal s)	% Min. error	% Max. error	% Avg. error
322	3	297	64.14 – 577.26	0.3025 – 0.2911	4.18	6.87	5.59
		294	64.14 – 577.26	0.3800 – 0.3766	0.74	2.86	2.13
		291	64.14 – 577.26	0.4939 – 0.4939	2.75	5.96	4.60
		288	64.14 – 577.26	0.7594 – 0.6654	0.69	8.49	5.36
		285	46.14 – 577.26	1.2225 – 0.9600	2.89	18.35	7.55
		282	64.14 – 577.26	1.7905 – 1.3700	0.23	22.22	7.25

TABLE 6. Deviation between experimental and calculated viscosity of waxy base oil (700) that has wax M.P. of 322 and wax concentration of 6 wt %.

Wax M.P. K	Wax conc. wt %	T, K	γ – range (s^{-1})	μ_{exp} range (m pascal s)	% Min. error	% Max. error	% Avg. error
322	6	297	64.14 – 577.26	0.3581 – 0.2881	4.94	16.25	10.46
		294	64.14 – 577.26	0.4939 – 0.3979	3.32	21.61	9.88
		291	64.14 – 577.26	0.8829 – 0.5351	0.61	2.53	1.22
		288	64.14 – 577.26	1.2842 – 0.8200	0.38	9.66	5.50
		285	46.14 – 577.26	1.9077 – 0.3000	0.95	17.12	10.14
		282	64.14 – 577.26	2.2906 – 1.9200	1.37	26.94	14.43

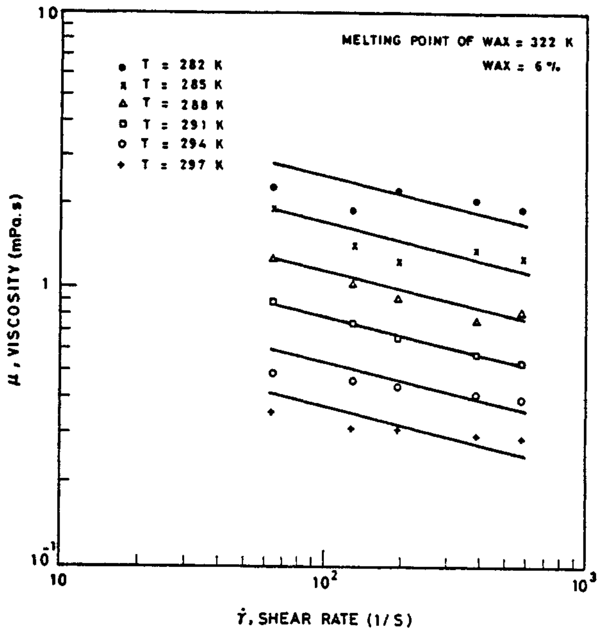

FIG. 5. Effect of temperature on the viscosity of waxy base oil (700) with 6% wax content and wax melting point of 322 K.

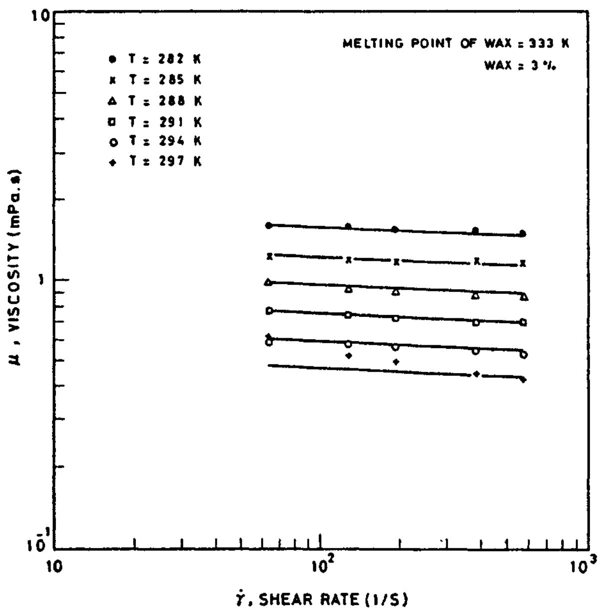

FIG. 6. Effect of temperature on the viscosity of waxy base oil (700) with 3% wax content and wax melting point of 333 K.

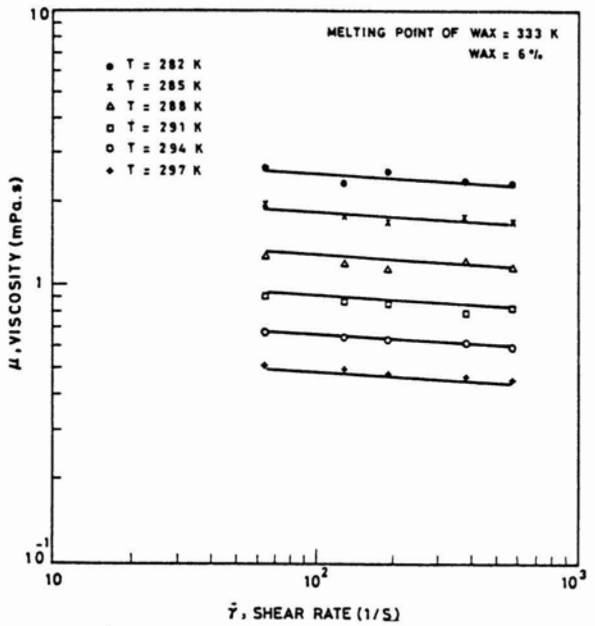

FIG. 7. Effect of temperature on the viscosity of waxy base oil (700) with 6% wax content and wax melting point of 333 K.

TABLE 7. Deviation between experimental and calculated viscosity of waxy base oil (700) that has wax M.P. of 333 and wax concentration of 3 wt %.

Wax M.P. K	Wax conc. wt %	T, K	γ-range (s^{-1})	μ_{exp} range (m pascal s)	% Min. error	% Max. error	% Avg. error
333	3	297	64.14 – 577.26	0.6112 – 0.4205	0.45	21.64	8.81
		294	64.14 – 577.26	0.5803 – 0.5282	1.72	4.14	2.63
		291	64.14 – 577.26	0.7594 – 0.6900	0.22	1.06	0.90
		288	64.14 – 577.26	0.9878 – 0.8700	1.16	2.91	1.97
		285	46.14 – 577.26	1.2225 – 0.1600	1.27	3.35	2.46
		282	64.14 – 577.26	1.5867 – 1.5000	0.64	3.84	2.05

TABLE 8. Deviation between experimental and calculated viscosity of waxy base oil (700) that has wax M.P. of 333 and wax concentration of 6 wt %.

Wax M.P. K	Wax conc. wt %	T, K	γ-range (s^{-1})	μ_{exp} range (m pascal s)	% Min. error	% Max. error	% Avg. error
333	6	297	64.14 – 577.26	0.5062 – 0.4548	1.87	4.01	3.00
		294	64.14 – 577.26	0.6729 – 0.5900	0.77	1.72	1.14
		291	64.14 – 577.26	0.9138 – 0.8200	1.26	4.57	4.01
		288	64.14 – 577.26	1.2842 – 0.1600	0.29	6.78	3.32
		285	46.14 – 577.26	1.9077 – 1.6500	1.67	5.51	3.39
		282	64.14 – 577.26	2.6611 – 2.3500	1.86	6.22	3.77

Generally the experimental data of the 3% wax oils tested show less deviation from the proposed equation than the waxy oil with 6% wax, also more deviations were noticed at lower temperatures tested. These deviations between experimental and predicted results are due to the limitation of using the power law model, since it is good for the shear rate range investigated only. Also experimental errors are due to the accuracy of the device used for shear stress and shear rate measurements finally, the super position technique used to develop the proposed model plays great part in viscosity prediction.

5. Conclusion

A correlation has been proposed to predict the viscosity of non-Newtonian oils as a function of temperature and shear rate. The correlation can be used for both Newtonian and non-Newtonian liquids. The correlation coefficients were obtained from regressing 180 experimental viscosity measurements for six type of waxy oil at different temperatures of 282, 285, 288, 291, 294, and 297 K. The proposed correlation gives an overall absolute error of 8.5% and maximum absolute error of 37.3%.

Nomenclature

A Coefficient of proposed equation.
B Coefficient of proposed equation.
C Coefficient of proposed equation.
T Temperature in K.
μ Viscosity (m pascal s).
$\dot{\gamma}$ Shear rate (1/s).

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مـعادلة لإيجـاد اللـزوجـة للزيـوت الشمعيـة اللانيـوتونيـة

طارق ف. الفارس ، أنيس ح. فقيها ، إبراهيم ص. المعتاز و إبراهيم م. الشمراني
قسم الهندسة الكيميائية ، كلية الهندسة ، جامعة الملك سعود
الرياض - المملكة العربية السعودية .

المستخلص . لقـد تم قياس الخواص الرايولوجية لستة أنواع من الزيوت الشمعية عند درجـات الحرارية التالية: **٢٨٢ ، ٢٨٥ ، ٢٨٨ ، ٢٩١ ، ٢٩٤ ، ٢٩٧** كلفن باستخدام جهاز دوار لقياس اللزوجة . وقد تم تطوير معادلة ايرنج التي تربط اللزوجة والحرارة ومعدل القص باستخدام طريقة التطابق لتصبح على الصورة التالية

$$\mu = Ae^{B/T}\ \dot{\gamma}^{C}$$

ولقد دلت النتائج المعملية على أن الخواص الرايولوجية للزيوت الشمعية تتغير من الصفة النيوتونية إلى الصفة اللانيوتونية عند انخفاض درجة الحرارة وزيادة كمية الشمع في الزيت .

ولقد وجد أن المعادلة المطورة تمثل النتائج المعملية بصورة مُرضية .