

Correlation for Estimating the Effects of Temperature on the Viscosity of Light Hydrocarbon Solvents

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Viscosity-temperature correlation has been developed for light hydrocarbon solvents. The correlation is based on one-parameter viscosity model developed by Puttagunta et al. (*Chem. Eng. Res. Des.*, Vol 70, 1992, p 627-631) for conventional crude oils, which has been modified by incorporating a solvent viscosity reduction factor, Φ . The correlation was compared with the model of Puttagunta et al. on 22 light hydrocarbon solvents for a total of 318 data points. The average absolute deviation improves to 1.9%, compared with 2.2% obtained with the model over a temperature range from -54.41 to 160 °C. The correlation can accurately predict the viscosity of any light hydrocarbon solvent without the need to determine multiple characteristic parameters. This eliminates the consumption of time, energy, and money by costly and cumbersome calculations.

Keywords crude oil fractions, hydrocarbon solvents, temperature, viscosity, viscosity estimation, viscosity model

1. Introduction

The viscosity of hydrocarbon solvents over a wide range of temperatures is essential in many engineering process calculations and designs. Because viscosity measurement at all the multiple and vast conditions present in the oil and gas industry is time-consuming, burdensome, and expensive, theoretical models are used to estimate the viscosity of hydrocarbon solvents. Many viscosity models have been proposed by researchers for simple liquids (Ref 1-11). However, it is still rare to find models that have reliably efficient predicting abilities. Often, large estimation errors occur when these models are used over a wide range of temperatures. Also, when used on substances other than those for which they were correlated, the models produce large deviations. Thus, the need for a more versatile and accurate prediction model exists.

Amin and Maddox (Ref 3) proposed a generalized correlation that predicts the kinematic viscosity of petroleum fractions as a function of temperature (T). The model requires the values of several characterization properties such as API gravity, 50% boiling point (T_b), and molecular weight (MW) to predict the viscosity of petroleum fractions. The equation is given as follows:

$$\eta = [-1.954 \times 10^{-3} + 0.0906 \exp(-7.773 \times 10^{-3} \cdot MW)] \times \left[\frac{67.45 + \exp(5.329 + 0.00329 \cdot T_b)}{T} \right] \quad (\text{Eq 1})$$

This model produced an average absolute deviation of 9.1% (Ref 9) when tested on 248 viscosity data points from Arab crude oil fractions. The high percent deviation produced indi-

cates that the model lacks the capability to predict viscosity with satisfactory accuracy.

The correlation proposed by Assael et al. (Ref 4) to predict the kinematic viscosity of liquid toluene as a function of temperature gave an average absolute deviation of 1.4%. The model is shown in Eq 2 as follows:

$$\frac{1}{\eta} = [6.035 \times 10^8 V^{2/3} (MRT)^{-0.5}] \times (0.524367 - 1.34765 V_r + 1.081113 V_r^2 - 0.25609 V_r^3) \quad (\text{Eq 2})$$

where

$$V_r = \frac{V}{V_o} \quad (\text{Eq 3})$$

and

$$V_o \times 10^6 = 129.770 - 0.2793623T + 6.7699 \times 10^{-4} T^2 - 6.36347 \times 10^{-7} T^3 \quad (\text{Eq 4})$$

In this model, M is molar mass, T is temperature, V is molar volume, and R is the gas constant. The disadvantage for this correlation is that its predicting capability is accurate only for toluene. New parameters must be determined for each hydrocarbon.

Dymond and Øye (Ref 7) proposed a correlation that predicts the dynamic viscosity of hydrocarbons as a function of temperature. The model requires a reference measurement of the viscosity, μ_o , of the hydrocarbon in question at 298.15 K, T_o . The model is represented by Eq 5.

$$\ln\left(\frac{\mu}{\mu_o}\right) = A + \frac{B}{\left(\frac{T}{T_o}\right)} + \frac{C}{\left(\frac{T}{T_o}\right)^2} + \frac{D}{\left(\frac{T}{T_o}\right)^3} \quad (\text{Eq 5})$$

Variables A , B , C , and D are parameters that are unique to each hydrocarbon. Thus, these factors must be determined by fitting

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them to experimentally determined data. This reduces proficiency and increases computation cost.

2. Correlation Development

The correlation proposed by Puttagunta et al. (Ref 1) was designed to estimate the kinematic viscosity of conventional petroleum liquid over large temperature ranges. The model is unique in the petroleum industry because it is straightforward and easy to use when modeling the viscosities of conventional crude oil and light hydrocarbons. The model has been previously proven capable of modeling accurate viscosities of crude oils based on one viscosity measurement at reference temperature and atmospheric pressure (Ref 1). The correlation, given in Eq 6, originally represented 65 data sets gathered from 20 different crude oils found around the world. The overall average absolute deviation was 0.8%, an excellent result for a total of 181 individual data points:

$$\log \eta = \frac{b}{1 + \left(\frac{T - 37.78}{310.93} \right)^S} + C \quad (\text{Eq 6})$$

where η is kinematic viscosity (cSt), T is temperature ($^{\circ}\text{C}$), C is given as -0.8690 , b is the characterization parameter defined as $b = \log_{10} \eta_{37.78\text{ }^{\circ}\text{C}} - C$, and S is the shape factor that relates to the characterization parameter as follows: $S = 0.28008b - 1.6180$.

In this study, to maximize accuracy while maintaining the simplicity of the correlation, an attempt has been made to modify and extend the Puttagunta et al. (Ref 1) model to predict the viscosity of hydrocarbon solvents. Because only extremely minor viscosity variations with temperature have been observed in simple low-viscosity solvents, the correlation has been modified to incorporate a viscosity reduction factor, represented as Φ . The viscosity reduction factor represents the minor change in viscosity with temperature and thus, is unique for each hydrocarbon solvent. This modification is shown in Eq 7. The incorporation of the viscosity reduction factor was done to achieve the most accurate and simple-to-use model that relates the viscosity of light hydrocarbons liquids to temperature.

$$\log \eta = \frac{b}{1 + \left(\frac{T - 37.78}{310.93} \right)^{\Phi}} + C \quad (\text{Eq 7})$$

The viscosity reduction factor values for several light hydrocarbon samples are shown in Table 1. These values were obtained by performing a constraint nonlinear regression on the viscosity and temperature data. The variables η and T in Eq 7 still represent kinematic viscosity (cSt) and temperature ($^{\circ}\text{C}$).

This modified correlation has been tested on 22 light hydrocarbon liquids at temperatures ranging from -54.41 to 160 $^{\circ}\text{C}$, as given in Table 2. The reference temperature of 37.78 $^{\circ}\text{C}$ (100 $^{\circ}\text{F}$) was maintained from the original correlation to ensure practicality and convenience. Measurement of viscosity at the reference temperature and pressure requires minimal cost and effort and, most importantly, satisfies the ASTM D445 standards for field viscosity measurement (Ref 12). The correlation requires only one viscosity at the reference condition to make predictions at other temperatures.

Table 1 Viscosity reduction factor, Φ , values for different solvent group

Sample	Φ value
Decane	1.8727
Toluene	1.8670
Hexane	0.7230
<i>cis</i> -Decalin	1.9283
<i>o</i> -Xylene	1.3014
HCCG (heavy catalyst cracked gasoline)	1.6989
Naphtha (heavy)	1.7400
Naphtha (light)	1.6071
Naphtha (intermediate)	1.7326
Cyclopentane	1.7684
Dimethyl carbonate	2.4560
Diethyl carbonate	2.1906
TriEGDME	2.1066
TEGDME	2.0960
Methylcyclohexane	1.9835
2,2,4,4,6,8,8-Heptamethylnonane	1.8936
Arabian light cut 244.5-262.5 $^{\circ}\text{C}$	1.9437
Arabian light cut 262.5-278.7 $^{\circ}\text{C}$	1.9016
Arabian light cut 278.7-294.5 $^{\circ}\text{C}$	1.9159
Samotlor crude oil IBP-62 $^{\circ}\text{C}$	1.7354
Samotlor crude oil 62-140 $^{\circ}\text{C}$	1.7989
Samotlor crude oil 140-240 $^{\circ}\text{C}$	1.9239

Table 2 List of data sources

Hydrocarbons	Number of data points	Viscosity at 37.78 $^{\circ}\text{C}$	Source
HCCG (heavy catalyst cracked gasoline)	7	1.111	In house
Decane	5	1.045	In house
<i>o</i> -Xylene	5	0.882	In house
Hexane	5	0.614	In house
Naphtha HRS	13	0.774	In house
Naphtha LRS	7	0.477	In house
Pure product naphtha	7	0.586	In house
Pure intermediate naphtha	6	0.621	In house
Pure diluent naphtha	7	0.461	In house
Cyclopentane	11	0.507	In house
Decane	4	0.982	Ref 13
TriEGDME	8	1.601	Ref 8
TEGDME	8	2.560	Ref 8
Dimethyl carbonate	7	0.473	Ref 8
Diethyl carbonate	8	0.667	Ref 8
Toluene	6	0.590	Ref 14
Toluene	11	0.598	Ref 15
Toluene	4	0.588	Ref 4
<i>cis</i> -Decalin	7	2.631	Ref 16
Methylcyclohexane	7	0.766	Ref 16
2,2,4,4,6,8,8-Heptamethylnonane	7	3.318	Ref 17
Arabian light cut 244.5-262.5 $^{\circ}\text{C}$	35	2.286	Ref 18
Arabian light cut 262.5-278.7 $^{\circ}\text{C}$		2.792	
Arabian light cut 278.7-294.5 $^{\circ}\text{C}$		3.484	
Samotlor crude oil IBP-62 $^{\circ}\text{C}$	127	0.398	Ref 19
Samotlor crude oil 62-140 $^{\circ}\text{C}$		0.611	
Samotlor crude oil 140-240 $^{\circ}\text{C}$		1.246	

3. Experimental Methods

A Canon-Fenske viscometer was used in accordance with the ASTM D445 (Ref 12) procedure to obtain kinematic viscosity data for 10 hydrocarbon solvents over a temperature range of 13.65 to 92.57 $^{\circ}\text{C}$. The data from these measurements, along with 245 data points collected from various literature sources, for a total of 318 data points, as shown in Table 2,

Table 3 Average absolute deviations (%) produced by Eq 6 and 7 for hydrocarbon solvents

Hydrocarbons	Average absolute deviations, %		Source
	Eq 6	Eq 7	
HCCG	2.27	2.16	In house
Decane	2.76	2.78	In house
<i>o</i> -Xylene	2.54	0.94	In house
Hexane	3.96	1.42	In house
Naphtha HRS	1.07	0.39	In house
Naphtha LRS	1.51	0.89	In house
Pure product naphtha	1.75	1.33	In house
Pure intermediate naphtha	1.99	1.80	In house
Pure diluent naphtha	2.21	1.45	In house
Cyclopentane	1.75	1.68	In house
Decane	1.59	1.44	Audonnet and Pádua (Ref 13)
TriEGDME	2.90	0.31	Comuñas et al. (Ref 8)
TEGDME	2.33	0.92	Comuñas et al. (Ref 8)
Dimethyl carbonate	4.73	1.92	Comuñas et al. (Ref 8)
Diethyl carbonate	3.72	0.82	Comuñas et al. (Ref 8)
Toluene	4.56	3.79	Assael et al. (Ref 14)
Toluene	4.41	3.93	Assael et al. (Ref 4)
Toluene	3.53	2.80	Assael et al. (Ref 15)
<i>cis</i> -Decalin	0.93	0.31	Zéberg-Mikkelsen et al. (Ref 16)
Methylcyclohexane	1.52	0.61	Zéberg-Mikkelsen et al. (Ref 16)
2,2,4,4,6,8,8-Heptamethylnonane	2.20	0.71	Zéberg-Mikkelsen et al. (Ref 17)
Total	2.55	1.50	...

Table 4 Average absolute deviations (%) produced by Eq 6 and 7 for Arabian light crude oil cuts from Kanti et al. (Ref 18)

Temperature range of cuts, °C	Average absolute deviations, %	
	Eq 6	Eq 7
150-162.5	0.47	1.07
162.5-185	4.65	4.34
185-206.1	3.00	3.02
206.1-225.9	1.97	1.80
225.9-244.5	0.46	0.61
244.5-262.5	0.48	0.40
262.5-278.7	2.43	2.48
278.7-294.5	3.10	3.36
Total	2.26	2.15

were used to obtain their viscosity reduction factor. The value of viscosity reduction parameter obtained for each hydrocarbon solvent by performing a constraint nonlinear regression on each data set is given in Table 1.

4. Results and Discussion

The Puttagunta et al. (Ref 1) one-parameter viscosity model (Eq 6) was validated with 318 data points from 22 light hydrocarbon solvents, over a temperature range of -54.41 to 160 °C. The calculated viscosity deviated from the experimental values by a mean of 2.2%. This overall average absolute deviation of 2.2% represents an excellent match between measured and calculated viscosity values, and well within an acceptable limit of experimental error. However, the correlation of the same data with Eq 7 by incorporating the value for the viscosity reduction factor, Φ , as listed in Table 1 for the 22 hydrocarbons, gave the best result. Eq 7 produced an overall average absolute deviation of 1.9%.

Table 5 Average absolute deviations (%) produced by Eq 6 and 7 for Samotlor crude oil fractions from Grigor'eva et al. (Ref 19)

Temperature range of fractions, °C	Average absolute deviations, %	
	Eq 6	Eq 7
Initial boiling point-62	1.05	1.06
Initial boiling point-120	1.56	1.66
62-85	1.86	2.21
85-105	2.38	2.45
62-140	0.55	0.54
Initial boiling point-180	1.82	1.71
Initial boiling point-195	1.32	1.14
105-140	1.23	0.92
120-180	1.18	3.67
140-180	1.41	2.48
140-240	2.86	2.60
180-240	3.91	3.68
Total	1.96	2.24

The average absolute deviations for each of the 22 hydrocarbon solvents produced by Eq 7 and 6 are compared in Tables 3 to 5. For hydrocarbon solvents shown in Table 3, Eq 7 gave far better viscosity estimations than Eq 6. Therefore, for the types of solvents displayed in Table 3, Eq 7 is the optimal model.

Tables 4 and 5 show that for crude oil fractions the better of the two models, in their ability to accurately estimate viscosity values, varies from fractions to fractions. Thus, either of the two models, Eq 6 or 7, can be applied to accurately predict the viscosity of crude oil fractions. The two models are closely matched in their predicting abilities for these types of solvents.

Figures 1 to 3 compare the deviations from experimental viscosity data obtained with both models, Eq 6 and 7, for *o*-Xylene, light straight-run naphtha, and dimethyl carbonate, respectively. It is apparent from the figures that the best match between experimental and predicted viscosity data for each

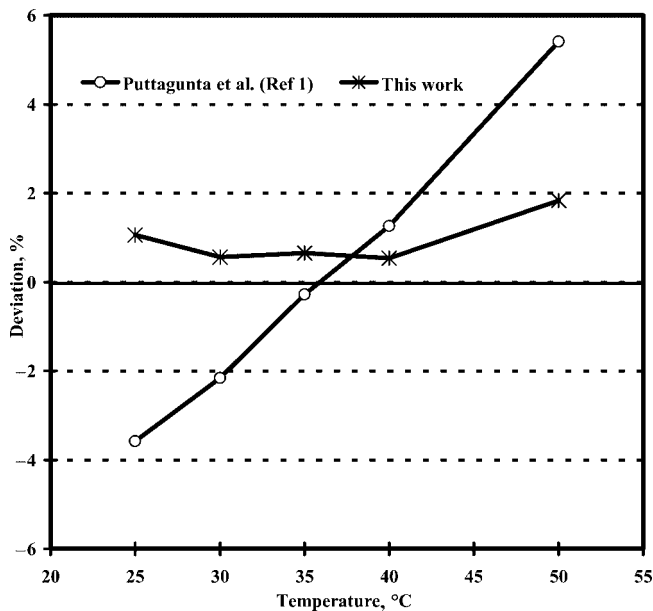


Fig. 1 Deviations of predicted viscosity data for *o*-Xylene

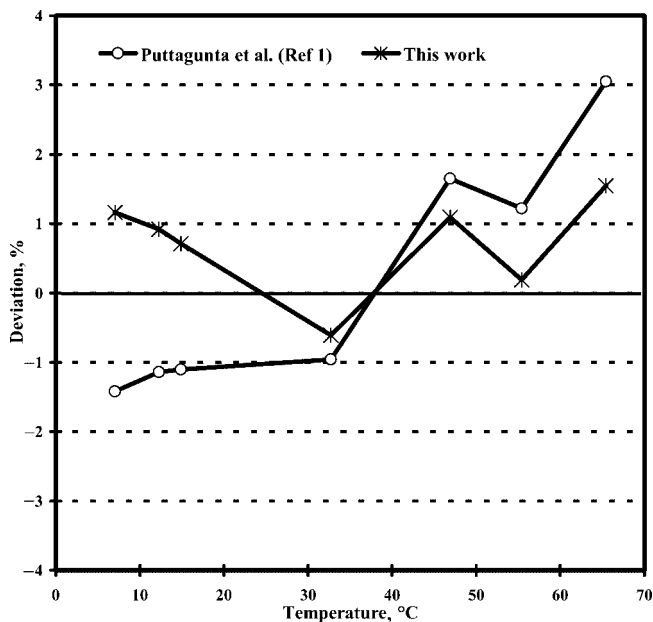


Fig. 2 Deviations of predicted viscosity data for light straight naphtha

solvent was obtained with Eq 7. The maximum deviations obtained with Eq 7 were generally within 2% compared with almost 5% obtained with Eq 6. This comparison demonstrates that Eq 7 is a more accurate model than Eq 6 for predicting viscosities of light hydrocarbon solvents.

Tables 6 and 7 compare the deviations from experimental viscosity produced by Eq 6 and 7 when applied to predict the viscosities of *cis*-Decalin and Samotlor crude oil fraction 180-240 °C. It is shown in Table 6 that Eq 7 generates the more accurate and reliable results for *cis*-Decalin. In fact, Eq 7 reduces the average absolute deviation of Eq 6 from 0.9% to 0.3%.

Table 7 demonstrates that for Samotlor crude oil fraction

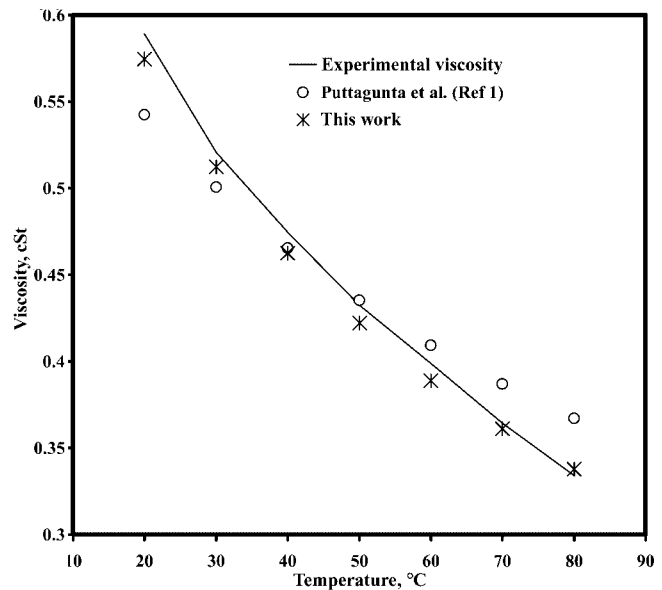


Fig. 3 Comparison of experimental and predicted viscosity data for dimethyl carbonate

Table 6 Predicted viscosity and absolute percent deviation calculated by Eq 6 and 7 at various temperatures for *cis*-Decalin

Temperature, °C	Experimental viscosity, cSt	Predicted viscosity, cSt		Absolute deviation, %	
		Eq 6	Eq 7	Eq 6(a)	Eq 7(b)
20	3.741	3.797	3.760	1.51	0.50
30	3.041	3.065	3.053	0.78	0.37
40	2.512	2.524	2.526	0.48	0.59
50	2.130	2.115	2.127	0.67	0.14
60	1.813	1.801	1.817	0.70	0.21
70	1.567	1.554	1.573	0.85	0.37
80	1.378	1.358	1.378	1.49	0.00

(a) AAD = 0.9%. (b) AAD = 0.3%

180-240 °C, the difference in accuracy between the two models is not that great. For crude oil fractions, Eq 6 and 7 can be used interchangeably, for neither of the models is noticeably more accurate.

Figures 4 to 6 compare the deviations from experimental viscosity data obtained with Eq 6 and 7, for Arabian light crude oil cut 262.5-278.7 °C and Samotlor crude oil fractions 62-140 °C and 180-240 °C. These figures present the data in such a manner that one can observe that neither correlation predicts the most accurate viscosity values more often than the other model for these cuts and fractions. Both equations can be used to accurately predict the viscosity of crude oil fraction and cuts.

For light hydrocarbons solvents, the low average absolute deviation percentages between experimentally determined kinematic viscosities and calculated viscosities based on the effect of temperature at atmospheric pressure show that Eq 7 is very accurate in predicting kinematic viscosity. Eq 6 was originally developed for predicting the viscosities of conventional crude oils and their fractions (Ref 1, 20), and thus it is inappropriate for accurate prediction of viscosities of hydrocarbon solvents.

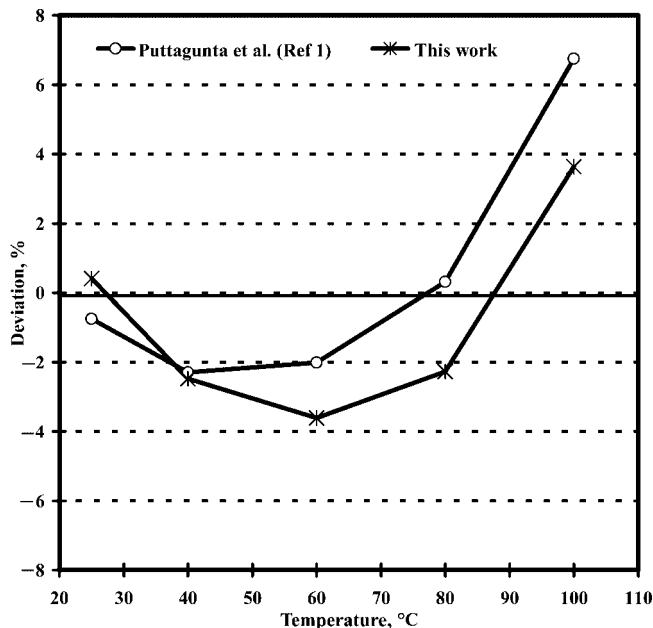


Fig. 4 Deviations of predicted viscosity data for Arabian light cut 262.5-278.7 °C

Table 7 Predicted viscosity and absolute percent deviation calculated by Eq 6 and 7 at various temperatures for Samotlor crude oil fraction 180-240 °C

Temperature, °C	Experimental viscosity, cSt	Predicted viscosity, cSt		Absolute deviation, %	
		Eq 6	Eq 7	Eq 6(a)	Eq 7(b)
-37.6	1.901	1.921	1.901	1.08	0.02
-28.9	1.600	1.623	1.609	1.42	0.55
-22.0	1.420	1.436	1.425	1.10	0.37
-10.0	1.170	1.185	1.179	1.28	0.76
0.0	1.020	1.028	1.024	0.80	0.42
10.0	0.901	0.905	0.902	0.39	0.13
20.0	0.805	0.805	0.804	0.05	0.10
30.4	0.725	0.722	0.722	0.42	0.48
32.6	0.713	0.706	0.706	0.93	0.97
41.7	0.665	0.648	0.649	2.50	2.48
49.4	0.614	0.606	0.607	1.27	1.19
59.4	0.572	0.559	0.560	2.26	2.12
70.6	0.528	0.515	0.516	2.53	2.34

(a) AAD = 1.2%. (b) AAD = 0.9%

5. Conclusions

The viscosity-temperature correlation, Eq 7, has been shown to give excellent estimations of experimental viscosities of hydrocarbon solvents. The predicted viscosities accurately matched the experimental viscosities with an averaged absolute deviation (AAD) of below 1% for hydrocarbon solvents, and an overall AAD of 1.9% with crude oil fractions. The viscosity reduction factor, Φ , values have been determined for 22 hydrocarbon solvents and crude oil fractions. The model is simple to use and, like the model by Puttagunta et al. (Ref 1), requires only one viscosity value at 37.78 °C (100 °F) and one atmosphere pressure to estimate viscosity at any given temperature. However, for 318 data points, Puttagunta model gave an aver-

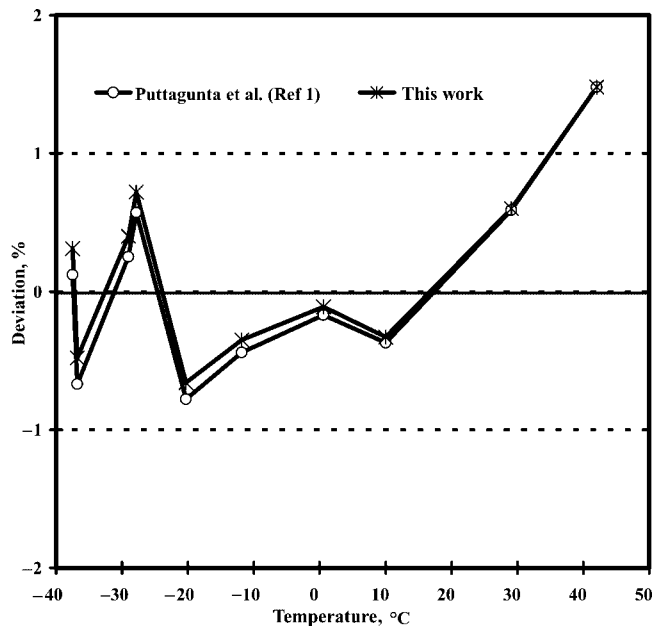


Fig. 5 Deviations of predicted viscosity data for Samotlor crude oil fraction 62-140 °C

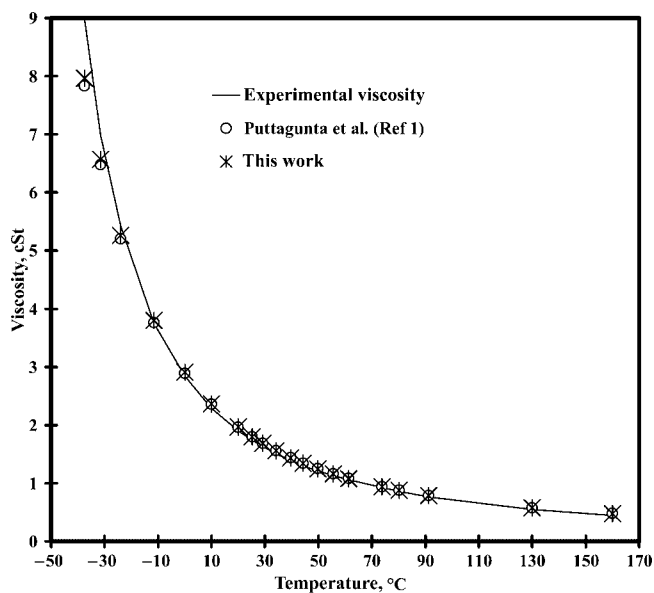


Fig. 6 Comparison of experimental and predicted viscosity data for Samotlor crude oil fraction 180-240 °C

age absolute deviation of 2.2% compared with 1.9% obtained with this model.

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