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Saturated Liquid Viscosity Correlations for Alternative Refrigerants

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This article presents dimensionless equations for the temperature dependence of the saturated liquid viscosity of R32, R123, R124, R125, R134a, R141b, and R152a valid over a temperature range of engineering interest. The correlation has the form $\Phi_D^n = A + BT_D$ where Φ_D is the dimensionless fluidity $(1/\eta_D)$ and T_D is a dimensionless temperature. n, A, and B are evaluated for each of the above refrigerants based on a least-squares fit to experimental data. This equation is found to provide an improved fit over those existing in the literature up to $T_D = 0.8$.

KEY WORDS: ozone friendly; refrigerants; viscosity.

1. INTRODUCTION

The saturated liquid viscosity is an important thermophysical property in the design of engineering systems involving refrigeration, heat pumping, Rankine cycle power plants, etc. Consequently, this has been a topic of investigation for refrigerants [1–3]. Although traditionally fluidity correlations as a function of the molar volume are more representative [4, 5], designers continue to seek temperature dependence of viscosity coefficient. A review of the relative effects of these correlations has been presented by Latini et al. [6] and Takahashi [7]. A relation between fluidity and dimensionless temperature has been developed by Srinivasan and Krishna Murthy [8] for CFCs and HCFCs in the methane family and CFCs of the ethane family.

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The Montreal Protocol has given a fresh impetus to experimental investigations on properties of "ozone-friendly" refrigerants. In the recent past, several experimental data sets have emerged and each set has an accompanying correlation. Many of the generalized correlations which have been applicable to chlorine containing refrigerants have not been succesful in providing an estimate of the saturated liquid viscosity of these newly synthesized refrigerants. Further, correlations accompanying the experimental data from several sources show large deviations (up to 20%) when applied to other sources of data [9] and more so when extrapolated outside their range of validity. There is a need to develop correlations for satured liquid viscosity applicable over a range of temperatures encountered in practical systems considering all the data. This paper attempts to develop such correlations for seven of the new refrigerants in the range from close to the triple point to approximately $0.9T_c$.

2. DEVELOPMENT OF CORRELATION

The procedure adopted is nearly the same as that described by Srinivasan and Krishna Murthy [8] with the change that the reduced fluidity is made dimensionless and its power is allowed to vary for each fluid (instead of 0.5 used by them)

$$\Phi_D^n = A + BT_D \tag{1}$$

where

$$\begin{aligned} \Phi_D &= 1/\eta_D \\ \eta_D &= \text{fac} \cdot \eta \end{aligned} \tag{2}$$

fac is the viscosity reduction factor given by

$$\text{fac} = V_c^{2/3}/[\{M(T_c - T_f)\}^{1/2} k^{1/2} N^{1/6}] \tag{3}$$

and the dimensionless temperature is defined as

$$T_D = (T - T_f)/(T_c - T_f) \tag{4}$$

In the above equations T is the temperature, η the viscosity, M the molecular weight, and V the molar volume. The subscripts $_c$ and $_f$ refer to the critical point and the normal freezing point. The constants k (the Boltzmann constant) and N (Avogadro's number) are common for all the refrigerants. Yet they are retained to maintain nondimensionality of the viscosity coefficient. The advantage is that any consistent system of units can be used for the calculation of the viscosity coefficient. n, A, and B are

Table I. Property Values and Constants in Eq. (1)

R	Source of viscosity data	No. of data points	T_c (K)	T_f (K)	M	ρ_c (kg · m^{-3})	fac	Index n	A	B
32	[10–13]	31	351.56	137.0	52.0	430	21,442	0.0006	0.99836	1.44711E−03
123	[14–16]	38	456.74	166.0	152.9	552	18,666	0.485	0.09730	0.59796
124	[10, 17, 18]	43	395.65	74.0	136.5	560	17,246	0.462	−0.07099	0.82621
125	[10, 13, 17, 18]	57	339.40	170.0	120.2	572	22,934	0.282	0.39030	0.42732
134a	[10, 11, 14, 16, 19–21]	95	374.22	172.2	102.0	514	21,948	0.432	0.19736	0.52645
141b	[16, 23, 24]	38	477.30	169.9	116.9	461	19,571	0.519	0.08564	0.60720
152a	[14, 24–26]	47	386.44	156.0	66.0	368	23,886	0.223	0.47392	0.42655

optimized through a least-squares fit to experimental data for each fluid under investigation.

The fluids studied are seven of the ozone friendly refrigerants, namely, R32, R123, R124, R125, R134a, R141b, and R152a. The sources of data and other relevant details are listed in Table I. Except for R123 and R134a, the property data used for other refrigerants are taken from McLinden [27]. For R123 and R134a data derived from our earlier work [28, 29] have been used. The differences between IPTS-68 and ITS-90 have been ignored, as it was found that its influence was insignificant for the fluids studied herein. No weighting factors were used, since all sources of experimental data were found to be of comparable precision.

3. RESULTS AND DISCUSSION

3.1. Results for R134a

This refrigerant has been the most widely investigated among the alternative refrigerants. There have been eight sources of data, each covering a different zone but the zone 260–320 K is common to all the data sets. Figure 1 shows the deviations $[(\eta_{exp}-\eta_{cal})/\eta_{exp}\times 100\%]$ with η_{cal} given by Eq. (1). In all the figures the zero line represents the Eq. (1). Most data sets have an associated correlation valid in the temperature range covered by

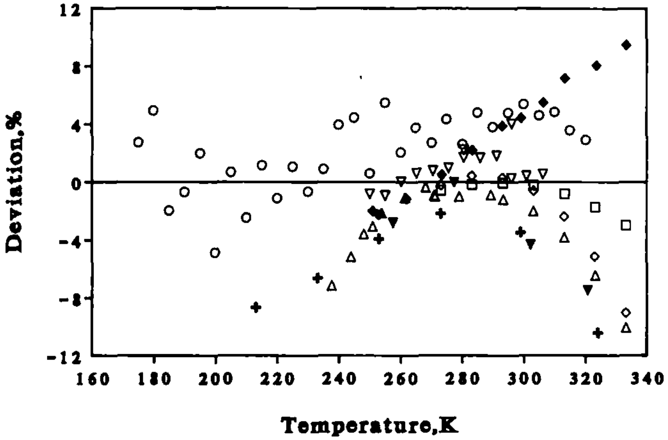

Fig. 1. Relative deviations of experimental data for saturated liquid viscosity of R134a measured by Ripple and Matar [10] (▽), Assael et al. [11] (◇), Kumagai and Takahashi [14] (□), Diller et al. [16] (○), Okubo et al. [19] (+), Oliveira and Wakeham [20] (△), Shankland et al. [21] (◆), and Lavrenchenko et al. [22] (▼) from values calculated with Eq. (1).

Table II. Details of Deviations (in %) from Correlations for R134a

Correlation of	Range (K)	Deviations (%) Max.	Min.	|Average|
Ripple and Matar [10]	250-306	14.8	−24.1	4.6
Assael et al. [11]	273-333	17	−4.7	4.4
Kumagai and Takahashi [14]	273-335	7.2	−21.4	6.5
Diller et al. [16]	175-320	13.6	−8.8	4.5
Okubo et al. [19]	213-335	16.1	−8.5	4.8
Oliveira and Wakeham [20]	238-345	17.7	−3.4	4.6
Shankland et al. [21]	251-333	7.2	−20.4	5.7
Eq. (1)	175-335	9.5	−10.4	3.9

the respective set. Those correlations were used to calculate the deviations when applied to other sources of experimental data but in the same temperature range of validity of the correlation. The deviations are shown in Fig. 2. Certain data sets [19] did not correspond to saturation state but to a compressed liquid state. Their fit of the experimental data was used to extrapolate to the saturation state. Since that involved use of reduced pressure (p/p_c) and reduced temperature (T/T_c), it is necessary to use a vapor pressure correlation which is optimized for T_c and p_c values chosen

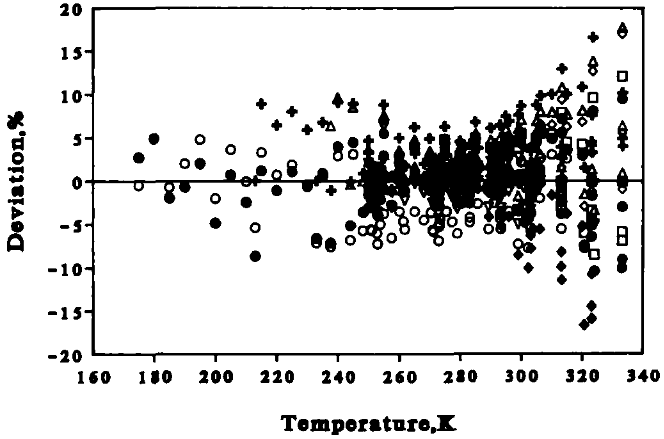

Fig. 2. Comparison of relative deviations from correlations given by Ripple and Matar [10] (▽), Assael et al. [11] (◇), Kumagai and Takahashi [14] (□), Diller et al. [16] (○), Okubo et al. [19] (+), Oliveira and Wakeham [20] (△), Shankland et al. [21] (◆), and Eq. (1) (●) for saturated liquid viscosity of R134a.

by them. Fortunately, this has been possible [30]. The range of maximum, minimum, and average deviations are listed in Table II. It can be seen that the present correlation is fairly successful in interpreting the saturated liquid viscosity data of R134a over a wide range of saturation temperatures. A limit of $T_D \leqslant 0.8(334\ \mathrm{K})$ had to be set because above this temperature the non-linearity is too pronounced. This upper limit is often adequate for several practical applications as engineering systems are seldom designed to operate above this temperature and below the critical point.

Krauss et al. [31] have derived viscosity correlations for R134a in which the coefficients of the residual term were optimized using the data of Okubo et al. [19] and Oliveira and Wakeham [20]. Equation (1) predicts systematically higher values than those listed in the tables of Krauss et al. [31]. The deviations range from about 3% at 290 K (the lowest temperature covered by them) to over 10% near 335 K [the upper temperature limit of Eq.(1)]. The trend is analogous to the deviations shown in Fig. 1 for these data of Okubo et al. [19] and Oliveira and Wakeham [20]. Considering that the stated precision of the correlation given by Krauss et al [31] is about 5% and Eq. (1) about 4% the disparity is not too discouraging.

3.2. Other Refrigerants

Figure 3 shows deviation plots for R123. Table III shows a comparison of the deviations of experimental data from various correlations.

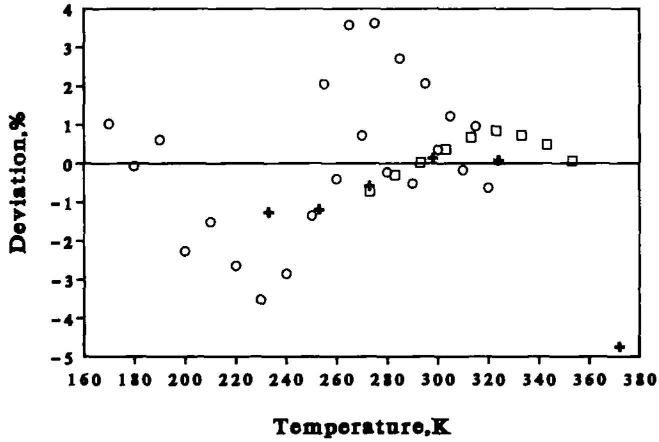

Fig. 3. Relative deviations of experimental data for saturated liquid viscosity of R123 measured by Kumagai and Takahashi [14] (□), Okubo and Nagashima [15] (+), and Diller et al. [16] (○) from values calculated with Eq. (1).

Table III. Details of Deviations (in %) from Correlations for Other Refrigerants

Correlation of	Range (K)	Deviations (%) Max.	Min.	|Average|
R-123				
Kumagai and Takahashi [14]	273–353	4.2	−3.1	1.3
Okubo and Nagashima [15]	233–372	4.4	−1.5	1.6
Eq. (1)	170–375	3.6	−4.5	1.7
R124				
Ripple and Matar [10]	251–313	4.4	−0.4	2.8
Diller and Peterson [17]	170–330	1.6	−3.7	1.7
Assael and Polimatidou [18]	273–333	2.1	−0.9	0.9
Eq. (1)	120–340	5.1	−4.9	2.1
R125				
Ripple and Matar [10]	250–302	0.6	−36.4	6.7
Diller and Peterson [17]	176–305	5.5	−31	4.8
Oliveira and Wakeham [13]	251–333	9.1	−5.3	4.5
Assael and Polimatidou [18]	273–333	3.3	−5.6	1.9
Eq. (1)	176–333	4.7	−7.6	2.8
R141b				
Diller et al. [16]	175–220	2.9	−9.8	4.5
Kumagai and Takahashi [23]	273–353	4.0	−1.1	2.1
Assael et al. [24]	273–333	4.7	0	2.4
Eq. (1)	175–353	3.4	−3.8	1.9
R152a				
Kumagai and Takahashi [14]	273–343	8.5	−4.8	2.6
Assael et al. [24]	273–333	1.8	−3.0	2.4
Philips and Murphy [25]	200–318	9.7	−9.8	5.0
van der Gulik [26]	243–373	10.5	−6.8	2.7
Eq. (1)	200–373	9.2	−4.5	2.6
R32				
Ripple and Matar [10]	251–293	0.5	−1.3	1.0
Assael et al. [11]	273–313	0.4	−4.9	1.9
Oliveira and Wakeham [13]	232–343	4.7	−0.4	1.8
Eq. (1)	231–313	2.0	−4.4	1.5

The correlation given by Diller et al. [16] was not used for comparison, as there were some discrepancies in the coefficients given by them for R123 [32]. The data of Okubo and Nagashima [15], which are for compressed liquid state, were extrapolated to saturation conditions using their correlation. The critical parameters T_c and p_c used in their viscosity correlations were the same as those used by McLinden [27] for the vapor pressure equation. Hence vapor pressure at the saturation state were calculated using the latter equation.

Deviation plots for R124, R125, R141b, R152a, and R32 are shown in Figs. 4 to 8. Table III shows the relative deviations of experimental data for

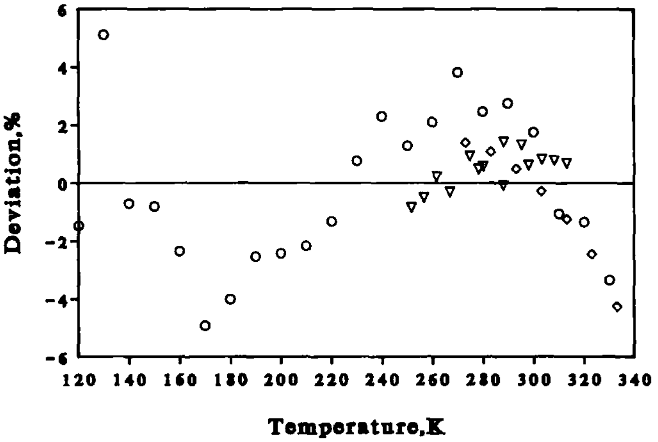

Fig. 4. Relative deviations of experimental data for saturated liquid viscosity of R124 measured by Ripple and Matar [10] (▽), Diller and Peterson [17] (○), and Assael and Polimatidou [18] (◇) from values calculated with Eq. (1).

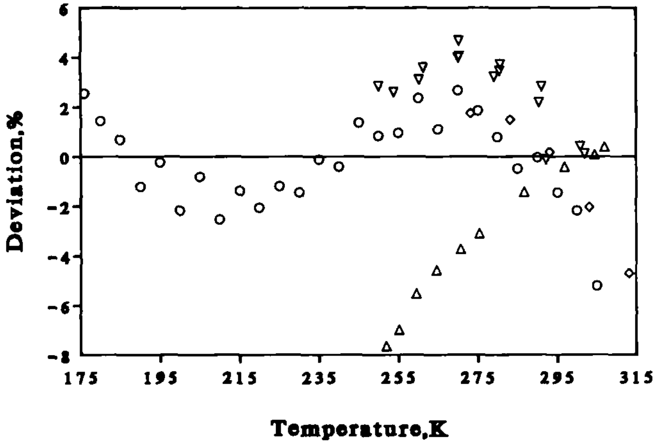

Fig. 5. Relative deviations of experimental data for saturated liquid viscosity of R125 measured by Ripple and Matar [10] (▽), Oliveira and Wakeham [13] (△), Diller et al. [17] (○), and Assael and Polimatidou [18] (◇) from values calculated with Eq. (1).

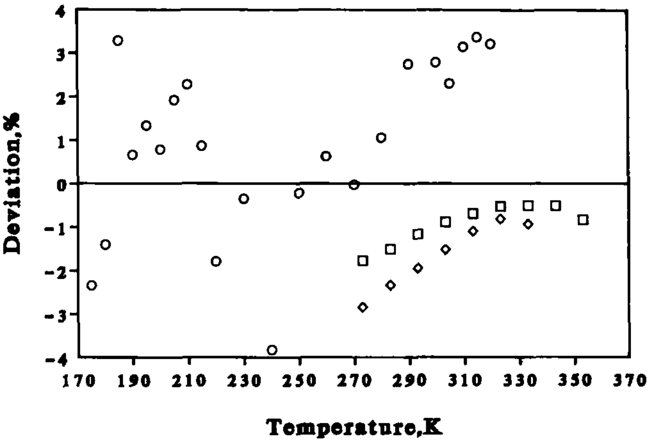

Fig. 6. Relative deviations of experimental data for saturated liquid viscosity of R141b measured by Diller et al. [16] (○), Kumagai and Takahashi [23] (□), and Assael et al. [24] (◇) from values calculated with Eq. (1).

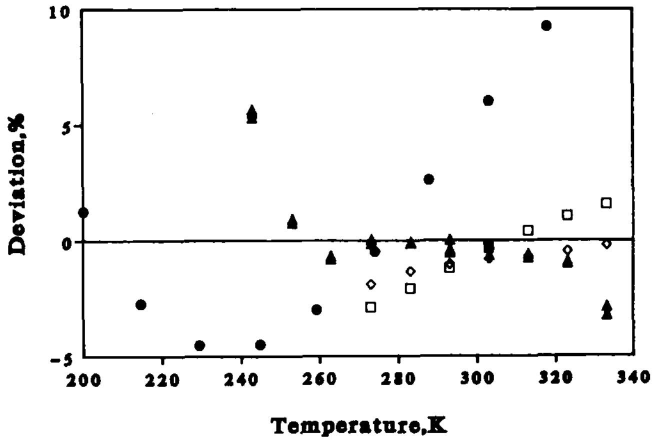

Fig. 7. Relative deviations of experimental data for saturated liquid viscosity of R152a measured by Kumagai and Takahashi [14] (□), Assael et al. [24] (◇), Philips and Murphy [25] (●), and van der Gulik [26] from values calculated with Eq. (1).

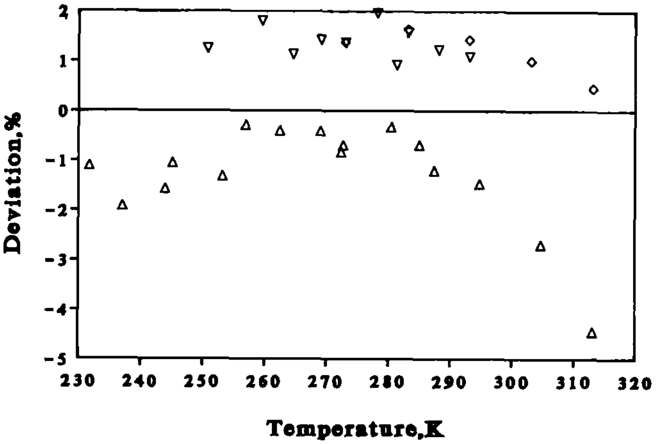

Fig. 8. Relative deviations of experimental data for saturated liquid viscosity of R32 measured by Ripple and Matar [10] (▽), Assael et al. [11] (◇), and Oliveira and Wakeham [13] (△), from values calculated with Eq. (1).

various refrigerants as per different correlations. A very wide temperature range has been covered by Diller and Paterson [17] for R124 and R125 and by Diller et al. [16] for R141b. It is seen that the present correlation gives a better correlation of their data for R124 below 160 K than their own correlation. For R124 fluidity at extrapolated freezing point is negative. This is because $T_f \sim 74$ K, whereas the lowest temperature at which data are available is 170 K unlike in other fluids where data close to T_f are available. The relation proposed by Ripple and Matar [10] could not be used for R124 below 189 K because the value of ρ_0 used in their correlation:

$$1/\eta = B(1/\rho - 1/\rho_0) \tag{5}$$

is smaller than experimental saturated densities.

In the case of R32 the optimized index is actually 0.0006 at which the average absolute deviation is 1.5%. It is not possible to confirm that the index can be that small. With $n = 0.5$ the average deviation is about 3%. Experimental data of Philips and Murphy [12] were systematically higher than the other two sets. Hence this set was not considered for the fit.

As far as the accuracy of Eq. (1) is concerned, it is comparable to several other correlations in the literature but the former covers a wider temperature range for a majority of refrigerants studied here. Particularly, in the low-temperature range which is of special interest in the design of evaporators, Eq. (1) provides a simple and reasonably accurate basis for calculation of saturated liquid viscosity.

4. CONCLUSIONS

A dimensionless equation has been proposed for the calculation of temperature dependence of saturated liquid viscosity of several new refrigerants. The parameters of this equation have been optimized from the available experimental data. The present correlations are found to represent the available data over a wider range of temperatures and the same accuracy compared to those available in the literature.

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