Viscosity modeling of several HFC refrigerants using the friction theory

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Abstract

The viscosity models of pentafluoroethane (R125), 1,1-difluoroethane (R152a), 1,1,1,2-tetrafluoroethane (R134a), difluoromethane (R32), and 1,1,1-trifluoroethane (R143a) have been correlated using the friction theory in conjunction with the Span–Wagner equation of state and Sato et al. equation of state. The obtained viscosity models cover a wide range of fluids states, including the supercritical region. And the models can represent the viscosities of the studied refrigerants to within or close to the uncertainty of the selected primary experimental data. It is apparent that this model is satisfactory and appropriate for most industrial applications. At the same time, the dilute gas viscosity has been correlated using only two constants for each refrigerant, and the results have an agreement with the uncertainty of the recommended data.
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1. Introduction

For the negative environmental impact of chlorofluorocarbons (CFCs), the Montreal Protocol has specified a schedule for the phase-out of CFCs. Some alternative refrigerants, such as pentafluoroethane (R125), 1,1-difluoroethane (R152a), 1,1,1,2-tetrafluoroethane (R134a), difluoromethane (R32), and 1,1,1-trifluoroethane (R143a), have been used in refrigeration systems, heat pumps, foam-blowing, and other applications. Viscosity as one of transport properties is indispensable for the process of equipment design and simulation. Consequently, there is a need for accurate models for viscosity calculations and predictions.

A great amount of models for calculating pure fluids and mixture viscosities have appeared in the literature, and extensive critical reviews of practical predictive and correlative methods may be found in the works of Poling et al. [1] and Monnery et al. [2]. Many viscosity models, however, are based on empirical approaches and only applicable to either the liquid or the gas phase. For example, the Lohrenz–Bray–Clark (LBC) correlation [3], which is an empirical fourth-degree polynomial in the reduced density, is one of the most widely used models for predicting the viscosity of hydrocarbon fluids. There also

exits many semi-theoretical models which can be applied to the entire phases range from dilute gas to liquid, such as the corresponding states method, the hard-sphere theory, the modified Chapman–Enskog method, square-well theory, free volume theory etc.

The corresponding states method [4–6] has been widely used to calculate the viscosity of hydrocarbons or refrigerants. Its accuracy, however, depends on the availability of experimental data in order to improve the correlation. Dymond and Assael [7–9] employed an approach based on the hard-sphere theory in order to correlate and predict the transport properties of dense fluids. The scheme has been successfully employed for hydrocarbons and refrigerants. Chung et al. [10] extended their earlier modification of the Chapman–Enskog theory for dilute gases to dense fluids and mixtures. This was done by introducing empirically correlated density and temperature dependent functions into Enskog hard sphere theory. Monnery et al. [11,12] developed a semi-theoretical three parameter model based on square-well theory for simultaneous correlation of liquid and gas phase viscosities. The model parameters were obtained from viscosity data and generalized with group contributions. The model has been used to correlate gas and liquid viscosities of a wide variety of compounds, including nonpolar, polar and hydrogen bonding. Boned et al. [13,14] proposed an approach in order to model the viscosity of Newtonian fluids, based on the free-volume concept which is also applicable to both gas and liquid states up to very high pressure.

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Differs from all previous approaches, the friction theory used in viscosity modeling based on the friction concepts of classical mechanics and the Van der Waals theory of fluids has been proposed by Quiñones-Cisneros recently [15–17]. This model has a sound theoretical background and can be applied to the entire phase from low to high pressure range. The basic idea of the approach is to use the analogy between shear flow and two sliding surfaces under shear stress, which is linked to normal stress through temperature-dependent friction coefficients. In this theory, viscosity is treated as a mechanical property rather than as a transport property. The viscosity of a specified fluid can be separated into dilute gas contribution and friction term. The friction term can be obtained from a connection between the Amontons-Coulomb friction law and the equation of state, which can be established through the repulsive and attractive pressure terms [40]. The friction theory has been applied to couple with various equations of state (EOS), such as cubic EOS [18–21] and PC-SAFT EOS [22–24], and applied to various types of fluids and fluid mixtures [22–40] including alcohols, n-alkanes, natural gas, and so on.

The novelty of the present work is that the friction theory has been extended to model several alternative refrigerants, including R125, R152a, R134a, R32, and R143a.

2. The friction theory viscosity model

According to the friction theory [15], the total viscosity η is separated into a dilute gas viscosity term η_0 and a residual friction term η_f,

$$\eta = \eta_0 + \eta_f \tag{1}$$

The dilute gas viscosity η_0 is defined as the viscosity at the zero-density limit, while the friction term η_f is related to friction concepts of classical mechanics.

2.1. The dilute gas viscosity term

In this work, an empirical equation for the dilute gas viscosity η_0 (mPa s) was obtained from the recommended viscosities of each refrigerants [83]. The results were given in Table 1.

$$\eta_0 = d_1 T^{0.25} + d_2 T^{2/3} \tag{2}$$

The average absolute deviation (AAD) and the temperature ranges were also presented in Table 1. The deviations of the calculated values of the dilute gas viscosities with Eq. (2) and recommended data were given in Fig. 1. The maximum AAD of the studied refrigerants was less than 0.21%, and it is sufficient for industrial applications.
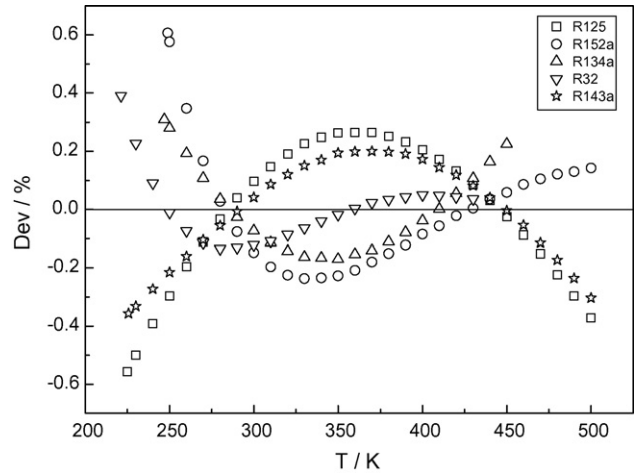

Fig. 1. Deviations between the calculated dilute gas viscosities of the studied refrigerants and recommended values [83].

2.2. The residual friction term

The residual friction term η_f can be expressed as follows:

$$\eta_f = k_i \frac{p_{id}}{p_c} + k_r \frac{\Delta p_r}{p_c} + k_a \frac{p_a}{p_c} + k_{ii} \frac{p_{id}^2}{p_c^2} + k_{rr} \frac{\Delta p_r^2}{p_c^2} + k_{aa} \frac{p_a^2}{p_c^2} \tag{3}$$

where k_r, k_a, k_i, k_{ii}, k_{rr}, k_{aa} are the friction coefficients and p_a is the attractive pressure term. For the repulsive pressure term p_r is defined as:

$$p_r = p_{id} + \Delta p_r \tag{4}$$

p_{id} and Δp_r is the ideal part and the residual term of the repulsive term, respectively. p_c is the critical pressure. The temperature-dependent coefficients can be expressed as follows [40]:

$$k_a = (a_0 + a_1 \varphi_1 + a_2 \varphi_2)\Gamma \tag{5}$$

$$k_{aa} = (A_0 + A_1 \varphi_1 + A_2 \varphi_2)\Gamma^3 \tag{6}$$

$$k_r = (b_0 + b_1 \varphi_1 + b_2 \varphi_2)\Gamma \tag{7}$$

$$k_{rr} = (B_0 + B_1 \varphi_1 + B_2 \varphi_2)\Gamma^3 \tag{8}$$

$$k_i = (c_0 + c_1 \varphi_1 + c_2 \Gamma)\Gamma \tag{9}$$

$$k_{ii} = (C_0 + C_1 \varphi_1 + C_2 \varphi_2)\Gamma^3 \tag{10}$$

where,

$$\varphi_1 = \exp(\Gamma) - 1 \tag{11}$$

$$\varphi_2 = \exp(\Gamma^2) - 1 \tag{12}$$

Table 1
Dilute gas viscosity constants for Eq. (2)

	R125	R152a	R134a	R32	R143a
d_1	-2.29889×10^{-3}	-2.32163×10^{-3}	-2.29209×10^{-3}	-2.52943×10^{-3}	-2.13391×10^{-3}
d_2	5.02409×10^{-4}	4.42365×10^{-4}	4.7842×10^{-4}	5.18484×10^{-4}	4.47033×10^{-4}
AAD%	0.21	0.17	0.13	0.09	0.15
T range (K)	225–500	249–500	247–450	221–430	226–500