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# Viscosity of Gaseous R404A, R407C, R410A, and R507[1]

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This paper presents new measurements of the viscosity of gaseous R404A (52 wt% R143a, 44 wt% R125, 4 wt% R134a), R407C (23 wt% R32, 25 wt% R125, 52 wt% R143a), R410A (50 wt% R32, 50 wt% R125), and R507 (50 wt% R143a, 50 wt% R125). These mixtures are recommended as substitutes for the refrigerants R22, R502, and R13B1. Measurements were carried out in an oscillating-disk viscometer. The obtained values of the viscosity are relative to the viscosity of nitrogen. The experiments were performed at atmospheric pressure over the temperature range 297 to 403 K and near the saturation line up to pressures of 0.6 $P_{\mathrm{crit}}$. The estimated uncertainty of the reported viscosities are ±0.5% for the viscosities at atmospheric pressure and ±1% along the saturation line, being limited by the accuracy of the available vapor pressure and density data. The experimental viscosities at atmospheric pressure are employed to determine the intermolecular potential parameters, $\sigma$ and $\varepsilon$, which provide the optimum representation of the data with the aid of the extended law of corresponding states developed by Kestin et al. A comparison of the experimental viscosity data with the values calculated by REFPROP, both at atmospheric pressure and along the saturation line, is presented.

**KEY WORDS:** gaseous; R404A; R407C; R410A; R507; refrigerants; saturation; viscosity.

## 1. INTRODUCTION

R22, R502, and R13B1, which are used as working fluids for different refrigeration applications, will be restricted or completely phased out in the near-future. The potential alternatives recommended by industry are either

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binary mixtures, R410A (50 wt% R32, 50 wt% R125) and R507 (50 wt% R143a, 50 wt% R125), or ternary mixtures, R404A (52 wt% R143a, 44 wt% R125, 4 wt% R134a) and R407C (23 wt% R32, 25 wt% R125, 52 wt% R134a). In this paper, we present the viscosities of these mixtures in the gaseous phase. The mixtures are treated as quasi-pure substances, and the presented data are valid for the given compositions. The viscosity data consist of the viscosity at low pressure (atmospheric pressure) and the viscosity values along four subcritical isotherms at pressures ranging from atmospheric to near the saturation pressure for the vapor phase of each substance. With knowledge of the vapor pressure and the extraplation of the isotherms up to the saturation conditions, the viscosity along the saturation line can be determined with reasonable accuracy. The accuracy is limited by the uncertainties of the density and vapor pressure data which have been used for the evaluation of the viscosity values.

## 2. EXPERIMENTAL

The measurements were performed in an oscillating-disk viscometer as used for our earlier viscosity measurements. The basic features and the principle for calibration of the viscometer are described in detail elsewhere [1–3]. According to the theory of the oscillating-disk viscometer [4–7], edge effects, which depend only on system geometry, have to be taken into account for a disk with a finite diameter. However, even when using corrections for these effects, absolute measurements are possible only as long as the thickness of the boundary layer $\delta$ at the oscillating disk is larger than the distance between the fixed plates defined as

$$\delta = \left(\frac{\eta \cdot t_0}{2 \cdot \pi \cdot \rho}\right)^{1/2} \gg b_1 + b_2 + d \tag{1}$$

where $\eta$ is the viscosity, $\rho$ is the density of the fluid, $t_0$ is the period of oscillation in vacuum, $b_1$ and $b_2$ are the distances between the oscillating disk and the upper and lower fixed plates, and $d$ is the thickness of the oscillating disk. For the refrigerants, due to the geometrical arrangment of our viscometer ($b_1 + b_2 + d \approx 3.521$ mm), condition (1) is satisfied only for viscosity meaurements at low pressures. At higher pressures and the corresponding higher densities of the refrigerants, condition (1) is not satisfied. Therefore, we have to evaluate the present experiments using the relative method suggested by Kestin et al. [5–7]. Prior to the viscosity measurements, the viscometer was calibrated with nitrogen to determine the edge-correction factor as a function of boundary-layer thickness. The viscosity values of nitrogen were taken from Stephan et al. [8]. The calibrations were performed at the same temperatures where the viscosity was to be investigated [2].

The refrigerants R507 (99.64%) and R410A (99.72%) were supplied by Solvay Fluor und Derivate GmbH (Germany). R407C (99.7%) was supplied by ICI Chemicals & Polymers Ltd. (UK), and R404A (99.67%) was supplied by Hoechst Chemikalien (Germany). The density of the fluids was evaluated with the aid of the correlations of Döring and Buchwald [9, 10] for R507 and R410A, with the equation of ICI [11] for R407C, and with REFPROP [12] for R404A.

## 3. RESULTS

### 3.1. Viscosity at Low Pressure

To extend the measurements over a wide range of temperatures, the viscosities at low pressure were measured separately. The experiments were performed at atmospheric pressure. The temperatures ranged from 298 to 400 K in the vapor phase. The results of the present experiments on the mixtures R404A, R407C, R410A, and R507 are listed in Table I.

**Table I.** Viscosity of Gaseous R404A, R407C, R410A, and R507 at Atmospheric Pressure

| $T$ (K) | $\rho$ ($\mathrm{kg \cdot m^{-3}}$) | $\eta_0$ ($\mu\mathrm{Pa \cdot s}$) | $T$ (K) | $\rho$ ($\mathrm{kg \cdot m^{-3}}$) | $\eta_0$ ($\mu\mathrm{Pa \cdot s}$) |
|---|---|---|---|---|---|
| | R404A | | | R407C | |
| 305.50 | 3.770 | 12.398 | 297.65 | 3.533 | 12.207 |
| 313.57 | 3.669 | 12.726 | 314.66 | 3.334 | 13.014 |
| 323.45 | 3.485 | 13.125 | 324.74 | 3.227 | 13.459 |
| 332.87 | 3.511 | 13.500 | 333.15 | 3.143 | 13.716 |
| 334.11 | 3.370 | 13.550 | 365.96 | 2.853 | 15.101 |
| 364.62 | 3.196 | 14.740 | 398.79 | 2.693 | 16.519 |
| 392.59 | 2.963 | 15.799 | 398.83 | 2.613 | 16.558 |
| | R410A | | | R507 | |
| 298.98 | 2.956 | 12.965 | 299.23 | 4.038 | 12.239 |
| 303.94 | 2.906 | 13.143 | 303.54 | 3.977 | 12.431 |
| 314.34 | 2.806 | 13.571 | 313.81 | 3.840 | 12.819 |
| 320.33 | 2.752 | 13.847 | 322.24 | 3.734 | 13.178 |
| 327.53 | 2.689 | 14.157 | 324.26 | 3.711 | 13.205 |
| 336.14 | 2.618 | 14.532 | 351.45 | 3.413 | 14.367 |
| 343.83 | 2.558 | 14.868 | 383.54 | 3.120 | 15.689 |
| 377.64 | 2.324 | 16.368 | 401.07 | 2.981 | 16.245 |
| 397.39 | 2.158 | 17.195 | | | |

The low-pressure viscosity $\eta_0$ of the investigated mixtures can be well represented by the Chapman–Enskog equation derived from the kinetic theory for dilute gases,

$$\eta_0 = \frac{5}{16}\frac{(M(k/\pi N_0)\,T)^{1/2}}{\sigma^2 \Omega_\eta(T^*)} = 2.6696 \times 10^{-2}\frac{(MT)^{1/2}}{\sigma^2 \Omega_\eta(T^*)} \tag{2}$$

In Eq. (2) the parameters are $k = 1.38066 \times 10^{-23}\ \mathrm{J \cdot K^{-1}}$, the Boltzmann constant; $M$ is the molar mass in $\mathrm{kg \cdot kmol^{-1}}$; $N_0 = 6.02204 \times 10^{26}\ \mathrm{kmol^{-1}}$, Avogadro's number; $\Omega_\eta(T^*)$ is the collision integral; $T^* = kT/\varepsilon$ is the reduced temperature; $T$ is the absolute temperature in K; $\eta_0$ is the viscosity in $\mu\mathrm{Pa \cdot s}$; and $\sigma$ and $\varepsilon$ are the characteristic potential parameters with the units of length and energy. For the collision integral $\Omega_\eta(T^*)$, we used the following equation presented by Kestin et al. [13].

$$\begin{aligned}\Omega_\eta(T^*) = \exp[&0.45667 - 0.53955(\ln T^*) + 0.187265(\ln T^*)^2\\ &- 0.03629(\ln T^*)^3 + 0.00241(\ln T^*)^4]\end{aligned} \tag{3}$$

The parameters $\sigma$ and $\varepsilon$ and, correspondingly, $\varepsilon/\kappa$, can be determined from the low-pressure viscosity data [14]. Table II gives the optimum values of the parameters $\sigma$ and $\varepsilon$ (as $\varepsilon/\kappa$) derived from the best fit to the present viscosity measurements. Figure 1 displays the deviations of the experimental data from the calculated values by Eqs. (2) and (3) with the values of the parameters $\sigma$ and $\varepsilon/\kappa$ listed in Table II. In no case does the deviation exceeed ±0.5%. The standard deviation is ±0.3%. Due to the theoretical basis of Eq. (2), we assume that the viscosity values can be extrapolated below the investigated temperature range with only a modest loss of accuracy.

There is one other set of experimental viscosity data at atmospheric pressure for the refrigerant R404A (SUVA HP62). These results have been published by Du Pont [15] in the form of an equation for temperatures

**Table II.** Potential Parameters $\varepsilon/\kappa$ and $\sigma$ for R404A, R407C, R410A, and R507 Obtained from Viscosity Measurements

| Refrigerant | $\varepsilon/\kappa$ (K) | $\sigma$ (nm) |
|---|---|---|
| R404A | 279.31 | 0.4968 |
| R407C | 339.72 | 0.4538 |
| R410A | 317.47 | 0.4324 |
| R507 | 294.33 | 0.4902 |

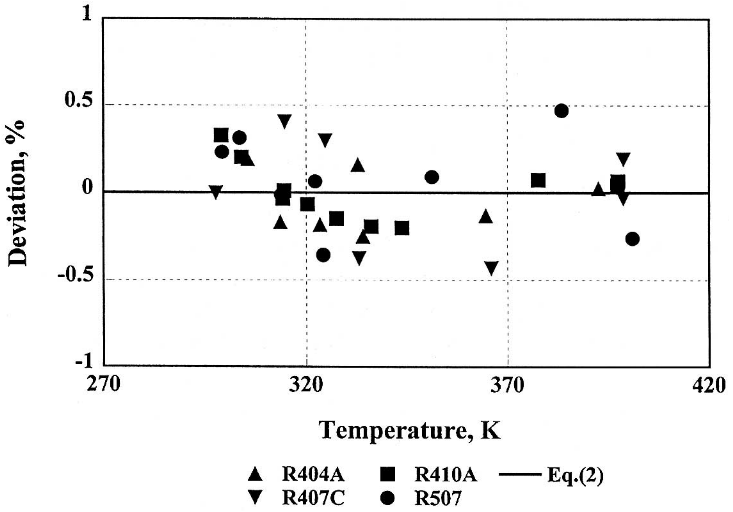

**Fig. 1.** Deviation of measured viscosity of R404A, R407C, R410A, and R507 at atmospheric pressure from the viscosity calculated by Eq. (2) as a function of temperature.

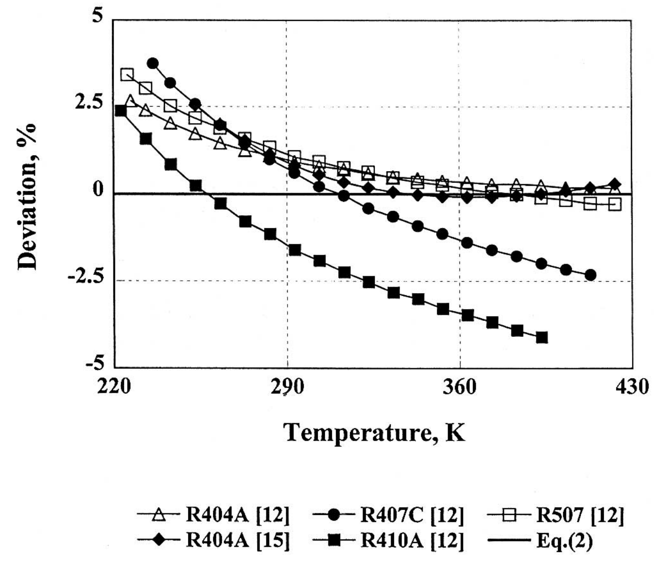

**Fig. 2.** Comparison between the present measurements of the viscosity of R404A, R407C, R410A, and R507 at atmospheric pressure represented by Eq. (2) and the values calculated with the program REFPROP [12] and Du Pont values for R404A [15].

between 253 and 423 K. To our knowledge, there are no further experimental data in the literature for the other subtances investigated in this work. Besides the equation of Du Pont for R404A, we have used the viscosity values calculated with REFPROP [12] to compare our results. Figure 2 shows the deviations of the viscosities taken from Refs. 12 and 15 from the best fit of our experimental data represented by Eq. (2) as the baseline. At temperatures above 280 K, the agreement between the viscosity values for R404A of Du Pont and REFPROP with the present data are within ±1%. For the extrapolated values at temperatures below 280 K, the differences increase to a maximum of +2.5%. The agreement between the experimental data for R507 and the calculated viscosities in Ref. 12 is also within ±1% for temperatures above 290 K. Below this temperature, the differences increase to +3.5%. Although the estimated viscosities in Ref. 12 for R404A and R507 agree well with the present data, the predicted viscosities for R407C and R410A show a distinctively different temperature departure, with deviations rising to ±4%. This might be the influence of the common polar component R32 (polarity ≈ 2 D) in the mixtures.

**Table III.** Viscosity of Gaseous R404A at Nominal Isotherms $T_n$

| $p$ (MPa) | $\rho$ $(\mathrm{kg \cdot m^{-3}})$ | $\eta$ $(\mu\mathrm{Pa \cdot s})$ | $p$ (MPa) | $\rho$ $(\mathrm{kg \cdot m^{-3}})$ | $\eta$ $(\mu\mathrm{Pa \cdot s})$ |
|---|---|---|---|---|---|
| | $T_n = 303.15$ K | | | $T_n = 313.15$ K | |
| 0.101 | 3.86 | 12.32 | 0.101 | 3.74 | 12.69 |
| 0.339 | 13.89 | 12.39 | 0.382 | 15.15 | 12.78 |
| 0.693 | 30.29 | 12.60 | 0.815 | 34.67 | 13.07 |
| 1.096 | 52.52 | 12.99 | 1.256 | 58.53 | 13.47 |
| 1.299 | 66.08 | 13.22 | 1.59 | 81.14 | 13.96 |
| 1.378 | 71.94 | 13.30 | 1.759 | 94.96 | 14.36 |
| 1.417 | 75.03 | 13.35 | 1.805 | 99.18 | 14.35 |
| | $T_n = 323.15$ K | | | $T_n = 333.15$ K | |
| 0.101 | 3.62 | 13.09 | 0.101 | 3.51 | 13.53 |
| 0.225 | 8.42 | 13.09 | 0.259 | 9.40 | 13.56 |
| 0.514 | 19.98 | 13.20 | 0.495 | 18.45 | 13.56 |
| 0.929 | 38.41 | 13.47 | 0.997 | 39.73 | 13.89 |
| 1.510 | 69.62 | 14.02 | 1.50 | 64.49 | 14.39 |
| 2.001 | 105.05 | 14.93 | 2.096 | 102.24 | 15.39 |
| 2.205 | 124.70 | 15.46 | 2.524 | 139.84 | 16.54 |
| 2.277 | 132.85 | 15.73 | 2.701 | 160.88 | 17.36 |
| 2.299 | 135.69 | 15.97 | 2.793 | 174.22 | 17.86 |
| | | | 2.827 | 179.84 | 18.10 |

### 3.2. Viscosity Along the Saturation Line

Measurement of the viscosity exactly at the saturated conditions is not possible with an oscillating-disk viscometer. Even a small droplet or adsorbed amount of the condensate vapor on the oscillating disk will change its mass and, consequently, the moment of inertia of the suspension system. The mass of the disk is a significant parameter which must be known very precisely for both calibration of the viscometer [5] and evaluation of the measured viscosity. To obtain viscosity values along the saturation line in the vapor phase with an oscillating-disk viscometer, we first measured the viscosity in the superheated vapor along isotherms as a function of pressure. From the extrapolation of the isotherms up to the dew pressure, we then estimated the viscosity values on the saturation line.

In the present work, four isotherms were investigated for each substance. The pressure was varied from atmospheric pressure up to pressures near saturation conditions. Due to increased uncertainties for the measurements near the critical region, the highest isotherm was selected to be at least 10 K below the critical isotherm. The results of the experiments on the

**Table IV.** Viscosity of Gaseous R407C at Nominal Isotherms $T_n$

| $p$ (MPa) | $\rho$ ($kg \cdot m^{-3}$) | $\eta$ ($\mu Pa \cdot s$) | $p$ (MPa) | $\rho$ ($kg \cdot m^{-3}$) | $\eta$ ($\mu Pa \cdot s$) |
|---|---|---|---|---|---|
| | $T_n = 297.15$ K | | | $T_n = 314.15$ K | |
| 0.101 | 3.55 | 12.19 | 0.101 | 3.29 | 12.99 |
| 0.289 | 10.55 | 12.12 | 0.279 | 9.53 | 12.96 |
| 0.608 | 23.36 | 12.06 | 0.468 | 16.41 | 12.99 |
| 0.911 | 37.18 | 12.50 | 1.106 | 42.79 | 13.29 |
| 0.995 | 41.37 | 12.64 | 1.353 | 54.87 | 13.52 |
| | | | 1.481 | 61.77 | 13.72 |
| | | | 1.504 | 63.06 | 13.80 |
| | | | 1.531 | 64.59 | 13.83 |
| | $T_n = 323.15$ K | | | $T_n = 333.15$ K | |
| 0.101 | 3.25 | 13.40 | 0.101 | 3.15 | 13.70 |
| 0.291 | 9.66 | 13.39 | 0.332 | 10.71 | 13.74 |
| 0.459 | 15.54 | 13.41 | 0.736 | 24.80 | 13.86 |
| 0.815 | 28.88 | 13.61 | 1.160 | 41.20 | 14.18 |
| 1.156 | 43.07 | 13.87 | 1.508 | 56.34 | 14.44 |
| 1.456 | 57.08 | 14.07 | 1.962 | 79.28 | 14.95 |
| 1.676 | 68.56 | 14.22 | 2.273 | 98.26 | 15.41 |
| 1.796 | 75.39 | 14.42 | 2.412 | 108.10 | 15.81 |
| 1.889 | 81.04 | 14.65 | 2.446 | 110.66 | 15.83 |
| 1.974 | 86.57 | 14.75 | 2.501 | 115.01 | 16.04 |

fluids R404A, R407C, R410A, and R507 in superheated vapor are given in Tables III to VI in terms of pressure along nominal isotherms. The primary values of the measured viscosities were corrected to the nominal isotherms by means of the linear dependence of the low-pressure viscosity upon temperature, which is already known from the measurements at low pressure. The corrections did not exceed 0.08% for all experimental values. Tables III to VI also contain the densities which were used for the evaluation of the present measurements. Based on these density values, the uncertainty in the reported data is estimated to be $\pm 0.6\%$ in the vapor phase.

The determination of the viscosity along the saturation line is demonstrated in Fig. 3, in which the viscosity isotherms of R404A at nominal temperatures of 303.15, 313.15, 323,15, and 333.15 K, as a representative for the other subtances, are plotted as a function of pressure. The plot shows also the fitted curves through the measured points. From the intersection of the fitted curves and the saturation pressure (dew pressure), shown as the vertical line for each isotherm, the viscosity on the saturation line has been defined. For extrapolating the viscosity values at the saturation

**Table V.** Viscosity of Gaseous R410A at Nominal Isotherms $T_n$

| $p$ (MPa) | $\rho$ (kg·m$^{-3}$) | $\eta$ ($\mu$Pa·s) | $p$ (MPa) | $\rho$ (kg·m$^{-3}$) | $\eta$ ($\mu$Pa·s) |
|---|---|---|---|---|---|
| | $T_n = 298.15$ K | | | $T_n = 304.15$ K | |
| 0.101 | 2.92 | 12.89 | 0.101 | 2.863 | 13.19 |
| 0.332 | 10.17 | 12.88 | 0.289 | 8.61 | 13.19 |
| 0.606 | 19.29 | 12.96 | 0.472 | 14.36 | 13.21 |
| 0.949 | 31.93 | 13.11 | 0.812 | 25.92 | 13.31 |
| 1.287 | 46.18 | 13.33 | 1.172 | 39.62 | 13.49 |
| 1.510 | 56.92 | 13.45 | 1.517 | 54.78 | 13.71 |
| 1.610 | 62.21 | 13.51 | 1.682 | 62.92 | 13.89 |
| 1.641 | 63.90 | 13.54 | 1.910 | 75.53 | 14.23 |
| | $T_n = 314.15$ K | | | $T_n = 324.15$ K | |
| 0.101 | 2.77 | 13.57 | 0.101 | 2.72 | 13.98 |
| 0.381 | 11.03 | 13.60 | 0.354 | 9.86 | 13.99 |
| 0.650 | 19.46 | 13.70 | 0.828 | 24.23 | 14.18 |
| 1.017 | 31.87 | 13.86 | 1.349 | 42.06 | 14.42 |
| 1.400 | 46.41 | 14.04 | 1.801 | 59.82 | 14.76 |
| 1.653 | 57.11 | 14.21 | 2.269 | 81.53 | 15.19 |
| 2.009 | 74.41 | 14.52 | 2.668 | 104.36 | 15.82 |
| 2.287 | 90.29 | 14.94 | 2.902 | 120.68 | 16.31 |
| 2.407 | 98.26 | 15.19 | 3.002 | 128.73 | 16.48 |
| 2.466 | 102.41 | 15.25 | 3.105 | 137.93 | 16.84 |

**Table VI.** Viscosity of Gaseous R507 at Nominal Isotherms $T_n$

| $p$ (MPa) | $\rho$ ($kg \cdot m^{-3}$) | $\eta$ ($\mu Pa \cdot s$) | $p$ (MPa) | $\rho$ ($kg \cdot m^{-3}$) | $\eta$ ($\mu Pa \cdot s$) |
|---|---|---|---|---|---|
| | $T_n = 299.15$ K | | | $T_n = 303.15$ K | |
| 0.101 | 3.98 | 12.24 | 0.101 | 3.94 | 12.41 |
| 0.372 | 15.74 | 12.22 | 0.215 | 8.72 | 12.42 |
| 0.719 | 32.59 | 12.55 | 0.390 | 16.28 | 12.51 |
| 1.099 | 54.80 | 12.90 | 0.642 | 28.07 | 12.69 |
| 1.210 | 62.40 | 12.96 | 1.019 | 48.39 | 12.99 |
| 1.271 | 66.89 | 13.06 | 1.330 | 68.91 | 13.33 |
| | | | 1.374 | 72.22 | 13.32 |
| | | | 1.412 | 75.19 | 13.39 |
| | $T_n = 313.15$ K | | | $T_n = 324.15$ K | |
| 0.101 | 3.81 | 12.79 | 0.101 | 3.71 | 13.20 |
| 0.367 | 14.67 | 12.87 | 0.386 | 14.86 | 13.29 |
| 0.720 | 30.46 | 13.58 | 0.581 | 22.97 | 13.37 |
| 1.240 | 58.27 | 13.58 | 1.001 | 42.23 | 13.70 |
| 1.542 | 78.13 | 13.97 | 1.300 | 57.92 | 13.99 |
| 1.684 | 89.15 | 14.22 | 1.603 | 76.05 | 14.44 |
| 1.762 | 95.82 | 14.43 | 2.082 | 112.79 | 15.36 |
| 1.819 | 101.06 | 14.47 | 2.287 | 134.26 | 16.11 |
| 1.855 | 104.54 | 14.61 | 2.321 | 138.23 | 16.22 |
| | | | 2.351 | 142.12 | 16.49 |

line to the lower temperatures, two additional values were estimated from the low-pressure experiments. One is at the dew temperature at normal pressure and the other at the inversion temperature, which is defined as

$$\frac{T_{\text{inv}}}{T_c} = T_r \approx 0.78 \tag{4}$$

for the refrigerants [1, 2], where $T_{\text{inv}}$ is the characteristic inversion temperature in K and $T_c$ is the critical temperature. The viscosities of refrigerants along the characteristic inversion isotherm are pressure independent. Hence, the viscosity at the saturation line and the viscosity at low pressure have the same value. With a hypothetical uncertainty of $\pm 5$ K for the inversion temperature, the corresponding viscosity value at saturation has an error of less than $\pm 2\%$.

Table VII lists the viscosity data for the vapor phase of R404A, R407C, R410A, and R507 at saturation conditions. The values of temperatures, and the corresponding vapor pressures, are taken from Refs. 9–12. For

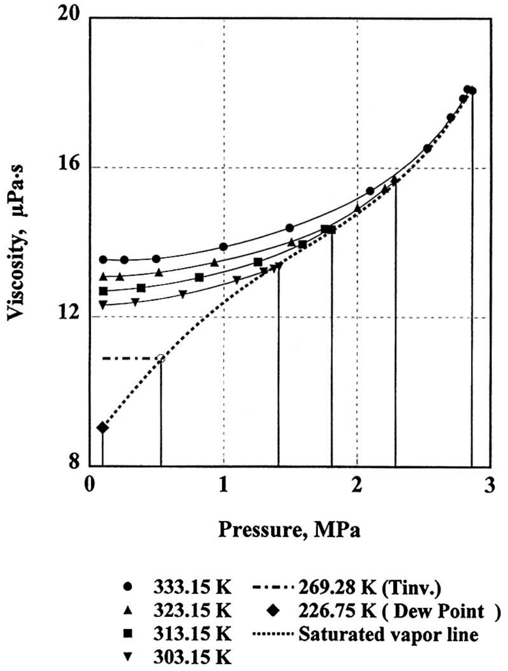

**Fig. 3.** Experimental viscosity values of R404A at subcritical isotherms in the vapor phase as a function of pressure.

practical use and comparison, the data were correlated by an equation of the form,

$$\eta_s = \frac{1}{\zeta \times 10^{-5} \sum_{n=0}^{3} a_n (T/T_c)^n} \tag{5}$$

where $T$ is the temperature in K, $T_c$ is the critical temperature in K, $\eta_s$ is the viscosity of saturated vapor in $\mu$Pa · s, and $\zeta$ is the viscosity parameter [14] in $\mathrm{Pa}^{-1} \cdot \mathrm{s}^{-1}$, defined as

$$\zeta = \frac{N_0^{1/3} (T_c R)^{1/6}}{M^{1/2} p_c^{2/3}} \tag{6}$$

$M$ is the molar mass; $N_0 = 6.02204 \times 10^{26}\ \mathrm{kmol}^{-1}$, Avogadro's number; $R = 8.314\ \mathrm{kJ} \cdot \mathrm{kmol}^{-1} \cdot \mathrm{K}^{-1}$, the gas constant; and $p_c$ is the critical pressure. The value of $\zeta$ and the coefficients $a_0 \cdots a_3$ for each substance are shown in Table VIII. The characteristic parameters of the fluids used in this work are

**Table VII.** Viscosity of R404A, R407C, R410A, and R507 Along the Saturation Line Obtained from the Measurements in the Vapor Phase

| $T$ (K) | $p$ (MPa) | $\eta$ ($\mu$Pa·s) | $T$ (K) | $p$ (MPa) | $\eta$ ($\mu$Pa·s) |
|---|---|---|---|---|---|
| | R404A | | | R407C | |
| 226.75 | 0.101 | 9.032 | 236.05 | 0.101 | 9.374 |
| 269.28 | 0.532 | 10.886 | 280.19 | 0.584 | 11.417 |
| 303.15 | 1.413 | 13.323 | 297.15 | 0.987 | 12.630 |
| 313.15 | 1.811 | 14.349 | 313.15 | 1.539 | 13.800 |
| 323.15 | 2.289 | 15.733 | 323.15 | 1.989 | 14.820 |
| 333.15 | 2.862 | 18.122 | 333.15 | 2.535 | 16.230 |
| | R410A | | | R507 | |
| 221.65 | 0.101 | 9.213 | 226.66 | 0.101 | 9.029 |
| 269.05 | 0.704 | 11.499 | 268.30 | 0.530 | 10.884 |
| 298.15 | 1.663 | 13.570 | 299.15 | 1.307 | 13.120 |
| 304.15 | 1.945 | 14.310 | 303.15 | 1.450 | 13.510 |
| 314.15 | 2.495 | 15.650 | 313.15 | 1.860 | 14.750 |
| 324.15 | 3.153 | 17.210 | 323.15 | 2.354 | 16.950 |

**Table VIII.** Viscosity Parameter $\xi$ [14] and Coefficients $a_0$ to $a_3$ for Eq. (5)

| Refrigerant | $\xi$ (Pa·s)$^{-1}$ | $a_0$ | $a_1$ | $a_2$ | $a_3$ |
|---|---|---|---|---|---|
| R404A | 42429.18 | 1.4719 | −4.2669 | 5.1983 | −2.2972 |
| R407C | 39175.02 | 1.0514 | −2.4759 | 2.7728 | −1.2315 |
| R410A | 40990.75 | 1.2398 | −3.3454 | 3.9880 | −1.7793 |
| R507 | 42170.05 | 2.0735 | −6.6294 | 8.2936 | −3.6473 |

**Table IX.** Characteristic Parameters for the Refrigerants R404A, R407C, R410A, and R507 [9–12]

| Refrigerant | $M$ (kg·kmol$^{-1}$) | $T_c$ (K) | $p_c$ (MPa) | $\rho_c$ (kg·m$^{-3}$) |
|---|---|---|---|---|
| R404A | 97.60 | 345.22 | 3.732 | 485.00 |
| R407C | 86.17 | 359.20 | 4.652 | 490.00 |
| R410A | 72.58 | 244.92 | 4.893 | 487.37 |
| R507 | 98.86 | 343.96 | 3.717 | 494.25 |

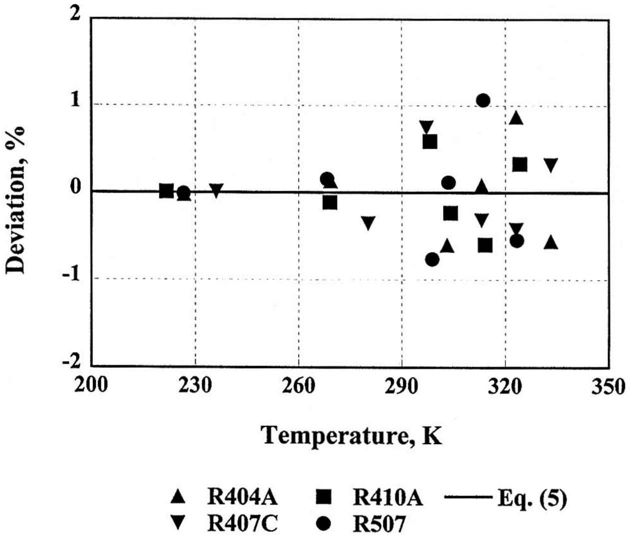

**Fig. 4.** Comparison between the present experimental values for the viscosity of R404A, R407C, R410A, and R507 at the saturated vapor line and the fitted curve represented by Eq. (5).

included in Table IX. Figure 4 shows the deviations of the experimental viscosity data from their calculated values by Eq. (5). The maximum deviation lies within ±1.1%, with an average deviation of ±0.65%.

To our knowledge, there are no other experimental data either in the vapor phase or along the saturation line for the substances investigated in the present work. For comparison with our data, the corresponding viscosity values calculated with REFPROP [12] were used. Figure 5 shows the differences between the present viscosity data and the viscosities calculated with REFPROP. The experimental data in Fig. 5 are shown as the baseline represented by Eq. (5). With the exception of R507 at the temperature 334 K ($T_c = 343.96$), the agreement between our experimental data and the estimated values by REFPROP for the refrigerants R404A, R407C, R410A, and R507 is within ±4%. The uncertainty in the prediction of the viscosity of refrigerants by REFPROP is estimated to be ±5% [12].

## 4. CONCLUSION

The viscosity of the refrigerants R404A, R407C, R410A, and R507 at low pressures can be represented with the aid of the Chapman–Enskog

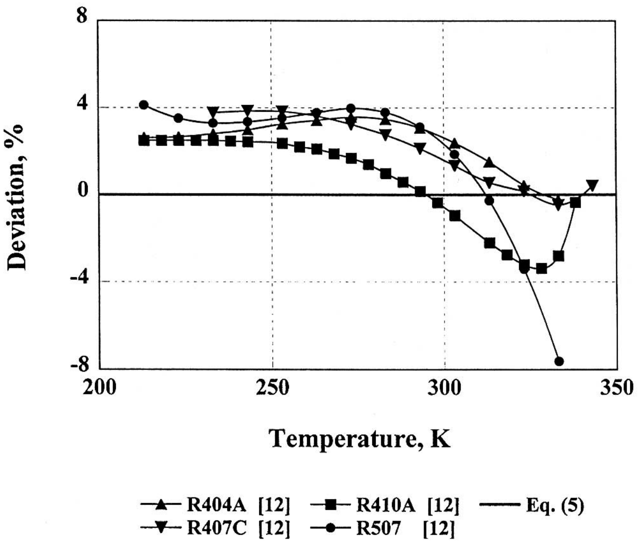

**Fig. 5.** Comparison between the present values for the viscosity of R404A, R407C, R410A, and R507 at the saturated vapor line represented by Eq. (5) and the viscosities calculated with the program REFPROP [12].

equation with a mean deviation of ±0.3%. The characteristic intermolecular parameters $\sigma$ and $\varepsilon/\kappa$ were evaluated for the investigated refrigerants. The viscosities of these refrigerants at the saturation line were evaluated by means of the measurments of the viscosity along the subcritical isotherms in the superheated vapor. The uncertainty of the viscosity along the saturation line, based on the density data used, has a maximum of ±1.1%, while the average deviation is ±0.65%.

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