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Viscosity of Mixed Refrigerants R404A, R407C, R410A, and R507A

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ABSTRACT

Mixed refrigerants R407C, R410A, R404A, and R507A have gained more and more importance in the last few years as a replacement for R22 and R502. New viscosity data of R404A, R407C, R410A, and R507A are presented. For all these refrigerants, the viscosity was measured for the saturated liquid and vapor and also for the superheated vapor. Viscosity was measured using a capillary tube method. Estimated uncertainties in experimental viscosities are, in general, less than or equal to $\pm 1.2\%$. All available literature viscosity data for R404A, R407C, R410A, and R507A were evaluated to identify the most accurate data on which to base the viscosity model. The viscosity is modeled with the residual concept. In this representation, the viscosity was composed of two contributions: a dilute gas term which is a function only of temperature, and a residual term which is a function only of density. The models cover a wide range of parameters except for the small region of the critical viscosity enhancement which is extremely close to the critical point and may be safely ignored in all practical application. The resulting correlations applicable for the viscosity of dilute gas, superheated vapor, and saturated liquid and vapor of R404A, R407C, R410A, and R507A are given. Comparisons are made for all available literature data.

NOMENCLATURE

P	pressure
Re	Reynolds number
T	temperature
ρ	density
η	viscosity
η_0	viscosity in zero-density limit
$\Delta\eta=\eta-\eta_0$	residual viscosity
$\Delta_c\eta$	critical viscosity enhancement
η_{exp}	experimental viscosity
η_{calc}	calculated viscosity

INTRODUCTION

Mixed refrigerants R407C (R32/R125/R134a, 23/25/52 wt %), R410A (R32/R125, 50/50 wt %), R404A (R125/R134a/143a, 44/4/52 wt %), and R507A (R125/R143a, 50/50 wt %) are recommended as a replacement for R22 and R502. Accurate viscosity data for these refrigerants are needed for the design of refrigeration equipment using refrigerant blends; the viscosity is particularly important for the design of the condenser and evaporator. Available literature viscosity data for these fluids are limited and do not cover a range of parameters required for the engineering applications (saturated-liquid and saturated-vapor viscosity and viscosity for the superheated vapors). There are two main sources of viscosity data of R404A, R407C, R410A, and R507A. Nabizadeh and Mayinger [1] measured the viscosity of gaseous R404A, R407C, R410A, and R507A at atmospheric pressure over a temperature range from 297 to 401 K and also the viscosity of the superheated vapors over a temperature range from 300 to 333 K and a pressure range from 0.1 to 3 MPa. The estimated uncertainty of the reported data are $\pm 0.5\%$ for the viscosity at atmospheric pressure and $\pm 1\%$ for the viscosity of the superheated vapors. Heide and Schenk [2] have measured the saturated liquid viscosity over a temperature range from 223 to 333 K with the estimated uncertainties $\pm 2\%$. The results of these works cover a range of reduced density from 0 to 0.25 and 1.7 to 2.7, respectively.

In this paper, we present new viscosity measurements of R404A, R407C, R410A, and R507A covering the "blank spaces" in the viscosity-density diagram and including vapor viscosity at atmospheric pressure, superheated vapor viscosity, and viscosity of saturated liquid and vapor.

EXPERIMENTAL PROCEDURE AND RESULTS

Viscosity of mixed refrigerants was measured using the modified capillary tube method. A detailed description of the viscometer and the experimental procedure are given in the earlier paper [3]. The experimental technique for the viscosity measurements involves creating a pressure difference within a glass mercury pump placed inside a high-pressure vessel. A special design feature of the pump provides for the return of mercury to its initial position after each experiment. Capillary tube with diameters of 0.076 and 0.92 mm and a length of approximately 50 mm were used in these experiments. Parameters for the mercury pump (initial pressure difference, final pressure difference, volume of the fluid flowing in the capillary over the time of experiment, etc.) were found by calibrations. The viscosity values were calculated taking into account the corrections for the capillary end effects, thermal expansion of the capillary tube, and kinetic-energy factor. The sum of these corrections did not exceed 0.4% of the measured viscosity. Also, the following assumptions about the experiment were taken into account: the fluid expands in the capillary tube; the fluid is compressed inside the pump during the experiment due to a decrease in the pressure difference associated with the decrease in the height of the mercury; some energy dissipates to create the kinetic energy of the fluid flow. As a consequence, an average value for the pressure drop, a density change due to the pressure change, and a change in the mass flow due to the pressure change have been employed.

In these experiments, temperature was measured to within ± 0.01 K using resistance thermometer, and pressure was measured to within ± 1 kPa with a digital pressure transducer. All measurements for vapor phase were done using a single capillary tube but different values of the pressure drop (from 1 to 3 kPa) corresponding to Reynolds number from 10 to 600. For liquid phase, *Re* numbers were in the limits of 150-300. Error in the measurement of the

pressure drop was ±0.2% and that in the flowrate was ±0.4%. The estimated uncertainties in the experimental viscosity data did not exceed ±1.2% at the 95% confidence level. Each experiment was repeated at least five times at each temperature. The deviation of the individual measurements from the average viscosity value at each temperature did not exceed ±0.25%.

Experiments for the saturated-liquid and saturated-vapor viscosities of R404A, R407C, R410A, and R507A were carried out over a temperature range from 253 to 333 K. In these experiments, the pressure was, respectively, higher and lower than saturated vapor pressure by approximately 0.005-0.01 MPa. Viscosity of the superheated vapor was measured at 373.15 K over a pressure range from 0.1 to 15 MPa. The density and vapor pressure for all fluids were calculated using REFPROP, Version 6.01 [4].

The obtained results are given in Tables. 1-3. The saturated-liquid viscosities and also the vapor viscosity at atmospheric pressure of R404A were published in our earlier paper [5].

Table 1. Experimental liquid viscosity data (μPa·s)near the saturated line.

R407C		R410A		R507A	
T (K)	η	T (K)	η	T (K)	η
253.15	271.8	253.15	216.2	253.15	250.2
273.15	209.7	273.15	164.7	273.15	186.6
293.15	163.8	293.15	126.8	293.15	142.4
313.15	125.6	313.15	97.3	313.15	103.4
323.15	110.6	333.15	70.9	333.15	73.7
333.15	95.2	338.15	64.0	338.15	64.9

Table 2. Experimental vapor viscosity data (μPa·s) near the saturated line.

R404A		R407C		410A		R507A	
T (K)	η	T (K)	η	T (K)	η	T (K)	η
253.04	10.42	253.80	10.21	253.13	10.75	253.38	10.27
262.13	10.84	263.08	10.63	263.28	11.41	263.01	10.82
273.78	11.48	274.27	11.27	272.14	11.86	273.21	11.40
288.60	12.38	283.43	11.83	282.83	12.53	283.40	12.02
294.37	12.82	291.61	12.06	293.39	13.32	294.36	12.76
307.34	13.77	304.25	12.98	303.02	14.11	303.63	13.71
315.28	14.91	313.19	13.89	314.29	15.40	314.12	14.90
323.23	16.05	324.37	15.11	323.44	16.91	321.85	16.13
332.04	18.47	333.11	16.50	331.95	19.03	332.70	19.44

Table 3. Experimental superheated vapor viscosity data (μPa·s) at T=353.15 K

R404A		R407C		R410A		R507A	
P (MPa)	η	P (MPa)	η	P (MPa)	η	P (MPa)	η
0.101	15.13	0.101	15.48	0.101	19.19	0.101	15.26
0.503	15.26	1.118	15.69	1.009	16.25	0.903	15.49
1.020	15.38	2.233	16.53	2.202	16.92	1.895	16.02
1.641	15.75	3.651	19.13	3.511	18.14	3.327	18.33
2.188	16.26	5.027	24.22	4.943	20.15	5.040	26.42
2.985	17.66	5.552	29.80	6.410	24.81	6.676	46.81
4.018	20.49	6.564	51.65	7.966	37.55	8.011	58.84
5.111	26.97	8.320	67.86	10.021	54.37	10.222	73.06
6.244	41.54	10.771	79.03	13.190	66.67	14.254	85.39
7.432	54.45	12.839	86.77				
9.632	67.62	15.028	93.15				
12.031	76.53						
14.242	83.22						

MODEL AND CORRELATIONS

The most known models for the viscosity calculations use the form of the sum of three contributions

$$\eta(\rho, T) = \eta_o(T) + \Delta\eta(\rho, T) + \Delta_c\eta(\rho, T) \tag{1}$$

Each contribution may be treated independently by using both theoretical and available experimental information.

The residual viscosity as a function of both density and temperature describes viscosity data over a wide range of parameters including high density region (liquid at very low temperatures, compressed liquid). For available viscosity data of R404A, R407C, R410A, and R507A, the residual viscosity as a function only of density provides good agreement between the experimental and calculated results. The residual viscosity as a function of density for R404A is shown in Fig. 1. The critical enhancement (that is essential for the thermal conductivity) is extremely close to the critical point and may be safely ignored in all practical application. Thus, in this representation, the viscosity was composed of two contributions: a dilute gas term which is a function only of temperature, and a residual term which is a function only of density:

$$\eta_0 = \sum_{i=0}^{i=2} a_i T^i \tag{2}$$

$$\Delta\eta = \sum_{j=1}^{j=6} b_j \rho^j \tag{3}$$

where T is in K, ρ is in kg/m^3. The coefficients a_i and b_j are given in Table 4.

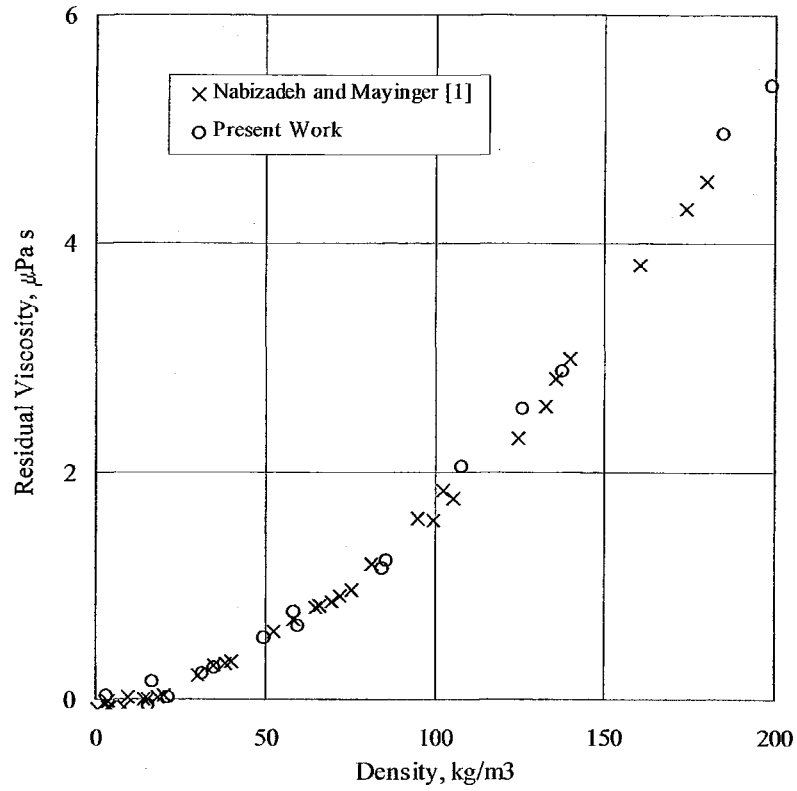

Fig. 1. Residual viscosity of R404A as a function of density

Table 4. Coefficients of Equations (2) and (3)

	R404A	R407C	R410A	R507A
a_0	$9.766 \cdot 10^{-1}$	$-1.507 \cdot 10^{0}$	$-2.695 \cdot 10^{0}$	$-2.530 \cdot 10^{0}$
a_1	$3.676 \cdot 10^{-2}$	$4.894 \cdot 10^{-2}$	$5.850 \cdot 10^{-2}$	$5.626 \cdot 10^{-2}$
a_2	$2.938 \cdot 10^{-6}$	$-9.305 \cdot 10^{-6}$	$-2.129 \cdot 10^{-5}$	$-2.323 \cdot 10^{-5}$
b_1	$2.260 \cdot 10^{-3}$	$-3.038 \cdot 10^{-3}$	$9.047 \cdot 10^{-3}$	$5.308 \cdot 10^{-4}$
b_2	$1.786 \cdot 10^{-4}$	$2.927 \cdot 10^{-4}$	$5.784 \cdot 10^{-5}$	$2.234 \cdot 10^{-4}$
b_3	$-4.202 \cdot 10^{-7}$	$-9.559 \cdot 10^{-7}$	$1.309 \cdot 10^{-7}$	$-6.742 \cdot 10^{-7}$
b_4	$8.489 \cdot 10^{-10}$	$1.739 \cdot 10^{-9}$	$-2.422 \cdot 10^{-10}$	$1.411 \cdot 10^{-9}$
b_5	$-8.670 \cdot 10^{-13}$	$-1.455 \cdot 10^{-12}$	$9.424 \cdot 10^{-14}$	$-1.388 \cdot 10^{-12}$
b_6	$3.566 \cdot 10^{-16}$	$4.756 \cdot 10^{-16}$	$3.933 \cdot 10^{-17}$	$5.274 \cdot 10^{-16}$

Comparisons were made for the calculated viscosities with the available published experimental results (Nabizadeh and Mayinger [1], Heide and Schenk [2]) and also with the data of present work. For R404A and R407C, the deviation $(\eta_{exp}-\eta_{calc})/\eta_{calc}\cdot 100\%$ is shown in Figs. 2 and 3 for all experimental data. Fig. 4 shows comparisons of the calculated and experimental viscosity data for the saturated liquid and saturated vapor of R410A and R507A. The agreement between the experimental data and the calculated viscosities is quite good: the deviations, in general, do not exceed +2% except for 1 experimental point for R410A (2.2%) and 5 experimental points for R404A (up to 3.5%).

Saturated-liquid and saturated-vapor viscosities of R404A, R407C, R410A, and R507A calculated with the Eqs. (2) and (3) are given in Table 5.

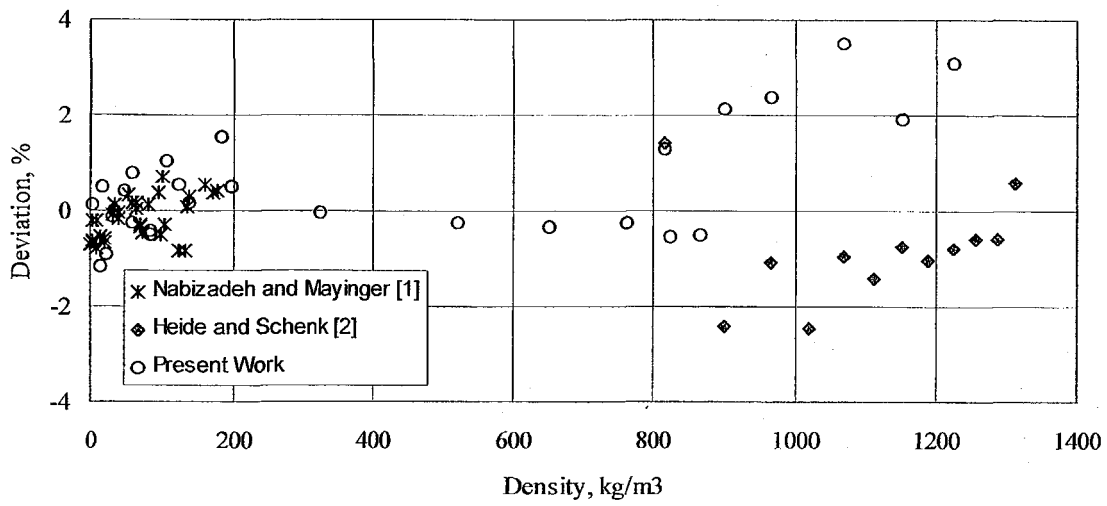

Fig. 2. Deviation of measured viscosity of R404A from the viscosity calculated by Eqs. (2) and (3) as a function of density

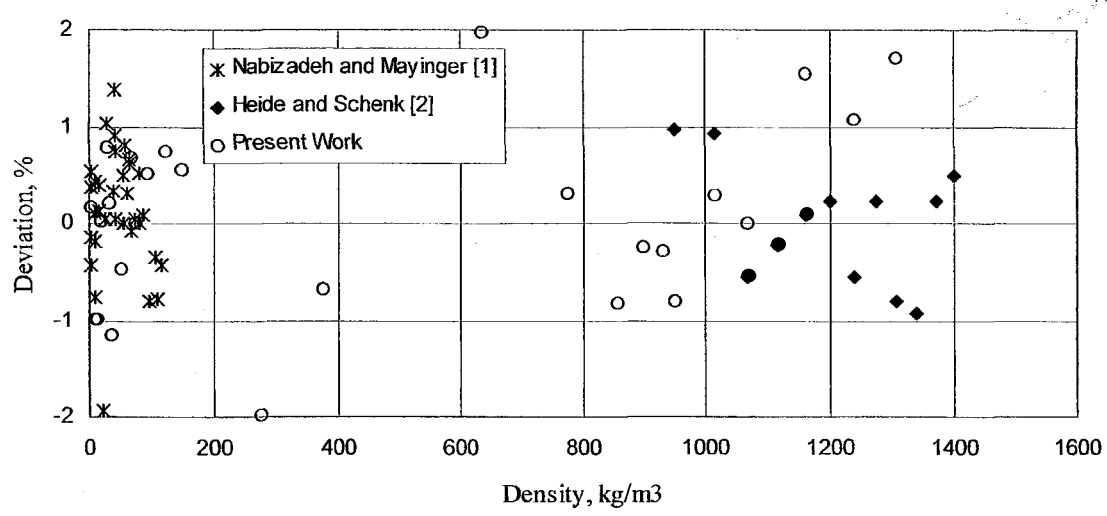

Fig. 3. Deviation of measured viscosity of R407C from the viscosity calculated by Eqs. (2) and (3) as a function of density

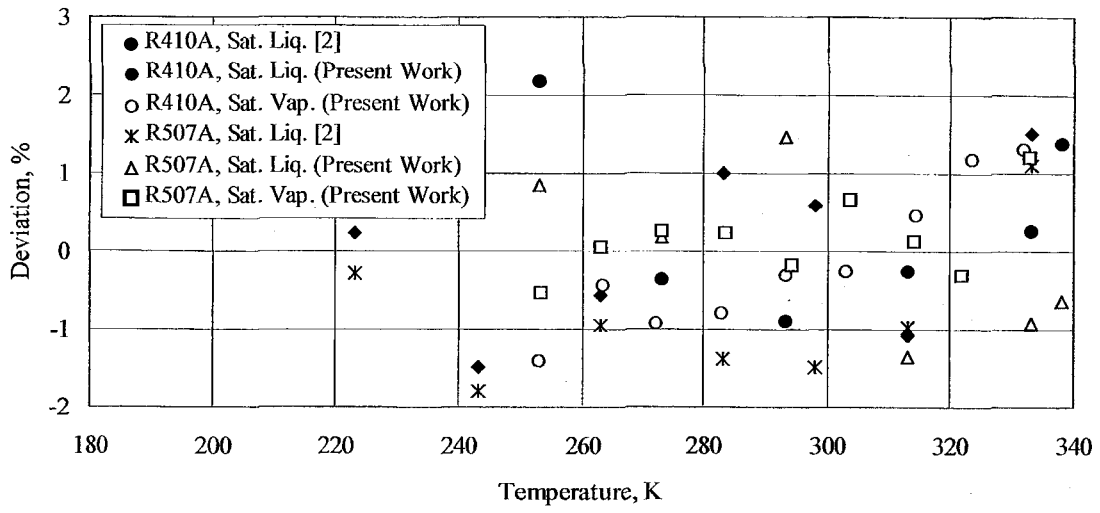

Fig. 4. Deviation of measured viscosity of R410A and R507A from the viscosity calculated by Eqs. (2) and (3) as a function of temperature

Table 5. Saturated-liquid and saturated-vapor viscosity (μPa·s) of mixed refrigerants

T, °C	R404A		R407C		R410A		R507A	
	Sat. Liquid	Sat. Vapor	Sat. Liquid	Sat. Vapor	Sat. Liquid	Sat. Vapor	Sat. Liquid	Sat. Vapor
-60	390.82	-	447.61	-	336.61	-	430.29	-
-50	344.67	-	393.34	-	300.73	-	376.05	-
-40	302.14	-	345.23	-	268.09	-	327.99	-
-30	264.67	10.13	304.18	9.83	238.61	10.37	284.59	9.83
-20	231.95	10.55	267.12	10.28	211.46	10.90	248.10	10.31
-10	202.83	10.99	235.05	10.74	187.44	11.45	214.94	10.82
0	177.32	11.46	207.47	11.21	165.29	12.03	186.26	11.37
10	155.27	12.00	182.67	11.72	145.73	12.65	161.80	11.98
20	135.19	12.63	161.27	12.29	127.94	13.34	140.31	12.69
30	118.15	13.43	142.53	12.96	111.88	14.16	121.55	13.57
40	102.49	14.48	125.61	13.79	97.55	15.19	104.81	14.74
50	88.20	16.01	110.28	14.88	84.10	16.66	89.64	16.45
60	73.92	18.56	95.96	16.38	70.71	19.19	74.37	19.35

CONCLUSIONS

New viscosity measurements for mixed refrigerants R404A, R407C, R410A, and R507A over a range of parameters are presented. Viscosity was measured using a capillary tube method with uncertainties ± 1.2 %. The viscosity is modeled with the residual concept where a residual term is a function only of density. The model covers a wide range of parameters including dilute gas, superheated vapor, and saturated liquid and vapor. The resulting viscosity correlations are given and comparisons are made for all available literature data.

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