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Thermal Conductivity of the Refrigerant Mixtures R404A, R407C, R410A, and R507A[1]

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New thermal conductivity data of the refrigerant mixtures R404A, R407C, R410A, and R507C are presented. For all these refrigerants, the thermal conductivity was measured in the vapor phase at atmospheric pressure over a temperature range from 250 to 400 K and also at moderate pressures. A modified steady-state hot-wire method was used for these measurements. The cumulative correction for end effects, eccentricity of the wire, and radiation heat transfer did not exceed 2%. Calculated uncertainties in experimental thermal conductivity are, in general, less than $\pm 1.5\%$. All available literature thermal conductivity data for R404A, R407C, R410A, and R507C were evaluated to identify the most accurate data on which to base the thermal conductivity model. The thermal conductivity is modeled with the residual concept. In this representation, the thermal conductivity 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 conditions except for the region of the thermal conductivity critical enhancement. The resulting correlations are applicable for the thermal conductivity of dilute gas, superheated vapor, and saturated liquid and vapor far away from the critical point. Comparisons are made for all available literature data.

KEY WORDS: hot-wire method; refrigerants; R404A; R407C; R410A; R507A; thermal conductivity; vapor phase.

1. INTRODUCTION

The refrigerant mixtures R404A (R125/R134a/143a, 44/4/52 wt%), R407C (R32/R125/R134a, 23/25/52 wt%), R410A (R32/R125, 50/50 wt%), and

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R507A (R125/R143a, 50/50 wt%) are recommended as replacements for R22 and R502. Accurate thermal conductivity data for these refrigerants are needed for the design of refrigeration equipment using refrigerant blends; the thermal conductivity is particularly important for the design of the condenser and evaporator. Available literature thermal conductivity data for these fluids are limited and do not cover the range of conditions required for engineering applications (saturated-liquid and saturated-vapor thermal conductivity and thermal conductivity for the superheated vapors). There are only a few sources of thermal conductivity data of R404A, R407C, R410A, and R507A. For R404A, the saturated liquid thermal conductivity was measured by the steady-state hot-wire method over a temperature range from 253 to 334 K with an estimated uncertainty of $\pm 1\%$ [1]. Hoffmann, Spindler, Hahne, and Sohns [2, 3] measured the thermal conductivity of liquid R407C, R410A, and R507A along the saturated line over a temperature range from 257 to 328 K using a transient hot-wire method. The estimated uncertainty of these data is $\pm 2\%$. They have also mentioned measurements of the saturated vapor thermal conductivity; however, the experimental results were not reported. Ro, Kim, and Jeong [4, 5] have measured the liquid thermal conductivity of R407C and R410A over a temperature range from 233 to 323 K and a pressure range from 2 to 20 MPa. They used a transient hot-wire method with estimated uncertainties of $\pm 2\%$. Gao, Nomura, Nagasaka, and Nagashima [6, 7] published measurements of the liquid thermal conductivity of R407C and R410A over a temperature range from 193 to 293 K and from 213 to 293 K, respectively, and a pressure range from 2 to 30 MPa with an estimated uncertainty of $\pm 0.7\%$.

A single set of data is available for the vapor thermal conductivity of R410A. Tanaka, Matsuo, and Taya measured the thermal conductivity of R32/R125 mixtures in the vapor phase along the 283.15 and 298.15 K isotherms over a pressure range from 0.1 to 1.1 MPa and a mole fraction range of R32 from 0.19 to 0.82 [8]. The thermal conductivity data of R410A found by interpolation of these results cover a range of reduced density from 0.01 to 0.08.

In this paper, we present new thermal conductivity measurements of R404A, R407C, R410A, and R507A covering part of the gaps in the thermal conductivity—the density outside the critical region, including the vapor thermal conductivity at atmospheric pressure and the superheated vapor.

2. MEASUREMENTS

The thermal conductivity was measured using a modified steady-state hot-wire method. A detailed description of the apparatus and the experimental technique is given elsewhere [1]. A special feature of this apparatus is the application of a thin-walled platinum capillary tube (outside diameter = 1.0 mm, inside diameter = 0.9 mm) as the outer resistance thermometer. A platinum wire (diameter = 0.1 mm and length = 80 mm) located inside this capillary tube is used as an electric heater and at the same time as the inner resistance thermometer. In order to center this wire inside the capillary tube, the latter was placed within a glass tube that can be adjusted in two orthogonal directions by set screws. The wire was centered by visual observation using a microscope. The frame for this apparatus was designed to have minimal clearance with the glass tube, thus eliminating convection heat transfer on the outside of the tube.

The thermal conductivity measuring cell was installed in a high-pressure vessel placed in a special constant temperature bath to provide temperature control to within ± 0.002 K. The temperatures of both resistance thermometers were determined by measuring the potential difference across each

Table I. Experimental Thermal Conductivity Data of R404A

Temperature (K)	Pressure (MPa)	Thermal conductivity ($mW \cdot m^{-1} \cdot K^{-1}$)	Temperature (K)	Pressure (MPa)	Thermal conductivity ($mW \cdot m^{-1} \cdot K^{-1}$)
252.80	0.101	9.90	313.29	0.833	15.55
253.03	0.101	9.91	313.40	0.836	15.62
273.26	0.101	11.51	313.33	1.234	16.38
273.38	0.102	11.54	313.46	1.235	16.43
273.29	0.534	12.28	313.39	1.466	16.90
273.50	0.538	12.39	313.49	1.466	16.96
293.16	0.102	12.98	313.34	1.762	17.92
293.27	0.102	13.10	313.45	1.763	17.98
293.20	0.310	13.44	334.25	0.101	16.02
293.31	0.311	13.46	334.33	0.101	16.04
293.22	0.688	14.12	334.23	0.677	16.72
293.31	0.690	14.16	334.30	0.679	16.75
293.19	0.944	14.67	334.23	0.922	17.11
293.26	0.945	14.78	334.31	0.924	17.13
313.37	0.101	14.44	334.26	1.345	17.73
313.51	0.101	14.47	334.36	1.347	17.75
313.38	0.455	14.96	334.28	1.688	18.52
313.53	0.458	15.10	334.34	1.689	18.55
334.27	2.173	19.91	334.36	2.763	22.34
334.38	2.176	19.93	365.48	0.101	18.27
334.27	2.450	20.74	365.54	0.101	18.31
334.47	2.450	20.78	393.02	0.101	20.26
334.25	2.762	22.29	393.09	0.101	20.22

thermometer relative to the potential across standard resistances. The uncertainty of these measurements using a digital voltmeter is estimated to be within ±1 nV. The pressure was measured with a digital pressure transducer to within ±1 kPa. During the thermal conductivity measurements, the temperature difference in the fluid sample between the wire and the capillary tube is 2 to 10 K.

The thermal conductivity was calculated taking into account corrections for end effects, eccentricity of the wire, and radiation heat transfer. The cumulative correction did not exceed 2% of the measured thermal conductivity values. Calculated uncertainties in the experimental thermal conductivity are less than ±1.5%.

3. RESULTS

Experiments for the thermal conductivity of R404A, R407C, R410A, and R507A at atmospheric pressure were carried out over a temperature range from 250 to 400 K. For the superheated vapor, the experiments were performed at four isotherms. In these experiments, the highest pressure was lower than the saturated vapor pressure by approximately 0.05 to 0.1 MPa.

Table II. Experimental Thermal Conductivity Data of R407C

Temperature (K)	Pressure (MPa)	Thermal conductivity ($mW \cdot m^{-1} \cdot K^{-1}$)	Temperature (K)	Pressure (MPa)	Thermal conductivity ($mW \cdot m^{-1} \cdot K^{-1}$)
253.27	0.101	9.68	314.41	1.235	15.91
253.45	0.101	9.70	314.30	1.512	16.63
272.13	0.101	11.15	314.42	1.513	16.63
272.22	0.101	11.17	333.22	0.101	15.82
272.17	0.387	11.67	333.29	0.102	15.82
272.28	0.388	11.66	333.24	0.556	16.24
293.00	0.101	12.76	333.31	0.558	16.27
293.11	0.101	12.79	333.23	0.987	16.80
293.02	0.434	13.28	333.35	0.989	16.76
293.13	0.435	13.32	333.20	1.446	17.28
293.00	0.822	13.77	333.31	1.446	17.34
293.15	0.823	13.81	333.20	1.880	18.22
314.26	0.101	14.40	333.33	1.882	18.31
314.38	0.101	14.44	333.21	2.447	19.88
314.25	0.456	14.88	333.30	2.448	19.91
314.39	0.458	14.87	363.05	0.101	18.11
314.28	0.877	15.41	363.13	0.101	18.14
314.42	0.879	15.44	389.70	0.101	20.12
314.27	1.234	15.93	389.83	0.101	20.09

Table III. Experimental Thermal Conductivity Data of R410A

Temperature (K)	Pressure (MPa)	Thermal conductivity ($mW \cdot m^{-1} \cdot K^{-1}$)	Temperature (K)	Pressure (MPa)	Thermal conductivity ($mW \cdot m^{-1} \cdot K^{-1}$)
255.04	0.101	9.98	314.21	0.512	14.86
260.32	0.101	10.43	314.37	0.513	14.89
274.02	0.101	11.43	314.22	1.011	15.58
274.16	0.101	11.44	314.34	1.012	15.62
274.04	0.377	11.75	314.23	1.632	16.56
274.12	0.378	11.80	314.36	1.633	16.61
274.08	0.712	12.35	314.25	2.012	17.09
274.17	0.713	12.34	314.43	2.012	17.16
294.26	0.101	12.92	314.19	2.353	18.03
294.32	0.101	12.94	314.35	2.354	18.22
294.30	0.507	13.49	331.97	0.101	15.73
294.38	0.507	13.53	332.05	0.102	15.73
294.25	0.944	14.15	332.00	0.622	16.28
294.39	0.946	14.18	332.10	0.625	16.27
294.26	1.376	14.92	332.01	1.102	16.74
294.41	1.377	15.01	332.10	1.104	16.75
314.17	0.101	14.40	331.96	1.722	17.78
314.30	0.101	14.41	332.07	1.724	17.68
331.95	2.345	18.50	332.09	3.690	22.76
332.06	2.347	18.51	346.17	0.101	16.85
331.99	3.004	19.98	349.37	0.101	17.08
332.12	3.007	20.06	384.03	0.101	19.56
332.00	3.325	20.85	387.25	0.101	19.78
332.13	3.327	20.84	404.52	0.101	21.04
332.01	3.688	22.69	409.81	0.101	21.52

The density and vapor pressure for all mixed refrigerants were calculated using REFPROP, Version 6.01 [9]. The results are given in Tables I to IV.

4. MODEL AND CORRELATIONS

The most well known models for the thermal conductivity calculations use the form of the sum of three contributions

$$\lambda(\rho, T) = \lambda_0(T) + \Delta\lambda(\rho, T) + \Delta_c\lambda(\rho, T) \tag{1}$$

where λ is the thermal conductivity, λ_0 is the thermal conductivity in the zero-density limit, $\Delta\lambda = \lambda - \lambda_0$ is the residual thermal conductivity, $\Delta_c\lambda$ is the critical thermal conductivity enhancement, T is the temperature, and ρ

Table IV. Experimental Thermal Conductivity Data of R507A

Temperature (K)	Pressure (MPa)	Thermal conductivity ($mW \cdot m^{-1} \cdot K^{-1}$)	Temperature (K)	Pressure (MPa)	Thermal conductivity ($mW \cdot m^{-1} \cdot K^{-1}$)
254.71	0.101	10.09	314.40	1.124	16.13
254.85	0.101	10.07	314.26	1.733	17.56
274.03	0.101	11.58	314.39	1.735	17.64
274.16	0.101	11.61	333.22	0.101	15.97
274.04	0.533	12.30	333.36	0.101	15.98
274.16	0.534	12.36	333.20	0.478	16.49
293.82	0.101	13.10	333.31	0.477	16.54
293.94	0.102	13.12	333.22	0.933	17.13
293.85	0.666	13.77	333.30	0.934	17.08
293.97	0.667	13.82	333.23	1.655	18.31
293.80	1.034	14.66	333.35	1.658	18.36
293.88	1.035	14.69	333.21	2.145	19.47
314.29	0.101	14.58	333.34	2.145	19.48
314.43	0.101	14.56	333.18	2.644	21.31
314.27	0.478	14.99	333.28	2.647	21.38
314.40	0.478	15.05	372.03	0.101	18.77
314.28	1.123	16.00	372.17	0.101	18.76

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

The residual thermal conductivity as a function of both density and temperature describes the thermal conductivity data over a wide range of parameters including the high density region (liquid at very low temperatures, compressed liquid). For the available thermal conductivity data of R404A, R407C, R410A, and R507A, the residual thermal conductivity as a function of only density provides good agreement between the experimental and calculated results.

The critical enhancement is significant for the thermal conductivity in the critical region, however, this information is currently unavailable for the refrigerants under consideration. Thus, in this representation, the critical enhancement was neglected, and the thermal conductivity was composed of two contributions: a dilute gas term which is a function of only temperature and a residual term which is a function of only density:

$$\lambda_0 = a_0 + a_1 T \tag{2}$$

$$\Delta\lambda = b_1 \rho + b_2 \rho^2 + b_3 \rho^3 + b_4 \rho^4 \tag{3}$$

where T is in K and ρ is in $kg \cdot m^{-3}$. The coefficients a_i and b_j are given in Table V.

Table V. Coefficients of Eqs. (2) and (3)

	R404A	R407C	R410A	R507A
a_0	-8.624	-9.628	-8.872	-8.656
a_1	7.360×10^{-2}	7.638×10^{-2}	7.410×10^{-2}	7.383×10^{-2}
b_1	3.222×10^{-2}	2.715×10^{-2}	3.576×10^{-2}	2.799×10^{-2}
b_2	2.569×10^{-5}	4.963×10^{-5}	-9.045×10^{-6}	3.065×10^{-5}
b_3	-2.693×10^{-8}	-4.912×10^{-8}	4.343×10^{-8}	-3.644×10^{-8}
b_4	2.007×10^{-11}	2.884×10^{-11}	-3.705×10^{-12}	2.609×10^{-11}

Comparisons were made for the calculated thermal conductivity with the available published experimental results [1–8] and also with the data of the present work. The deviations are shown in Fig. 1 for liquid R404A and R407C and in Fig. 2 for liquid R410A and R507A. Figure 3 shows comparisons of the calculated and experimental thermal conductivity data for R404A, R407C, R410A, and R507A in the vapor phase. The agreement between the experimental data and the calculated thermal conductivity is quite satisfactory: the deviations, in general, do not exceed $\pm 3.5\%$ in the

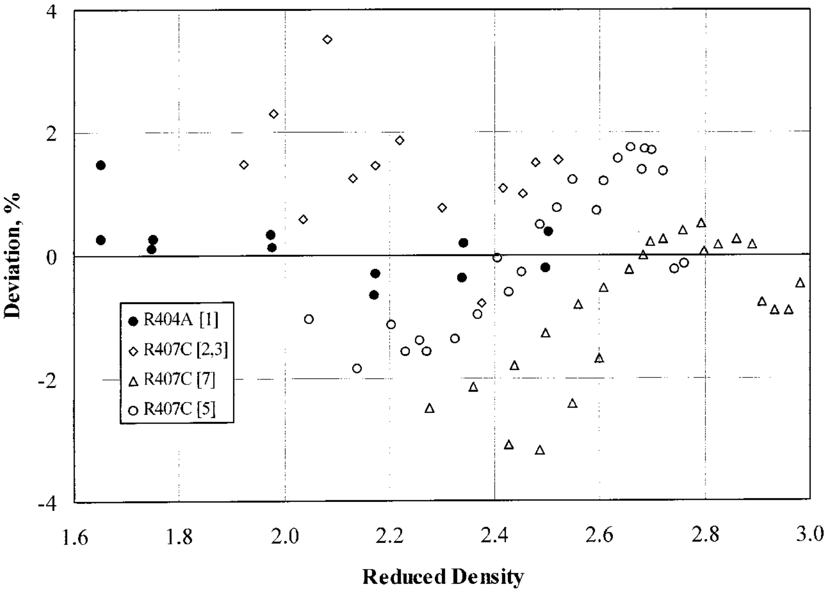

Fig. 1. Deviations ($100(\lambda_{exp} - \lambda_{calc})/\lambda_{calc}$) of measured thermal conductivity of liquid R404A and R407C from the thermal conductivity calculated by Eqs. (2) and (3) as a function of reduced density.

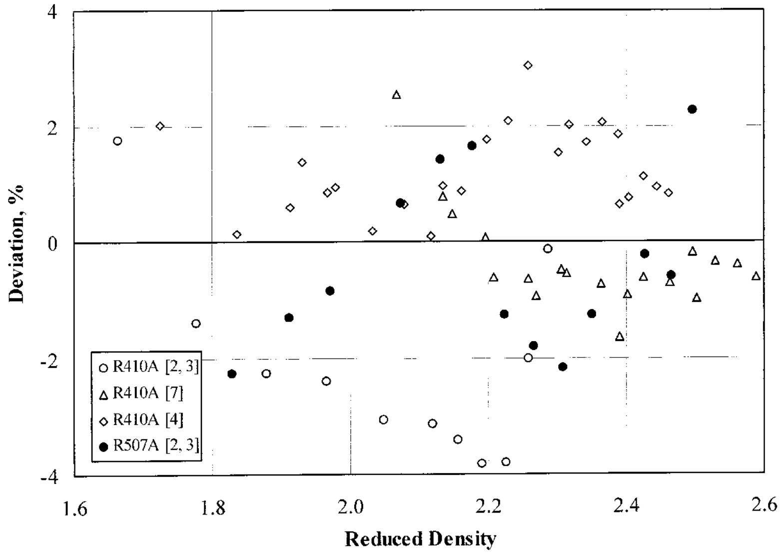

Fig. 2. Deviations ($100(\lambda_{exp} - \lambda_{calc})/\lambda_{calc}$) of measured thermal conductivity of liquid R410A and R507A from the thermal conductivity calculated by Eqs. (2) and (3) as a function of reduced density.

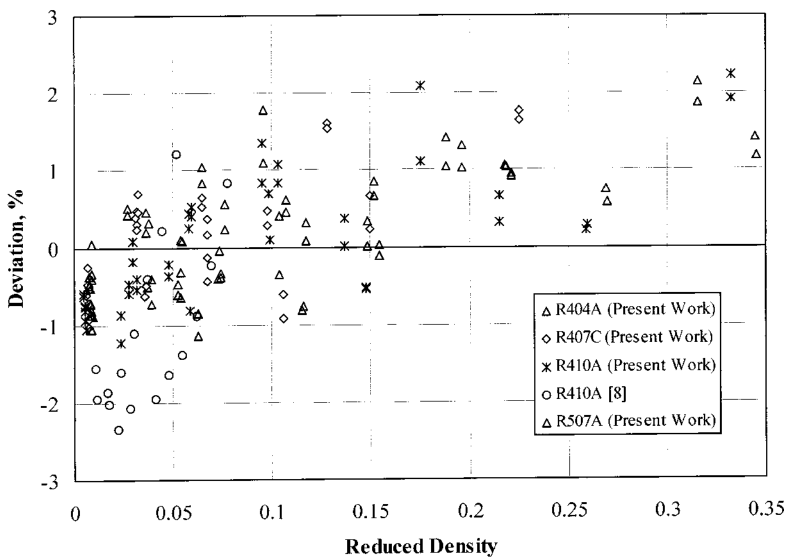

Fig. 3. Deviations ($100(\lambda_{exp} - \lambda_{calc})/\lambda_{calc}$) of measured vapor thermal conductivity of R404A, R407C, R410A, and R507A from the thermal conductivity calculated by Eqs. (2) and (3) as a function of reduced density.

liquid phase (except for a few experimental points for R410A) and $\pm 2.3\%$ in the vapor phase.

5. CONCLUSIONS

New thermal conductivity measurements for the mixed refrigerants R404A, R407C, R410A, and R507A in the vapor phase are presented. The thermal conductivity was measured using a modified steady-state hot-wire method with uncertainties of $\pm 1.5\%$. The thermal conductivity is modeled with the residual concept where a residual term is a function of only density. The model covers a wide range of parameters outside the critical region. The resulting thermal conductivity correlations are given, and comparisons are made for all available literature data.

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