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Thermal Conductivity of Ternary Refrigerant Mixtures of HFC-32/125/134a in the Liquid Phase

X. Gao,[1] Y. Nagasaka,[1,2] and A. Nagashima[1]

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The liquid thermal conductivity of two ternary mixtures of HFC-32/125/134a (23.0/25.0/52.0 and 19.0/43.8/37.2 wt%) was measured using a transient hot-wire instrument in the temperature ranges from 193 to 293 K and from 213 to 293 K, respectively, and in the pressure range from 2 to 30 MPa. The thermal conductivity has an estimated uncertainty of $\pm 0.7\%$. For engineering purposes, the thermal conductivity data were correlated using a polynomial in temperature and pressure for each mixture with a standard deviation of 0.6%.

KEY WORDS: HFC-32/125/134a; refrigerant; R-407C; ternary mixture; thermal conductivity; transient hot-wire method.

1. INTRODUCTION

The phase-out of hydrochlorofluorocarbons (HCFCs) by the end of 2020 requires the development of alternatives for HCFC-22, which is widely used as the working fluid in refrigeration and air-conditioning systems. At present, mixtures consisting of HFC-32, HFC-125, and HFC-134a, such as HFC-32/125, HFC-32/134a, and HFC-32/125/134a, are proposed as the most similar replacements for HCFC-22. Practical application of these mixtures as working fluids requires accurate and reliable thermal conductivity information to design refrigeration systems. Thermal conductivity measurements for the binary mixtures of HFC-32/125 and HFC-32/134a are reported in the preceding paper [1]. In the present work, we report thermal conductivity measurements for two ternary mixtures of HFC-32/125/134a in the liquid phase over wide temperature and pressure ranges.

[1] Department of System Design Engineering, Keio University, 3-14-1 Hiyoshi, Yokohama 223-8522, Japan.

[2] To whom correspondence should be addressed.

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2. EXPERIMENTAL

The thermal conductivity measurements for the ternary HFC refrigerant mixtures were performed in a transient hot-wire instrument described in detail elsewhere [2]. The hot wire was made of platinum with a diameter of 10 μm and an effective length of about 50 mm. Two electrical voltage potential leads of the same platinum wire were spot-welded at each side of the hot wire to compensate for end effects. The temperature of the sample was measured with a platinum resistance thermometer calibrated on ITS-90 to within an expanded uncertainty of ± 0.12 K. The pressure was measured with a precise digital pressure gauge to within an expanded uncertainty of ± 0.142 MPa. The NIST Database REFPROP Version 6.0 [3] was employed to calculate the densities of the ternary mixtures of HFC-32/125/134a with an estimated uncertainty of ± 0.1%.

The sample of HFC-32 was supplied by Showa Denko Co, Ltd., with a stated purity of better than 99.98 wt%. The samples of HFC-125 and HFC-134a were provided by Du Pont–Mitsui Fluorochemicals Co, Ltd., with purities of better than 99.6 and 99.9 wt%, respectively. The mixture samples of HFC-32/125/134a were prepared gravimetrically and loaded into the measurement cell in the liquid phase. After the measurement, the samples in the measurement cell were removed, and their composition was checked using gas chromatography. The uncertainties of compositions of HFC-32 and HFC-125 for the mixtures of HFC-32/125/134a were estimated to be ± 0.42 and ± 0.44 wt%, respectively. The ISO guide to the expression of uncertainty in measurement [4] was used to evaluate the uncertainties of temperature, pressure, mass fractions of the mixtures, and thermal conductivity in the present study. The thermal conductivity was estimated to have an expanded uncertainty of ± 0.7%.

Before making the measurements on these HFC ternary refrigerant mixtures, the thermal conductivity of liquid toluene was measured. The experimental results for toluene were compared with our previous work [5] and the IUPAC recommended values [6] to check the performance of the transient hot-wire instrument. While measuring the thermal conductivity of these mixtures, the influence of the polarization of the sample, the electrical current leakage of the hot wire, and the occurrence of the initial natural convection were checked carefully. Since distortion of the linearity of the temperature rise of the hot wire versus the logarithmic time during the measurement was not evident, the influences of the polarization and the electrical current leakage were considered to be negligible. Three or four measurements were repeated at each state point, and the reproducibility of the experimental results was checked. Only those experimental data whose reproducibility was better than ± 0.5% were considered to be reliable.

The final thermal conductivity was the average value of three or four measurements.

3. RESULTS AND DISCUSSION

The thermal conductivity of the two ternary mixtures of HFC-32/125/134a with mass fractions of 23.0/25.0/52.0 wt% (R-407C) and 19.0/43.8/37.2 wt% (33.4/33.3/33.3 mol%) was measured in the temperature ranges from 193 to 293 K and from 213 to 293 K, respectively, and in the pressure range from 2 to 30 MPa. All experimental data for the two mixtures are listed in Tables I and II. The experimental thermal conductivity data were represented by the following polynomial in temperature and pressure for each mixture:

$$\lambda = \sum_{n=0}^{2} a_n P^n + T \sum_{n=0}^{2} b_n P^n + T^2 \sum_{n=0}^{2} c_n P^n \qquad (1)$$

Table I. Thermal Conductivity of the Mixture of HFC-32/125/134a (23.0/25.0/52.0 wt%)

Temperature (K)	Pressure (MPa)	Density ($kg \cdot m^{-3}$)	Thermal conductivity, λ ($W \cdot m^{-1} \cdot K^{-1}$)
193.2	2	1491	0.1346
193.2	10	1503	0.1372
193.2	20	1517	0.1405
193.1	30	1530	0.1440
213.1	2	1435	0.1250
213.1	10	1449	0.1281
213.1	20	1466	0.1319
213.0	30	1481	0.1351
233.1	2	1375	0.1147
233.0	10	1394	0.1186
233.0	20	1414	0.1227
233.0	30	1432	0.1265
253.0	2	1312	0.1044
253.0	10	1336	0.1087
253.0	20	1361	0.1134
253.0	30	1382	0.1178
272.8	2	1244	0.0934
272.8	10	1275	0.0978
272.8	20	1306	0.1033
272.8	30	1332	0.1083
292.8	2.5	1170	0.0853
292.8	10	1210	0.0911
292.7	20	1249	0.0968
292.7	30	1280	0.1019

Table II. Thermal Conductivity of the Mixture of HFC-32/125/134a (19.0/43.8/37.2 wt%)

Temperature (K)	Pressure (MPa)	Density ($kg \cdot m^{-3}$)	Thermal conductivity, λ ($W \cdot m^{-1} \cdot K^{-1}$)
213.1	2	1460	0.1174
213.1	10	1476	0.1211
213.1	20	1494	0.1246
213.1	30	1510	0.1287
233.2	2	1398	0.1081
233.2	10	1418	0.1126
233.1	20	1440	0.1162
233.1	30	1459	0.1197
253.1	2	1333	0.0977
253.1	10	1358	0.1024
253.1	20	1385	0.1067
253.0	30	1408	0.1122
272.9	2	1261	0.0874
272.8	10	1295	0.0923
272.8	20	1329	0.0985
272.8	30	1356	0.1040
293.0	2.5	1182	0.0797
293.0	10	1226	0.0852
292.9	20	1269	0.0917
292.8	30	1303	0.0958

The coefficients of the correlation for the two ternary mixtures are listed in Tables III and IV. The correlation reproduces the experimental results for the mixture of HFC-32/125/134a (23.0/25.0/52.0 wt%) with a standard deviation of 0.6% and a maximum deviation of -1.3% as shown in Fig. 1, and reproduces the experimental results for the mixture of HFC-32/125/134a (19.0/43.8/37.2 wt%) with a standard deviation of 0.6% and a maximum deviation of -1.6%, as shown in Fig. 2.

Table III. Optimum Values of the Coefficients a_n, b_n, and c_n in Eq. (1) for HFC-32/125/134a (23.0/25.0/52.0 wt%)

	a_n	b_n	c_n
$n=0$	2.4106×10^{-1}	-5.7480×10^{-4}	1.2348×10^{-7}
$n=1$	3.4192×10^{-4}	-3.1331×10^{-6}	1.5343×10^{-8}
$n=2$	-3.1568×10^{-6}	6.2997×10^{-8}	-2.3306×10^{-10}

Table IV. Optimum Values of the Coefficients a_n, b_n, and c_n in Eq. (1) for HFC-32/125/134a (19.0/43.8/37.2 wt%)

	a_n	b_n	c_n
$n=0$	2.3710×10^{-1}	-6.0741×10^{-4}	2.1479×10^{-7}
$n=1$	3.6106×10^{-3}	-2.9716×10^{-5}	6.8733×10^{-8}
$n=2$	-1.3123×10^{-4}	1.1012×10^{-6}	-2.3096×10^{-9}

For the mixture of HFC-32/125/134a (23.0/25.0/52.0 wt%), there are two other studies available, which were performed using the transient hot-wire instruments. Jeong et al. [7] made measurements of the liquid thermal conductivity in the temperature range from 233 to 333 K and in the pressure range from 2 to 20 MPa with an uncertainty of $\pm 2\%$. Spindler et al. [8] measured the saturated liquid thermal conductivity in the

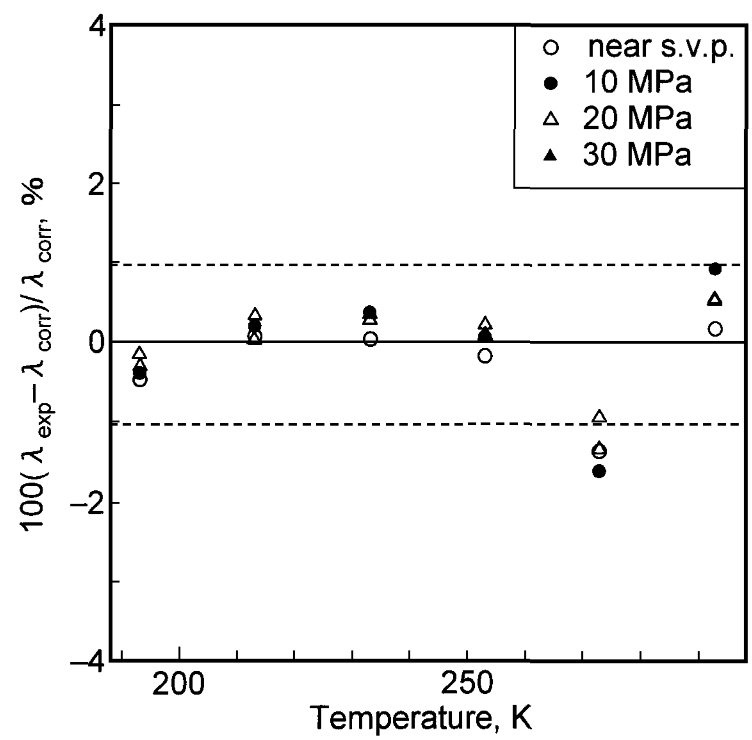

Fig. 1. Percentage deviations of the present experimental data from Eq. (1) for the mixture of HFC-32/125/134a (23.0/25.0/52.0 wt%).

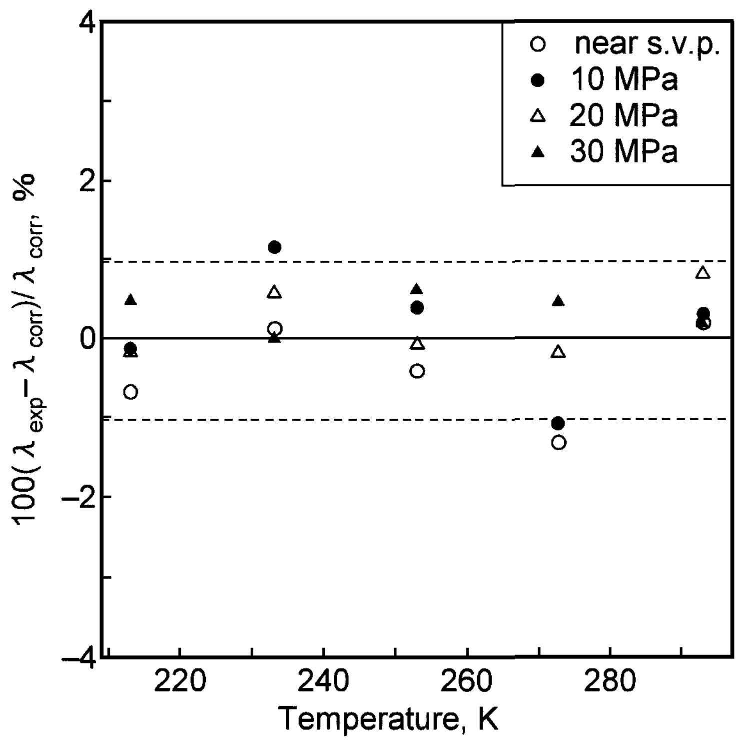

Fig. 2. Percentage deviations of the present experimental data from Eq. (1) for the mixture of HFC-32/125/134a (19.0/43.8/37.2 wt%).

temperature range from 223 to 333 K with an uncertainty of $\pm 2\%$. The comparison of the experimental results of these two studies with the present correlation is plotted in Fig. 3. It is found that the experimental results of Jeong et al. and those of Spindler et al. agree well with the present correlation to within the mutual uncertainty.

The present experimental results of thermal conductivity are significantly lower than the predicted values of REFPROP 6.0. The average absolute deviation and the maximum deviation of the present experimental results based on the thermal conductivity predictions of REFPROP 6.0 for the HFC-32/125/134a system are 7.1 and -8.8%, respectively. In view of the marked deviations between the experimental results of thermal conductivity and the REFPROP 6.0 predicted values, some other precise thermal conductivity measurements for ternary HFC refrigerant mixtures are urgently needed. Also, the reliability of the thermal conductivity prediction model in REFPROP 6.0 should be checked and improved.

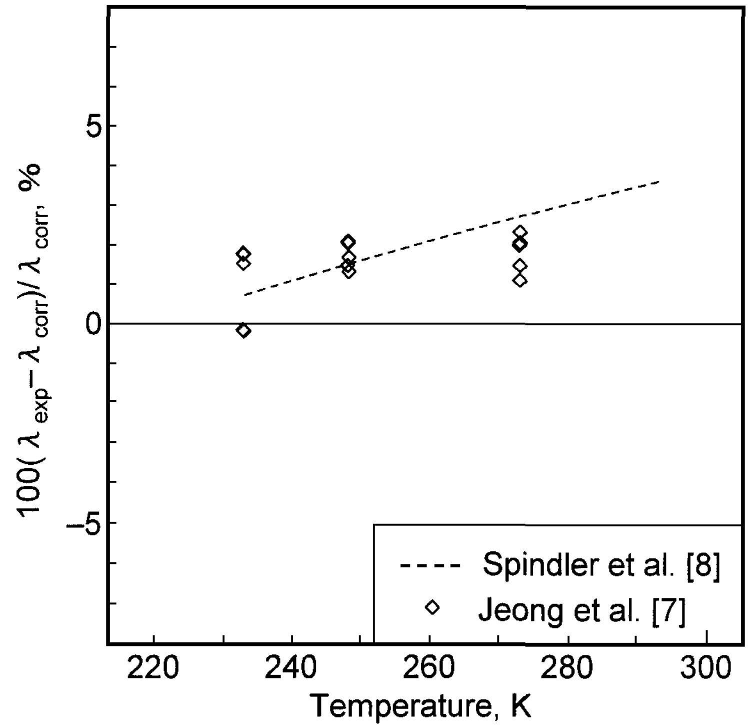

Fig. 3. Comparisons of Eq. (1) for the mixture of HFC-32/125/134a (23.0/25.0/52.0 wt%) with other measurements.

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