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Measurements of the Thermal Conductivity of R22, R123, and R134a in the Temperature Range 250–340 K at Pressures up to 30 MPa

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This paper reports new, absolute measurements of the thermal conductivity of the liquid refrigerants R22, R123, and R134a in the temperature range 250–340 K at pressures from saturation up to 30 MPa. The measurements, performed in a transient hot-wire instrument employing two anodized tantalum wires as the heat source, have an estimated uncertainty of ±0.5%. A recently developed semiempirical scheme is employed to correlate successfully the thermal conductivity and the viscosity of these refrigerants, as a function of their density.

KEY WORDS: high pressure; R123; R134a; R22; refrigerants; thermal conductivity; transient hot-wire technique.

1. INTRODUCTION

The harmful effects of the presently used refrigerant fluids has prompted a worldwide research program aiming to their substitution. Thus, the measurement of their properties has become very important. Moreover, a recent survey of literature values for the thermal conductivity of some refrigerants has demonstrated that there are discrepancies that exceed the estimated uncertainties [1].

In the particular case of the application of the transient hot-wire technique to the measurement of the thermal conductivity, these discrepancies are believed to be attributed to the use of bare wires as the heat source [2, 3]. Most of the liquid refrigerants are polar fluids with very good solvent properties. Laesecke et al. [2] reported that in the measurement

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of the thermal conductivity of R134a with the use of bare platinum wires, the electrical isolation between the wires and the cell is degraded to approximately 5 MΩ, while for nonpolar fluids this isolation is greater than 30 MΩ. Furthermore, an electrochemical potential was observed between the hot wires and the cell wall. The same phenomenon was previously reported by Ross et al. [3]. These observations are thought to be due to the solubility of very dilute quantities of ionic impurities. These impurities, although they do not significantly affect the thermodynamic and transport properties of the liquid, alter the electrical conduction between the hot wires and the cell wall and thus introduce an error in the transient hot-wire thermal-conductivity measurements. One way to avoid this error is to introduce a fixed DC polarization voltage between the cell wall and the hot wires [2]. A better way, in our opinion [4], is to insulate electrically the hot wires from the liquid. The way to achieve this electrical insulation is to employ anodized tantalum wires as the heat source.

In a recent paper [4] measurements of the thermal conductivity of liquid refrigerants R11 (trichlorofluoromethane) and R12 (dichlorodifluoromethane) were presented. The measurements were performed in a newly developed transient hot-wire instrument that employed for the heat source, two tantalum wires electrically insulated from the liquid by the formation of an anodic oxide film in their surface. The novelty of this technique is that it avoids the unexpected electrical effects discussed above.

At present possible alternatives to the commonly used refrigerants R11 and R12 are the refrigerants R123 (1, 1-dichloro-2, 2, 2-trifluoroethane) and R134a (1, 1, 1, 2-tetrafluoroethane), while R22 (difluorochloromethane) is considered a current short-term alternative. In this paper, new absolute measurements of the thermal conductivity of the refrigerants R22, R123, and R134a are presented.

2. EXPERIMENTS

The thermal-conductivity measurements were performed in the transient hot-wire instrument described in detail elsewhere [4]. Two 25-μm-diameter anodized tantalum wires were used as the heat source. During measurements the leak current [4] was always registered and it was never greater than 1 μA. All measurements were performed from just above the saturation pressure up to 30 MPa along the 253.15, 273.15, 293.15, 313.15, and 333.15 K isotherms. The thermal conductivity of toluene was measured before and after each liquid, to ensure the continuing good operation of the instrument. These measurements were found to agree with our previously reported measurements [4] within ±0.1%. The precision of the instrument

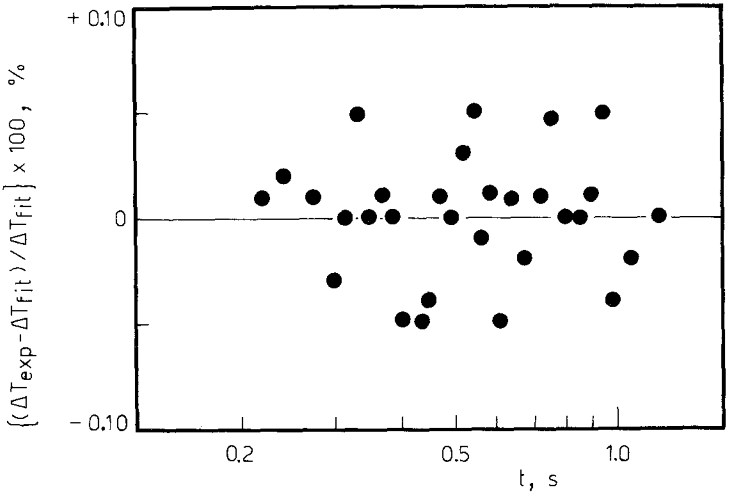

Fig. 1. Percentage deviations of the measured temperature rise as a function of time, from linearity for a typical run of R123 at 333.15 K and 3.9 MPa.

is ±0.1%, while the estimated uncertainty of the measurements is believed to be ±0.5%.

The sample of R22 was supplied by SICNG Chemical Industries of Northern Greece SA with a certified purity better than 99.95%. The samples of R123 and R134a were supplied by Hoechst Hellas with a certified purity better than 99.8 and 99.9% respectively. Before the introduction of the samples in the system, the system was evacuated for a long period of time.

As also reported previously [4], for the temperature range studied and for the three liquids presented here, no radiation correction was necessary. In Fig. 1 the percentage deviations of the experimental temperature rise, ΔT, as a function of time for a typical run of R123 at 333.15 K are shown. It can be seen that not only is no curvature or systematic trend is apparent, but also the maximum deviation is less than ±0.05%. In the transient hot-wire measurements the effect of radiation would have been to curve the otherwise linear representation of the experimental temperature rise as a function of time [4–6].

3. RESULTS

The measurements of the thermal conductivity of R22, R123, and R134a, listed in Tables I to III, were performed along the isotherms of 253.15, 273.15, 293.15, 313.15, and 333.15 K from just above the saturation pressure up to about 30 MPa. In these tables values corrected to nominal

Table I. Measurements of the Thermal Conductivity of R22

Pressure P (MPa)	Temperature T (K)	Thermal conductivity $\lambda(T, P)$ $(\mathrm{mW \cdot m^{-1} \cdot K^{-1}})$	Density $\rho(T_{\mathrm{nom}}, P)$ $(\mathrm{kg \cdot m^{-3}})$	Thermal conductivity $\lambda(T_{\mathrm{nom}}, P)$ $(\mathrm{mW \cdot m^{-1} \cdot K^{-1}})$
				$T_{\mathrm{nom}} = 253.15$ K
1.00	252.84	104.3	1349	104.2
3.88	252.78	105.7	1358	105.5
7.33	252.67	107.5	1368	107.3
10.80	252.75	109.2	1378	109.0
13.75	252.67	110.6	1386	110.4
16.90	252.54	112.4	1394	112.2
20.20	252.54	114.1	1401	113.8
				$T_{\mathrm{nom}} = 273.15$ K
1.00	273.52	94.6	1282	94.8
4.39	273.64	96.7	1297	96.9
7.95	273.54	98.8	1310	99.0
10.71	273.43	100.4	1319	100.5
14.10	273.43	102.3	1330	102.4
17.95	273.38	104.5	1342	104.6
21.63	273.25	106.4	1352	106.4
25.10	273.33	108.1	1361	108.2
				$T_{\mathrm{nom}} = 293.15$ K
1.42	293.13	85.4	1212	85.4
4.18	293.08	87.6	1227	87.6
7.16	293.06	89.8	1242	89.8
10.61	293.02	92.2	1257	92.2
14.30	292.91	94.6	1272	94.5
17.90	292.85	96.8	1285	96.7
21.62	292.95	98.9	1297	98.8
24.93	292.86	100.7	1307	100.6
				$T_{\mathrm{nom}} = 313.15$ K
1.80	313.45	75.7	1130	75.9
4.12	313.22	78.1	1149	78.1
6.98	313.09	80.9	1169	80.9
10.10	313.06	83.4	1188	83.4
13.03	312.99	85.8	1203	85.7
16.13	313.00	88.0	1218	87.9
19.00	312.86	90.0	1230	89.9
				$T_{\mathrm{nom}} = 333.15$ K
2.80	333.20	66.7	1036	66.7
7.10	333.32	71.7	1087	71.8
10.75	333.25	75.5	1118	75.5
14.70	333.15	79.2	1145	79.2
18.63	333.06	82.4	1167	82.4
22.60	333.03	85.1	1186	85.1
26.58	332.92	87.4	1203	87.3

Table II. Measurements of the Thermal Conductivity of R123

Pressure P (MPa)	Temperature T (K)	Thermal conductivity $\lambda(T, P)$ $(\mathrm{mW \cdot m^{-1} \cdot K^{-1}})$	Density $\rho(T_{\mathrm{nom}}, P)$ $(\mathrm{kg \cdot m^{-3}})$	Thermal conductivity $\lambda(T_{\mathrm{nom}}, P)$ $(\mathrm{mW \cdot m^{-1} \cdot K^{-1}})$
				$T_{\mathrm{nom}} = 253.15$ K
0.10	253.32	88.8	1581	88.9
3.54	253.32	90.0	1586	90.1
7.05	253.24	91.3	1591	91.3
10.08	253.24	92.1	1596	92.1
13.10	253.23	93.1	1600	93.1
16.13	253.30	94.1	1604	94.1
23.80	253.35	96.3	1614	96.4
				$T_{\mathrm{nom}} = 273.15$ K
0.10	273.65	83.5	1527	83.6
4.11	273.16	84.8	1535	84.8
8.28	273.23	86.1	1544	86.1
12.41	273.30	87.6	1551	87.6
16.31	273.21	89.0	1558	89.0
20.27	273.15	90.3	1564	90.3
23.50	273.10	91.3	1570	91.3
28.30	273.02	92.9	1577	92.9
				$T_{\mathrm{nom}} = 293.15$ K
0.24	293.24	78.0	1475	78.0
4.23	293.01	79.5	1486	79.5
8.00	293.46	81.0	1496	81.1
12.30	293.24	82.5	1506	82.5
16.30	293.05	83.9	1515	83.9
20.12	293.15	85.2	1523	85.2
23.82	292.99	86.6	1530	86.6
				$T_{\mathrm{nom}} = 313.15$ K
0.30	313.27	72.6	1423	72.6
4.16	313.17	74.2	1437	74.2
7.71	313.28	75.7	1449	75.7
11.11	313.15	77.1	1459	77.1
14.40	313.15	78.4	1468	78.4
17.07	313.17	79.5	1475	79.5
20.11	313.16	80.6	1483	80.6
23.42	313.10	81.9	1491	81.9
				$T_{\mathrm{nom}} = 333.15$ K
0.50	333.27	67.2	1370	67.2
3.90	333.23	68.9	1386	68.9
7.25	333.18	70.4	1400	70.4
10.70	333.22	72.0	1413	72.0
14.05	333.07	73.6	1424	73.6
17.02	333.14	74.8	1434	74.8

Table III. Measurements of the Thermal Conductivity of R134a

Pressure P (MPa)	Temperature T (K)	Thermal conductivity $\lambda(T, P)$ $(\text{mW} \cdot \text{m}^{-1} \cdot \text{K}^{-1})$	Density $\rho(T_{\text{nom}}, P)$ $(\text{kg} \cdot \text{m}^{-3})$	Thermal conductivity $\lambda(T_{\text{nom}}, P)$ $(\text{mW} \cdot \text{m}^{-1} \cdot \text{K}^{-1})$
				$T_{\text{nom}} = 253.15$ K
0.64	253.03	100.6	1357	100.6
2.71	253.08	101.8	1363	101.8
5.08	252.99	103.2	1369	103.1
8.38	253.17	104.8	1377	104.8
11.80	253.33	106.5	1386	106.6
15.62	253.15	108.3	1394	108.3
19.00	253.24	109.8	1402	109.8
22.43	252.97	111.3	1409	111.2
				$T_{\text{nom}} = 273.15$ K
0.64	273.31	91.8	1296	91.9
2.80	273.33	93.3	1303	93.4
5.08	273.39	94.6	1311	94.7
8.12	273.18	96.6	1320	96.6
10.02	273.24	98.1	1326	98.1
14.22	273.20	99.9	1338	99.9
17.50	273.04	101.6	1347	101.6
20.55	273.09	103.0	1355	103.0
				$T_{\text{nom}} = 293.15$ K
0.64	293.08	83.4	1226	83.4
3.88	293.00	85.7	1242	85.6
6.93	293.41	87.8	1256	87.9
9.93	293.27	89.8	1269	89.9
12.80	293.29	91.5	1280	91.6
15.33	293.38	92.9	1288	93.0
18.73	293.46	94.7	1300	94.8
				$T_{\text{nom}} = 313.15$ K
1.71	313.17	75.6	1152	75.6
4.28	313.20	77.9	1171	77.9
7.33	313.04	80.5	1190	80.5
9.90	313.10	82.4	1204	82.4
12.82	313.03	84.4	1219	84.4
15.77	313.00	86.2	1232	86.2
18.59	313.15	88.0	1244	88.0
				$T_{\text{nom}} = 333.15$ K
1.90	333.30	67.3	1056	67.4
5.00	333.10	70.7	1093	70.7
8.11	333.09	73.6	1120	73.6
11.21	333.03	76.2	1143	76.2
14.40	333.20	78.5	1163	78.5
17.32	333.20	80.5	1178	80.5

temperatures are also shown. Since this correction amounts to less than ±0.1%, no additional error is introduced.

For the measurements of the thermal conductivity of R22, the density values used were obtained from Platzer et al. [7], having a maximum quoted uncertainty of ±0.2%. In the case of the measurements of the thermal conductivity of R123, density values were obtained from an equation of state presented by Piao et al. [8] with a maximum quoted uncertainty of ±0.5%, for the temperature range 270–550 K and up to 15-MPa pressure. For the present measurements extrapolation was required. The extrapolated density values were in agreement within the aforementioned quoted uncertainty, with the low-temperature saturation values of Maezawa et al. [9] and the high-pressure values of Kubota [10]. For the thermal-conductivity measurements of R134a, the density values used were obtained by an equation of state presented by Piao et al. [11], with a maximum quoted uncertainty of ±0.5%, for the temperature range 240–480 K and up to 15-MPa pressure. For the present high-pressure measurements extrapolation was again performed. The extrapolated density values were found to agree within the aforementioned quoted uncertainty, with the high pressure values of Kubota [10].

For each liquid studied here, all measurements of the thermal conductivity, λ, have been correlated for interpolation purposes by a least-squares regression analysis to an equation of the form

$$\lambda = \sum_{i=0}^{2} \sum_{j=0}^{2} C_{ij} \left[\frac{P}{P_c}\right]^i \left[\frac{T}{T_c}\right]^j \tag{1}$$

Table IV. Coefficients and Constants of Eq. (1)

Coefficients C_{ij} ($\mathrm{mW \cdot m^{-1} \cdot K^{-1}}$)	R22	R123	R134a
C_{00}	190.73	154.26	206.66
C_{01}	−81.676	−112.70	−153.01
C_{02}	−66.078	−9.588	−6.5382
C_{10}	7.631	8.471	14.689
C_{11}	−28.101	−25.449	−39.946
C_{12}	29.752	22.393	32.209
C_{20}	1.3293	−0.7535	−1.8861
C_{21}	−1.8846	2.4144	5.3581
C_{22}	0	−1.946	−3.9593
P_c (MPa)	4.9900	3.6655	4.0650
T_c (K)	369.33	456.85	374.30
σ (%)	±0.06	±0.06	±0.05

where P and T are the absolute pressure and temperature in MPa and K, and P_c and T_c are the critical constants. The values of the coefficients C_{ij} and the constants P_c and T_c are given in Table IV, together with the standard deviation of the fits. The maximum standard deviation is 0.06%.

In Table V, thermal-conductivity values along the saturation line are presented. These values have been obtained by extrapolating Eq. (1), while their validity can easily be confirmed by comparison with the measurements performed just above the saturation line.

In Fig. 2 the percentage deviations of the thermal-conductivity values of other investigators at saturation pressure from the values of Eq. (1) are presented. In the case of the thermal conductivity of R22, the values of Yata et al. [12], performed in a relative manner in a transient hot-wire instrument with a quoted uncertainty of ±1.5%, agree with the present values within the mutual uncertainty. The values of Geller et al. [13], also performed in a relative manner in a transient hot-wire instrument with a quoted uncertainty of ±3%, agree with the present values up to 300 K, while they deviate more at higher temperatures. Large deviations show also the measurements of Tauscher [14], but these are attributed to inaccurate data of toluene used for the calibration of his transient hot-wire. In the case of the thermal-conductivity measurements at saturation pressure of R123 and R134a, the values of Ueno et al. [15], performed in a transient

Table V. The Thermal Conductivity of R22, R123, and R134a at Saturation

Liquid	Temperature T_s (K)	Pressure P_s (MPa)	Density ρ_s ($kg \cdot m^{-3}$)	Thermal conductivity $\lambda(T_s, P_s)$ ($mW \cdot m^{-1} \cdot K^{-1}$)
R22	253.15	0.246	1346	103.8
	273.15	0.498	1281	94.5
	293.15	0.910	1209	89.9
	313.15	1.532	1128	75.5
	333.15	2.425	1030	66.4
R123	253.15	0.101	1567	88.9
	273.15	0.101	1521	83.5
	293.15	0.101	1473	78.0
	313.15	0.152	1423	72.6
	333.15	0.279	1369	67.1
R134a	253.15	0.133	1356	100.3
	273.15	0.294	1296	91.7
	293.15	0.571	1226	83.3
	313.15	1.017	1146	75.0
	333.15	1.682	1053	67.2

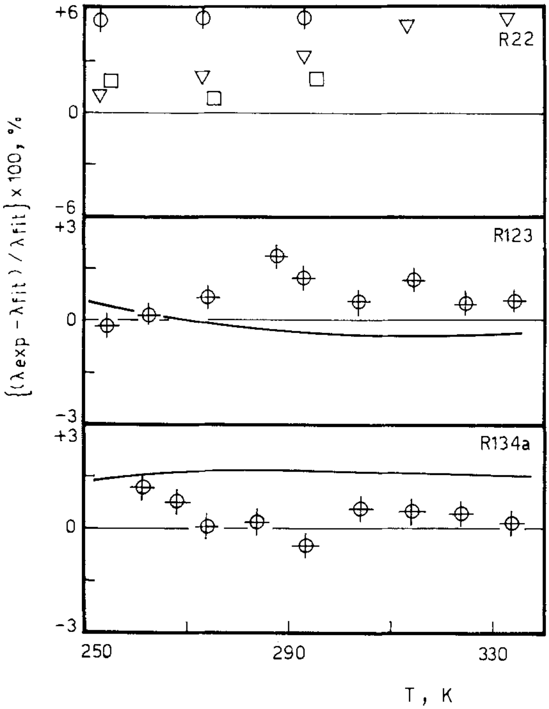

Fig. 2. Percentage deviations of the experimental values of the thermal conductivity of R22, R123, and R134a along the saturation pressure, from Eq. (1). (□) Ref. 12; (▽) Ref. 13; (ф) Ref. 14; (——) Ref. 15; (⌖) Ref. 16.

hot-wire instrument with a quoted uncertainty of ±0.5%, show a good agreement with the present values. The values of Gross et al. [16], also performed in a relative manner in a transient hot-wire instrument with a quoted uncertainty of ±2%, show deviations within the mutual uncertainty of the instruments.

In Fig. 3, the percentage deviations of the present high-pressure measurements of R22 from those calculated by Eq. (1) are shown. The maximum deviation is less than 0.2%. In the same figure the high-pressure measurements of two more investigators are shown. The measurements of Geller et al. [13], discussed above, agree with the present measurements up to 300 K, above which they show deviations up to 6%. The measurements of Tsvetkov and Laptyev [17], performed in a steady-state coaxial-cylinders instrument with a quoted uncertainty of ±2%, agree with the present measurements within the mutual uncertainty.

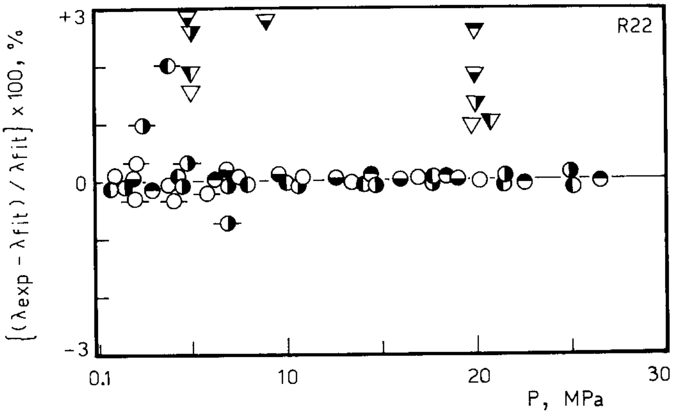

Fig. 3. Percentage deviations of the experimental high-pressure measurements of the thermal conductivity of R22, from Eq. (1). Present work: (○) 253.15 K; (◐) 273.15 K; (◑) 293.15 K; (◒) 313.15 K; (◓) 333.15 K. Ref. 13: (▽) 253.15 K; (⧨) 273.15 K; (⧩) 293.15 K; (▽) 313.15 K; (▼) 333.15 K. Ref. 17: (—○—) 313.15 K; (—◐—) 319.15 K; (—◑—) 323.15 K.

In Fig. 4, the percentage deviations of the present high-pressure measurements of R123 from those calculated by Eq. (1) are shown. The maximum deviation is less than 0.2%. In the same figure the high-pressure measurements of three more investigators are shown. The measurements of Yata et al. [12] and Ueno et al. [15], discussed previously, agree within

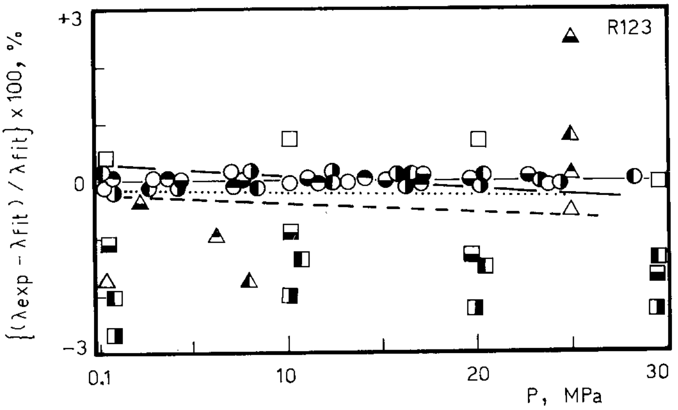

Fig. 4. Percentage deviations of the experimental high-pressure measurements of the thermal conductivity of R123, from Eq. (1). Present work: (○) 253.15 K; (◐) 273.15 K; (◑) 293.15 K; (◒) 313.15 K; (◓) 333.15 K. Ref. 12: (□) 262.6 K; (◧) 282.5 K; (◨) 302.7 K; (⬓) 325.4 K. Ref. 15: (——) 253.15 K; (·····) 293.15 K; (– – –) 333.15 K. Ref. 18: (△) 283.7 K; (◭) 298.8 K; (▲) 313.7 K; (◮) 323.8 K.

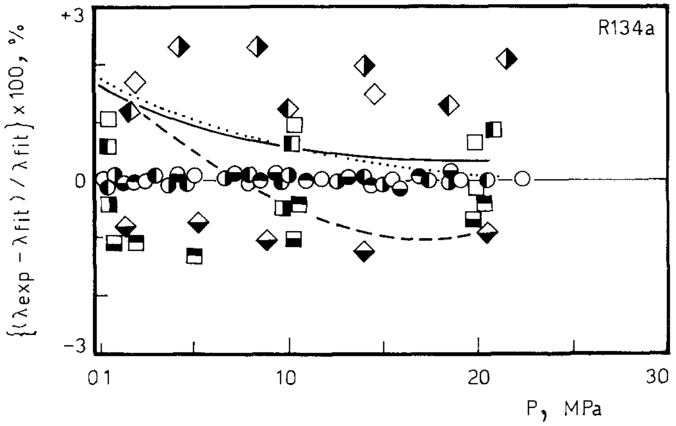

Fig. 5. Percentage deviations of the experimental high-pressure measurements of the thermal conductivity of R134a, from Eq. (1). Present work: (○) 253.15 K; (◐) 273.15 K; (◑) 293.15 K; (◒) 313.15 K; (◓) 333.15 K. Ref. 2: (◇) 263 K; (⬖) 283 K; (⬗) 303 K; (⬙) 323 K. Ref. 12: (□) 254.4 K; (◧) 273.7 K; (◨) 292.6 K; (⬓) 314.5 K; (⬒) 334.2 K. Ref. 15: (——) 253.15 K; (······) 293.15 K; (——) 333.15 K.

the mutual uncertainties of the instruments. The measurements of Tanaka et al. [18], performed in a relative manner in a transient hot-wire instrument with a quoted uncertainty of ±1%, show slightly larger deviations.

In the case of the high-pressure thermal-conductivity measurements of R134a presented in Fig. 5, a similar situation can be observed. The maximum deviation of the present measurements from those calculated with Eq. (1) is less than 0.15%. The measurements of Yata et al. [12] and Ueno et al. [15], discussed previously, just agree with the mutual uncertainties of the instruments. The measurements of Laesecke et al. [2], performed in a transient hot-wire instrument, show a 2% maximum deviation from the present values, although most of their data are within 1% of the present values. The values of Ross et al. [3] have not been included in the figure as they were only preliminary measurements.

It should finally be noted here that most investigators who used the transient hot-wire technique employed bare wires as the heat source. Therefore, larger deviations than their quoted uncertainties from the present measurements are not to be unexpected for the reasons outlined in Section 1.

4. DISCUSSION

Whereas Eq. (1) is suitable for interpolation, it has little or no value for extrapolation. For such purposes it has been shown [19–21] that a correlation in terms of the molar volume, V, is much more suitable. In the case of the viscosity and the thermal conductivity, this scheme, described in detail elsewhere [19], suggests that the dimensionless thermal conductivity, λ^*, and viscosity, η^*, defined by the equations

$$\lambda^* = 1.936 \times 10^7 \left[\frac{M}{RT}\right]^{1/2} \lambda V^{2/3} \tag{2}$$

$$\eta^* = 6.035 \times 10^8 \left[\frac{1}{MRT}\right]^{1/2} \eta V^{2/3} \tag{3}$$

are functions of the reduced molar volume $V_r = (V/V_0)$, where V_0 is a characteristic molar volume of the liquid, weakly dependent on temperature. In the above two equations (all quantities in SI units), M represents the molar mass, R the universal gas constant, and T the absolute temperature. According to this scheme [19] the aforementioned functions were calculated to be

$$\log\left[\frac{\lambda^*}{R_\lambda}\right] = 1.0655 - 3.538 V_r^{-1} + 12.120 V_r^{-2} - 12.469 V_r^{-3} + 4.562 V_r^{-4} \tag{4}$$

$$\begin{aligned}\log\left[\frac{\eta^*}{R_\eta}\right] = {} & 1.0945 - 9.26324 V_r^{-1} + 71.0385 V_r^{-2} - 301.9012 V_r^{-3} \\ & + 797.69 V_r^{-4} - 1221.977 V_r^{-5} + 987.5574 V_r^{-6} \\ & - 319.4636 V_r^{-7}\end{aligned} \tag{5}$$

where R_λ and R_η are constants accounting for deviations from the behavior of smooth hard spheres [19]. In the case of pure *n*-alkanes [19] and aromatic hydrocarbons [21], experimental measurements were used to calculate the temperature dependence of the characteristic molar volumes and the values of the above constants. It was thus shown [19–21] that this scheme can correlate and predict the viscosity, the thermal conductivity, and the diffusion coefficient with a 5% uncertainty over a temperature range 100–400 K and up to 600-MPa pressure.

The present thermal-conductivity measurements together with other existing viscosity measurements for R22 [22–26], R123 [23, 26, 27], and R134a [23, 24, 26, 28] were consequently used to calculate the temperature dependence of the characteristic molar volumes, V_0 ($10^6\,\mathrm{m}^3\cdot\mathrm{mol}^{-1}$) and the values of the constants R_λ and R_η for each liquid, as

R22: $R_\lambda = 1.57, \quad R_\eta = 1.10$

$$V_0 = 76.0767 - 0.38774T + 1.2708\times10^{-3}T^2 - 1.4708\times10^{-6}T^3 \tag{6}$$

R123: $R_\lambda = 1.81, \quad R_\eta = 1.53$

$$V_0 = -142.667 + 2.0274T - 6.5454\times10^{-3}T^2 + 6.7886\times10^{-6}T^3 \tag{7}$$

R134a: $R_\lambda = 1.55, \quad R_\eta = 1.10$

$$V_0 = -41.965 + 1.0565T - 4.1647\times10^{-3}T^2 + 5.3314\times10^{-6}T^3 \tag{8}$$

Equations (2)–(8) form a consistent set of equations for the correlation and prediction of the thermal conductivity and viscosity of R22, R123, and R134a. In Figs. 6 and 7, the percentage deviations of the experimental thermal conductivity and viscosity values from those calculated by the above scheme are shown. The experimental measurements shown cover the temperature range 240–360 K and the pressure range from saturation to 40 MPa. It can be seen that the maximum deviation is less than 5% in both figures.

5. CONCLUSION

New measurements of the thermal conductivity of R22, R123, and R134a are presented from just above the saturation pressure up to 30 MPa along the 253.15, 273.15, 293.15, 313.15, and 333.15 K isotherms. The

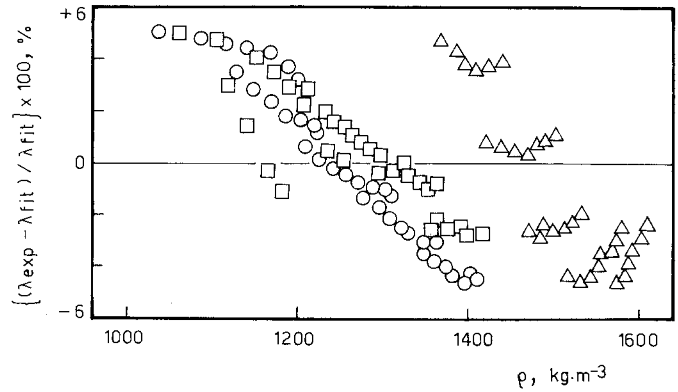

Fig. 6. Percentage deviations of the experimental thermal-conductivity measurements from the values calculated by the scheme of Eqs. (2)–(8). Present work: (○) R22; (△) R123; (□) R134a.

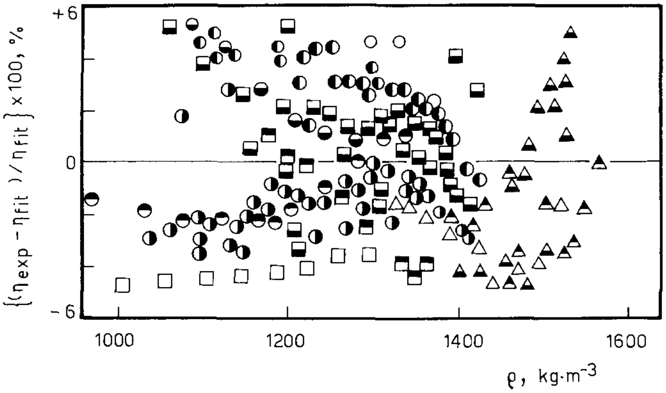

Fig. 7. Percentage deviations of the experimental viscosity measurements from the values calculated by the scheme of Eqs. (2)–(8). R22: (○) Ref. 22; (◒) Ref. 23; (◓) Ref. 24; (◑) Ref. 25; (◐) Ref. 26. R123: (△) Ref. 23; (▲) Ref. 26; (◭) Ref. 27. R134a: (□) Ref. 23; (⬓) Ref. 26; (⬒) Ref. 28.

measurements, performed in a transient hot-wire instrument employing two anodized tantalum wires, have an estimated uncertainty of ±0.5%.

Based on these measurements and other viscosity measurements, a recently developed semiempirical scheme is employed successfully to correlate and predict the thermal conductivity and the viscosity of R22, R123, and R134a over the temperature range 240–360 K and up to 40 MPa pressure with an uncertainty better than 5%.

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