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Measurements of the Viscosity of R11, R12, R141b, and R152a in the Temperature Range 270–340 K at Pressures up to 20 MPa

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This paper reports new measurements of the liquid viscosity of R11, R12, R141b, and R152a in the temperature range 270 to 340 K and pressures up to 20 MPa. The measurements have been carried out in a vibrating-wire instrument calibrated with respect to the standard reference value of the viscosity of water. It is estimated that the uncertainty of the present viscosity data is one of 0.5%. The experimental data have been represented by polynomial functions of temperature and pressure for the purposes of interpolation. A recently developed semiempirical scheme, based on considerations of hard-sphere theory, is employed to correlate successfully the viscosity and the thermal conductivity of these refrigerants as a function of their density.

KEY WORDS: high pressure; refrigerants; R11; R12; R141b; R152a; vibrating-wire technique; viscosity.

1. INTRODUCTION

Among the fluids considered as substitutes for the environmentally harmful R11 (trichlorofluormethane) and R12 (dichlorodifluoromethane) refrigerants, R141b (1,1-dichloro-1-fluoroethane) and R152a (1,1-difluoroethane) are among the possible candidates. As the time of the final decision is approaching, the need for accurate measurements of the equilibrium as well as the transport properties becomes more pronounced. In the specific case of the liquid viscosity for the four aforementioned refrigerants, very few

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measurements exist, and these are mostly at saturation conditions. Furthermore, the discrepancies between the investigators, up to 20% in an extreme case, far exceed the quoted uncertainties.

The large discrepancies observed in the measurement of the viscosity of liquid refrigerants are attributed mostly to three main effects: impurities in the samples, electrolytic effects in the instruments, and incapability of some instruments to be calibrated with water. The measurements presented in this paper are believed, as has been shown [1, 3], to be free of all these effects.

The vibrating-wire technique has already been proved to be capable of attaining high accuracy in the measurement of the viscosity of liquids. The viscometer, calibrated against water over its whole range of measurements, enables high-pressure measurements with an uncertainty of about $\pm 0.5\%$. Measurements of the viscosity of water [1], alcohols [2], and refrigerants R134a and R32[3] have already been published.

2. EXPERIMENTS

The vibrating-wire viscometer employed for the present measurements has been described in detail elsewhere [1-3] and is not repeated here. It should however, be pointed out that the entire instrument (including even electrical leads) is made out of stainless steel with the exception of the vibrating wire itself and the inner weight [1], which are made out of tungsten. This arrangement was found to be necessary to eliminate electrolytic effects [1, 3] due to the dissimilar metals present in the earlier version of the instrument. Sealing of the vessel was achieved with an especially fabricated PTFE-coated Viton O-ring to protect the O-ring from chemical attack [1]. Water, whose viscosity is very accurately known, is used for calibration of the viscometer. Taking all parameters into account, the uncertainty of the instrument is thus estimated to be $\pm 0.5\%$ while the precision and the reproducibility of the measurements are about $\pm 0.1\%$. The use of water in the instrument served also as a check that no electrolytic effects were taking place. Samples were introduced after evacuation of the system and a stainless-steel 20- to 30-μm filter in the inlet of the instrument ensured that no solid particles from the bottles could enter. The viscosity of water was measured before and after each liquid to ensure the continuing good operation of the instrument.

The samples of R11 and R12 were supplied by SICNG Chemical Industries of Northern Greece S.A., both at stated purities of better than 99.95%. The sample of R141b was supplied by Elf Atochem S.A. and the sample of R152a by Du Pont de Nemours International S.A., both at a stated purity of better than 99.9%.

3. RESULTS

The measurements of the viscosity of the four refrigerants were carried out along four isotherms, 273.15, 293.15, 313.15, and 333.15 K, from above saturation pressure up to 20 MPa. The density values employed in the calculation of the viscosity of R11, R12, and R152a were obtained from empirical correlations published by Blanke and Weiß [4, 5], with a quoted uncertainty of $\pm 0.01\%$. These correlations were based on their measurements and cover all the present range. In the case of R141b, the density values were obtained from an equation published by Defibaugh et al. [6] with a quoted uncertainty of $\pm 0.05\%$. This equation, however, covered the pressure range up to 6 MPa only. Since to our knowledge no other measurement-based equation or measurements of the density of R141b are available, we have extrapolated this equation to 20 MPa. It should be noted that the extrapolated density values agree with the corresponding-states values produced by Diller et al. [7] within 0.1%.

Tables I to IV show the experimental measurements of the viscosity of R11, R12, R141b, and R152a. All measurements of each refrigerant have been correlated as a function of the reduced temperature, T_r ($= T/T_c$, where T_c is the critical temperature) and reduced pressure, P_r ($= P/P_c$, where P_c is the critical pressure), for the purpose of interpolation only, by an equation of the form

$$\eta = \sum_{i=0}^{2} \sum_{j=0}^{3} C_{ij} P_r^i T_r^j \tag{1}$$

The values of all constants are shown in Table V. Critical constants shown in Table V were obtained from the literature—R11 [8], R12 [4], R141b [6], and R152a [32]. In the same table the maximum deviation and the standard deviation of each fit are also shown. The largest maximum deviation of all viscosity measurements is 0.11%, while the largest standard deviation is 0.05%. It should also be point out that the above equation was employed to calculate the values at nominal temperatures shown in Tables I to IV, together with the experimental values.

In Table VI, the viscosity at saturation conditions is shown for the four refrigerants. These values have been obtained by the use of Eq. (1), while values for the saturation pressure, P_s, and saturation density, ρ_s, are obtained from the respective density references discussed previously.

In Figs. 1 and 2, the deviations of other investigators' experimental values of the viscosity of the four refrigerants at saturation, from the values calculated by Eq. (1), are shown. It is worth pointing out that except for the measurements of Phillips and Murphy [9] performed in 1970, all other measurements have been performed the last 3 years. The measurements of

Table I. Measurements of the Viscosity of R11

Pressure P (MPa)	Temperature T (K)	Viscosity $\eta(T, P)$ (μPa · s)	Density $\rho(T_{nom}, P)$ (kg · m^{-3})	Viscosity $\eta(T_{nom}, P)$ (μPa · s)
		$T_{nom} = 273.15$ K		
1.40	273.146	531.8	1536	531.6
3.15	273.164	540.4	1540	540.7
4.50	273.164	547.4	1542	547.3
5.90	273.144	554.3	1545	554.4
7.40	273.272	561.0	1548	561.9
9.00	273.325	569.0	1551	570.0
9.90	273.240	573.9	1553	574.6
16.00	273.199	605.2	1565	605.4
		$T_{nom} = 293.15$ K		
2.30	293.173	430.1	1492	430.2
4.60	293.194	440.1	1498	440.2
6.90	293.189	449.9	1503	450.1
9.30	293.203	460.3	1509	460.5
11.70	293.173	470.8	1514	470.8
14.20	293.139	481.4	1520	481.7
16.60	293.201	491.8	1525	492.0
18.90	293.221	501.8	1529	502.0
		$T_{nom} = 313.15$ K		
2.15	313.184	352.1	1444	352.2
4.40	313.214	360.5	1451	360.8
6.80	313.201	369.8	1458	369.9
9.20	313.162	378.9	1464	379.1
11.45	313.214	387.7	1470	387.6
13.70	313.198	396.0	1476	396.2
16.10	313.189	405.2	1482	405.4
18.50	313.207	414.2	1487	414.5
		$T_{nom} = 333.15$ K		
1.60	333.141	291.1	1392	291.1
4.15	333.202	299.9	1402	300.1
6.60	333.145	308.6	1410	308.7
8.55	333.168	315.8	1416	315.5
10.50	333.205	322.2	1422	322.3
12.40	333.109	329.1	1428	329.0
14.40	333.246	335.8	1434	336.0
16.40	333.202	342.9	1440	343.1

Table II. Measurements of the Viscosity of R12

Pressure P (MPa)	Temperature T (K)	Viscosity $\eta(T, P)$ (μPa·s)	Density $\rho(T_{nom}, P)$ (kg·m^{-3})	Viscosity $\eta(T_{nom}, P)$ (μPa·s)
		$T_{nom} = 273.15$ K		
1.15	273.242	252.7	1399	253.1
2.65	273.215	258.2	1406	258.2
3.70	273.176	261.8	1410	261.8
5.55	273.142	267.9	1417	268.0
7.25	273.284	273.1	1423	273.5
9.25	273.176	279.8	1430	279.9
11.00	273.226	285.1	1435	285.3
12.70	273.199	290.3	1441	290.5
		$T_{nom} = 293.15$ K		
1.80	293.169	206.3	1336	206.2
3.20	293.155	210.8	1343	210.9
5.30	293.153	217.8	1354	217.8
7.05	293.162	223.2	1362	223.3
9.10	293.173	229.7	1371	229.7
11.05	293.178	235.5	1379	235.6
13.20	293.173	241.8	1388	241.8
15.10	293.162	247.1	1395	247.2
		$T_{nom} = 313.15$ K		
2.55	313.171	168.8	1267	168.9
4.40	313.189	175.2	1280	175.2
5.90	313.198	180.2	1290	180.2
7.30	313.219	184.6	1298	184.7
8.20	313.123	187.5	1304	187.5
9.30	313.187	190.8	1310	190.8
10.45	313.166	194.1	1316	194.3
11.65	313.219	197.6	1322	197.7
		$T_{nom} = 333.15$ K		
3.00	333.221	137.4	1186	137.6
4.30	333.207	142.2	1200	142.4
5.40	333.202	146.3	1210	146.3
6.45	333.148	149.8	1220	149.9
7.90	333.276	154.5	1232	154.6
9.10	333.180	158.2	1241	158.4
10.70	333.301	162.9	1252	163.2
12.20	333.150	167.4	1262	167.4

Table III. Measurements of the Viscosity of R141b

Pressure P (MPa)	Temperature T (K)	Viscosity $\eta(T, P)$ (μPa·s)	Density $\rho(T_{nom}, P)$ ($kg \cdot m^{-3}$)	Viscosity $\eta(T_{nom}, P)$ (μPa·s)
		$T_{nom} = 273.15$ K		
0.85	273.233	544.8	1281	545.5
2.70	273.208	555.4	1284	555.4
4.70	273.192	565.8	1288	566.2
6.90	273.242	577.6	1291	578.0
8.60	273.183	586.5	1294	587.1
10.30	273.245	595.2	1297	596.3
12.10	273.251	605.4	1300	606.0
14.35	273.164	618.1	1303	618.1
		$T_{nom} = 293.15$ K		
2.15	293.201	435.4	1247	435.9
4.30	293.201	445.1	1251	445.4
6.75	293.201	456.1	1256	456.3
9.00	293.194	466.1	1260	466.3
11.20	293.153	476.0	1264	476.1
14.10	293.187	488.9	1270	489.0
16.60	293.183	499.9	1274	500.1
18.60	293.267	508.6	1278	509.0
		$T_{nom} = 313.15$ K		
1.80	313.143	352.3	1209	352.1
4.30	313.136	361.7	1214	361.7
7.00	313.189	372.0	1220	372.0
9.35	313.178	381.0	1225	380.9
11.40	313.166	388.6	1229	388.7
13.70	313.159	397.5	1234	397.5
16.40	313.168	407.5	1239	407.8
18.90	313.130	417.3	1243	417.3
		$T_{nom} = 333.15$ K		
1.20	333.198	288.0	1167	288.1
3.05	333.159	294.6	1172	294.5
5.20	333.198	301.7	1178	302.0
6.90	333.102	308.1	1182	307.9
8.80	333.230	314.3	1186	314.6
11.65	333.166	324.5	1193	324.5
14.10	333.102	333.1	1198	333.0
16.45	333.244	341.2	1202	341.2

Table IV. Measurements of the Viscosity of R152a

Pressure P (MPa)	Temperature T (K)	Viscosity $\eta(T, P)$ (μPa·s)	Density $\rho(T_{nom}, P)$ (kg·m^{-3})	Viscosity $\eta(T_{nom}, P)$ (μPa·s)
		$T_{nom} = 273.15$ K		
1.45	273.226	218.6	962	218.9
3.25	273.206	223.2	966	223.4
4.85	273.178	227.3	970	227.3
6.60	273.135	231.6	974	231.6
8.30	273.176	235.7	978	235.7
10.00	273.203	239.6	982	239.8
11.75	273.229	243.6	985	243.9
13.30	273.178	247.6	988	247.5
		$T_{nom} = 293.15$ K		
1.65	293.231	174.9	916	175.1
4.15	293.267	181.0	924	181.0
6.40	293.217	186.1	930	186.2
8.45	293.208	190.7	936	190.9
10.85	293.180	196.1	943	196.2
13.10	293.208	200.9	948	201.0
15.40	293.153	205.9	954	205.9
17.70	293.189	210.5	959	210.6
		$T_{nom} = 313.15$ K		
1.95	313.239	140.8	865	141.0
3.80	313.230	145.4	873	145.5
5.55	313.162	149.7	880	149.6
7.20	313.262	153.0	886	153.4
9.50	313.205	158.3	895	158.4
11.30	313.239	162.1	901	162.1
13.15	313.143	165.9	906	165.9
15.00	313.171	169.6	912	169.4
		$T_{nom} = 333.15$ K		
2.40	333.260	114.9	806	114.9
3.50	333.198	117.8	814	117.9
5.00	333.230	121.6	823	121.7
6.50	333.207	125.4	831	125.4
8.00	333.157	128.8	839	128.8
9.65	333.257	132.4	847	132.4
11.40	333.168	135.9	854	136.0
13.20	333.189	139.2	862	139.3

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

Coefficients C_{ij} (μPa·s)	R11	R12	R141b	R152a
C_{00}	10,148.6	3,162.34	12,673.8	2,817.96
C_{01}	−37,890.8	−8,729.07	−49,402.6	−7,662.37
C_{02}	49,761.7	8,717.06	67,183.0	7,401.25
C_{03}	−22,489.2	−3,102.53	−31,283.9	−2,504.58
C_{10}	160.22	119.18	205.64	125.52
C_{11}	−389.49	−280.89	−529.35	−302.45
C_{12}	261.29	188.02	366.56	199.69
C_{13}	0	0	0	0
C_{20}	0	−16.25	0	−16.82
C_{21}	0	44.01	0	46.49
C_{22}	0	−30.44	0	−32.46
C_{23}	0	0	0	0
P_c (MPa)	4.4026	4.129	4.230	4.517
T_c (K)	471.15	384.981	477.26	386.41
Max. dev. (%)	0.11	0.11	0.08	0.11
σ (%)	±0.03	±0.03	±0.04	±0.05

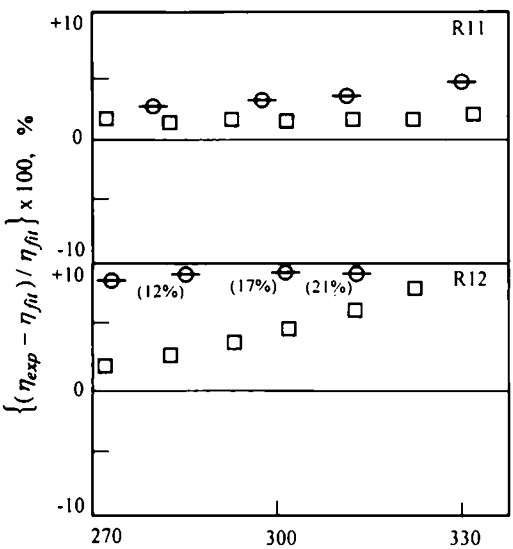

Fig. 1. Percentage deviations of the viscosity measurements of R11 and R12 along the saturation line, from Eq. (1). (⊖) Ref. 9; (□) Ref. 11.

Phillips and Murphy [9] were performed in an Ubbelohde suspended level-type viscometer calibrated with diethyl ether. The uncertainty of the measurements is not quoted. The deviations from the present values rise to 20%. The viscometer employed by Phillips and Murphy contained a coiled capillary. Their neglect of the effects of the curvature of the capillary upon the efflux times measured in the viscometer could have contributed to systematic errors in the reported viscosities, especially at low viscosities. The viscosity measurements of R152a of van der Gulik [10] were carried

Table VI. Viscosity of R11, R12, R141b, and R152a at Saturation

Fluid	Temperature T_s (K)	Pressure P_s (MPa)	Density ρ_s ($kg \cdot m^{-3}$)	Viscosity $\eta(T_s, P_s)$ ($\mu Pa \cdot s$)
R11	273.15	0.04	1533	524.8
	283.15	0.06	1510	468.5
	293.15	0.09	1487	420.7
	303.15	0.13	1463	379.8
	313.15	0.18	1438	344.7
	323.15	0.24	1413	314.1
	333.15	0.31	1387	286.6
R12	273.15	0.31	1396	250.1
	283.15	0.43	1363	224.8
	293.15	0.57	1329	202.0
	303.15	0.75	1293	181.6
	313.15	0.96	1254	163.3
	323.15	1.22	1213	146.8
	333.15	1.53	1168	131.9
R141b	273.15	0.03	1280	541.0
	283.15	0.04	1262	478.8
	293.15	0.07	1243	426.6
	303.15	0.09	1224	382.9
	313.15	0.13	1205	345.8
	323.15	0.18	1185	313.6
	333.15	0.25	1164	284.7
R152a	273.15	0.26	959	215.9
	283.15	0.37	936	192.8
	293.15	0.51	912	172.3
	303.15	0.69	887	154.3
	313.15	0.91	860	138.4
	323.15	1.18	831	124.6
	333.15	1.50	800	112.5

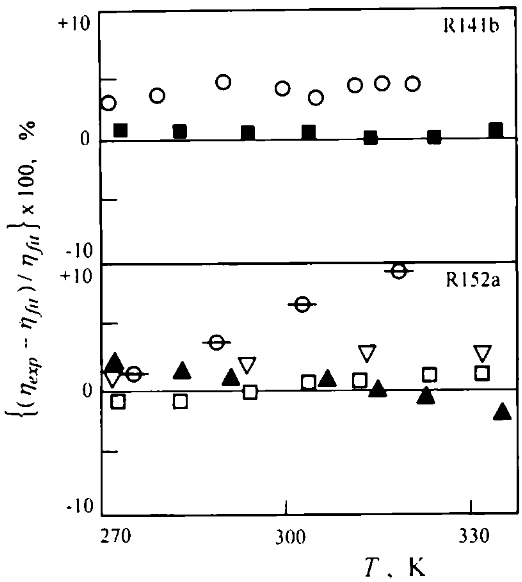

Fig. 2. Percentage deviations of the viscosity measurements of R141b and R152a along the saturation line, from Eq. (1). (⊖) Ref. 9; (▲) Ref. 10; (□) Ref. 11; (■) Ref. 12; (○) Ref. 13; (▽) Ref. 14.

out in a calibrated vibrating-wire instrument and at a quoted uncertainty of about ±1%. The maximum deviation of these values from those calculated by Eq. (1) is −2.9%. The measurements of Kumagai and Takahashi [11, 12] were carried out in a capillary viscometer calibrated with water and chloroform with a quoted uncertainty of about 1%. Except in the case of the viscosity of R12, in all other three refrigerants these values agree with the present set within the mutual uncertainties. In the case of the viscosity of R12 a different slope was observed, with deviations rising to 10% at the highest temperature. Since no other investigator has measured the viscosity of R12 recently, no other comment can be made except that this difference between the two sets is alarming. Diller et al. [13] measured the viscosity of R141b employing a torsional-crystal viscometer. Its reproducibility was checked by ethane to 2%. The uncertainty of the measurements is not quoted. This set of measurements deviate from the present values up to 5%. Finally, Arnemann and Kruse [14] employed a falling-body viscometer calibrated with various oils and water, to measure the viscosity of R152a. The uncertainty of the measurements is not quoted. This set shows deviations of up to 2.5% from the present values.

In the case of high-pressure measurements of the viscosity, to our knowledge the only available set of measurements is that of Diller et al. [13] at 300 K. This set seems to be shifted in pressure from the present values by about 3%.

4. DISCUSSION

Whereas Eq. (1) is suitable for interpolation, it has little or no value for extrapolation. For such purposes it has been shown [15–17] 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 [15], suggests that the dimensionless viscosity, η^*, and thermal conductivity, λ^*, defined by the equations

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

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

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 [15] the aformentioned functions were calculated to be

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

$$\log\left[\frac{\lambda^*}{R_\lambda}\right] = 1.0655 - 3.538 V_r^{-1} + 12.120 V_r^{-2} - 12.469 V_r^{-3} + 4.562 V_r^{-4} \tag{5}$$

where R_η and R_λ are constants accounting for deviations from the behavior of smooth hard spheres [15]. In the case of pure n-alkanes [15], aromatic hydrocarbons [16], alcohols [17], and some refrigerants [18], 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 [15–18] that this scheme can correlate and predict the viscosity, the thermal conductivity, and the diffusion coefficient with a 5% uncertainty over the temperature range 100–400 K and up to 600 MPa pressure.

Table VII. Constants R_η and R_λ and Coefficients a_i of Eq. (6)

	R11	R12	R141b	R152a
R_η	1.200	0.980	1.400	1.014
R_λ	1.640	1.510	1.585	1.470
a_0 ($10^5 m^3 \cdot mol^{-1}$)	6.751667	10.04425	16.56554	15.55339
a_1 ($10^7 m^3 \cdot mol^{-1} \cdot K^{-1}$)	−0.507283	−3.47825	−10.19797	−11.48044
a_2 ($10^{10} m^3 \cdot mol^{-1} \cdot K^{-2}$)	0.272575	5.72568	32.81475	37.49422
a_3 ($10^{12} m^3 \cdot mol^{-1} \cdot K^{-3}$)	0	0	−3.69437	−4.09760

All the aforementioned viscosity measurements together with other existing thermal conductivity measurements were consequently used to calculate the temperature dependence of the characteristic molar volumes, V_0 ($m^3 \cdot mol^{-1}$) and the values of the constants R_η and R_λ for each liquid. The characteristic molar volume, V_0, was subsequently fitted to a cubic expansion of the absolute temperature as

$$V_0 = \sum_{i=0}^{3} a_i T^i \tag{6}$$

Table VIII. Comparison of Experimental Viscosity Values with those Calculated from Eqs. (2)–(6)

Liquid	First author	Ref. No.	Temp. range (K)	Press. max. (MPa)	No. of data	Deviation 5-10%	Deviation >10%
R11	Present work		273–334	20	39	—	—
	Kumagai	11	273–354	Sat.	9	—	—
	Phillips	9	254–352	Sat.	7	1	—
R12	Present work		273–334	16	39	—	—
	Kumagai	11	273–344	Sat.	8	8	—
R141b	Present work		273–334	19	39	—	—
	Diller	13	250–320	30	27	—	—
	Kumagai	12	273–354	Sat.	9	—	—
R152a	Present work		273–334	18	39	—	—
	Kumagai	11	273–344	Sat.	8	—	—
	Arnemann	14	253–333	Sat.	8	—	—
	van der Gulik	10	253–373	Sat.	33	—	—
	Phillips	9	259–319	Sat.	5	1	—
Total					270	10	0

The coefficients a_i and the constants R_η and R_λ for each liquid are shown in Table VII. The above Eqs. (2)-(6) form a consistent set of equations for the correlation and prediction of the viscosity and thermal conductivity of R11, R12, R141b, and R152a.

In Table VIII a comparison of the experimental viscosity values with those calculated from Eqs. (2)-(6) is presented. Only the R12 viscosity measurements of Phillips and Murphy [9] have not been included in the analysis for the reasons discussed in the previous section. For consistency purposes, for R141b and R152a the density values used in the analysis were the ones discussed in this work. In the case of R11 and R12 and to include a wider range of temperatures and pressure, density values were obtained from Platzer et al. [8]. The ranges of temperature and pressure shown in the table are restricted to the available density and saturation pressure

Table IX. Comparison of Experimental Thermal Conductivity Values with Those Calculated from Eqs. (2)-(6)

Liquid	First author	Ref. No.	Temp. range (K)	Press. max. (MPa)	No. of data	Deviation 5-10%	Deviation > 10%
R11	Assael	19	253–334	21	35	—	—
	Kitazawa	20	232–323	21	11	—	—
	Yata	21	233–397	Sat.	9	2	1
	Takizawa	25	233–274	Sat.	5	—	—
	Tauscher	26	233–349	Sat.	12	1	—
R12	Assael	19	253–334	23	40	—	—
	Yata	21	264–361	Sat.	9	6	1
	Venart	22	300–380	21	48	5	—
	Geller	23	250–374	60	39	4	—
	Tauscher	26	253–294	Sat.	5	1	—
R141b	Gurova	29	270–300	Sat.	7	—	—
	Papadaki	31	273–290	Sat.	3	—	—
	Yata	28	273–354	21	15	7	—
R152a	Assael	18	253–334	23	37	1	—
	Kesselman	24	253–334	Sat.	9	—	—
	Tauscher	26	253–299	Sat.	5	—	—
	Gross	27	253–314	7	24	1	—
	Yata	28	265–343	31	20	—	—
	Kim	30	273–324	21	20	6	—
Total					353	34	2

data. A total of 270 experimental measurements was considered. Only 10 (3.7%) of them were found to deviate more than 5% from the scheme, and none more than 10%.

Finally, in Table IX a comparison of the experimental thermal conductivity values with those calculated from Eqs. (2)–(6) is presented. A total of 353 experimental measurements was considered. Of these measurements, 34 (9.6%) were found to deviate more than 5% from the scheme, and only 2 were found to deviate more than 10%.

Considering the fact that the experimental measurements shown cover a temperature range 250–400 K and a pressure range from saturation to 30 MPa, the deviations presented are regarded as quite satisfactory.

5. CONCLUSION

New measurements of the viscosity of R11, R12, R141b, and R152a have been presented. The measurements were performed in a recently modified vibrating-wire instrument and cover a temperature range from 270 to 340 K at pressures up to 20 MPa. The overall uncertainty in the reported data is $\pm 0.5\%$, an estimate confirmed by the measurement of the viscosity of water. From the discussion of the results, it seems that still more accurate measurements are required.

Based on the present measurements and other thermal conductivity measurements, a recently developed semiempirical scheme is successfully employed to correlate and predict the viscosity and thermal conductivity of these four refrigerants over the temperature range 250–400 K and up to 50 MPa pressure, with an uncertainty better than 5%.

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