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Thermal conductivity of HFC-152a in the temperature range 300 to 455 K at pressures up to 55 MPa

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Abstract. Thermal conductivity of HFC-152a was measured in a coaxial cylinder cell operating in a steady state. The measurements were performed along several quasi-isotherms between 300 and 455 K in the gas phase and the liquid phase. The pressure range covered varies from 0.1 to 55 MPa. An empirical equation is presented which describes the thermal conductivity outside the critical region as a function of temperature and density from 300 to 455 K. A careful analysis of the various sources of error leads to an estimated uncertainty of approximately $\pm 1.5\%$.

1 Introduction

The thermophysical properties of HFC-152a (1,1-difluoroethane) have been recently widely investigated since this hydrofluorocarbon is expected to be an environmentally acceptable alternative to the refrigerant HCFC-12 (dichlorodifluoromethane). Previous measurements of the thermal conductivity of HFC-152a, were mainly carried out in the liquid phase, and the results reported contained significant discrepancies. We investigated the influence of temperature and pressure on the thermal conductivity of HFC-152a both in the liquid phase and the gas phase above the critical temperature. The measurements were performed with the object of separating the three contributions to the thermal conductivity:

$$\lambda(T, \rho) = \lambda_0(T) + \delta\lambda(T, \rho) + \Delta\lambda(T, \rho) , \quad (1)$$

where $\lambda_0(T)$ is the dilute-gas thermal conductivity, $\delta\lambda(T, \rho)$ is the residual thermal conductivity, and $\Delta\lambda(T, \rho)$ is the critical enhancement. Experimental data for the liquid phase and for the gas phase far away from the critical point were the only ones taken into consideration to determine the so-called background term:

$$\lambda_B(T, \rho) = \lambda_0(T) + \delta\lambda(T, \rho) . \quad (2)$$

Measurements in the critical region and in the gas phase below the critical point, which include significant enhancement of the thermal conductivity due to critical fluctuations, will be reported later. The density was calculated with an equation of state reported by Tillner-Roth (1995) with the critical parameters:

$$T_c = 386.41 \text{ K}, \quad p_c = 4.5157 \text{ MPa}, \quad \text{and} \quad \rho_c = 368 \text{ kg m}^{-3} .$$

2 Experimental apparatus

The thermal conductivity of HFC-152a was measured in an apparatus with vertical coaxial cylinders operating in the steady-state mode. The same device was used for the measurement of the thermal conductivity of 1-chloro-1,1-difluoroethane (HCFC-142b) (Sousa et al 1992), HFC-125 (Le Neindre and Garrabos 1999a), and HFC-134a (Le Neindre

and Garrabos 1999b). A detailed description of the cell and of the method of measurement was published by Le Neindre and Tufeu (1991). The accuracy of thermal conductivity data ($\pm 1.5\%$) was slightly improved over previous estimations by using a quartz transducer and a Keithley nanovoltmeter, for pressure and temperature measurements, respectively. The sample was provided by Elf-Atochem, and its purity was estimated to be better than 99.8% according to the manufacturer's analysis.

3 Dilute-gas thermal conductivity

The results of measurement of the thermal conductivity at atmospheric pressure are listed as a function of temperature in table 1. The experimental data were fitted with a linear equation:

$$\lambda_0/\text{mW m}^{-1} \text{ K}^{-1} = -21.35 + 0.114T/\text{K} . \quad (3)$$

The temperature dependence of the thermal conductivity of the dilute gas can also be represented by an expression derived from the kinetic theory of gases. The thermal conductivity is related to the reduced effective collision cross-sections which contain all the contributions of translational, rotational, vibrational, and electronic degrees of freedom. As there is a lack of reliable experimental data on the vibrational collision number, we used for the calculation of the thermal conductivity in the zero density the practical engineering form:

$$\lambda_0(T) = \frac{0.177568(T/M)^{0.5} C_P^\circ/R}{\sigma^2 \Omega_\lambda^*} , \quad (4)$$

where T is the absolute temperature, M is the molecular weight ($M = 66.05$ g), R is the gas constant, Ω_λ^* is the reduced effective collision cross-section for thermal conductivity, and C_P° is the ideal isobaric heat capacity. The same scaling factors $\varepsilon/k = 249$ K and $\sigma = 0.519$ nm, corresponding to the effective Lennard-Jones 12–6 potential parameters, determined by a least-squares fit of viscosity data at atmospheric pressure by Krauss et al (1996) were used. The ideal specific heat at constant pressure was calculated from the data tabulated by Yokozeki et al (1998):

$$\frac{C_P^\circ}{R} / \text{mol} = \sum_{i=0}^5 c_i (T/\text{K})^i , \quad (5)$$

where

$$\begin{aligned} c_0 &= 3.7871, & c_1 &= 3.584311 \times 10^{-3}, \\ c_2 &= 6.779161 \times 10^{-5}, & c_3 &= -1.312923 \times 10^{-7}, \\ c_4 &= 1.01661 \times 10^{-10}, & c_5 &= -2.9179666 \times 10^{-14}. \end{aligned}$$

Table 1. The thermal conductivity of HFC-152a at atmospheric pressure.

T K	λ mW m ⁻¹ K ⁻¹	T K	λ mW m ⁻¹ K ⁻¹	T K	λ mW m ⁻¹ K ⁻¹
298.38	12.7	377.18	21.73	401.73	24.61
304.58	13.41	384.85	22.36	404.05	24.57
305.37	13.56	385.26	22.66	405.97	24.74
316.39	14.65	387.43	22.88	416.18	26.12
331.30	16.27	391.58	23.13	425.53	27.35
348.60	18.35	392.00	23.52	425.54	27.35
355.24	19.16	393.58	23.56	434.01	28.35
358.28	19.34	396.55	24.04	455.57	30.48
358.34	19.42	397.10	23.74		
367.41	20.67	401.10	24.61		

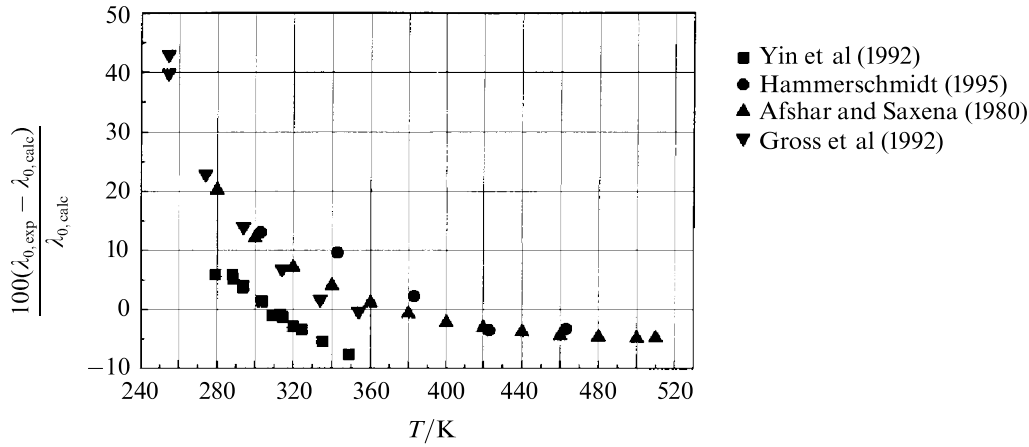


Figure 1. Percentage deviations of experimental data for the thermal conductivity of HFC-152a at atmospheric pressure from the values calculated with the equation $\lambda_0/\text{mW m}^{-1} \text{K}^{-1} = -21.35 + 0.114T/\text{K}$.

The reduced collision integral Ω_λ^* was estimated as a function of reduced temperature, $T^* = kT/\varepsilon$, by using a functional expansion:

$$\Omega_\lambda^* = \sum_{j=1}^3 A_j (1/T^*)^j, \quad (6)$$

where

$$A_1 = 0.444358, \quad B_1 = 0.327867, \quad C_1 = 0.1936835.$$

The deviations of the present experimental thermal conductivity data from their optimal representation by equations (4), (5), (6) are within $\pm 4\%$. The agreement, as expected, is better at high temperature as there is a strong variation of C_p° around room temperature. The agreement with the theory is very satisfactory for viscosity and thermal conductivity in the temperature range where experimental data are available. Equation (3) has a slope larger than the other ones reported in the literature, so our experimental data are generally lower at low temperature and higher at high temperature, with equation (3) intersecting the experimental data of Afshar and Saxena (1980) at 370 K, Yin et al (1992) at 306 K, and Hammerschmidt (1995) near 397 K. Figure 1 shows the deviations between these experimental data and equation (3).

4 Dense-fluid thermal conductivity

In order to determine the excess function or the residual term of the thermal conductivity $\delta\lambda(\rho, T)$, we have performed measurements in the liquid phase and in the supercritical gas phase far away from the critical region along eight quasi-isotherms at 307.5, 321.4, 340.2, 358.5, 378.1, 391.1, 434.0, and 455.4 K. Experimental results are listed in tables 2–5. The residual function for the thermal conductivity has been represented by a six-order polynomial of the form, in the density range 0–1000 kg m^{-3} :

$$\frac{\delta\lambda}{A_c} = \sum_{i=1}^6 b_i \left(\frac{\rho}{\rho_c} \right)^i, \quad (7)$$

where ρ_c is the critical density, and the coefficients b_i are

$$b_1 = 0.43441321, \quad b_2 = -0.004764833,$$

$$b_3 = 1.67482, \quad b_4 = -1.646236,$$

$$b_5 = 0.6179547, \quad b_6 = -0.0774724,$$

and $A_c = 21.6 \text{ mW m}^{-1} \text{K}^{-1}$.

Table 2. Thermal conductivity of HFC-152a along the quasi-isotherms 307.5 K and 321.4 K.

$\frac{p}{\text{MPa}}$	$\frac{T}{\text{K}}$	$\frac{\rho}{\text{kg m}^{-3}}$	$\frac{\lambda}{\text{mW m}^{-1} \text{K}^{-1}}$	$\frac{T}{\text{K}}$	$\frac{\rho}{\text{kg m}^{-3}}$	$\frac{\lambda}{\text{mW m}^{-1} \text{K}^{-1}}$
1	307.65	361.4	97.64			
1.5				321.53	848.3	91.78
2	307.64	888.3	98.73	321.52	850.7	92.42
3	307.63	892.0	99.85	321.51	855.5	93.55
4	307.62	895.6	100.61	321.50	860.0	94.71
5	307.61	899.0	101.38	321.48	864.3	95.73
6	307.60	902.3	102.36	321.47	868.4	96.59
7	307.60	905.5	103.16	321.47	872.3	97.47
8	307.59	908.6	103.97	321.46	876.1	98.19
9	307.58	911.6	104.38	321.45	879.7	99.28
10	307.57	914.5	105.21	321.44	883.3	100.02
11	307.57	917.4	105.84	321.43	886.7	100.77
12	307.56	920.2	106.48	321.42	890.0	101.73
13	307.55	922.9	107.34	321.41	893.2	102.51
14	307.55	925.5	108.00	321.41	896.2	103.10
15	307.54	928.1	108.66	321.40	899.3	103.90
16	307.54	930.6	109.33	321.39	902.2	104.71
17	307.53	933.1	110.02	321.39	905.0	105.33
18	307.52	935.5	110.71	321.38	907.8	105.96
19	307.52	937.9	111.41	321.37	910.5	106.59
20	307.51	940.2	111.88	321.36	913.2	107.44
21	307.51	942.4	112.59	321.36	915.8	108.09
22	307.50	944.7	113.31	321.35	918.3	108.75
23	307.50	946.9	113.80	321.35	920.8	109.19
24	307.49	949.0	114.29	321.34	923.2	109.86
25	307.49	951.1	115.03	321.34	925.6	110.31
26	307.48	953.2	115.53	321.34	927.9	111.00
27	307.48	955.3	116.29	321.33	930.2	111.69
28	307.47	957.3	116.80	321.33	932.5	112.16
29	307.47	959.2	117.32	321.32	934.7	112.63
30	307.47	961.2	117.58	321.32	936.8	113.34
31	307.46	963.1	118.10	321.31	939.0	113.82
32	307.46	965.0	118.63	321.31	941.1	114.31
33	307.46	966.8	119.16	321.30	943.1	114.80
34	307.45	968.6	119.70	321.30	945.1	115.29
35	307.45	970.4	120.24	321.30	947.1	115.79
36	307.44	972.2	120.79	321.29	949.1	116.29
37	307.44	974.0	121.34	321.29	951.0	117.05
38	307.44	975.7	121.90	321.28	952.9	117.56
39	307.43	977.4	122.46	321.28	954.8	118.08
40	307.43	979.1	123.03	321.28	956.6	118.60
41	307.42	980.7	123.60	321.27	958.4	119.12
42	307.42	982.4	124.18	321.27	960.2	119.65
43	307.42	984.0	124.47	321.26	962.0	120.46
44	307.41	985.6	125.06	321.26	963.7	121.00
45	307.42	987.2	124.18	321.25	965.5	121.55
46	307.41	988.7	126.24	321.25	967.2	122.10
47	307.40	990.3	126.85	321.25	968.8	122.66
48	307.40	991.8	127.45	321.24	970.5	123.22
49	307.39	993.3	128.07	321.24	972.1	123.79
50	307.39	994.8	128.69	321.23	973.8	124.36
51	307.39	996.3	129.00	321.23	975.4	125.23
52	307.38	997.7	129.63	321.23	976.9	125.81
53	307.38	999.2	130.26	321.22	978.5	126.40
54	307.37	1000.6	130.91	321.22	980.0	127.00

Table 3. Thermal conductivity of HFC-152a along the quasi-isotherms 340.2 K and 358.5 K.

$\frac{p}{\text{MPa}}$	$\frac{T}{\text{K}}$	$\frac{\rho}{\text{kg m}^{-3}}$	$\frac{\lambda}{\text{mW m}^{-1} \text{K}^{-1}}$	$\frac{T}{\text{K}}$	$\frac{\rho}{\text{kg m}^{-3}}$	$\frac{\lambda}{\text{mW m}^{-1} \text{K}^{-1}}$
2	340.40	790.9	84.45			
3	340.39	798.3	85.72	358.65	726.7	77.23
3.5				358.63	733.1	78.54
4	340.37	805.0	86.74	358.62	738.9	79.29
5	340.36	811.3	87.92	358.61	749.4	80.68
6	340.35	817.1	88.83	358.59	758.6	82.11
7	340.34	822.6	89.77	358.58	766.9	83.26
8	340.32	827.8	91.04	358.57	774.5	84.44
9	340.31	832.7	92.01	358.56	781.5	85.48
10	340.30	837.4	93.01	358.55	788.0	86.54
11	340.29	841.9	94.03	358.54	794.0	87.63
12	340.28	846.1	95.07	358.53	799.7	88.56
13	340.27	850.2	95.78	358.52	805.1	89.51
14	340.26	854.2	96.45	358.51	810.2	90.48
15	340.25	858.0	97.41	358.50	815.1	91.47
16	340.25	862.0	98.15	358.49	819.8	92.49
17	340.24	865.2	98.92	358.49	824.2	93.31
18	340.23	868.6	99.67	358.48	828.5	93.94
19	340.22	871.9	100.45	358.47	832.6	94.79
20	340.22	875.1	101.04	358.47	836.5	95.66
21	340.21	878.3	101.84	358.46	840.3	96.32
22	340.21	881.3	102.44	358.46	844.0	96.99
23	340.20	884.3	103.26	358.45	847.6	97.67
24	340.19	887.2	104.10	358.45	851.0	98.36
25	340.18	890.0	104.73	358.44	854.4	99.29
26	340.18	892.8	105.38	358.43	857.6	100.00
27	340.17	895.4	106.02	358.43	860.8	100.73
28	340.17	898.1	106.90	358.42	863.9	101.46
29	340.16	900.6	107.34	358.42	866.9	102.20
30	340.16	903.2	108.02	358.41	869.8	102.96
31	340.15	905.6	108.70	358.41	872.7	103.46
32	340.15	908.1	109.16	358.41	875.5	104.23
33	340.14	910.4	109.86	358.40	878.2	104.76
34	340.14	912.8	110.56	358.40	880.9	105.28
35	340.13	915.0	111.04	358.39	883.5	105.81
36	340.13	917.3	111.51	358.39	886.1	106.35
37	340.12	919.5	112.24	358.39	888.6	106.89
38	340.12	921.6	112.73	358.38	891.0	107.44
39	340.12	923.8	113.22	358.38	893.4	107.99
40	340.11	925.9	113.72	358.37	895.8	108.55
41	340.11	927.9	114.22	358.37	898.1	109.12
42	340.11	929.9	114.73	358.37	900.4	109.69
43	340.10	931.9	115.24	358.36	902.6	110.26
44	340.10	933.9	115.76	358.36	904.9	110.84
45	340.09	935.8	116.27	358.36	907.0	111.43
46	340.09	937.7	116.80	358.35	909.2	112.03
47	340.09	939.6	117.33			
48	340.08	941.4	117.87			
49	340.08	943.3	118.41			
50	340.08	945.1	118.95			
51	340.07	946.9	119.50			
52	340.07	948.6	120.05			
53	340.07	950.4	120.62			
54	340.06	952.1	121.18			
55	340.06	953.8	121.75			

Table 4. Thermal conductivity of HFC-152a along the quasi-isotherms 378.1 K and 391.1 K.

$\frac{p}{\text{MPa}}$	$\frac{T}{\text{K}}$	$\frac{\rho}{\text{kg m}^{-3}}$	$\frac{\lambda}{\text{mW m}^{-1} \text{K}^{-1}}$	$\frac{T}{\text{K}}$	$\frac{\rho}{\text{kg m}^{-3}}$	$\frac{\lambda}{\text{mW m}^{-1} \text{K}^{-1}}$
4	378.19	624.3	70.08			
4.5	378.17	641.8	71.46			
5	378.16	655.2	72.53			
5.5	378.15	666.3	73.39			
6	378.13	675.8	74.40	391.18	588.5	68.03
7	378.11	691.9	76.09	391.15	622.7	70.25
8	378.09	705.1	77.44	391.13	645.7	72.30
9	378.08	716.6	78.84	391.11	663.5	73.96
10	378.06	726.7	80.00	391.10	678.2	75.52
11	378.05	735.8	81.34	391.09	690.8	76.77
12	378.04	744.0	82.26	391.08	701.8	78.07
13	378.03	751.6	83.35	391.06	711.7	79.41
14	378.02	758.7	84.32	391.06	720.7	80.20
15	378.01	765.2	85.30	391.05	728.9	81.41
16	377.99	771.4	86.31	391.04	736.5	82.65
17	377.99	777.2	87.17	391.03	743.6	83.72
18	377.99	782.7	88.05	391.02	750.2	84.59
19	377.97	788.0	88.94	391.02	756.4	85.48
20	377.96	793.0	89.86	391.01	762.3	86.40
21	377.95	797.7	90.79	391.00	767.9	87.32
22	377.94	802.3	91.74	391.00	773.2	88.27
23	377.94	806.7	92.51	390.99	778.3	89.24
24	377.93	810.9	93.30	390.99	783.1	89.74
25	377.92	815.0	94.10	390.98	787.8	90.49
26	377.92	818.9	94.91	390.98	792.2	90.99
27	377.91	822.7	95.53	390.97	796.5	91.76
28	377.91	826.4	96.37	390.97	800.7	92.55
29	377.90	830.0	97.01	390.96	804.7	93.34
30	377.89	833.5	97.87	390.96	808.6	93.88
31	377.89	836.8	98.53	390.95	812.3	94.98
32	377.88	840.1	99.20	390.95	816.0	95.82
33	377.88	843.3	99.87	390.95	819.5	96.38
34	377.87	846.4	100.56	390.94	822.9	96.96
35	377.87	849.4	101.02	390.94	826.3	97.83
36	377.86	852.4	101.72	390.93	829.5	98.72
37	377.86	855.3	102.43	390.93	832.7	99.32
38	377.86	858.1	102.91	390.93	835.8	99.93
39	377.85	860.8	103.64	390.92	838.8	100.55
40	377.85	863.5	104.13	390.92	841.8	101.17
41	377.84	866.2	104.63	390.92	844.7	101.80
42	377.84	868.8	105.12			
43	377.84	871.3	105.88			
44	377.83	873.8	106.39			
45	377.83	876.2	106.91			
46	377.83	878.6	107.43			

Figure 2 shows the deviations between experimental data reported in this work and equation (2) as a function of density. The data of Assael et al (1993) are within 1.5% and 2% lower than the corresponding values calculated by equation (2). The comparison with the data of Gurova et al (1999) which cover the same density range, but at lower temperature, shows a systematic deviation. Their data are lower, and the deviation from equation (2) ranges from -4% at 293 K, -2.8% at 272 K, -5.2% at 249 K, -4.9% at 223 K, to -3.4% at 212 K. There is also a smaller systematic deviation between equation (2) and the data of Kim et al (1993) which is of the order of -2.3% at 223 K,

Table 5. Thermal conductivity of HFC-152a along the quasi-isotherms 434.0 K and 455.4 K.

$\frac{p}{\text{MPa}}$	$\frac{T}{\text{K}}$	$\frac{\rho}{\text{kg m}^{-3}}$	$\frac{\lambda}{\text{mW m}^{-1} \text{K}^{-1}}$	$\frac{T}{\text{K}}$	$\frac{\rho}{\text{kg m}^{-3}}$	$\frac{\lambda}{\text{mW m}^{-1} \text{K}^{-1}}$
0.1	434.02	1.84	28.36	455.58	1.75	30.48
0.5	434.01	9.41	28.60	455.60	8.92	30.75
1	434.00	19.38	28.89	455.56	18.3	30.98
1.5	433.99	29.98	29.14	455.55	28.1	31.30
2	433.98	41.31	29.49	455.54	38.5	31.56
2.5	433.97	53.47	29.80	455.54	49.4	31.88
3	433.96	66.59	30.12	455.53	61.1	32.40
3.5	433.96	80.86	30.44	455.52	73.4	32.55
4	433.94	96.49	31.10	455.50	86.5	33.13
4.5	433.54	114.01	31.72	455.48	100.6	33.90
5	433.50	133.32	33.28	455.46	115.7	34.78
6	433.45	179.61	35.72	455.42	149.3	36.74
7	433.36	239.50	40.34	455.36	188.3	39.41
8	433.24	313.54	49.69	455.30	233.1	43.16
9	433.18	388.45	56.03	455.23	282.4	48.49
10	433.15	448.43	59.63	455.18	333.0	52.68
11	433.13	492.52	62.37	455.14	380.3	56.39
12	433.11	525.70	64.64	455.12	421.7	59.30
13	433.10	551.84	67.35	453.78	462.0	61.55
14	433.09	573.26	68.90	453.77	490.8	63.55
15	433.08	591.37	70.25	453.76	515.2	64.60
16	433.07	607.05	71.94	453.74	536.2	67.27
17	433.06	620.86	73.11	453.73	554.4	68.44
18	433.06	633.21	74.32	453.72	570.5	70.16
19	433.05	644.38	75.57	453.72	584.9	71.18
20	433.04	654.58	76.54	453.71	597.9	72.49
21	433.04	663.98	77.86	453.70	609.7	73.58
22	433.04	672.69	78.88	453.70	620.5	74.98
23	433.03	680.81	79.93	453.69	630.5	76.14
24	433.03	688.41	80.65	453.68	639.8	77.33
25	433.02	695.57	81.74	453.68	648.5	78.26
26	433.02	702.34	82.87	453.68	656.7	79.20
27	433.02	708.74	83.64	453.67	664.3	79.84
28	433.01	714.83	84.42	453.67	671.6	80.49
29	433.01	720.64	85.21	453.67	678.4	81.15
30	433.01	726.19	86.03	453.66	685.0	81.83
31	433.00	731.51	86.85	453.66	691.2	82.86
32	433.00	736.60	87.69	453.66	697.1	83.56
33	433.00	741.50	88.55	453.65	702.8	84.27
34	432.99	746.23	89.43	453.65	708.3	85.36
35	432.99	750.78	90.32	453.64	713.5	86.48
36	432.99	755.18	90.77	453.64	718.6	87.25
37	432.99	759.43	91.23	453.64	723.4	88.02
38	432.99	763.54	91.69	453.63	728.1	88.81
39	432.99	767.53	92.16	453.63	732.6	89.62
40	432.99	771.41	92.63	453.63	737.0	90.43

−2.6% at 248 K, −2.6% at 273 K, −2% at 298 K, and −1.2% at 328 K. The agreement between equation (2) and the data of Gross et al (1992) is good and the mean deviations are respectively 1.7% at 263 K, 1.6% at 273 K, 0.6% at 283 K, 0.7% at 293 K, 0.8% at 303 K, 0.7% at 313 K, 0.6% at 323 K, 0.6% at 333 K, 0.8% at 343 K, 0.7% at 353 K, and 0.1% at 363 K. The mean percentage deviations of our data from the data of Yata et al (1992) are 1.3% at 265 K, −0.6% at 282 K, −2.9% at 303 K, −5.8% at 323 K, and −7.5% at 342 K. The experimental data of Grebenkov et al (1994) are systematically lower. The mean

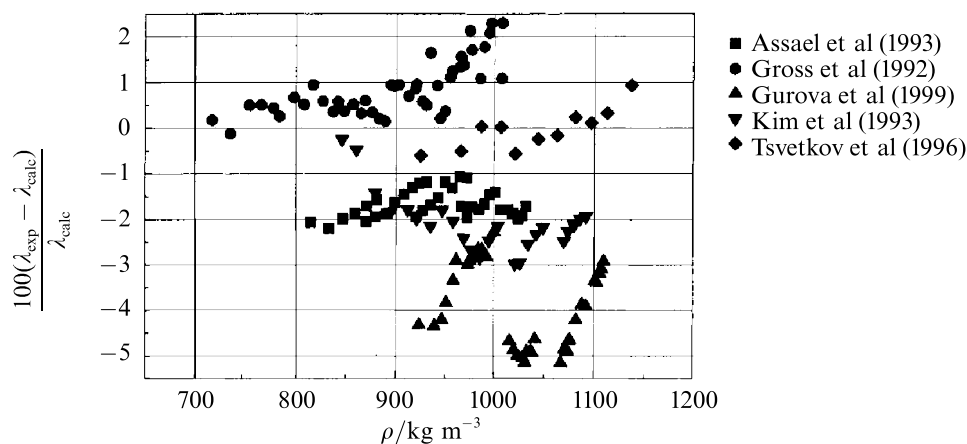


Figure 2. Percentage deviations of the experimental data for the thermal conductivity of HFC-152a from the corresponding values calculated with equation (2) containing the background term.

deviations with respect to equation (2) are -4% at 294 K, -4.6% at 300 K, -4.8% at 321 K, -6.2% at 341 K, -6.7% at 362 K, -8.0% at 381 K, and -7.7% at 398 K. The mean deviations of the experimental results of Tsvetkov et al (1996), who performed experiments from 189 K and 299 K along the 8 MPa isobar, from equation (2) are within $\pm 0.4\%$.

5 Conclusion

New measurements of the thermal conductivity of HFC-152a are presented in the temperature range 300 to 455 K along eight quasi-isotherms and at pressures up to 55 MPa, with an estimated uncertainty of $\pm 1.5\%$. An equation was fitted which can be used to calculate the thermal conductivity from 300 to 455 K with an uncertainty of $\pm 1.5\%$. The deviations of the low-temperature data of Assael et al (1993), Kim et al (1993), Tsvetkov et al (1996), and Gross et al (1992) agree with the correlation to within their respective experimental uncertainties. It is obvious that in the critical region an additional functional form must be added to take into account the critical enhancement.

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