Thermal Conductivity of Refrigerants in a Wide Range of Temperature and Pressure

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Thermal conductivities of refrigerant 12 (dichlorodifluoromethane), refrigerant 113 (1,1,2-trichloro-1,2,2-trifluoroethane), refrigerant 114 (1,2-dichloro-1,1,2,2-tetrafluoroethane), and refrigerant C318 (perfluorocyclobutane) were critically evaluated and correlated on the basis of a comprehensive literature survey. Recommended values were established for a wide range of temperatures and pressures, extending up to three times the critical density and excluding the critical region. Using the residual concept, a dilute-gas function and an excess function of simple form were developed for each refrigerant. The average accuracy obtained is $\sim 6\%$.

Key words: correlation; dichlorodifluoromethane; 1,2-dichloro-1,1,2,2-tetrafluoroethane; dilute-gas function; evaluation; excess function; fluid state; perfluorocyclobutane; recommended values; refrigerant 12; refrigerant 113; refrigerant 114; refrigerant C318; thermal conductivity; 1,1,2-trichloro-1,2,2-trifluoroethane.

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1. Introduction

Refrigerant 12 (dichlorodifluoromethane), refrigerant 113 (1,1,2-trichloro-1,2,2-trifluoroethane), refrigerant 114 (1,2-dichloro-1,1,2,2-tetrafluoroethane), and refrigerant C318 (perfluorocyclobutane) play, among others, an important role as working fluids in refrigeration and other technologies. Among these technologies are the conversion of waste heat by means of Organic-Rankine-Cycles, heat transformation and heat pumps. It is evident that the thermophysical properties of the working fluids in such processes should be known to a sufficiently high degree of accuracy. However, not only accurate experimental data are needed; equally important are correlation functions for process simulation and apparatus design in a wide range of fluid states. Whereas the thermal and caloric properties of the

TABLE 1. Specific data.

	Refr. 12	Refr. 113	Refr. 114	Refr. C318
Formula[a]	CCl_2F_2	CCl_2FCClF_2	$CClF_2CClF_2$	C_4F_8
M_r	120.914	187.376	170.922	200.031
p_c	41.31	33.79	33.93	27.84
T_c	385.15	487.25	418.85	388.46
T_b	243	320.42	275.44	266.88
T_t	115.15	236.55	179	232.96

[a] M_r: Molecular weight.
p_c: Critical pressure in bar.
T_c: Critical temperature in K.
T_b: Normal boiling temperature in K.
T_t: Triple point temperature in K.

refrigerants are known to some extent and thermal equations of state have been established,[1,2] the knowledge about transport properties, especially the thermal conductivity, is limited.

Therefore, it seems to be necessary to review critically the existing data in order to provide the designer of processes and apparatus as well as the user of computer codes with reliable tables and correlation functions of thermal conductivity.

2. Data Survey

This data evaluation is based on ~170 publications. Finally 45 publications for refrigerant 12, 34 publications for refrigerant 113, 23 publications for refrigerant 114, and 16 publications for refrigerant C318 could be used because in these papers data in numerical form as tables and correlation functions are published.

Most of them report thermal conductivities of liquids at the saturation state or at atmospheric pressure. Apart from this, measurements in the dilute gaseous state and on the pressure dependence in the liquid state are available. Very rare are measurements in the dense gaseous state. Only a few experimental data sets exist in this region for refrigerant 12. Whereas for refrigerant C318 one pressure-dependent series of measurements in the gaseous state could be found, it seems that the thermal conductivity of refrigerant 113 and refrigerant 114 has not been measured yet in the dense gaseous region.

Some characteristic properties of these refrigerants are compiled in Table 1.

3. Correlation Procedure

According to the residual concept, the thermal conductivity $\lambda(\rho,T)$ of a pure fluid at a given density ρ and temperature T can be considered to be composed of a dilute-gas term $\lambda_0(T)$ which depends on temperature only, an excess term $\Delta\lambda_R(\rho,T)$ which accounts for the density or pressure dependence, respectively, and a contribution $\Delta\lambda_c(\rho,T)$ which represents the so-called critical enhancement in a region extending around the vapor-liquid critical point.[3-5] Hence,

$$\lambda(\rho,T) = \lambda_0(T) + \Delta\lambda_R(\rho,T) + \Delta\lambda_c(\rho,T) . \quad (1)$$

This correlation technique requires a thermal equation of state to convert the pressure and temperature coordinates of the measurements into densities. Using Bender's equation of state, which was applied to many substances by Polt,[1] the available experimental thermal conductivity data could be fitted in the whole pressure and temperature range.

The representation of the thermal conductivity $\Delta\lambda_R \times(\rho,T)$ as a function of density and temperature did not show any significant splitting of the isotherms for each refrigerant up to three times the critical density. Therefore, as for many other substances, a dependence on temperature can be neglected.[6,7] The error due to this simplification lies approximately within the uncertainty of the measurements.

Because no adequate experimental data in the critical region were available, the critical enhancement term $\Delta\lambda_c(\rho,T)$ was not considered here.

The aforementioned facts lead to the simplified form of Eq. (1):

$$\lambda(\rho,T) = \lambda_0(T) + \Delta\lambda_R(\rho) . \quad (2)$$

This equation was used to calculate the three-dimensional surfaces of the thermal conductivity in the temperature, pressure plane and the corresponding data tables compiled in Appendix C. In the following the dilute-gas function and the excess function of each refrigerant will be discussed in detail.

4. Dilute-Gas Function

Following the residual concept, first a dilute-gas function must be found. It turned out that for each refrigerant the dependence of the thermal conductivity λ_0 (in mW/m K) on temperature T (in K) could be represented by a straight line:

$$\lambda_0(T) = \xi(C_1 + C_2T) . \quad (3)$$

The adjustable specific coefficients C_1 (dimensionless) and C_2 (in 1/K) are compiled in Table 2 for each refrigerant

TABLE 2. Dilute-gas function, Eq. (3).

	Refr. 12	Refr. 113	Refr. 114	Refr. C318
C_1	− 2.849 787 8	− 4.039 109 2	− 4.414 193 4	− 7.708 139 2
C_2	10.338 094	17.894 056	16.535 328	24.281 282
ξ/mW m^{-1} K^{-1}	1.9	1.28	1.38	1.13
T Range/K	200–600	240–490	260–500	240–450
Error	1%	3%	1%	1%

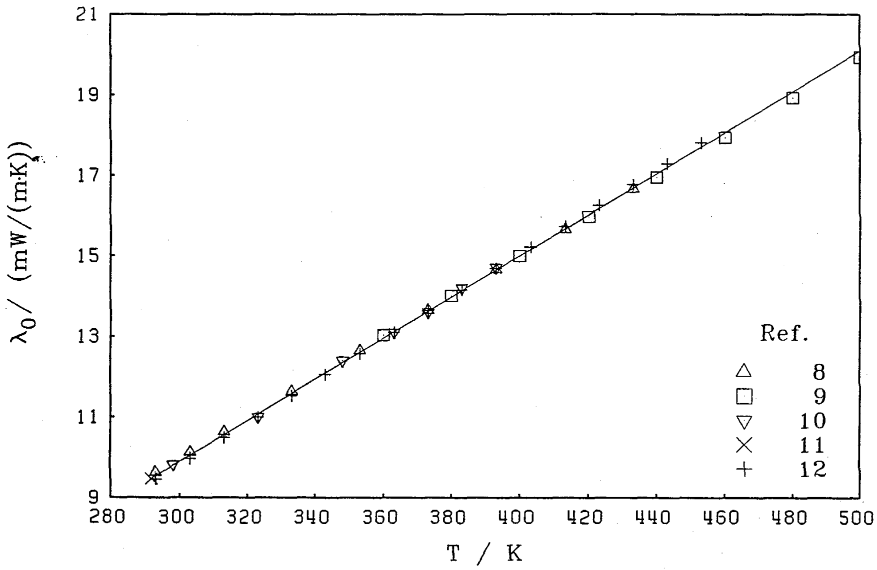

FIG. 1. Dilute-gas function of refrigerant 12 together with the selected experimental data.

together with the specific group

$$\xi = (R^{5/6}p_c^{2/3})/(T_c^{1/6}M^{1/2}N_A^{1/3}), \qquad (4)$$

(in mW/m K) which is derived from a dimensional analysis. Herein R represents the universal gas constant and N_A the Avogadro number. The lower and upper temperature limits of the validity range (T-Range in Table 2) are not strictly based on measurements. However, the straight-line form of Eq. (3) allows an extrapolation beyond the limits where experimental data exist. The last line of Table 2 (Error) shows the estimated inaccuracy of the correlation. Additionally, in Appendix A other available data sets are compared with the actual dilute-gas functions. This is done by means of departure plots.

4.1. Refrigerant 12

The thermal conductivity of refrigerant 12 in the dilute-gas state has been measured quite often. Finally, the five data sets of Geller *et al.*,[8] Venart *et al.*[9] (high-temperature data were omitted), Makita *et al.*,[10] Peters *et al.*[11] and Tsvetkov *et al.*[12] (low-temperature data were omitted) were selected. They are plotted in Fig. 1 together with the dilute-gas function [Eq. (3)], represented by a straight line.

The corresponding deviations are plotted in Fig. 2. It is

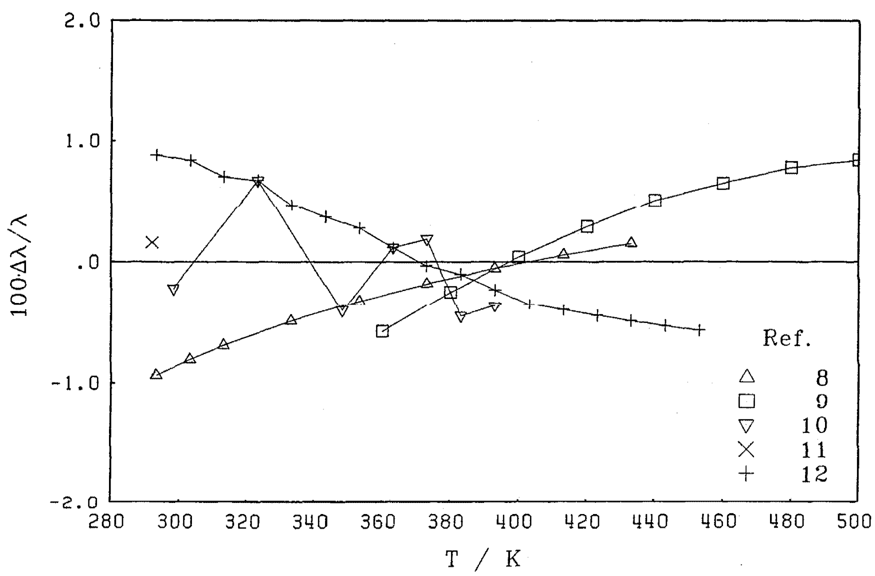

FIG. 2. Relative deviations of the dilute-gas function of refrigerant 12 from the selected experimental data.

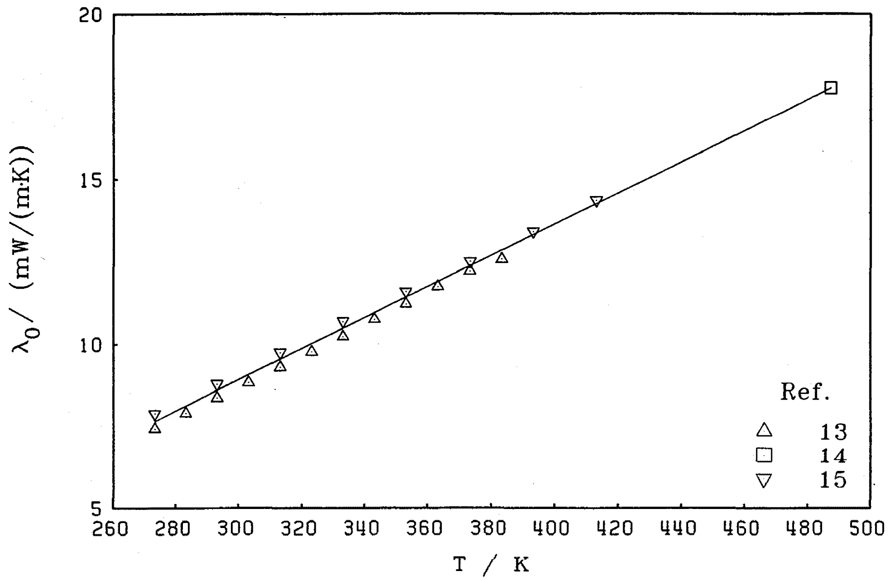

FIG. 3. Dilute-gas function of refrigerant 113 together with the selected experimental data.

obvious that the data could be fitted with an uncertainty of less than 1%.

4.2. Refrigerant 113

Only three publications report experimental data of the thermal conductivity of refrigerant 113 in the dilute-gas state. The data of Cherneeva[13] and Tsvetkov *et al.*[14,15] were used to establish the dilute-gas function and are plotted in Fig. 3.

The measurements of Cherneeva[13] and Tsvetkov,[15] covering the same temperature range, deviate systematically as can be seen in Fig. 4. For this reason no better accuracy than 3% could be assigned.

4.3. Refrigerant 114

In case of refrigerant 114, five experimental data sets in the dilute-gas region could be found. Four of them, namely those of Keyes[16] (one high-temperature point was omitted), Dijkema *et al.*,[17] and Tsvetkov *et al.*[14,15] were used for the correlation. They are shown in Fig. 5 together with the dilute-gas function. The corresponding deviations are plotted in Fig. 6. The fit yielded an overall uncertainty of ~1%.

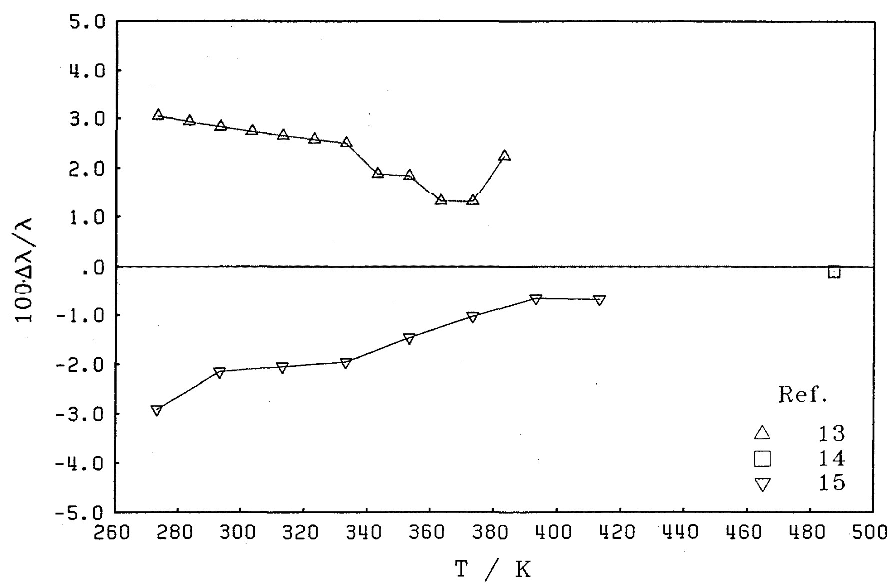

FIG. 4. Relative deviations of the dilute-gas function of refrigerant 113 from the selected experimental data.

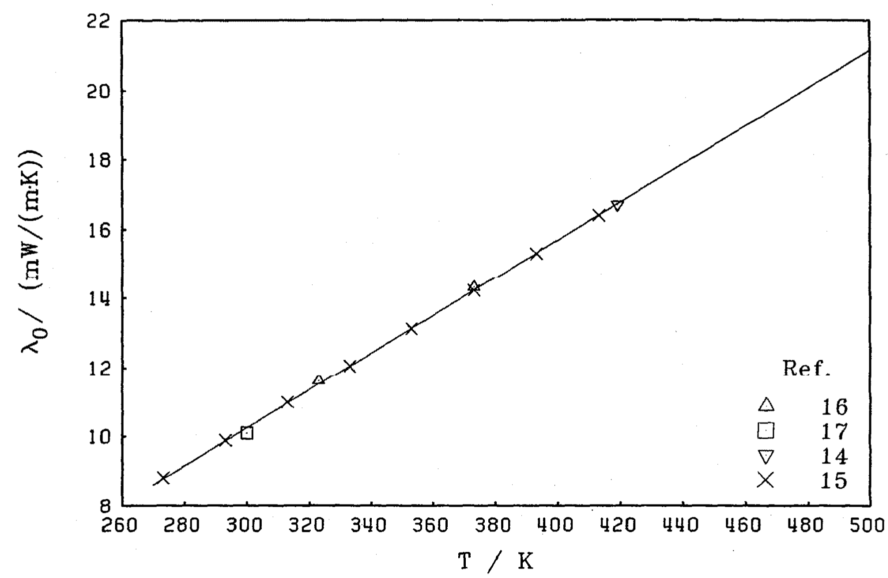

FIG. 5. Dilute-gas function of refrigerant 114 together with the selected experimental data.

4.4. Refrigerant C318

Only two experimental thermal conductivity data sets in the dilute-gas region are available for refrigerant C318. In this case the data of Geller *et al.*[19] were selected for the correlation and are plotted together with the dilute-gas function in Fig. 7.

The departure plot in Fig. 8 shows that the data could be fitted within 1%.

5. Excess Function

The excess thermal conductivity $\Delta\lambda_R$ can be calculated by subtracting the corresponding dilute-gas value λ_0 from the actual thermal conductivity λ at the same temperature T. The excess values found in this way are, in case of the refrigerants considered here, only a function of density. The dependence of $\Delta\lambda_R$ (in mW/m K) on density ρ (in mol/l) could be represented by a simple polynomial:

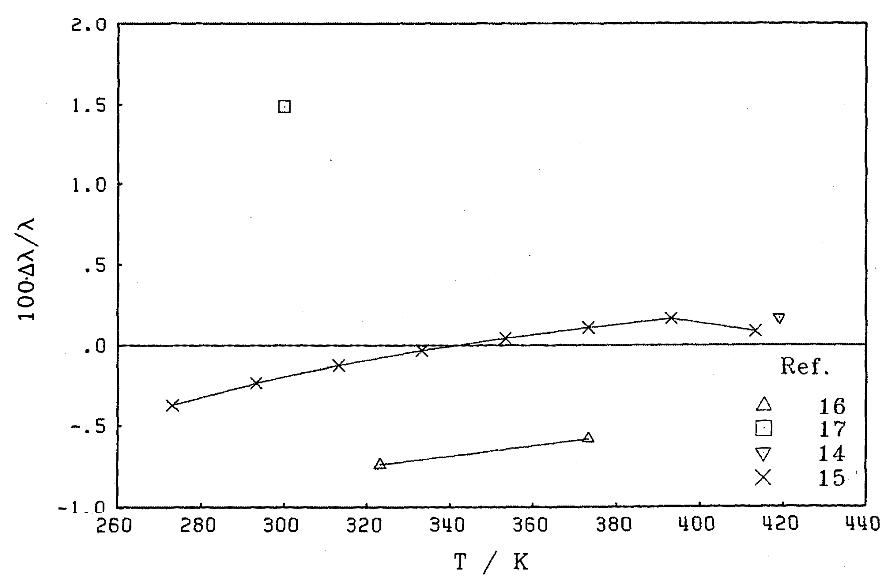

FIG. 6. Relative deviations of the dilute-gas function of refrigerant 114 from the selected experimental data.

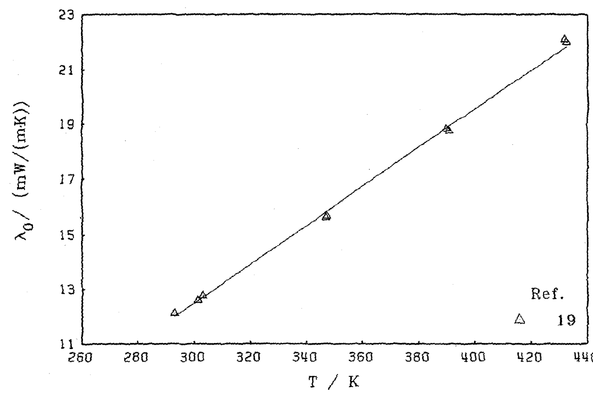

FIG. 7. Dilute-gas function of refrigerant C318 together with the selected experimental data.

$$\Delta\lambda_R(\rho) = \xi \sum_{i=1}^{n} D_i(\rho/\rho_c)^i. \tag{5}$$

Herein ξ represents the same reduction factor already used for the dilute-gas function. It is compiled in Table 3 together with the critical density ρ_c (in mol/l) and the adjustable specific coefficients D_i (dimensionless) for each refrigerant. The range of validity (ρ-range) is limited and it is obvious that there are data missing in the intermediate density regions. The pressure and temperature ranges where Eq. (5) is valid can be deduced from the limits of the data tables in Appendix C. The estimated inaccuracy of the correlations is listed in the last line of Table 3 (Error). Graphic comparisons with other data sets are compiled in Appendix B.

5.1. Refrigerant 12

Among the refrigerants considered here the thermal conductivity of refrigerant 12 has been investigated most of-

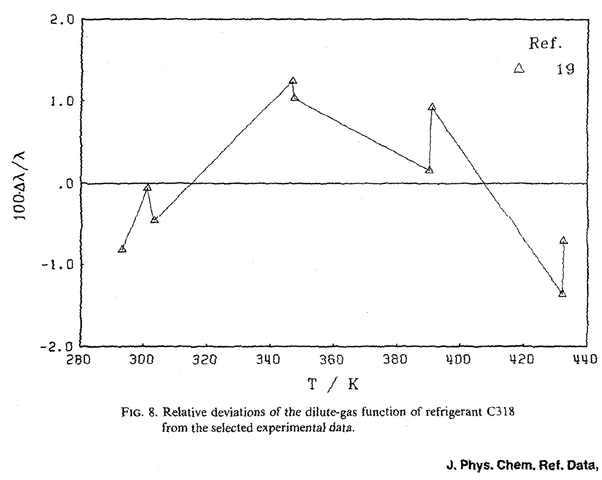

FIG. 8. Relative deviations of the dilute-gas function of refrigerant C318 from the selected experimental data.

TABLE 3. Excess function, Eq. (5).

	Refr. 12	Refr. 113	Refr. 114	Refr. C318
D_1	0.824 543 02	4.624 403 4	7.142 954 5	5.403 515 0
D_2	14.887 641	− 1.177 209 8	− 2.745 380 6	− 1.493 600 0
D_3	− 13.347 132	2.327 765 8	2.453 072 0	3.042 681 2
D_4	5.511 817 7	...	...	...
D_5	− 0.672 773 83	...	...	...
ξ/mW m^{-1} K^{-1}	1.9	1.28	1.38	1.13
ρ_c/mol l^{-1}	4.62	3.07	3.4	3.1
ρ Range/mol l^{-1}	0–13.5	5.5–9.5	6–9	0–0.6; 6–9
Error	6%	5%	5%	4%

ten. In Fig. 9 the seven experimental data sets used for the correlation are marked by symbols. In the low- and intermediate density range data of Venart *et al.*[9] were used, completed by the data sets of Yata *et al.*,[20] Geller *et al.*,[8] Tauscher,[21] Djalalian,[22] Tsvetkov *et al.*,[23] and Sadykov *et al.*[24] at higher densities.

Venart *et al.*[9] observed a critical enhancement of the thermal conductivity at temperatures between 300 and 400 K but excluded these data from further representation of their results. Nevertheless, a slight deformation of the excess function [Eq. (5)], represented by a solid line, is obvious between the density limits of 2 and 6 mol/*l* in Fig. 9. Therefore a polynomial of fifth degree was used to represent the excess thermal conductivity in the whole density range up to three times the critical density.

The quality of the fit can be estimated from Fig. 10 where the deviations are scattering in a range of about ± 6%. This relatively high scatter in comparison to the other refrigerants is due to the aforementioned critical region effect and the discrepancies between the data of Venart *et al.*[9] and Yata *et al.*[20] at high densities, although both used a transient hot-wire device for their measurements.

5.2. Refrigerant 113

For refrigerant 113 only thermal conductivity data in the liquid region were found within a density range of 5.5 to 9.5 mol/*l*. The measurements of Yata *et al.*,[20] Braun *et al.*,[25] Fischer,[26] Slyusarev,[27] Tauscher,[21] and Kitazawa *et al.*[28] were used to fit the coefficients of the excess function, which is a polynomial of third degree. It is drawn through the origin in Fig. 11, but must not be used outside the density range mentioned above.

The data could be fitted within an uncertainty of 5% as can be seen from Fig. 12.

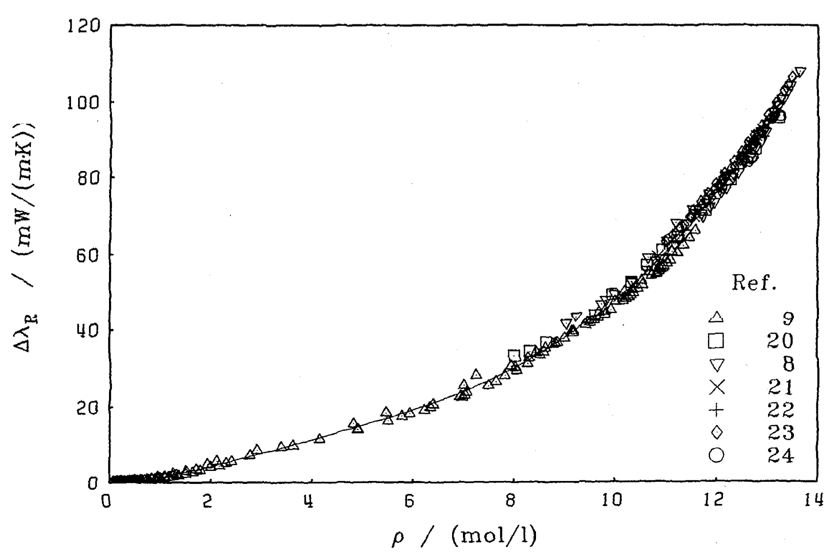

FIG. 9. Excess function of refrigerant 12 together with the selected experimental data.

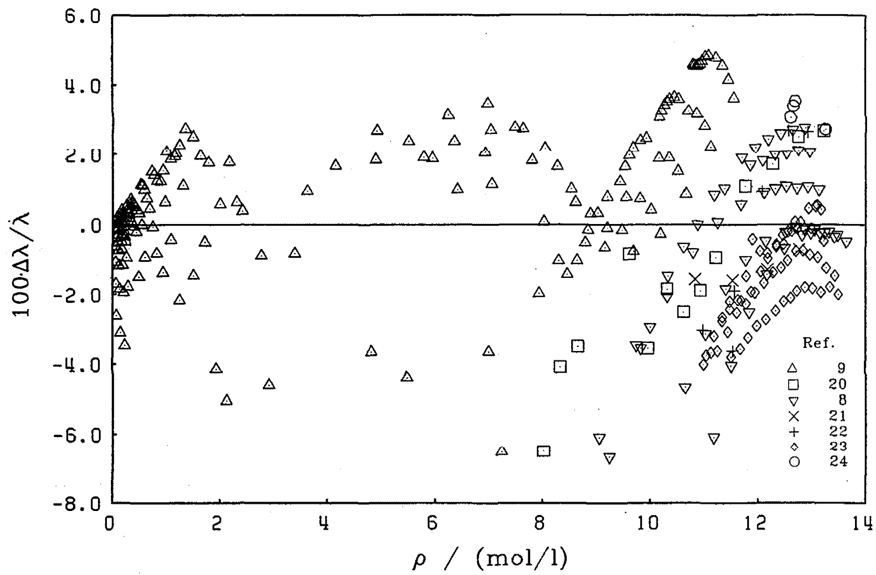

FIG. 10. Relative deviations of the excess function of refrigerant 12 from the selected experimental data.

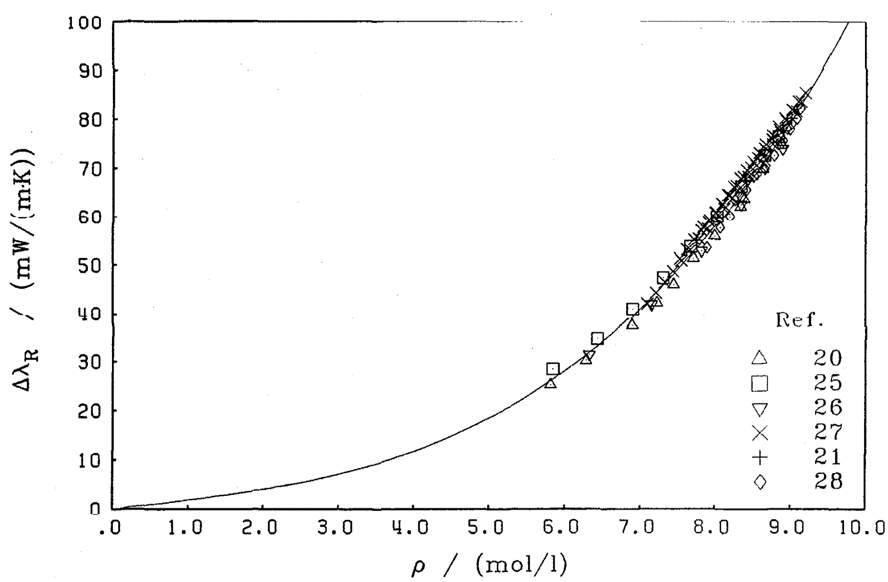

FIG. 11. Excess function of refrigerant 113 together with the selected experimental data.

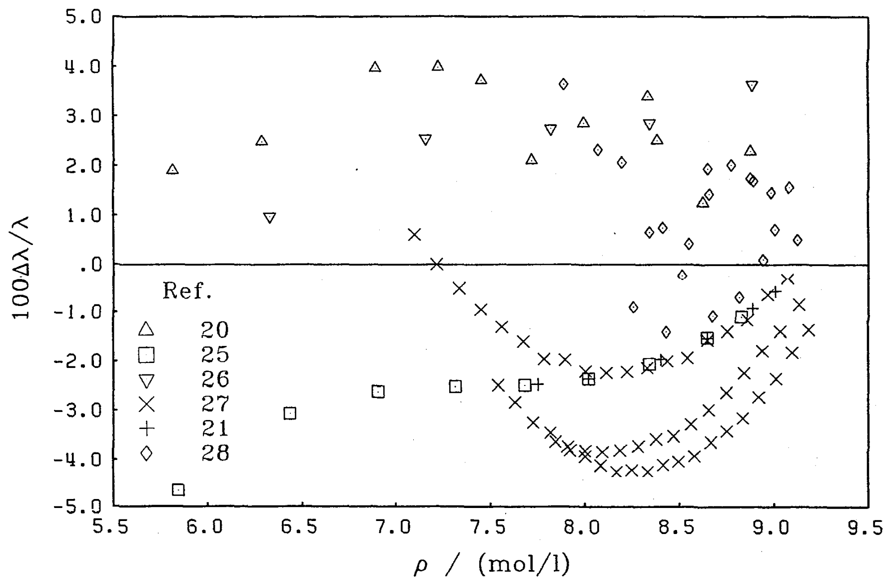

FIG. 12. Relative deviations of the excess function of refrigerant 113 from the selected experimental data.

5.3. Refrigerant 114

The situation for refrigerant 114 is very similar to that of refrigerant 113. Using the data of Yata *et al.*,[20] Slyusarev,[27] Kesselman *et al.*,[29] Tauscher,[21] and Powell *et al.*[30,31] a density range of 6 to 9 mol/*l* could be covered. These data sets are plotted in Fig. 13 together with the excess function, a polynomial of third degree.

In Fig. 14 the corresponding deviations of the fit are plotted. The correlation yielded an uncertainty of ~5%.

5.4. Refrigerant C318

The most comprehensive investigation of the pressure dependence of the thermal conductivity of refrigerant C318

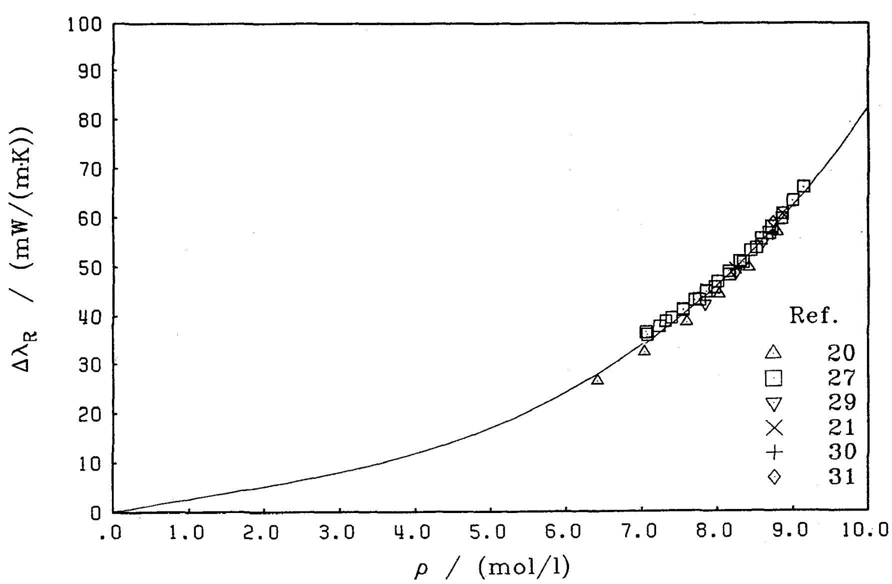

FIG. 13. Excess function of refrigerant 114 together with the selected experimental data.

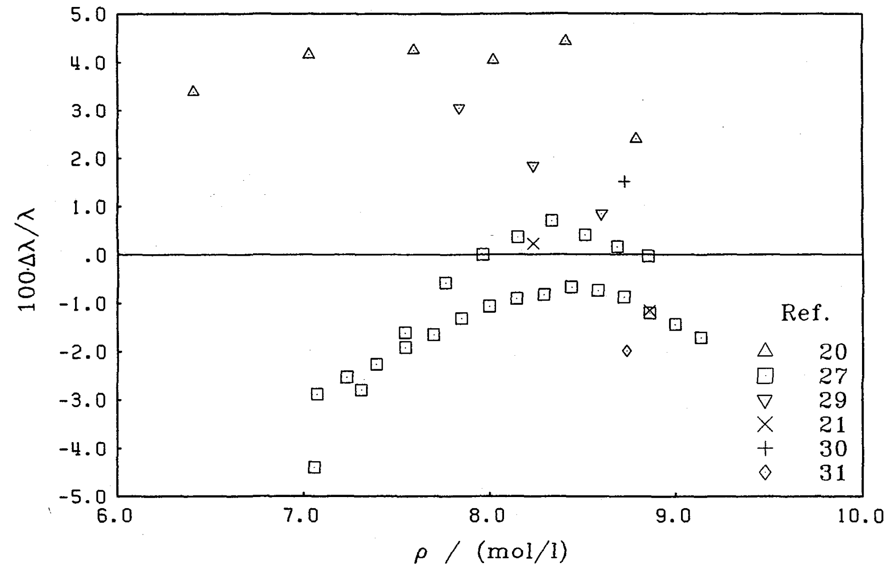

FIG. 14. Relative deviations of the excess function of refrigerant 114 from the selected experimental data.

has been carried out by Geller *et al.*[19] His data are the only experimental data in the dense gaseous state and in the critical region.

The measured isobars exhibit an anomalous enhancement in a density range of about 0.6 to 5 mol/*l*, extending around the critical point. Because no other experimental values far away from the critical point and hence free of a critical enhancement could be found, this region had to be omitted. Therefore, one observes a gap in the representation of the excess function shown in Fig. 15.

The low-density range up to 0.6 mol/*l* and the high-density range of 6 to 9 mol/*l* could be combined using a polynomial of third degree. In the low-density range only the measurements of Geller *et al.*[19] were available whereas in the high-density range the data of Kesselman *et al.*,[32] Tauscher,[21] and Powell *et al.*[30] were used. For better distinc-

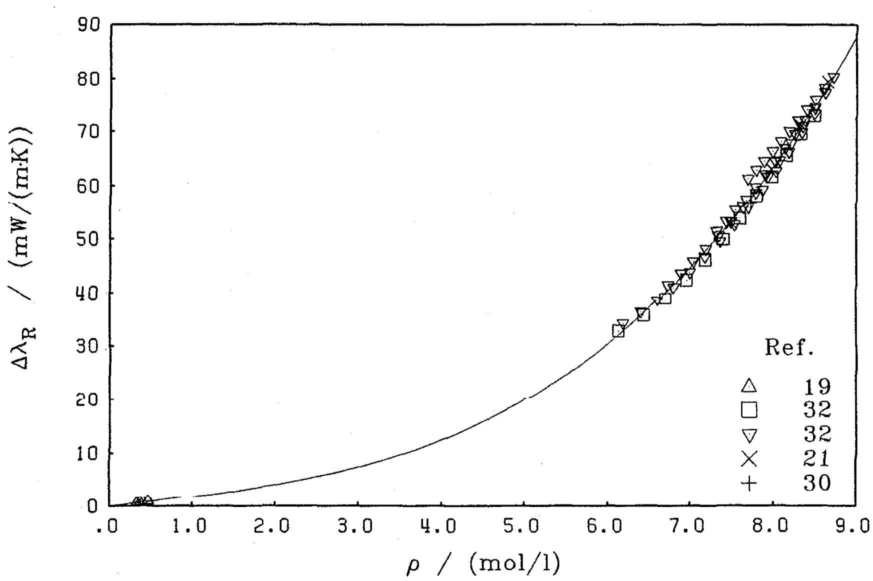

FIG. 15. Excess function of refrigerant C318 together with the selected experimental data.

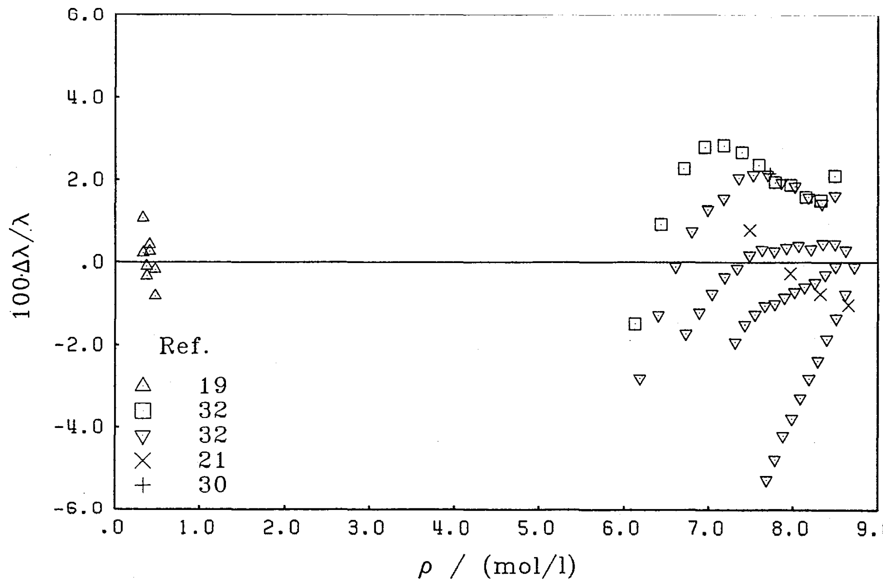

FIG. 16. Relative deviations of the excess function of refrigerant C318 from the selected experimental data.

tion from the high-pressure data of Kesselman *et al.*[32] his saturated-liquid data were marked by squares.

The departure plot in Fig. 16 demonstrates that the low-density data of Geller *et al.*[19] show a scatter of 1%, and the error amounts to ~4% at higher densities.

6. Conclusions

Based on the most reliable literature data, a comprehensive set of thermal conductivities of refrigerant 12, refrigerant 113, refrigerant 114, and refrigerant C318 were established by means of the residual concept. This implies that for each refrigerant a dilute-gas function and an excess function were formulated. These functions are of simple form. They are an important instrument in process-simulation runs and apparatus design. The overall average accuracy that could be obtained is ~6%.

New measurements are necessary to fill the data gaps in the dilute-gas region and especially in the dense-gas region, all the more, as only four of the existing series of measurements[9,20,28,57] have been carried out using a transient hot-wire device, the most precise instrument to date.

7. Acknowledgments

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APPENDIX A

Comparison of other literature data with the dilute gas function.

a. Refrigerant 12.

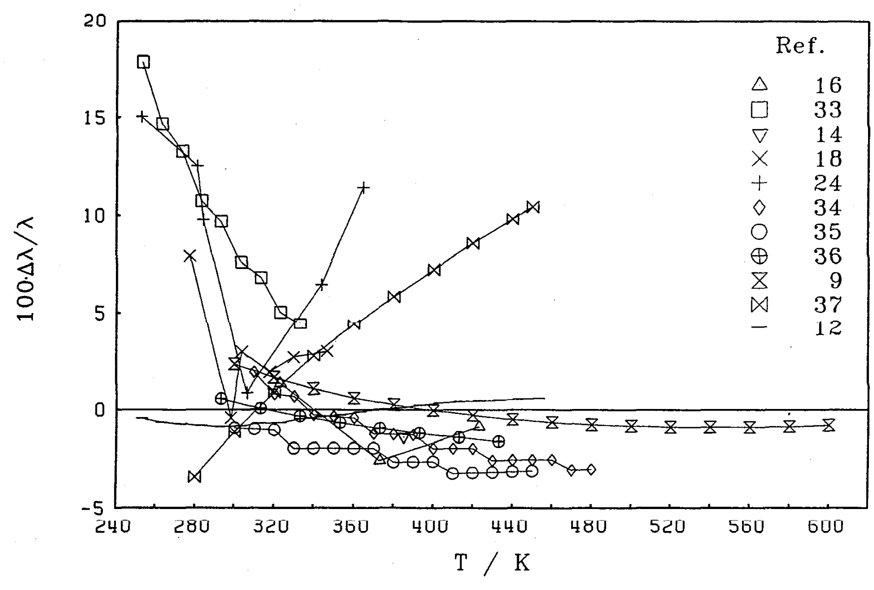

FIG. A1. Relative deviations of experimental data from the dilute-gas function of refrigerant 12.

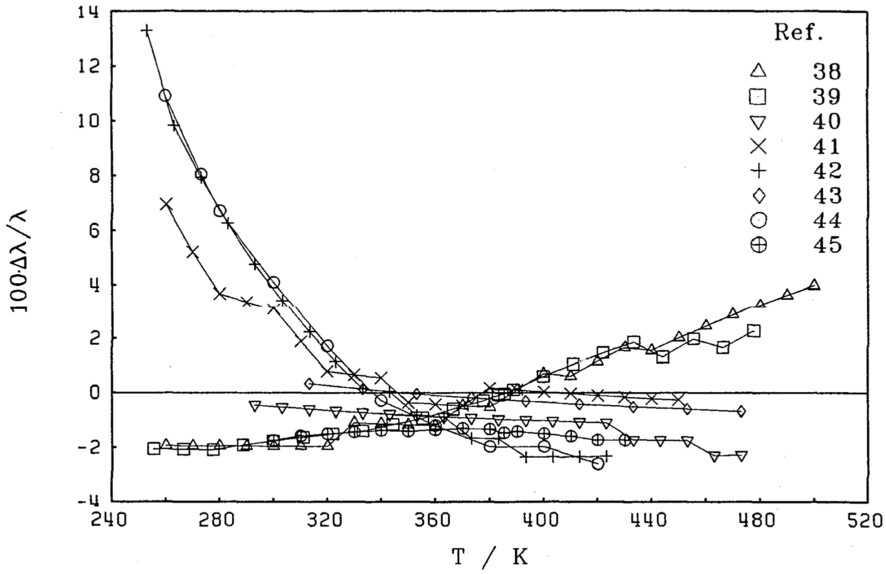

FIG. A2. Relative deviations of other compilations from the dilute-gas function of refrigerant 12.

b. Refrigerant 113.

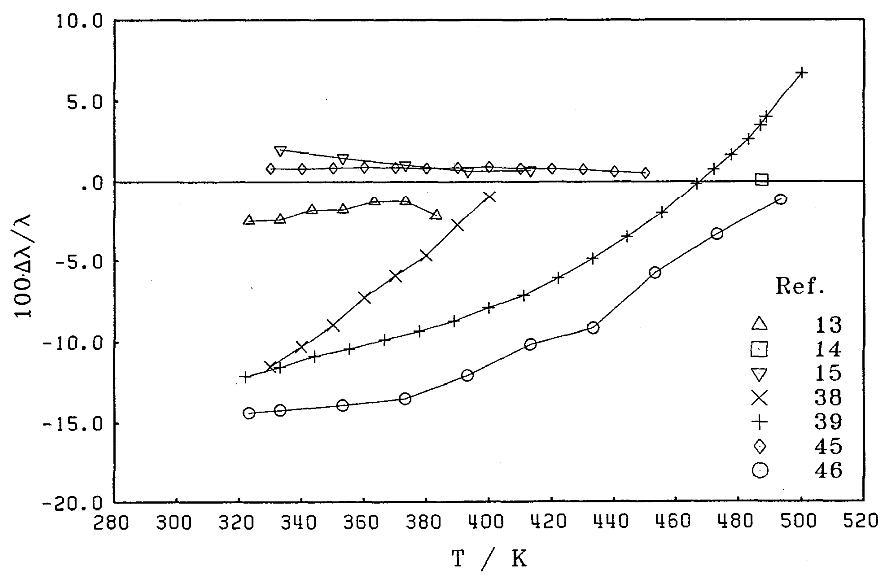

FIG. A3. Relative deviations of other data from the dilute-gas function of refrigerant 113.

c. Refrigerant 114.

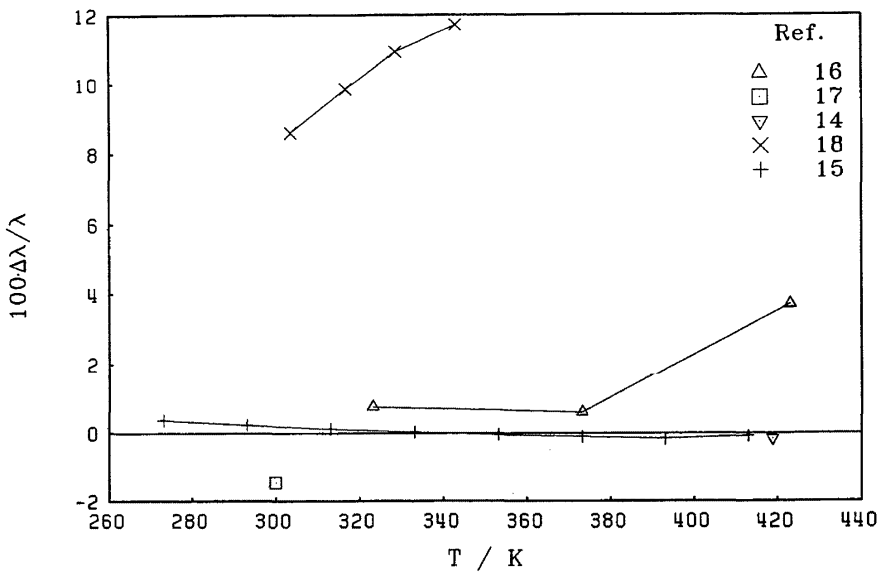

FIG. A4. Relative deviations of experimental data from the dilute-gas function of refrigerant 114.

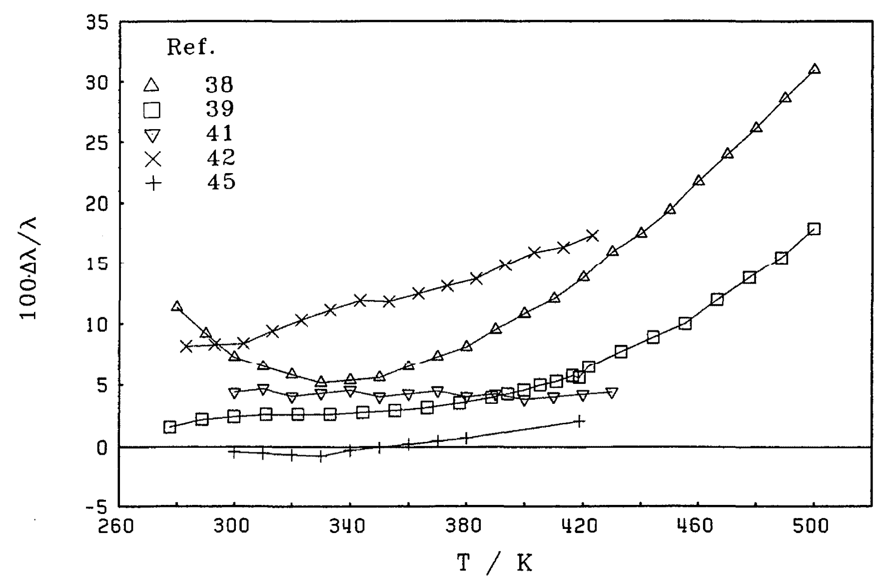

FIG. A5. Relative deviations of other compilations from the dilute-gas function of refrigerant 114.

d. Refrigerant C318.

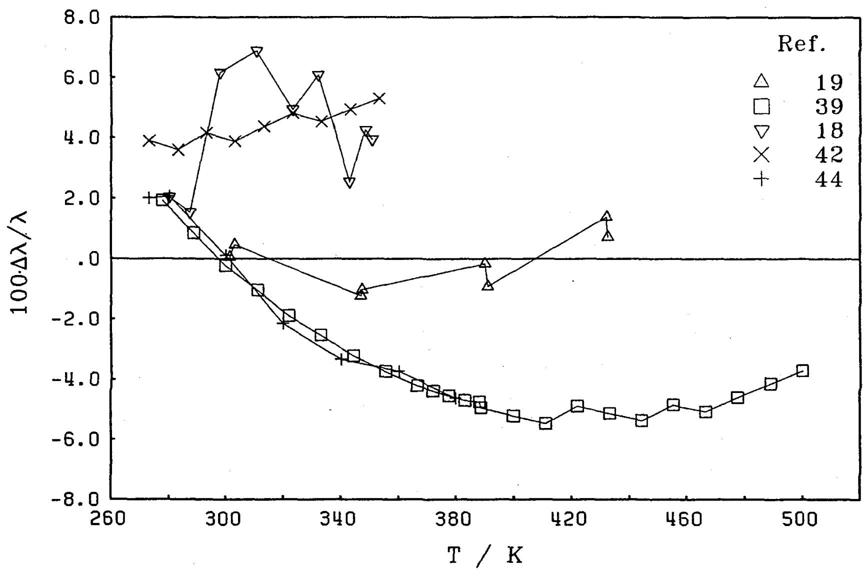

FIG. A6. Relative deviations of other data from the dilute-gas function of refrigerant C318.

APPENDIX B

Comparison of other literature data with the excess function.

a. Refrigerant 12.

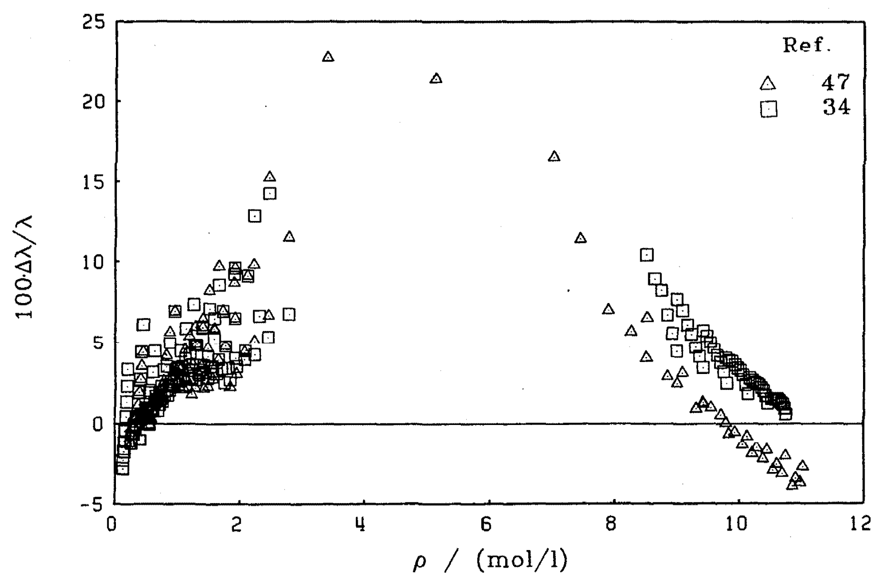

FIG. B1. Relative deviations of experimental data from the excess function of refrigerant 12.

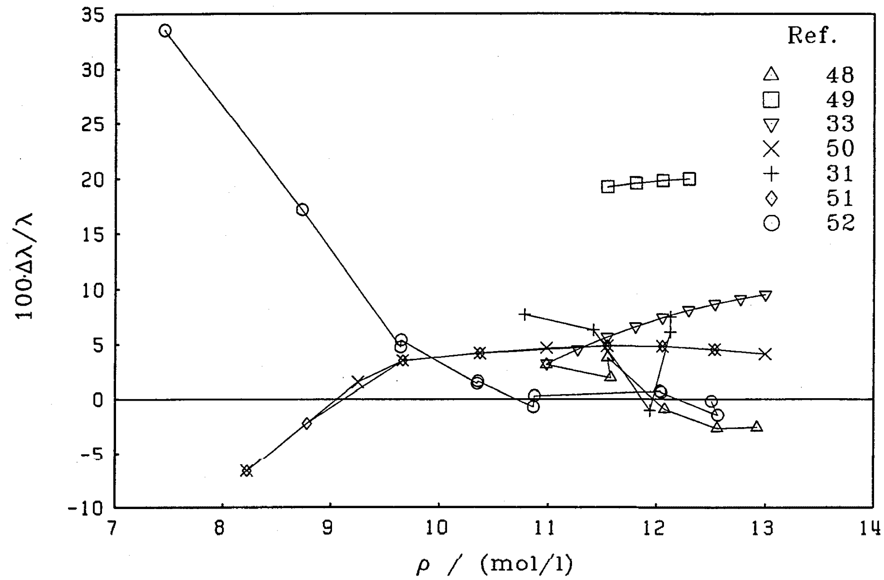

FIG. B2. Relative deviations of other compilations from the excess function of refrigerant 12.

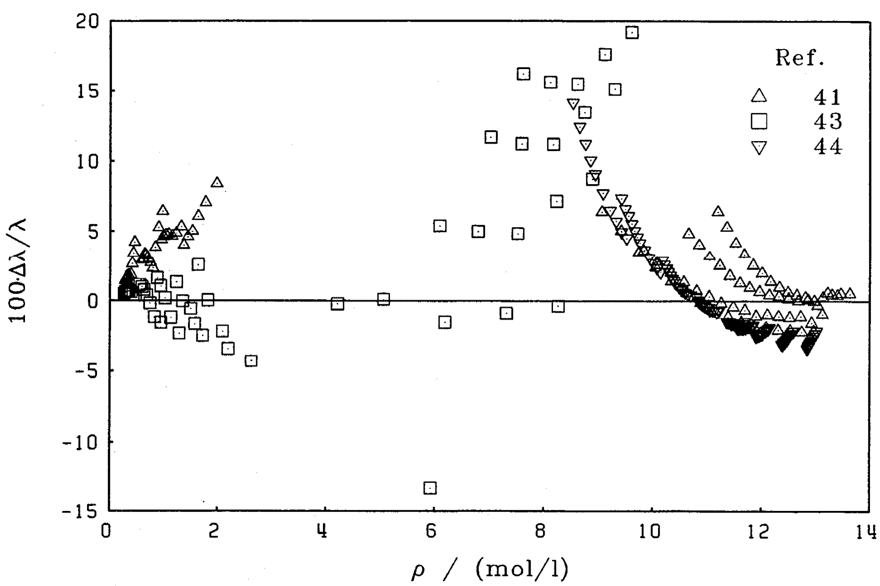

FIG. B3. Relative deviations of experimental data from the excess function of refrigerant 12 (saturated liquid).

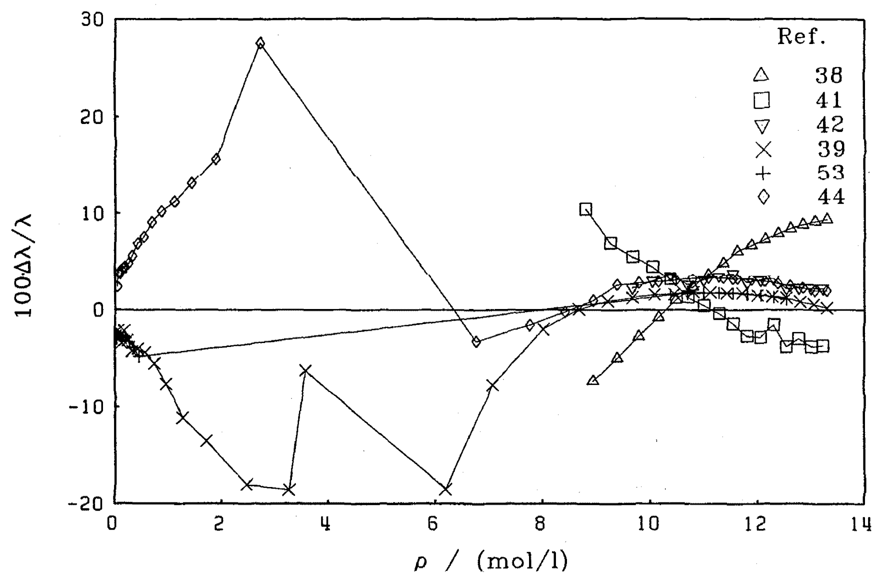

FIG. B4. Relative deviations of other compilations from the excess function of refrigerant 12 (saturation line).

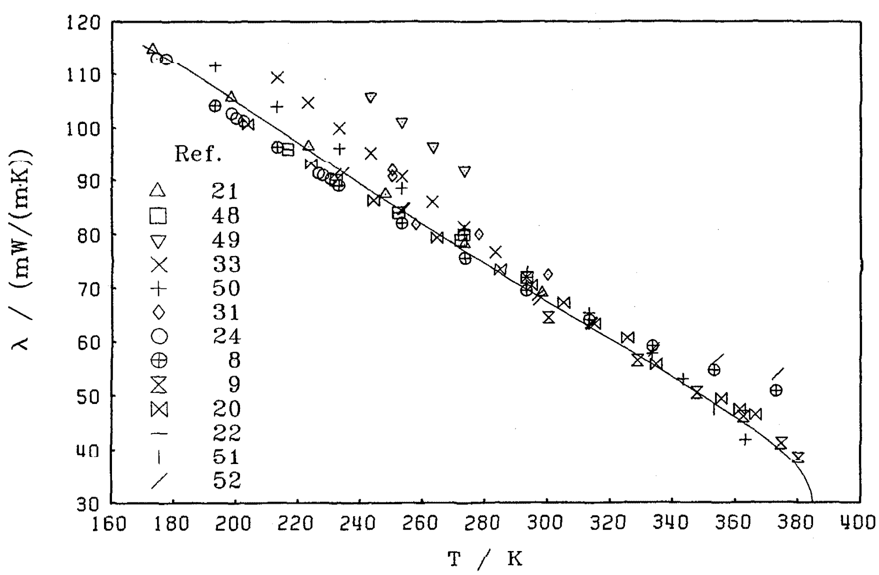

FIG. B5. Recommended saturated-liquid line of refrigerant 12 compared with experimental data.

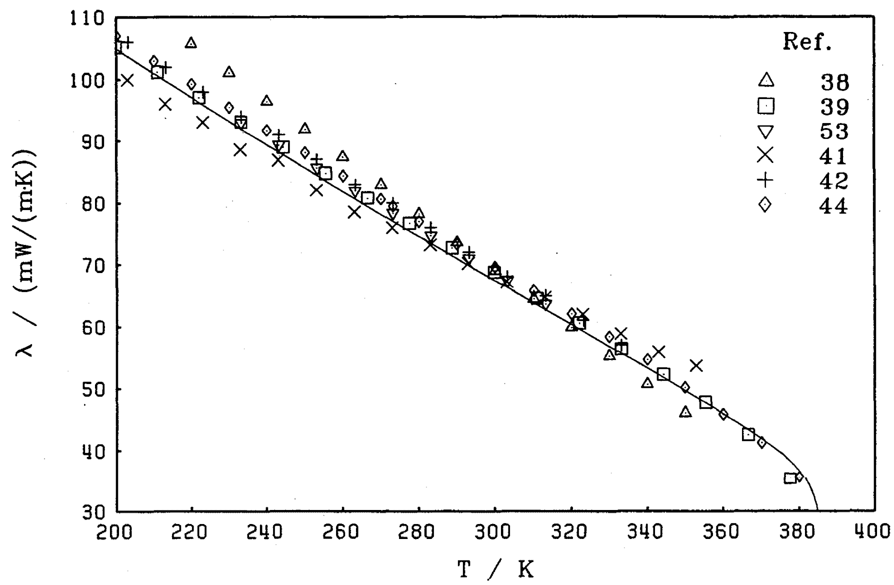

FIG. B6. Recommended saturated-liquid line of refrigerant 12 compared with other compilations.

b. Refrigerant 113.

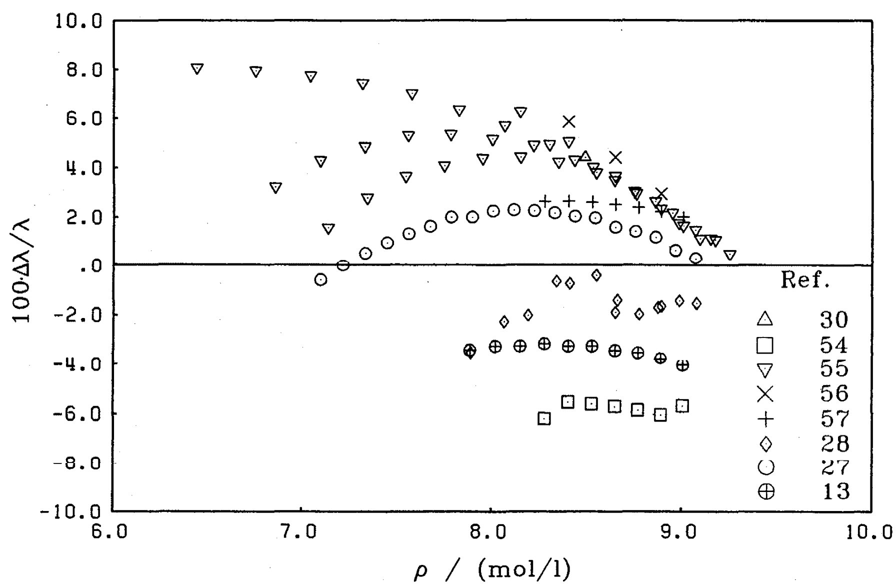

FIG. B7. Relative deviations of experimental data from the excess function of refrigerant 113.

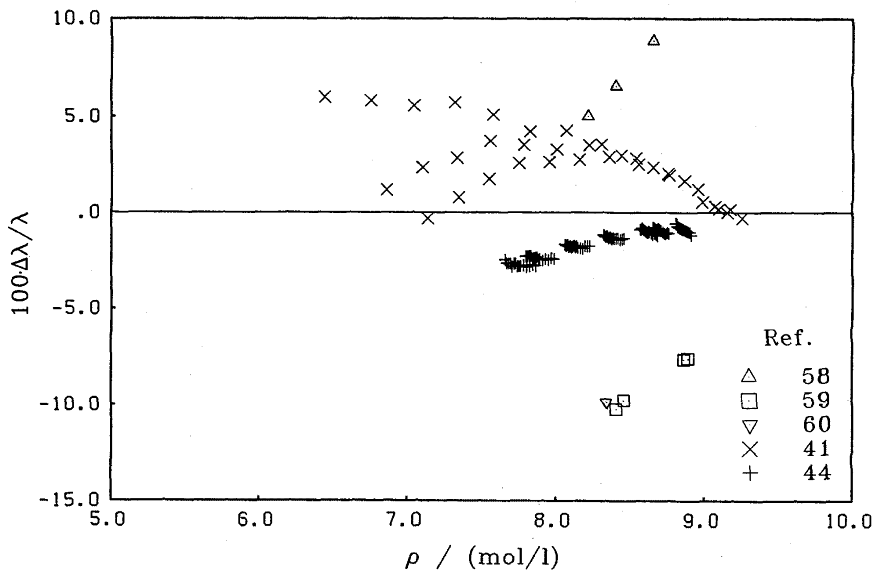

FIG. B8. Relative deviations of other compilations from the excess function of refrigerant 113.

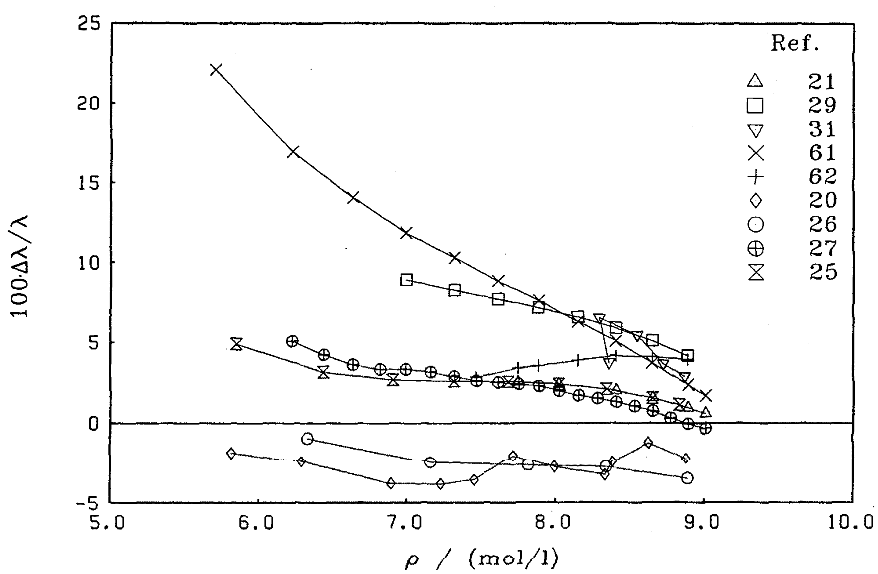

FIG. B9. Relative deviations of experimental data from the excess function of refrigerant 113 (saturated liquid).

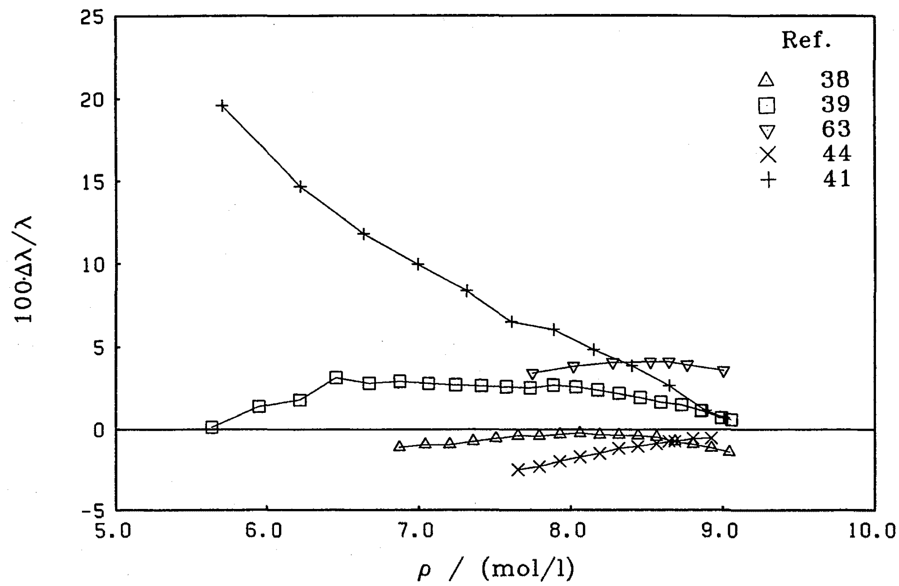

FIG. B10. Relative deviations of other compilations from the excess function of refrigerant 113 (saturated liquid).

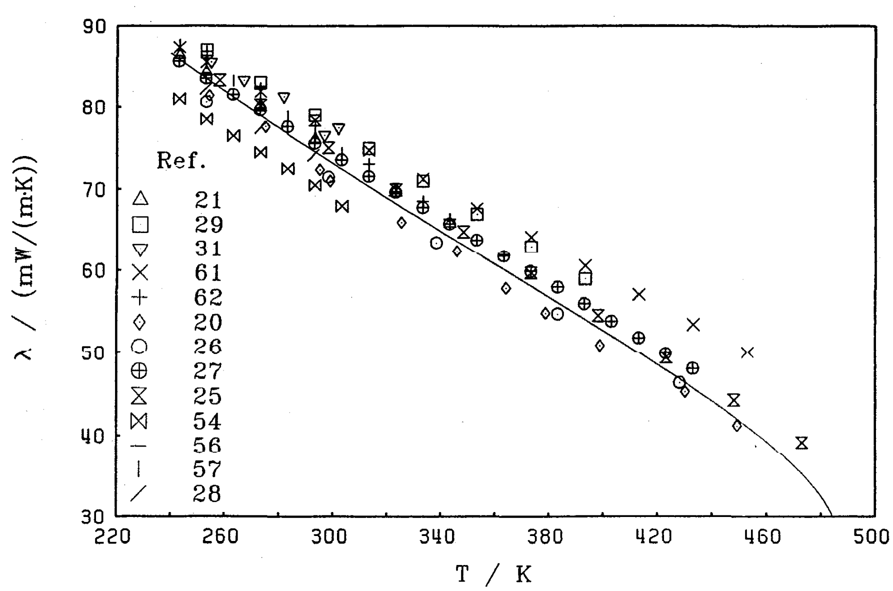

FIG. B11. Recommended saturated-liquid line of refrigerant 113 compared with experimental data.

c. Refrigerant 114.

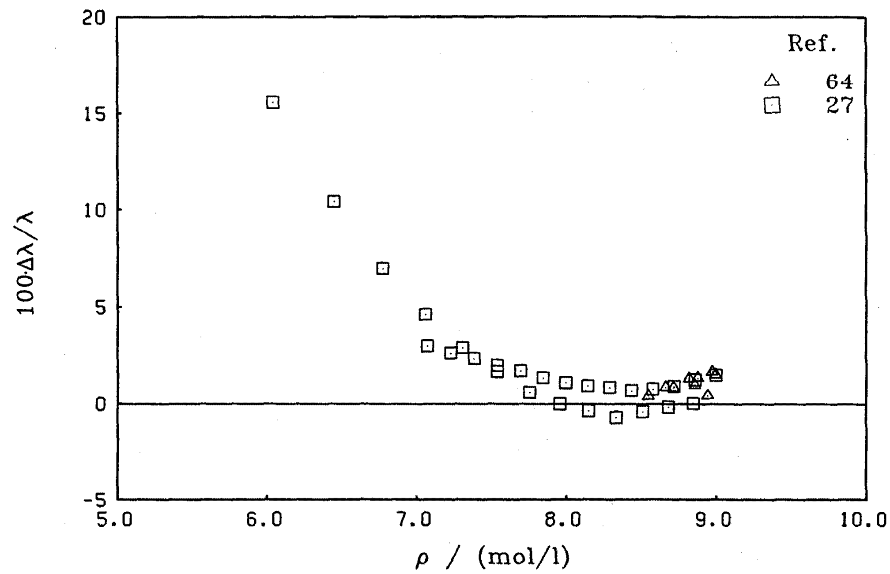

FIG. B12. Relative deviations of other data from the excess function of refrigerant 114.

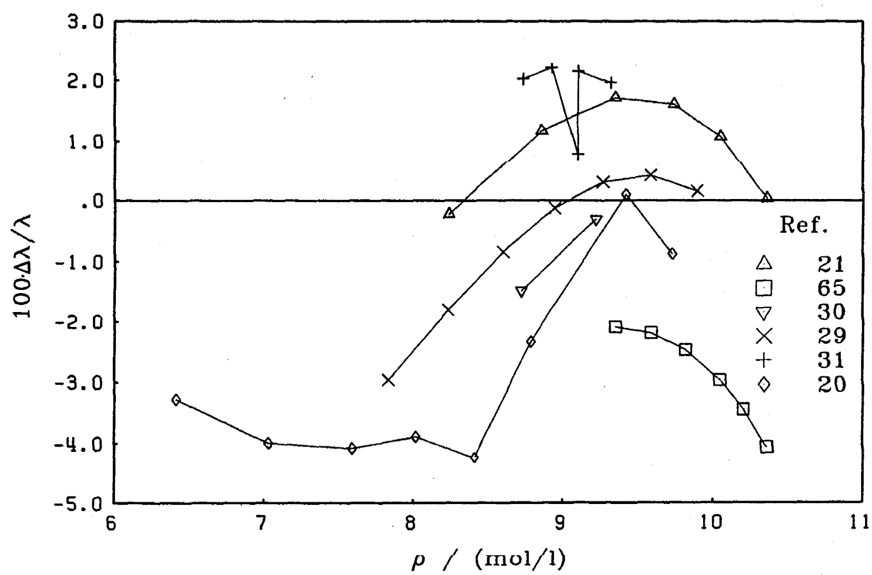

FIG. B13. Relative deviations of experimental data from the excess function of refrigerant 114 (saturated liquid).

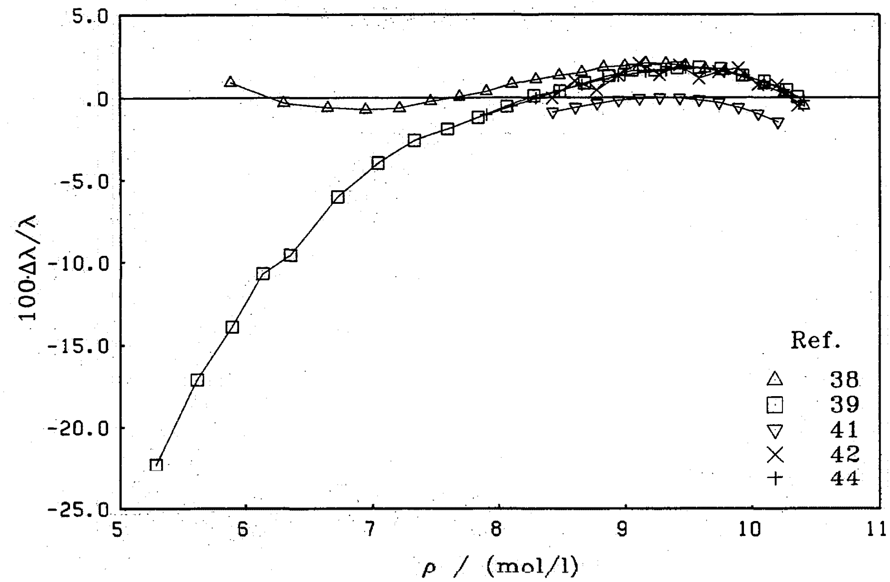

FIG. B14. Relative deviations of other compilations from the excess function of refrigerant 114 (saturated liquid).

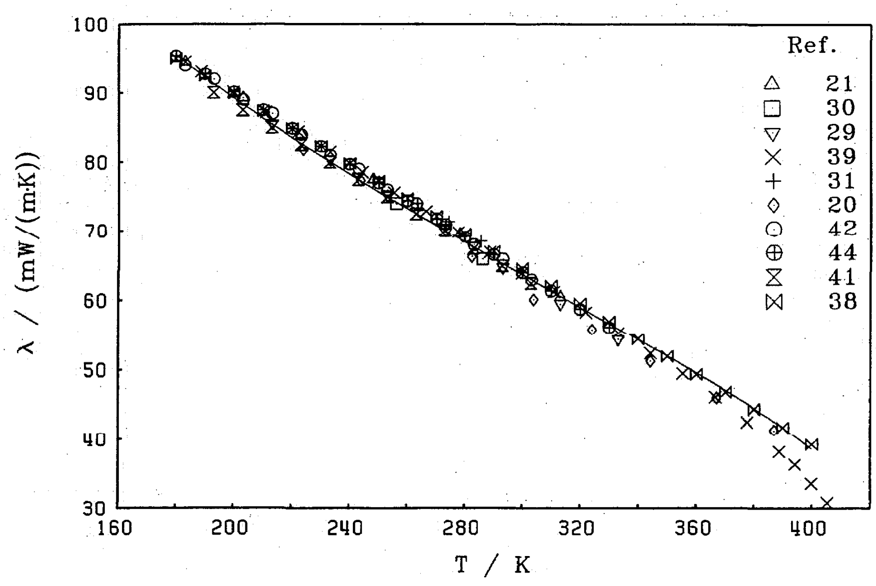

FIG. B15. Recommended saturated-liquid line of refrigerant 114 compared with other data.

d. Refrigerant C318.

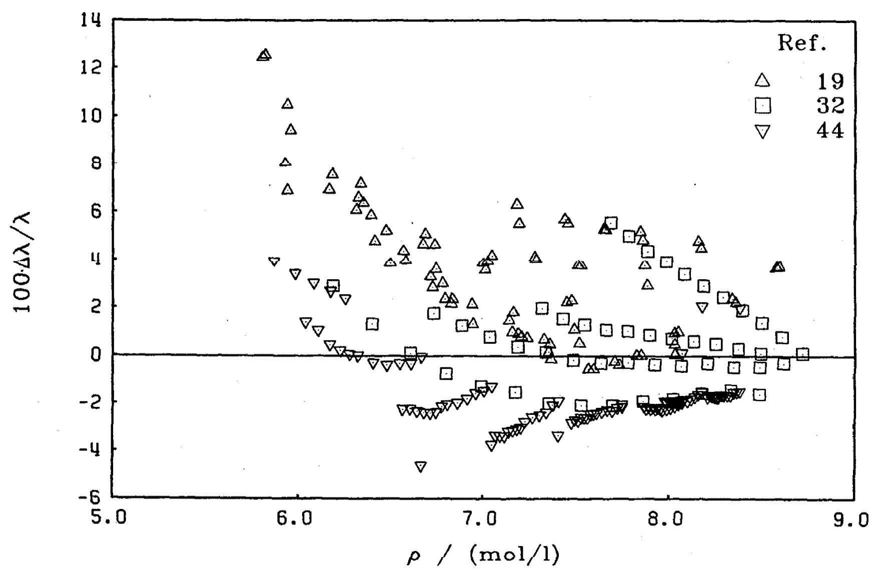

FIG. B16. Relative deviations of other data from the excess function of refrigerant C318.

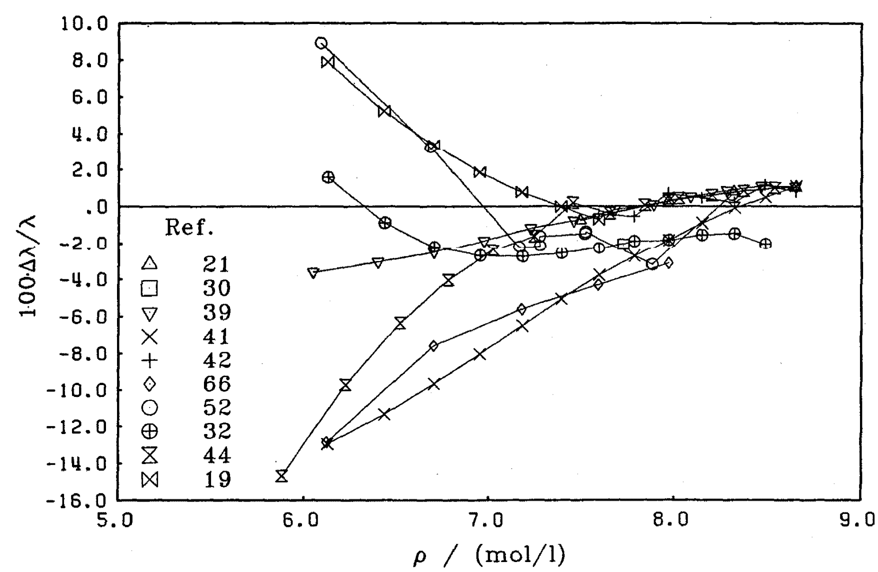

FIG. B17. Relative deviations of other data from the excess function of refrigerant C318 (saturated liquid).

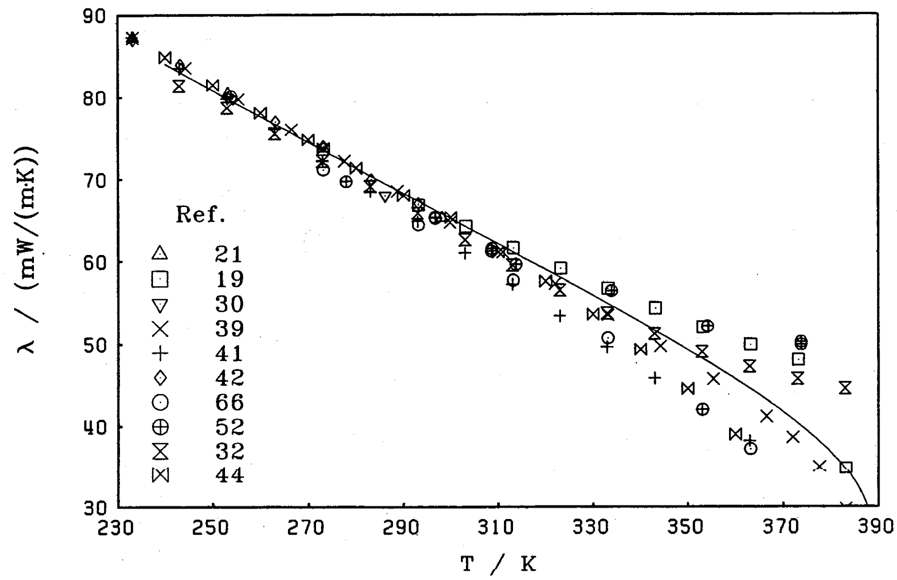

FIG. B18. Recommended saturated-liquid line of refrigerant C318 compared with other data.

APPENDIX C

Recommended values.

a. Refrigerant 12.

Table C1. Thermal conductivity (mW/m·K) of refrigerant 12

T (K) \ p (bar)	1.00	10.00	20.00	30.00	40.00	50.00	60.00	70.00	80.00	90.00	100.00
200.00	104.99	105.30	105.64	105.97	106.30	106.62	106.94	107.26	107.57	107.88	108.18
220.00	97.17	97.53	97.91	98.29	98.66	99.03	99.39	99.75	100.10	100.45	100.79
240.00	89.42	89.83	90.28	90.71	91.14	91.56	91.97	92.38	92.78	93.17	93.56
260.00	7.85	82.32	82.84	83.35	83.84	84.32	84.80	85.26	85.72	86.16	86.60
280.00	8.87	74.97	75.58	76.18	76.76	77.32	77.87	78.40	78.92	79.43	79.92
300.00	9.89	67.67	68.42	69.14	69.83	70.50	71.14	71.76	72.35	72.94	73.50
320.00	10.91	11.32	61.22	62.13	62.98	63.79	64.56	65.29	65.99	66.66	67.31
340.00	11.93	12.28	53.66	54.93	56.07	57.10	58.06	58.95	59.79	60.58	61.34
360.00	12.95	13.26	14.15	46.87	48.72	50.23	51.52	52.68	53.72	54.69	55.59
380.00	13.98	14.24	14.95	16.55	38.59	42.39	44.61	46.31	47.72	48.96	50.07
400.00	15.00	15.24	15.83	16.97	19.19	25.38	35.61	39.32	41.60	43.34	44.79
420.00	16.02	16.24	16.75	17.65	19.14	21.57	25.64	30.98	35.08	37.79	39.78
440.00	17.04	17.24	17.69	18.45	19.59	21.25	23.54	26.52	29.84	32.87	35.33
460.00	18.06	18.24	18.65	19.30	20.24	21.52	23.18	25.21	27.51	29.90	32.15
480.00	19.08	19.25	19.62	20.19	20.99	22.05	23.36	24.92	26.67	28.53	30.39
500.00	20.10	20.26	20.59	21.10	21.81	22.71	23.80	25.08	26.50	28.01	29.56
520.00	21.12	21.27	21.58	22.04	22.66	23.45	24.39	25.47	26.67	27.95	29.27
540.00	22.14	22.28	22.56	22.98	23.54	24.24	25.07	26.01	27.05	28.16	29.31
560.00	23.16	23.30	23.56	23.94	24.45	25.08	25.81	26.65	27.57	28.55	29.56
580.00	24.18	24.31	24.55	24.91	25.37	25.94	26.61	27.36	28.18	29.05	29.96
600.00	25.20	25.32	25.55	25.88	26.31	26.83	27.43	28.11	28.86	29.65	30.47

Table C1. Thermal conductivity (mW/m·K) of refrigerant 12 -- continued

T (K)	p (bar) 150.00	200.00	250.00	300.00	350.00	400.00	450.00	500.00	550.00	600.00
200.00	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
220.00	102.44	104.00	105.48	106.89	108.24	109.54	-------	-------	-------	-------
240.00	95.41	97.14	98.78	100.33	101.81	103.23	104.59	105.90	107.16	108.39
260.00	88.68	90.60	92.40	94.10	95.71	97.25	98.72	100.13	101.49	102.80
280.00	82.25	84.39	86.36	88.21	89.96	91.61	93.19	94.70	96.15	97.55
300.00	76.12	78.48	80.64	82.64	84.52	86.30	87.98	89.59	91.13	92.60
320.00	70.27	72.87	75.22	77.38	79.39	81.28	83.07	84.76	86.39	87.94
340.00	64.70	67.57	70.11	72.43	74.57	76.56	78.44	80.22	81.92	83.54
360.00	59.43	62.59	65.33	67.79	70.05	72.14	74.10	75.96	77.72	79.41
380.00	54.52	57.98	60.91	63.51	65.87	68.04	70.07	71.99	73.80	75.54
400.00	50.02	53.79	56.90	59.61	62.05	64.29	66.37	68.33	70.18	71.95
420.00	46.01	50.09	53.34	56.14	58.63	60.91	63.02	65.00	66.88	68.66
440.00	42.57	46.92	50.27	53.12	55.64	57.93	60.05	62.03	63.91	65.69
460.00	39.79	44.30	47.71	50.56	53.07	55.35	57.45	59.42	61.28	63.05
480.00	37.68	42.25	45.65	48.47	50.94	53.18	55.25	57.18	59.01	60.75
500.00	36.21	40.70	44.04	46.80	49.22	51.40	53.41	55.29	57.07	58.76
520.00	35.27	39.60	42.85	45.53	47.86	49.97	51.91	53.73	55.46	57.10
540.00	34.73	38.86	42.00	44.59	46.84	48.86	50.73	52.48	54.14	55.73
560.00	34.50	38.41	41.44	43.93	46.09	48.04	49.83	51.51	53.10	54.62
580.00	34.48	38.19	41.11	43.51	45.59	47.46	49.17	50.78	52.31	53.76
600.00	34.63	38.15	40.96	43.28	45.28	47.08	48.72	50.26	51.72	53.11

Table C2. Thermal conductivity of refrigerant 12, saturation line

p (bar)	T (K)	λ (mW/m·K)
.92530E-02	170.0	115.67
.22283E-01	180.0	112.42
.49061E-01	190.0	108.79
.99502E-01	200.0	4.79
.99502E-01	200.0	104.96
.18751	210.0	5.30
.18751	210.0	101.06
.33116	220.0	5.82
.33116	220.0	97.15
.55269	230.0	6.33
.55269	230.0	93.26
.87811	240.0	6.85
.87811	240.0	89.42
1.3369	250.0	7.37
1.3369	250.0	85.63
1.9613	260.0	7.90
1.9613	260.0	81.89
2.7865	270.0	8.43
2.7865	270.0	78.21
3.8496	280.0	8.98
3.8496	280.0	74.57
5.1901	290.0	9.54
5.1901	290.0	70.98
6.8494	300.0	10.13
6.8494	300.0	67.42
8.8711	310.0	10.76
8.8711	310.0	63.89
11.301	320.0	11.44
11.301	320.0	60.37
14.188	330.0	12.19
14.188	330.0	56.86
17.585	340.0	13.07
17.585	340.0	53.33
21.550	350.0	14.12
21.550	350.0	49.73
26.153	360.0	15.46
26.153	360.0	46.00
31.480	370.0	17.33
31.480	370.0	41.92
37.674	380.0	20.57
37.674	380.0	36.67
41.297	385.15	27.95

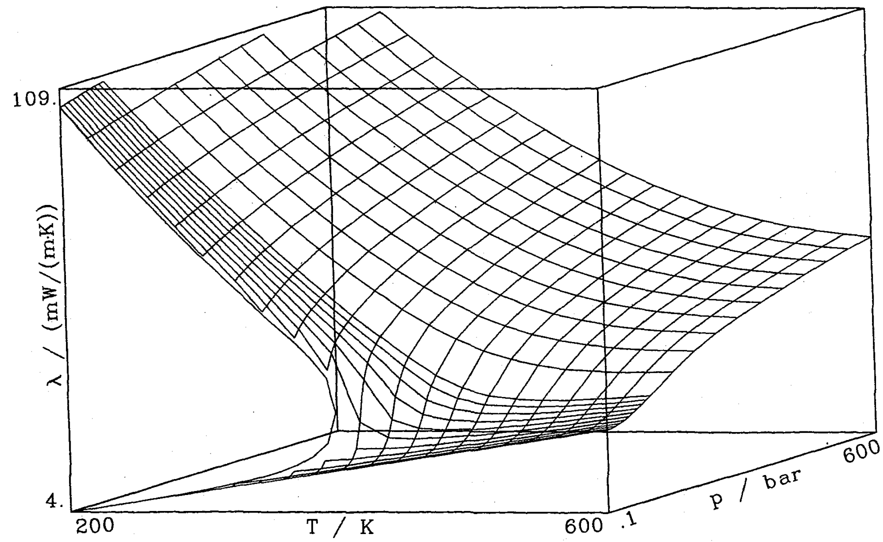

FIG. C1. Thermal conductivity surface of refrigerant 12 over the temperature, pressure plane.

b. Refrigerant 113.

Table C3. Thermal conductivity (mW/m·K) of refrigerant 113

T (K)	p (bar) 1.00	10.00	20.00	30.00	40.00	50.00	60.00	70.00	80.00	90.00	100.00
240.00	86.61	86.81	87.03	87.25	87.46	87.67	87.89	88.10	88.31	88.51	88.72
250.00	84.27	84.48	84.71	84.94	85.16	85.39	85.61	85.83	86.05	86.27	86.48
260.00	81.97	82.19	82.43	82.67	82.91	83.14	83.37	83.61	83.84	84.06	84.29
270.00	79.70	79.94	80.19	80.44	80.69	80.94	81.19	81.43	81.67	81.91	82.15
280.00	77.48	77.73	78.00	78.27	78.53	78.79	79.05	79.31	79.56	79.81	80.06
290.00	75.30	75.56	75.85	76.13	76.41	76.68	76.96	77.23	77.49	77.76	78.02
300.00	73.16	73.43	73.73	74.03	74.33	74.62	74.91	75.19	75.47	75.75	76.02
310.00	71.04	71.33	71.66	71.97	72.29	72.59	72.90	73.20	73.49	73.79	74.07
320.00	68.95	69.27	69.61	69.95	70.28	70.60	70.93	71.24	71.55	71.86	72.17
330.00	10.34	67.22	67.59	67.95	68.30	68.65	68.99	69.32	69.65	69.98	70.30
340.00	10.81	65.19	65.58	65.97	66.34	66.71	67.08	67.43	67.78	68.12	68.46
350.00	11.28	63.17	63.59	64.01	64.41	64.81	65.19	65.57	65.94	66.30	66.66
360.00	11.75	61.16	61.61	62.06	62.49	62.92	63.33	63.73	64.13	64.51	64.89
370.00	12.22	59.14	59.64	60.12	60.59	61.04	61.48	61.91	62.33	62.74	63.14
380.00	12.69	57.10	57.65	58.18	58.69	59.18	59.65	60.11	60.56	61.00	61.42
390.00	13.16	55.04	55.65	56.23	56.78	57.32	57.83	58.33	58.81	59.27	59.73
400.00	13.63	52.93	53.61	54.26	54.87	55.45	56.01	56.55	57.07	57.57	58.05
410.00	14.10	50.75	51.53	52.26	52.94	53.58	54.19	54.78	55.34	55.87	56.39
420.00	14.57	-------	49.38	50.21	50.98	51.69	52.37	53.01	53.61	54.19	54.75
430.00	15.04	-------	47.12	48.09	48.97	49.78	50.53	51.23	51.89	52.52	53.12
440.00	15.51	-------	44.69	45.87	46.90	47.83	48.67	49.45	50.18	50.86	51.51
450.00	15.98	-------	41.96	43.48	44.74	45.82	46.78	47.66	48.46	49.21	49.91
460.00	16.45	-------	-------	40.82	42.43	43.73	44.85	45.84	46.74	47.56	48.33
470.00	16.92	-------	-------	-------	39.88	41.53	42.86	44.00	45.01	45.92	46.76
480.00	17.39	-------	-------	-------	-------	-------	40.79	42.13	43.27	44.29	45.21
490.00	17.86	-------	-------	-------	-------	-------	-------	-------	41.53	42.66	43.67
500.00	18.33	-------	-------	-------	-------	-------	-------	-------	-------	-------	42.17

Table C3. Thermal conductivity (mW/m·K) of refrigerant 113 -- continued

	p (bar)							
T (K)	125.00	150.00	175.00	200.00	225.00	250.00	275.00	300.00
240.00	89.23	89.73	90.22	90.71	91.19	91.67	92.13	92.59
250.00	87.01	87.54	88.05	88.56	89.06	89.55	90.04	90.52
260.00	84.85	85.40	85.93	86.46	86.98	87.50	88.00	88.50
270.00	82.73	83.31	83.87	84.42	84.96	85.49	86.02	86.53
280.00	80.67	81.27	81.86	82.43	82.99	83.55	84.09	84.62
290.00	78.66	79.29	79.90	80.50	81.08	81.66	82.22	82.78
300.00	76.70	77.35	77.99	78.62	79.23	79.82	80.41	80.98
310.00	74.78	75.47	76.13	76.79	77.42	78.04	78.65	79.24
320.00	72.91	73.63	74.32	75.00	75.66	76.31	76.94	77.55
330.00	71.08	71.83	72.56	73.27	73.95	74.62	75.28	75.91
340.00	69.28	70.07	70.84	71.57	72.29	72.99	73.66	74.32
350.00	67.52	68.35	69.15	69.92	70.67	71.39	72.09	72.77
360.00	65.80	66.67	67.51	68.31	69.09	69.84	70.56	71.27
370.00	64.11	65.02	65.90	66.74	67.55	68.33	69.08	69.81
380.00	62.44	63.41	64.33	65.20	66.04	66.85	67.63	68.39
390.00	60.81	61.82	62.79	63.70	64.58	65.42	66.23	67.01
400.00	59.20	60.27	61.28	62.24	63.15	64.02	64.86	65.66
410.00	57.61	58.75	59.81	60.81	61.76	62.66	63.53	64.36
420.00	56.05	57.25	58.36	59.41	60.40	61.34	62.24	63.10
430.00	54.51	55.78	56.96	58.05	59.08	60.05	60.98	61.87
440.00	53.00	54.35	55.58	56.72	57.79	58.80	59.76	60.68
450.00	51.51	52.94	54.23	55.43	56.55	57.59	58.58	59.53
460.00	50.05	51.56	52.93	54.18	55.34	56.42	57.44	58.41
470.00	48.61	50.22	51.65	52.96	54.16	55.28	56.34	57.34
480.00	47.21	48.91	50.42	51.78	53.03	54.19	55.28	56.30
490.00	45.83	47.64	49.22	50.64	51.94	53.13	54.25	55.30
500.00	44.50	46.41	48.07	49.55	50.89	52.12	53.27	54.35

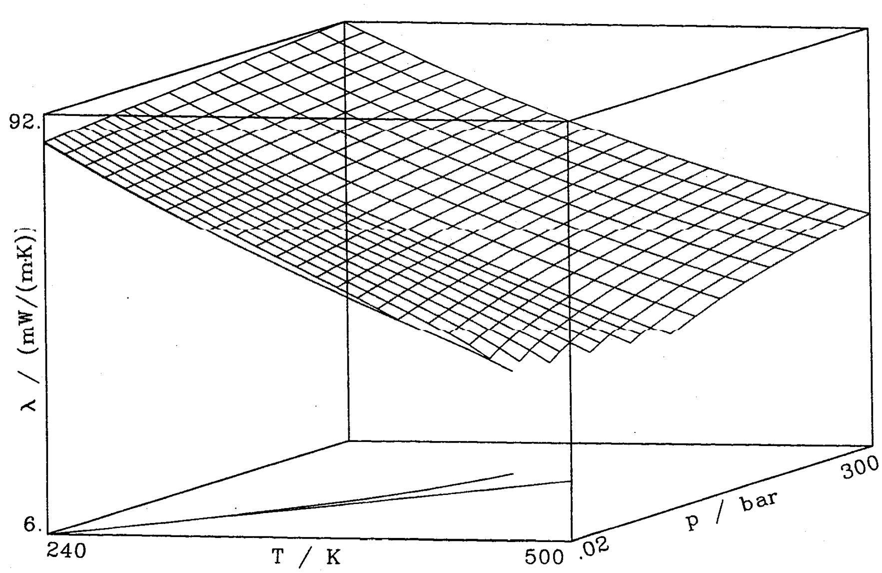

FIG. C2. Thermal conductivity surface of refrigerant 113 over the temperature, pressure plane.

Table C4. Thermal conductivity of refrigerant 113, saturation line

p (bar)	T (K)	λ (mW/m·K)
.23263E-01	240.0	6.11
.23263E-01	240.0	86.59
.43397E-01	250.0	6.59
.43397E-01	250.0	84.25
.76593E-01	260.0	7.06
.76593E-01	260.0	81.94
.12875	270.0	7.53
.12875	270.0	79.68
.20728	280.0	8.01
.20728	280.0	77.46
.32119	290.0	8.49
.32119	290.0	75.28
.48101	300.0	8.97
.48101	300.0	73.14
.69878	310.0	9.46
.69878	310.0	71.03
.98793	320.0	9.95
.98793	320.0	68.95
1.3631	330.0	10.44
1.3631	330.0	66.90
1.8402	340.0	10.95
1.8402	340.0	64.86
2.4360	350.0	11.46
2.4360	350.0	62.84
3.1683	360.0	11.98
3.1683	360.0	60.83
4.0555	370.0	12.51
4.0555	370.0	58.83
5.1171	380.0	13.05
5.1171	380.0	56.82
6.3733	390.0	13.60
6.3733	390.0	54.81
7.8453	400.0	14.18
7.8453	400.0	52.78
9.5552	410.0	14.77
9.5552	410.0	50.72
11.527	420.0	15.38
11.527	420.0	48.61
13.785	430.0	16.03
13.785	430.0	46.45
16.359	440.0	16.72
16.359	440.0	44.21
19.280	450.0	17.46
19.280	450.0	41.83
22.586	460.0	18.30
22.586	460.0	39.26

c. Refrigerant 114.

Table C5. Thermal conductivity (mW/m·K) of refrigerant 114

T (K) \ p (bar)	1.00	10.00	20.00	30.00	40.00	50.00	60.00	70.00	80.00	90.00	100.00
280.00	9.16	68.78	69.14	69.50	69.84	70.19	70.52	70.85	71.17	71.49	-------
290.00	9.71	66.42	66.81	67.20	67.57	67.94	68.30	68.65	69.00	69.34	69.67
300.00	10.25	64.08	64.51	64.93	65.33	65.73	66.12	66.49	66.86	67.23	67.58
310.00	10.80	61.75	62.22	62.68	63.12	63.55	63.96	64.37	64.77	65.16	65.53
320.00	11.34	59.42	59.94	60.44	60.92	61.39	61.84	62.28	62.71	63.12	63.53
330.00	11.88	57.06	57.64	58.20	58.73	59.24	59.74	60.21	60.67	61.12	61.56
340.00	12.43	54.66	55.32	55.94	56.54	57.11	57.65	58.17	58.67	59.15	59.62
350.00	12.97	52.18	52.95	53.67	54.33	54.97	55.57	56.14	56.69	57.21	57.72
360.00	13.52	-------	50.50	51.34	52.10	52.82	53.49	54.12	54.72	55.30	55.85
370.00	14.06	-------	47.92	48.92	49.82	50.64	51.40	52.10	52.77	53.40	54.00
380.00	14.61	-------	45.11	46.37	47.46	48.42	49.29	50.09	50.83	51.52	52.18
390.00	15.15	-------	-------	43.59	44.96	46.12	47.14	48.05	48.89	49.66	50.38
400.00	15.70	-------	-------	40.36	42.26	43.71	44.93	45.99	46.94	47.81	48.60
410.00	16.24	-------	-------	-------	-------	41.13	42.64	43.90	44.99	45.97	46.85
420.00	16.79	-------	-------	-------	-------	-------	-------	41.76	43.03	44.14	45.12
430.00	17.33	-------	-------	-------	-------	-------	-------	-------	-------	42.32	43.42
440.00	17.88	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
450.00	18.42	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
460.00	18.97	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
470.00	19.51	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
480.00	20.06	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
490.00	20.60	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
500.00	21.14	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------

Table C5. Thermal conductivity (mW/m·K) of refrigerant 114 -- continued

T (K) \ p (bar)	110.00	120.00	130.00	140.00	150.00	160.00	170.00	180.00	190.00	200.00
280.00	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
290.00	70.00	70.32	70.64	70.95	71.26	71.56	71.86	-------	-------	-------
300.00	67.93	68.27	68.61	68.94	69.26	69.58	69.89	70.20	70.51	70.81
310.00	65.91	66.27	66.62	66.97	67.32	67.65	67.98	68.31	68.63	68.94
320.00	63.92	64.31	64.69	65.06	65.42	65.78	66.13	66.47	66.80	67.13
330.00	61.98	62.39	62.80	63.19	63.57	63.95	64.32	64.68	65.03	65.38
340.00	60.08	60.52	60.95	61.37	61.77	62.17	62.56	62.94	63.31	63.67
350.00	58.21	58.68	59.14	59.58	60.02	60.44	60.85	61.25	61.64	62.02
360.00	56.37	56.88	57.37	57.85	58.31	58.75	59.19	59.61	60.02	60.42
370.00	54.57	55.12	55.64	56.15	56.64	57.11	57.57	58.02	58.45	58.88
380.00	52.80	53.39	53.96	54.50	55.02	55.52	56.01	56.48	56.94	57.38
390.00	51.06	51.70	52.31	52.89	53.44	53.98	54.49	54.99	55.47	55.94
400.00	49.35	50.04	50.70	51.32	51.92	52.48	53.03	53.55	54.06	54.55
410.00	47.67	48.42	49.13	49.80	50.44	51.04	51.62	52.17	52.70	53.22
420.00	46.02	46.84	47.61	48.33	49.01	49.65	50.26	50.84	51.40	51.94
430.00	44.41	45.31	46.14	46.91	47.63	48.31	48.96	49.57	50.16	50.72
440.00	42.85	43.82	44.72	45.54	46.31	47.03	47.71	48.36	48.97	49.56
450.00	-------	-------	43.36	44.24	45.05	45.81	46.53	47.20	47.85	48.46
460.00	-------	-------	-------	-------	43.86	44.66	45.41	46.12	46.79	47.42
470.00	-------	-------	-------	-------	-------	-------	44.36	45.10	45.79	46.45
480.00	-------	-------	-------	-------	-------	-------	-------	-------	44.87	45.54
490.00	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------
500.00	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------

Table C6. Thermal conductivity of refrigerant 114, saturated liquid

p (bar)	T (K)	λ (mW/m·K)
.18840E-02	180.0	95.50
.32250E-02	185.0	93.87
.53150E-02	190.0	92.28
.84700E-02	195.0	90.75
.13096E-01	200.0	89.25
.19707E-01	205.0	87.79
.28935E-01	210.0	86.36
.41543E-01	215.0	84.96
.58439E-01	220.0	83.58
.80682E-01	225.0	82.23
.10949	230.0	80.90
.14625	235.0	79.59
.19251	240.0	78.29
.24999	245.0	77.02
.32057	250.0	75.76
.40633	255.0	74.51
.50946	260.0	73.28
.63234	265.0	72.06
.77749	270.0	70.85
.94758	275.0	69.64
1.1454	280.0	68.45
1.3739	285.0	67.26
1.6361	290.0	66.09
1.9352	295.0	64.91
2.2744	300.0	63.74
2.6572	305.0	62.58
3.0870	310.0	61.42
3.5675	315.0	60.26
4.1022	320.0	59.10
4.6950	325.0	57.94
5.3498	330.0	56.78
6.0705	335.0	55.61
6.8612	340.0	54.44
7.7262	345.0	53.26
8.6697	350.0	52.08
9.6963	355.0	50.88
10.811	360.0	49.67
12.017	365.0	48.43
13.322	370.0	47.18
14.730	375.0	45.89
16.246	380.0	44.57
17.877	385.0	43.20
19.629	390.0	41.77
21.511	395.0	40.26
23.529	400.0	38.64

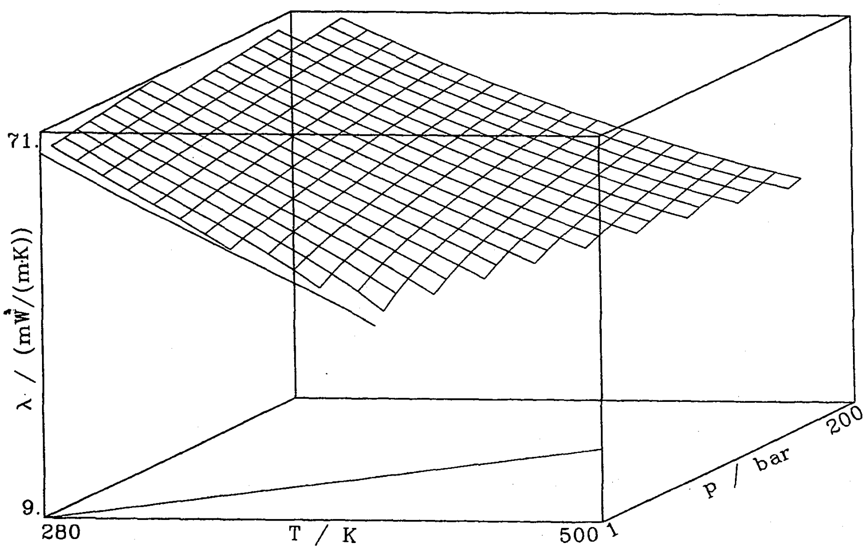

FIG. C3. Thermal conductivity surface of refrigerant 114 over the temperature, pressure plane.

d. Refrigerant C318.

Table C7. Thermal conductivity (mW/m·K) of refrigerant C318

	p (bar)										
T (K)	1.00	10.00	20.00	30.00	40.00	50.00	60.00	70.00	80.00	90.00	100.00
240.00	84.10	84.45	84.84	85.21	85.58	85.95	86.31	86.66	87.01	87.36	87.70
250.00	80.86	81.24	81.65	82.06	82.46	82.85	83.23	83.61	83.99	84.36	84.72
260.00	77.66	78.07	78.51	78.95	79.38	79.80	80.22	80.62	81.02	81.42	81.80
270.00	10.37	74.93	75.42	75.89	76.36	76.81	77.26	77.70	78.12	78.55	78.96
280.00	11.07	71.82	72.36	72.88	73.38	73.88	74.36	74.83	75.29	75.74	76.18
290.00	11.78	68.73	69.32	69.89	70.45	70.99	71.51	72.02	72.52	73.00	73.48
300.00	12.48	65.64	66.30	66.94	67.55	68.14	68.71	69.27	69.80	70.33	70.84
310.00	13.19	62.53	63.28	63.99	64.67	65.32	65.95	66.56	67.14	67.71	68.26
320.00	13.90	59.37	60.23	61.04	61.80	62.53	63.23	63.89	64.53	65.15	65.74
330.00	14.60	56.10	57.12	58.06	58.93	59.75	60.52	61.26	61.96	62.64	63.28
340.00	15.31	52.65	53.90	55.01	56.02	56.96	57.84	58.66	59.43	60.17	60.88
350.00	16.02	16.85	50.47	51.85	53.06	54.15	55.15	56.07	56.94	57.75	58.52
360.00	16.72	17.51	46.68	48.49	49.99	51.29	52.45	53.50	54.47	55.37	56.22
370.00	17.43	18.17	-------	-------	46.75	48.35	49.72	50.93	52.03	53.04	53.97
380.00	18.14	18.85	-------	-------	-------	-------	46.94	48.36	49.61	50.74	51.77
390.00	18.84	19.52	-------	-------	-------	-------	-------	-------	47.22	48.49	49.63
400.00	19.55	20.20	-------	-------	-------	-------	-------	-------	-------	-------	-------
410.00	20.26	20.89	-------	-------	-------	-------	-------	-------	-------	-------	-------
420.00	20.96	21.57	-------	-------	-------	-------	-------	-------	-------	-------	-------
430.00	21.67	22.26	-------	-------	-------	-------	-------	-------	-------	-------	-------
440.00	22.38	22.95	-------	-------	-------	-------	-------	-------	-------	-------	-------
450.00	23.08	23.64	-------	-------	-------	-------	-------	-------	-------	-------	-------

Table C7. Thermal conductivity (mW/m·K) of refrigerant C318 -- continued

T (K)	p (bar) 150.00	200.00	250.00	300.00	350.00	400.00	450.00	500.00	550.00	600.00
240.00	89.35	90.91	92.39	93.81	95.17	-------	-------	-------	-------	-------
250.00	86.46	88.11	89.66	91.14	92.55	93.91	95.22	96.48	-------	-------
260.00	83.65	85.38	87.01	88.56	90.03	91.44	92.79	94.09	95.35	96.56
270.00	80.92	82.75	84.46	86.07	87.60	89.06	90.46	91.80	93.09	94.34
280.00	78.27	80.20	81.99	83.67	85.27	86.78	88.22	89.61	90.94	92.22
290.00	75.71	77.74	79.62	81.37	83.03	84.59	86.08	87.51	88.88	90.19
300.00	73.22	75.36	77.33	79.16	80.88	82.50	84.04	85.51	86.91	88.26
310.00	70.80	73.07	75.14	77.05	78.83	80.50	82.09	83.59	85.03	86.42
320.00	68.47	70.87	73.03	75.02	76.87	78.59	80.23	81.77	83.25	84.66
330.00	66.20	68.74	71.01	73.08	74.99	76.78	78.45	80.04	81.55	83.00
340.00	64.02	66.70	69.08	71.23	73.21	75.05	76.77	78.40	79.94	81.41
350.00	61.90	64.74	67.23	69.46	71.51	73.40	75.17	76.83	78.41	79.91
360.00	59.87	62.87	65.46	67.78	69.89	71.84	73.65	75.35	76.96	78.49
370.00	57.90	61.07	63.79	66.19	68.36	70.36	72.21	73.95	75.59	77.14
380.00	56.02	59.36	62.19	64.67	66.91	68.96	70.85	72.62	74.29	75.87
390.00	54.21	57.74	60.68	63.24	65.54	67.63	69.57	71.37	73.07	74.67
400.00	52.50	56.20	59.25	61.89	64.25	66.39	68.36	70.19	71.92	73.54
410.00	50.87	54.75	57.91	60.63	63.04	65.22	67.23	69.09	70.83	72.48
420.00	49.34	53.39	56.65	59.44	61.90	64.12	66.16	68.05	69.82	71.48
430.00	-------	52.12	55.48	58.33	60.84	63.10	65.17	67.08	68.87	70.55
440.00	-------	50.95	54.39	57.30	59.86	62.15	64.24	66.18	67.98	69.68
450.00	-------	-------	53.39	56.35	58.94	61.27	63.38	65.33	67.15	68.86

Table C8. Thermal conductivity of refrigerant C318, saturation line

p (bar)	T (K)	λ(mW/m·K)
.28147	240.0	8.27
.28147	240.0	84.08
.46898	250.0	9.00
.46898	250.0	80.84
.74542	260.0	9.73
.74542	260.0	77.65
1.1372	270.0	10.47
1.1372	270.0	74.49
1.6739	280.0	11.22
1.6739	280.0	71.36
2.3878	290.0	11.99
2.3878	290.0	68.27
3.3139	300.0	12.77
3.3139	300.0	65.18
4.4893	310.0	13.58
4.4893	310.0	62.10
5.9534	320.0	14.41
5.9534	320.0	59.00
7.7486	330.0	15.28
7.7486	330.0	55.86
9.9201	340.0	16.19
9.9201	340.0	52.64
12.518	350.0	17.16
12.518	350.0	49.29
15.601	360.0	18.23
15.601	360.0	45.71

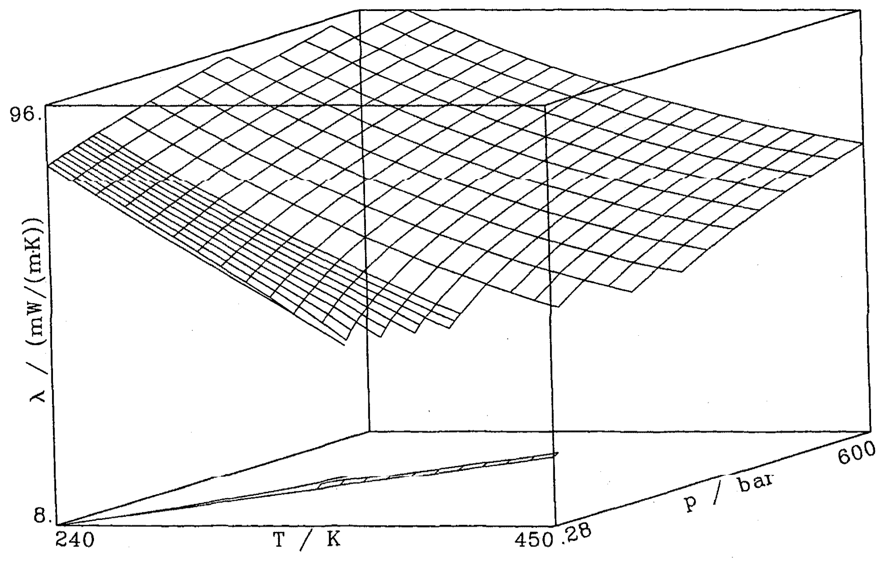

FIG. C4. Thermal conductivity surface of refrigerant C318 over the temperature, pressure plane.