International Journal of Thermophysics, Vol. 17, No. 3, 1996

Thermal Conductivities of New Refrigerants R125 and R32 Measured by the Transient Hot-Wire Method[1]

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Thermal conductivity measurements are reported for the new refrigerants pentafluoroethane (R125) and difluoromethane (R32), which are suggested to replace chlorodifluoroethane (R22) as components of a mixture. Transient hot-wire experiments were performed which cover both the liquid and the vapor states at temperatures and pressures ranging from $t = -40$ to 90°C and from $p = 1$ to 60 bar. Uncertainties keep within 1.6% for liquid and 2.0% for vapor states. The results are correlated with density and temperature. In addition, temperature-dependent correlations are presented for practical calculations for (i) saturated liquid, (ii) saturated vapor, and (iii) dilute gas (which approximately equals the vapor state at ambient pressure). Finally, the results are compared with data from the literature and also with the respective thermal conductivities of R22.

KEY WORDS: refrigerants; pentafluoroethane; difluoromethane; R32; R125; thermal conductivity; transient hot-wire method; transport properties.

1. INTRODUCTION

In the present paper, transient hot-wire measurements of thermal conductivity are reported for the new refrigerants R32 and R125, substances which are suggested to replace R22 as components of a mixture.

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[1] Paper presented at the Twelfth Symposium on Thermophysical Properties, June 19–24, 1994, Boulder, Colorado, U.S.A.

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2. EXPERIMENTS

The transient hot-wire method as the leading technique for measuring thermal conductivity of fluids has been described in several publications [1–7], where both its theory and its practical application to various fluids have been presented. In our experimental setup, a platinum wire with radius $r_w = 8.5\ \mu m$ has been used, together with application of a polarization voltage as suggested for polar fluids (for more details, see Ref. 6).

The test fluids R125 and R32 (Table I) were supplied by Du Pont Company with a purity of 99.8%. Inert gases which may be absorbed in the fluids were removed by a series of solidification/evacuation/melting procedures. Prior to the experiments, the complete hot-wire instrument was repeatedly evacuated and rinsed with the fluid to be investigated. Finally, the device was completely filled with the respective liquid by distillation from the container. The thermodynamic state inside the test volume can be changed by two means, namely, temperature variation (of the water bath, in which the instrument is submerged) and density variation (by affecting the total volume inside the system and/or the total mass of fluid). Series of measurements in the liquid are performed along isotherms starting at some high pressure in the subcooled liquid and expanding step by step until the saturation state is attained. In the case of the vapor, a series of measurements typically starts in the superheated state at a pressure of about 1 bar; the pressure is then gradually raised to near-saturation.

The accuracy of measured thermal conductivities was analyzed thoroughly [7] and the maximum uncertainties for liquid and vapor were found to remain within 1.6 and 2%, respectively. Major uncertainties are due to deviations from the ideal mathematical model of a line source in an infinite medium, effects of convection and radiation, the limited accuracy of the Wheatstone bridge used for the measurements, and some additional effects as discussed in Ref. 3.

Table I. Basic Data of the Test Fluids R32 and R125—Supplemented by R22

			Temperature				
Fluid	Structure	Molar mass ($g \cdot mol^{-1}$)	Triple (°C)	n.b. (°C)	critical (°C)	Pressure, critical (bar)	Density ($kg \cdot m^{-3}$)
R32	CH_2F_2	50.02	−136.2	−51.8	78.4	58.3	430
R125	C_2HF_5	120.02	−103.0	−48.5	66.3	35.9	571
R22	$CHClF_2$	86.47	−160.2	−40.9	96.2	49.9	513

3. RESULTS

Results of the thermal conductivity measurements are listed in Tables II (for R32) and III (for R125), together with temperature (ITS 90), pressure, and density as calculated from equations given in Refs. 8 and 9. Thermal conductivity of fluid substances is usually plotted vs density, and monotonously rising isotherms are obtained (if only states far away from the critical are considered) with dilute gas conductivities which increase with temperature. The ranges of liquid (high density) and vapor (low density) are plotted separately for both of the substances in Figs. 1 to 4, with the isotherms indicated as solid lines. The density effect is superimposed by an additional temperature effect, which is the dominating one for vapors (Figs. 2 and 4) but is almost vanishing for liquids (Figs. 1 and 3). The measured results are correlated with temperature and density by Eq. (1), which represents the background conductivity composed as a sum of the temperature-dependent dilute-gas term ($\lambda_0 = a_0 + a_1 t$) and the density-dependent excess or residual term with a negligible temperature effect:

$$\lambda(t, \rho) = a_0 + a_1 t + a_2 \rho + a_3 \rho^2 + a_4 \rho^3 + a_5 \rho^4 \tag{1}$$

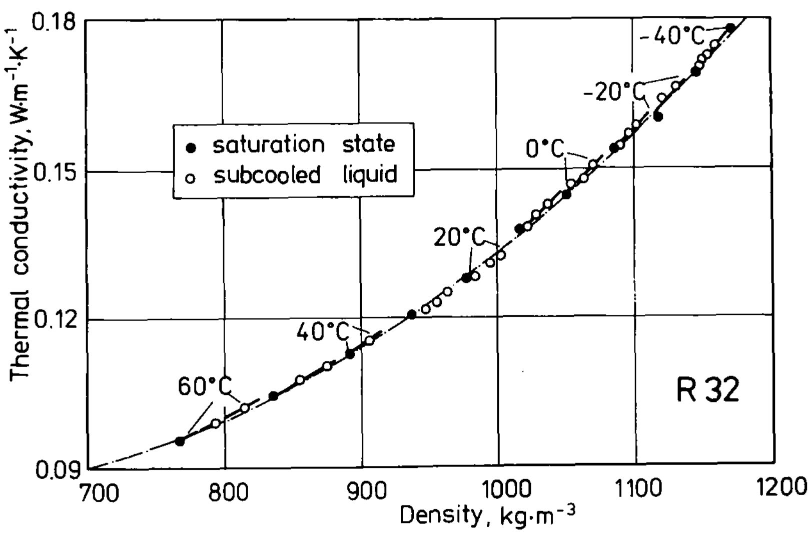

Fig. 1. Thermal conductivity of R32 versus density (liquid states).

Table II. Measured Thermal Conductivities for R32

t (°C)	p (bar)	ρ_{calc} ($kg \cdot m^{-3}$)	λ ($W \cdot m^{-1} \cdot K^{-1}$)
−39.7	10.60	1170.9	0.17762
−29.7	61.94	1159.8	0.17448
−29.7	36.61	1154.3	0.17239
−29.7	21.14	1151.5	0.17143
−29.7	11.89	1148.5	0.17038
−29.4	2.78	1145.5	0.16886
−19.5	60.97	1131.8	0.16594
−19.5	20.43	1121.3	0.16359
−19.6	4.09	1118.4	0.15981
−9.6	2.02	1102.3	0.15828
−9.6	40.85	1096.1	0.15683
−9.6	20.83	1090.0	0.15411
−9.6	5.84	1085.1	0.15367
0.5	61.71	1070.4	0.15027
0.4	41.41	1063.8	0.14748
0.4	15.92	1054.4	0.14639
0.5	8.14	1051.0	0.14429
10.4	61.16	1037.6	0.14264
10.5	41.47	1029.3	0.14058
10.4	25.72	1022.8	0.13788
10.4	11.07	1016.0	0.13740
20.4	61.04	1002.9	0.13223
20.4	45.61	995.4	0.13065
20.4	24.91	984.4	0.12782
20.5	14.70	978.2	0.12750
30.5	59.83	964.3	0.12491
30.5	46.98	956.4	0.12279
30.6	33.52	947.1	0.12114
30.6	19.22	936.8	0.12039
40.4	39.96	906.2	0.11491
40.4	24.62	891.5	0.11257
50.5	61.82	874.9	0.11003
50.5	44.71	855.2	0.10752
50.6	31.22	835.4	0.10427
60.6	61.87	814.7	0.10218
60.6	50.88	794.0	0.09908
60.6	39.41	766.4	0.09558

Table II. *(Continued)*

t (°C)	p (bar)	ρ_{calc} ($kg \cdot m^{-3}$)	λ ($W \cdot m^{-1} \cdot K^{-1}$)
−8.1	5.89	15.94	0.1220
−7.9	3.31	8.41	0.01134
−7.6	2.01	4.95	0.01079
−7.5	0.96	2.32	0.01061
11.4	10.77	29.00	0.01437
11.5	9.15	23.72	0.01403
11.7	7.74	19.50	0.01345
11.8	6.05	14.72	0.01290
11.9	3.51	8.19	0.01225
11.9	2.57	5.90	0.01213
12.1	1.08	2.42	0.01181
31.1	15.47	40.10	0.01667
31.4	12.84	31.69	0.01548
31.4	9.62	22.51	0.01453
31.1	7.14	16.14	0.01406
31.4	3.82	8.25	0.01405
31.7	2.50	5.32	0.01329
31.9	0.98	2.04	0.01321
51.0	29.14	85.02	0.02218
51.1	26.16	71.23	0.02086
51.2	23.41	60.46	0.01949
51.3	20.62	50.80	0.01837
51.4	18.15	43.07	0.01758
51.5	14.55	32.87	0.01663
51.4	11.71	25.56	0.01597
51.8	7.71	16.07	0.01530
51.6	4.13	8.32	0.01493
51.7	2.56	5.07	0.01483
51.8	1.11	2.18	0.01461
70.8	39.92	116.10	0.02655
70.8	39.62	114.44	0.02621
70.8	35.65	95.30	0.02457
70.9	33.54	86.51	0.02252
71.0	30.01	73.43	0.02220
71.1	26.63	62.29	0.02026
71.2	21.15	46.41	0.01898
71.3	15.76	32.75	0.01786
71.2	12.13	24.36	0.01741
71.4	8.77	17.11	0.01672
71.4	6.57	12.59	0.01658
71.5	3.96	7.43	0.01634
71.6	2.49	4.63	0.01605
71.8	0.98	1.79	0.01590

Table III. Measured Thermal Conductivities for R125

t (°C)	p (bar)	ρ_{calc} ($kg \cdot m^{-3}$)	λ ($W \cdot m^{-1} \cdot K^{-1}$)
−18.7	12.74	1415.1	0.08421
−19.7	3.33	1411.1	0.08426
−9.7	70.33	1399.8	0.08320
−9.7	52.49	1390.6	0.08175
−9.7	32.09	1379.2	0.08049
−9.6	17.57	1371.3	0.07931
−9.6	4.79	1370.0	0.07929
0.4	64.00	1358.5	0.07822
0.4	50.62	1350.5	0.07717
0.4	35.36	1340.8	0.07596
0.4	18.52	1329.1	0.07485
0.5	6.71	1320.1	0.07464
10.4	69.00	1320.5	0.07441
10.4	51.00	1307.7	0.07276
10.4	31.66	1292.6	0.07092
10.4	13.98	1276.9	0.07059
20.4	57.72	1267.2	0.07004
20.4	31.43	1241.7	0.06789
20.4	16.75	1224.8	0.06684
20.4	14.59	1222.1	0.06598
30.4	62.79	1223.7	0.06691
30.4	48.91	1207.8	0.06576
30.4	36.91	1192.4	0.06441
30.4	21.35	1168.8	0.06247
30.4	15.69	1158.8	0.06177
40.4	61.98	1170.3	0.06292
40.4	51.73	1154.7	0.06202
40.4	41.69	1137.7	0.06028
40.4	29.76	1113.6	0.05861
40.4	23.62	1098.6	0.05810
40.3	20.02	1088.5	0.05746
50.3	62.00	1110.5	0.05890
50.3	50.06	1085.5	0.05710
50.3	37.38	1051.1	0.05554
50.3	25.24	1000.2	0.05321
60.4	61.76	1040.2	0.05535
60.4	47.31	991.9	0.05297
60.3	37.66	938.8	0.05058
60.4	34.52	910.5	0.05079

Table III. *(Continued)*

t (°C)	p (bar)	ρ_{calc} $(kg \cdot m^{-3})$	λ $(W \cdot m^{-1} \cdot K^{-1})$
−18.43	3.31	21.20	0.01252
−18.40	2.20	13.46	0.01224
−18.30	1.21	7.14	0.01212
1.4	5.94	36.89	0.01426
1.5	4.47	26.37	0.01395
1.5	3.46	19.85	0.01374
1.8	2.12	11.71	0.01365
1.9	1.04	5.62	0.01343
21.2	10.93	69.43	0.01633
21.3	7.99	46.38	0.01569
21.4	4.84	26.02	0.01526
21.6	2.96	15.34	0.01514
21.8	1.11	5.56	0.01493
31.1	14.24	92.65	0.01767
31.2	11.20	66.33	0.01712
31.3	7.96	43.57	0.01662
41.0	19.17	134.96	0.01921
41.1	15.68	97.30	0.01822
41.2	13.82	81.54	0.01769
41.2	11.83	66.55	0.01768
41.3	8.22	43.00	0.01726
41.5	6.16	31.08	0.01701
41.6	4.10	19.97	0.01681
41.7	1.80	8.51	0.01662
50.8	24.86	196.68	0.02216
50.9	22.71	160.59	0.02063
51.0	20.70	135.75	0.02026
51.1	17.78	107.05	0.01908
51.1	13.01	70.52	0.01821
51.3	10.14	52.20	0.01800
51.4	7.01	34.33	0.01774
51.6	3.88	18.15	0.01746
51.7	1.80	8.24	0.01744
60.6	27.30	195.60	0.02312
60.8	25.40	169.30	0.02189
61.0	23.85	153.53	0.02090
61.0	20.62	122.00	0.02053
61.1	17.34	95.73	0.01929
61.1	14.70	77.35	0.01895

Table III. (*Continued*)

t (°C)	p (bar)	ρ_{calc} (kg · m^{-3})	λ (W · m^{-1} · K^{-1})
61.2	13.35	68.69	0.01907
61.3	9.80	47.80	0.01887
61.4	6.95	32.60	0.01830
61.5	4.05	18.32	0.01812
61.7	1.82	8.02	0.01807
70.5	31.51	220.45	0.02443
70.8	28.26	178.87	0.02309
70.8	26.47	160.10	0.02212
70.8	23.05	129.50	0.02084
70.8	21.30	115.90	0.02072
70.8	17.79	91.30	0.02022
71.0	15.42	76.50	0.01958
71.0	6.86	30.70	0.01930
71.0	4.23	18.50	0.01893
80.7	36.46	208.70	0.02406
80.8	33.16	177.40	0.02299
81.0	30.15	128.60	0.02178
80.9	24.29	103.80	0.02118
80.9	18.06	87.60	0.02093
81.0	13.11	60.10	0.02027
81.1	9.91	44.00	0.02016
81.2	7.07	30.60	0.01974
80.9	4.37	18.50	0.01991
81.1	1.92	8.00	0.01988

with λ in W · m^{-1} · K^{-1}, t in °C, ρ in kg · m^{-3}, and coefficients as listed in Table IV. Average and maximum deviations between measured data and those calculated from Eq. (1) amount to 1.5 and 5.1 %, respectively, for R32 and to 0.8 and 2.8 % for R125.

Saturation-state experiments could be performed only in the liquid phase. Respective results are represented in Figs. 1 and 3 as filled symbols interconnected by dashed–dotted curves. In the case of the vapor phase, hot-wire experiments failed close to saturation state due to condensation on the wires. Therefore extrapolation along isotherms up to saturation density was required for construction of respective saturation lines, which are again indicated as dashed–dotted curves in Figs. 2 and 4. To improve the correlation for the dilute-gas region, an additional regression was performed with only the vapor-state results:

$$\lambda(t, \rho) = b_0 + b_1 t + b_2 \rho + b_3 \rho^2 + b_4 \rho^3 + b_5 \rho^4 \qquad (2)$$

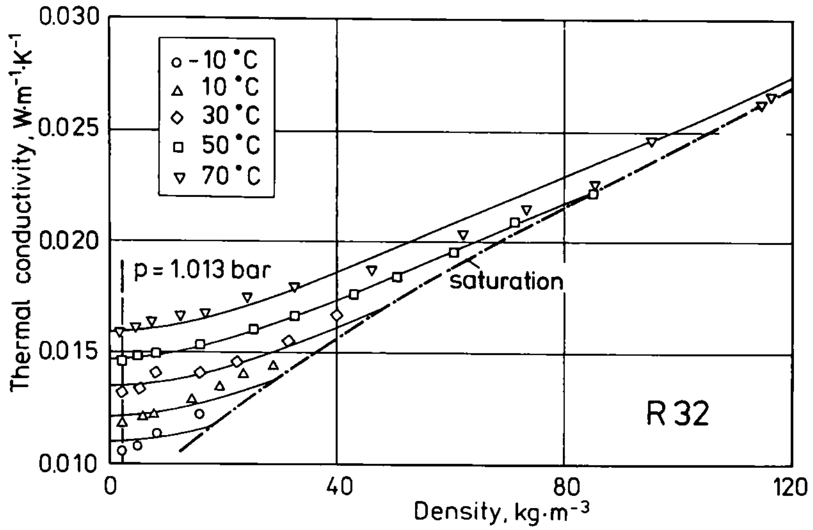

Fig. 2. Thermal conductivity of R32 versus density (vapor states) with isotherms as calculated from Eq. (2).

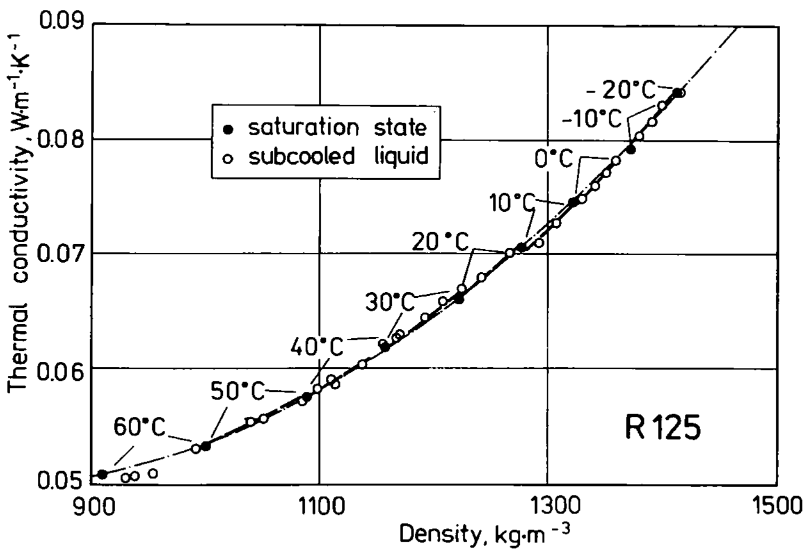

Fig. 3. Thermal conductivity of R125 versus density (liquid states).

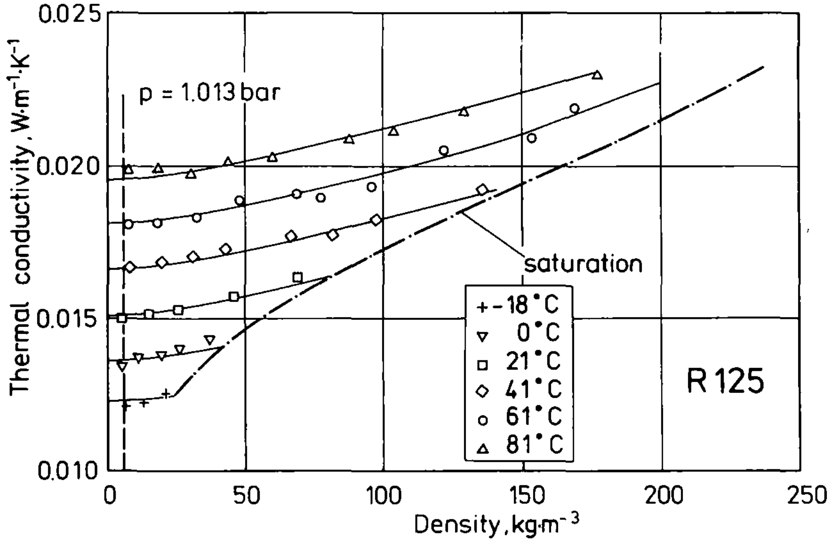

Fig. 4. Thermal conductivity of R125 versus density (vapor states) with isotherms as calculated from Eq. (2).

Coefficients are listed in Table V. By setting $b_2 = 0$, Eq. (2) contains no linear term in density and thus the density effect is strongly reduced close to the dilute-gas state.

For practical calculations, thermal conductivities for the saturation states (liquid and vapor) and also for the vapor state at ambient pressure ($p = 1.013$ bar) are of special interest. The latter ones approximately equal the dilute-gas state, which can easily be obtained from Eq. (2) by setting $\rho = 0$:

$$\lambda_0 = b_0 + b_1 t \tag{3}$$

Measured results and extrapolated conductivities for liquid and vapor

Table IV. Coefficients in Eq. (1)

	a_0	a_1	a_2	a_3	a_4	a_5
R32	0.0109723	5.77550×10^{-5}	9.31033×10^{-5}	6.37052×10^{-8}	-1.50746×10^{-10}	1.13899×10^{-13}
R125	0.0134765	7.17477×10^{-5}	1.31572×10^{-5}	7.04810×10^{-8}	-8.81454×10^{-11}	4.05117×10^{-14}

Table V. Coefficients of Eqs. (2) and (3)

	b_0	b_1	b_2	b_3	b_4	b_5
R32	0.0116203	6.12245×10^{-5}	0	2.43711×10^{-6}	-2.30405×10^{-8}	7.84471×10^{-11}
R125	0.0136023	7.33978×10^{-5}	0	3.45855×10^{-7}	-2.53852×10^{-9}	7.30234×10^{-12}

saturation states yield the following expressions, which are plotted in Fig. 5 together with measured results (for the coefficients, see Table VI):

$$\lambda' = c_0 + c_1 t \tag{4}$$

$$\lambda'' = d_0 + d_1 t + d_2 t^2 \tag{5}$$

Vapor thermal conductivities in ambient (λ_0) and saturation (λ'') states agree well at low temperatures, e.g., at the normal boiling point, but diverge at higher temperatures, where thermal conductivity is enhanced due to critical phenomena. Figure 5 also allows for a comparison between

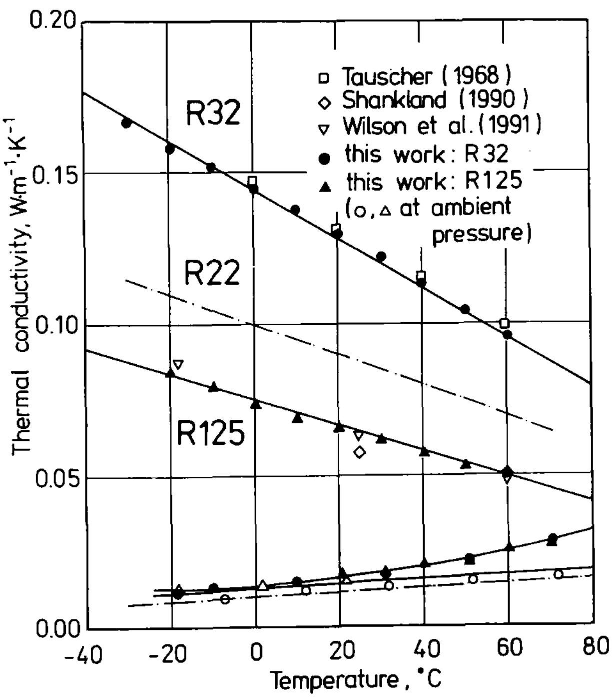

Fig. 5. Thermal conductivities of R125 and R32 in saturation states (liquid and vapor) and also for ambient pressure (vapor).

Table VI. Coefficients of Eqs. (4) and (5)

	c_0	c_1	d_0	d_1	d_2
R32	0.144406	-8.15468×10^{-4}	0.0128820	1.02638×10^{-4}	1.39213×10^{-6}
R125	0.0751149	-4.25636×10^{-4}	0.0136169	9.15667×10^{-5}	1.80195×10^{-6}

the present R32 and R125 results and the R22 curves (dashed–dotted lines) as suggested by ASHRAE [10]. The liquid-state thermal conductivity of R32 is highest, exceeding both the R22 values at the same temperature (by about 40%) and the R125 data (by about 100%). At vapor state (saturation or ambient) deviations between R125 and R32 are not significant, amounting to about 3 to 10%. Our own results are supplemented by some data available from the literature. The deviation between our's and Tauscher's [11] liquid R32 data is less than 2 or 3%. Regarding liquid R125, only three points by Wilson et al. [12] and two points by Shankland [13] were found in the literature. The former ones deviate from ours by between 2 and 5.2%; the latter ones, by 6 and 14.3%. The only vapor values, reported by Wilson et al. [12] for ambient pressure, differ from our data by 4.9 to 8.3%.

4. SUMMARY

We performed thermal conductivity measurements for several new refrigerants in the course of the last 7 years. Our R123, R134a, and R152a results, which have been published earlier [6], are now supplemented by the present data for R32 and R125 in both liquid and vapor states. The investigations cover wide ranges of temperature and pressure. Measured data have been correlated and respective equations are presented for all the substances.

ACKNOWLEDGMENTS

This investigation has been funded by the German "Bundesministerium für Forschung und Technologie" (BMFT). It is part of the New Refrigerants Research Program of the "Deutscher Kältetechnischer Verein" (DKV). The experiments have been performed during our stay at the "Institut für Thermodynamik und Wärmetechnik," Stuttgart University, under the guidance of Prof. Dr.-Ing. E. Hahne. The tested fluids were supplied by DuPont Company, Geneva, Switzerland.

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