Vapor-phase Thermal Conductivity of Binary Mixtures of Cyclopentane and R134a with R365mfc

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ABSTRACT: The thermal conductivity of mixtures of R365mfc (1,1,1,3,3-pentafluorobutane), with R134a (1,1,1,2-tetrafluoroethane) and cyclopentane were measured using a transient hot-wire method, in the pressure range between 0.1013 and 0.7 MPa and temperatures between 311 and 413 K. The composition of the measured mixtures was 93.0% R365mfc + 7.0% R134a (kg/kg), 27.0% R365mfc + 73.0% R134a (kg/kg) and 62.8% R365mfc + 37.2% Cyclopentane (kg/kg). The Wassiljewa mixing rules modified by Mason and Saxena and the Extended Corresponding States Theory were used to correlate and to predict the experimental results obtained, with an average absolute deviation of 1.8 and 10%, respectively.

KEY WORDS: blowing agents, fluoroalkanes, mixture, R365mfc, thermal conductivity, transient hot-wire method.

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INTRODUCTION

Rigid polyurethane foams (PUR) belong to the most effective insulation materials commercially available. Therefore, PUR foams are widely used for technical insulation purposes, e.g. in the appliance industry or for technical refrigeration processes. The heat transfer through the foam, that is important for the properties as an insulating material, is around 65% due to the blowing agents trapped inside of the cellular-foam formed by the polymer. Also, the pressure generated by the gaseous blowing agent and CO_2 in the closed cells of the foam has a strong influence on the stability of the foam.

Until recently, CFC-11 was the most widely used blowing agent to fill the closed cells in a polyurethane foam. Since 1987, with the establishment of the Montreal Protocol, and its reinforcement in 1992 in Copenhagen, a lot of research has been produced in order to find adequate substitutes for chlorofluorocarbons (CFC) in general, CFC-11 in particular. The vapor-phase thermal conductivity of several potential blowing agents, pure fluids as well as mixtures, has been measured. The vapor-phase thermal conductivity of pure fluids such as cyclopentane, and hydrofluorocarbons (HFC) derived from methane, ethane, propane and butane [1,2], and cyclopentane mixtures with lower boiling hydrocarbons have been recently measured [3,4]. In a previous paper [5], the vapor-phase thermal conductivity of R365mfc was measured at pressures up to 0.5 MPa and in the temperature range from 336.85 to 378.40 K. In the same line of research, this work addresses the measurement and correlation of the vapor-phase thermal conductivity of mixtures of R365mfc and R134a and R365mfc and cyclopentane in the pressure range 0.1013–0.8 MPa and in the temperature range of 311.25–413.28 K. The experimental method used was the transient hot-wire method, which is the IUPAC reference method [6].

The modified Wassiljewa mixing rules [13] modified by Mason and Saxena [14,15] were used to calculate the thermal conductivity of the mixtures investigated. The Extended Corresponding States Theory (ECST) [7] was used for predicting the experimental results.

EXPERIMENTAL

The experimental thermal conductivity measurements were carried out in an apparatus based on the transient hot-wire method [6]. Research on the use of a bare platinum wire or an anodized tantalum wire to measure the thermal conductivity of vapor polar compounds was

been done by other authors [8] and indicates that the results obtained with both methods were in good agreement.

An overview of the development and technical details of the measurements of the thermal conductivity of gases has been given elsewhere [9,10]. The measuring cell (stainless steel, 1.4571) with a length of 267 mm and diameter of 48 mm consists of two parallel chambers with bare platinum wires of different lengths (ratio of lengths ≈ 0.28) and 10 μm in diameter. The second wire was used to compensate the end effects. The cavity around the hot wires is made of stainless steel and has a diameter of 16 mm. The instrument is capable of operation from 298 to 523 K at pressures up to 2 MPa. The temperature was controlled with an air thermostat within ± 0.1 K. The temperature was measured using calibrated PT 100 resistance thermometers with an uncertainty within ± 0.1 K, which might lead to an error of $\pm 0.01 \, \mathrm{mW \, m^{-1} \, K^{-1}}$ or 0.06% for the thermal conductivity of R365mfc. More information on the apparatus has been given elsewhere [2]. The pressure sensors used in the measurements of the thermal conductivity were transducers from Keller, which were calibrated using a pressure balance (DESGRANGES ET HUOT; Druckblock 410, Type 26000 M, Terminal 20000). The uncertainty of the pressure measurement is within ± 0.1 kPa.

The basic theory behind the transient hot-wire method is given by Healy et al. [11]. The essential feature of the transient hot-wire method is the precise determination of the transient temperature with a thin metallic wire. This is determined from measurements of the resistance of the wire over a period of a few seconds followed by the initiation of the heating cycle, with a $\Delta T = (2.000 \pm 0.025)$ K. This resistance (temperature) is recorded with a digital voltmeter during the transient run. For cylindrical wires, with radius r_0, the ideal temperature rise ΔT on the surface of the wire can be calculated using Equation (1).

$$\Delta T_{\mathrm{id}} = \frac{q}{4\pi\lambda(T_{\mathrm{ref}}, \rho_{\mathrm{ref}})} \ln \frac{4at}{r_0^2 C} \qquad (1)$$

where $\lambda(T_{\mathrm{ref}}, \rho_{\mathrm{ref}})$ is the thermal conductivity at the temperature and density reference conditions, a is thermal diffusivity, $a = \lambda/(\rho C_P)$, q is the heat flow through the wire, t is the time, and $C = \exp(\gamma) = 1.7811\ldots$ is the exponential of Euler's constant γ.

In this work, several corrections to the ideal transient hot-wire method were made. These corrections can be divided in two main sources: corrections due to the wire and due to the existence of an outer

isothermal boundary layer. In the first correction, the finite radius of the wire (5 μm) is accounted for, which produces a short-time temperature lag relative to the ideal model. The second correction accounts for the penetration of the fluid temperature gradient to the outer cell wall, which leads to the transition from transient conduction into an infinite medium to steady-state conduction in a concentric cylindrical region. At lower pressures the linear region in the temperature rise versus the logarithm of elapsed time is reduced. This is due to the high thermal diffusivity of the gas, which is inversely proportional to the gas density.

In this work, the lowest pressures of the measurements were selected to give a sufficiently large linear portion to obtain reliable results for the slope of the temperature rise versus logarithm of time. For each temperature, between 40 and 80 individual data points were taken at different pressures.

Before starting the thermal conductivity measurements with the R365mfc mixtures, the accuracy of the apparatus was checked by measuring the thermal conductivity of carbon dioxide at two temperatures. The values obtained are in excellent agreement (relative difference of $\pm 0.03\%$) with the IUPAC recommended reference values [12]. The uncertainty at the level of 95% confidence of the experimental data, including the extrapolation of the data to atmospheric pressure, is estimated to be within $\pm 3\%$.

THERMAL CONDUCTIVITY MODELING

Two methods were used to calculate the thermal conductivity of the mixtures measured in this work: the Wassiljewa [13] mixing rules modified by Mason and Saxena [14,15] and the Extended Corresponding States Theory [7,16]. The gas mixture thermal conductivity, λ_m, using the Wassiljewa mixing rules can be calculated using Equation (2),

$$\lambda_m = \sum_{i=1}^{n} \frac{y_i \lambda_i}{\sum_{j=1}^{n} y_j A_{ij}} \tag{2}$$

where n is the number of components of the mixture, λ_i is the thermal conductivity of pure component i, y_i and y_j are mole fractions of i and j, respectively. The Wassiljewa function, A_{ij}, can be calculated as proposed by Mason and Saxena in Equation (3),

$$A_{ij} = \frac{\varepsilon \left[1 + \left(\lambda_{\mathrm{tri}}/\lambda_{\mathrm{trj}} \right)^{1/2} \left(M_i/M_j \right)^{1/4} \right]^2}{\left[8 \left(1 + M_i/M_j \right) \right]^{1/2}} \tag{3}$$

where M is the molecular weight, ε is an adjustable parameter near unity and λ_{tr} is the monatomic value of the thermal conductivity. The ratio of translational thermal conductivities, $\lambda_{tri}/\lambda_{trj}$, was calculated as proposed by Roy and Thodos [15],

$$\frac{\lambda_{tri}}{\lambda_{trj}} = \frac{\Gamma_j[\exp(0.0464T_{ri}) - \exp(-0.2412T_{ri})]}{\Gamma_i\left[\exp\left(0.0464T_{rj}\right) - \exp\left(-0.2412T_{rj}\right)\right]} \quad (4)$$

where T_r is the reduced temperature and Γ is given by Equation (5).

$$\Gamma = 210\left(\frac{T_c M^3}{P_c^4}\right)^{1/6} \quad (5)$$

The thermal conductivity was also predicted using the Extended Corresponding States Theory according to the formalism of Ely and Hanley [7], where the thermal conductivity is considered to be a summation of two terms: one arising from the transfer of energy due translational effects, λ^{trans}, and the other due to the internal degrees of freedom, λ^{int}. Thus,

$$\lambda(\rho, T) = \lambda^{trans}(\rho, T) + \lambda^{int}(T) \quad (6)$$

The contribution to λ^{trans} is expressed as a sum of a low-density contribution, λ^*, and a density-dependent contribution, λ^+,

$$\lambda^{trans}(\rho, T) = \lambda^*(T) + \lambda^+(\rho, T) \quad (7)$$

The exact equations to calculate these contributions have been derived before [7,16]. It was observed that the density-dependent translational contribution, $\lambda^+(\rho, T)$, is almost negligible for the thermal conductivity of low pressure gases (below few tenths of a percent), and the shape factors could be set to unity. The term $\lambda^{int}(T)$ has the dominating role in the thermal conductivity value of low-pressure gases. It is usually calculated using the modified Eucken correction for polyatomic gases [19]

$$\lambda^{int} = \frac{f_{int}\eta^*}{M}\left(Cp^{id} - \frac{5R}{2}\right) \quad (8)$$

where η^* is the dilute-gas viscosity, which can be estimated from kinetic theory, Cp^{id} the constant pressure ideal gas heat capacity, R the

universal gas constant and f_{int} a proportionality factor. In this work, Cp^{id} was calculated using Joback's group-contribution method [15]. In the original Eucken correlation, f_{int} is constant and equal to 1×10^{-3} when R and Cp^{id} are in $J\,mol^{-1}\,K^{-1}$, η^* is in $\mu Pa\,s$, M is in $g\,mol^{-1}$ and λ is in $W\,m^{-1}\,K^{-1}$. Huber et al. [16] used the value 1.32×10^{-3}. In this work, the thermal conductivity was calculated using the relationship suggested by Chapman and Cowling [20]

$$f_{int} = \frac{M\rho D}{\eta} \tag{9}$$

where D is the self-diffusion coefficient calculated by the Lee and Thodos correlation [21].

RESULTS

For three different mixtures, Mixture A, 93.0% R365mfc + 7.0% R134a (kg/kg), Mixture B, 27.0% R365mfc + 73.0% R134a (kg/kg) and Mixture C, 62.8% R365mfc + 37.2% Cyclopentane (kg/kg), the vapor-phase thermal conductivity was measured for different pressures at constant temperature. The experimental results are listed in Tables 1–3. In Figures 1–3, the pressure dependence of the thermal conductivity for each mixture in the working temperature range is presented. The usual behavior of gas thermal conductivity with pressure [15] is sometimes not observed. Instead, the thermal conductivity decreases with rising pressure. A possible explanation for this fact is a formation of an electric layer on the surface of the naked platinum wire due to the polar characteristics of the working fluids. These kind of fluids can solvate cations in the measuring cell, and with an increase of pressure, more molecules are engaged in the solvation process, meaning that less molecules are available for the energy transfer, and consequently the gas thermal conductivity decreases. The phenomenon increases with the increasing temperature. For example, in Figure 2, Mixture B, 27.0% of R365mfc with 73.0% of R134a (kg/kg), shows the increase of this effect with temperature.

The pressure dependence of the experimental results can be represented by a linear function

$$\lambda = a^{(1)}P + a^{(0)} \tag{6}$$

where P is the pressure in MPa and λ is in $mW\,m^{-1}\,K^{-1}$, as presented in the Tables 4–6, where $a^{(1)}$ and $a^{(0)}$ are the coefficients of the linear

Table 1. Vapor-phase thermal conductivity of mixture A, 93.0% of R365mfc + 7.0% of R134a (kg/kg), from 327.54 to 388.65 K; data points at 0.1013 MPa are extrapolated values.

$T = 327.54$ K		$T = 339.08$ K		$T = 354.59$ K		$T = 369.28$ K		$T = 388.65$ K	
P (MPa)	λ (mW m^{-1} K^{-1})	P (MPa)	λ (mW m^{-1} K^{-1})	P (MPa)	λ (mW m^{-1} K^{-1})	P (MPa)	λ (mW m^{-1} K^{-1})	P (MPa)	λ (mW m^{-1} K^{-1})
0.1013	17.59	0.1013	18.82	0.1013	20.21	0.1013	21.68	0.1013	23.91
0.1201	17.49	0.1189	18.92	0.1693	20.22	0.2251	21.41	0.2063	23.83
0.1202	17.51	0.1189	18.86	0.1714	20.18	0.2251	21.41	0.2064	23.74
0.1202	17.49	0.1191	18.65	0.1735	20.14	0.2252	21.47	0.2065	23.90
0.1203	17.43	0.1204	18.87	0.1751	20.17	0.2252	21.45	0.2065	23.81
0.1204	17.57	0.1206	18.84	0.1760	20.22	0.2253	21.52	0.2065	23.81
0.1205	17.54	0.1206	18.70	0.1777	20.20	0.2253	21.49	0.2066	23.98
0.1206	17.48	0.1209	18.69	0.2085	20.02	0.2253	21.51	0.2066	23.80
0.1206	17.49	0.1409	18.71	0.2117	19.84	0.2253	21.56	0.2066	23.83
0.1207	17.52	0.1413	18.64	0.2133	19.92	0.2254	21.56	0.2066	23.87
0.1208	17.52	0.1420	18.60	0.2135	19.77	0.2254	21.39	0.2066	23.88
0.1216	17.44	0.1426	18.61	0.2141	19.90	0.2803	21.27	0.3215	23.47
0.1493	17.34	0.1432	18.65	0.2147	20.03	0.2803	21.29	0.3216	23.42
0.1495	17.37	0.1436	18.54	0.2168	19.92	0.2804	21.36	0.3216	23.51
0.1499	17.35	0.1437	18.56	0.2172	20.02	0.2805	21.41	0.3216	23.49
0.1502	17.47	0.1439	18.54	0.2185	19.91	0.2807	21.44	0.3216	23.54
0.1505	17.31	0.1442	18.52	0.2188	19.81	0.2808	21.31	0.3217	23.41
0.1509	17.37	0.1446	18.53	0.2191	19.98	0.2809	21.31	0.3217	23.51
0.1513	17.38	0.1448	18.49	0.2201	19.96	0.2809	21.34	0.3217	23.35
0.1518	17.37	0.1450	18.38	0.2264	19.73	0.2810	21.30	0.3218	23.33
0.1521	17.29	0.1636	18.46	0.2304	19.79	0.2812	21.37	0.3218	23.36
0.1526	17.31	0.1646	18.44	0.2348	19.69	0.3674	21.15	0.4407	23.25
0.1530	17.38	0.1657	18.41	0.2512	19.93	0.3674	21.14	0.4408	23.17
0.1749	17.21	0.1669	18.48	0.2532	19.94	0.3675	21.16	0.4408	23.17
0.1752	17.25	0.1680	18.44	0.2552	19.97	0.3675	21.12	0.4408	23.11
0.1758	17.22	0.1693	18.38	0.2569	19.85	0.3676	21.17		

(continued)

Table 1. Continued.

T = 327.54 K		T = 339.08 K		T = 354.59 K		T = 369.28 K		T = 388.65 K	
P (MPa)	λ (mW m^{-1} K^{-1})	P (MPa)	λ (mW m^{-1} K^{-1})	P (MPa)	λ (mW m^{-1} K^{-1})	P (MPa)	λ (mW m^{-1} K^{-1})	P (MPa)	λ (mW m^{-1} K^{-1})
0.1013	17.59	0.1013	18.82	0.1013	20.21	0.1013	21.68	0.1013	23.91
0.1760	17.29	0.1705	18.39	0.2576	19.91	0.3676	21.17	0.4409	23.13
0.1769	17.24	0.1719	18.36	0.2587	19.91	0.3676	21.10	0.4409	23.19
0.1771	17.29	0.1939	18.43	0.2594	19.96	0.3676	21.20	0.4410	23.08
0.1777	17.25	0.1948	18.34	0.2598	19.96	0.3676	21.05	0.4410	23.14
0.1782	17.28	0.1970	18.42	0.2622	19.89	0.3676	21.21	0.4410	23.24
0.1786	17.24	0.1976	18.44	0.2644	19.94	0.4501	20.97	0.4410	23.21
0.1787	17.28	0.1988	18.36	0.2671	19.93	0.4502	21.21	0.5641	23.09
0.1795	17.24	0.2000	18.36	0.2686	19.96	0.4502	21.11	0.5642	23.11
0.1917	17.16	0.2006	18.44	0.2757	19.83	0.4502	21.06	0.5642	23.05
0.1927	17.15	0.2008	18.33	0.2803	19.94	0.4502	21.07	0.5642	22.89
0.1938	17.15			0.2851	19.85	0.4502	21.00	0.5642	23.12
0.1948	17.23			0.2859	19.84	0.4503	21.04	0.5643	23.03
0.1958	17.24			0.2886	19.82	0.4503	21.06	0.5643	22.98
0.1966	17.13			0.2901	19.86	0.4503	21.09	0.5643	23.04
0.1968	17.11			0.2911	19.88	0.4504	21.15	0.5643	22.95
0.1973	17.01			0.2936	19.87			0.5644	23.04
0.1975	17.27			0.2989	19.78			0.6676	23.23
				0.3000	19.76			0.6678	23.15
				0.3140	19.82			0.6683	23.25
				0.3223	19.82			0.6683	22.94
				0.3310	19.82			0.6684	22.95
				0.3369	19.76			0.6685	22.90
				0.3428	19.73			0.6685	22.99
								0.6686	23.05
								0.6686	22.94

Table 2. Vapor-phase thermal conductivity of mixture B, 27.0% of R365mfc + 73.0% of R134a (kg/kg), from 311.25 to 365.84 K; data points at 0.1013 MPa are extrapolated values.

$T = 311.25$ K		$T = 332.78$ K		$T = 365.84$ K	
P (MPa)	λ (mW m^{-1} K^{-1})	P (MPa)	λ (mW m^{-1} K^{-1})	P (MPa)	λ (mW m^{-1} K^{-1})
0.1013	15.70	0.1013	17.99	0.1013	21.41
0.1740	15.64	0.1930	17.80	0.2190	21.36
0.1741	15.69	0.1931	17.83	0.2191	21.25
0.1741	15.60	0.1931	17.85	0.2192	21.26
0.1741	15.67	0.1931	17.89	0.2192	21.34
0.1741	15.62	0.1932	17.94	0.2193	21.22
0.1741	15.62	0.1933	17.90	0.2194	21.25
0.1741	15.73	0.1933	17.90	0.2196	21.29
0.1741	15.65	0.1934	17.83	0.2196	21.31
0.1741	15.73	0.1937	18.01	0.2197	21.35
0.1742	15.66	0.1938	18.07	0.2687	21.19
0.2182	15.60	0.2681	17.77	0.2688	21.17
0.2183	15.63	0.2682	17.69	0.2688	21.11
0.2184	15.61	0.2682	17.67	0.2688	21.23
0.2185	15.58	0.2682	17.70	0.2690	21.14
0.2185	15.58	0.2682	17.72	0.2690	21.07
0.2186	15.62	0.2683	17.70	0.2691	21.13
0.2186	15.54	0.3444	17.62	0.2692	21.22
0.2187	15.55	0.3444	17.58	0.2692	21.26
0.2545	15.59	0.3444	17.62	0.3252	21.00
0.2554	15.54	0.3445	17.59	0.3253	21.13
0.2558	15.60	0.3445	17.59	0.3253	20.98
0.2564	15.52	0.3445	17.61	0.3255	21.09
0.2569	15.52	0.4726	17.46	0.3255	21.08
0.2574	15.60	0.4726	17.64	0.3255	20.98
0.2578	15.54	0.4726	17.59	0.3255	21.07
0.2583	15.56	0.4727	17.43	0.3255	20.97
0.2587	15.53	0.4728	17.55	0.3256	20.96
0.2592	15.54	0.4729	17.51	0.3852	20.84
0.2921	15.60	0.4730	17.47	0.3853	20.96
0.2922	15.56	0.4731	17.51	0.3853	20.90
0.2924	15.56			0.3853	20.86
0.2926	15.51			0.3853	20.87
0.2929	15.50			0.3853	20.89
0.2932	15.56			0.3853	20.91
0.2934	15.55			0.3853	20.94
0.2937	15.54			0.3853	20.88
0.2939	15.56			0.3854	20.94
0.2942	15.58			0.4524	21.05
0.3320	15.55			0.4524	20.89
0.3320	15.50			0.4524	20.95

(*continued*)

Table 2. Continued.

T = 311.25 K		T = 332.78 K		T = 365.84 K	
P (MPa)	λ (mW m⁻¹ K⁻¹)	P (MPa)	λ (mW m⁻¹ K⁻¹)	P (MPa)	λ (mW m⁻¹ K⁻¹)
0.3322	15.55			0.4525	20.98
0.3322	15.55			0.4525	20.95
0.3323	15.53			0.4525	20.95
0.3324	15.49			0.4525	21.05
0.3326	15.54			0.4525	20.93
0.3327	15.50			0.4526	20.84
0.3329	15.51			0.4526	20.93
0.3329	15.55			0.5311	20.84
				0.5312	20.75
				0.5313	20.78
				0.5314	20.74
				0.5316	20.89
				0.5318	20.96
				0.5319	20.76
				0.5321	20.67
				0.5323	20.74
				0.5326	20.84

equation. The values for atmospheric pressure were attained by an extrapolation of the experimental data at higher pressures. In the same tables, the temperature dependence of the thermal conductivity is represented by a linear function

$$\lambda = b^{(1)}T + b^{(0)} \tag{7}$$

where T is the temperature in K, $b^{(1)}$ and $b^{(0)}$ are the coefficients. If experimental data are available for four or more temperatures between the melting temperature and 90% of the critical temperature, the Dymond equation [11] can be used.

$$\lambda = A\big[1 + B(1 - T_r)^{1/3} + C(1 - T_r)^{2/3} + D(1 - T_r)\big] \tag{8}$$

where T_r is the reduced temperature and A, B, C and D are adjustable coefficients. As expected, the Dymond equation represents the experimental results better than the linear equation.

Figures 4 and 5 show the experimental thermal conductivity at 0.1013 MPa and the results of the thermal conductivity predicted with ECST. The ECST was described in detail in an earlier paper [5]. In Figure 6, the thermal conductivity at 0.1013 MPa of Mixtures A–C is compared with the thermal conductivity of some pure blowing agents,

Table 3. Vapor-phase thermal conductivity of Mixture C, 62.8% of R365mfc + 37.2% of cyclopentane (kg/kg), from 354.78 to 415.67 K; data points at 0.1013 MPa are extrapolated values.

T = 354.78 K		T = 370.53 K		T = 384.37 K		T = 397.27 K		T = 415.67 K	
P (MPa)	λ (mW m^{-1} K^{-1})	P (MPa)	λ (mW m^{-1} K^{-1})	P (MPa)	λ (mW m^{-1} K^{-1})	P (MPa)	λ (mW m^{-1} K^{-1})	P (MPa)	λ (mW m^{-1} K^{-1})
0.1013	19.90	0.1013	21.83	0.1013	23.50	0.1013	25.35	0.1013	27.57
0.1091	19.86	0.1068	21.88	0.1091	23.45	0.1130	25.33	0.2125	27.24
0.1092	19.86	0.1068	21.81	0.1091	23.71	0.1132	25.37	0.2125	27.31
0.1094	19.85	0.1069	21.74	0.1091	23.57	0.1132	25.44	0.2126	27.28
0.1095	19.86	0.1069	21.81	0.1091	23.52	0.1132	25.34	0.2127	27.09
0.1095	19.80	0.1069	21.79	0.1091	23.50	0.1132	25.59	0.2127	27.20
0.1096	19.85	0.1070	21.97	0.1091	23.59	0.1133	25.49	0.2127	27.35
0.1098	19.86	0.1072	21.63	0.1091	23.44	0.1134	25.40	0.2127	27.44
0.1099	19.73	0.1074	21.91	0.1091	23.81	0.1138	25.63	0.2127	27.60
0.1100	19.85	0.1078	21.79	0.1091	23.57	0.1138	25.74	0.2128	27.47
0.1366	19.66	0.1081	21.76	0.1092	23.59	0.1655	25.23	0.3014	27.13
0.1368	19.73	0.1366	21.62	0.1093	23.55	0.1662	25.03	0.3016	27.11
0.1369	19.63	0.1377	21.57	0.1093	23.52	0.1671	25.02	0.3017	27.11
0.1372	19.68	0.1389	21.58	0.1093	23.55	0.1675	25.11	0.3017	27.08
0.1373	19.71	0.1400	21.60	0.1722	23.21	0.1678	24.99	0.3017	27.04
0.1376	19.74	0.1425	21.54	0.1722	23.14	0.1679	24.95	0.3020	27.13
0.1378	19.59	0.1437	21.44	0.1723	23.09	0.1681	25.07	0.3021	27.01
0.1380	19.73	0.1450	21.49	0.1723	23.27	0.1683	24.94	0.3025	27.10
0.1381	19.69	0.1459	21.61	0.1723	23.19	0.1683	25.07	0.3038	27.10
0.1529	19.52	0.1468	21.54	0.1723	23.25	0.2370	24.78	0.4012	26.73
0.1539	19.41	0.1682	21.53	0.1724	23.32	0.2385	24.68	0.4015	26.79
0.1548	19.53	0.1691	21.42	0.1726	23.31	0.2391	24.89	0.4019	26.72
0.1557	19.60	0.1701	21.44	0.1728	23.32	0.2395	24.70	0.4024	26.82
0.1567	19.52	0.1713	21.45	0.1730	23.22	0.2402	24.94	0.4030	26.76
0.1577	19.43	0.1725	21.47	0.2287	22.94	0.2403	24.86	0.4037	26.69
0.1588	19.69	0.1739	21.48	0.2288	23.02	0.2406	24.69	0.4044	26.67
0.1600	19.59	0.1753	21.50	0.2289	23.12	0.2409	24.72	0.4050	26.80
0.1609	19.46	0.1767	21.49	0.2293	22.93	0.2412	24.76	0.4063	26.70

Table 3. Continued.

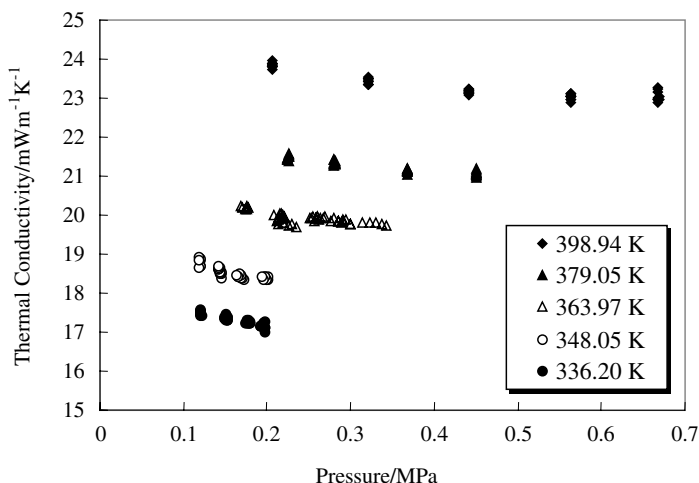| T = 354.78 K		T = 370.53 K		T = 384.37 K		T = 397.27 K		T = 415.67 K	
P (MPa)	λ (mW m^{-1} K^{-1})	P (MPa)	λ (mW m^{-1} K^{-1})	P (MPa)	λ (mW m^{-1} K^{-1})	P (MPa)	λ (mW m^{-1} K^{-1})	P (MPa)	λ (mW m^{-1} K^{-1})
0.1617	19.47	0.1777	21.36	0.2296	22.90	0.2414	24.59	0.4976	26.51
0.1646	19.55	0.1802	21.45	0.2298	23.05	0.3089	24.53	0.4979	26.75
0.1658	19.44	0.1837	21.34	0.2298	22.94	0.3091	24.53	0.4982	26.72
0.1669	19.56	0.1837	21.34	0.2301	22.86	0.3098	24.63	0.4985	26.71
0.1681	19.57	0.1844	21.35	0.2302	22.91	0.3098	24.50	0.4988	26.45
0.1694	19.47	0.1847	21.34	0.2304	23.03	0.3104	24.74	0.4992	26.55
0.1707	19.42	0.1853	21.39	0.2308	22.81	0.3108	24.59	0.4996	26.61
0.1721	19.45	0.1856	21.34	0.2956	22.76	0.3109	24.54	0.5001	26.68
0.1734	19.36	0.1864	21.34	0.2959	22.84	0.3112	24.60	0.5006	26.47
0.1749	19.44	0.1871	21.32	0.2963	22.88	0.3118	24.76	0.5012	26.45
		0.1879	21.28	0.2964	22.78	0.3125	24.50	0.6067	26.38
		0.1888	21.27	0.2967	22.84	0.3651	24.60	0.6072	26.39
		0.1897	21.50	0.2967	22.80	0.3653	24.28	0.6081	26.50
				0.2971	22.78	0.3655	24.46	0.6086	26.43
				0.2978	22.75	0.3657	24.39		
				0.2982	22.75	0.3659	24.49		
				0.2987	22.82	0.3660	24.44		
				0.3983	22.52	0.3660	24.33		
				0.3988	22.58	0.3662	24.56		
				0.3992	22.62	0.3663	24.42		
				0.3996	22.62	0.3666	24.70		
				0.4001	22.63	0.4318	24.24		
				0.4004	22.64	0.4321	24.30		
				0.4008	22.60	0.4321	24.32		
				0.4011	22.62	0.4322	24.42		
				0.4012	22.60	0.4328	24.33		
				0.4013	22.71	0.4329	24.37		
						0.4332	24.41		
						0.4332	24.41		
						0.4334	24.29		
						0.4335	24.44		

Figure 1. Pressure dependence of the thermal conductivity of 93.0% of R365mfc with 7.0% of R134a (kg/kg) at temperatures between 336.20 and 398.94 K.
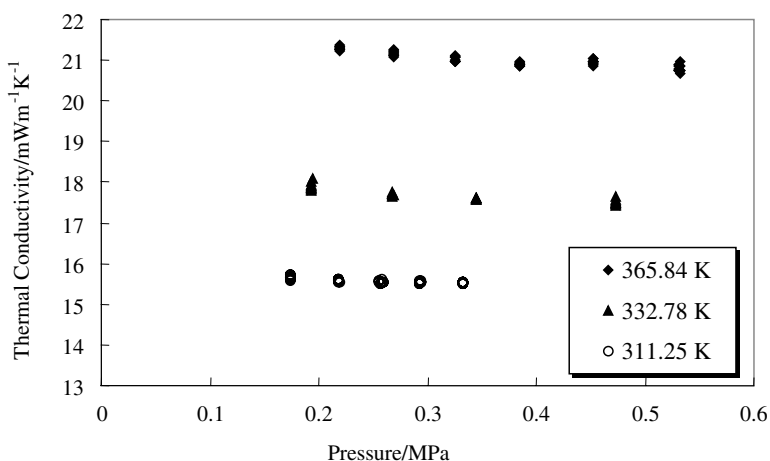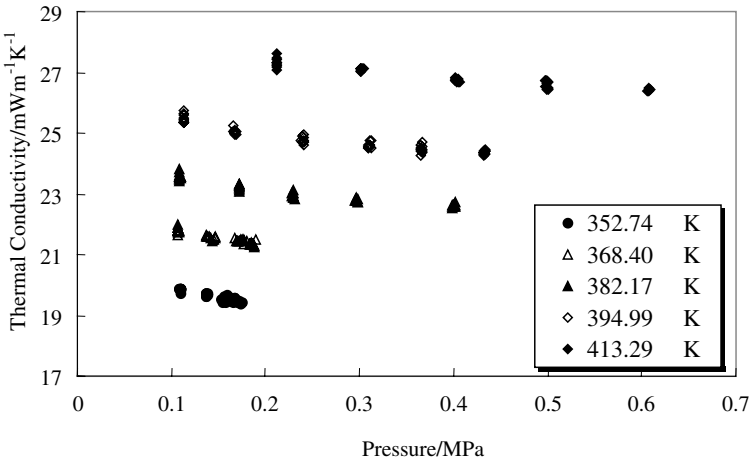

Figure 2. Pressure dependence of the thermal conductivity of 27.0% of R365mfc with 73.0% of R134a (kg/kg) at temperatures between 311.25 and 365.84 K.

both present and past: carbon dioxide, cyclopentane, HCFC141b, and CFC11 [4].

In Figures 7 and 8, the thermal conductivity of the mixtures R365mfc + R134a and R365mfc + cyclopentane at 0.1013 MPa as a function of the mole fraction of R365mfc is presented. Due to the

Figure 3. Pressure dependence of the thermal conductivity of 62.8% of R365mfc with 37.2% of cyclopentane (kg/kg) at temperatures between 352.74 and 413.29 K.

Table 4. Pressure and temperature dependence of the gas thermal conductivity of mixture A, 93.0% of R365 mfc with 7.0% of R134a (kg/kg).

Pressure dependence, Equation (6)

$a^{(1)}$	$a^{(0)}$	Temperature (K)
−4.444	18.034	327.54
−4.974	19.316	339.08
−1.982	20.410	354.59
−1.82	21.860	369.28
−1.77	24.085	388.65

Temperature dependence, Equation (8)

A	B	C	D	Pressure (MPa)
46.062	−1.2327	1.1973	−1.1669	0.1

similar thermal conductivity of the pure components in the investigated temperature range, in both systems the thermal conductivity goes through an extremum with rising content of R365mfc. While in the system R365mfc + cyclopentane (Figure 8), the thermal conductivity goes through a maximum with increasing content of R365mfc in the mixture; it goes through a minimum in the system R365mfc + R134a

Table 5. Pressure and temperature dependence of the gas thermal conductivity of mixture B, 27.0% of R365mfc with 73.0% of R134a (kg/kg).

Pressure dependence, Equation (6)

$a^{(1)}$	$a^{(0)}$	Temperature (K)
−0.7958	15.780	311.25
−1.341	18.121	332.78
−1.465	21.556	365.84

Temperature dependence, Equation (7)

$b^{(1)}$	$b^{(0)}$	Pressure (MPa)
0.1045	−16.8057	0.1

Table 6. Pressure and temperature dependence of the gas thermal conductivity of mixture C, 62.8% of R365mfc with 37.2% of cyclopentane (kg/kg).

Pressure dependence, Equation (6)

$a^{(1)}$	$a^{(0)}$	Temperature (K)
−6.29	20.531	354.78
−5.53	22.384	370.53
−3.29	23.832	384.37
−3.29	25.676	397.27
−2.44	27.814	415.67

Temperature dependence, Equation (8)

A	B	C	D	Pressure (MPa)
32.024	1.1686	−2.5352	−0.21493	0.1

(Figure 7). This latter behavior is similar to the behavior of the binary systems argon + n-pentane and argon + diethylether [22].

The modified Wassiljewa mixing rules by Mason and Saxena and ECST were applied to correlate and to predict the experimental results of these mixtures. In Table 7, the adjustable parameter, ε, for the modified Wassiljewa mixing rules is presented. As can be seen from Figures 7 and 8, the predictive ECST model shows a larger deviation from the experimental data, which is partly due to the fact that ECST does not precisely predict the pure-component thermal conductivity. For the systems investigated, the thermal conductivity predicted with ECST
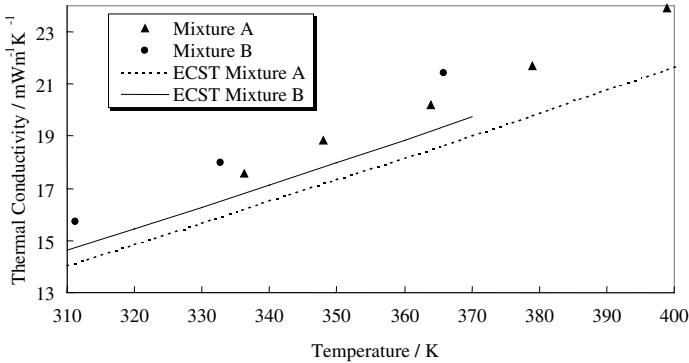
Figure 4. Experimental thermal conductivity at 0.1013 MPa compared with the ECST results for mixture A, 93.0% of R365mfc + 7.0% of R134a (kg/kg) and for mixture B, 27.0% of R365mfc + 73.0% of R134a (kg/kg).
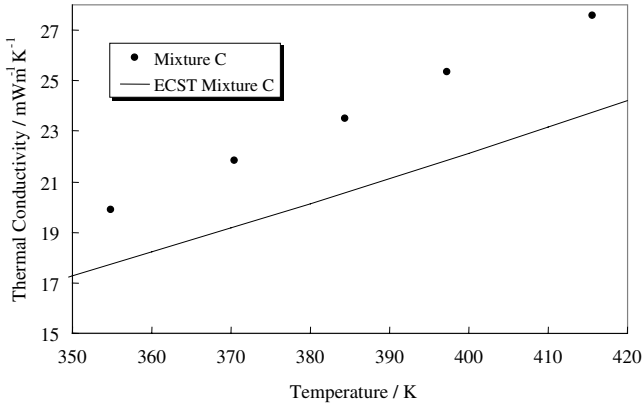

Figure 5. Experimental thermal conductivity at 0.1013 MPa compared with the ECST results for Mixture C, 62.8% of R365mfc + 37.2% of cyclopentane (kg/kg).

does not go through a maximum or minimum with changing composition of the mixture. Further work is needed in this field.

CONCLUSIONS

For mixtures of different composition of cyclopentane and R134a with R365mfc, the vapor-phase thermal conductivity was measured using the transient hot-wire method. Especially at higher temperatures, an unusual behavior of the vapor-phase thermal conductivity was observed that needs further investigation. Due to the similar thermal
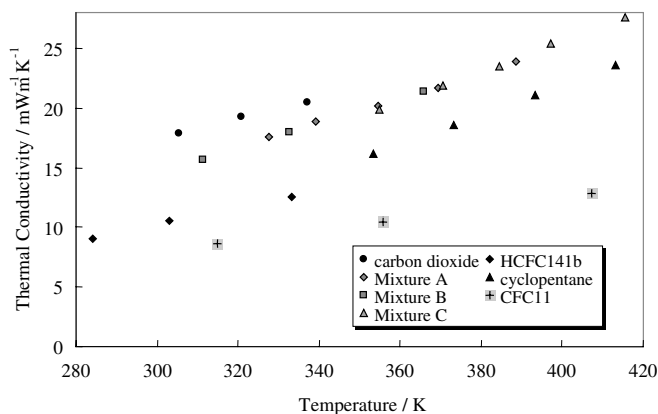
Figure 6. Experimental thermal conductivity of mixtures A–C and of pure blowing agents carbon dioxide, cyclopentane, HCFC141b, and CFC11 as a function of temperature at 0.1013 MPa.
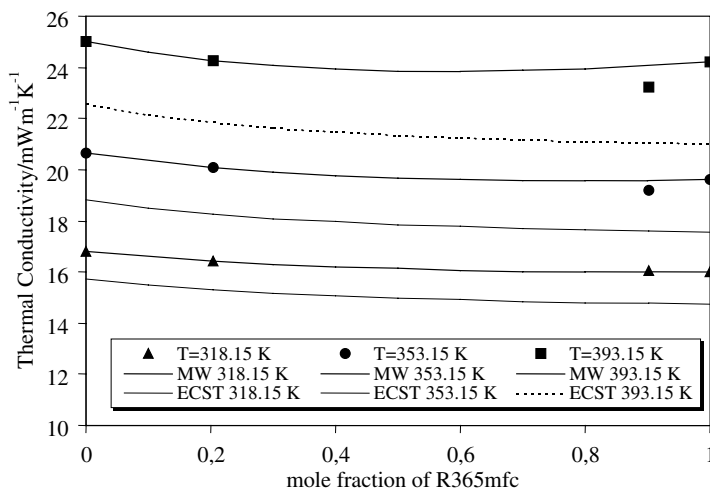

Figure 7. Comparison of the experimental thermal conductivity for the mixture of R365mfc with R134a at 0.1013 MPa with the modified Wassiljewa mixing rules and ECST.

conductivity of the pure components in the investigated temperature range, in both systems the thermal conductivity goes through an extremum with rising content of R365mfc.

The experimental data could be well correlated by using the modified Wassiljewa mixing rules by Mason and Saxena. Predictions using ECST
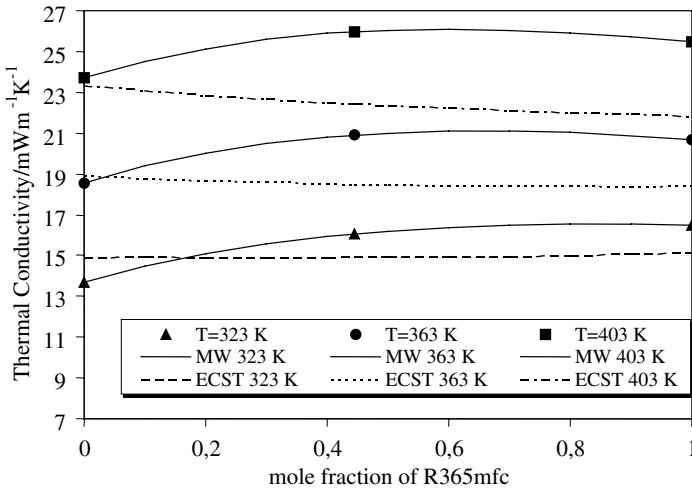
Figure 8. Comparison of the experimental thermal conductivity for the mixture of R365mfc with cyclopentane at 0.1013 MPa with the modified Wassiljewa mixing rules and ECST.

Table 7. The adjustable parameters, ε, of the Equation (4).

R365mfc with R134a		R365mfc with Cyclopentane	
T (K)	ε	*T* (K)	ε
318.15	1.02934	323.00	0.91503
353.15	1.03994	363.00	0.90813
393.15	1.06107	403.00	0.92500

lead to thermal conductivities that are in general lower than the experimental data. For the systems investigated, the thermal conductivities predicted with ECST do not go through a maximum or a minimum with changing composition of the mixture. Further research work is needed in this field.

NOMENCLATURE

Greek Symbols

$\lambda =$ thermal conductivity
$\gamma =$ Euler's constant
$\rho =$ density

Latin Symbols

$a =$ thermal diffusivity
$b =$ cell radius
$C =$ heat capacity
$C =$ constant, $C = \exp(\gamma)$
$P =$ total pressure
$q =$ heat flow through the wire
$r =$ radius of the wire
$T =$ temperature
$t =$ time
$\Delta T =$ temperature rise of the wire

Subscripts

$0 =$ designates the surface of the wire
$C =$ critical conditions
id $=$ ideal
$P =$ at constant pressure
$r =$ reduced value
ref $=$ at reference conditions

ACKNOWLEDGMENTS

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