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Relative Permittivity Measurements of Gaseous, Liquid, and Supercritical Dimethyl Ether

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The relative permittivity (ϵ_r) of dimethyl ether (DME) was measured as a function of temperature and pressure in the gaseous, liquid, and supercritical states. The temperature and pressure ranges studied were (303 to 403) K and (0.04 to 33.2) MPa, respectively. The relative permittivity was fitted to the reduced density (ρ_r) using the function $(\epsilon_r - 1)/(2\epsilon_r + 1)$, and the apparent dipole moment (μ^*) of the liquid phase was calculated using Kirkwood's theory of molecular polarizability.

Introduction

There is increasing demand for the chemical industry to develop new, cleaner, more acceptable chemical processes. One area for process modification is the solvent. An increasing amount of research is focusing on supercritical fluids as alternatives to conventional organic solvents. Supercritical fluids are used in chromatographic, reaction, and extraction process applications. They are of interest because the fluid density is a highly tunable function of pressure. Density-dependent properties such as viscosity, diffusivity, and relative permittivity (often called the dielectric constant) can be altered by up to an order of magnitude at temperatures close to the critical temperature (T_c) simply by altering the pressure. The relative permittivity (ϵ_r) is a macroscopic material property that is strongly related to molecular structure and can play an important role in solution properties.[1,2] Measurement of ϵ_r has been shown to be a useful technique for characterizing molecular interactions and molecular ordering.[3−5]

Dimethyl ether (DME) has been used as an aerosol propellant,[6] a refrigerant,[7,8] and a mobile phase in chromatographic applications[9] and has also been investigated as an alternative fuel.[10,11] Several publications report using DME as an alternative solvent for reaction[12,13] and extraction processes.[14,15]

Several research groups have investigated thermodynamic and physical properties of DME including saturated densities,[16] compressed liquid densities,[17,18] liquid viscosities,[19] vapor pressures,[20,21] surface tensions,[22,23] and critical parameters ($T_c = 400.4$ K; $P_c = 5.36$ MPa; $\rho_c = 272$ kg·m^{-3}),[16] but few researchers have characterized the fundamental solvent properties of this fluid. Lunt and Rau[24] reported that the relative permittivity of DME at 298 K was unaffected by frequency in the range (1 to 1000) kHz. Marsden and Maass[25] measured the relative permittivity of gaseous and liquid DME along the saturation curve from (298 to 409) K. In a later study, Lawley and Sutton[26] investigated the molecular association of DME in gas mixtures by measuring the pressure dependence of the relative permittivity. Gee et al.[27] reported the variation in the relative permittivity of DME against temperature in the range of (155 to 258) K. This work aims to further characterize the solvent properties of DME by reporting compressed liquid and supercritical relative permittivity data of the commercial grade solvent over a range of temperatures and pressures.

Experimental Section

The relative permittivity was measured using a direct capacitance method with the apparatus shown in Figure 1. The capacitance cell (CC) was connected to a Hewlett-Packard 4284A precision LCR meter (20 Hz to 1 MHz) using coaxial RG-316/U electrical leads (maximum working temperature 473 K) fitted with BNC connectors. The high-pressure electrical connectors for CC were supplied by Sitec Sieber Engineering (Switzerland). These were connected to an alternating six-plate capacitor manufactured at Industrial Research Limited. The capacitor plate spacing was 1 mm, and each circular plate was 20 mm in diameter.

The apparatus was heated in an oven to the desired temperature, which was monitored using a Type K ServoTech thermocouple (± 0.5 K), T1. The capacitance of CC was measured in air with an applied potential of 1.0 V at 60.0 kHz. The cell capacitance (C_o) was measured to be 16.55 pF and was found to be independent of temperature. The pressure dependence of the cell constant was negligible over the pressure ranges studied. Prior to experiment CC was purged with DME to remove the air, and pressure was applied using piston pump MP1. Pressure was monitored using gauge P1. Pressure measurements made in the liquid and supercritical phases have an associated uncertainty of ± 0.2 MPa. For gaseous phase measurements the pressures have an uncertainty of ± 0.02 MPa. The capacitance (C) of DME at given temperature and pressure conditions was measured, and ϵ_r was given by

$$\epsilon_r = \frac{C}{C_o} \qquad (1)$$

Each data point is the average of at least three replicate measurements (maximum standard deviation, σ, for a given condition over all temperatures and pressures studied = 0.01). Each replicate measurement was made by refilling CC with DME.

DME was supplied by Damar Industries Limited (New Zealand) with a purity of 99.8 % by volume and was used immediately as received. Impurities as stated by certificate of analysis were as follows: water, 60.0 μL·L^{-1}; methanol, 1.0

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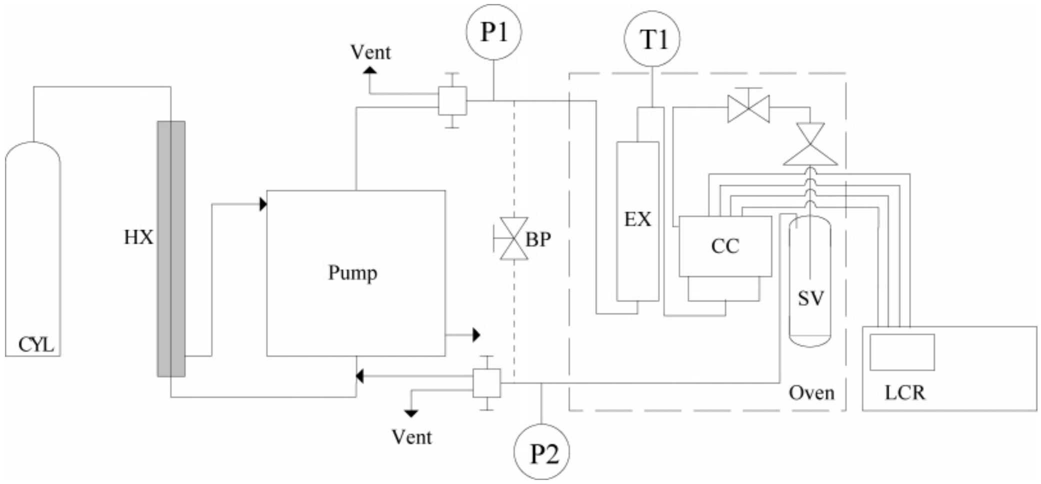

Figure 1. Apparatus used to measure the relative permittivity (ϵ_r) of DME: CYL, solvent cylinder; HX, heat exchanger; P1/2, pressure gauge; T1, temperature monitor; BP, bypass valve; CC, capacitance cell; LCR, Hewlett-Packard 4284A high-precision LCR meter (20 Hz to 1 MHz).

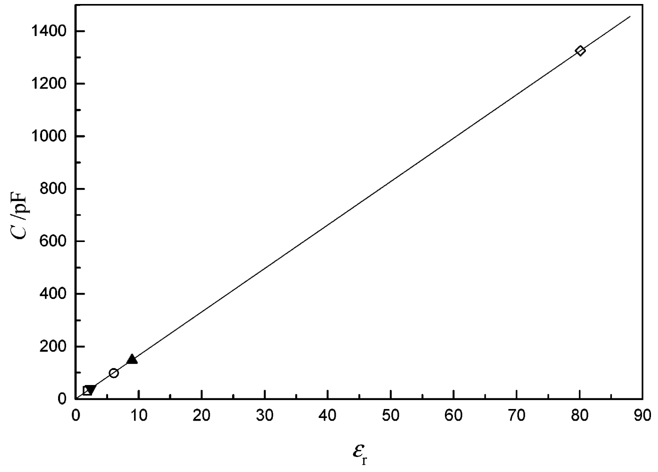

Figure 2. Measured capacitance (C) values vs expected (literature) relative permittivities (ϵ_r) for several pure liquids (ambient temperature and pressure) to determine the stray capacitance of the capacitance cell, CC: □, hexane;[28] ▼, toluene;[29] ○, ethyl acetate;[30] ▲, dichloromethane;[31] ◊, water.[32] $C = 16.5499\ \epsilon_r + 0.0550$ (standard deviation, $\sigma = 2.243$ pF).

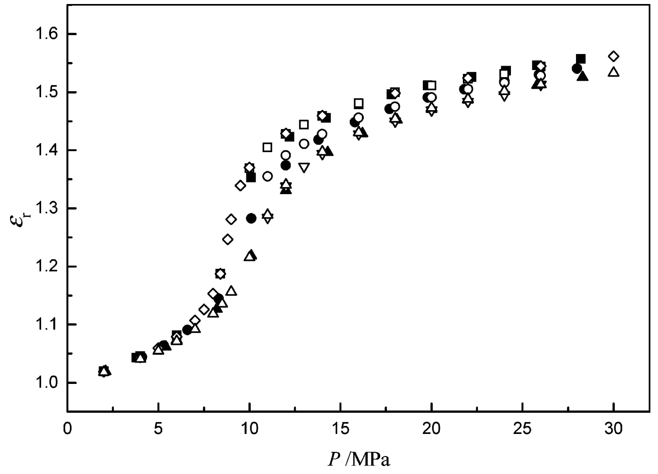

Figure 3. Validation of the equipment used in this work. Comparison of carbon dioxide relative permittivities (ϵ_r) with literature values: □, ref 33, 313.7 K; ○, ref 33, 318.3 K; ▽, ref 33, 323.3 K; ◊, ref 34, 313.2 K; △, ref 34, 323.2 K; ■, this work, 312.8 K; ●, this work, 318.0 K; ▲, this work, 323.5 K.

μL·L^{-1}; oil, 3.0 μL·L^{-1}; other gases (oxygen, carbon dioxide, nitrogen, propane, butane), volume fraction of 0.1 %.

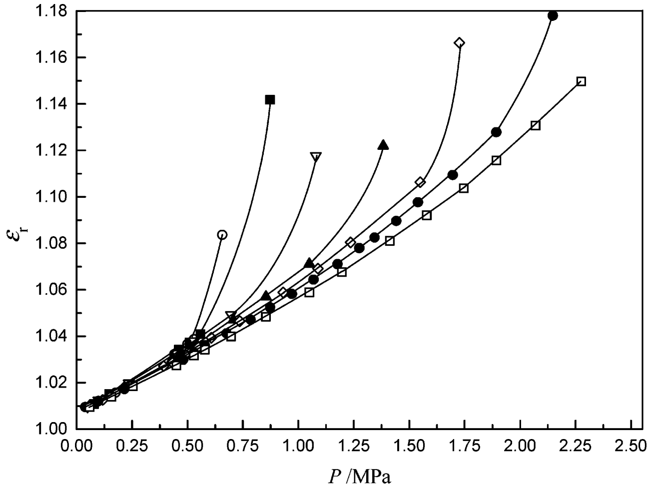

Figure 4. Pressure dependence of the relative permittivity (ϵ_r) of gaseous DME at various temperatures: ○, 303.7 K; ■, 313.3 K; ▽, 323.0 K; ▲, 333.4 K; ◊, 343.2 K; ●, 353.1 K; □, 363.4 K. Lines are drawn to aid the eye.

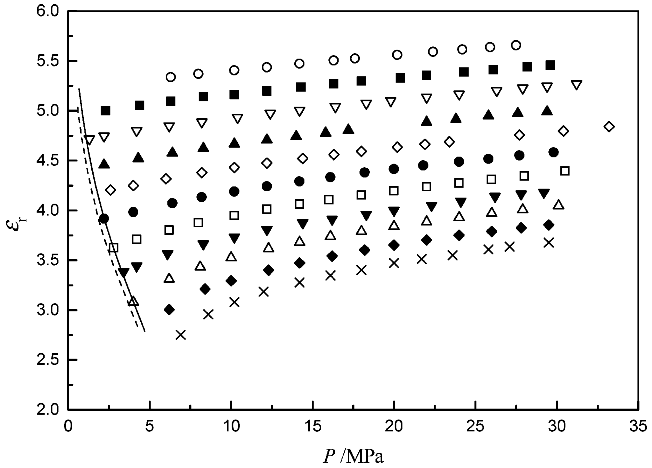

Figure 5. Pressure dependence of the relative permittivity (ϵ_r) of liquid and supercritical DME at various temperatures: ○, 303.7 K; ■, 313.3 K; ▽, 323.0 K; ▲, 333.4 K; ◊, 343.2 K; ●, 353.1 K; □, 363.4 K; ▼, 372.9 K; △, 382.9 K; ♦, 393.0 K; ×, 402.9 K; —, saturated liquid values from eq 2 in this work; - -, saturated liquid values of ref 25.

The equipment was validated at both ambient and high-pressure conditions. The stray capacitance of CC was obtained from the intercept of Figure 2, which shows a plot of expected

Table 1. Relative Permittivity (ϵ_r) Values for Gaseous (g), Liquid, and Supercritical DME at (303 to 403) K[a]

P/MPa	ϵ_r	ρ_{cal}/kg·m^{-3}	P/MPa	ϵ_r	ρ_{cal}/kg·m^{-3}	P/MPa	ϵ_r	ρ_{cal}/kg·m^{-3}	P/MPa	ϵ_r	ρ_{cal}/kg·m^{-3}	P/MPa	ϵ_r	ρ_{cal}/kg·m^{-3}
	T/K = 303.7			T/K = 313.3			T/K = 323.0			T/K = 333.4			T/K = 343.2	
0.18	1.01(6)(g)		0.08	1.01(1)(g)		0.05	1.01(0)(g)		0.43	1.03(0)(g)		0.06	1.01(0)(g)	
0.32	1.02(5)(g)		0.15	1.01(5)(g)		0.10	1.01(2)(g)		0.46	1.03(1)(g)		0.12	1.01(3)(g)	
0.44	1.03(2)(g)		0.46	1.03(4)(g)		0.24	1.02(0)(g)		0.54	1.03(6)(g)		0.22	1.01(8)(g)	
0.46	1.03(4)(g)		0.51	1.03(7)(g)		0.45	1.03(3)(g)		0.71	1.04(7)(g)		0.39	1.02(7)(g)	
0.50	1.03(7)(g)		0.56	1.04(1)(g)		0.53	1.03(8)(g)		0.85	1.05(7)(g)		0.43	1.02(9)(g)	
0.53	1.03(9)(g)		0.77	1.05(7)(g)		0.70	1.04(9)(g)		1.05	1.07(1)(g)		0.49	1.03(2)(g)	
0.66	1.08(4)(g)		0.87	1.14(2)(g)		1.08	1.11(8)(g)		1.38	1.12(2)(g)		0.55	1.03(5)(g)	
6.3	5.34	666.1	2.3	5.00	641.9	1.3	4.72	621.4	2.2	4.46	602.7	0.61	1.03(9)(g)	
8.0	5.37	669.4	4.4	5.05	647.2	2.2	4.74	624.5	4.3	4.52	610.2	0.74	1.04(6)(g)	
10.2	5.41	672.7	6.3	5.10	651.7	4.2	4.80	630.6	6.4	4.58	616.7	0.93	1.05(9)(g)	
12.2	5.44	675.7	8.3	5.14	656.3	6.2	4.85	635.7	8.3	4.62	622.1	1.09	1.06(9)(g)	
14.2	5.47	679.1	10.2	5.16	658.4	8.2	4.89	640.0	10.2	4.67	627.1	1.24	1.08(0)(g)	
16.3	5.50	682.1	12.2	5.20	662.0	10.4	4.93	644.8	12.2	4.71	631.4	1.55	1.10(6)(g)	
17.6	5.52	683.9	14.3	5.24	665.8	12.4	4.97	649.1	14.0	4.74	635.3	1.73	1.16(6)(g)	
20.2	5.56	687.3	16.3	5.27	669.0	14.2	5.01	652.3	15.8	4.78	638.9	2.6	4.21	582.7
22.4	5.59	690.0	18.0	5.30	671.7	16.4	5.04	655.9	17.2	4.81	641.9	4.0	4.25	588.4
24.2	5.62	692.2	20.4	5.33	674.7	18.3	5.07	659.3	22.0	4.89	650.2	6.0	4.32	596.8
25.9	5.64	694.1	22.0	5.35	677.1	19.8	5.10	661.8	23.8	4.92	653.3	8.2	4.38	604.3
27.5	5.66	696.0	24.3	5.39	680.1	22.0	5.13	665.2	25.8	4.95	656.4	10.2	4.43	610.5
			26.1	5.41	682.4	24.0	5.17	668.2	27.6	4.97	659.0	12.2	4.48	615.7
			28.2	5.44	685.0	26.3	5.20	671.6	29.4	4.99	660.7	14.4	4.52	620.8
			29.6	5.46	686.4	27.9	5.23	674.0				16.3	4.56	625.3
						29.4	5.25	675.8				18.0	4.59	628.9
						31.2	5.27	678.1				20.2	4.64	633.5
												21.9	4.67	636.7
												23.4	4.69	639.2
												27.7	4.76	646.3
												30.4	4.80	650.4
												33.2	4.84	655.0
	T/K = 353.1			T/K = 363.4			T/K = 372.9			T/K = 382.9			T/K = 393.0	
0.04	1.01(0)(g)		0.85	1.04(8)(g)		3.4	3.38	498.5	4.0	3.08	457.3	6.2	3.01	
0.10	1.01(2)(g)		1.05	1.05(9)(g)		4.2	3.44	508.3	6.2	3.31	499.2	8.4	3.21	
0.22	1.01(7)(g)		1.20	1.06(8)(g)		6.1	3.57	528.1	8.1	3.43	519.6	10.0	3.30	
0.48	1.03(0)(g)		1.41	1.08(1)(g)		8.3	3.66	543.2	10.0	3.53	534.2	12.3	3.40	
0.53	1.03(3)(g)		1.58	1.09(2)(g)		10.2	3.73	553.1	12.3	3.62	547.9	14.2	3.47	
0.58	1.03(6)(g)		1.75	1.10(4)(g)		12.2	3.81	563.8	14.2	3.68	557.1	16.2	3.54	
0.68	1.04(1)(g)		1.89	1.11(6)(g)		14.4	3.88	572.9	16.1	3.74	565.3	18.2	3.60	
0.78	1.04(7)(g)		2.07	1.13(1)(g)		16.2	3.91	577.0	18.0	3.79	572.2	20.0	3.65	
0.87	1.05(2)(g)		2.28	1.15(0)(g)		18.3	3.96	582.4	20.0	3.84	578.9	22.0	3.70	
0.97	1.05(8)(g)		2.8	3.63	525.7	20.0	4.00	586.7	22.0	3.89	584.8	24.0	3.75	
1.07	1.06(4)(g)		4.2	3.71	538.4	22.3	4.05	592.9	24.0	3.93	590.4	26.0	3.79	
1.18	1.07(1)(g)		6.2	3.80	552.0	24.1	4.09	600.5	26.0	3.97	595.5	27.8	3.83	
1.27	1.07(8)(g)		8.0	3.88	562.7	26.2	4.14	606.4	27.9	4.01	600.1	29.5	3.86	
1.34	1.08(2)(g)		10.2	3.95	572.5	27.8	4.16	609.3	30.1	4.05	605.0			
1.44	1.09(0)(g)		12.2	4.01	580.7	29.2	4.18	611.3						
1.54	1.09(8)(g)		14.2	4.06	587.3								T/K = 402.9	
1.70	1.10(9)(g)		16.0	4.11	593.1							6.9	2.75[b]	
1.89	1.12(8)(g)		18.0	4.16	598.8							8.6	2.96[b]	
2.15	1.17(8)(g)		20.0	4.20	603.9							10.2	3.08[b]	
2.2	3.92	556.0	22.0	4.24	608.6							12.0	3.19[b]	
4.0	3.98	565.0	24.0	4.28	613.1							14.2	3.28[b]	
6.4	4.07	576.8	26.0	4.31	617.3							16.1	3.35[b]	
8.2	4.13	584.8	28.0	4.35	621.2							18.0	3.40[b]	
10.2	4.19	591.9	30.5	4.40	626.7							20.0	3.47[b]	
12.2	4.24	598.6										21.7	3.51[b]	
14.2	4.29	604.4										23.6	3.55[b]	
16.1	4.33	609.5										25.8	3.61[b]	
18.2	4.38	614.9										27.1	3.64[b]	
20.0	4.42	619.0										29.5	3.68[b]	
21.8	4.45	622.9												
24.0	4.49	627.2												
25.8	4.52	630.4												
27.7	4.55	634.0												
29.8	4.58	637.3												

[a] Liquid densities (ρ_{cal}) at (303 to 383) K were calculated using eq 2. Numbers in parentheses for the gas-phase data indicate the third decimal place value. [b] Supercritical.

(literature) ϵ_r versus measured C for several pure liquids (hexane,[28] toluene,[29] ethyl acetate,[30] dichloromethane,[31] and water[32]) of known ϵ_r under ambient conditions. The stray capacitance was subtracted from the measured capacitance values. Carbon dioxide ϵ_r values from this work are compared to literature values[33,34] at various temperatures and elevated pressures in Figure 3. The ambient and high-pressure ϵ_r values from this work varied from literature values[28−34] by no more than 1.5 %. DME ϵ_r measurements were carried out in the gaseous, liquid, and supercritical states with an uncertainty of

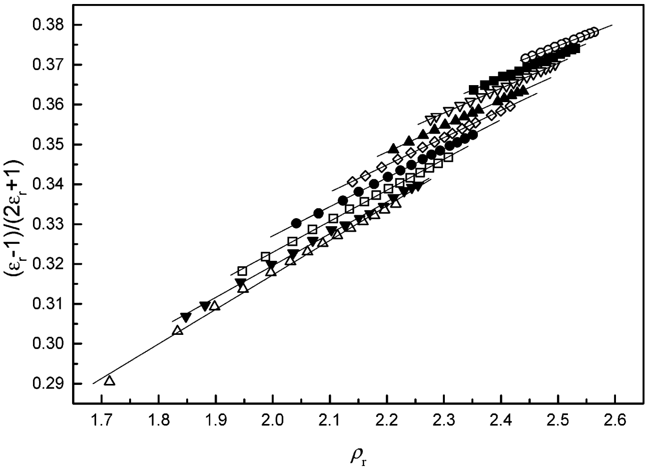

Figure 6. Linear dependency of ($\epsilon_r - 1$)/($2\epsilon_r + 1$) on the reduced density (ρ_r) of liquid DME. The standard deviation (σ) for each linear correlation is given in parentheses: ○, 303.7 K (3.4×10^{-5}); ■, 313.3 K (9.3×10^{-5}); ▽, 323.0 K (6.4×10^{-5}); ▲, 333.4 K (9.6×10^{-5}); ◇, 343.2 K (1.0×10^{-4}); ●, 353.1 K (1.2×10^{-4}); □, 363.4 K (2.6×10^{-4}); ▼, 372.9 K (5.1×10^{-4}); △, 382.9 K (8.5×10^{-4}).

± 1.5 %. Values of DME liquid densities from (303 to 383) K were calculated from the equations of Ihmels and Lemmon,[17] with an uncertainty of ± 0.1 %.

Results

Figures 4 and 5 show the relative permittivity of DME as a function of temperature and pressure compiled from the data in Table 1. The relative permittivity increases with increasing pressure and decreasing temperature. Hence, the isothermal density dependence, $(\delta\epsilon_r/\delta\rho)_T$, of ϵ_r is always positive, and ϵ_r has a linear dependency on density. The observed temperature dependent behavior is due to the presence of a dipole in the DME molecule. As temperature is increased the molecular thermal motion increases, and the ability of the molecules to orient and align their dipoles with the applied electric field is reduced. This reduced alignment of dipoles leads to a reduction in ϵ_r at higher temperatures.

As carried out previously for hydrofluorocarbon solvents,[35] the relative permittivity data was fitted to

$$\frac{\epsilon_r - 1}{2\epsilon_r + 1} = A + B\rho_r \qquad (2)$$

where ρ_r is the reduced density ($\rho_r = \rho/\rho_c$, where ρ is the density at given temperature and pressure conditions and ρ_c is the critical density), and A and B are constants given by

$$A = 0.4892297 - 0.000879626T \qquad (3)$$

$$B = 0.0002663T - 0.019856933 \qquad (4)$$

where T is the temperature in K. Fitting was carried out using literature[17] liquid densities from (303 to 383) K, and the correlation has a maximum deviation in density, [(calculated − literature)/calculated] × 100, of ± 1.9 %. The function ($\epsilon_r - 1$)/($2\epsilon_r + 1$) varies linearly with the isothermal reduced density (Figure 6), and the constants of proportionality vary linearly with T (Figure 7). Liquid densities (ρ_{cal}) for DME at (303 to 383) K and (1.3 to 33.2) MPa calculated using eq 2 are reported in Table 1.

The saturated liquid densities of DME were calculated according to Wu et al.,[16] and eq 2 was used to calculate the saturated liquid ϵ_r values at (303 to 393) K. The results are compared to the values of Marsden and Maass[25] in Figure 5. The values in this work are slightly greater than those reported by Marsden and Maass with a maximum deviation of ± 5.6 %. The DME used by Marsden and Maass was distilled before use, and the observed deviation could be due to the impurities present in the commercial grade solvent used in the current work.

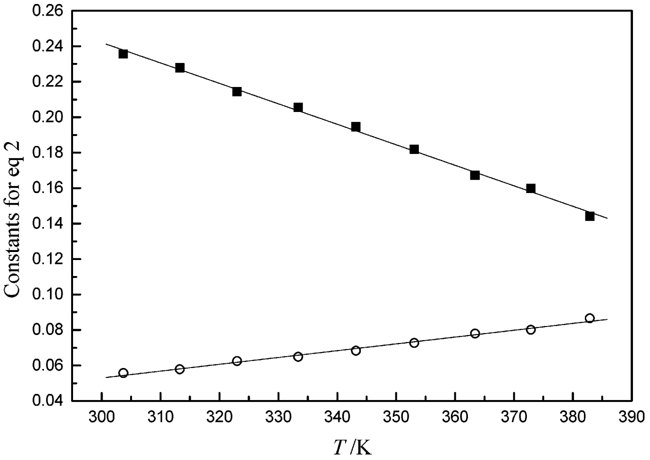

Figure 7. Linear dependency on temperature for the constants of proportionality for eq 2. The standard deviation (σ) for each linear correlation is given in parentheses: ■, A (0.002); ○, B (0.001).

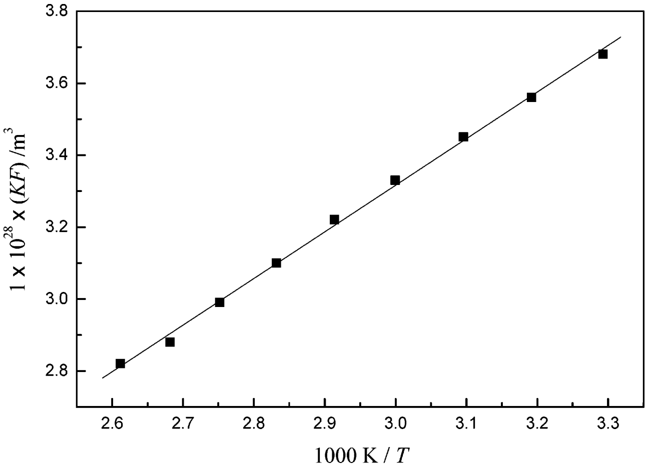

Figure 8. Determination of the apparent dipole moment (μ^*) of DME in the liquid phase by the Kirkwood representation ($\sigma = 1.44 \times 10^{-30}$ m^3).

It has been shown previously[36] that Kirkwood's theory of molecular polarizability[37] can be used to estimate the dipole moment of liquid solvents. The apparent dipole moment (μ^*) of a polar liquid can be related to ϵ_r through

$$\mathrm{KF} = \frac{(\epsilon_r - 1)(2\epsilon_r + 1)}{9\epsilon_r}\left(\frac{3M}{N_A\rho}\right) = \left(\alpha + \frac{\mu^{*2}}{3\epsilon_o k_B T}\right) \qquad (5)$$

where M is the molar mass, N_A is the Avogadro constant, α is the molecular polarizability, ϵ_o is the vacuum permittivity, and k_B is the Boltzmann constant.

By performing a linear regression as a function of $1/T$, the value of μ^* can be determined. The Kirkwood function (KF) was approximately independent of density at each temperature. The mean KF is plotted as a function of $1/T$ from (303 to 383) K in Figure 8, giving a μ^* value for DME of $\{(6.89 \pm 0.1) \times 10^{-30}\}$ C·m. The uncertainty is based on the uncertainties associated with the density values (± 0.1 %),[17] temperature measurements (± 0.5 K), and relative permittivity values (± 1.5 %). The gas-phase dipole moment (μ) for DME is reported to be 4.37×10^{-30} C·m.[38] The apparent liquid-phase dipole moment is greater than that of the gas phase because of the dipole inducing effect of neighboring molecules in the liquid state. The apparent liquid-phase and gas-phase dipole moments are related through $\mu = g^{1/2}\mu^*$, where g is the Kirkwood correlation parameter, which is a measure of the restriction to rotation imposed by a cage of molecules around a given molecule.[36]

Conclusion

The relative permittivity of gaseous, liquid, and supercritical DME has been measured at temperatures ranging from (303 to 403) K and at pressures from (0.04 to 33.2) MPa. Under these conditions, the isothermal pressure dependence of the relative permittivity, $(\delta\epsilon_r/\delta P)_T$, is always positive and the isobaric temperature dependence, $(\delta\epsilon_r/\delta T)_P$, is always negative. The relative permittivity has been fitted to the reduced density at (303 to 383) K using the function $(\epsilon_r - 1)/(2\epsilon_r + 1)$. At pressures above the saturation curve and in the temperature range of (303 to 383) K, this function can be used to calculate the liquid densities of DME to within ± 1.9 % of experimental values. The apparent dipole moment of DME in the liquid phase is also reported.

Acknowledgment

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Literature Cited

(1) Dannhauser, W.; Flueckinger, A. F. Dielectric constant and intermolecular association of some liquid nitriles. *J. Phys. Chem.* **1964**, *68*, 1814−1819.

(2) Janini, G. M.; Katrib, A. H. Determination of the dipole moment of polar compounds in nonpolar solvents. *J. Chem. Educ.* **1983**, *60*, 1087−1088.

(3) Ghanadzadeh, A.; Beevers, M. S. Effect of surface and molecular structure on the dielectric behaviour in thick layers of cyanobiphenyl liquid crystals. *J. Mol. Liq.* **2002**, *100*, 47−57.

(4) Ghanadzadeh, A.; Beevers, M. S. Dielectric investigations and molecular association in non-mesogenic and mesogenic solutions. *J. Mol. Liq.* **2003**, *102*, 365−377.

(5) Ghanadzadeh, A.; Mamaghani, M.; Anbir, J. Dipole moments and intermolecular association of some carbonyl compounds in nonpolar solvents. *J. Solution Chem.* **2003**, *32*, 625−636.

(6) Bohnenn, L. J. M. DME: further data on this alternative propellant. *Manuf. Chem. Aerosol News* **1978**, *August*, 39 and 63.

(7) Bobbo, S.; Camporese, R. (Vapour + liquid) equilibrium measurements and correlations of the refrigerant mixture {dimethyl ether (RE170) + 1, 1,1,3,3,3-hexafluoropropane (R236fa)} at the temperatures (303.68 and 323.75) K. *J. Chem. Thermodyn.* **1998**, *30*, 1041−1046.

(8) Jung, D.; Lee, H.; Bae, D.; Oho, S. Nucleate boiling heat transfer coefficients of flammable refrigerants. *Int. J. Refrig.* **2004**, *27*, 409−414.

(9) Leyendecker, D.; Schmitz, F. P.; Klesper, E. Chromatography with sub- and supercritical eluents: The influence of temperature, pressure and flow-rate on the behavior of dimethyl and diethyl ether. *J. Chromatogr.* **1984**, *315*, 19−30.

(10) de Pontes, M.; Espinoza, R. L.; Nicolaids, C. P.; Scholz, J. H.; Scurrell, M. S. Dimethyl ether: a fuel for the 21st century. *Natural Gas Conversion IV*; Studies Surface Science and Catalysis No. 107; Elsevier Science B.V.: Amsterdam, 1997; pp 117−125.

(11) Müller, J. T.; Urban, P. M.; Hölderich, W. F.; Colbow, K. M.; Zhang, J.; Wilkinson, D. P. Electro-oxidation of dimethyl ether in a polymer-electrolyte-membrane fuel cell. *J. Electrochem. Soc.* **2000**, *147*, 4058−4060.

(12) Chopey, N. Newsfront: hydrogenation in single phase shows promise. *Chem. Eng.* **2003**, *110*, 33−34.

(13) Lu, J.; Lazzaroni, M. J.; Hallett, J. P.; Bommarius, A. S.; Liotta, C. L.; Eckert, C. A. Tunable solvents for homogeneous catalyst recycle. *Ind. Eng. Chem. Res.* **2004**, *43*, 1586−1590.

(14) Catchpole, O. J.; Grey, J. B.; Perry, N. B.; Burgess, E. J.; Redmond, W. A.; Porter, N. G. Extraction of chili, black pepper, and ginger with near-critical CO_2, propane, and dimethyl ether: analysis of the extracts by quantitative nuclear magnetic resonance. *J. Agric. Food Chem.* **2003**, *51*, 4853−4860.

(15) Drescher, M.; Peter, S.; Weidner, E. Investigations on physical refining of animal fats and vegetable oils. *Fett/Lipid* **1999**, *4*, 138−141.

(16) Wu, J.; Liu, Z.; Wang, B.; Pan, J. Measurement of the critical parameters and the saturation densities of dimethyl ether. *J. Chem. Eng. Data* **2004**, *49*, 704−708.

(17) Ihmels, E. C.; Lemmon, E. W. Experimental densities, vapor pressures, and critical point, and a fundamental equation of state for dimethyl ether. *Fluid Phase Equilib.* **2006**, doi: 10.1016/j.fluid.2006.09.016.

(18) Bobbo, S.; Scattolini, M.; Fedele, L.; Camporese, R. Compressed liquid densities and saturated liquid densities of dimethyl ether (RE170). *J. Chem. Eng. Data* **2005**, *50*, 1667−1671.

(19) Wu, J.; Liu, Z.; Bi, S.; Meng, X. Viscosity of saturated liquid dimethyl ether from (227 to 343) K. *J. Chem. Eng. Data* **2003**, *48*, 426−429.

(20) McGarry, J. Correlation and prediction of the vapor pressures of pure liquids over large pressure ranges. *Ind. Eng. Chem. Proc. Des. Dev.* **1983**, *22*, 313−322.

(21) Wu, J.; Liu, Z.; Pan, J.; Zhao, W. Vapor pressure measurements of dimethyl ether from (233 to 399) K. *J. Chem. Eng. Data* **2004**, *49*, 32−34.

(22) Jasper, J. J. The surface tension of pure liquid compounds. *J. Phys. Chem. Ref. Data* **1972**, *1*, 841−1009.

(23) Wu, J.; Liu, Z.; Wang, F.; Ren, C. Surface tension of dimethyl ether from (213 to 368) K. *J. Chem. Eng. Data* **2003**, *48*, 1571−1573.

(24) Lunt, R. W.; Rau, M. A. G. The variation of the dielectric constants of some organic liquids with frequency in the range 1 to 10^3 kilocycles. *Proc. R. Soc.* **1930**, *A126*, 213−230.

(25) Marsden, J.; Maass, O. The discontinuity in the dielectric constant of liquids and their saturated vapors at the critical temperature. *Can. J. Res.* **1935**, *13B*, 296−307.

(26) Lawly, K. P.; Sutton, L. E. Molecular association in some gas mixtures by the pressure dependence of the dielectric constant and density. *Trans. Faraday Soc.* **1963**, *59*, 2680−2692.

(27) Gee, N.; Shinsaka, K.; Dodelet, J-P.; Freeman, G. R. Dielectric constant against temperature for 43 liquids. *J. Chem. Thermodyn.* **1986**, *18*, 221−234.

(28) Dornte, R. E.; Smyth, C. P. The dielectric polarization of liquids. X. The polarization and refraction of the normal paraffins. *J. Am. Chem. Soc.* **1930**, *52*, 3546−3552.

(29) Williams, J. W.; Krchma, I. J. The dielectric constants of binary mixtures. *J. Am. Chem. Soc.* **1926**, *48*, 1888−1896.

(30) Thenappan, T.; Prabakar Devaraj, A. Dielectric studies on binary polar mixtures of propanoic acid with esters. *J. Mol. Liq.* **2006**, *123*, 72−79.

(31) Morgan, S. O.; Lowry, H, H.; Dielectric, polarization of some pure organic compounds in the dissolved, liquid and solid states. *J. Phys. Chem.* **1930**, *34*, 2385−2432.

(32) Åkerlöf, G. Dielectric constants of some organic solvent−water mixtures at various temperatures. *J. Am. Chem. Soc.* **1932**, *54*, 4125−4139.

(33) Hourri, A.; St-Arnaud, J. M.; Bose, T. K. Solubility of solids in supercritical fluids from the measurements of the dielectric constant: Application to CO_2-naphthalene. *Rev. Sci. Instrum.* **1998**, *69*, 2732−2737.

(34) Moriyoshi, T.; Kita, T.; Uosaki, Y. Static relative permittivity of carbon dioxide and nitrous oxide up to 30 MPa. *Ber. Bunsen. Phys. Chem.* **1993**, *97*, 589−596.

(35) Abbott, A. P.; Eardley, C. A.; Tooth, R. Relative permittivity measurements of 1,1,1,2-tetrafluoroethane (HFC 134a), pentafluoroethane (HFC 125) and difluoromethane (HFC 32). *J. Chem. Eng. Data* **1999**, *44*, 112−115.

(36) Barao, T.; Nieto de Castro, C. A.; Mardolcar, U. V.; Okambawa, R.; St-Arnaud, J. M. Dielectric constant, dielectric virial coefficients and dipole moments of 1,1,1,2-tetrafluoroethane. *J. Chem. Eng. Data* **1995**, *40*, 1242−1248.

(37) Kirkwood, J. G. The dielectric polarization of polar liquids. *J. Chem. Phys.* **1939**, *7*, 911−919.

(38) Blukis, U.; Kasai, P. H.; Myers, R. J. Microwave spectra and structure of dimethyl ether. *J. Chem. Phys.* **1963**, *38*, 2753−2760.

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