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Liquid Densities, Kinematic Viscosities, and Heat Capacities of Some Ethylene Glycol Dimethyl Ethers at Temperatures from 283.15 to 423.15 K

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Liquid densities and heat capacities at 1 MPa, and kinematic viscosities at atmospheric pressure of monoethylene glycol dimethyl ether (MEGDME), diethylene glycol dimethyl ether (DEGDME), triethylene glycol dimethyl ether (TrEGDME), tetrathylene glycol dimethyl ether (TEGDME), pentaethylene glycol dimethyl ether (PeEGDME), and polyethylene glycol 250 dimethyl ether (PEGDME 250) were measured in the temperature range from 283.15 to 423.15 K. For each substance, experimental data were correlated with temperature using empirical polynomial equations. The experimental data were also used to evaluate the predictive capability of some estimation methods of liquid densities and heat capacities for the studied ethylene glycol dimethyl ethers. The densities estimated by the Yen–Woods equation agree with our experimental values with a root-mean-square relative deviation (RMSD) of 3.21 % for all ethylene glycol dimethyl ethers. The best estimated results of liquid heat capacities were obtained from the Rowlinson equation based on the corresponding-states principle, with a RMSD of 1.12%. The group-contribution methods give the worst results, especially at high temperatures.

KEY WORDS: corresponding states; density; ethylene glycol dimethyl ether; group-contribution method; heat capacity; viscosity.

1. INTRODUCTION

Due to the CFC problem, there is a growing interest in the use of absorption cycles for upgrading waste heat and refrigeration cycles. The $NH_3 + H_2O$

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and $H_2O + LiBr$ systems are well known as classical working pairs in absorption technology. However, these systems show important disadvantages at high temperatures. Therefore, investigations on new working fluid pairs for use in absorption heat pumping systems have increased considerably in recent years. Organic working pairs containing some ethylene glycol dimethyl ethers $CH_3O(CH_2CH_2O)_nCH_3$ as absorbents have been proposed to overcome the drawbacks of classical working pairs [1–4]. In order to do so, reliable data for the thermophysical properties of these compounds over a wide range of temperatures are needed. In the literature, thermophysical property data for these compounds are scarce and at very limited conditions of temperature and pressure. Most measurements have been made at atmospheric pressure and at temperatures in the range from 283.15 to 323.15 K.

To complete our previous work [5–9], systematic experimental measurements and theoretical analysis of some physical properties for ethylene glycol dimethyl ethers have been performed. In this paper, we report experimental measurements of liquid densities and viscosities in the temperature range from 283.15 to 423.15 K and heat capacities from 313.15 to 421 K for ethylene glycol dimethyl ethers and polyethylene glycol 250 dimethyl ether. These experimental data have also been correlated by polynomial equations, and compared with some results estimated by group-contribution methods and methods based on the corresponding-states principle.

2. EXPERIMENTS

2.1. Materials

The ethylene glycol dimethyl ethers studied were: monoethylene glycol dimethyl ether (Fluka, >99.0%), diethylene glycol dimethyl ether (Fluka, >99.5%), triethylene glycol dimethyl ether (Fluka, >98.0%), tetraethylene glycol dimethyl ether (Fluka, >98.0%), pentaethylene glycol dimethyl ether (Clariant Gmbh, >99.5%), and PEGDME 250 (Fluka, purum). As reference fluids, we used *n*-heptane (Fluka, >99.5%), *n*-octane (Panreac, >99.5%), *n*-dodecane (Sigma, >99.0%), *n*-tridecane (Sigma, >99.0%), benzene (Panreac, >99.5%), ethanol (Panreac, >99.5%), and deionized distilled water. All fluids were used without further purification but kept over molecular sieves for several days. Then, they were degassed by ultrasonic treatment (Elma Type 480/H-2) immediately before use. Actually, polyethylene glycol 250 dimethyl ether (PEGDME 250) is a mixture of ethylene glycol dimethyl ethers with different n values ($n = 3$ to 9), but is often considered as a pseudo pure compound [10]. PEGDME 250 used in this work was analyzed by gas chromatography, with the molar percentage composition for $n = 3$, 2.4%; $n = 4$, 12.8%; $n = 5$, 26.6%; $n = 6$, 31.8%; $n = 7$, 20.8%; $n = 8$, 5.04%; and $n = 9$, 0.5%. The molecular weight and pseudo n value for this compound are 298.21 and 5.723, respectively.

2.2. Equipment

2.2.1. Density

Densities of the liquids were measured with an electronic digital densimeter (Anton Paar DMA 60/602 HP). The pressure of the system was applied with a pressure generator (HiP Model 50-6-15). Vacuum was achieved with a vacuum pump Telstar type 80/70. The vibrating-tube temperature was regulated by a Julabo F-20 HC thermostat, and read by a digital precision thermometer (Anton Paar MKT 100) with a micro RTD probe calibrated in the temperature working range with an accuracy of ± 0.01 K.

2.2.2. Kinematic Viscosity

Kinematic viscosities of the liquids were measured with Ubbelohde-type glass capillary tube viscometers (I, 0a and 0c) with a Schott–Geräte automatic measuring unit (Model AVS 310) in a thermostated bath (CT 1450/2). The bath was filled with deionized water to operate in the temperature range from 283.15 to 343.15 K, and with silicon oil Baysilone M-20 for higher temperatures up to 423.15 K.

2.2.3. Heat Capacity

Liquid heat capacities at a constant pressure of 1 MPa were measured with a calorimeter (Setaram C-80 II) with heat capacity vessels. These vessels, with a capacity of 11 cm^3, were built to allow thermal expansion of a liquid sample. The pressure over the liquid sample was applied with nitrogen through a tube of 1.6 mm diameter. To avoid diffusion of nitrogen into the sample, 4 m of the tube completely filled with the sample were used between the vessel and the interface area. A more detailed description has been given by Coxam et al. [11].

2.3. Experimental Procedure

2.3.1. Density

Prior to the density measurements, the system was heated and evacuated simultaneously for several hours to remove any residual moisture. Then, the sample was introduced in the pressure generator, and pumped carefully into the system. Once the system was filled completely with the sample, the exit valve was closed and the pressure increased to 1 MPa. Vacuum and water were used as reference fluids for the calibration of the densimeter. To check the densimeter and the experimental procedure used, the liquid densities of benzene and ethanol at 1 MPa pressure have been measured in the range, 283.15 to 423.15 K, and compared with those of Kratzke et al. [12] and the TRC tables [13], respectively. Our experimental results are in good agreement with literature values, the overall average absolute deviation with both sets of data being less than 0.1%. The precision of our measured densities is estimated to be within $\pm 2 \times 10^{-5}\ \mathrm{g \cdot cm^{-3}}$.

2.3.2. Kinematic Viscosity

A calibration of the viscometers was performed to determine the characteristic constants C_1 and C_2 for each capillary in the working equation:

$$\nu = C_1 t - C_2 / t \qquad (1)$$

where ν and t are the kinematic viscosity and flow time, respectively. Depending on the capillary size, the values of C_1 and C_2 were determined by comparing with the kinematic viscosity of *n*-dodecane or *n*-octane from the TRC tables [13] and the corresponding measured flow time. The measuring procedure was checked with *n*-heptane for capillary 0a from 283.15 to 333.15 K and with *n*-tridecane for capillary 0c from 333.15 to 423.15 K. Good agreement between our experimental viscosities and literature values [13] has been obtained for *n*-heptane and *n*-tridecane, with maximum deviations within ±1%. The precision of the kinematic viscosity data is better than $5 \times 10^{-4}\ \mathrm{mm^2 \cdot s^{-1}}$.

2.3.3. Heat Capacity

Isobaric heat capacities of the liquids were measured following the method described extensively by Coxam et al. [11]. The heat capacities of a sample were determined in three steps: the measuring cell was filled successively with vacuum, water, and the sample, while the reference cell was kept under vacuum. Our experimental results for ethanol and *n*-heptane have been compared with the recommended values [14] in the entire temperature range. The maximum deviation between our results and the literature data is 0.42%.

3. EXPERIMENTAL RESULTS AND CORRELATION

3.1. Density

In this work, the densities of the ethylene glycol dimethyl ethers were determined at 1 MPa from 283.15 to 423.15 K at intervals of 10 K. At this

Table I. Experimental Liquid Densities and Kinematic Viscosities of the *n*-Ethylene Glycol Dimethyl Ethers (from $n = 1$ to 5) and PEGDME 250

	MEGDME ($n=1$)		DEGDME ($n=2$)		TrEGDME ($n=3$)	
T (K)	ρ $(\mathrm{kg \cdot m^3})$	ν $(\mathrm{mm^2 \cdot s^{-1}})$	ρ $(\mathrm{kg \cdot m^{-3}})$	ν $(\mathrm{mm^2 \cdot s^{-1}})$	ρ $(\mathrm{kg \cdot m^{-3}})$	ν $(\mathrm{mm^2 \cdot s^{-1}})$
283.15	877.52	0.5697	953.98	1.355	994.12	2.734
293.15	867.65	0.5148	945.11	1.146	985.69	2.189
303.15	857.18	0.4691	935.69	0.9893	976.72	1.803
313.15	846.29	0.4304	925.91	0.8670	967.43	1.519
323.15	834.99	0.3975	915.91	0.7697	957.92	1.302
333.15	823.48	0.3701	905.73	0.6904	948.29	1.135
343.15	811.72	—	895.41	0.6223	938.57	1.014
353.15	799.65	—	884.95	0.5740	928.82	0.9046
363.15	787.45	—	874.48	0.5276	919.06	0.8142
373.15	774.99	—	863.95	0.4867	909.28	0.7385
383.15	762.25	—	853.31	0.4525	899.52	0.6750
393.15	749.18	—	842.65	0.4244	889.83	0.6206
403.15	735.74	—	831.87	0.3981	880.10	0.5725
413.15	721.79	—	821.06	0.3736	870.41	0.5311
423.15	707.36	—	810.18	—	860.76	0.4942

	TEGDME ($n=4$)		PeEGDME ($n=5$)		PEGDME 250	
T (K)	ρ $(\mathrm{kg \cdot m^3})$	ν $(\mathrm{mm^2 \cdot s^{-1}})$	ρ $(\mathrm{kg \cdot m^{-3}})$	ν $(\mathrm{mm^2 \cdot s^{-1}})$	ρ $(\mathrm{kg \cdot m^{-3}})$	ν $(\mathrm{mm^2 \cdot s^{-1}})$
283.15	1019.8	4.882[a]	1038.6	7.995	1044.4	9.792
293.15	1011.6	3.706[a]	1029.5	5.870	1035.5	7.215
303.15	1002.9	2.942[a]	1020.4	4.496	1026.4	5.457
313.15	993.81	2.413[a]	1011.3	3.571	1017.4	4.290
323.15	984.56	2.038	1002.3	2.914	1008.4	3.464
333.15	975.16	1.734	993.34	2.434	999.51	2.870
343.15	965.77	1.500	984.37	2.071	990.62	2.391
353.15	956.38	1.314	975.42	1.793	981.70	2.096
363.15	947.00	1.164	966.44	1.576	972.84	1.857
373.15	937.63	1.040	957.47	1.395	963.77	1.662
383.15	928.30	0.9388	948.47	1.245	955.10	1.521
393.15	919.06	0.8538	939.50	1.122	946.16	1.380
403.15	909.86	0.7815	930.47	1.019	937.20	1.258
413.15	900.76	0.7189	921.38	0.9304	928.18	1.147
423.15	891.70	0.6642	912.26	0.8546	919.13	1.060

[a] From the literature [7].

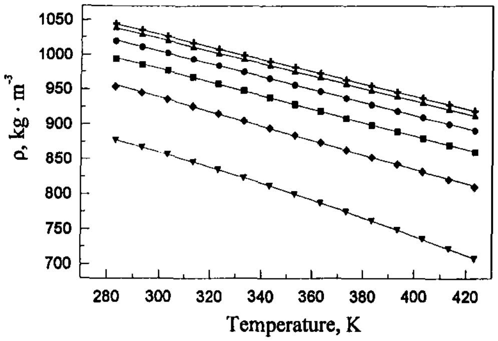

Fig. 1. Experimental densities of the ethylene glycol dimethyl ethers. (▼ MEGDME, ◆ DEGDME, ■ TrEGDME, ● TEGDME, ▲ PeEGDME, + PEGDME 250, — calculated by Eq. (2)).

pressure, the boiling points of MEGDME and DEGDME were above 423.15 K, so they were in the liquid state over the selected temperature range. Ninety data points of the measured densities are presented in Table I. In Fig. 1 it can be seen how the density decreases with the temperature, and also how the difference in densities between two successive ethylene glycol dimethyl ethers decreases with the increase of n value.

Liquid densities ρ ($\mathrm{kg \cdot m^{-3}}$) were correlated by the following equation

$$\rho = a_0 + a_1 T + a_2 T^2 \tag{2}$$

where T is the temperature in K, and the equation coefficients: a_0, a_1, and a_2 for the different ethylene glycol dimethyl ethers ($n = 1, 5$) and PEGDME 250 are listed in Table II, where the root-mea*n*-square relative deviations (RMSD) are also included. The RMSD is defined by

$$\mathrm{RMSD} = 100 \left\{ \frac{1}{N} \sum_i \left(\frac{X_e - X_c}{X_e} \right)_i^2 \right\}^{1/2}$$

where N, X_e, and X_c represent the number of data points and the experimental and calculated values, respectively. The RMSD value between experimental densities and the values calculated from Eq. (2) for all studied substances is 0.03%. It indicates that Eq. (2) is very suitable for describing the temperature dependence of liquid densities of ethylene glycol dimethyl ethers in the temperature range studied.

Density data for MEGDME in the literature [15–17] at atmospheric pressure and at temperatures from 283.15 to 333.15 K matched very well with those from Eq. (2). Sharipov and Bairamova [15] also studied the

Table II. Parameters of the Liquid Density Equation [Eq. (2)] and RMSD Values for the *n*-Ethylene Glycol Dimethyl Ethers (from $n = 1$ to 5) and PEGDME 250 in the Temperature Range of 283.15 to 423.15 K

	a_0	a_1	$a_2 \times 10^2$	RMSD (%)
MEGDME	1046.185	−0.1800856	−0.146497	0.02
DEGDME	1177.752	−0.6233535	−0.058146	0.03
TrEGDME	1234.656	−0.7701351	−0.027056	0.04
TEGDME	1282.694	−0.9242925	—	0.04
PeEGDME	1293.419	−0.9004714	—	0.01
PEGDME 250	1297.211	−0.8932571	—	0.01

effects of temperature and pressure on the densities of MEGDME. The relative deviation of their experimental data at 30 MPa from Eq. (2) increased from 0.2 to 1.2% with a temperature increase from 298.15 to 423.15 K. For DEGDME, good agreement between literature values [17–20] and those from Eq. (2) has been found, with an average deviation of better than 0.2%. The densities of TrEGDME from 278.15 to 308.15 K in Refs. 17, 21, and 22 are in very good agreement with those given by Eq. (2). The densities of TEGDME from 283.15 to 313.15 K [17, 21, 23, 24] deviated from Eq. (2) with a maximum value of 0.15%. Also, Esteve et al. [7] and Olivé [25] measured the densities at atmospheric pressure in the temperature ranges of 283.15 to 333.15 K and 283.15 to 393.15 K, respectively; both sets of data agree very well with the values calculated from Eq. (2).

3.2. Kinematic Viscosity

The kinematic viscosities at atmospheric pressure of the ethylene glycol dimethyl ethers were measured from 283.15 to 423.15 K at 10 K intervals. Because of the wide temperature and kinematic viscosity ranges studied, different capillaries were used in order to minimize the kinetic correction factor.

For the measurements of the viscosities of MEGDME and DEGDME, the capillary 0a was used from 283.15 to 333.15 K and capillary 0c for DEGDME up to 413.15 K. The viscosities of TrEGDME and PeEGDME were measured with capillaries 0a and I, respectively. Capillary I was also used to measure the viscosities of PEGDME 250 from 283.15 to 323.15 K, and capillary 0a up to 423.15 K. Finally, capillary 0a was also used for TEGDME from 323.15 to 423.15 K. A total of 70 experimental kinematic viscosities for the ethylene glycol dimethyl ethers is presented in Table I, together with the kinematic viscosities of TEGDME

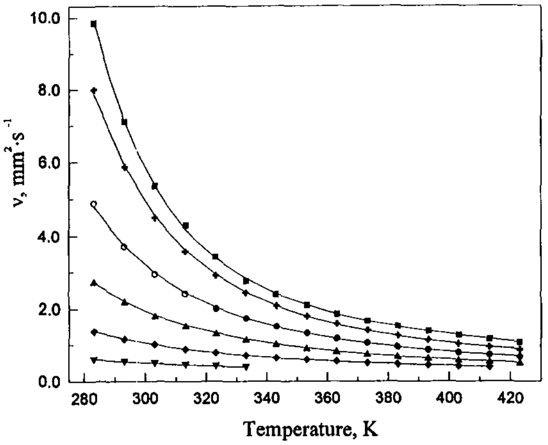

Fig. 2. Experimental kinematic viscosities of the ethylene glycol dimethyl ethers. (▼ MEGDME, ◆ DEGDME, ▲ TrEGDME, ● TEGDME, + PeEGDME, ■ PEGDME 250, ○ TEGDME Esteve et al. [7], — calculated by Eq. (3)).

from 283.15 to 323.15 K from our previous work [7]. Figure 2 shows how the kinematic viscosity of ethylene glycol dimethyl ethers decreases with temperature, and also how it increases with the n value.

Liquid kinematic viscosities ν ($\mathrm{mm}^2 \cdot \mathrm{s}^{-1}$) of each compound were fitted to the equation:

$$\ln \nu = b_0 + \frac{b_1}{T} + b_2 T + b_3 T^2 \tag{3}$$

where T is the temperature in K. The RMSD values and equation coefficients b_0, b_1, b_2, and b_3 for all the studied substances are summarized in Table III. The minimum value of RMSD is 0.04% for MEGDME, while the maximum RMSD is 0.54% for TEGDME.

The kinematic viscosities for MEGDME measured by Muhuri and Hazra [26] and Das et al. [27] from 298.15 to 318.15 K showed maximum relative deviations of 0.6% from Eq. (3). Also, the relative deviation of the experimental viscosity data of Amalendu and Yoginder [28] from Eq. (3) was less than 1%. However, the values measured by Wallace and Nathews [29] had higher deviations of about 2 to 3%. The viscosities of DEGDME found in Refs. 18, 20, and 30 were generally lower than those from Eq. (3) by about 0.8 to 3%. The viscosities of Wallace et al. [31] for TrEGDME showed deviations of 0.8%, while the relative deviation of those taken from

Table III. Parameters of the Liquid Kinematic Viscosity Equation [Eq. (3)] and RMSD Values for the *n*-Ethylene Glycol Dimethyl Ethers (from $n = 1$ to 5) and PEGDME 250 in the Temperature Range of 283.15 to 423.15 K

	b_0	b_1	$b_2 \times 10$	$b_3 \times 10^4$	RMSD (%)
MEGDME	5.304061	—	−0.3100030	0.3631	0.04
DEGDME	−19.28200	3085.081	0.4043370	−0.3442	0.22
TrEGDME	−30.32947	4694.764	0.6892472	−0.5942	0.31
TEGDME	−33.77740	5385.225	0.7572302	−0.6369	0.54
PeEGDME	−43.83568	6829.982	1.009870	−0.8489	0.30
PEGDME 250	−40.21308	6499.263	0.8992399	−0.7385	0.35

Table IV. Experimental Liquid Heat Capacities at Constant Pressure C_p ($\mathrm{kJ \cdot kg^{-1} \cdot K^{-1}}$) of the *n*-Ethylene Glycol Dimethyl Ethers (from $n = 1$ to 5) and PEGDME 250

T (K)	MEGDME	DEGDME	TrEGDME
312.56	2.137	2.089	2.069
322.46	2.161	2.105	2.081
334.84	2.180	2.123	2.091
347.21	2.220	2.145	2.113
359.57	2.250	2.167	2.133
371.93	2.293	2.198	2.158
384.35	2.330	2.228	2.185
396.65	2.369	2.261	2.217
409.05	2.421	2.290	2.238
421.45	2.482	2.330	2.275

T (K)	TEGDME	PeEGDME	PEGDME 250
312.53	2.066	2.063	2.070
322.45	2.076	2.069	2.071
332.35	2.085	2.077	2.072
342.25	2.097	2.087	2.086
352.16	2.115	2.100	2.106
362.06	2.129	2.116	2.115
371.96	2.144	2.133	2.132
381.86	2.162	2.151	2.154
391.74	2.181	2.169	2.168
401.64	2.208	2.196	2.196
411.55	2.234	2.220	2.221
421.46	2.250	2.236	2.238

Ref. 32 was about 2% at 313.15 K and 6.5% at 353.15 K. Stephan and Hengerer [33] measured the viscosities of TEGDME which deviate by 5% from Eq. (3).

3.3. Heat Capacity

Experimental liquid heat capacities were measured from 312.53 to 423 K at 1 MPa. In this work, we used successive temperature increments of 10 and 15 K for MEGDME, DEGDME, and TrEGDME, while for TEGDME, PeEGDME, and PEGDME all increments were 10 K. The heating rate was, in all cases, 0.3 $\mathrm{K \cdot min^{-1}}$. Also, the densities obtained in this work were used in the calculation of the heat capacity. The experimental heat capacity data are summarized in Table IV, and their changes with temperature are shown in Fig. 3.

Liquid heat capacities C_P ($\mathrm{kJ \cdot kg^{-1} \cdot K^{-1}}$) were correlated with temperature for each compound by the equation

$$C_P = c_0 + c_1(T - 273.15) + c_2(T - 273.15)^2 \tag{4}$$

The RMSD values and coefficients c_0, c_1, and c_2 for each ethylene glycol dimethyl ether ($n = 1, 5$) and PEGDME 250 are presented in Table V. The agreement between experimental liquid heat capacities and the values calculated from Eq. (4) is very good with an overall average RMSD value

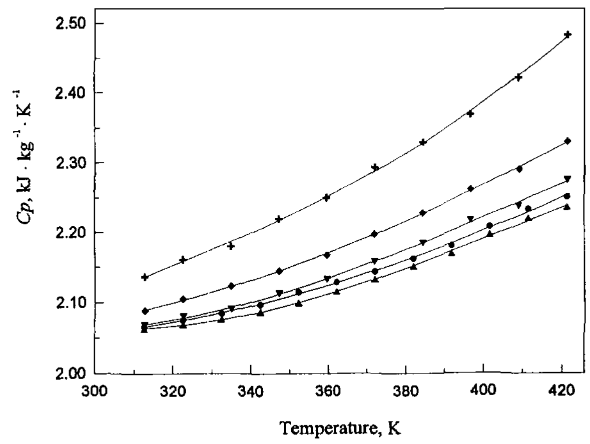

Fig. 3. Experimental heat capacities of the ethylene glycol dimethyl ethers. (+ MEGDME, ◆ DEGDME, ▼ TrEGDME, ● TEGDME, ▲ PeEGDME, — calculated by Eq. (4)).

Table V. Parameters of the Liquid Heat Capacity Equation [Eq. (4)] and RMSD Values for the *n*-Ethylene Glycol Dimethyl Ethers (from $n = 1$ to 5) and PEGDME 250 in the Temperature Range of 323.15 to 423.15 K

	c_0	$c_1 \times 10^4$	$c_2 \times 10^5$	RMSD (%)
MEGDME	2.085796	8.7586	1.189	0.17
DEGDME	2.049139	7.0712	0.800	0.08
TrEGDME	2.039050	4.1981	0.791	0.13
TEGDME	2.046740	1.5252	0.845	0.11
PeEGDME	2.049841	−0.6984	0.917	0.11
PEGDME 250	2.058210	−2.3533	3.304	0.19

of 0.14%. The heat capacities at constant pressure of DEGDME reported by Zabrinsky and Ruzicka [14] deviate from Eq. (4) by about 0.3% at 310 K and 1.4% at 350 K. For TrEGDME, C_P experimental data of Ref. 14 in the temperature range of 310 to 350 K had a maximum deviation of 0.7% from Eq. (4), while the experimental data of Trejo et al. [34] at 298.15 K and Tovar [35] from 283.15 to 308.15 K matched very well with our data. Kriebel and Löffer [36] also measured the heat capacities of TEGDME from 293 to 425 K. The deviation between Kriebel's values and those from Eq. (4) is 2.5%.

4. ESTIMATION OF LIQUID DENSITY AND HEAT CAPACITY

The experimental liquid densities and heat capacities were used to evaluate the predictive capability of some semi-theoretical methods in the literature.

4.1. Density

For density estimation the equations of Yen–Woods [37] and Gunn–Yamada [38] based on the corresponding-states principle were used in this work. Since the critical properties and the acentric factor needed for these equations were not available, several methods were used to estimate them. The value of the critical temperature T_c for each ethylene glycol dimethyl ether was estimated based on the method of Constantinou and Gani [39], while the critical volume V_c value was obtained with Ambrose's method [40]. The group-contribution method of Han and Peng [41] was applied to predict the acentric factor ω of each compound. The values of the molecular weight M, ω, T_c, and V_c for each ethylene glycol dimethyl ether are given in Table VI. The RMSD values between experimental and

Table VI. Molecular Weight M, Acentric Factor ω, Critical Temperature T_c, and Critical Volume V_c for the n-Ethylene Glycol Dimethyl Ethers (from $n = 1$ to 5) and PEGDME 250

	N	M	ω	T_c (K)	V_c ($cm^3 \cdot mol^{-1}$)
MEGDME	1	90.120	0.357	541.99	300.4
DEGDME	2	134.18	0.521	612.98	430.6
TrEGDME	3	178.23	0.673	663.85	560.8
TEGDME	4	222.28	0.813	703.52	691.0
PeEGDME	5	266.23	0.943	736.05	821.2
PEGDME 250	5.723	298.21	1.028	749.07	915.1

Table VII. RMSD (%) of Liquid Densities Estimated by the Yen–Woods and Gunn–Yamada Equations and the Experimental Data for each n-Ethylene Glycol Dimethyl Ether

	n	Yen–Woods	Gunn–Yamada
MEGDME	1	1.10	1.61
DEGDME	2	3.02	5.12
TrEGDME	3	3.85	9.89
TEGDME	4	3.78	15.0
PeEGDME	5	3.36	20.2
PEGDME 250	5.723	3.38	24.1

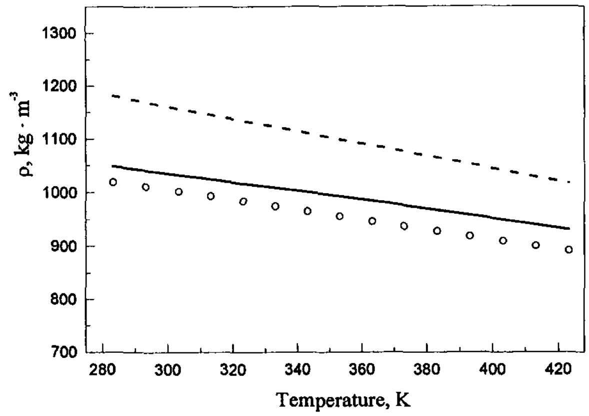

Fig. 4. Estimated and experimental liquid densities of TEGDME. (○ Experimental,—— Yen–Woods equation, ---- Gunn–Yamada equation).

estimated densities for our investigated compounds are listed in Table VII. Typical estimated results for tetraethylene glycol dimethyl ether ($n = 4$) are shown in Fig. 4. From Table VII, it can be seen that the results estimated from the Yen–Woods equation are generally much better than those from the Gunn–Yamada equation. The RMSD values of our investigated compounds for the Yen–Woods equation are within $\pm 3.85\%$, while for the Gunn–Yamada equation the maximum value of RMSD is about 25%.

4.2. Heat Capacity

For estimating the liquid heat capacity of a pure substance, the Sterning–Brown equation [42], the Rowlinson equation [43], and the Rowlinson–Bondi equation [43], developed on the basis of the corresponding-states principle, were used. The heat capacity of the investigated compounds in the ideal gas-state used in these equations, was estimated by the group-contribution method of Joback [40].

The RMSD values between experimental liquid heat capacities and estimated results are summarized in Table VIII. Typical estimated results for tetraethylene glycol dimethyl ether ($n = 4$) are shown in Fig. 5. Table VIII and Fig. 5 show that the results estimated from the Rowlinson equation are the closest to our experimental data, while the Rowlinson–Bondi equation is the worst. The average RMSD values of all investigated substances for the Sterning–Brown, Rowlinson, and Rowlinson–Bondi equations are 3.26, 1.12 and 4.75%, respectively. The group-contribution methods of Missenard [44] and of Reid and San Jose [45] were also used for estimating liquid heat capacities of the investigated substances, but their estimated results are much worse than those from the equations based on the corresponding-states principle, especially at high temperatures.

Table VIII. RMSD (%) of Liquid Heat Capacity Estimated by the Sterning–Brown, Rowlinson, and Rowlinson–Bondi Methods and the Experimental Data for Each *n*-Ethylene Glycol Dimethyl Ether

	Sterning–Brown	Rowlinson	Rowlinson–Bondi
MEGDME	1.26	0.68	1.86
DEGDME	1.80	0.69	3.92
TrEGDME	2.78	0.79	4.97
TEGDME	3.91	1.22	6.05
PeEGDME	4.42	1.27	6.46
PEGDME 250	5.37	2.09	7.37

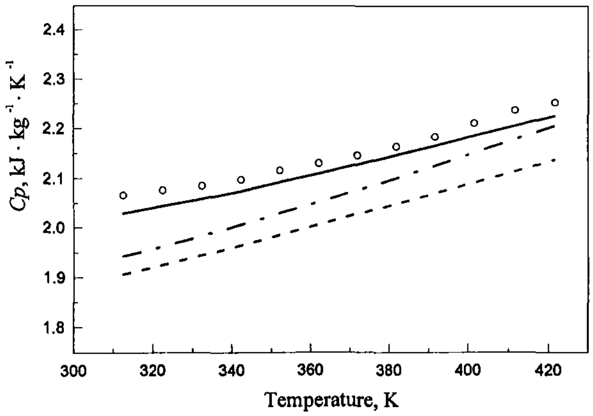

Fig. 5. Estimated and experimental liquid heat capacities of TEGDME. (○ Experimental, —— Rowlinson equation, --- Sterning–Brown equation, ---- Rowlinson–Bondi equation).

5. CONCLUSIONS

In this paper, we have verified that our apparatuses and experimental procedures can be used for the accurate measurements of liquid density, kinematic viscosity, and heat capacity in a wide temperature range. We have reported liquid densities and heat capacities at 1 MPa, and kinematic viscosities at atmospheric pressure of ethylene glycol dimethyl ethers (from $n = 1$ to 5) and PEGDME 250 in the temperature range of 283.15 to 423.15 K. In general, with an increase of n value at constant temperature, the liquid density and kinematic viscosity also increase, while the liquid specific heat capacity decreases. For each investigated substance, the liquid density and kinematic viscosity decrease with temperature, while the liquid heat capacity increases.

All experimental data for the three thermophysical properties have been separately fitted to different empirical equations, and the equation's parameters have been provided in this paper. The equations of Yen–Woods and Gunn–Yamada have been used to estimate the liquid densities of ethylene glycol dimethyl ethers. The results show that the Yen–Woods equation is much better than the Gunn–Yamada equation. The maximum RMSD value of the Yen–Woods equation for all investigated substances is less than 3.85%.

Finally, we have applied three equations derived from the corresponding-states principle to estimate the liquid heat capacities of all investigated substances. The average RMSD values for the Sterning–Brown, Rowlinson, and Rowlinson–Bondi equations are 3.26, 1.12 and 4.75%, respectively. The Rowlinson equation always gives the best predicted results. The group-contribution methods of Missenard [44] and Reid and San Jose [45] have also been used to estimate liquid heat capacities of ethylene glycol dimethyl ethers, but their results are much worse than those from the equations based on the corresponding-states principle, especially at high temperatures.

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