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Experimental Dynamic Viscosities of 2,3-Dimethylpentane up to 60 MPa and from (303.15 to 353.15) K Using a Rolling-Ball Viscometer†

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The main motivation of this work is to verify the reliability of a high-pressure viscosity measurement technique that was recently installed in our laboratory. A total of 2520 experimental measurements of the rolling time have been performed. Hexane and decane were used to calibrate the apparatus, and the dynamic viscosity of heptane has been measured to verify the calibration method. Our results agree with the literature values with average absolute deviations lower than the experimental uncertainty (±2%). In a second step, hexane, heptane, and decane have been used as reference substances, and the calibration has been verified again by determining the dynamic viscosity of toluene. A comparison has been established between the experimental dynamic viscosity measured in this work for toluene and the reference correlation recommended by IUPAC, obtaining an absolute average deviation of 0.9% and a maximum deviation of 2%. Furthermore, 99 density (up to 45 MPa and from 298.15 K to 353.15 K) and 84 dynamic viscosity (up to 60 MPa and at six temperatures ranging from 303.15 K to 353.15 K) measurements of liquid 2,3-dimethylpentane are also reported.

1. Introduction

Instrumentation for measuring high-pressure viscosity is of great importance because of the need of transport property data for process design and development in supercritical fluid-based technologies. High-pressure viscosity data are also needed in traditional processes such as lubrication, tertiary oil recovery, and polymer processing among others. Furthermore, studies of the viscosity as a function of both pressure and temperature are also of fundamental interest because often it is not economically viable to make measurements for a wide range of fluid compositions at different pressures and temperatures. Predictive models can provide a useful and more economical alternative to this problem, although the reliability of predictive methods depends greatly on the accuracy and availability of experimental data.

Although the temperature dependence of the viscosity of pure substances and mixtures is the subject of numerous publications, its pressure dependence has not been studied as often. For this reason, several groups are working to extend the database of viscosities at high pressures. Our current research project has the objective to provide reliable experimental viscosity data for different polyol ester lubricants under elevated pressure conditions. With this aim, a high-pressure viscosity measurement technique (rolling-ball viscometer Ruska 1602-830) was installed recently in our laboratory. To our knowledge, only the Barrufet group[1,2] has published viscosity measurements (for pure alkanes, binary and ternary mixtures of alkanes and CO_2 + *n*-alkanes) performed with this Ruska viscometer. Other noncommercial rolling-body viscometers are currently used by other authors.[3−5] The main motivation of this work is to verify the reliability of this technique.

For this purpose, several *n*-alkanes (hexane, heptane, and decane) and toluene have been used as reference substances and for the verification of the calibration method. Toluene was the second reference liquid to be proposed by IUPAC (after water) because its unusually wide temperature range in the liquid phase (178 to 384) K makes it an ideal reference liquid for viscosity calibration purposes and apparatus validation.[6] Furthermore, in the present work, new dynamic viscosity measurements of liquid 2,3-dimethylpentane up to 60 MPa at six temperatures in the range of (303.15 to 353.15) K are reported. In addition, density data of this last compound up to 45 MPa and from (298.15 to 353.15) K are presented.

Experimental Section

Materials. Hexane (molar mass 86.177 $g\cdot mol^{-1}$) and heptane (molar mass 100.204 $g\cdot mol^{-1}$) were obtained from Fluka with a purity of 99.5%. Decane (molar mass 142.285 $g\cdot mol^{-1}$) was obtained from Sigma with a purity of 99%. Toluene (molar mass 92.141 $g\cdot mol^{-1}$) and 2,3-dimethylpentane (molar mass 100.204 $g\cdot mol^{-1}$) were obtained from Aldrich with purities of 99.8% and 99%, respectively. These chemicals were subjected to no further purification.

Viscosity Measurement Technique. The high-pressure viscosity technique consists of a commercial rolling-ball viscometer (Ruska 1602−830) and a pressure line that requires the construction and setup of several pieces of equipment and peripherals. Figure 1 is a schematic general view of the equipment. The Ruska rolling-ball viscometer has been designed to operate in the viscosity range of (0.1 to 3000) mPa·s and consists of the mechanical test assembly and the control unit (Chromalox 2104) with a digital watch. The mechanical assembly is a stainless steel high-pressure housing fixed to a base allowing circular movements. This housing has a finely honed and lapped cylindrical bore in which a stainless steel ball rolls on a polished surface. A plug, containing the barrel seal and a

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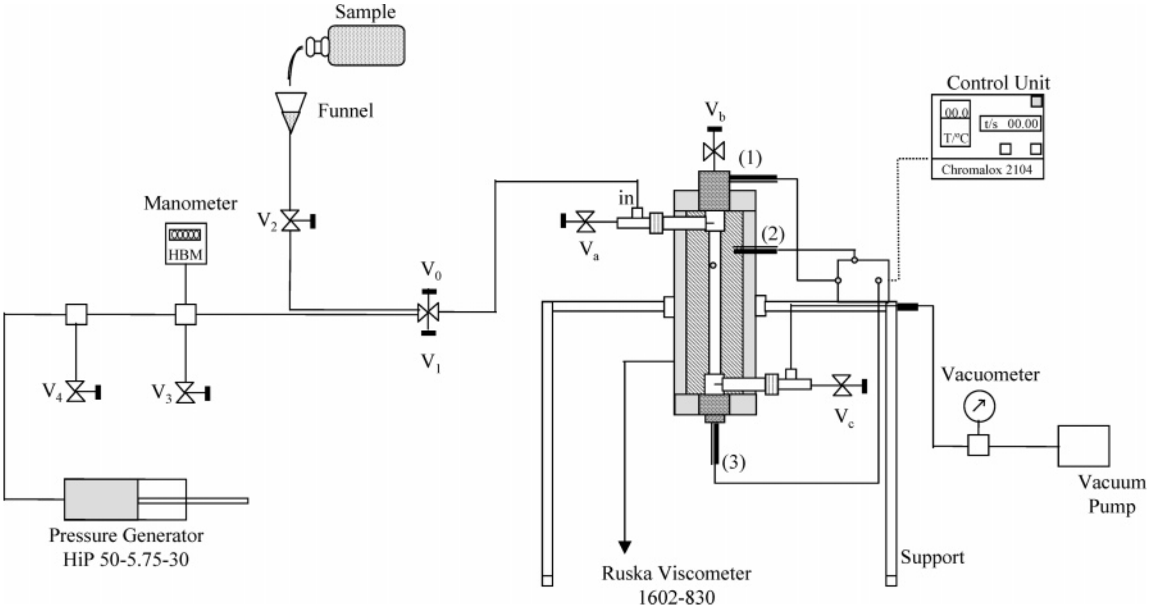

Figure 1. Description of the device: (1) coils, (2) PT 100 thermometer, (3) chronometer connected to the Chromalox control unit.

solenoid, closes the housing on its upper end, and another plug, containing the bottom contact, closes the lower end. When the barrel seal is closed, both ends of the barrel are sealed, so the sphere falls through the fluid inside the barrel. The solenoid holds the steel ball at the top of the measuring barrel. The ball will not fall through the fluid sample until the solenoid current is interrupted. The watch (unit control) is activated electronically when the current is interrupted and is stopped automatically when the ball reaches the end of its travel. The measurements can be conducted with the unit inclined an angle, θ, of 23°, 45°, or 70° with the horizontal. The angle at which the sphere is rolling and the sphere diameter should be selected by taking into account the viscosity range. Thus for higher viscosities, the higher angle and the sphere with the lower diameter should be utilized.

This equipment uses an electronic heating jacket control system to perform measurements at accurately controlled temperatures. This eliminates the need for circulating hot water through coils or submerging the mechanical test assembly in a tank of hot oil or water. The temperature is measured with a PT 100 thermometer with an accuracy of ± 0.1 K. A pressure line (Figure 1) is connected to the viscometer that consists of a set of valves and tubes, a HiP pressure generator, an HBM PE300 manometer with an uncertainty of 0.07 MPa, and a vacuum pump (Pfeifer-Balzers, model Duo 004B). Barrufet et al.[1] and Estrada-Baltazar et al.[2] have utilized the same commercial viscometer with different pressure devices to measure the viscosity of pure liquids. Their equipment permits the study of mixtures whose components are in different states at ambiance temperature and atmospheric pressure, for example, CO_2 + decane.

Working Equation. The dynamic viscosity η is a function of the time, $t(\theta)$, required for the ball to roll from one end of a fluid-filled tube to the other at a fixed angle θ, the density difference between the ball and the fluid, $\Delta\rho = \rho_{\text{ball}} - \rho_{\text{fluid}}$, and apparatus parameters a and b, according to the following working equation:

$$\eta(p, T) = a(T, p, \theta) + b(T, p, \theta)\, t(\theta)\, \Delta\rho \qquad (1)$$

For the calibration functions in eq 1, $a(T, p, \theta)$ and $b(T, p, \theta)$, reference density and viscosity measurements under similar ranges of $t\Delta\rho$ at the same pressure and temperature conditions are required.

Calibration Procedure. To perform the calibration, hexane, heptane, and decane have been used. The reference density and viscosity values (needed in eq 1) were taken from the correlations reported by Cibulka et al.[7−9] and from the published experimental data of Oliveira et al.[10] and Assael et al.,[11] respectively. Oliveira et al.[10] and Assael et al.[11] have reported the viscosity of these alkanes with an experimental uncertainty of ±0.5% and over the temperature interval of (303.15 to 348.15) K and up to 250 MPa. To evaluate the viscosity at our temperatures and pressures, the experimental values reported by Oliveira et al.[10] and Assael et al.[11] have been correlated. The experimental viscosity data on each isotherm, $\eta(P)$, were fit with the following Tait-like equation[12]

$$\eta(P) = A \exp\left[B \ln\left(\frac{C + p}{C + 0.1}\right)\right] \qquad (2)$$

where the constants A, B, and C are determined over each isotherm and for each liquid (hexane, heptane, and decane). The standard deviations of the correlations along the different isotherms are lower than 0.6×10^{-3} mPa·s for hexane, 1.5×10^{-3} mPa·s for heptane, and 3.4×10^{-3} mPa·s for decane. The behavior of the viscosity data of Oliveira et al.[10] and Assael et al.[11] on an isobar as a function of temperature, $\eta(T)$, have been correlated by using the following modification of Andrade's equation:[13]

$$\eta(T) = A \exp\left(\frac{B}{T - C}\right) \qquad (3)$$

The constants A, B, and C of eq 3 were determined for each isobar and for each liquid. The standard deviations of the correlations along the different isobars are lower than 4×10^{-5} mPa·s for heptane and 1×10^{-5} mPa·s for hexane and decane. To analyze the ability of eqs 2 and 3 to reproduce the experimental data of Oliveira et al.[10] and Assael et al.,[11] it is necessary to introduce several quantities. If η_{exptl} represents the experimental viscosity and η_{cor} represents the viscosity obtained from eqs 2 or 3, then we define for each pair (η_{exptl}, η_{cor}) the relative percentage deviation as $\text{Dev} = 100(1 - (\eta_{\text{cor}}/\eta_{\text{exptl}}))$ and the absolute percentage deviation as Abs Dev = |Dev|. For all points considered, we define the three following characteristic quantities: average absolute deviation (AAD) = $1/N\sum_{i=1}^{N}$ Abs Dev(i), the maximum deviation (D_{max})= Max (Abs Dev(i)), and finally the average deviation (bias) = $1/N\sum_{i=1}^{N}$ Dev(i). N is the total number of points that have been compared. These definitions are also used to compare the experimental values obtained in this work with those reported by other authors.

Equations 2 and 3 reproduce the viscosity values reported by Oliveira et al.[10] for hexane and decane with average absolute deviations of 0.1% and the values of Assael et al.[11] for heptane with an average absolute deviation of 0.2%. The maximum deviations are 0.3%, 0.5%, and 1% for hexane, heptane, and decane, respectively.

To perform the calibration of the viscometer (determination of $a(T, p, \theta)$ and $b(T, p, \theta)$ functions) at each measured temperature and pressure, the reference viscosity is plotted against the product, $t\Delta\rho$ (eq 1), and one calibration straight line is fit to these points. As a result, a total of 84 straight calibration lines are used over all of the pressure and temperature intervals.

Table 1. Experimental Dynamic Viscosities, η/mPa·s, versus Temperature and Pressure for Heptane and Toluene

	T/K					
p/MPa	303.15	313.15	323.15	333.15	343.15	353.15
			Heptane			
0.1	0.368	0.330	0.303	0.273	0.245	0.231
1	0.371	0.334	0.306	0.276	0.247	0.233
5	0.387	0.348	0.319	0.289	0.260	0.246
10	0.408	0.368	0.336	0.306	0.277	0.262
15	0.429	0.388	0.354	0.323	0.294	0.278
20	0.450	0.407	0.371	0.340	0.310	0.293
25	0.471	0.427	0.389	0.357	0.326	0.307
30	0.492	0.446	0.406	0.374	0.341	0.322
35	0.514	0.465	0.424	0.390	0.357	0.336
40	0.535	0.484	0.442	0.407	0.372	0.349
45	0.556	0.503	0.461	0.423	0.387	0.361
50	0.578	0.522	0.479	0.439	0.402	0.374
55	0.600	0.542	0.498	0.456	0.416	0.386
60	0.622	0.562	0.517	0.472	0.431	0.397
			Toluene			
0.1	0.525	0.469	0.422	0.382	0.349	0.320
1	0.526	0.474	0.427	0.386	0.351	0.320
5	0.544	0.487	0.439	0.397	0.362	0.331
10	0.568	0.509	0.458	0.413	0.376	0.344
15	0.593	0.529	0.476	0.430	0.391	0.359
20	0.617	0.550	0.495	0.446	0.406	0.373
25	0.640	0.570	0.514	0.463	0.421	0.387
30	0.662	0.590	0.533	0.480	0.437	0.401
35	0.685	0.610	0.552	0.497	0.453	0.415
40	0.707	0.630	0.572	0.515	0.469	0.429
45	0.729	0.651	0.592	0.533	0.485	0.443
50	0.752	0.671	0.612	0.551	0.502	0.458
55	0.774	0.693	0.633	0.571	0.520	0.473
60	0.797	0.715	0.654	0.590	0.537	0.488

Table 2. A, B, C, D, and E_i Parameters of Equation 4, Standard Deviations (σ), and Relative Deviations (AAD, bias, and D_{max})

parameters	heptane	2,3-dimethylpentane
A/mPa·s	0.0044328	0.0590725
B/K	1821.673	272.7206
C/K	−109.09894	151.68369
D	0.9442871	1.213609
E_0/MPa	96.9261	496.3865
E_1/MPa·K^{-1}	0.0682841	−2.259608
E_2/MPa·K^{-2}	−0.0003911	0.0031792
σ/mPa·s	0.003	0.002
AAD%	0.5	0.4
bias %	−0.02	−0.2
D_{max}%	2.1	1.6

Results and Discussion

In this work, the rolling time, t, for hexane, heptane, decane, toluene, and 2,3-dimethylpentane have been measured with the device at up to 60 MPa at six temperatures ranging from (303.15 to 353.15) K. A total of 2520 experimental measurements of the time have been performed with the unit inclined at an angle of $\theta = 23°$ and with a 6.50-mm-diameter ball ($\rho_{ball} = 7.7709$ g·cm^{-3}). The falling-time value was taken as the average of six measurements performed at thermal and mechanical equilibrium, with its standard uncertainty lower than 0.2%.

In a first step, hexane and decane have been used to calibrate the viscometer, and the viscosity of heptane has been determined in order to verify the reliability of the calibration method between (303.15 and 353.15) K and from (0.1 to 60) MPa. Taking into account temperature, pressure, and rolling-time accuracies and the density and viscosity uncertainties of the reference fluids (hexane and decane), we have estimated a final uncertainty of less than ±2% in our dynamic viscosity measurements. This uncertainty is comparable to that estimated by other authors for similar devices.[1,14–18] The experimental viscosity values of heptane are reported in Table 1. To compare our experimental data with those reported by other authors[11,19–24] and because of the absence of a recommended reference equation for this fluid, the following equation[25] has been used to correlate our ηTp experimental surface

$$\eta(p, T) = A \exp\left[\frac{B}{T - C}\right] \exp\left[D \ln\left(\frac{p + E(T)}{0.1\ \mathrm{MPa} + E(T)}\right)\right] \quad (4)$$

where A, B, C, and D were assumed to be temperature-independent and $E(T)$ is a second-order polynomial: $E(T) = E_0 + E_1T + E_2T^2$. The parameters and deviations (average absolute deviation AAD, maximum deviation D_{max}, bias, and standard deviation[12]) are reported in Table 2. Using this equation, we have obtained a standard deviation of 0.003 mPa·s, and the average absolute and maximum deviations between the experimental values of this work and those obtained from the correlation are 0.5% and 2.1%, respectively. The experimental values of heptane have been compared with the data reported by other authors (Table 3) as shown in Figure 2a. If the comparison is performed without extrapolation (i.e., up to 60 MPa and from 303.15 to 353.15 K (pT working conditions of our equipment)), then 98 literature points can be compared. The average absolute deviations between the correlation of eq 4 of our experimental data and those reported by Assael et al.,[11] Agaev and Golubev,[19] Naziev et al.,[20] Kanti et al.,[21] Baylaucq et al.,[22] Kashiwagi and Makita,[23] and Kuss and Pollmann[24] are (1.0, 2.1, 1.9, 3.4, 1.0, 0.3, and 1.7)%, respectively, with maximum deviations of (1.9, 5.2, 4.1, 6.0, 2.1, 0.7, and 2.8)%. All average deviations, except that obtained with the Kanti et al.[21] values, are lower or close to the experimental uncertainty (±2%). Over these 98 data points, the number of points with relative absolute deviations higher than 2% is 22. Our data present good agreement (1%) with the experimental values measured by Assael et al.[11] with a vibrating-wire viscometer with an uncertainty of ±0.5%.

If the comparison is performed over larger pT ranges, then an extrapolation of our experimental data is needed. For this task, eq 4 has been used. Over the pressure interval of (0.1 to 80) MPa and for temperatures from (290.65 to 400) K, a total of 197 experimental points have been compared, and the number of data with relative

Table 3. Temperature and Pressure Ranges of the Literature Data to Which Our Experimental Measurements Were Compared

authors	$(T_{\min} - T_{\max})$/K	$(p_{\min} - p_{\max})$/MPa	N^a
	Heptane		
Agaev and Golubev[19]	300−400	0.1−50	88
Assael et al.[11]	303.15−348.15	0.1−100	27
Naziev et al.[20]	290.65−385.15	0.1−50	35
Kanti et al.[21]	313.15−353.15	0.1−40	12
Baylaucq et al.[22]	303.15−343.15	0.1−100	15
Kashiwagi and Makita[23]	298.15−348.15	0.1−100	19
Kuss and Pollmann[24]	313.15	0.1−150	3
	2,3-Dimethylpentane		
Chevalier et al.[29]	298.15	0.1	1
Bouzas et al.[30]	298.15	0.1	1

[a] N is the number of experimental points that have been compared (up to 80 MPa).

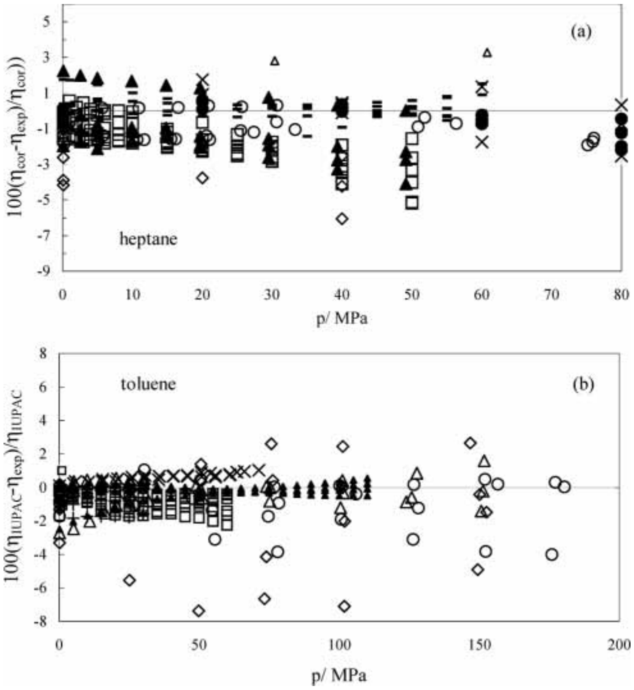

Figure 2. (a) Deviations between the correlated values using eq 4 and Table 2, η_{cor}, and different literature experimental data, η_{lit} for heptane: −, this work; ○, Assael et al.;[11] □, Agaev and Golubev;[19] ▲, Naziev et al.;[20] ◇, Kanti et al.;[21] ×, Baylaucq et al.;[22] ●, Kashiwagi et al.;[23] △, Kuss and Pollmann.[24] (b) Deviations between the IUPAC recommended equation[6] for toluene and several experimental data: □, this work; ○, Vieira dos Santos and Nieto de Castro;[31] △, Oliveira and Wakeham;[10] ◇, Dymond et al.;[32] ×, Assael et al.;[33] +, Krall et al.;[34] ▲, Kashiwagi and Makita.[23]

absolute deviations higher than 2% (experimental uncertainty) is 43. Under these conditions, the average absolute deviations with the literature values of Assael et al.,[11] Agaev and Golubev,[19] Naziev et al.,[20] Baylaucq et al.,[22] Kashiwagi and Makita,[23] and Kuss and Pollmann[24] are (1.0, 1.6, 1.6, 1.1, 0.6, and 2.2)%, respectively, with maximum deviations of (1.9, 5.2, 4.1, 2.5, 2.2, and 3.3)%. Therefore, this extrapolation increases the deviations very slightly.

In a second step, heptane has been also been considered to be a reference fluid for the calibration performed by using hexane, heptane, and decane. A typical calibration straight line is shown in Figure 3 at 323.15 K and 30 MPa. To verify the calibration again, the viscosity of toluene has been measured; the values are also reported in Table 1. In the case of toluene, we have directly compared the experimental values reported in this work with those obtained at our pT conditions from the IUPAC reference correlation proposed by Assael et al.[6] using the hard-sphere scheme. This correlation is valid for the interval of (213 to 373.15) K and from atmospheric pressure to 250 MPa. Assael et al. have estimated that for densities up to 0.920 g·cm^{-3} the uncertainty of the viscosity values generated by their correlation is about ±2%. Our experimental data agree with those obtained from this IUPAC reference correlation with an average absolute deviation of 0.9% and a maximum deviation of 2.2%. This result can also be seen in Figure 2b, where a comparison between different experimental viscosity data of toluene and the reference correlation proposed by IUPAC is presented.

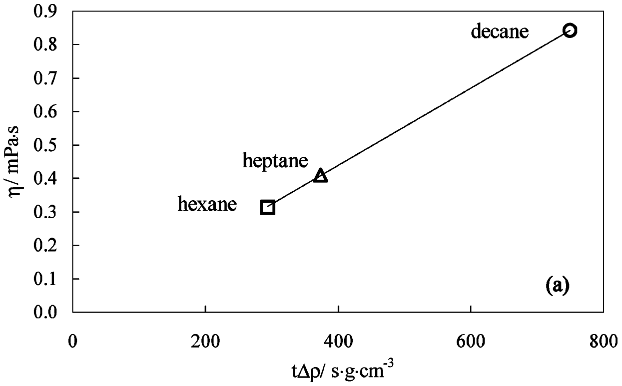

Figure 3. Calibration straight line (η against $t\Delta\rho$) at 323.15 K and 30 MPa: □, hexane; △, heptane; ○, decane.

Once the calibration procedure and its validation were finished, 2,3-dimethylpentane viscosities have been determined over the temperature interval of (303.15 to 353.15) K and up to 60 MPa. There is an absence of thermophysical data for this fluid at pressures higher than atmospheric. The densities of 2,3-dimethylpentane needed in eq 1 for the dynamic viscosity determination are reported in Table 4 and have been measured over the temperature interval of (298.15 to 353.15) K and at pressures up to 45 MPa (maximum working pressure). Details about the *PVT* equipment used for density measurements are given in previous papers.[26,27] The accuracy in temperature was ±0.01 K, that in pressure was ±0.02 MPa, and the experimental density uncertainty was ±1 × 10^{-4} g·cm^{-3}. The following equation has been used for density correlation against pressure and temperature:

$$\rho(T, p) = \frac{A_0 + A_1 T + A_2 T^2}{1 - C \ln\left(\dfrac{B_0 + B_1 T + B_2 T^2 + p}{B_0 + B_1 T + B_2 T^2 + 0.1\ \text{MPa}}\right)} \qquad (5)$$

where ρ is in g·cm^{-3}, T is in K, and p is in MPa. The A_i parameters are obtained by correlating the density values at atmospheric pressure against the temperature (A_0 = 8.8387 × 10^{-1}, A_1 = −4.3857 × 10^{-4}, and A_2 = −7.0304 × 10^{-3}). The C (0.0855) and B_i (B_0 = 340.3880, B_1 = −1.378060, and B_2 = 1.4439 × 10^{-3}) coefficients are calculated by adjusting the density values against both the temperature and the pressure (different from atmospheric pressure). Equation 5 represents the experimental density values over the temperature interval of (298.15 to 353.15) K and at pressures up to 45 MPa with a standard deviation of 1 × 10^{-4} g·cm^{-3}.

To determine the viscosity up to 60 MPa and because the experimental density values were measured up to 45

Table 4. Experimental Densities ρ/g·cm^{-3} vs Temperature T and Pressure p for 2,3-Dimethylpentane

	T/K								
p/MPa	298.15	283.15	293.15	303.15	313.15	323.15	333.15	343.15	353.15
				ρ/g·cm^{-3}					
0.1	0.7076	0.7032	0.6949	0.6863	0.6776	0.6687	0.6597	0.6506	0.6413
1	0.7083	0.7040	0.6957	0.6872	0.6786	0.6698	0.6609	0.6519	0.6427
5	0.7116	0.7074	0.6993	0.6911	0.6828	0.6743	0.6658	0.6572	0.6485
10	0.7155	0.7115	0.7036	0.6957	0.6877	0.6796	0.6715	0.6633	0.6551
15	0.7191	0.7153	0.7077	0.7000	0.6923	0.6845	0.6767	0.6689	0.6611
20	0.7227	0.7189	0.7115	0.7041	0.6966	0.6891	0.6816	0.6741	0.6666
25	0.7260	0.7223	0.7151	0.7079	0.7007	0.6934	0.6862	0.6789	0.6717
30	0.7292	0.7256	0.7186	0.7116	0.7045	0.6975	0.6905	0.6835	0.6765
35	0.7322	0.7287	0.7219	0.7150	0.7082	0.7013	0.6945	0.6877	0.6809
40	0.7352	0.7317	0.7250	0.7183	0.7116	0.7050	0.6983	0.6917	0.6851
45	0.7380	0.7346	0.7280	0.7215	0.7150	0.7084	0.7020	0.6955	0.6891
50				0.7246[a]	0.7181[a]	0.7118[a]	0.7054[a]	0.6991[a]	0.6929[a]
55				0.7275[a]	0.7212[a]	0.7149[a]	0.7087[a]	0.7026[a]	0.6965[a]
60				0.7303[a]	0.7241[a]	0.7180[a]	0.7119[a]	0.7059[a]	0.6999[a]

[a] Extrapolated values from eq 5.

Table 5. Experimental Dynamic Viscosities η/mPa·s vs Temperature T and Pressure p for 2,3-Dimethylpentane

	T/K					
p/MPa	303.15	313.15	323.15	333.15	343.15	353.15
			η/mPa·s			
0.1	0.356	0.324	0.290	0.262	0.244	0.232
1	0.360	0.328	0.294	0.266	0.247	0.234
5	0.377	0.343	0.308	0.280	0.260	0.246
10	0.398	0.361	0.326	0.298	0.276	0.261
15	0.419	0.380	0.344	0.316	0.292	0.276
20	0.441	0.399	0.362	0.334	0.309	0.291
25	0.462	0.418	0.381	0.352	0.325	0.306
30	0.485	0.438	0.399	0.369	0.342	0.321
35	0.507	0.458	0.418	0.387	0.359	0.336
40	0.530	0.479	0.437	0.404	0.376	0.350
45	0.553	0.500	0.457	0.422	0.393	0.365
50	0.576	0.522	0.476	0.439	0.410	0.381
55	0.600	0.544	0.496	0.457	0.428	0.395
60	0.624	0.566	0.517	0.474	0.445	0.411

MPa, eq 5 has been used for density extrapolation. Previously, Comuñas et al.[25] and Et-Tahir et al.[28] used a similar method. Table 5 reports the experimental dynamic viscosity data of 2,3-dimethylpentane, and Figure 4 shows their pressure and density dependencies. The viscosity increases with increasing density with a small curvature, with all of the points under different T, P conditions falling approximately in the same curve (Figure 4b). The viscosity values have been correlated against temperature and pressure by using eq 4, obtaining a standard deviation of 0.002 mPa·s. The parameters and deviations are reported in Table 2. The average and maximum relative deviations between the experimental values and those obtained from eq 4 are 0.4% and 1.6%, respectively. Our dynamic viscosity value for 2,3-dimethylpentane at atmospheric pressure and 298.15 K (interpolated from eq 4) agrees with the value reported by Chevalier et al.[29] with a relative deviation of −0.3% and with the data of Bouzas et al.[30] with a relative deviation of −2.6%. Our value at 298.15 K and 0.1 MPa presents a deviation lower than the experimental uncertainty (2%) from the data reported by Chevalier. The relative deviation between Bouzas et al.'s and Chevalier et al.'s data is 2.3%.

From eq 4, it is easy to obtain by differentiation the temperature viscosity coefficient $(\partial\eta/\partial T)_p$ and the pressure viscosity coefficient $(\partial\eta/\partial p)_T$:

$$\left(\frac{\partial\eta}{\partial p}\right)_T = \eta(p, T)\frac{D}{p + E(T)} \tag{6}$$

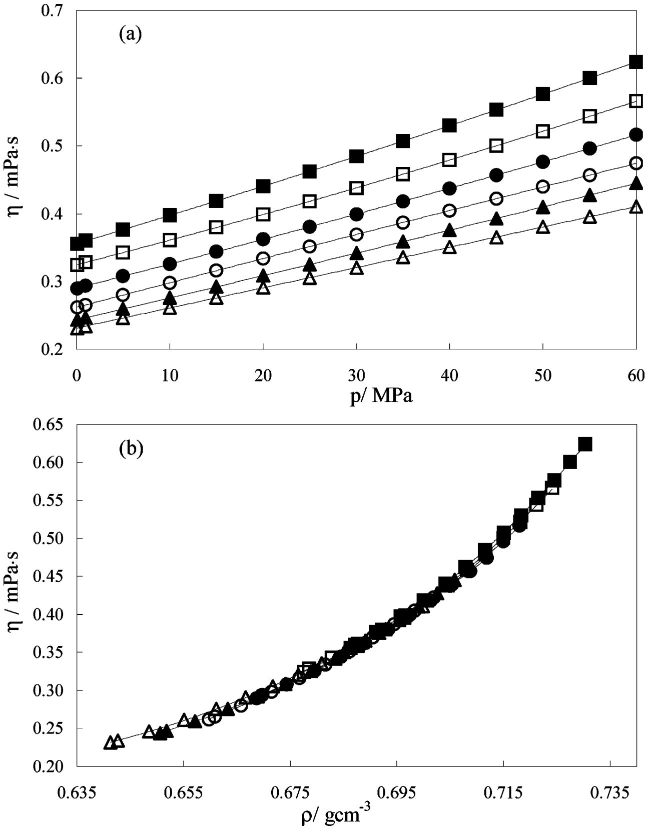

Figure 4. Experimental liquid dynamic viscosity, η, for 2,3-dimethylpentane against pressure (a) and density (b): ■, 303.15 K; □, 313.15 K; ●, 323.15 K; ○, 333.15 K; ▲, 343.15 K; △, 353.15 K.

$$\left(\frac{\partial\eta}{\partial T}\right)_p = \eta(p, T)\left[\frac{-B}{(T - C)^2}\right] + A \exp\left[\frac{B}{T - C}\right] D(E_1 + 2E_2 T)\frac{0.1 - p}{[0.1 + E(T)][p + E(T)]} \tag{7}$$

The $(\partial\eta/\partial T)_p$values are less than zero, becoming more negative when the pressure increases or the temperature decreases, as can be seen in Figure 5. On the contrary, the pressure viscosity coefficient is positive, increasing when either the pressure increases or the temperature decreases.

Conclusions and Future Work

The results obtained for heptane and toluene demonstrate the appropriate working of the rolling-ball viscom-

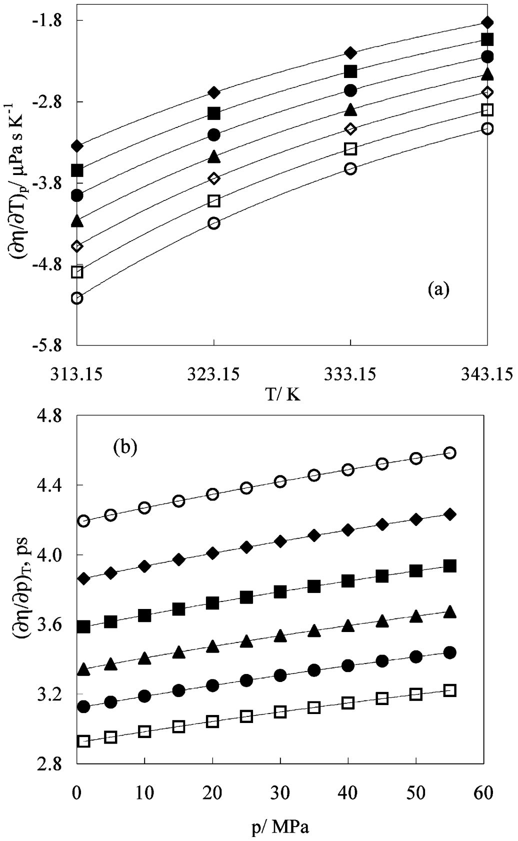

Figure 5. (a) Temperature−viscosity coefficient $(\partial\eta/\partial T)_p$/mPa·s·K^{-1} vs temperature: ◆, 0.1 MPa; ■, 10 MPa; ●, 20 MPa; ▲, 30 MPa; ◇, 40 MPa; □, 50 MPa; ○, 60 MPa. (b) Pressure−viscosity coefficient $(\partial\eta/\partial p)_T$/ps vs pressure: ○, 303.15 K; ◆, 313.15 K; ■, 323.15 K; ▲, 333.15; ●, 343.15 K; □, 353.15 K.

eter recently installed in our laboratory over the viscosity range of (0.234 to 0.803) mPa·s with an estimated uncertainty of ±2%. New viscosity data are reported for 2,3-dimethylpentane over the temperature interval of (303.15 to 353.15) K and up to 60 MPa. In addition, new density data of this last compound up to 45 MPa and from (298.15 to 353.15) K are presented. The validation over wide viscosity ranges (up to 200 mPa·s) will be performed soon in order to study several lubricant fluids.

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