# Measurement of the Viscosity of Liquid Cyclopentane Obtained with a Vibrating Wire Viscometer at Temperatures between (273 and 353) K and Pressures below 45 MPa

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The viscosity of liquid cyclopentane has been measured with a vibrating wire viscometer at temperatures from (273 to 353) K at pressures up to 45 MPa with a standard ($k = 1$) uncertainty of < 0.7 %. These results differ from literature values by ≤ ± 1 % at $T < 313$ K. At $T > 313$ K and $p$ up to 45 MPa, they lie within 1 % from the values obtained by extrapolation of the equation proposed by Assael et al. (*Int. J. Thermophys*. **2004**, *25*, 13−20). We have combined our measurements of viscosity with those reported by Assael and Dalaouti (*High Temp.−High Pressure* **2000**, *32*, 179−184) and Harris et al. (*J. Chem. Eng. Data* **2004**, *49*, 138−142) with densities from the modified Tait equation of Cibulka and Tagaki (*J. Chem. Eng. Data* **1999**, *44*, 1105−1128) to provide a correlation for the viscosity of cyclopentane at temperatures between (219 to 353) K and pressures below 200 MPa that represent the measured values with a standard deviation of ± 0.4 %. Other literature values are compared with this correlation.

## Introduction

Recently,[1] we reported the design of a vibrating wire viscometer along with measurements of the viscosity of methylbenzene and two certified reference fluids for viscosity at temperatures in the range from (298 to 373) K at pressures up to 40 MPa to validate the operation of the instrument. These measurements covered the viscosities from (0.3 to 100) mPa·s with a standard uncertainty of about 0.6 %[1] and relative deviations between the experimental and literature values of less than ± 1 %.

In this paper, we report measurements of the viscosity of liquid cyclopentane at temperatures in the range (273 to 353) K at pressures between (0.1 and 45) MPa. Assael et al.[2] reviewed seven publications[3−9] that report measurements of the viscosity of liquid cyclopentane; ref 9 reports a smoothing equation to their experimental values but did not report the values while another source cited by Assael et al.[2] was a private communication to those authors. Three sets of measurements in the literature extend to $p \gg 0.1$ MPa: Assael and Dalaouti[4] report results at temperatures from (219 to 309) K and $p \leq 25$ MPa; Harris et al.[5] at temperatures between (258 and 298) K and pressures below 380 MPa; and Brazier and Freeman[8] at $T = 303$ K and $p \leq 400$ MPa. In addition to the references listed in ref 2, Ma et al.[10] measured the viscosity of cyclopentane along the vapor−liquid equilibria line and also cited values of the density. Four other publications[11−14] report viscosities of cyclopentane either over a more limited range of temperatures or where cyclopentane is one component in a mixture and values of pure cyclopentane are provided for completeness. The results reported here have been compared with the above measurements and the correlations recommended by Assael et al.[2] and by Harris et al.[5]

## Experimental Section

Cyclopentane was supplied by Sigma-Aldrich with mass fraction purity stated to be greater than 0.99. The sample was dried over activated grade 0.4 nm molecular sieves for several weeks prior to use. GLC with FID and a capillary column indicated a mass fraction $w > 0.9995$. The mass fraction of water in the sample was determined by a Karl Fisher titration using a Radiometer analytical titrator, TIM 550, and found to be at $3 \cdot 10^{-5}$.

The apparatus, working equations, and analyses have been described in ref 1, and only the important features of the apparatus are described here. Values of the uncertainty in the measured quantities are listed. For measurements with cyclopentane, the vibrating wire was formed from tungsten wire of diameter 0.05 mm that was obtained from Goodfellow (Cambridge, U.K.) with a mass fraction purity > 99.95 %. The wire was about 40 mm long, clamped at both ends and tensioned to have a resonance frequency in vacuum of about 1.6 kHz. The temperature was determined with a platinum resistance thermometer with an uncertainty of ± 0.01 K. Pressures were generated with a hydraulic pump and measured, relative to atmospheric pressure, using a dial gauge that was, when calibrated against a dead-weight gauge, found to have an uncertainty of ± 0.05 MPa. Ambient pressure was obtained from a mercury barometer with an uncertainty of ± 0.1 kPa. The sinusoidal voltage applied to the wire was generated by a lock-in amplifier and the amplitude varied between (1 and 2) mV. During the course of the measurements reported, the resonance quality factor $Q$ varied

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**Table 1. Experimental Viscosities $\eta$ of Liquid Cyclopentane Obtained with a Vibrating Wire of Diameter about 0.05 mm and Densities $\rho$ Calculated from Cibulka and Takagi[16] at Temperature $T$ and Pressure $p$**

| $T$/K | $p$/MPa | $\rho$/kg·m$^{-3}$ | $\eta$/mPa·s |
|---|---|---|---|
| 273.15 | 0.1 | 764.84 | 0.5628 |
| | 10 | 772.46 | 0.6148 |
| | 30 | 786.01 | 0.7203 |
| | 40 | 792.07 | 0.7767 |
| 293.15 | 0.1 | 745.36 | 0.4413 |
| | 10 | 754.11 | 0.4827 |
| | 30 | 769.37 | 0.5708 |
| | 40 | 776.09 | 0.6167 |
| 298.15 | 0.1 | 740.41 | 0.4167 |
| | 10 | 749.47 | 0.4583 |
| | 30 | 765.20 | 0.5409 |
| | 40 | 772.10 | 0.5846 |
| 313.15 | 10 | 735.55 | 0.392 |
| | 30 | 752.79 | 0.4646 |
| | 45 | 763.75 | 0.5222 |
| 333.15 | 10 | 717.01 | 0.3247 |
| | 30 | 736.60 | 0.3882 |
| | 45 | 748.76 | 0.4364 |
| 353.15 | 15 | 704.99 | 0.2868 |
| | 30 | 721.16 | 0.3291 |
| | 45 | 734.68 | 0.3727 |

from 14 at $\eta$(273 K, 40 MPa) ≈ 0.78 mPa·s to 34 at which $\eta$(353 K, 15 MPa) ≈ 0.29 mPa·s.

The radius of the wire was found to be 0.02475 mm from measurements in methylbenzene at a temperature of 298.15 K and a pressure of 0.1 MPa at which the viscosity and density were obtained from the correlation of Assael et al.[15] The internal damping factor $\Delta_0$ was assumed equal to $4.9\cdot10^{-5}$ as reported previously for a sample of wire taken from the same spool.[1] In the analysis, the density of cyclopentane was required at each experimental temperature and pressure, and it was obtained from the correlation reported by Cibulka and Takagi.[16] Based on our previous work,[1] we estimate the standard uncertainty in viscosity to be less than ± 1 %.

## Results and Discussion

Our measurements of the viscosity of cyclopentane at temperatures between (273 and 353) K and pressures in the range of (0.1 to 45) MPa are listed in Table 1 along with the densities from the correlation of Cibulka and Takagi.[16] The viscosity results from Table 1 were fit to the empirical Vogel−Fulcher−Tammann function:

$$\eta(T,p)/\mathrm{mPa\cdot s} = \exp\left\{a + b(p/\mathrm{MPa}) + \frac{c + d(p/\mathrm{MPa}) + e(p/\mathrm{MPa})^2}{(T/\mathrm{K}) - T_0}\right\} \quad (1)$$

with a standard deviation of ± 0.1 %. The six parameters so obtained are listed in Table 2. Our results deviate, as shown in Figure 1, from eq 1 by less than ± 0.3 %, well within the estimated standard uncertainty of the measurements of about ± 1 %. Our measurements extend the temperature range at which the viscosity of cyclopentane has been measured at pressures above 0.1 MPa by 45 K and the pressure by about 20 MPa over those reported by Assael and Dalaouti.[4]

***Comparison with Literature Data.*** The literature sources, of which we are aware, of the viscosity of cyclopentane along with the measurement technique and source of density are summarized in Table 3. Figure 1 also shows deviations from eq 1 of the viscosities reported by Assael and Dalaouti[4] and those of Harris et al.[5] at pressures below 50 MPa at temperatures that overlap our range of (273 to 353) K and at $p > 0.1$ MPa. Assael and Dalaouti[4] used a vibrating wire viscometer and stated that the uncertainties increased from ± (0.5 to 1) % as the temperature decreased from (310 to 210) K. Harris et al.[5] used a falling sinker viscometer and estimated the uncertainty in their viscosities to be about ± 1 %. The deviations, shown in Figure 1, are random even though the systematic errors in falling sinker and vibrating wire viscometers are quite different. Equation 1 is empirical, and perhaps not surprisingly, extrapolation to temperatures and pressures outside the range of the fit was not successful. At a pressure of about 50 MPa the viscosity obtained from eq 1 differed by about 1 % from those reported by Harris et al.,[5] and this difference increased with increasing pressure to be +10 % (that is a factor of 10 greater than the uncertainty of our measurements) at a pressure twice our highest value of about 90 MPa. The differences increased rapidly as the pressure increased from (90 to 380) MPa. The viscosities reported by Harris et al.[5] at $p < 50$ MPa differed from eq 1 by about 1 % at $T = 258$ K, that is about 15 K below our lowest temperature. Hence eq 1 appears to extrapolate well over a limited temperature range but not well with pressure.

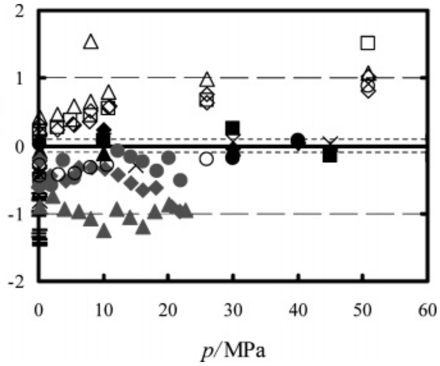

**Figure 1.** Relative deviations $\Delta\eta/\eta = \{\eta(\mathrm{expt}) - \eta(\mathrm{calc})\}/\eta(\mathrm{calc})$ of the experimentally determined viscosity $\eta$(expt) from the value obtained from eq 1 $\eta$(calc) as a function of $p > 0.1$ MPa. ●, this work $T = 273$ K; ▲, this work $T = 293$ K; ◆, this work $T = 298$ K; +, this work $T = 313$ K; ■, this work $T = 333$ K; ×, this work $T = 353$ K; ○, Harris et al.[5] at $T = 273$ K and $p < 50$ MPa; □, Harris et al.[5] at $T = 278$ K and $p < 50$ MPa; △, Harris et al.[5] at $T = 287$ K and $p < 50$ MPa; ◇, Harris et al.[5] at $T = 298$ K and $p < 50$ MPa; gray circle, Assael and Dalaouti[4] at $T = 273$ K; gray triangle, Assael and Dalaouti[4] at $T = 293$ K; gray diamond, Assael and Dalaouti[4] at T = 308 K; - - -, standard deviation of the fit of our data to eq 1 of ± 0.1 %; and − −, standard uncertainty in our measurements of ± 1 %.

Two equations,[2,5] both Padé approximates, have been proposed in the literature to represent measurements of the viscosity of cyclopentane, independent of ours, as a function of density and temperature. Both equations have the form:

$$\eta(T, V_r) = \sqrt{T}(1 + e_0V_r)/(e_1 + e_2V_r + e_3V_r^2) \quad (2)$$

where $V_r$ is a reference volume given by

$$V_r = V + e_4(T - T_r) + e_5(T - T_r)^2 \quad (3)$$

where $V$ is the molar volume at ($T$, $p$), $T_r$ is a reference temperature, and the six parameters $e_i$ were adjusted to represent specific sets of viscosities reported in the literature. Assael et al.[2] used eqs 2 and 3 to represent viscosities reported in refs 3 to 5 that covered temperatures from (220 to 310) K and pressures below 25 MPa with a standard deviation of 1 % at a confidence interval of 0.95. The correlation also included measurements that were reported as a private communication to Assael et al.;[2] consequently, these values are not included in our deviation plots. Harris et al.[5] used algebraically identical equations and

**Table 2. Coefficients of Equation 1 Adjusted to Best Fit the Measurements of Viscosity Reported in Table 1**

| $a$ | $b$ | $c$ | $d$ | $e$ | $T_0$ |
|---|---|---|---|---|---|
| −4.38219635 | 0.01265040 | 1120.20755931 | −1.03932754 | −0.00777493 | −21.16678787 |

**Table 3. Measurements of the Viscosity $\eta$ of Cyclopentane Reported in the Literature Obtained with a Vibrating Wire (VW), Falling Body (FB), Rolling Ball (RB), and Capillary Flow(CF) Viscometer over a Temperature Range $T_{\min}$ to $T_{\max}$ with Maximum Pressures $p_{\max}$ and Estimated Uncertainty $u$ along with the Source of Density $\rho$ and the Maximum Relative Deviations $(|\Delta\eta\ |\eta)_{\max}{}^{a}$ of $\eta$ from Equations 2 and 3 with Coefficients in Table 4**

| first author | ref | $(T_{\min}$ to $T_{\max})$/K | $p_{\max}$/MPa | $100\ (|\Delta\eta|/\eta)_{\max}$ | $u$ | method | $\rho$ source |
|---|---|---|---|---|---|---|---|
| Levin | 3 | 298 | 0.1 | 0.1 | 0.7 % | CF | pycnometer |
| Assael | 4 | 219 to 309 | 23 | 0.7 ($p = 0.1$ MPa)<br>1.2 ($p < 23\ \eta$/MPa) | ± 0.5 %[b] | VW | ref 17 |
| Ma | 10 | 253 to 353 | 0.2 | 0.6 ($p = 0.1$ MPa)<br>4.3 ($p < 0.2$ MPa) | ± 2 % | CF | ref 18 > 323 K<br>ref 20 ≤ 323 K |
| Harris | 5 | 258 to 298 | 0.1 | 0.8 ($p = 0.1$ MPa) | ± 0.2 % | CF | Anton Paar DMA−5000 |
| | | 258 to 298 | 380 | 1.0 ($p < 200$ MPa) | ±1 % | FB | refs 21, 22 |
| Brazier | 8 | 303 | 400 | 0.7 ($p = 0.1$ MPa)<br>10 ($p < 200$ MPa) | not stated | RB | Bellows dilatometer |
| Fischer | 9 | 250 to 315 | 0.1 | 0.1 at 250 K<br>3.7 at 315 K | 0.2 % | CF | Heraeus-Paar DMA-02C |
| Guzmán | 11 | 283 to 313 | 0.1 | 0.5 | $\pm 1 \times 10^{-4}$ mm$^2$·s$^{-1}$<br>(kinematic viscosity) | CF | Anton Paar DMA-58 |
| Oswal | 12 | 303 | 0.1 | 1.5 | ± 0.002 mPa·s | CF | Anton Paar DMA-60/601 |
| Pereiro | 13 | 293 to 313 | 0.1 | 0.6 | ± 0.01 mPa·s | CF | Anton Paar DSA-5000 |
| González | 14 | 293 to 303 | 0.1 | 0.4 | ± 0.01 mPa·s | CF | Anton Paar DSA-5000 |
| this work | | 273 to 353 | 45 | 0.5 ($p = 0.1$ MPa)<br>1.2 ($p < 45$ MPa) | ± 0.6 % | VW | ref 16 |

[a] $|\Delta\eta| = \eta_{\text{exptl}} - \eta_{\text{calcd}}$. [b] $u = \pm 1$ % at low temperature.

**Table 4. Coefficients $e_i$ of Equations 2 and 3 Obtained by Regression to the Viscosities Listed in Table 1 Combined with Those Reported by Harris et al.[7] at $p < 200$ MPa and Assael and Dalaouti[4] with the Density from the Correlation of Cibulka and Tigaki[16] [a]**

| $i$ | $e_i$ |
|---|---|
| 0 | $7866.277 \times 10^{-6}$ mol·cm$^{-3}$ |
| 1 | 770188.311 K$^{0.5}$·Pa$^{-1}$·s$^{-1}$ |
| 2 | −20859.264 K$^{0.5}$· Pa$^{-1}$·s$^{-1}$·mol·cm$^{-3}$ |
| 3 | 141.924 K$^{0.5}$·Pa$^{-1}$·s$^{-1}$·mol$^2$·cm$^{-6}$ |
| 4 | $34247.660 \times 10^{-6}$ cm$^3$·mol$^{-1}$·K$^{-1}$ |
| 5 | $-49.782 \times 10^{-6}$ cm$^3$·mol$^{-1}$·K$^{-2}$ |

[a] In eqs 2 and 3, $M = 0.0701340$ kg·mol$^{-1}$ and $T_r = 273.15$ K.

represented solely their viscosity measurements at temperatures between (258 and 298) K and pressures below 380 MPa, with a standard deviation of 0.3 % with six slightly different parameters. Equations 2 and 3 require knowledge of the density. Assael et al.[2] obtained densities from a correlation reported by Baonza et al.[17] that covered temperatures between (193 and 298) K at pressures below 104 MPa while Harris et al.[5] developed their own modified Tait equation based on literature densities. This equation was used to extrapolate the densities from the highest pressure of the measurements selected from the literature of 196 MPa to the highest pressure at which they reported the viscosity, 380 MPa. Harris et al.[5] tabulated their estimated densities.

The equation for the density of cyclopentane reported by Cibulka and Tagaki[16] is based on their critical evaluation of the ($\rho$, $T$, $p$) data from the literature. The equation in ref 16 is a modified Tait equation for temperatures between (192 and 353) K and $p \leq 196$ MPa that represented the selected data sets with a standard deviation of < 0.2 %. The difference between the densities listed by Harris et al.[5] and those obtained from the correlation of Cibulka and Tagaki[16] increase linearly from about 0.02 % at $p = 0.1$ MPa to 1 % at $p = 380$ MPa. Fortunately, the working equations for a falling sinker (as also are those for a vibrating wire) viscometer are insensitive to the value of the density and differences of about 1 % in the density should not introduce significant systematic errors in the viscosities reported in refs 4 or 5 or here.

The correlation of Cibulka and Tagaki[16] was used to estimate the density of cyclopentane at the temperatures and pressures at which we had measured the viscosity. The densities from ref 16 were used in eqs 2 and 3 with both the parameters recommended by Assael et al.[2] and, separately, with the parameters provided by Harris et al.[5] In both cases, the estimated viscosity, when compared to our measurements, differed by less than ± 1 %, and this agreement is surprisingly good particularly for that of Assael et al.[2] because their equation was based on literature data from $T = (220$ to $310)$ K, 53 K lower in temperature than our measurements, and $p < 25$ MPa while our data covers the range $T = (273$ to $353)$ K and $p < 45$ MPa, that is almost a factor of 2 higher in pressure and 45 K higher in temperature. In view of this agreement, we compared the measurements reported by Harris et al.[5] with estimates obtained from the correlation of Assael et al.[2] in this case using the densities tabulated by Harris et al.[5] Surprisingly, the predictions deviated from the experimental values by less than 1 % at pressures below 200 MPa, about 8 times the maximum of 25 MPa used in the regression by Assael et al.[2] This comparison indicates viscosities can be obtained from eqs 2 and 3 with the coefficients of Assael et al.[2] and the densities of Harris et al.[5] within 1 % at pressure below 200 MPa and temperatures in the range of (258 to 298) K. At higher pressures, the differences increased with increasing pressure but did not exceed 20 % at $T = 268$ K and $p = 380$ MPa.

In view of these comparisons and the desire to have an equation to represent the viscosity of cyclopentane over the widest possible temperature and pressure range, we combined the measurements of Assael and Dalaouti[4] and Harris et al.[5] with ours and estimated the density at the cited temperatures and pressures from the correlation of Cibulka and Tagaki[16] at temperatures between (258 to 353) K and pressures from (0.1 to 196) MPa where $p = 196$ MPa is the maximum recommended pressure in ref 16. The six parameters $e_i$ of eqs 2 and 3 were adjusted by a least-squares fit to the values listed in Table 4. The equations represented the measurements with a standard deviation of ± 0.4 %. Figure 2 shows the measurements as deviations

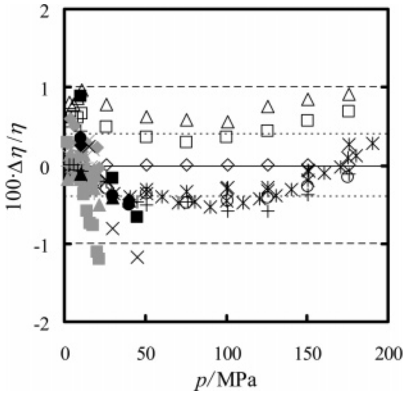

**Figure 2.** Relative deviations $\Delta\eta/\eta = \{\eta(\text{expt}) - \eta(\text{calc})\}/\eta(\text{calc})$ of the experimentally determined viscosity $\eta$(expt) from the value $\eta$(calc) obtained from eqs 2 and 3 with coefficients of Table 4 as a function of pressure. ●, This work $T = 273$ K; ▲, this work $T = 293$ K; ◆, this work $T = 298$ K; +, this work $T = 313$ K; ■, this work $T = 333$ K; ×, this work $T = 353$ K; *, Harris et al.[5] at $T = 263$ K and $p < 200$ MPa; +, Harris et al.[5] at $T = 268$ K and $p < 200$ MPa; ○, Harris et al.[5] at $T = 273$ K and $p < 200$ MPa; □, Harris et al.[5] at $T = 278$ K and $p < 200$ MPa; △, Harris et al.[5] at $T = 287$ K and $p < 200$ MPa; ◇, Harris et al.[7] at $T = 298$ K and $p < 200$ MPa; gray times sign, Assael and Dalaouti[4] at $T = 219$ K; gray plus sign, Assael and Dalaouti[4] at $T = 233$ K; gray diamond, Assael and Dalaouti[4] at $T = 253$ K; gray circle, Assael and Dalaouti[4] at $T = 273$ K; gray triangle, Assael and Dalaouti[4] at $T = 293$ K; gray square, Assael and Dalaouti[4] at $T = 308$ K; - - -, standard deviation of the fit of ± 0.4 %; and — —, standard uncertainty in the measurements of ± 1 %.

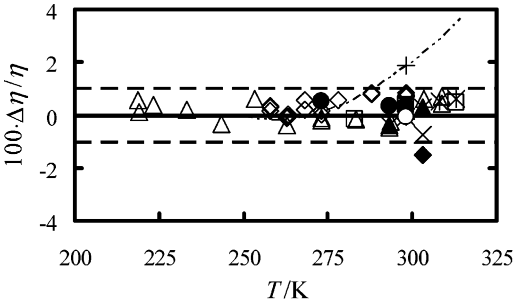

**Figure 3.** Relative deviations $\Delta\eta/\eta = \{\eta(\text{expt}) - \eta(\text{calc})\}/\eta(\text{calc})$ of the experimentally determined viscosity $\eta$(expt) from the value obtained from eqs 2 and 3 $\eta$(calc) with coefficients from Table 4 as a function of temperature and $p = 0.1$ MPa. ●, This work; △, Assael and Dalaouti;[4] ◇, Harris et al.;[5] □, Guzman et al.;[11] *, Pereiro et al.;[13] ▲, Gonzalez et al.;[14] ×, at 303.15 K by Brazier and Freeman;[8] ◆, at 303.15 K by Oswal et al.;[12] O, at 298.15 K by Levien and Mills;[3] +, at 298.15 K by Fischer and Weiss;[9] — ·· —, equation of Fischer and Weiss;[9] - - -, standard uncertainty in our measurements of ± 1 %.

from eqs 2 and 3 with coefficients of Table 4. These deviations are random, and all but three values are within the uncertainty cited for each of the instruments used and listed in Table 3.

Brazier and Freeman[8] report measurements of the density of cyclopentane at $T = 303$ K and pressures in the range of (0.1 to 450) MPa that were not included by Cibulka and Tagaki[16] in their correlation. We have compared the values from ref 8 at pressures between (203 and 456) MPa with those from ref 16 and find a difference of 0.9 % at $p = 200$ MPa and 1.1 % at $p = 450$ MPa. We consider the remarkably good agreement at $p = 450$ MPa between the density reported in ref 8 and the value obtained by extrapolating the equation of Cibulka and Tagaki[16] to be fortuitous and insufficient validation for estimating densities from ref 16 over the whole temperature range of interest, (219 to 353) K, and $p$ from (196 to 380) MPa. However, if we assume the densities obtained from ref 16 hold from $T = (219$ to $353)$ K and $p$ from (196 to 380) MPa and compare the viscosities from eqs 2 and 3 using the coefficients of Table 4 with the measurements of Harris et al.,[5] the differences are found to increase with increasing pressure. For example, at $p = 380$ MPa and $T = 268$ K, the worst case, the difference was about 8 % while, rather surprisingly at the same pressure but at $T = 298$ K the difference in viscosity was only 2.7 %. Furthermore, if we use the above densities calculated in the expanded pressure range and adjust the coefficients of eq 2 and 3 to include the viscosity measurements by Harris et al.[5] from (200 to 380) MPa, the deviations in the measured viscosity for the whole pressure and temperature range are less than ± 1 % and similar in sign and magnitude to those shown in Figure 2. However, in the absence of other independent measurements of density to validate the correlation of Cibulka and Tagaki[16] over the extended pressure range from (196 to 400) MPa, we do not provide here the coefficients obtained from that fit. Brazier and Freeman[8] also reported viscosities at 303 K up to 400 MPa measured with a falling ball viscometer that was calibrated with a series of unnamed liquids over the pressure range. The viscosities obtained from ref 8 are not shown in Figure 1 because at the pressures that overlap the abscissa of Figure 1 their result is about 7 % above eq 1 at $p = 50$ MPa and is outside the scale of the ordinate axis. The viscosities cited in ref 8 deviate from the correlation of Harris et al.[5] when the densities used are the measurements reported in ref 8, by 4.2 % at $p = 50$ MPa. At higher pressures the differences vary in a systematic manner from 8.7 % at $p = 100$ MPa to −2.8 % at $p = 300$ MPa; if the density used in the calculation is taken from ref 16 the difference is 6.3 % at $p = 50$ MPa and increases with increasing pressure to be 14 % at $p = 400$ MPa.

At $p = 0.1$ MPa the viscosities reported in refs 3 to 5, 8, 11, 13, and 14 deviate from eqs 2 and 3, as shown in Figure 3, by less than ± 1 % and within the uncertainty of the various measurements. The viscosity reported at 298 K in ref 9 differs by +1.8 % from eqs 2 and 3. Ref 9 only reported an equation from $T = (250$ to $315)$ K that differs from the values from eqs 2 and 3 by −0.2 % at 250 K and +3.7 % at 315 K. Their reported accuracy was ± 0.2 %. The reason for the discrepancy is not clear as the cyclopentane was carefully purified by distillation and the viscometer was calibrated with two fluids, water and 1,2-dicyclohexylethane, to obtain the Hagenback correction (which in a capillary viscometer results from end effects and kinetic energy terms). 1,2-Dicyclohexylethane has a viscosity of ≈ 1.87 mPa·s at 293.15 K. In general, the Hagenback correction becomes significant at low viscosity so one of the calibration fluids should have a viscosity close to the lowest value measured. Calibration with a fluid having high viscosity can lead to systematic uncertainties, particularly at higher temperatures, where the viscosity is lower. The value at 303 K in ref 12 differs from eqs 2 and 3 by −1.5 %, which is probably within a realistic estimate of the uncertainties of the measurements. In general, the agreement between results from such different techniques is exceptional.

There is one other set of viscosity measurements of liquid cyclopentane reported in the archival literature by Ma et al.[10] along the vapor−liquid equilibria line for temperatures between (253 and 353) K. Ma et al.[10] listed values of the density at the temperatures of their viscosity measurements estimated from the references given in Table 3. These measurements, as Figure 4 shows with the open diamonds, deviate from the values estimated from eqs 2 and 3 and the coefficients of Table 4 when the densities were taken from ref 10 with a systematic undulation that reaches a maximum of 11 % at a temperature 338 K, about 6 times the estimated uncertainty in viscosity. Ma et al.[10] did not provide estimates of the vapor pressure to allow calculation

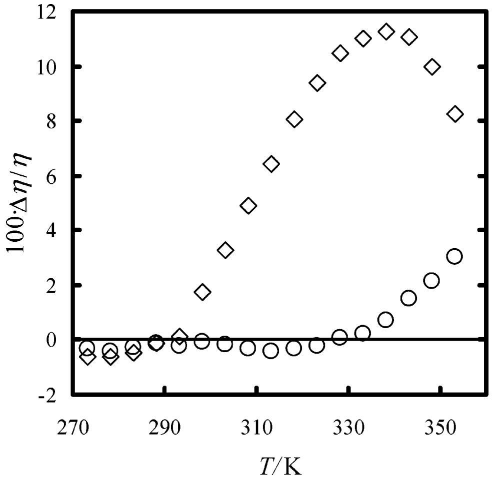

**Figure 4.** Relative deviations $\Delta\eta/\eta = \{\eta(\text{expt}) - \eta(\text{calc})\}/\eta(\text{calc})$ of the viscosity $\eta$(expt) reported by Ma et al.[10] from $\eta$(calc) obtained from eqs 2 and 3 with coefficients of Table 4 at the vapor pressure as a function of temperature. ◇, with the densities reported by Ma et al.;[10] and ○, Ma et al.[10] with densities estimated from the correlation of Cibulka and Tagaki[16] at the vapor pressure obtained from the TRC Tables[19] and the temperatures reported in ref 10.

of the densities from the correlation of Cibulka and Tagaki.[16] To do so, we obtained the vapor pressures of (0.05 to 0.25) MPa at the temperatures listed in ref 10 of (253 to 353) K from the TRC Thermodynamic Tables—Hydrocarbons.[19] Not surprisingly, the density reported by Ma et al.[10] differed from values estimated with the correlation of Cibulka and Tagaki[16] at the vapor pressure with a systematic undulation that was identical in form to that shown in Figure 4 for the viscosity except with a maximum difference of about 1.5 %. In view of the results of this comparison, we repeated the calculation of the viscosities from eqs 2 and 3 with the coefficients from Table 4 with the densities estimated from Cibulka and Tagaki[16] at the vapor pressure from ref 19 and compared these estimates with the values reported by Ma et al.[10] and, as shown in Figure 4, found the deviations decreased significantly to be less than ± 0.3 % at $T < 338$ K, well within the cited uncertainty of the measurements of Ma et al.[10] of ± 2 %, but at higher temperatures the differences increased to be about 3 % at $T = 353$ K, probably for the reason given above. Acetone with $\eta \approx 0.4$ mPa·s at $T = 297$ K was the lowest viscosity calibration fluid used by Ma et al.[10] while $\eta$ for cyclopentane at $T = 353$ K was $\approx 0.129$ mPa·s. Hence it is possible that the difference observed is due to incorrect calibration of their viscometer. We conclude from our comparisons that the densities cited by Ma et al.[10] are incorrect and more importantly an error in the density input to eqs 2 and 3 is magnified so that the calculated uncertainty in viscosity is considerably greater than the uncertainty in the density. For example, along the vapor pressure, a 1.7 % uncertainty in density gives rise to 11.2 % uncertainty in viscosity.

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## Literature Cited

(1) Kandil, M. E.; Marsh, K. N.; Goodwin, A. R. H. Vibrating wire viscometer with wire diameters of (0.05 and 0.15) mm: results for methylbenzene and two fluids with nominal viscosities at $T = 298$ K and $p = 0.01$ MPa of (14 and 232) mPa·s at temperatures between (298 and 373) K and pressures below 40 MPa. *J. Chem. Eng. Data* **2005**, *50*, 647−655.

(2) Assael, M. J.; Bauer, H.; Dalaouti, N. K.; Harris, K. R. Reference correlation for the viscosity of liquid cyclopentane from 220 to 310 K at pressures to 25 MPa. *Int. J. Thermophys.* **2004**, *25*, 13−20.

(3) Levien, B.; Mills, R. Mutual diffusion, intradiffusion and viscosity coefficients for mixtures of cyclopentane and cyclooctane at 298.15 K. *Aust. J. Chem.* **1980**, *33*, 1977−1985.

(4) Assael, M. J.; Dalaouti, N. K. Measurement of the viscosity of cyclopentane from 210 to 310 K and pressures up to 25 MPa. *High Temp.−High Pressures* **2000**, *32*, 179−184.

(5) Harris, K. R.; Newitt, P. J.; Woolf, L. A. Temperature and density dependence of the viscosity of cyclopentane. *J. Chem. Eng. Data* **2004**, *49*, 138−142.

(6) Timmermans, J.; Hennaut-Roland, M. Work of the International Bureau of Physicochemical Standards. VIII. Physical constants of twenty organic compounds. *J. Chim. Phys. Phys. Chim. Biol.* **1937**, *34*, 693−696.

(7) Khalilov, Kh. M. Viscosity of isooctane, cyclopentane, cyclohexane, and of their saturated vapors. *Zh. Fiz. Khim.* **1962**, *36*, 2474−2476.

(8) Brazier, D. W.; Freeman, G. R. Effects of pressure on the density, dielectric constant, and viscosity of several hydrocarbons and other organic liquids. *Can. J. Chem.* **1969**, *47*, 893−899.

(9) Fischer, J.; Weiss, A. Transport properties of liquids. V. Self-diffusion, viscosity, and mass density of ellipsoidal shaped molecules in the pure liquid phase. *Ber. Dtsch. Bunsen-Ges.* **1986**, *90*, 896−905.

(10) Ma, R.-F.; Shi, L.; Duan, Y.-Y.; Han, L.-Z.; Liu, N.-X. Saturated liquid viscosity of cyclopentane and isopentane. *J. Chem. Eng. Data* **2003**, *48*, 1418−1421.

(11) Guzmán, C.; Lafuente, C.; Santafe, J.; Royo, F. M.; Urieta, J. S. Thermodynamic and transport properties of binary mixtures containing 1,3-dioxolane. *Int. J. Thermophys.***1999**, *20*, 1435−1448.

(12) Oswal, S. L.; Maisuria, M. M.; Gardas, R. L. Viscosity of binary mixtures of cycloalkane with cycloalkane, alkane and aromatic hydrocarbon at 303.15 K. *J. Mol. Liq.* **2003**, *108*, 199−215.

(13) Pereiro, A. B.; Rodríguez, A.; Canosa, J.; Tojo, J. Density, viscosity, and speed of sound of dialkyl carbonates with cyclopentane and methyl cyclohexane at several temperatures. *J. Chem. Eng. Data* **2004**, *49*, 1392−1399.

(14) González, B.; Dominguez, A.; Tojo, J. Dynamic viscosities of the binary systems cyclohexane and cyclopentane with acetone, butanone, or 2-pentanone at three temperatures $T = (293.15, 298.15, \text{and } 303.15)$ K. *J. Chem. Eng. Data* **2005**, *50*, 1462−1469.

(15) Assael, M. J.; Avelino, H. M. T.; Dalaouti, N. K.; Fareleira, J. M. N. A.; Harris, K. R. Reference correlation for the viscosity of liquid toluene from 213 to 373 K at pressures to 250 MPa. *Int. J. Thermophys.* **2001**, *22*, 789−799.

(16) Cibulka, I.; Takagi, T. $P$-$\rho$-$T$ data of liquids: summarization and evaluation. 6. Nonaromatic hydrocarbons ($C_n$, $n \geq 5$) except $n$-alkanes $C_5$ to $C_{16}$. *J. Chem. Eng. Data* **1999**, *44*, 1105−1128.

(17) Baonza, V. G.; Alonso, M. C.; Delgado, J. N. Study of the equation of state of cyclopentane from 193 to 298 K and pressures up to 104 MPa. *Ber. Bunsen-Ges. Phys. Chem.* **1992**, *96*, 1859−1868.

(18) Beaton, C. F.; Hewitt, G. F. *Physical Property Data for the Design Engineer*; Hemisphere: New York, 1988.

(19) TRC Thermodynamic Tables. Hydrocarbons, 1991, k-2010. Thermodynamics Research Center, National Institute of Standards and Technology: Boulder, CO.

(20) McLinden, M. O.; Klein, S. A.; Lemmon, E. W.; Perkins, A. P. *NIST Thermodynamic and Transport Properties of Refrigerants and Refrigerant Mixtures (REFPROP), NIST Standard Reference Database 23*, version 6.01; National Institute of Standards and Technology: Gaithersburg, MD, 1998.

(21) Malhotra, R.; Woolf, L. A. Thermodynamic Properties of 2,2,4-trimethylpentane. *Int. J.Thermophys.* **1990**, *11*, 1059−1073.

(22) Malhotra, R.; Woolf, L. A. Extrapolation of ($p$,$V$,$T$) data for liquids. *High Temp.−High Pressures* **1991**, *23*, 107−110.

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