

Measurements of the Viscosity of Benzene, Toluene, and *m*-Xylene at Pressure up to 80 MPa

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New absolute measurements of the viscosity of benzene, toluene, and *m*-xylene are presented. The measurements were performed in a recently developed vibrating-wire instrument, at temperatures of 303.15 and 323.15 K and pressures up to 80 MPa. The overall uncertainty in the reported viscosity data is estimated to be $\pm 0.5\%$.

KEY WORDS: benzene; high pressure; toluene; viscosity; vibrating wire; *m*-xylene.

1. INTRODUCTION

In recent years semiempirical schemes, based on the exact hard-sphere theory of transport properties, have been applied to the correlation and prediction of these properties. In a recent paper [1], the thermal conductivity, the viscosity, and the self-diffusion coefficient of liquid *n*-alkanes were satisfactorily simultaneously correlated with an uncertainty of $\pm 5\%$, and universal curves were developed for the prediction of these properties in a wide range of temperatures and pressures. In order to extend the applicability of this scheme to other groups of liquids, accurate high-pressure measurements of the viscosity are essential.

In a previous paper [2], a new vibrating-wire instrument for the measurement of the viscosity of liquids at high pressures was described. The instrument, based on a complete theory, permits the absolute measurements of the viscosity with an estimated uncertainty less than

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$\pm 0.5\%$. In this paper, absolute measurements of the viscosity of benzene, toluene, and *m*-xylene at 303.15 and 323.15 K and up to 80 MPa pressure are presented.

2. EXPERIMENTAL

According to the ideal model of the technique, a thin vertical wire, constrained not to move at its two ends, is placed in the liquid. If an oscillation is initiated by the displacement of the wire from its equilibrium position then, following a short-lived initial transient, the motion will conform to a damped, simple harmonic motion [2, 3],

$$y = y_0 e^{(i-\Delta)\omega t} \quad (1)$$

with an angular frequency ω and a logarithmic decrement Δ . In circumstances when the length of the wire is much larger than its radius, and provided that the amplitude of the motion is sufficiently small, it has been shown that it is possible to linearize the Navier–Stokes equations and relate the viscosity, μ , and density, ρ , of the fluid to the values of ω and Δ and to their corresponding values *in vacuo*, ω_0 and Δ_0 . In these circumstances, coupled with a distinct set of design criteria, the working equation for the viscometer, can be written [2, 3] as

$$\Delta = \frac{(\rho/\rho_s)k' + 2\Delta_0}{2[1 + (\rho/\rho_s)k]} \quad (2)$$

In this equation ρ_s denotes the density of the wire material, while the quantities k and k' are given by

$$k = -1 + 2 \operatorname{Im}(A) \quad (3)$$

and

$$k' = 2 \operatorname{Re}(A) + 2\Delta \operatorname{Im}(A) \quad (4)$$

where

$$A = (i - \Delta) \left[1 + \frac{2K_1 [[(i - \Delta)\Omega]^{1/2}]}{[(i - \Delta)\Omega]^{1/2} K_0 [[(i - \Delta)\Omega]^{1/2}]} \right] \quad (5)$$

and

$$\Omega = \frac{\rho\omega R^2}{\mu} \quad (6)$$

In the above equations, K_0 and K_1 are modified Bessel functions. Equations (1)–(6) represent a consistent set from which the viscosity of a liquid can be calculated from the frequency of oscillation, ω , the logarithmic decrement, Δ , in the liquid, and the logarithmic decrement, Δ_0 , *in vacuo*.

The actual instrument used for these measurements has been described in detail elsewhere [2] and is presented only briefly here. A 100- μ m-diameter, 50-mm-length, tungsten wire was used as the vibrating wire. Constant tensioning of the wire was accomplished by a two-weight assembly at the bottom of the wire. The volumes of the two weights (the inner one is made from tungsten and the outer one from stainless steel) are chosen so that the net effect of changing the density of the surrounding liquid results in a negligible effect upon the frequency of oscillation. Two permanent magnets, made from samarium–cobalt and placed around the wire, are used for the electromagnetic initiation of the oscillations of the wire and their detection. Following initiation of the motion, the signal induced in the vibrating wire is observed with a bridge in which the wire forms one arm. The out-of-balance signal, amplified by 30,000 times, is then observed with an A/D converter coupled to a microcomputer. This configuration enables sampling of the oscillation signal at a rate of 50 kHz with a resolution of 12 bits. The values of the logarithmic decrement and the frequency of oscillation are then obtained from the recorded data with the aid of a nonlinear least-squares fitting procedure.

The samples of benzene and *m*-xylene used for these measurements were supplied by B.D.H. Ltd. with nominal purities of 99.8 and 99.0%, respectively, while the sample of toluene was supplied by Merck with a nominal purity of 99.5%.

3. RESULTS

As described in a previous paper [2], the uncertainty of the instrument was found to be $\pm 0.5\%$. In order to check the continuing good operation of the instrument, the viscosity of toluene was measured at atmospheric pressure as a function of temperature (Table I), before and after each set of measurements. The values obtained were found to agree with those obtained by Gonçalves et al. [4] (in an absolute Ubbelohde capillary viscometer with an uncertainty of $\pm 0.3\%$) within $\pm 0.1\%$, which is well within the mutual uncertainty of both instruments.

In Tables II, III, and IV the present measurements of the viscosity of benzene, toluene, and *m*-xylene at 303.15 and 323.15 K as a function of pressure, are presented. The density data used for the measurements of benzene were obtained from Li [5] and Dymond et al. [6], with an

Table I. Viscosity of Toluene as a Function of Temperature at Atmospheric Pressure

Temperature (K)	Viscosity ($\mu\text{Pa}\cdot\text{s}$)
303.15	522.7
304.72	513.8
312.52	470.6
322.24	426.0
323.15	421.6
334.69	376.9

uncertainty less than $\pm 0.1\%$. The density data used for the measurements of toluene were obtained by Kashiwagi et al. [7], while the density data for *m*-xylene are those used by Taxis et al. [8], both with an uncertainty less than $\pm 0.1\%$. Since the density data for *m*-xylene extended only up to 55-MPa pressure, the measurements of the viscosity of *m*-xylene were restricted to this pressure range.

Table II. Viscosity of Benzene at 303.15 and 323.15 K, as a Function of Pressure

303.15 K			323.15 K		
Pressure (MPa)	Density ($\text{kg}\cdot\text{m}^{-3}$)	Viscosity ($\mu\text{Pa}\cdot\text{s}$)	Pressure (MPa)	Density ($\text{kg}\cdot\text{m}^{-3}$)	Viscosity ($\mu\text{Pa}\cdot\text{s}$)
0.10	868.3	562.7	0.10	846.8	438.1
5.37	872.8	588.5	5.37	851.8	456.5
10.44	876.8	614.5	10.34	856.3	476.0
15.50	880.8	640.5	15.40	860.7	496.2
20.57	884.5	667.5	20.27	864.7	516.6
25.74	888.2	695.4	25.64	869.0	538.4
30.90	891.8	724.5	30.90	873.1	560.6
35.87	895.1	752.6	35.26	876.3	579.4
41.14	898.5	783.8	39.72	879.5	598.8
46.10	901.6	814.3	45.90	883.8	626.4
50.97	904.5	844.1	50.26	886.8	645.8
55.02	906.9	870.1	55.02	889.9	668.5
59.38	909.4	897.3	62.11	894.3	702.0
			62.92	894.8	706.3
			69.41	898.7	735.9

Table III. Viscosity of Toluene at 303.15 and 323.15 K, as a Function of Pressure

303.15 K			323.15 K		
Pressure (MPa)	Density (kg · m ⁻³)	Viscosity (μPa · s)	Pressure (MPa)	Density (kg · m ⁻³)	Viscosity (μPa · s)
0.10	857.8	522.7	0.10	839.0	421.6
5.78	862.4	546.0	5.17	843.6	437.9
10.54	866.0	566.5	10.44	848.1	456.2
15.50	869.7	587.6	15.40	852.2	473.9
20.87	873.5	611.3	20.27	856.0	491.3
26.04	877.1	634.3	25.53	860.0	510.0
30.70	880.2	655.2	30.50	863.6	527.9
35.77	883.4	678.6	35.57	867.2	547.3
40.94	886.6	702.7	40.63	870.7	565.6
45.90	889.6	726.7	45.80	874.1	585.0
50.87	892.5	750.8	50.76	877.2	602.8
55.83	895.4	775.4	54.01	879.2	615.6
60.90	898.2	800.6	55.83	880.3	624.0
63.53	899.6	812.1	61.10	883.5	644.2
			66.17	886.5	663.7
			71.33	889.4	684.0

Table IV. Viscosity of *m*-Xylene at 303.15 and 323.15 K, as a Function of Pressure

303.15 K			323.15 K		
Pressure (MPa)	Density (kg · m ⁻³)	Viscosity (μPa · s)	Pressure (MPa)	Density (kg · m ⁻³)	Viscosity (μPa · s)
0.10	856.1	549.4	0.10	840.0	444.4
5.17	860.0	570.4	5.57	844.6	463.0
10.64	864.0	594.3	10.44	848.5	480.8
15.40	867.3	616.4	15.00	852.0	496.9
20.57	870.9	640.5	19.76	855.6	515.2
25.74	874.3	664.3	25.48	859.7	536.4
30.80	877.5	687.8	30.50	863.2	555.6
35.57	880.5	711.5	35.26	866.3	574.7
40.63	883.5	737.5	40.63	869.7	596.2
45.80	886.4	762.9	45.50	872.6	614.6
50.87	889.2	788.3	49.45	874.9	630.5
			56.34	878.6	658.1

For comparison purposes, we have used a Tait-like equation to correlate each isotherm of the present measurements as

$$\ln \left[\frac{\mu}{\mu_0} \right] = E \ln \left[\frac{D + P}{D + 0.1} \right] \quad (7)$$

where μ_0 represents the experimental viscosity at atmospheric pressure. The values of the constants for each isotherm for the three liquids are shown in Table V. In the same table, the standard deviation of each fit is shown. It can be seen that the maximum standard deviation is $\pm 0.1\%$.

In Fig. 1 the deviations of the present experimental measurements of the viscosity of benzene, from those correlated by Eq. (7), are presented. It can be seen that the maximum deviation is less than $\pm 0.2\%$. In the same figure measurements of other investigators are also included. The only other absolute measurements are those performed by Knapstad et al. [9] at atmospheric pressure in an oscillating cylinder viscometer, with an uncertainty of $\pm 0.5\%$. The deviation of these measurements from those correlated by Eq. (7) is less than 0.25%, which is well within the mutual uncertainty of the two instruments. The other measurements included in Fig. 1 were all performed on a relative basis. The fitted measurements of Kashiwagi and Makita [10], performed in a torsionally vibrating crystal instrument with an uncertainty of $\pm 2\%$, show a maximum deviation of 0.5% from the present measurements. The measurements of Dymond et al. [6], performed in a self-centering falling-body viscometer with an uncertainty of $\pm 2\%$, show a maximum deviation of 0.6% from the present measurements. Also, the measurements of Parkhurst and Jonas [11] performed in a rolling-ball viscometer and those of Collings and McLaughlin [12], performed in a torsionally vibrating quartz-crystal viscometer, both show a deviation of less than 1% from the present

Table V. Coefficients of Eq. (7)

Liquid	Temperature (K)	μ_0 ($\mu\text{Pa} \cdot \text{s}$)	E	D (MPa)	σ (%)
Toluene	303.15	522.66	1.871	237.9	± 0.06
	323.15	421.63	1.586	199.4	± 0.09
Benzene	303.15	562.72	2.718	316.1	± 0.03
	323.15	438.10	2.179	257.0	± 0.10
<i>m</i> -Xylene	303.15	549.40	2.326	301.6	± 0.08
	323.15	444.40	1.757	223.9	± 0.09

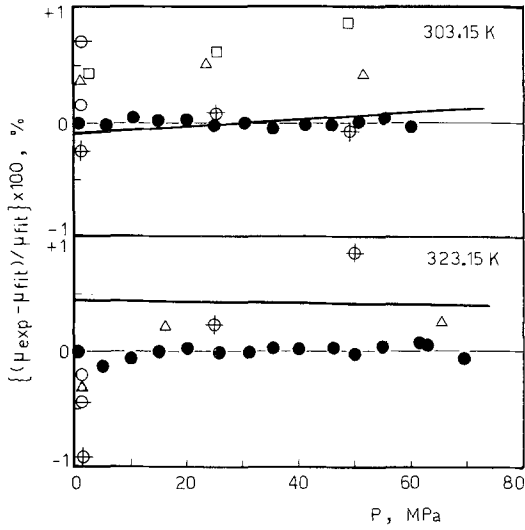


Fig. 1. The deviations of the experimental measurements of the viscosity of benzene from Eq. (7). (●) Present work; (△) Ref. 6; (○) Ref. 9; (—) Ref. 10; (□) Ref. 11; (⊕) Ref. 12; (⊙) Ref. 13.

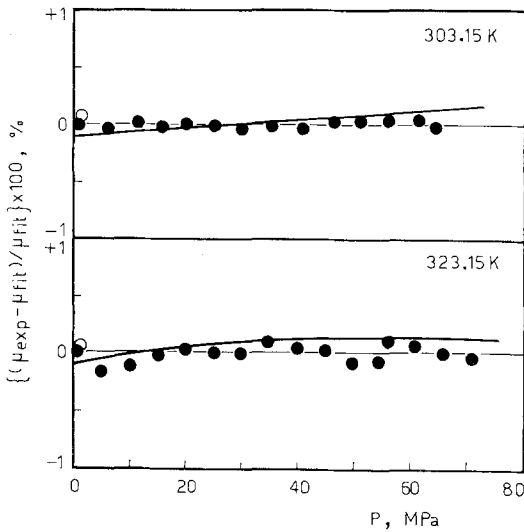


Fig. 2. The deviations of the experimental measurements of the viscosity of toluene from Eq. (7). (●) Present work; (○) Ref. 4; (—) Ref. 10.

measurements, which is well within the uncertainty of the instruments. At atmospheric pressure the measurements of Howard and Pike [13], performed in a Cannon-Ubbelohde viscometer, calibrated with water, show a 0.7% deviation from the present measurements.

In Fig. 2 the deviations of the present experimental measurements of the viscosity of toluene from those correlated by Eq. (7) are presented. It can be seen that the maximum deviation is less than $\pm 0.2\%$. In the same figure measurements of other investigators are also included. The atmospheric-pressure measurements of Goncalves et al. [4] were performed in an Ubbelohde-type viscometer on an absolute basis with an uncertainty of $\pm 0.3\%$. The maximum deviation of these measurements from the correlation of Eq. (7) is less than 0.1%. The other set of measurements included in Fig. 2 are the high-pressure measurements of Kashiwagi and Makita [10], performed in a torsionally vibrating quartz crystal on a relative basis, with an uncertainty of $\pm 2\%$. The maximum deviation of these measurements from the correlation of Eq. (7) is less than 0.2%, which is well within the mutual uncertainty of the two instruments.

In Fig. 3 the deviations of the present experimental measurements of the viscosity of *m*-xylene from those correlated by Eq. (7) are presented. It can be seen that the maximum deviation is less than $\pm 0.2\%$. To our knowledge no other absolute measurements of the viscosity of *m*-xylene

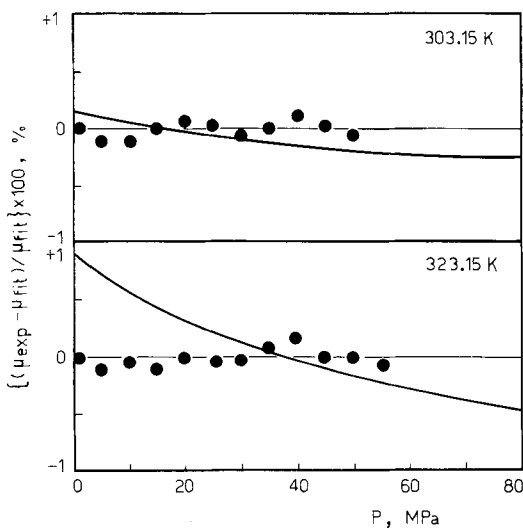


Fig. 3. The deviations of the experimental measurements of the viscosity of *m*-xylene from Eq. (7). (●) Present work; (—) Ref. 10.

exist. The only other measurements included in Fig. 3 are those of Kashiwagi and Makita [10], performed in a torsionally vibrating quartz-crystal viscometer on a relative basis, with an uncertainty of $\pm 2\%$. The maximum deviation of these measurements from the correlation of Eq. (7) is less than 1%, which is well within the mutual uncertainty of the two instruments.

4. CONCLUSIONS

New absolute measurements of the viscosity of benzene, toluene, and *m*-xylene at 303.15 and 323.15 K and at pressures up to 80 MPa were presented. The uncertainty of the measurements is estimated to be $\pm 0.5\%$.

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