Viscosity measurements of *ortho*-xylene, *meta*-xylene, *para*-xylene and ethylbenzene

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Abstract

The compressed liquid viscosities of *ortho*-xylene, *meta*-xylene, *para*-xylene and ethylbenzene were measured using a vibrating-wire viscometer at different temperatures and pressures. The measurements were performed over the temperature ranges of (273 to 373) K for *o*-xylene and *m*-xylene, (293 to 373) K for *p*-xylene and (253 to 373) K for ethylbenzene, at pressures from (0.1 to 30) MPa, except for ethylbenzene for which the pressure range was up to 35 MPa. The combined expanded uncertainty of the reported viscosity is better than 2% with a confidence level of 0.95 ($k = 2$). The experimental data were correlated with the empirical Andrade-Tait equation which reproduced the results with the average absolute percentage deviations of 0.25%, 0.15%, 0.16% and 0.23% for *o*-xylene, *m*-xylene, *p*-xylene and ethylbenzene, respectively. The present results are in good agreement with most of the literature values.

Keywords: *o*-Xylene, *m*-Xylene, *p*-Xylene, Ethylbenzene, Viscosity, Vibrating-wire.

1. Introduction

The xylene family consists of three isomers of dimethyl benzene which are distinguished by the designations of *ortho*-(*o*-)xylene, *meta*-(*m*-)xylene, and *para*-(*p*-)xylene. Ethylbenzene, which has the same chemical formula C_8H_{12} and consists of a benzene ring with an additional ethyl group is commonly considered as the fourth isomer [1]. Xylene isomers are colorless, sweet-smelling liquids occurring naturally in crude oil and are also found in gasoline and to some extent kerosene. Xylenes, that are the basis for the synthesis of many organic compounds, are of great importance as raw materials and solvents in the petrochemical industry and in medical applications. They are normally produced as a mixed stream that contains *o*-xylene, *m*-xylene, *p*-xylene, and ethylbenzene. It is difficult to efficiently separate these aromatic compounds due to their low relative volatility and the high degree of purity required for the final products [2].

In order to simulate and optimize the separation process, along with many other chemical engineering operations, one needs thermodynamic and transport property data. There is thus a growing industrial need to establish reference values of thermophysical properties of pure fluids that are both accurate and thermodynamically consistent [3]. Furthermore, the values of pure fluids also serve as the starting point for the prediction of thermophysical properties of mixtures. For example, the well-developed Vesovic and Wakeham (VW) method that can be used to predict accurately the viscosity of a variety of different mixtures, relies on obtaining the effective parameters for mixtures from a knowledge of the viscosity of pure species [4,5].

At present, no viscosity correlation covering the wide ranges of temperature and pressure for xylene isomers is available. The only exception is *p*-xylene for which a reference correlation of viscosity was reported recently by Balogun *et al.* [6]. The development of an accurate correlation relies on having the best available experimental data. Hence, measurements of the viscosity of *o*-xylene, *m*-xylene and ethylbenzene over the wide temperature and pressure ranges reported in the present work will also serve as input data for developing the viscosity correlations for these xylene isomers.

2. Experimental Section

2.1. Chemicals

The sources of the samples were as follows: *o*-xylene and ethylbenzene were supplied by Thermo Fisher Scientific Inc. with a mass fraction purity of 0.99 and 0.998, respectively; *m*-xylene was supplied by Alfa Aesar (China) Chemicals Co. Ltd. with a mass fraction purity of 0.99; and *p*-xylene was supplied by Aladdin Industrial Corporation with a mass fraction purity of 0.99. All of the sample purities were specified by the suppliers, and no further analysis or purification was attempted. A full specification of the samples is given in table 1.

2.2. Apparatus

The vibrating-wire viscometer is used to measure the viscosity of fluids over wide temperature and pressure ranges, because of its simplicity, rigorous mathematical description and well-established working equations. The theory that describes the motion of a wire within a fluid has been reviewed by Retsina *et al.* [7,8], Padua *et al.* [9], and Kandil *et al.* [10]. In this work, the viscosity was measured using the experimental arrangement where both ends of the wire were clamped in a steady state vibrating-wire viscometer which has been described, in detail, previously [11,12]. The viscometer consists of a tungsten wire, supplied by Metal Cutting, with a nominal radius of $(50.00 \pm 0.32) \mu\text{m}$ and a nominal length of 58 mm, a pair of samarium- cobalt magnets with a length of about 40 mm, and a custom-made stainless steel vessel with a maximum design pressure of 70 MPa. The wire, subject to a permanent magnetic field, was driven to transverse oscillation by introducing a sinusoidal voltage generated by a function generator (Model: 33220A, Agilent). An electromotive force is induced at the wire ends in response to the wire's velocity of oscillation, which is related to the viscosity and density of the fluid. The in-phase and quadrature voltages across the wire were detected with the lock-in amplifier (Model: SR830, Stanford Research Systems) over the frequency range $(f_r \pm 5g)$, where f_r is the resonance frequency, and g is the half-width of the resonance curve. For each fluid at a given temperature and pressure, the measured complex voltages were analyzed according to the working equations and a value of the viscosity of the fluid was obtained. The calibration and validation of the present apparatus has been described in our previous work [11], and it was used in this work without any changes. A diagram of the experimental system is shown in figure 1.

A thermostatic bath was used to maintain the constant temperature of the apparatus. The temperature was measured with a calibrated 100 Ω platinum resistance thermometer connected to a DMM (model: 3458A, Agilent). The combined expanded uncertainty of temperature with level of confidence 0.95 ($k=2$) is $U_c(T) = 12$ mK. The pressure was generated with a manual piston pump (model: 50-6-15, HIP) and measured by a high pressure transducer (model: P3MB, HBM) with a pressure range up to 100 MPa. A nanovolt meter (model: 34420A, Agilent) with $7^{1/2}$ digits resolution was employed for the transformation of the pressure transducer measurement signal. The combined expanded uncertainty of pressure $U_c(p) = 0.12$ MPa ($k = 2$). Taking into account the uncertainties of temperature and pressure, repeatability of measurements, regression procedure and the density of fluid, the combined expanded uncertainty of viscosity with level of confidence 0.95 ($k = 2$) is estimated to be better than 2%.

3. Results and Correlations

A knowledge of the accurate value of density of the fluid is essential in order to obtain the viscosity from the working equations of the vibrating-wire viscometer [10]. The density values of *o*-xylene, *m*-xylene, *p*-xylene and ethylbenzene at a given temperature and pressure were calculated using the equations of state (EOS), developed by Zhou *et al.* [1] for each xylene isomer. Uncertainties in density of *o*-xylene, *m*-xylene, *p*-xylene and ethylbenzene are estimated to be better than (0.1 to 0.2)% in the liquid region, at the temperature and pressure of interest to this work. The viscosity measurements of *o*-xylene and *m*-xylene were performed along 11 isotherms over the temperature range of (273 to 373) K and at pressures from (0.1 to 30) MPa. The viscosities of *p*-xylene were measured at pressures from (0.1 to 30) MPa, along 9 isotherms from (293 to 373) K. With regard to ethylbenzene, the viscosity measurements were carried out along 13 isotherms from (253 to 373) K and at pressures from (0.1 to 35) MPa. The experimental data of the four fluids are listed in tables 2 to 5 together with the densities calculated from the EOS of Zhou *et al.* [1]. Figure 2 illustrates the temperature dependence of the viscosity of *o*-xylene, *m*-xylene, *p*-xylene and ethylbenzene at 0.1 MPa, while figure 3 presents the viscosity of xylene isomers as a function of pressure at nominal

temperature of 293 K. We observe the similarity of the viscosity-temperature gradient which indicates a probable universal behaviour within the xylene family. The linear increase of viscosity with pressure, within the pressure range measured in this work illustrated in figure 3, is also observed at other temperatures. We also note that the viscosity of *o*-xylene exhibits largest deviation from the other isomers. This is expected and is in line with other thermophysical properties. It can be nominally traced to the difference in values of the critical parameters; while the critical temperature and critical density of *m*-xylene, *p*-xylene and ethylbenzene are within ~0.1% and ~1.5%, respectively, of each other, the critical temperature of *o*-xylene is ~2.3% above, while the critical density is 13% below the values of other isomers. For the purpose of comparing the results of this work with those reported in literature, the experimental viscosity data were correlated with the following empirical Andrade-Tait equation, proposed originally by Baylaucq *et al.* [13]

$$\eta(p,T)/\text{mPa} \cdot \text{s} = A \left(\frac{(p/\text{MPa}) + E(T)}{(p_0/\text{MPa}) + E(T)} \right)^D \exp \left(\frac{B}{(T/\text{K}) - C} \right) \quad (1)$$

where η is the viscosity, T is the temperature, p is the pressure, $p_0 = 0.1 \text{ MPa}$, $E(T) = E_0 + E_1(T/\text{K}) + E_2(T/\text{K})^2$ and A , B , C , D , E_0 , E_1 , E_2 are the coefficients. To assess the performances of the correlations and perform the comparison with other experimental data, the average absolute percentage deviation (AAD), the maximum absolute percentage deviation (MAD) and the average percentage deviation (Bias) are used. The optimal coefficients in equation (1) and the deviations are summarized in table 6 for each isomer. The Andrade-Tait equation can reproduce the viscosity values presented in this work very well. The AAD for *o*-xylene, *m*-xylene, *p*-xylene and ethylbenzene are 0.25%, 0.15%, 0.16% and 0.23%, and the MAD are 0.80%, 0.69%, 0.41% and 0.65%, respectively.

4. Discussion

There exists a large number of viscosity measurements on different xylene isomers, as amply demonstrated for *p*-xylene by, Balogun *et al.* [6]. They collected 706 data points reported in 83 papers for the viscosity of *p*-xylene, but the vast majority of the data were

measured at atmospheric pressure mostly around room temperature [6]. It is outside the scope of this work to compare the current results with all of the available experimental data. Instead, based on the choice of primary data selected for the development of the correlation for *p*-xylene [6], we have selected a set of data for each fluid that covers temperature and pressure range of interest to this work.

4.1. *o*-Xylene

The relative deviations for *o*-xylene of the current measurements, along with the selected literature data, from the representation given by equation (1) are plotted as the function of temperature in figure 4. Thorpe and Rodger [14] measured the viscosity of *o*-xylene at atmospheric pressure with a capillary viscometer covering the temperature range from (273 to 414) K. Their values are consistently lower than the base line, given by equation (1), with deviations ranging from -0.3% to -2.3%. Geist and Cannon [15] reported three measurements at atmospheric pressure using a capillary viscometer. The agreement with the equation (1), with the AAD of 1.0%, is observed. Mamedov and co-workers [16,17] performed the experiments at pressures up to 40 MPa using capillary viscometer with a claimed uncertainty of 1.2%. The two data sets of Mamedov appear to be very similar, both of which are reproduced, for temperatures higher than 320 K, with the AAD of about 0.7% in the temperature and pressure ranges considered in this work. However, the data set at 298 K exhibits systematic deviations of up to 5 %, both from the present data and the selected literature data.

Kashiwagi and Makita [18] measured the viscosity of *o*-xylene by a torsional crystal viscometer along four isotherms at pressure up to 110 MPa. The average absolute deviation is 1.7% with a maximum deviation of -1.9% with most of the data laying below the currently reported values at all four isotherms. Et-Tahir *et al.* [19] also reported the measurements at high pressure by means of the falling body viscometer with a claimed uncertainty of 2%. The deviations cover the range from -0.9% to 3.8% and the magnitude of the deviations is broadly in agreement with what was observed for *p*-xylene [6]. The atmospheric pressure viscosity data of Yang *et al.* [20] and Serrano *et al.* [21] are reproduced with an AAD of 1%, while that of Bauer and Mehlender [22] exhibit AAD of 1.7%. All of the three data sets show the negative deviations.

4.2. *m*-Xylene

Figure 5 illustrates the relative deviations of the selected experimental results from the representation given by equation (1) for *m*-xylene. Both Assael *et al.* [23] and Caudwell *et al.* [24] measured the viscosity of *m*-xylene at high pressure with the vibrating-wire viscometer, which have a reported uncertainty of 0.5% and 2%, respectively. The AAD of Caudwell *et al.* [24] data is 0.4%, while that of Assael *et al.* [23] data is 1.0%. The high pressure measurements of Kashiwagi and Makita [18] and atmospheric pressure viscosity data of Thorpe and Rodger [14], Geist and Cannon [15], Yang *et al.* [20] and Serrano *et al.* [21], are all also reproduced with AAD better than 1.0%. The viscosity values measured by Mamedov *et al.* [17,25] are in general smaller than the other reported data. The AAD, MAD and Bias are 2.5%, 2.5% and -4.3%, respectively with systematic trends observed at all isotherms.

4.3. *p*-Xylene

Recently, Balogun *et al.* [6] provided a reference correlation of the viscosity of *p*-xylene covering a wide range of temperatures (from the triple point to 673 K) and pressures (up to 110 MPa) based on critical review of all of the available experimental data. The estimated uncertainty of the correlation, within the temperature range of interest to this work, is given as 1% at atmospheric pressure, increasing to 2% at the higher pressures. Figure 6 illustrates the deviations between our experimental data and the Balogun *et al.* [6] correlation. The agreement is very good with AAD, MAD and Bias of 0.6%, 1.2% and 0.6%, respectively.

For completeness, we also include the comparison for *p*-xylene of the relative deviations of the current measurements and the selected literature data from the representation given by equation (1). As illustrated in figure 7, the agreement between the available viscosity data is quite good, most of the data are represented within 2%. The results from Et-Tahir *et al.* [19] exhibit larger scatter than data of other authors as has been already illustrated by Balogun *et al.* [6] and is in line with what we have seen for other xylene isomers. The three data sets of Mamedov *et al.* [17,26,27], exhibit AAD of 1.1% with only two data points outside 2%. The viscosity data of Thorpe and Rodger [14], Serrano *et al.* [21], Exarchos *et al.* [28], and Nissema and Koskenniska [29], which were measured at atmospheric pressure, are represented with AAD of better than 0.8%.

4.4. Ethylbenzene

The relative deviations for ethylbenzene of the current measurements, along with the selected literature data, from the representation given by equation (1), are plotted as the function of temperature in figure 8. Again we observe a good agreement within 2% between the current measurements and the selected experimental data. The data of Kashiwagi and Makita [18] show negative deviations and an AAD of 1.7%. The only other data set that covers high pressure is due to Krahn and Luft [30] who measured the viscosity at pressures up to 195 MPa using a rolling ball viscometer with a claimed uncertainty of 2%. Only one single data point that exhibits deviation of -0.9% lies in the temperature and pressure ranges of this work. The atmospheric data of Thorpe and Rodger [14] exhibit a Bias of -2.0% with a maximum deviation of -2.9% at 363 K. The other atmospheric data of Geist and Cannon [15], Yang *et al.* [31] and Barlow *et al.* [32], who measured the viscosity data of ethylbenzene at very low temperatures, are reproduced within better than 1.6%.

5. Conclusions

The viscosity measurements of *o*-xylene, *m*-xylene, *p*-xylene and ethylbenzene are reported at different temperatures and pressures. A, steady state vibrating-wire viscometer, with wire clamped at both ends, which has a combined expanded uncertainty of 2% with a confidence level of 0.95 ($k = 2$), was employed in this work. The measurements were performed over the temperature range of (273 to 373) K for *o*-xylene and *m*-xylene, (293 to 373) K for *p*-xylene and (253 to 373) K for ethylbenzene, at pressures from (0.1 to 30) MPa, except for ethylbenzene for which the pressure range was extended to 35 MPa. The results were correlated successfully with the empirical Andrade-Tait equation. The resulting correlation reproduces the current measurements for *o*-xylene, *m*-xylene, *p*-xylene and ethylbenzene with AAD of 0.25%, 0.15%, 0.16% and 0.23%, respectively. The present results are in agreement with most of the selected literature data for *o*-xylene, *m*-xylene, *p*-xylene and ethylbenzene within 2%.

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TABLE CAPTIONS

TABLE 1 Specification of chemical samples.

TABLE 2 Experimental viscosities η and calculated densities ρ of *o*-xylene at temperatures T and pressures p .

TABLE 3 Experimental viscosities η and calculated densities ρ of *m*-xylene at temperatures T and pressures p .

TABLE 4 Experimental viscosities η and calculated densities ρ of *p*-xylene at temperatures T and pressures p .

TABLE 5 Experimental viscosities η and calculated densities ρ of ethylbenzene at temperatures T and pressures p .

TABLE 6 Coefficients and deviations from measured data of the representation given by equation (1) for *o*-xylene, *m*-xylene, *p*-xylene and ethylbenzene.

FIGURE CAPTIONS

FIGURE 1. Schematic diagram of experimental system: (A) manual piston pump; (B) vacuum pump; (C) sample container; (D) pressure transducer; (E) vibrating wire viscometer; (F) thermostatic bath; (G) wasting recycle; (V1 ~V5) valves.

FIGURE 2. Viscosity of *o*-xylene, *m*-xylene, *p*-xylene and ethylbenzene as a function of temperature at 0.1 MPa. ○, *o*-xylene; □, *m*-xylene; ●, *p*-xylene; and △, ethylbenzene.

FIGURE 3. Viscosity of *o*-xylene, *m*-xylene, *p*-xylene and ethylbenzene as a function of pressure at 293 K. ○, *o*-xylene; □, *m*-xylene; ●, *p*-xylene; and △, ethylbenzene.

FIGURE 4. Relative deviations for *o*-xylene as a function of temperature between the experimental data, η_{exp} , and the calculated values based on equation (1), η_{cal} . ●, this work; ◇, Thorpe and Rodger [14]; *, Geist and Cannon [15]; ×, Mamedov *et al.* [16]; ○, Mamedov *et al.* [17]; △, Kashiwagi and Makita [18]; —, Et-Tahir *et al.* [19]; □, Yang *et al.* [20]; ◁, Serrano *et al.* [21]; ◆, Bauer and Meerlender [22].

FIGURE 5. Relative deviations for *m*-xylene as a function of temperature between the experimental data, η_{exp} , and the calculated values based on equation (1), η_{cal} . ●, this work; ◇, Thorpe and Rodger [14]; *, Geist and Cannon [15]; ○, Mamedov *et al.* [17]; △, Kashiwagi and Makita [18]; —, Et-Tahir *et al.* [19]; □, Yang *et al.* [20]; ◁, Serrano *et al.* [21]; +, Assael *et al.* [23]; ▽, Caudwell *et al.* [24]; ×, Mamedov *et al.* [25].

FIGURE 6. Relative deviations for *p*-xylene as a function of temperature between the experimental data of this work, η_{exp} , and the calculated values based on the correlation of Balogun *et al.* [6], η_{cal} . ●, 0.1 MPa; □, 1 MPa; ◇, 5 MPa; △, 10 MPa; ▽, 15 MPa; ×, 20 MPa; +, 25 MPa; ○, 30 MPa.

FIGURE 7. Relative deviations for *p*-xylene as a function of temperature between the experimental data, η_{exp} , and the calculated values based on equation (1), η_{cal} . ●, this work; ◇, Thorpe and Rodger [14]; ○, Mamedov *et al.* [17]; △, Kashiwagi and Makita [18]; —, Et-Tahir *et al.* [19]; ◁, Serrano *et al.* [21]; ◆, Mamedov and Panchenkov [26]; ×, Mamedov *et al.* [27]; +, Exarchos *et al.* [28]; ▽, Nissema and Koskenniska [29].

FIGURE 8. Relative deviations for ethylbenzene as a function of temperature between the experimental data, η_{exp} , and the calculated values based on equation (1), η_{cal} . ●, this work; ◇, Thorpe and Rodger [14]; *, Geist and Cannon [15]; △, Kashiwagi and Makita [18]; +, Krahn and Luft [30]; □, Yang *et al.* [31]; ▽, Barlow *et al.* [32].

TABLE 1

Specification of chemical samples.

chemical name	CAS number	source	initial mass fraction purity
<i>o</i> -xylene	95-47-6	Thermo Fisher Scientific	0.99
<i>m</i> -xylene	108-38-3	Alfa Aesar	0.99
<i>p</i> -xylene	106-42-3	Aladdin	0.99
ethylbenzene	100-41-4	Thermo Fisher Scientific	0.998

TABLE 2

Experimental viscosities η and calculated densities ρ of *o*-xylene at temperatures T and pressures p .^{a, b}

T/K	p/MPa	$\rho/\text{kg}\cdot\text{m}^{-3}$	$\eta_{\text{exp}}/\text{mPa}\cdot\text{s}$
273.48	0.1	896.72	1.1017
273.48	1	897.29	1.1126
273.48	5	899.73	1.1545
273.48	10	902.69	1.2091
273.48	15	905.57	1.2642
273.48	20	908.37	1.3191
273.48	25	911.10	1.3777
273.48	30	913.75	1.4359
283.22	0.1	888.57	0.9464
283.22	1	889.15	0.9529
283.22	5	891.72	0.9859
283.21	10	894.83	1.0310
283.21	15	897.85	1.0749
283.21	20	900.77	1.1209
283.21	25	903.61	1.1687
283.21	30	906.37	1.2159
293.04	0.1	880.33	0.8196
293.04	1	880.95	0.8252
293.04	5	883.63	0.8535
293.04	10	886.90	0.8901
293.05	15	890.06	0.9269
293.05	20	893.11	0.9685
293.05	25	896.08	1.0062
293.06	30	898.95	1.0477
302.87	0.1	872.05	0.7178
302.87	1	872.70	0.7228
302.88	5	875.52	0.7489
302.88	10	878.95	0.7794
302.88	15	882.27	0.8128
302.87	20	885.47	0.8457
302.87	25	888.57	0.8790
302.87	30	891.57	0.9126
312.66	0.1	863.76	0.6371
312.67	1	864.44	0.6414
312.67	5	867.43	0.6635
312.66	10	871.04	0.6901
312.67	15	874.51	0.7185
312.66	20	877.87	0.7486

312.66	25	881.11	0.7781
312.66	30	884.24	0.8077
321.85	0.1	855.92	0.5744
321.85	1	856.66	0.5794
321.86	5	859.80	0.5991
321.85	10	863.59	0.6241
321.85	15	867.23	0.6489
321.86	20	870.72	0.6748
321.86	25	874.10	0.6987
321.85	30	877.37	0.7248
332.47	0.1	846.81	0.5150
332.47	1	847.59	0.5176
332.48	5	850.93	0.5347
332.48	10	854.95	0.5575
332.48	15	858.78	0.5798
332.48	20	862.47	0.6029
332.48	25	866.02	0.6273
332.48	30	869.44	0.6504
343.06	0.1	837.64	0.4586
343.07	1	838.46	0.4624
343.07	5	842.03	0.4782
343.07	10	846.28	0.4990
343.08	15	850.34	0.5195
343.09	20	854.21	0.5401
343.08	25	857.95	0.5603
343.08	30	861.53	0.5817
353.04	0.1	828.92	0.4177
353.04	1	829.79	0.4196
353.03	5	833.59	0.4342
353.02	10	838.10	0.4549
353.02	15	842.39	0.4725
353.02	20	846.47	0.4922
353.02	25	850.38	0.5113
353.01	30	854.13	0.5312
362.85	0.1	820.23	0.3838
362.85	1	821.17	0.3862
362.85	5	825.20	0.4001
362.85	10	829.97	0.4169
362.86	15	834.49	0.4340
362.86	20	838.78	0.4506
362.87	25	842.87	0.4690
362.87	30	846.83	0.4842
372.83	0.1	811.30	0.3528
372.84	1	812.28	0.3556

372.84	5	816.58	0.3683
372.85	10	821.64	0.3831
372.86	15	826.41	0.4015
372.86	20	830.93	0.4156
372.85	25	835.24	0.4324
372.86	30	839.35	0.4477

^a The combined expanded uncertainty $U_c(k = 2)$ are $U_c(T) = 12$ mK, $U_c(p) = 0.12$ MPa and $U_c(\eta) = 2$ % with confidence level of 0.95.

^b Density ρ was calculated from Zhou *et al.* [1] EOS.

TABLE 3

Experimental viscosities η and calculated densities ρ of *m*-xylene at temperatures T and pressures p .^{a, b}

T/K	p/MPa	$\rho/\text{kg}\cdot\text{m}^{-3}$	$\eta_{\text{exp}}/\text{mPa}\cdot\text{s}$
273.56	0.1	880.86	0.7948
273.55	1	881.43	0.8029
273.55	5	883.95	0.8274
273.54	10	887.01	0.8601
273.55	15	889.95	0.8952
273.55	20	892.81	0.9293
273.54	25	895.58	0.9681
273.54	30	898.27	1.0079
283.24	0.1	872.67	0.7000
283.25	1	873.26	0.7070
283.25	5	875.91	0.7291
283.24	10	879.13	0.7574
283.25	15	882.23	0.7883
283.25	20	885.23	0.8196
283.25	25	888.12	0.8530
283.25	30	890.94	0.8858
293.07	0.1	864.29	0.6215
293.06	1	864.94	0.6255
293.07	5	867.74	0.6440
293.07	10	871.13	0.6692
293.07	15	874.39	0.6957
293.06	20	877.55	0.7224
293.06	25	880.63	0.7497
293.07	30	883.58	0.7757
302.90	0.1	855.84	0.5542
302.90	1	856.52	0.5571
302.88	5	859.51	0.5751
302.90	10	863.09	0.5980
302.89	15	866.52	0.6204
302.90	20	869.83	0.6450
302.88	25	873.05	0.6673
302.87	30	876.14	0.6903
313.30	0.1	846.83	0.4952
313.29	1	847.55	0.4982
313.30	5	850.72	0.5142
313.30	10	854.53	0.5341
313.31	15	858.16	0.5548
313.31	20	861.66	0.5757

313.31	25	865.02	0.5968
313.31	30	868.31	0.6180
323.01	0.1	838.33	0.4499
323.01	1	839.11	0.4531
323.01	5	842.47	0.4670
323.00	10	846.52	0.4847
323.02	15	850.34	0.5032
323.02	20	854.01	0.5220
323.02	25	857.55	0.5411
323.02	30	860.95	0.5599
333.10	0.1	829.42	0.4087
333.11	1	830.24	0.4110
333.11	5	833.83	0.4237
333.11	10	838.11	0.4414
333.11	15	842.18	0.4585
333.11	20	846.05	0.4756
333.12	25	849.77	0.4931
333.12	30	853.33	0.5101
342.98	0.1	820.60	0.3731
342.98	1	821.48	0.3761
342.98	5	825.31	0.3882
342.98	10	829.85	0.4036
342.98	15	834.15	0.4205
342.97	20	838.25	0.4363
342.97	25	842.15	0.4516
342.97	30	845.90	0.4678
352.89	0.1	811.65	0.3436
352.89	1	812.61	0.3460
352.89	5	816.67	0.3581
352.89	10	821.49	0.3728
352.89	15	826.05	0.3867
352.88	20	830.37	0.4014
352.88	25	834.49	0.4162
352.88	30	838.41	0.4310
362.69	0.1	802.70	0.3175
362.70	1	803.70	0.3200
362.70	5	808.05	0.3307
362.70	10	813.17	0.3452
362.71	15	817.98	0.3587
362.71	20	822.53	0.3726
362.71	25	826.86	0.3859
362.71	30	830.99	0.3995
372.50	0.1	793.62	0.2936
372.50	1	794.69	0.2964

372.51	5	799.34	0.3070
372.51	10	804.78	0.3199
372.51	15	809.89	0.3331
372.51	20	814.69	0.3463
372.51	25	819.23	0.3587
372.51	30	823.55	0.3715

^a The combined expanded uncertainty $U_c(k=2)$ are $U_c(T) = 12$ mK, $U_c(p) = 0.12$ MPa and $U_c(\eta) = 2$ % with confidence level of 0.95.

^b Density ρ was calculated from Zhou *et al.* [1] EOS.

TABLE 4

Experimental viscosities η and calculated densities ρ of *p*-xylene at temperatures T and pressures p .^{a, b}

T/K	p/MPa	$\rho/\text{kg}\cdot\text{m}^{-3}$	$\eta_{\text{exp}}/\text{mPa}\cdot\text{s}$
293.04	0.1	861.17	0.6444
293.04	1	861.83	0.6494
293.04	5	864.72	0.6720
293.04	10	868.22	0.6997
293.03	15	871.58	0.7277
293.03	20	874.83	0.7569
293.03	25	877.98	0.7883
293.03	30	881.03	0.8186
302.86	0.1	852.65	0.5762
302.86	1	853.35	0.5804
302.87	5	856.40	0.5995
302.87	10	860.07	0.6244
302.88	15	863.61	0.6499
302.88	20	867.01	0.6747
302.88	25	870.30	0.7023
302.89	30	873.47	0.7274
312.76	0.1	844.03	0.5150
312.76	1	844.78	0.5186
312.77	5	847.99	0.5356
312.77	10	851.88	0.5575
312.76	15	855.59	0.5806
312.76	20	859.17	0.6027
312.76	25	862.61	0.6263
312.76	30	865.93	0.6494
322.62	0.1	835.40	0.4653
322.63	1	836.18	0.4689
322.64	5	839.60	0.4833
322.64	10	843.68	0.5038
322.64	15	847.60	0.5240
322.64	20	851.35	0.5442
322.64	25	854.96	0.5653
322.65	30	858.43	0.5861
332.58	0.1	826.61	0.4206
332.58	1	827.45	0.4237
332.58	5	831.08	0.4383
332.58	10	835.41	0.4564
332.58	15	839.53	0.4745
332.58	20	843.48	0.4930

332.58	25	847.26	0.5109
332.57	30	850.90	0.5304
342.27	0.1	817.99	0.3815
342.27	1	818.88	0.3842
342.28	5	822.73	0.3977
342.28	10	827.31	0.4144
342.29	15	831.65	0.4314
342.28	20	835.79	0.4482
342.29	25	839.75	0.4649
342.29	30	843.54	0.4833
352.21	0.1	809.06	0.3483
352.21	1	810.01	0.3507
352.20	5	814.12	0.3634
352.20	10	818.98	0.3791
352.20	15	823.56	0.3945
352.20	20	827.94	0.4111
352.20	25	832.09	0.4263
352.20	30	836.07	0.4423
362.73	0.1	799.49	0.3194
362.74	1	800.49	0.3217
362.75	5	804.89	0.3331
362.76	10	810.06	0.3467
362.76	15	814.93	0.3616
362.77	20	819.53	0.3756
362.81	25	823.89	0.3915
362.82	30	828.07	0.4050
372.71	0.1	790.29	0.2936
372.71	1	791.38	0.2960
372.71	5	796.08	0.3061
372.70	10	801.60	0.3203
372.70	15	806.76	0.3341
372.69	20	811.63	0.3480
372.69	25	816.24	0.3614
372.69	30	820.61	0.3752

^a The combined expanded uncertainty $U_c(k=2)$ are $U_c(T) = 12$ mK, $U_c(p) = 0.12$ MPa and $U_c(\eta) = 2$ % with confidence level of 0.95.

^b Density ρ was calculated from Zhou *et al.* [1] EOS.

TABLE 5

Experimental viscosities η and calculated densities ρ of ethylbenzene at temperatures T and pressures p .^{a, b}

T/K	p/MPa	$\rho/\text{kg}\cdot\text{m}^{-3}$	$\eta_{\text{exp}}/\text{mPa}\cdot\text{s}$
253.23	0.1	901.57	1.2005
253.22	1	902.11	1.2109
253.21	5	904.40	1.2585
253.22	10	907.17	1.3112
253.24	15	909.87	1.3678
253.23	20	912.51	1.4227
253.23	25	915.08	1.4793
253.24	30	917.58	1.5353
253.22	35	920.04	1.5933
263.22	0.1	892.90	1.0207
263.22	1	893.45	1.0280
263.21	5	895.86	1.0633
263.20	10	898.80	1.1101
263.20	15	901.65	1.1601
263.21	20	904.41	1.2071
263.21	25	907.09	1.2568
263.22	30	909.72	1.3044
263.21	35	912.27	1.3502
273.21	0.1	884.23	0.8832
273.17	1	884.84	0.8919
273.15	5	887.41	0.9249
273.18	10	890.47	0.9635
273.19	15	893.45	1.0026
273.15	20	896.38	1.0421
273.16	25	899.20	1.0818
273.15	30	901.94	1.1232
273.15	35	904.60	1.1632
283.16	0.1	875.60	0.7737
283.13	1	876.23	0.7784
283.16	5	878.90	0.8028
283.14	10	882.17	0.8372
283.17	15	885.29	0.8678
283.15	20	888.35	0.9017
283.17	25	891.29	0.9314
283.16	30	894.16	0.9641
283.16	35	896.95	0.9964
293.26	0.1	866.82	0.6786
293.20	1	867.52	0.6832

293.18	5	870.37	0.7056
293.24	10	873.76	0.7327
293.23	15	877.08	0.7607
293.24	20	880.27	0.7871
293.22	25	883.40	0.8173
293.24	30	886.40	0.8447
293.26	35	889.30	0.8724
303.15	0.1	858.17	0.6033
303.17	1	858.84	0.6074
303.18	5	861.85	0.6268
303.20	10	865.47	0.6499
303.19	15	868.96	0.6744
303.17	20	872.34	0.6989
303.18	25	875.57	0.7235
303.19	30	878.71	0.7502
303.18	35	881.76	0.7739
313.12	0.1	849.45	0.5386
313.12	1	850.16	0.5427
313.11	5	853.36	0.5596
313.10	10	857.21	0.5812
313.12	15	860.87	0.6039
313.09	20	864.43	0.6261
313.10	25	867.82	0.6490
313.08	30	871.13	0.6722
313.10	35	874.29	0.6940
322.97	0.1	840.73	0.4865
322.98	1	841.50	0.4895
322.98	5	844.89	0.5042
322.98	10	848.95	0.5245
322.98	15	852.83	0.5440
322.97	20	856.55	0.5648
322.98	25	860.13	0.5856
322.98	30	863.57	0.6060
322.98	35	866.89	0.6259
332.91	0.1	831.89	0.4422
332.92	1	832.72	0.4448
332.91	5	836.31	0.4595
332.92	10	840.61	0.4780
332.92	15	844.71	0.4961
332.92	20	848.63	0.5149
332.92	25	852.39	0.5331
332.92	30	855.99	0.5516
332.92	35	859.47	0.5706
342.81	0.1	823.01	0.4022

342.80	1	823.89	0.4049
342.81	5	827.74	0.4186
342.80	10	832.29	0.4356
342.80	15	836.63	0.4524
342.80	20	840.75	0.4691
342.80	25	844.70	0.4869
342.80	30	848.47	0.5045
342.80	35	852.11	0.5223
352.73	0.1	814.02	0.3693
352.73	1	814.97	0.3720
352.72	5	819.06	0.3851
352.73	10	823.90	0.4003
352.73	15	828.48	0.4164
352.72	20	832.83	0.4335
352.73	25	836.97	0.4495
352.73	30	840.93	0.4654
352.72	35	844.73	0.4807
362.66	0.1	804.92	0.3390
362.66	1	805.93	0.3418
362.66	5	810.29	0.3538
362.67	10	815.44	0.3685
362.66	15	820.29	0.3838
362.66	20	824.88	0.3986
362.66	25	829.23	0.4137
362.66	30	833.40	0.4289
362.67	35	837.37	0.4429
372.61	0.1	795.69	0.3127
372.60	1	796.78	0.3155
372.59	5	801.46	0.3272
372.59	10	806.94	0.3410
372.59	15	812.08	0.3541
372.59	20	816.92	0.3688
372.59	25	821.50	0.3822
372.59	30	825.86	0.3967
372.59	35	830.02	0.4108

^a The combined expanded uncertainty $U_c(k=2)$ are $U_c(T) = 12$ mK, $U_c(p) = 0.12$ MPa and $U_c(\eta)$ = 2 % with confidence level of 0.95.

^b Density ρ was calculated from Zhou *et al.* [1] EOS.

TABLE 6

Coefficients and deviations from measured data of the representation given by equation (1) for *o*-xylene, *m*-xylene, *p*-xylene and ethylbenzene.

Parameters	<i>o</i> -xylene	<i>m</i> -xylene	<i>p</i> -xylene	ethylbenzene
<i>A</i>	0.024618	0.020307	0.010372	0.018391
<i>B</i>	885.66	979.69	1397.2	1055.9
<i>C</i>	40.432	6.4905	-45.110	0.53294
<i>D</i>	1.6393	1.4412	1.4676	1.1636
<i>E</i> ₀	-336.20	-143.31	-40.201	-263.62
<i>E</i> ₁	3.1151	2.0011	1.3633	2.5529
<i>E</i> ₂	-0.0045756	-0.0031126	-0.0021781	-0.0040050
AAD ^a	0.25	0.15	0.16	0.23
MAD ^a	0.80	0.69	0.41	0.65
Bias ^a	0.001	0.000	0.000	-0.001

^a AAD is given by $\frac{100}{N} \sum_{i=1}^{i=N} |(\eta_{i,\text{exp}} - \eta_{i,\text{cal}})/\eta_{i,\text{exp}}|$, MAD is given by $\max(100 \cdot |(\eta_{i,\text{exp}} - \eta_{i,\text{cal}})/\eta_{i,\text{exp}}|)$, and Bias is given by $\frac{100}{N} \sum_{i=1}^{i=N} ((\eta_{i,\text{exp}} - \eta_{i,\text{cal}})/\eta_{i,\text{exp}})$, where *N* is the number of data points, $\eta_{i,\text{exp}}$ is the experimental viscosity, and $\eta_{i,\text{cal}}$ is the calculated viscosity with the equation (1).

FIGURE 1. Schematic diagram of experimental system: (A) manual piston pump; (B) vacuum pump; (C) sample container; (D) pressure transducer; (E) vibrating wire viscometer; (F) thermostatic bath; (G) wasting recycle; (V1 ~V5) valves.

FIGURE 2. Viscosity of *o*-xylene, *m*-xylene, *p*-xylene and ethylbenzene as a function of temperature at 0.1 MPa. O, *o*-xylene; □, *m*-xylene; ●, *p*-xylene; and △, ethylbenzene.

FIGURE 3. Viscosity of *o*-xylene, *m*-xylene, *p*-xylene and ethylbenzene as a function of pressure at 293 K. O, *o*-xylene; $\square$, *m*-xylene; $\bullet$, *p*-xylene; and $\triangle$, ethylbenzene.

FIGURE 4. Relative deviations for o-xylene as a function of temperature between the experimental data, η_{exp} , and the calculated values based on equation (1), η_{cal} . ●, this work; ◇, Thorpe and Rodger [14]; *, Geist and Cannon [15]; ×, Mamedov *et al.* [16]; O, Mamedov *et al.* [17]; △, Kashiwagi and Makita [18]; —, Et-Tahir *et al.* [19]; □, Yang *et al.* [20]; ◁, Serrano *et al.* [21]; ◆, Bauer and Meerlender [22].

FIGURE 5. Relative deviations for *m*-xylene as a function of temperature between the experimental data, η_{exp} , and the calculated values based on equation (1), η_{cal} . ●, this work; ◇, Thorpe and Rodger [14]; *, Geist and Cannon [15]; O, Mamedov *et al.* [17]; △, Kashiwagi and Makita [18]; —, Et-Tahir *et al.* [19]; □, Yang *et al.* [20]; ◁, Serrano *et al.* [21]; +, Assael *et al.* [23]; ▽, Caudwell *et al.* [24]; ×, Mamedov *et al.* [25].

FIGURE 6. Relative deviations for p -xylene as a function of temperature between the experimental data of this work, η_{exp} , and the calculated values based on the correlation of Balogun *et al.* [6], η_{cal} . ●, 0.1 MPa; □, 1 MPa; ◇, 5 MPa; △, 10 MPa; ▽, 15 MPa; ×, 20 MPa; +, 25 MPa; ○, 30 MPa.

FIGURE 7. Relative deviations for *p*-xylene as a function of temperature between the experimental data, η_{exp} , and the calculated values based on equation (1), η_{cal} . ●, this work; ◇, Thorpe and Rodger [14]; ○, Mamedov *et al.* [17]; △, Kashiwagi and Makita [18]; —, Et-Tahir *et al.* [19]; ◁, Serrano *et al.* [21]; ◆, Mamedov and Panchenkov [26]; ×, Mamedov *et al.* [27]; +, Exarchos *et al.* [28]; ▽, Nissema and Koskenniska [29].

FIGURE 8. Relative deviations for ethylbenzene as a function of temperature between the experimental data, η_{exp} , and the calculated values based on equation (1), η_{cal} . ●, this work; ◇, Thorpe and Rodger [14]; *, Geist and Cannon [15]; △, Kashiwagi and Makita [18]; +, Krahn and Luft [30]; □, Yang *et al.* [31]; ▽, Barlow *et al.* [32].