

Reference correlation of the viscosity of *ortho*-xylene from 273 K to 673 K and up to 110 MPa

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Abstract

A new correlation for the viscosity of *ortho*-xylene (*o*-xylene) is presented. The correlation is based upon a body of experimental data that has been critically assessed for internal consistency and for agreement with theory. It is applicable in the temperature range from 273 K to 673 K at pressures up to 110 MPa. The overall uncertainty of the proposed correlation, estimated as the combined expanded uncertainty with a coverage factor of 2, varies from 1 % for the viscosity at atmospheric pressure to 5 % for the highest temperatures and pressures of interest. Tables of the viscosity, generated by the relevant equations, at selected temperatures and pressures, and along the saturation line, are provided.

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1. Introduction

There is a growing industrial need to establish reference values of thermophysical properties of pure fluids that are both accurate and thermodynamically consistent.¹ Not only are such values useful in their own right, but they also serve as the starting point for the prediction of thermophysical properties of mixtures. For thermodynamic properties the reference values are obtained by recourse to substance-specific equation of state (EoS) that provides a general framework to correlate the measured properties and ensures thermodynamic consistency. For transport properties no such general framework is available and one develops separate correlations for different transport properties. Under the auspices of International Union of Pure and Applied Chemistry (IUPAC), a research program has been initiated to develop representations of the viscosity and thermal conductivity of industrially important fluids. The first fluid studied in this program was carbon dioxide² and since then a plethora of viscosity correlations have been produced, using the same philosophy, covering among others: simple fluids,³⁻⁵ water⁶, normal alkanes⁷⁻¹⁴ and cyclic and aromatic hydrocarbons.¹⁵⁻¹⁹ The present study is a continuation of recent work on xylene isomers that has so far produced the viscosity correlations for *para*-xylene (*p*-xylene)¹⁷ and *meta*-xylene (*m*-xylene).¹⁹ The aim is to critically assess the data available in the literature, and provide a correlation for the viscosity of *ortho*-xylene (*o*-xylene) that is valid over a wide range of temperature and pressure, covering the vapor, liquid, and supercritical fluid states.

ortho-Xylene (C₁₀H₈) is an aromatic hydrocarbon that consists of benzene ring and two –CH₃ groups in positions 1 and 2. At ambient conditions it is a colorless liquid that has been widely used in the industrial process, mainly for production of phthalic anhydride, which is an important raw material for the production of dyes, pesticides and alkyd resins. The values of its critical temperature, pressure and density are very similar to those of *p*-xylene and hence the thermophysical properties of both isomers exhibit analogous behavior. The thermodynamic properties of *o*-xylene are well catered for, by an up-to-date EoS,²⁰ while the thermal conductivity correlation has also become recently available.²¹ At present, no correlation of viscosity, valid over a wide range of temperature and pressure, is available and if one wants to predict the viscosity of *o*-xylene, one has to rely on generic correlations^{22,23} developed for a wide variety of fluids that have invariably traded the range of applicability for accuracy.

2. Experimental Viscosity Data

Appendix A summarizes, to the best of our knowledge, the experimental measurements of the viscosity of *o*-xylene reported in the literature,²⁴⁻⁹² detailing the temperature and pressure ranges, number of data points measured and the technique employed to perform the measurements. Overall, measurements of the viscosity of *o*-xylene were reported in 69 papers resulting in 699 data points. Most of the papers (61 papers, 192 data points) report only the value of liquid viscosity at atmospheric pressure, around room temperature, usually as part of a measurement program of viscosity of mixtures containing *o*-xylene. Appendix A also contains two reference works^{93,94} that report recommended tabulated values of the viscosity of *o*-xylene. Following the recommendation adopted by the IUPAC Subcommittee of Transport Properties (now known as The International Association for

Transport Properties (IATP)), a critical assessment of the experimental data was performed to classify the data as primary and secondary, using well-established criteria⁹⁵ that have been widely disseminated.²⁻¹⁹ Based on these criteria, 10 datasets were considered primary viscosity data. Table 1 summarizes the primary data^{24,28,33,34,38,39,40,45,75,92} detailing the temperature and pressure ranges, the uncertainty attributed to the measurements, authors claimed purity of the sample, and the technique employed to perform the measurements. The choice of primary data is discussed in more detail in section 3 that also provides a comparison of the data by different workers. Based on this comparison and on the development of previous correlations, it was in some cases necessary to modify the authors claimed uncertainty. The Table 1 contains the estimates of the uncertainty ascribed by the authors of the present work to each data set, following the analysis presented in section 3.

TABLE 1. Primary data used in developing the viscosity correlation of *o*-xylene

Authors	Year publ.	Technique employed ^a	Purity (%)	Uncertainty (%)	No. of data	Temperature range (K)	Pressure range (MPa)
Thorpe and Rodger ²⁴	1894	C	--	1.0	24	273-414	0.1
Geist and Cannon ²⁸	1946	C	--	0.5	3	273-313	0.1
Mamedov <i>et al.</i> ³³	1967	C	99.7	4.0	38 ^b	498-548	0.1-39.3
Mamedov <i>et al.</i> ³⁴	1975	C	99.7	4.0	36 ^b	498-548	0.1-40
Kashiwagi and Makita ³⁸	1982	TC	99	2.0	48	298-348	0.1-110
Abdullaev and Akhundov ³⁹	1983	C	--	1.5	27 ^c	473-673	0.1-4.1
Bauer and Meerlender ⁴⁰	1984	C	99.4	0.2	3	293-298	0.1
Serrano <i>et al.</i> ⁴⁵	1990	C	99.68	1.0	7	273-303	0.1
Yang <i>et al.</i> ⁷⁵	2007	C	99.5	1.0	7	298-353	0.1
Meng <i>et al.</i> ⁹²	2016	VW	99	2.0	88	273-373	0.1-30

^a C, capillary; TC, torsional crystal; VW, vibrating wire.

^b Data below 498 K were excluded from the primary data sets.

^c One outlier point removed from the analysis.

Figure 1 shows the temperature and pressure range of the measurements outlined in Appendix A with primary and secondary data distinguished. The primary data cover a wide range of temperatures and pressures of interest. The data is extensive in the liquid phase, but in the vapor phase only two sets of measurements are available.

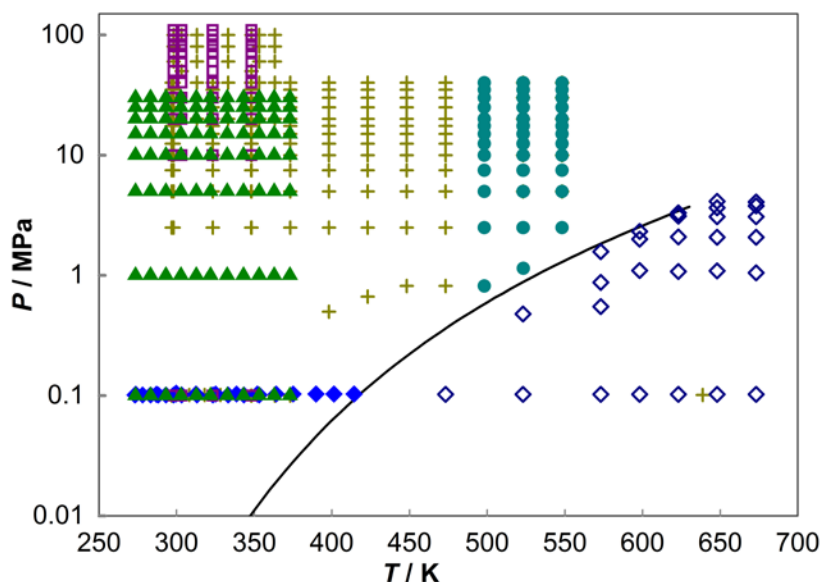


FIG. 1. Distribution of the available experimental viscosity data of *o*-xylene. Primary data: (●) Mamedov *et al.*,^{33,34} (□) Kashiwagi and Makita;³⁸ (◇) Abdullaev and Akhundov;³⁹ (▲) Meng *et al.*;⁹² (◆) data at 0.1 MPa;^{24,28,40,45,75} Secondary data: (+).

Experimental measurements of viscosity are usually reported at a given temperature and pressure. For the development of a viscosity correlation that makes use of the available theory to provide guidance, temperature and density are the natural variables. Hence one requires an EoS to convert (T, P) pairs into corresponding (T, ρ) pairs. For the purposes of this work we have used a recent EoS developed by Zhou *et al.*²⁰ that covers the thermodynamic space from the triple point to 700 K, and up to 70 MPa. The uncertainties in density generated by this EoS range from 0.1 % in the compressed-liquid region to 1.0 % in the critical and vapor regions.²⁰ Recently, Wu *et al.*⁹⁶ measured the density of *o*-xylene along several isotherms up to 523.2 K and at pressures up to 265 MPa, with an uncertainty of 0.75 % (at coverage factor of 2 for an interval having a confidence level of approximately 95%). The deviations of the measurements of Wu *et al.*⁹⁶ from EoS developed by Zhou *et al.*²⁰ are shown in Fig. 2. The agreement is within 0.5 % for most of the data, except for the low pressure data at 523.2 K, where the deviations up to 1 % are observed. This indicates that Zhou *et al.*²⁰ EoS can be safely extrapolated to pressures higher than 70 MPa. In this work we have used Zhou *et al.*²⁰ EoS to generate the densities of *o*-xylene up to 673 K and 110 MPa, which is the upper temperature and pressure limit of the primary data summarized in Table 1. We note that the use of Wu *et al.*⁹⁶ measured density values, instead of those calculated by EoS, would result in changes in viscosity of up to 6%. As expected the sensitivity is highest at the largest values of density. This further emphasises the need for making use of density data of low uncertainty when developing reliable viscosity correlations.

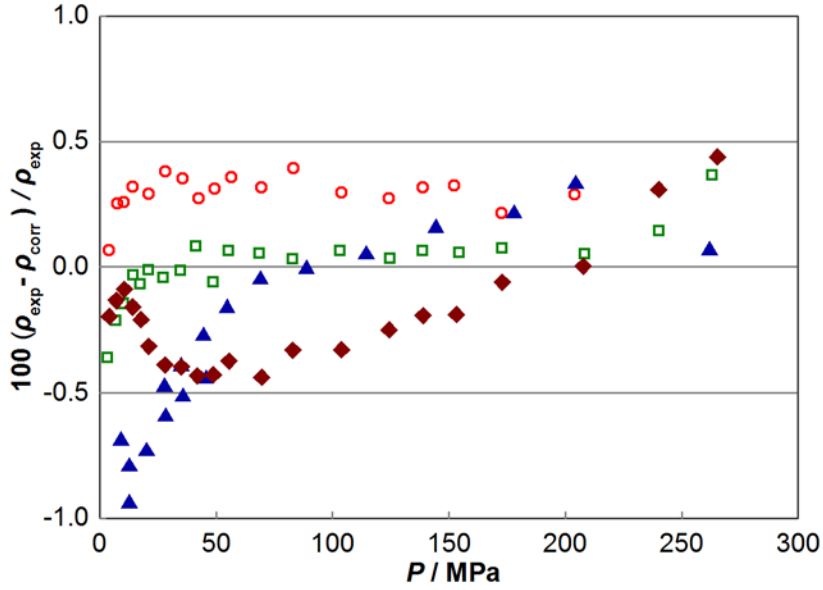


FIG. 2. Percentage deviations $[100(\rho_{\text{exp}} - \rho_{\text{corr}}) / \rho_{\text{exp}}]$ of the experimental density data⁹⁶ from the calculated values using EoS developed by Zhou *et al.*²⁰ (○) 295 K; (□) 325 K; (◆) 424 K; (▲) 523 K

3. Methodology and Analysis

It is customary⁹⁷ in developing correlations of transport properties to take advantage of theoretical guidance to the functional form of the correlation as a function of temperature and density. Hence we express the viscosity η as the sum of four contributions,

$$\eta(\rho, T) = \eta_0(T) + \eta_1(T)\rho + \Delta\eta(\rho, T) + \Delta\eta_c(\rho, T) \quad (1)$$

where ρ is the molar density, T is the temperature and the different contributions to viscosity, η_0 , η_1 , $\Delta\eta$ and $\Delta\eta_c$ are the zero-density viscosity, the first-density coefficient, the residual viscosity and the critical enhancement, respectively. The advantage of decomposing the viscosity in this fashion is that it is possible to examine each contribution in turn and by making use of current theoretical developments, in conjunction with the available experimental data, provide a more robust analysis of the zero-density viscosity, the first-density coefficient, and the critical enhancement than would have been possible by simply fitting to empirical functional forms.²⁻¹⁹

3.1. The zero-density and initial-density terms

The situation for *o*-xylene is similar to that encountered with *m*-xylene,¹⁹ that the paucity of data in the vapour phase does not allow for obtaining the zero-density and initial-density terms by fitting to experimental data. Hence, we take the same approach as we took in developing the correlation for *m*-xylene and noting the similarities in the critical properties of *o*- and *p*-xylene we make use of the zero-density and initial density viscosity of *p*-xylene, developed earlier,¹⁷ to estimate $\eta_0(T)$ and $\eta_1(T)$ terms for *o*-xylene. As discussed in Ref. 17 the approach is viable as the low density correlation, $\eta_0(T) +$

$\eta_1(T)\rho$, for *p*-xylene was based on accurate and extensive data of Vogel and Hendl⁹⁸ that covered a temperature range (338 to 635) K and were measured in a quartz oscillating-disk viscometer with the claimed experimental uncertainty of 0.15 - 0.3 %. Furthermore the adjustment for *o*-xylene involved increasing the zero-density viscosity only by 1 %. The correction factor was chosen such that the low-density data of Abdullaev and Akhundov³⁹ is recaptured within its quoted uncertainty.

Figure 3, illustrates the deviations of the primary data of Abdullaev and Akhundov³⁹ for two xylene isomers from their respective correlations. It is clear that the developed *o*-xylene correlation for $\eta_0(T) + \eta_1(T)\rho$ reproduces the available experimental data with the same uncertainty as was the case for *p*-xylene.

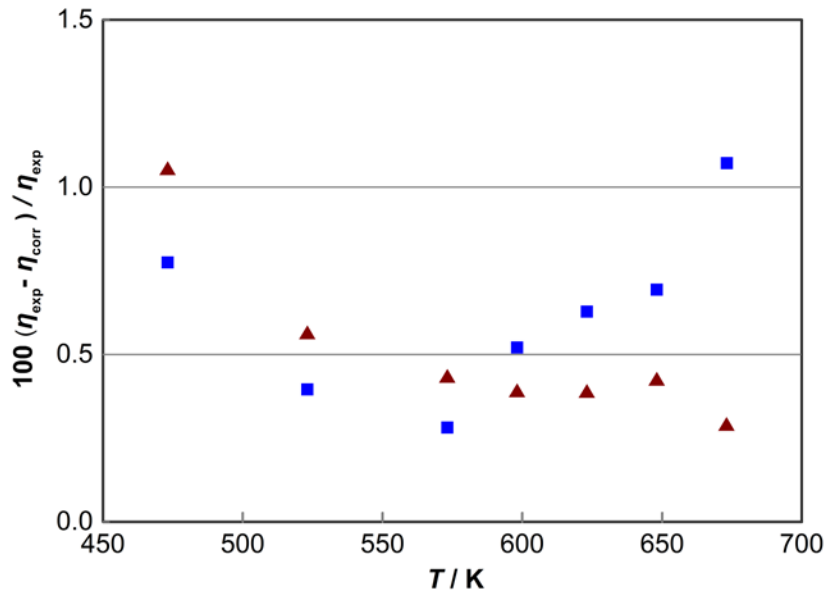


FIG. 3. Percentage deviations [100(\eta_{exp} - \eta_{corr})/\eta_{exp}] of the available experimental data of Abdullaev and Akhundov³⁹ in the vapor phase at 0.1 MPa. (■) *p*-xylene (▲) *o*-xylene.

For completeness we present the equations for the two terms and the relevant coefficients. The viscosity in the zero-density limit was represented using a practical engineering form as,¹⁷

$$\eta_0(T) = 1.01\eta_{0,p-xylene} = 0.22225 \frac{\sqrt{T}}{S_\eta} \quad (2)$$

where $\eta_0(T)$ is given in units of $\mu\text{Pa s}$, T is the temperature in Kelvin and S_η is the effective collision cross-section in nm^2 given by

$$\ln(S_\eta/\text{nm}^2) = A_0 + \frac{B_0}{T} + \frac{C_0}{T^2} \quad (3)$$

where A_0 , B_0 and C_0 are the adjustable parameters and take the value of $A_0 = -1.4933$, $B_0 = 473.2 \text{ K}$ and $C_0 = -57033 \text{ K}^2$.

The initial-density dependence is given by a simple empirical function,

$$\eta_1(T)\rho = \left(A_1 + \frac{B_1}{T} + \frac{C_1}{T^2}\right)\rho \quad (4)$$

where ρ is the molar density in units of mol l^{-1} and A_1 , B_1 and C_1 are the adjustable parameters, with the values of $A_1 = 13.2814 \text{ } \mu\text{Pa s mol}^{-1} \text{ l}$, $B_1 = -10862.4 \text{ } \mu\text{Pa s K mol}^{-1} \text{ l}$ and $C_1 = 1664060 \text{ } \mu\text{Pa s K}^2 \text{ mol}^{-1} \text{ l}$.

Based on the agreement with the primary data and uncertainty associated with *p*-xylene correlation we ascribe uncertainty of 1 % to the viscosity correlation in the vapor phase, below 0.2 MPa, in the temperature range (338 to 673) K. We do not recommend the use of Eqs (2) and (4) to predict the viscosity of the *o*-xylene vapor at temperatures below 338 K. The lack of experimental data and the empirical nature of the equations make the extrapolation rather uncertain. However, the use of Eqs (2) and (4), as part of Eq. (1), to predict the liquid viscosity from 273 to 338 K is recommended since the contribution of low density terms to the overall liquid viscosity is small.

3.2. The critical enhancement and the residual viscosity terms

In the vicinity of the critical point the viscosity of the pure fluid exhibits an enhancement that diverges at the critical point.⁹⁹ The enhancement is significant only in a relative narrow window in temperature and density round the critical point.^{2,7} Based on the previous studies,^{3,5,6,8-13,15-19} the viscosity critical enhancement of *o*-xylene is taken as zero. The total lack of industrial applications of *o*-xylene near its critical temperature and the existence of only a single experimental viscosity datum³⁹ further supports this choice.

There is no theoretical guidance for the residual-viscosity contribution and hence the existence of accurate experimental data covering a wide range of temperature and pressure is paramount for developing reliable correlations. A number of authors^{27,33,34,36,38,46,92} have measured the viscosity of *o*-xylene at wide range of temperatures and at pressures higher than atmospheric, as illustrated in Fig. 1. Based on the analysis of the measurement techniques and the authors measurements on other fluids we have chosen four datasets as primary in the liquid region. Mamedov and co-workers^{33,34} performed the experiments using capillary viscometer with a claimed uncertainty of 1.2 %. Our work on the development of the correlations of *p*- and *m*-xylene^{17,19} indicates that a more conservative estimate of uncertainty of 2-4 % would be more appropriate. The later work of Mamedov³⁶ contains no new experimental data, but only the analysis of the data obtained in 1967,³³ hence it was not included in primary data. Kashiwagi and Makita³⁸ used a torsional crystal viscometer, while Meng *et al.*⁹² used the vibrating wire viscometer. Both two sets of authors claimed uncertainty of 2 % which is well-supported by their measurements on other fluids.¹⁵⁻¹⁹ The primary data in the liquid state, thus covered the temperature range (273 to 548) K and pressures from 0.1 MPa up to 110 MPa.

The primary data set also contains five sets of viscosity measurements^{24,28,40,45,75} of liquid *o*-xylene at atmospheric pressure covering the temperature range (273 to 414) K. The choice followed our previous work on *p*-xylene¹⁷ and *m*-xylene¹⁹ and was based on careful analysis of the available data based on a number of criteria, as described previously.¹⁹ We have designated the early *o*-xylene data of Thorpe and Rodger²⁴ as primary, although up to now most workers classified it as

secondary.^{16-18,100} Our analysis of their measurements of benzene,¹⁶ *p*-xylene,¹⁷ toluene,¹⁸ *m*-xylene,¹⁹ and *n*-heptane,¹⁰⁰ indicates the deviations on average of better than 0.5 % when compared with the most recent reference correlations for these fluids. The inclusion of their data set increased the high temperature limit, at atmospheric pressure in the liquid phase, from (353 to 414) K. We have assigned these data a conservative uncertainty of 1.0%. We have also assigned the same uncertainty to the data of Serrano et al. based on the analysis of agreement of their data for *p*- and *m*-xylene with other authors.^{17,19}

Figures 4-7 illustrate the comparison of high pressure data of different authors that were measured along the same isotherms.

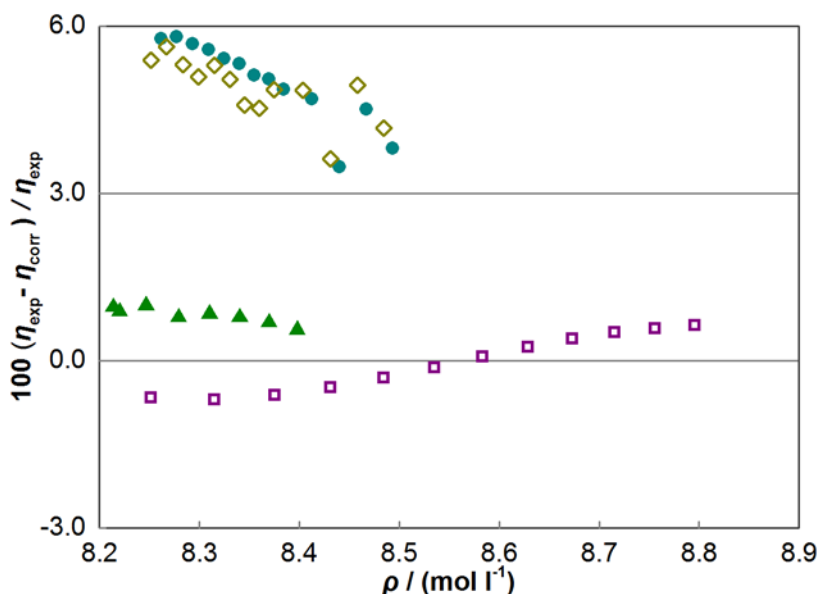


FIG. 4. Comparison of the experimental liquid viscosity data at high pressure at nominal temperature of 298 K. (●) Mamedov *et al.* (297 K);³³ (◇) Mamedov *et al.*;³⁴ (□) Kashiwagi and Makita;³⁸ (▲) Meng *et al.* (293 K).⁹²

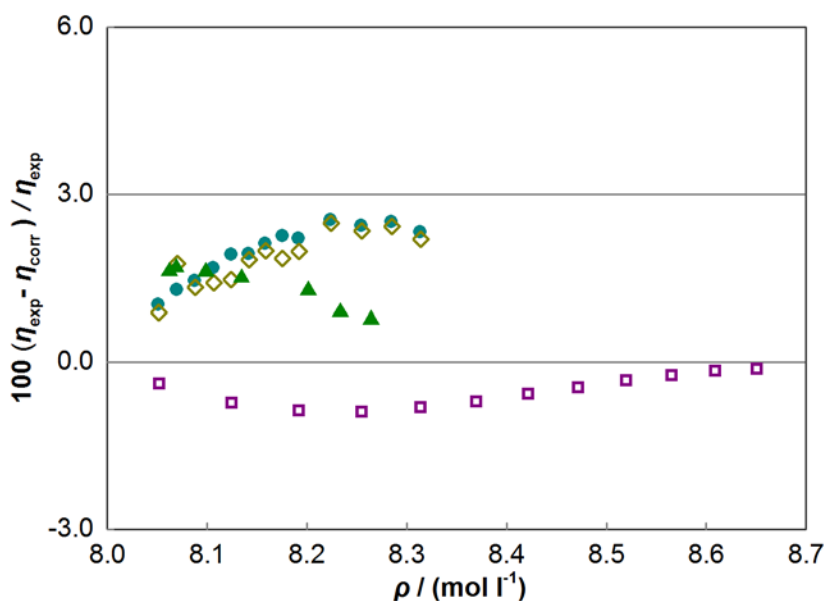


FIG. 5. Comparison of the experimental liquid viscosity data at high pressure at nominal temperature of 323 K. (●) Mamedov *et al.*;³³ (◇) Mamedov *et al.*;³⁴ (□) Kashiwagi and Makita;³⁸ (▲) Meng *et al.* (322 K).⁹²

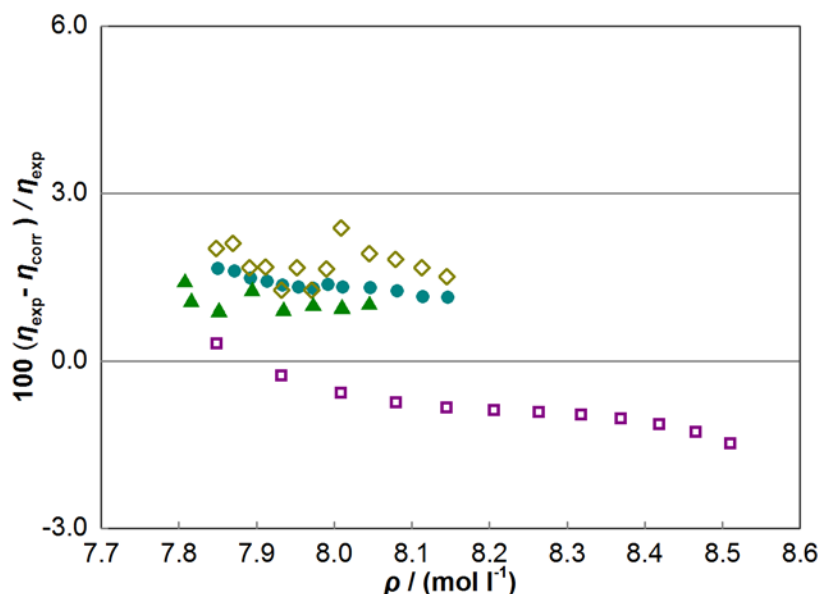


FIG. 6. Comparison of the experimental liquid viscosity data at high pressure at nominal temperature of 348 K. (●) Mamedov *et al.*,³³ (◇) Mamedov *et al.*,³⁴ (□) Kashiwagi and Makita,³⁸ (▲) Meng *et al.* (353 K).⁹²

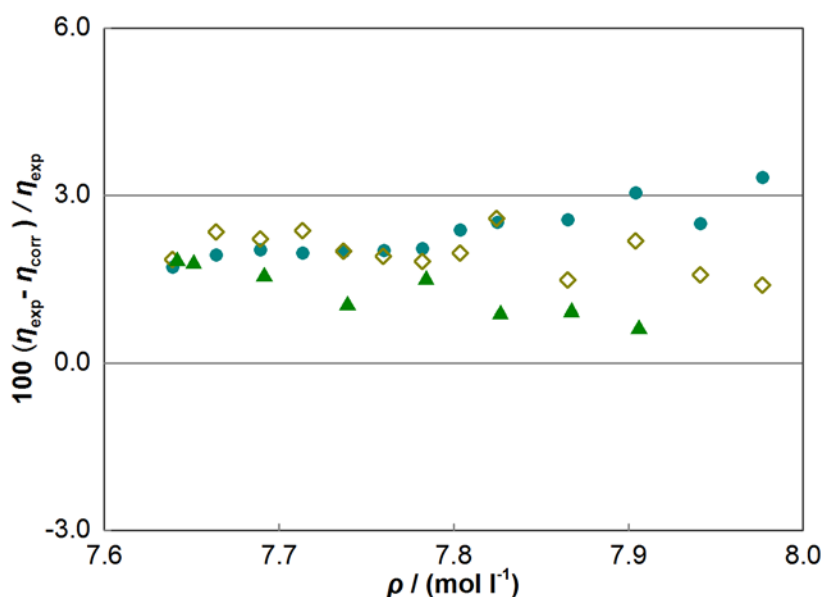


FIG. 7. Comparison of the experimental liquid viscosity data at high pressure at nominal temperature of 373 K. (●) Mamedov *et al.*,³³ (◇) Mamedov *et al.*,³⁴ (▲) Meng *et al.*⁹²

We observe that in the temperature range (323 to 373) K there is a general agreement among the data of three labs to within their estimated uncertainty. However, at 298 K the data of Mamedov *et al.*^{33,34} lay approximately 3-6 % above the data of other workers, with deviations increasing as we approach the liquid saturation line. Similar qualitative behavior was observed for *m*-xylene¹⁹ where for number of isotherms, but not all, Mamedov *et al.* data showed systematic deviation from other data. Figure 8 illustrates the behaviour of Mamedov *et al.* data^{33,34} at low pressures (0.1 to 0.82) MPa as a function of temperature. The baseline used is the final correlation and we have also plotted Thorpe and Rodger data²⁴ for comparison, as it covers an extended range of temperatures. We observe that

at temperatures higher than 373 K the deviations increase markedly from the data of Thorpe and Roger. The inclusion of Mamedov et al. data along isotherms (398 to 473) K, that cover pressure up to 40 MPa, in the primary data set resulted in other primary data (Kashiwagi and Makita³⁸ and Meng *et al.*⁹²) displaying systematic deviations outside their claimed uncertainty. Hence, we have eliminated Mamedov *et al.*^{33,34} data below 498 K from the primary data set. We have however used their data, with new estimate of uncertainty, in high temperature region (498 to 548) K to extend the temperature range of the developed correlation. We have made a conservative estimate of their uncertainty to be 4 % based on the correlation for *m*-xylene where we also included only their high temperature data. The inclusion of the high temperature data in the final correlation explains why the deviations, illustrated in Fig. 8, decrease above 473 K.

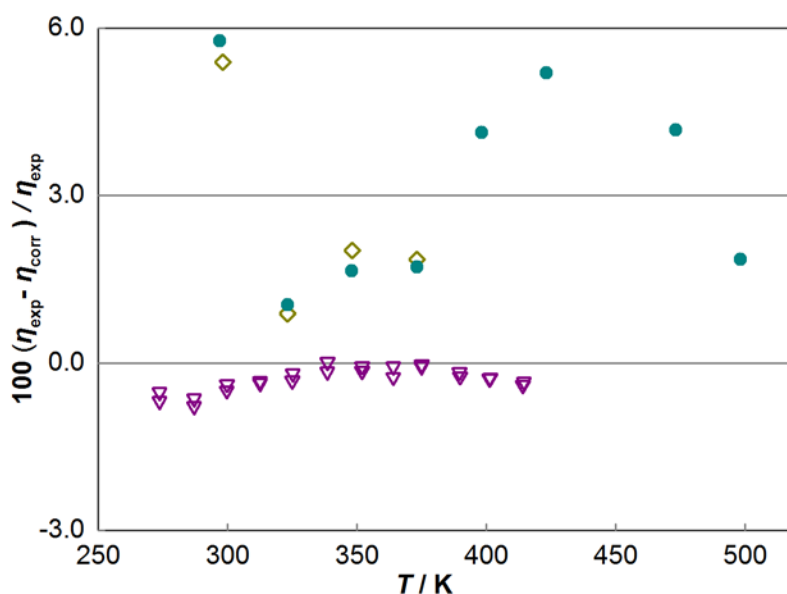


FIG. 8. Comparison of the experimental liquid viscosity data with the data of Thorpe and Rodger. (∇) Thorpe and Rodger;²⁴ (\bullet) Mamedov *et al.*,³³ (\diamond) Mamedov *et al.*³⁴

We have also included the data of Abdullaev and Akhundov³⁹ measured in the vapor phase as the primary data set. The measurements carried out in the capillary viscometer cover the temperature range (473 to 673) K and pressures up to 4.1 MPa. Good agreement of the viscosity data measured by the same authors in the same viscometer for *p*- and *m*-xylene indicates that the claimed uncertainty of 1.5 % is justified.

In summary 281 data points covering the temperature range (273 to 673) K and pressures up to 110 MPa measured in ten different viscometers were used as the primary data for the development of the residual viscosity contribution. All the viscosity data were converted from the $\eta(T,P)$ to $\eta(T,\rho)$ representation by means of Zhou *et al.* EoS.²⁰ The residual viscosity was generated by subtracting from each data point the zero-density value, Eqs. (2) and (3), and the initial density contribution, Eq. (4). In line with previous work,^{15,17,19} we have constrained the fitting of the experimental viscosity data in such a way that the resulting correlation within the two-phase region is a continuous, monotonically increasing function of density at all temperatures, except at low densities where the decreasing initial-

density dependence extends partially into the two-phase region. The residual viscosity is represented as a function in reduced temperature, $T_r = T/T_c$, and reduced density, $\rho_r = \rho/\rho_c$, as,

$$\Delta\eta(\rho_r, T_r) = (\rho_r^{2/3} T_r^{1/2})f(\rho_r, T_r) \quad (5)$$

by taking advantage of the hard sphere result,^{101,102} as already used in correlating the viscosity of benzene,¹⁶ *p*-xylene,¹⁷ and *m*-xylene¹⁹. We choose the function $f(\rho_r, T_r)$ to consist of terms of the general form $(D_i + E_i/T_r^{k_i})\rho_r^{n_i}$, where D_i , E_i , k_i and n_i are the adjustable coefficients. The choice was purely empirical, as we observed that such a function exhibits a monotonic increase within the two-phase region. The final function $f(\rho_r, T_r)$ for *o*-xylene is given by,

$$f(\rho_r, T_r) = (D_0 + E_0/T_r^{k_0})\rho_r^{n_0} + D_1\rho_r^{n_1} + E_2\rho_r^{n_2}/T_r^{k_2} + (D_3\rho_r + E_3T_r)\rho_r^{n_3} + D_4\rho_r^{n_4} \quad (6)$$

Following the development of *p*-xylene correlation,¹⁷ we have used fractional powers to allow us more flexibility in fitting the experimental data with the constraint imposed on the behavior in the two-phase region.

The procedure adopted during this analysis used the 1stOpt (First Optimization) software for statistical computing¹⁰³ to fit primary data to Eq. (6). The uncertainties quoted in Table 1 were used to determine relative weights for all the primary data. The optimal coefficients D_i , E_i , k_i and n_i are shown in Table 2, while the critical temperature T_c (630.259 K) and critical density ρ_c (2.6845 mol l⁻¹) were obtained from Ref. 20.

TABLE 2. Coefficients for the representation of the residual viscosity, Eq. (6)

i	D_i	n_i	E_i	k_i
0	-2.05581×10^{-3}	10.3	2.65651×10^{-3}	0.8
1	2.38762	3.3	--	--
2	--	25	1.77616×10^{-12}	4.4
3	10.4497	0.7	-18.2446	--
4	15.9587	0.4	--	--

Figures 9-10 illustrate the percentage deviation of the primary viscosity data from the developed viscosity correlation, Eqs. (1)-(6). Figure 9 illustrates the agreement with the experimental data in the liquid region for pressures higher than atmospheric. The experimental data of Kashiwagi and Makita³⁸ and Meng *et al.*⁹² are reproduced by the proposed correlation within their claimed experimental uncertainty of 2.0 %, except for one data point of Meng *et al.*⁹² The data of Mamedov *et al.*^{33,34} exhibit the deviations, from (-2.4 to 2.9) %, that are within the assigned uncertainty of 4 %, over the temperature range (498 to 548) K.

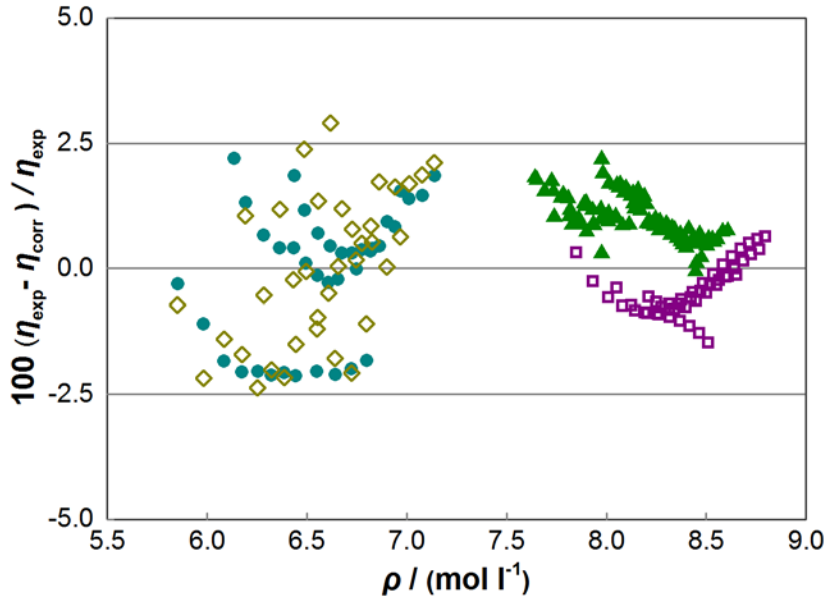


FIG. 9. Percentage deviations $[100(\eta_{\text{exp}} - \eta_{\text{corr}}) / \eta_{\text{exp}}]$ of the primary experimental viscosity data in the liquid region from the values calculated by Eqs. (1) - (6). (●) Mamedov *et al.*;³³ (◇) Mamedov *et al.*;³⁴ (□) Kashiwagi and Makita;³⁸ (▲) Meng *et al.*⁹²

Figure 10 illustrates the agreement of the developed viscosity correlation with the primary experimental data at atmospheric pressure that cover the temperature range (273 to 414) K, in the liquid phase. Most of the data are reproduced within 1 %. The exception is the data of Meng *et al.*⁹², which has the average absolute deviation of 1.3 %.

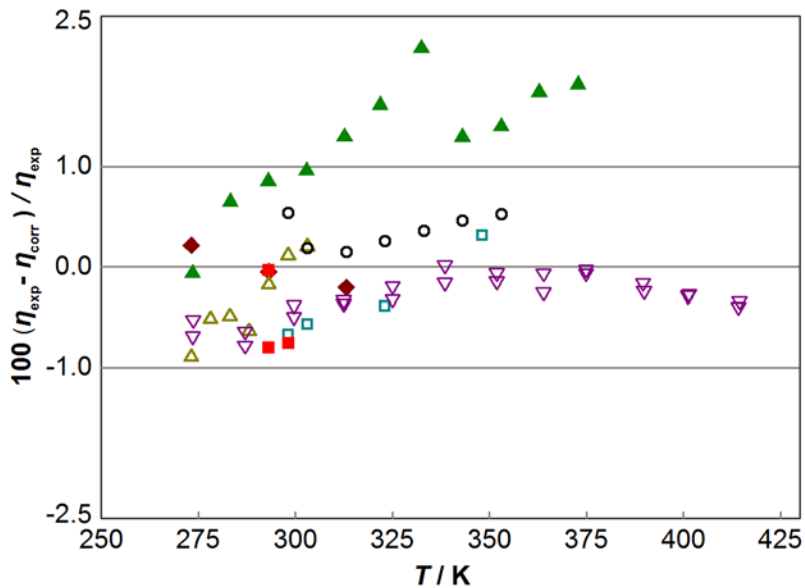


FIG. 10. Percentage deviations $[100(\eta_{\text{exp}} - \eta_{\text{corr}}) / \eta_{\text{exp}}]$ of the primary experimental viscosity data measured at 0.1 MPa from the calculated values using Eqs. (1) - (6). (▽) Thorpe and Rodger;²⁴ (◆) Geist and Cannon;²⁸ (□) Kashiwagi and Makita;³⁸ (■) Bauer and Mehlender;⁴⁰ (△) Serrano *et al.*;⁴⁵ (O) Yang *et al.*;⁷⁵ (▲) Meng *et al.*⁹²

Table 3 summarizes the agreement between the primary experimental data and the proposed viscosity correlation for *o*-xylene in the liquid, dense vapor and supercritical regions. The correlation recaptures the entire set of primary data with an average absolute deviation (AAD) of 0.9 %, bias of 0.2 % and maximum deviation of 3.7 %. We have estimated the overall uncertainty of the correlation defined as the combined expanded uncertainty with a coverage factor of 2 as follows: (i) at atmospheric pressure, both in the vapor and liquid phase, we estimate the uncertainty to be 1.0 %; (ii) in the liquid region for pressures above atmospheric and temperature below 373 K, we estimate the uncertainty to be 2.0 % while for temperatures above 373 K and pressures up to 40 MPa we estimate the uncertainty to be 4.0 %; (iii) in the high pressure vapor and supercritical region, we estimate the uncertainty to be 2.5 %; (iv) in the region (> 548 K and > 40 MPa) and (liquid < 0.1 MPa) where no experimental data are available we conservatively estimate the uncertainty to be 5 %.

TABLE 3. Evaluation of the *o*-xylene viscosity correlation against the primary experimental data.

Authors	Year publ.	AAD ^a (%)	Bias ^b (%)	MD ^c (%)
Thorpe and Rodger ²⁴	1894	0.3	-0.3	-0.8
Geist and Cannon ²⁸	1946	0.2	0.0	0.2
Mamedov <i>et al.</i> ³³	1967	1.1	-0.1	2.2
Mamedov <i>et al.</i> ³⁴	1975	1.3	0.0	2.9
Kashiwagi and Makita ³⁸	1982	0.6	-0.4	-1.5
Abdullaev and Akhundov ³⁹	1983	0.9	0.1	3.7
Bauer and Meerlender ⁴⁰	1984	0.5	-0.5	-0.8
Serrano <i>et al.</i> ⁴⁵	1990	0.4	-0.3	-0.9
Yang <i>et al.</i> ⁷⁵	2007	0.4	0.4	0.5
Meng <i>et al.</i> ⁹²	2016	1.0	1.0	2.2
Entire primary data set		0.9	0.2	3.7

$$^a\text{AAD, Average Absolute Deviation} = 100/N \sum |(\eta_{\text{exp}} - \eta_{\text{corr}})/\eta_{\text{exp}}|.$$

$$^b\text{Bias} = 100/N \sum (\eta_{\text{exp}} - \eta_{\text{corr}})/\eta_{\text{exp}}.$$

^cMD, Maximum deviation.

4. Overall Viscosity Correlation

The viscosity correlation of *o*-xylene as a function of temperature and density is represented by Eqs. (1)-(6) with the coefficients given in Table 2. The correlation is valid in an extended temperature (273 to 673 K) and pressure (up to 110 MPa) range. In the vapor phase the lower temperature limit corresponds to 338 K. The proposed correlation does not exhibit any unphysical behavior when extrapolated to temperatures as low as the triple point (247.985 K).²⁰ Although the extrapolation is not recommended, as it is not possible to estimate the uncertainties, the increase in viscosity and decrease in the zero-density viscosity with decreasing temperature is monotonic and smooth.

Figure 11 illustrates the behavior of the viscosity correlation as a function of density along the 300 and 600 K isotherms. We observe a 260 fold increase in viscosity over the range of densities covered, with a steep increase in viscosity at the highest densities. Nevertheless, the proposed correlation is well-behaved within the two-phase region, where no data are available to constrain the correlation; for all isotherms, viscosity exhibits monotonic increase with density except at low densities, of up to 1.3 mol l^{-1} , where the decreasing initial-density dependence extends into the two-phase region. The behavior at densities corresponding to the two-phase region makes the present correlation suitable as the basis of developing a reference corresponding-states correlation for cyclic hydrocarbons⁹⁷ or as part of the VW model¹⁰⁴⁻¹⁰⁶ to predict the viscosity of mixtures containing *o*-xylene.

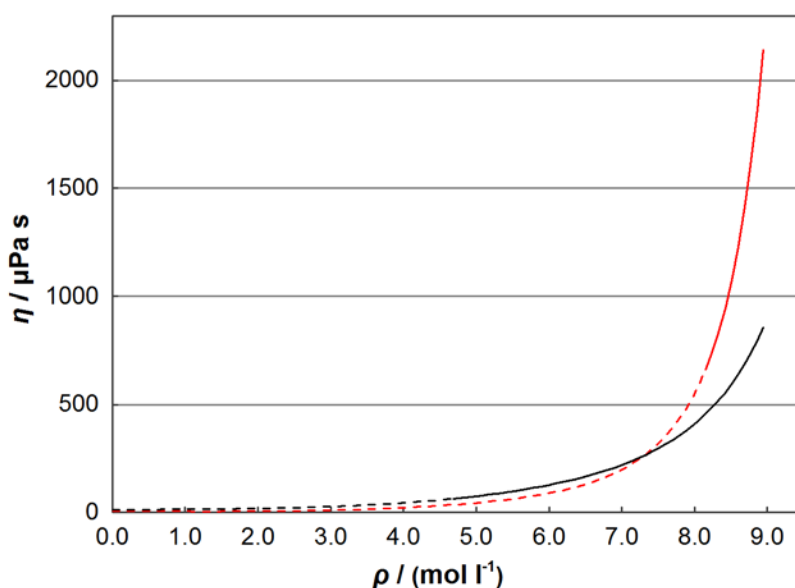


FIG. 11. Viscosity of *o*-xylene as a function of density along a couple of isotherms. (red solid line) 300 K, liquid phase; (red dashed line) 300 K, two-phase region; (black solid line) 600 K, liquid phase; and (black dashed line) 600 K, two-phase region.

Figure 12 summarizes the estimated combined expanded uncertainty with coverage factor of 2 of the proposed viscosity correlation as a function of temperature and pressure. Table 4 contains the recommended values of viscosity of *o*-xylene at a selected number of temperatures and pressures which broadly cover the range of the proposed viscosity correlation. Table 5 contains the recommended values of viscosity of *o*-xylene along the saturation line.

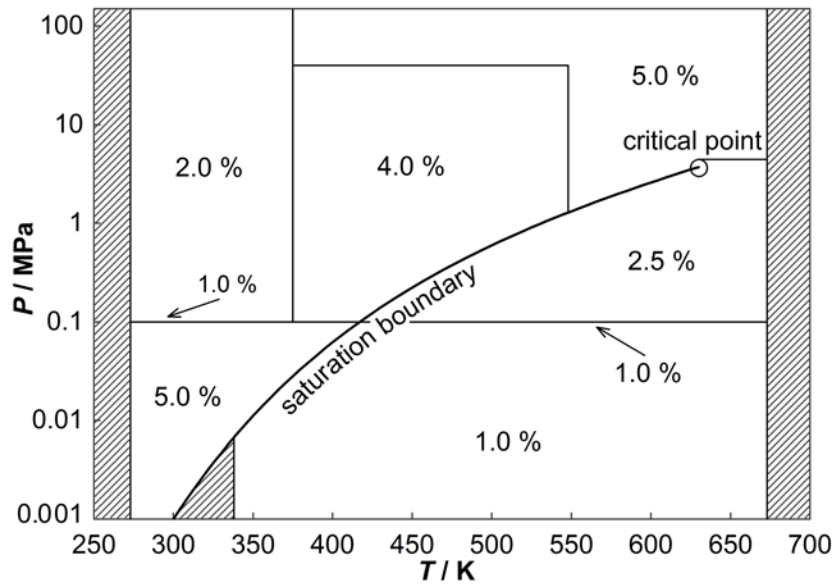


FIG. 12. The extent of the viscosity representation and its estimated uncertainty. No representation is available in the hatched region.

TABLE 4. Recommended viscosity values $\mu\text{Pa s}$

P MPa	T / K											
	280	300	320	340	360	380	400	450	500	550	600	650
0	6.32	6.67	7.04	7.43	7.83	8.24	8.66	9.72	10.79	11.85	12.90	13.94
0.1	989.4	738.3	577.1	466.6	386.7	326.6	279.9	9.73	10.82	11.90	12.96	14.01
0.5	992.9	740.8	579.1	468.2	388.1	327.9	281.1	200.3	10.93	12.07	13.18	14.26
1	997.3	744.1	581.6	470.3	390.0	329.5	282.6	201.6	148.3	12.27	13.43	14.54
2	1006.3	750.6	586.7	474.5	393.6	332.7	285.6	204.2	151.1	108.9	14.00	15.10
4	1024.2	763.6	596.9	482.9	400.7	339.1	291.4	209.4	156.5	116.0	76.27	17.73
6	1042.3	776.8	607.1	491.3	407.9	345.5	297.2	214.5	161.6	122.2	86.58	47.50
8	1060.6	790.1	617.4	499.7	415.1	351.8	303.0	219.5	166.5	127.8	94.44	61.73
10	1079.1	803.5	627.7	508.1	422.3	358.2	308.7	224.3	171.3	133.0	101.1	71.41
20	1174.4	872.0	680.3	550.7	458.3	389.6	336.9	247.8	192.9	155.1	126.0	101.5
50	1490.9	1095.8	848.9	684.6	569.3	484.6	420.4	313.3	249.0	206.7	176.5	153.2
110	2289.1	1645.4	1250.1	992.9	816.5	690.0	595.7	441.8	351.4	293.3	253.5	224.5

TABLE 5. Recommended viscosity values along the saturation line

T/K	P_v/MPa	Vapor		Liquid	
		$\rho/(\text{mol l}^{-1})$	$\eta/(\mu\text{Pa s})$	$\rho/(\text{mol l}^{-1})$	$\eta/(\mu\text{Pa s})$
273.15	0.0002	0.0001	-	8.4485	1107.6
293.15	0.0007	0.0003	-	8.2905	810.5
313.15	0.0021	0.0008	-	8.1314	624.6
333.15	0.0055	0.0020	-	7.9701	499.8
353.15	0.0127	0.0044	7.69	7.8060	411.1
373.15	0.0265	0.0087	8.09	7.6382	345.2
393.15	0.0507	0.0160	8.50	7.4658	294.5
413.15	0.0901	0.0274	8.93	7.2877	254.6
433.15	0.1506	0.0446	9.36	7.1025	222.3
453.15	0.2389	0.0692	9.81	6.9087	195.6
473.15	0.3625	0.1036	10.28	6.7042	173.0
493.15	0.5297	0.1506	10.77	6.4862	153.4
513.15	0.7495	0.2141	11.30	6.2506	135.8
533.15	1.0320	0.3000	11.88	5.9916	119.4
553.15	1.3884	0.4174	12.53	5.6991	103.8

Figure 13 summarizes the deviations of the selected secondary data, consisting of at least four data points, measured at atmospheric pressure, from the current correlation. Although the number of measurements are within the acceptable 1-2 % there are a number of data sets that exhibit much larger deviations. Figure 14 exhibits the only four sets of secondary experimental data that extend to higher pressure. The deviations of the data of Bridgman²⁷ at 303 K display the deviations within 1.6 %, which is in agreement with what we have observed for *p*- and *m*-xylene. However, his data at 348 K is systematically 4-7 % below the proposed correlation. The data of Et-Tahir *et al.*⁴⁶ display large scatter at some isotherms, with maximum deviation of 4.7 %; the behavior is similar to what we observed for *m*-xylene, but not for *p*-xylene where Et-Tahir *et al.*⁴⁶ data were classified as primary. The secondary data of Mamedov *et al.*^{33,34} at temperatures (298 to 473) K display systematic trends at certain temperatures with maximum deviation of 5.8 %.

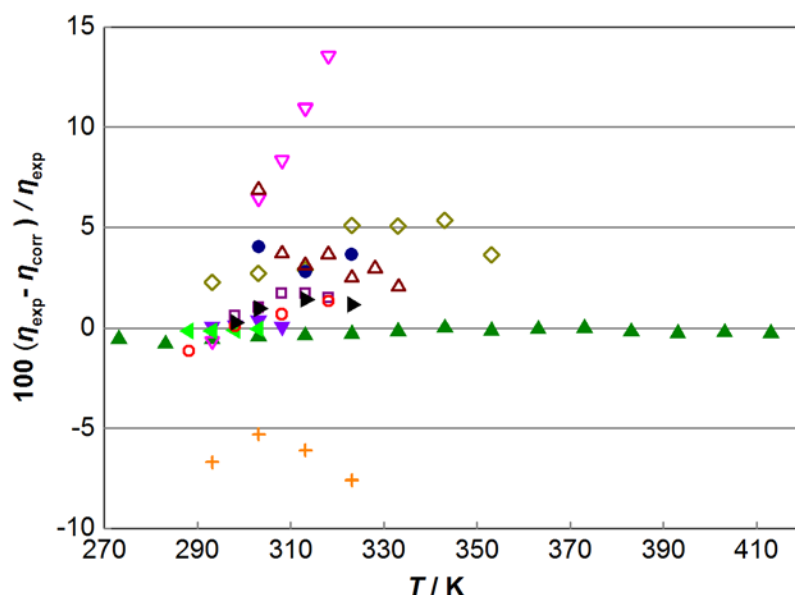


FIG. 8. Percentage deviations $[100(\eta_{\text{exp}} - \eta_{\text{corr}}) / \eta_{\text{exp}}]$ of the selected secondary experimental viscosity data measured at 0.1 MPa from the calculated values using Eqs. (1) - (6). (\blacktriangle) Batschinski;²⁵ (\diamond) Panchenkov *et al.*;³¹ (∇) Swain *et al.*;^{50,51,59,61} (\blacktriangledown) Moumouzias *et al.*;⁵⁴ (\bullet) Prasad *et al.*;⁵⁵ (\square) Ali *et al.*;⁷¹ (\blacktriangleleft) Al-Kandary *et al.*;⁷² (\circ) Nain *et al.*;⁷⁴ (\triangle) Song *et al.*;⁷⁷ (\blacktriangleright) Ciocirlan *et al.*;⁷⁸ ($+$) Dikio *et al.*^{90,91}

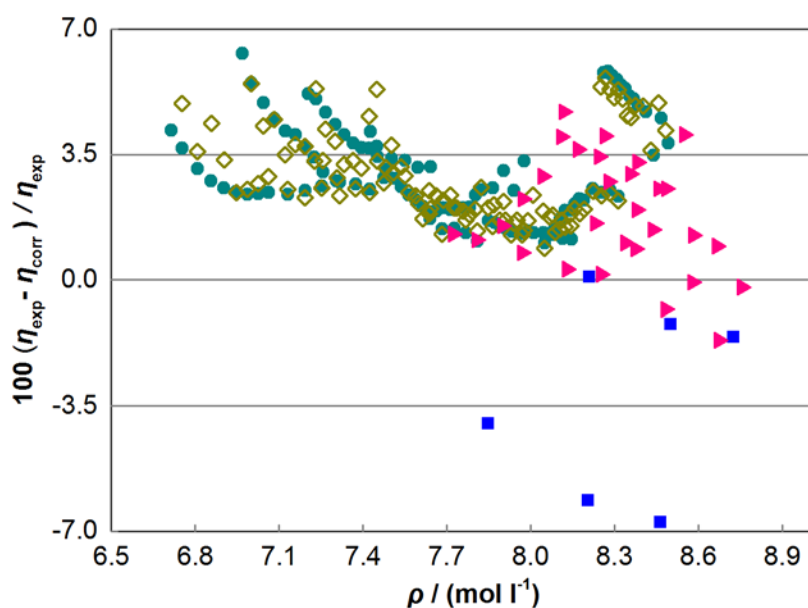


FIG. 9. Percentage deviations $[100(\eta_{\text{exp}} - \eta_{\text{corr}}) / \eta_{\text{exp}}]$ of the selected secondary experimental viscosity data at high pressures from the calculated values using Eqs. (1) - (6). (\blacksquare) Bridgman;²⁷ (\bullet) Mamedov *et al.*;³³ (\diamond) Mamedov *et al.*;³⁴ (\blacktriangleright) Et-Tahir *et al.*⁴⁶

Although no other viscosity correlation of *o*-xylene is available in open literature there are a couple of tables of recommended values^{93,94} and Yaws recommended equation²³ all for liquid viscosity at atmospheric pressure. The agreement between the tabulated values of Golubev⁹³ and NIST/TRC database⁹⁴ and the present correlation is very good and the deviations do not exceed ± 0.4 %. However, the Yaws proposed equation²³ for the liquid viscosity shows larger deviations from the

current correlation with a systematic trend extending from -2.7 % to 2.0 % in the temperature range (273 to 413) K.

5. Computer-Program Verification

Table 6 is provided to assist the user in computer-program verification. The viscosity calculations are based on the tabulated temperatures and densities.

TABLE 6. Sample points for computer verification of the correlating equations

T (K)	ρ (mol l ⁻¹)	η (μ Pa s)
300	0.0000	6.670
300	0.0400	6.598
300	8.2369	738.286
300	8.7845	1645.436
400	0.0000	8.658
400	0.0400	8.634
400	7.4060	279.954
400	8.2291	595.652
600	0.0000	12.904
600	0.0400	13.018
600	7.2408	253.530

6. Conclusion

A new wide-ranging correlation for the viscosity of *o*-xylene has been developed based on critically-evaluated experimental data. The correlation is valid to pressures up to 110 MPa and temperatures up to 673 K. In the liquid part of the phase diagram the lower temperature limit is 273 K, while in the vapor part of the phase diagram it is 338 K. The correlation is expressed in terms of temperature and density, and the densities were obtained from the equation of state of Zhou *et al.*²⁰ The overall uncertainty, using a coverage factor of 2, of the proposed correlation is less than 5.0 %, however this uncertainty varies depending on thermodynamic state and is summarized in more detail in Fig. 12.

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7. Appendix: Viscosity measurements of *o*-xylene

Table 7. Viscosity measurements of *o*-xylene

Authors	Year publ.	Technique employed ^a	No. of data	Temperature range (K)	Pressure range (MPa)
Thorpe and Rodger ²⁴	1894	C	24	273-414	0.1
Batschinski ²⁵	1913	C	15	273-413	0.1
Kremann <i>et al.</i> ²⁶	1914	C	2	285-337	0.1
Bridgman ²⁷	1926	FB	10	303-348	0.1-600
Geist and Cannon ²⁸	1946	C	3	273-313	0.1
Timmermans and Hennaut-Roland ²⁹	1955	C	2	288-303	0.1
Petro and Smyth ³⁰	1957	C	3	293-333	0.1
Panchenkov <i>et al.</i> ³¹	1958	C	7	293-353	0.1
Khalilov ³²	1961	-	1	639	0.1
Mamedov <i>et al.</i> ³³	1967	C	142	297-548	0.1-40
Mamedov <i>et al.</i> ³⁴	1975	C	136	298-548	0.1-40
Dhillon and Chugh ³⁵	1976	C	2	298-308	0.1
Mamedov ³⁶	1979	C	30	298-548	2.5-40
Reddy and Naidu ³⁷	1981	C	1	298	0.1
Kashiwagi and Makita ³⁸	1982	TC	48	298-348	0.1-110
Abdullaev and Akhundov ³⁹	1983	C	28	473-673	0.1-4.1
Bauer and Meerlender ⁴⁰	1984	C	3	293-298	0.1
Al-Madfai <i>et al.</i> ⁴¹	1985	C	1	298	0.1
Ramanjaneyulu <i>et al.</i> ⁴²	1987	C	1	303	0.1
Rathnam ⁴³	1988	C	1	303	0.1
Chevalier <i>et al.</i> ⁴⁴	1990	C	1	298	0.1
Serrano <i>et al.</i> ⁴⁵	1990	C	7	273-303	0.1
Et-Tahir <i>et al.</i> ⁴⁶	1995	C	5	298-363	0.1
Et-Tahir <i>et al.</i> ⁴⁶	1995	FB	25	298-363	20-100
Petrino <i>et al.</i> ⁴⁷	1995	C	1	298	0.1
Ramachandran <i>et al.</i> ⁴⁸	1995	C	1	303	0.1
Singh <i>et al.</i> ⁴⁹	1995	C	1	298	0.1
Swain <i>et al.</i> ⁵⁰	1997	C	5	293-318	0.1
Swain <i>et al.</i> ⁵¹	1998	C	4	303-318	0.1
Goud <i>et al.</i> ⁵²	1999	C	1	308	0.1
Ivanciuc <i>et al.</i> ⁵³	1999	-	1	293	0.1
Moumouzias <i>et al.</i> ⁵⁴	1999	C	4	293-308	0.1
Prasad <i>et al.</i> ⁵⁵	1999	FB	4	293-323	0.1
Wegner <i>et al.</i> ⁵⁶	1999	-	1	298	0.1
Katritzky <i>et al.</i> ⁵⁷	2000	-	1	293	0.1
Price and Soderman ⁵⁸	2000	-	1	298	0.1
Swain <i>et al.</i> ⁵⁹	2000	C	5	293-318	0.1
Gupta and Singh ⁶⁰	2001	C	1	298	0.1

Swain <i>et al.</i> ⁶¹	2001	C	5	293-318	0.1
George and Sastry ⁶²	2003	C	2	298-308	0.1
Katyal <i>et al.</i> ⁶³	2003	C	3	293-313	0.1
Lark <i>et al.</i> ⁶⁴	2003	C	2	298-303	0.1
Jain and Singh ⁶⁵	2004	C	1	303	0.1
Singh <i>et al.</i> ⁶⁶	2004	C	1	298	0.1
Yang <i>et al.</i> ⁶⁷	2004	C	3	298-323	0.1
Rathnam <i>et al.</i> ⁶⁸	2005	C	2	303-313	0.1
Singh <i>et al.</i> ⁶⁹	2005	C	1	298	0.1
Ali <i>et al.</i> ⁷⁰	2006	C	1	308	0.1
Ali <i>et al.</i> ⁷¹	2006	C	5	298-318	0.1
Al-Kandary <i>et al.</i> ⁷²	2006	RC	4	288-303	0.1
Das <i>et al.</i> ⁷³	2006	C	2	303-313	0.1
Nain ⁷⁴	2007	C	4	288-318	0.1
Yang <i>et al.</i> ⁷⁵	2007	C	7	298-353	0.1
Rathnam <i>et al.</i> ⁷⁶	2008	C	1	303	0.1
Song <i>et al.</i> ⁷⁷	2008	C	7	303-333	0.1
Ciocirlan and Iulian ⁷⁸	2009	C	4	298-323	0.1
Dominguez-Perez <i>et al.</i> ⁷⁹	2009	C	1	298	0.1
Nain <i>et al.</i> ⁸⁰	2009	C	1	298	0.1
Rathnam <i>et al.</i> ⁸¹	2009	C	2	303-313	0.1
Sastry <i>et al.</i> ⁸²	2009	C	2	298-308	0.1
Yang <i>et al.</i> ⁸³	2009	C	3	298-318	0.1
Yarranton and Satyro ⁸⁴	2009	-	1	298	0.1
Habibullah <i>et al.</i> ⁸⁵	2010	C	2	308-318	0.1
Rathnam <i>et al.</i> ⁸⁶	2010	C	2	303-313	0.1
Bhatia <i>et al.</i> ⁸⁷	2011	C	2	298-308	0.1
Rathnam <i>et al.</i> ⁸⁸	2011	C	2	303-313	0.1
Zarei and Salami ⁸⁹	2012	C	1	298	0.1
Dikio <i>et al.</i> ⁹⁰	2013	RC	4	293-323	0.1
Dikio ⁹¹	2014	RC	4	293-323	0.1
Meng <i>et al.</i> ⁹²	2016	VW	88	273-373	0.1-30

Tables of collected data

Golubev ⁹³	1970	-	14	273-413	0.1
NIST/TRC database 85 ⁹⁴	2003	-	29	268-418	0.1

^aC, capillary; FB, falling body; TC, torsional crystal; VW, vibrating wire; RB, rolling body; RC, rotating cylinder.