# Reference correlation of the viscosity of *meta*-xylene from 273 K to 673 K and up to 200 MPa

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Abstract

A new correlation for the viscosity of *meta*-xylene (*m*-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 200 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.

Recently, research and development of state-of-the-art viscosity correlations have gained renewed impetus. 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 basic philosophy of the program is to make use of the best available experimental data, selected on the basis of a critical analysis of the measurement methods. This information is complemented with guidance available from theory to produce accurate, consistent, and theoretically sound representations of the transport properties over the widest range of thermodynamic states possible. The first fluid studied in this program was carbon dioxide[2] and since then a plethora of viscosity correlations have been produced, using the same philosophy, covering among others: simple fluids,[3-5] alkanes[6-13] and water.[14] Recently the work has been extended to cyclic and aromatic hydrocarbons.[15-18] The present study is a continuation of this effort. The aim of this work is to critically assess the data available in the literature, and provide a correlation for the viscosity of *meta*-xylene that is valid over a wide range of temperature and pressure, covering the vapor, liquid, and supercritical fluid states.

*meta*-Xylene ($C_{10}H_8$) is an aromatic hydrocarbon that consists of benzene ring and two $-CH_3$ groups in positions 1 and 3. At ambient conditions it is a colorless liquid that has limited industrial usage as a raw material, compared to *p*-xylene and *o*-xylene, and is primarily used as a solvent. It occurs naturally in crude oil and is also found in gasoline and to some extent kerosene. 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 *m*-xylene are well catered for, by an up-to-date EOS,[19] while the thermal conductivity correlation has also become recently available.[20] 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 *m*-xylene, one has to rely on generic correlations[21,22] 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 *m*-xylene reported in the literature,[23-88] 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 *m*-xylene were reported in 66 papers resulting in 913 data points. Unsurprisingly, the vast majority of researchers (56 papers, 173 data points) have measured only the value of the liquid viscosity at atmospheric pressure, mostly around room temperature, usually as part of a measurement program of viscosity of mixtures containing *m*-xylene. Appendix A also contains two reference works[89,90] that report recommended tabulated values of the viscosity of *m*-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. For this purpose, we used a set of well-established criteria[91] that among other things classify primary data as data obtained with an experimental apparatus for which a complete working equation is available and for which a high precision in measuring the viscosity has been achieved. Furthermore, the criteria stipulate that guarantee of the purity of the sample, including the description of purification methods, should be available. However, in many cases, such a narrow definition unacceptably limits the range of the data representation. Consequently, within the primary data set, it is also necessary to include results that extend over a wide range of conditions, albeit with poorer accuracy, provided they are consistent with other more accurate data or with theory. Based on these criteria, 11 datasets were considered primary data. Table 1 summarizes the primary data[23,31,34,35,38,39,43,45,68,71,88] detailing the temperature and pressure ranges, the authors' claimed uncertainty and 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.

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

| Authors | Year publ. | Technique employed[a] | Purity (%) | Claimed uncertainty (%) | No. of data | Temperature range (K) | Pressure range (MPa) |
|---|---|---|---|---|---|---|---|
| Thorpe and Rodger[23] | 1894 | C | -- | -- | 26 | 273-408 | 0.1 |
| Geist and Cannon[31] | 1946 | C | -- | 0.5 | 3 | 273-313 | 0.1 |
| Mamedov *et al.*[34] | 1968 | C | 99.4 | 1.2 | 67[b] | 473-548 | 0.1-39.3 |
| Mamedov *et al.*[35] | 1975 | C | 99.4 | 1.2 | 48[b] | 473-548 | 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 | 28 | 473-673 | 0.1-4.3 |
| Serrano *et al.*[43] | 1990 | C | 99.7 | 0.4 | 8 | 273-303 | 0.1 |
| Assael *et al.*[45] | 1991 | VW | 99 | 0.5 | 23 | 303-323 | 0.1-56.3 |
| Yang *et al.*[68] | 2007 | C | 99.5 | 1.0 | 7 | 298-353 | 0.1 |
| Caudwell *et al.*[71] | 2009 | VW | 99 | 2.0 | 81 | 298-473 | 0.1-198.5 |
| Meng *et al.*[88] | 2016 | VW | 99 | 2.0 | 88 | 273-373 | 0.1-30 |

[a] C, capillary; TC, torsional crystal; VW, vibrating wire;
[b] Data below 473 K were excluded from the primary data sets.

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 we only have one set of measurements.
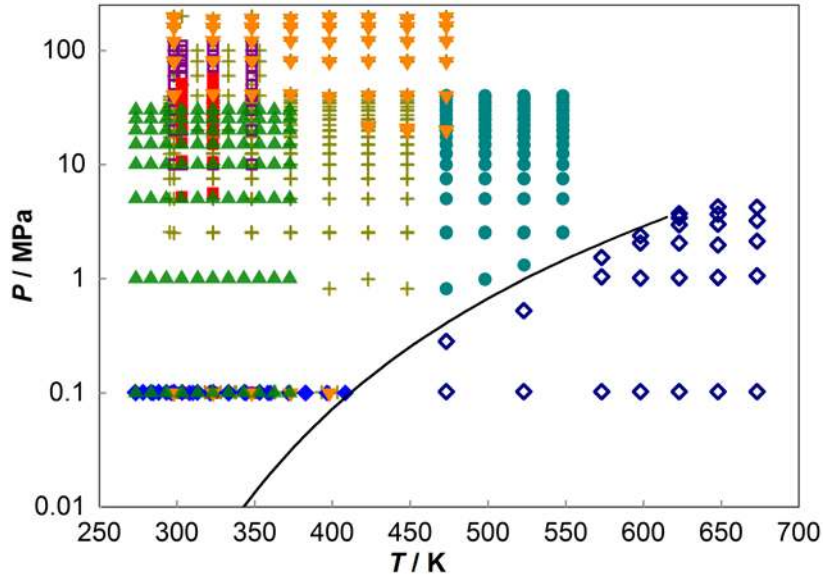
F<small>IG</small>. 1. Distribution of the available experimental viscosity data of *m*-xylene. Primary data: (●) Mamedov *et al.*;[34,35] (□) Kashiwagi and Makita;[38] (◇) Abdullaev and Akhundov;[39] (■) Assael *et al.*;[45] (▼) Caudwell *et al.*;[71] (▲) Meng *et al.*;[88] (◆) data at 0.1 MPa;[23,31,43,68] Secondary data: (+).

Experimental measurements of viscosity are usually reported at a given temperature and pressure. In some cases, experimentally determined densities were also provided. 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. The use of EOS-generated density, rather than the one reported as part of the viscosity measurements, provides an additional level of consistency and further reduces the uncertainty of the developed viscosity correlation. For the purposes of this work we have used a recent EOS developed by Zhou *et al.*[19] that covers the thermodynamic space from the triple point to 700 K, and up to 200 MPa. Uncertainties in density are estimated to be ±0.2 % in the compressed-liquid region and ±1.0 % elsewhere.

### 3. Methodology and Analysis

It is customary[92] 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 $\eta$ as the sum of four contributions,

$$\eta(\rho, T) = \eta_0(T) + \eta_1(T)\rho + \Delta\eta(\rho, T) + \Delta\eta_c(\rho, T) \tag{1}$$

where $\rho$ is the molar density, *T* is the temperature and the different contributions to viscosity, $\eta_0$, $\eta_1$, $\Delta\eta$ 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.[2-18]

### 3.1. The zero-density and initial-density terms

Only one set of measurements of the viscosity of *m*-xylene exists in the vapor phase.[39] It was obtained by Abdullaev and Akhundov[39] in a capillary viscometer, the same instrument that they had employed to measure the viscosity of *p*-xylene. The measurements cover a wide temperature range 473-673 K, but only 7 measurements were performed at sufficiently low pressures (atmospheric pressure or below) to be of use in developing the correlation for the zero-density and initial density viscosity terms. Furthermore, as no experimental data is available at temperatures below 473 K ( $T_r <$ 0.77 ), a large region of vapor phase is inaccessible. Hence, noting the similarities in the critical properties of *m*- and *p*-xylene we made 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 *m*-xylene. The low density correlation, $\eta_0(T) + \eta_1(T)\rho$, for *p*-xylene was based on accurate and extensive data of Vogel and Hendl[93] 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 %. The developed low-density correlation for *p*-xylene,[17] reproduced Vogel and Hendl[93] data to within their experimental uncertainty and more importantly reproduced the Abdullaev and Akhundov data[39] also within their experimental uncertainty. Thus, we have adjusted the *p*-xylene correlation to reproduce the Abdullaev and Akhundov,[39] measurements of *m*-xylene at atmospheric pressure to within the same absolute average deviation (AAD), as was the case for *p*-xylene. The adjustment involved increasing the zero-density viscosity by 0.5 %. As the adjustment is small, the approach was deemed reasonable. Fig. 2 illustrates the deviations of Abdullaev and Akhundov[39] data for two xylene isomers from their respective correlations. It is clear that the developed *m*-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.
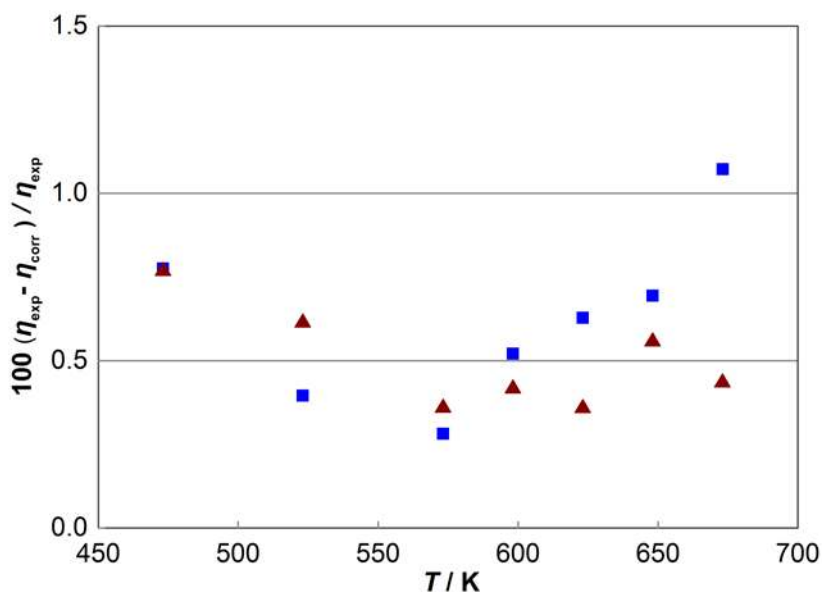


FIG. 2. Percentage deviations [$100(\eta_{exp}-\eta_{corr})/\eta_{exp}$] of the available experimental data of Abdullaev and Akhundov[39] in the vapor phase at 0.1 MPa. (■) *p*-xylene (▲) *m*-xylene.

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]

$$\eta_0(T) = 1.005\eta_{0,p-\text{xylene}} = 0.22115 \frac{\sqrt{T}}{S_\eta}$$

(2)

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

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

(3)

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

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

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

(4)

where $\rho$ 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 $\mu$Pa s $mol^{-1}$ l, $B_1$ = -10862.4 $\mu$Pa s K $mol^{-1}$ l and $C_1$ = 1664060 $\mu$Pa s $K^2$ $mol^{-1}$ 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 *m*-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.[94] 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,[3,5,6,8-13,15-18] the viscosity critical enhancement of *m*-xylene is taken as zero. The total lack of industrial applications of *m*-xylene near its critical temperature and the existence of an only single experimental viscosity datum[39] 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[27,34,35,38,45,47,58,71,88] have measured the viscosity of $m$-xylene at wide range of temperatures and at pressures higher than atmospheric, as illustrated in Fig. 1. We initially considered the data obtained in viscometers capable of producing primary data and supplemented it with the data obtained in other viscometers of proven providence. Based on this analysis, of the measurement techniques and the authors measurements on other fluids, we have chosen 5 datasets as primary in the liquid region. Mamedov and co-workers[34,35] performed the experiments using capillary viscometer with a claimed uncertainty of 1.2 %. Our work on the development of the correlation of $p$-xylene indicates that uncertainty of 2 % would be more appropriate.[17] Kashiwagi and Makita[38] used a torsional crystal viscometer, while Caudwell et al.[71] and Meng et al.[88] used the vibrating wire viscometer. All three sets of authors claimed uncertainty of 2 % which is well-supported by their measurements on other fluids.[15,17-18,71,95] Assael et al.[45] also measured the viscosity of $m$-xylene in the vibrating wire viscometer, but with lower uncertainty of 0.5 %. The primary data in the liquid state, thus covered the temperature range (273 to 548) K and pressures from 0.1 MPa up to 198.5 MPa.

Figures 3-6 illustrate the comparison of high pressure data of different authors that were measured along the same isotherms.
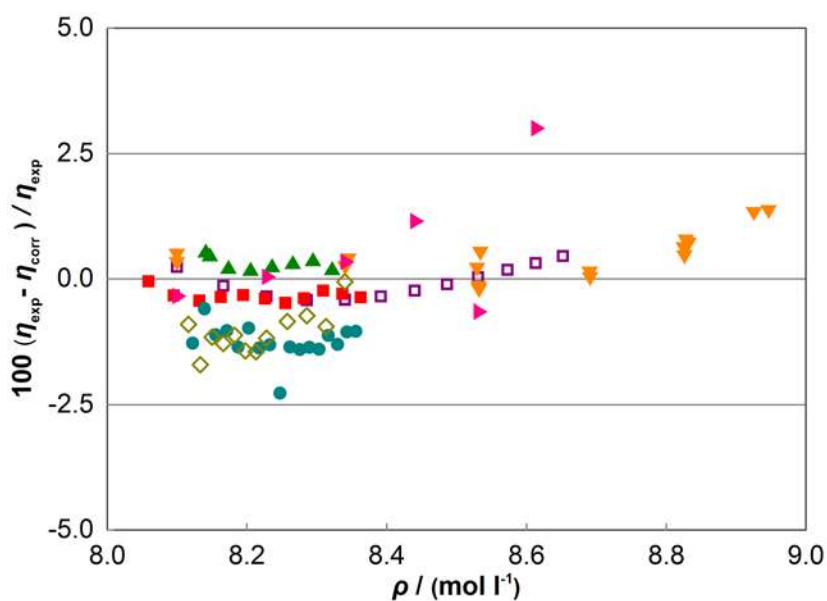


FIG. 3. Comparison of the experimental liquid viscosity data at high pressure at nominal temperature of 298 K. (●) Mamedov et al. (295 K);[34] (◇) Mamedov et al.;[35] (□) Kashiwagi and Makita;[38] (■) Assael et al. (303 K);[45] (▶) Et-Tahir et al.;[47] (▼) Caudwell et al.;[71] (▲) Meng et al. (293 K).[88]
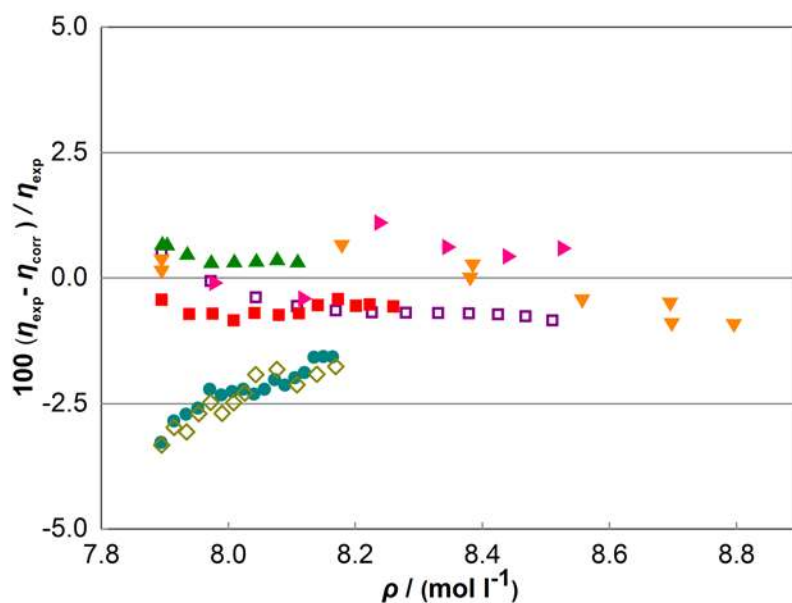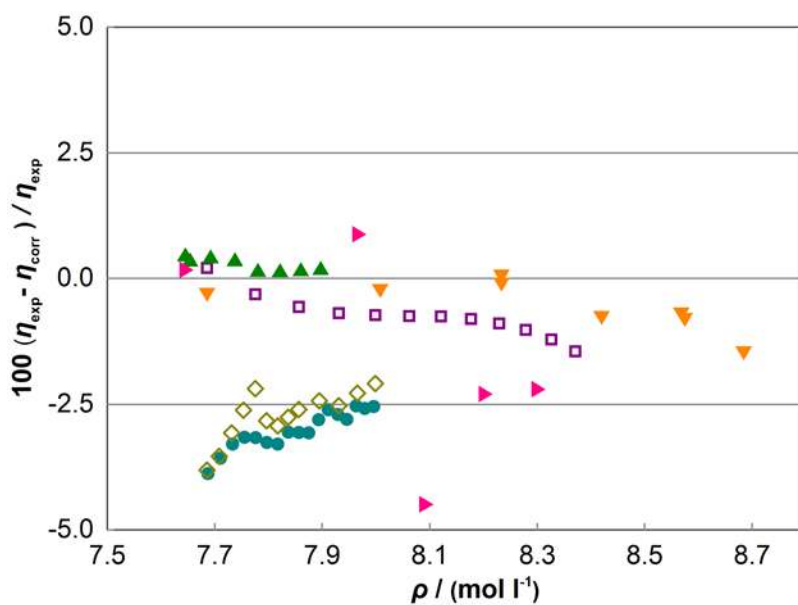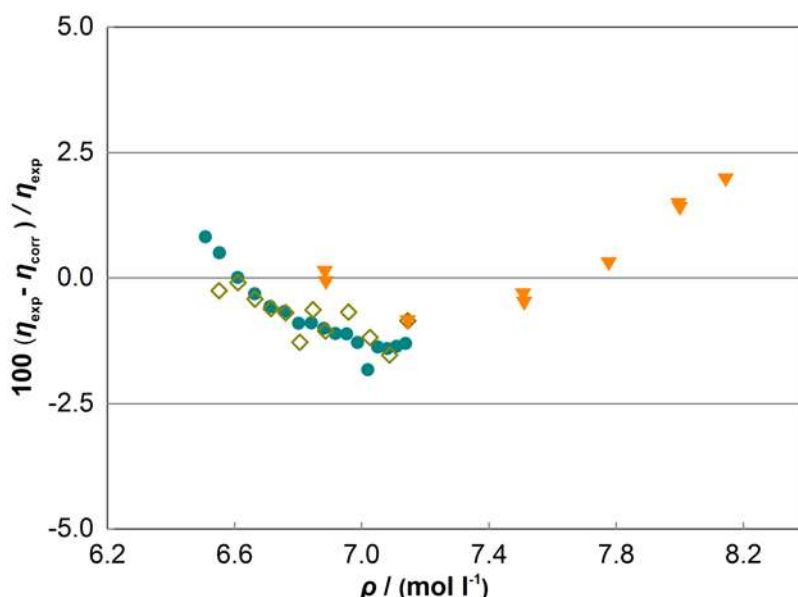
FIG. 4. Comparison of the experimental liquid viscosity data at high pressure at nominal temperature of 323 K. (●) Mamedov et al.;[34] (◇) Mamedov et al.;[35] (□) Kashiwagi and Makita;[38] (■) Assael et al.;[45] (▶) Et-Tahir et al. (313 K);[47] (▼) Caudwell et al.;[71] (▲) Meng et al.[88]



FIG. 5. Comparison of the experimental liquid viscosity data at high pressure at nominal temperature of 348 K. (●) Mamedov et al.;[34] (◇) Mamedov et al.;[35] (□) Kashiwagi and Makita;[38] (▶) Et-Tahir et al. (353 K);[47] (▼) Caudwell et al.;[71] (▲) Meng et al. (353 K).[88]

FIG. 6. Comparison of the experimental liquid viscosity data at high pressure at nominal temperature of 473 K. (●) Mamedov et al.;[34] (◇) Mamedov et al.;[35] (▼) Caudwell et al.[71]

We observe that data of Mamedov et al.[34,35] at temperatures (303 to 373) K lays approximately 2-4 % below the data of other workers, with deviations increasing as we approach the liquid saturation line. Similar qualitative behavior was observed for p-xylene.[17] However at 298 K the Mamedov et al.[34,35] data are consistent with other data, see Figure 3, and at 423 K and 473 K, see Figure 6, the agreement with Caudwell et al.[71] data is within 1-2 %, in the range of pressures where the two sets overlap. The magnitude of the deviations observed for m-xylene indicates that our estimate of uncertainty, based on Mamedov et al.[34,35] measurements for p-xylene of 2 % is optimistic and that a more conservative estimate of 4 % is more appropriate. Rather than use the data of relatively low uncertainty as primary, in the temperature range where plentiful good quality data exists, we have eliminated Mamedov et al.[34,35] data below 473 K from the primary data set. We have however used their data, with new estimate of uncertainty, in high temperature region (473 to 548) K to extend the temperature range of the developed correlation. We also note that the data by Et-Tahir et al.[47] shows, at some isotherms, larger scatter than other available data. So, although we have used Et-Tahir et al. [47] data as primary for the development of p-xylene correlation, for m-xylene we have consigned it to secondary data set, as other more accurate and consistent data are available.

We have also included the data of Abdullaev and Akhundov[39] 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 4.3 MPa. Good agreement of the viscosity data measured by the same authors in the same viscometer for p-xylene indicates that the claimed uncertainty of 1.5 % is justified.

The primary data set also contains 4 sets of viscosity measurements[23,31,43,68] of liquid m-xylene at atmospheric pressure covering the temperature range (273 to 408) K. The choice followed our previous work on p-xylene[17] and was based on careful analysis of the available data that involved: (i) use of viscometer capable of producing primary data set; (ii) low quoted uncertainty that is supported

by other measurements by the same authors; in this instance measurements of viscosity of cyclic and aromatic hydrocarbons[15-18] were used; (iii) large temperature range. We have designated the early *m*-xylene data of Thorpe and Rodger[23] as primary, although up to now most workers classified it as secondary.[16-18,96] Our analysis of their measurements of benzene,[16] *p*-xylene,[17] toluene,[18] and *n*-heptane,[96] 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 from 353 K to 408 K and allowed further comparison with Mamedov data. In summary 427 data points covering the temperature range (273 to 673) K and pressures up to 198.5 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 the recent EOS of Zhou *et al.*[19] 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). The resulting data set, exhibits classical features of the $\eta(T,\rho)$ representation: (i) viscosity increases steeply at temperatures and densities near the solidification line and (ii) there are no data along subcritical isotherms at densities that lie within the two-phase region. As discussed previously[8,15,17] this makes the choice of the functional form to fit the data rather difficult. As a result, a number of existing viscosity correlations exhibit non-monotonic behavior in the two-phase region. This is not surprising as there is no viscosity data at these densities to guide the correlation. Although this is not an issue if one is only interested in the viscosity of a pure substance, it limits the use of such viscosity correlations as a reference equation or to represent a particular species when calculating mixture viscosity. Hence, it precludes their use in corresponding states[92] or in VW models.[97-99]

In this work 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,

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

by taking advantage of the hard sphere result,[100,101] as already used in correlating the viscosity of benzene[16] and *p*-xylene.[17] 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 *m*-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 computing[102] to fit primary data to Eq. (6). The uncertainties quoted in Table 1 were used to determine relative weights for all the primary data, except for Mamedov *et al.*[34,35] were an uncertainty of 4 % was used. The optimal coefficients $D_i$, $E_i$, $k_i$ and $n_i$ are shown in Table 2, while the critical temperature $T_c$ (616.89 K) and critical density $\rho_c$ (2.665 mol l$^{-1}$) were obtained from Ref. 19.

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

| $i$ | $D_i$ | $n_i$ | $E_i$ | $k_i$ |
|---|---|---|---|---|
| 0 | -0.268950 | 6.8 | 0.320971 | 0.3 |
| 1 | -0.0290018 | 3.3 | -- | -- |
| 2 | -- | 22.0 | $1.72866 \times 10^{-10}$ | 3.2 |
| 3 | 14.7728 | 0.6 | -18.9852 | -- |
| 4 | 17.1128 | 0.4 | -- | -- |

Figures 7-8 illustrate the percentage deviation of the primary viscosity data from the developed viscosity correlation, Eqs. (1)-(6). Figure 7 illustrates the agreement with the experimental data in the liquid region for pressures higher than atmospheric. All the experimental data[34,35,38,45,71,88] are reproduced by the proposed correlation within 2.0 %, which is within the claimed experimental uncertainty of most data. The exception is Assael *et al.*[45] data, where the maximum observed deviation of 0.8 % exceeds the claimed experimental uncertainty, but only just.
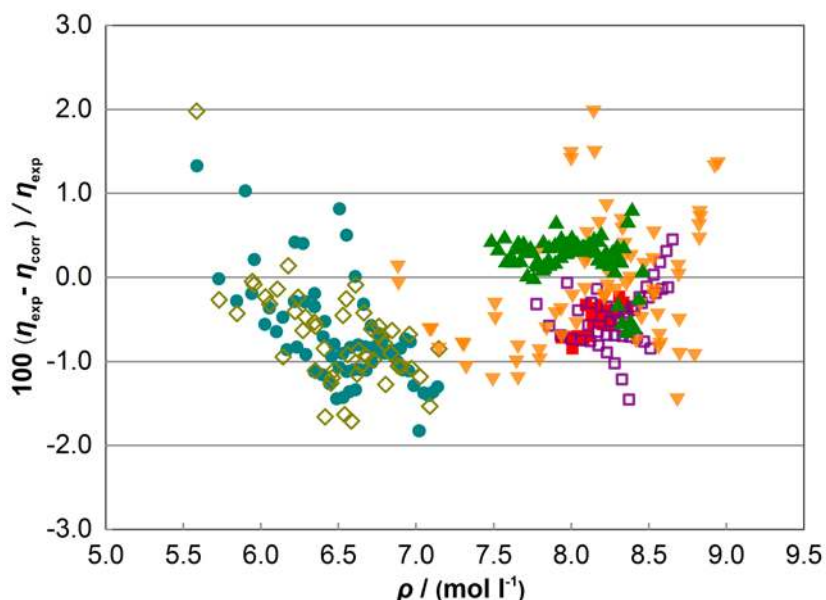


FIG. 7. Percentage deviations [$100(\eta_{exp}-\eta_{corr})/\eta_{exp}$] of the primary experimental viscosity data in the liquid region from the values calculated by Eqs. (1)-(6). (●) Mamedov *et al.*;[34] (◇) Mamedov *et al.*;[35] (□) Kashiwagi and Makita;[38] (■) Assael *et al.*;[45] (▼) Caudwell *et al.*;[71] (▲) Meng *et al.*[88]

Figure 8 illustrates the agreement of the developed viscosity correlation with the primary experimental data at atmospheric pressure that cover the temperature range (273 to 408) K, in the liquid phase. All of the data are reproduced within 1.4 %.
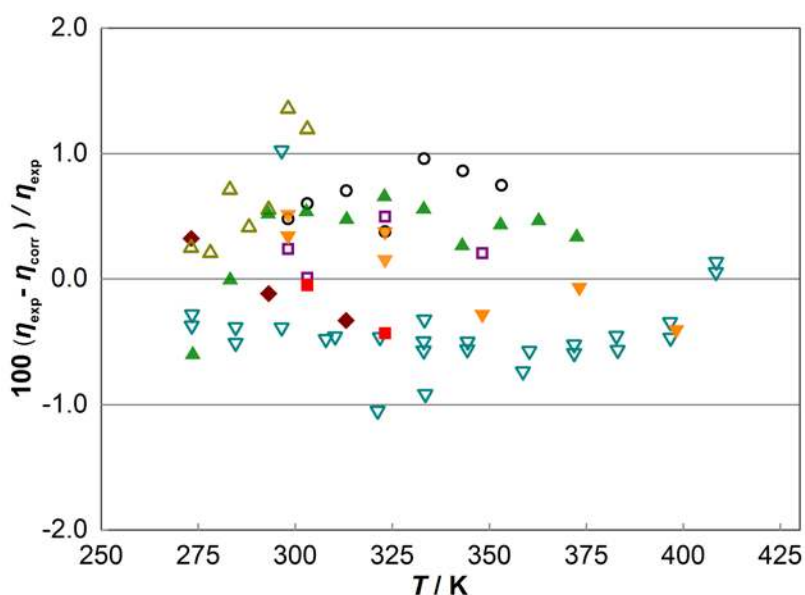


FIG. 8. Percentage deviations [$100(\eta_{exp}-\eta_{corr})/\eta_{exp}$] of the primary experimental viscosity data measured at 0.1 MPa from the calculated values using Eqs. (1)-(6). ($\bigtriangledown$) Thorpe and Rodger;[23] ($\blacklozenge$) Geist and Cannon;[31] ($\square$) Kashiwagi and Makita;[38] ($\triangle$) Serrano et al.;[43] ($\blacksquare$) Assael et al.;[45] ($\bigcirc$) Yang et al.;[68] ($\blacktriangledown$) Caudwell et al.;[71] ($\blacktriangle$) Meng et al.[88]

Table 3 summarizes the agreement between the primary experimental data and the proposed viscosity correlation for m-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 0.6 %, bias of -0.2 % and maximum deviation of -3.0 %. 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 473 K, we estimate the uncertainty to be 2.0 % while for temperatures above 473 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 *m*-xylene viscosity correlation against the primary experimental data.

| Authors | Year publ. | AAD[a] (%) | Bias[b] (%) | MD[c] (%) |
|---|---|---|---|---|
| Thorpe and Rodger[23] | 1894 | 0.5 | -0.4 | -1.0 |
| Geist and Cannon[31] | 1946 | 0.3 | 0.0 | -0.3 |
| Mamedov *et al.*[34] | 1968 | 0.8 | -0.7 | -1.8 |
| Mamedov *et al.*[35] | 1975 | 0.8 | -0.7 | 2.0 |
| Kashiwagi and Makita[38] | 1982 | 0.5 | -0.4 | -1.5 |
| Abdullaev and Akhundov[39] | 1983 | 0.8 | 0.4 | -3.0 |
| Serrano *et al.*[43] | 1990 | 0.8 | 0.8 | 1.4 |
| Assael *et al.*[45] | 1991 | 0.5 | -0.5 | -0.8 |
| Yang *et al.*[68] | 2007 | 0.7 | 0.7 | 1.0 |
| Caudwell *et al.*[71] | 2009 | 0.6 | -0.1 | 2.0 |
| Meng *et al.*[88] | 2016 | 0.3 | 0.2 | 0.8 |
| | | | | |
| **Entire primary data set** | | 0.6 | -0.2 | -3.0 |

[a]AAD, Average Absolute Deviation $= {100}/{N} \Sigma \left| (\eta_{exp} - \eta_{corr})/\eta_{exp} \right|$

[b]Bias $= {100}/{N} \Sigma \left( \eta_{exp} - \eta_{corr} \right)/\eta_{exp}$

[c]MD, Maximum deviation

## 4. Overall Viscosity Correlation

The viscosity correlation of *m*-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 200 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 (225.3 K). 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 9 illustrates the behavior of the viscosity correlation as a function of density along the 300 and 600 K isotherms. We observe a 450 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 1.0 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 hydrocarbons[92] or as part of the VW model[97-99] to predict the viscosity of mixtures containing *m*-xylene.
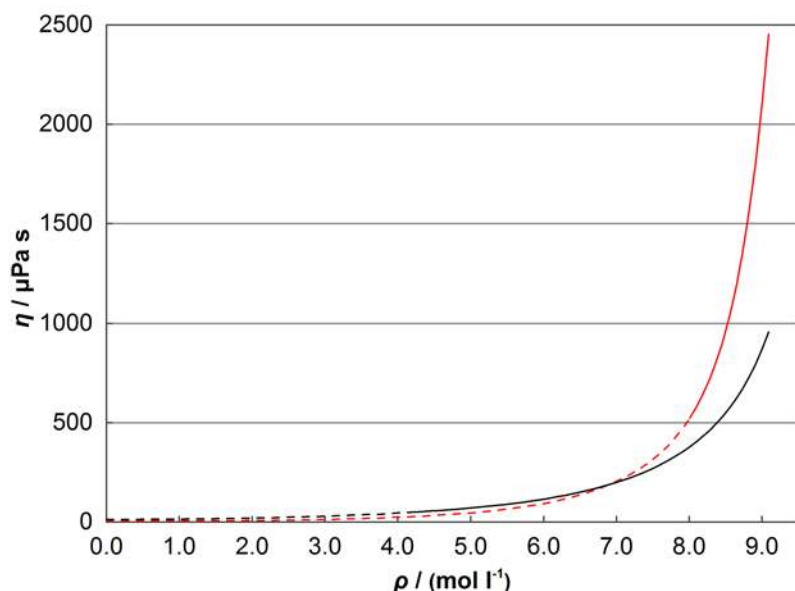
FIG. 9. Viscosity of *m*-xylene as a function of density along a couple of isotherms. (red solid line) 300 K, liquid phase; (red dashed line) 300 K, two-phase region; (black solid line) 600 K, liquid phase; and (black dashed line) 600 K, two-phase region.

Figure 10 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 *m*-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 *m*-xylene along the saturation line.
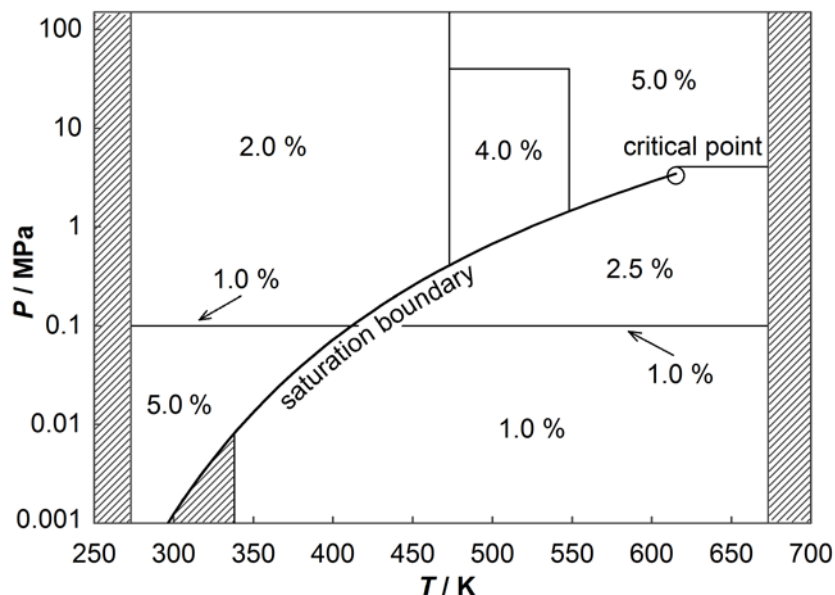


FIG. 10. The extent of the viscosity representation and its estimated uncertainty. No representation is available in the hatched region.

TABLE 4. Recommended viscosity values μPa s

| P | T / K | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MPa | 280 | 300 | 320 | 340 | 360 | 380 | 400 | 450 | 500 | 550 | 600 | 650 |
| 0 | - | - | - | 7.39 | 7.79 | 8.20 | 8.62 | 9.67 | 10.73 | 11.79 | 12.84 | 13.87 |
| 0.1 | 731.0 | 569.7 | 460.3 | 382.0 | 322.9 | 276.4 | 238.8 | 9.67 | 10.76 | 11.83 | 12.89 | 13.93 |
| 0.5 | 733.4 | 571.5 | 461.8 | 383.3 | 324.0 | 277.5 | 239.8 | 170.0 | 10.83 | 11.96 | 13.06 | 14.13 |
| 1 | 736.4 | 573.8 | 463.7 | 384.9 | 325.5 | 278.9 | 241.1 | 171.2 | 122.5 | 12.13 | 13.27 | 14.36 |
| 2 | 742.3 | 578.4 | 467.5 | 388.1 | 328.3 | 281.5 | 243.6 | 173.6 | 125.0 | 87.25 | 13.82 | 14.86 |
| 4 | 754.3 | 587.6 | 475.0 | 394.5 | 334.1 | 286.8 | 248.6 | 178.3 | 129.8 | 93.31 | 60.21 | 17.73 |
| 6 | 766.4 | 596.9 | 482.5 | 400.9 | 339.8 | 292.0 | 253.5 | 182.8 | 134.4 | 98.61 | 69.00 | 39.84 |
| 8 | 778.5 | 606.2 | 490.1 | 407.4 | 345.5 | 297.2 | 258.4 | 187.2 | 138.8 | 103.4 | 75.44 | 51.43 |
| 10 | 790.7 | 615.6 | 497.6 | 413.8 | 351.2 | 302.4 | 263.2 | 191.6 | 143.0 | 107.9 | 80.83 | 58.82 |
| 20 | 853.5 | 663.4 | 535.9 | 446.0 | 379.3 | 327.8 | 286.6 | 212.3 | 162.4 | 127.2 | 101.2 | 81.67 |
| 50 | 1057.3 | 816.3 | 656.2 | 544.8 | 463.7 | 402.2 | 353.9 | 268.4 | 212.1 | 172.6 | 143.9 | 122.5 |
| 100 | 1458.4 | 1111.7 | 883.0 | 725.8 | 613.4 | 529.9 | 465.7 | 355.5 | 285.0 | 235.9 | 199.9 | 172.8 |
| 150 | 1949.0 | 1468.9 | 1152.5 | 936.1 | 782.9 | 670.6 | 585.6 | 443.3 | 355.1 | 294.5 | 250.3 | 216.8 |
| 200 | 2541.9 | 1898.8 | 1473.6 | 1183.4 | 979.0 | 830.3 | 719.0 | 536.4 | 426.4 | 352.6 | 299.2 | 258.7 |

TABLE 5. Recommended viscosity values along the saturation line

| T/K | $P_V$/MPa | Vapor | | Liquid | |
|---|---|---|---|---|---|
| | | $\rho$/(mol l$^{-1}$) | $\eta$/(μPa s) | $\rho$/(mol l$^{-1}$) | $\eta$/(μPa s) |
| 273.15 | 0.0002 | 0.0001 | - | 8.2997 | 803.8 |
| 293.15 | 0.0008 | 0.0003 | - | 8.1396 | 617.1 |
| 313.15 | 0.0025 | 0.0010 | - | 7.9769 | 493.1 |
| 333.15 | 0.0066 | 0.0024 | - | 7.8113 | 405.9 |
| 353.15 | 0.0151 | 0.0052 | 7.65 | 7.6421 | 341.2 |
| 373.15 | 0.0312 | 0.0102 | 8.05 | 7.4687 | 291.0 |
| 393.15 | 0.0590 | 0.0186 | 8.46 | 7.2903 | 250.8 |
| 413.15 | 0.1039 | 0.0316 | 8.87 | 7.1056 | 217.6 |
| 433.15 | 0.1722 | 0.0510 | 9.30 | 6.9134 | 189.7 |
| 453.15 | 0.2713 | 0.0788 | 9.74 | 6.7118 | 165.9 |
| 473.15 | 0.4093 | 0.1175 | 10.20 | 6.4982 | 145.3 |
| 493.15 | 0.5953 | 0.1706 | 10.69 | 6.2694 | 127.3 |
| 513.15 | 0.8392 | 0.2428 | 11.21 | 6.0203 | 111.3 |
| 533.15 | 1.1518 | 0.3416 | 11.79 | 5.7433 | 96.85 |
| 553.15 | 1.5456 | 0.47916 | 12.47 | 5.4256 | 83.42 |

Figure 11 summarize 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 12 exhibits the only three sets of secondary experimental data that extend to higher pressure. The deviation of data of Bridgman[27] display the AAD of 1.5 %, which is in agreement with what we observed for *p*-xylene. The data of Et-Tahir *et al.*[47] display large scatter with maximum deviation of -4.5 %, while the data of Mamedov *et al.*[34,35] display systematic trends at certain temperatures with maximum deviation of -3.8 %.
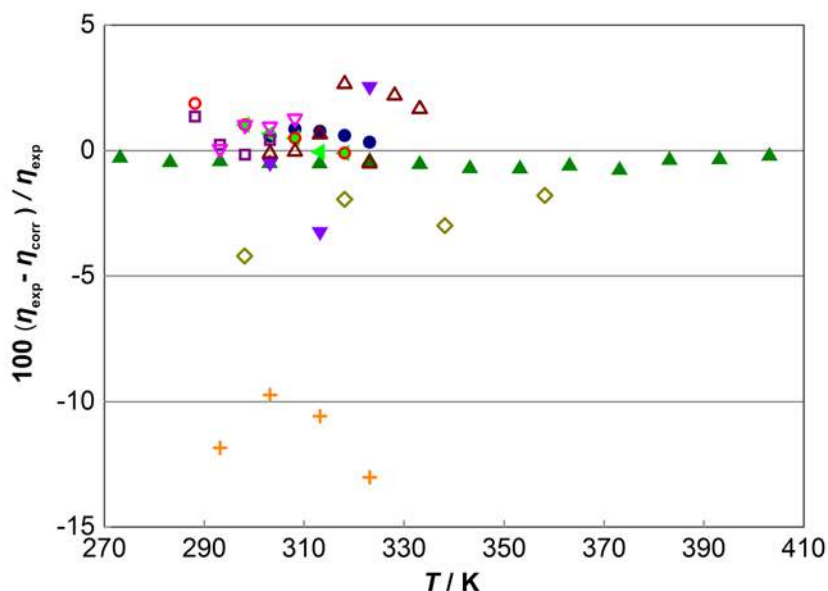
FIG. 11. Percentage deviations [100($\eta_{exp}$-$\eta_{corr}$)/$\eta_{exp}$] of the selected secondary experimental viscosity data measured at 0.1 MPa from the calculated values using Eqs. (1) - (6). (▲) Batschinski;[24] (◇) Oshmyansky et al.;[41] (▽) Moumouzias et al.;[51] (▼) Prasad et al.;[52] (●) Saleh et al.;[62] (◄) Ali et al.[65] (□) Al-Kandary et al.;[66] (○) Nain et al.;[67] (△) Song et al.;[70] (+) Dikio et al.[85,87]
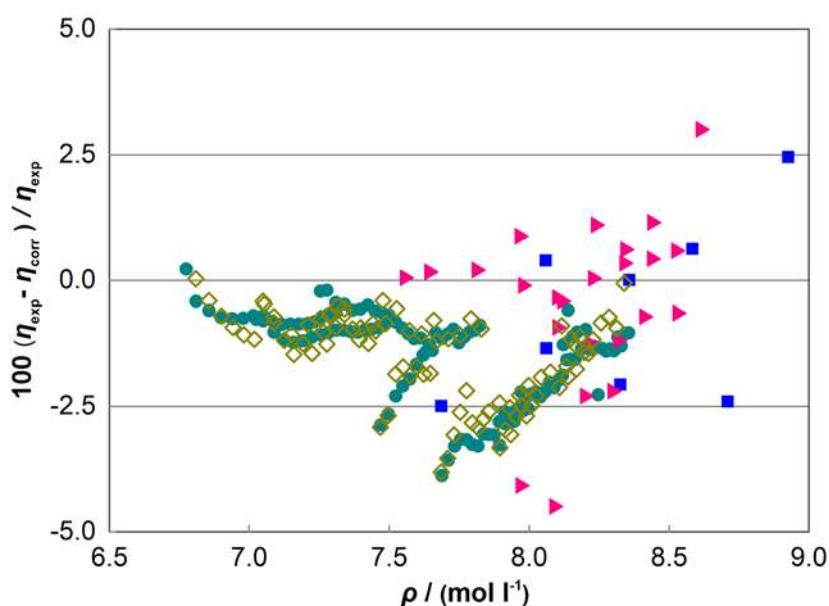


FIG. 12. Percentage deviations [100($\eta_{exp}$-$\eta_{corr}$)/$\eta_{exp}$] of the selected secondary experimental viscosity data at high pressures from the calculated values using Eqs. (1) - (6). (■) Bridgman;[27] (●) Mamedov et al.;[34] (◇) Mamedov et al.;[35] (►) Et-Tahir et al.[47]

Although no other viscosity correlation of *m*-xylene is available in open literature there are a couple of tables of recommended values[89,90] and Yaws recommended equation[22] all for liquid viscosity at atmospheric pressure. The agreement between the tabulated values of Golubev[89] and NIST/TRC database[90] and the present correlation is very good and the deviations do not exceed ±1 %. However, the Yaws proposed equation[22] for the liquid viscosity shows large deviations from the current

correlation with a systematic trend extending from -4.6 % to 4.6 % in the temperature range (273 to 403) 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

| $T$ | $\rho$ | $\eta$ |
|---|---|---|
| (K) | (mol l$^{-1}$) | (µPa s) |
| 300 | 0 | 6.637 |
| 300 | 0.0400 | 6.564 |
| 300 | 8.0849 | 569.680 |
| 300 | 8.9421 | 1898.841 |
| 400 | 0 | 8.616 |
| 400 | 0.0400 | 8.585 |
| 400 | 7.2282 | 238.785 |
| 400 | 8.4734 | 718.950 |
| 600 | 0 | 12.841 |
| 600 | 0.0400 | 12.936 |
| 600 | 7.6591 | 299.164 |


## 6. Conclusion

A new wide-ranging correlation for the viscosity of *m*-xylene has been developed based on critically-evaluated experimental data. The correlation is valid to pressures up to 200 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.*[19] 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 Figure 10.


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# Appendix A - Viscosity measurements of *m*-xylene

| Authors | Year publ. | Technique employed[a] | No. of data | Temperature range (K) | Pressure range (MPa) |
|---|---|---|---|---|---|
| Thorpe and Rodger[23] | 1894 | C | 26 | 273-408 | 0.1 |
| Batschinski[24] | 1913 | C | 14 | 273-403 | 0.1 |
| Kremann *et al.*[25] | 1914 | C | 2 | 285-337 | 0.1 |
| Miller[26] | 1924 | - | 2 | 283-293 | 0.1 |
| Bridgman[27] | 1926 | FB | 12 | 303-348 | 0.1-800 |
| Timmermans and Hennaut-Roland[28] | 1930 | C | 2 | 298-303 | 0.1 |
| De Carli[29] | 1931 | C | 2 | 293-303 | 0.1 |
| Houseman and Keulegan[30] | 1931 | C | 2 | 298-303 | 0.1 |
| Geist and Cannon[31] | 1946 | C | 3 | 273-313 | 0.1 |
| Teitel'baum *et al.*[32] | 1950 | - | 1 | 293 | 0.1 |
| Petro and Smyth[33] | 1957 | C | 3 | 293-333 | 0.1 |
| Mamedov *et al.*[34] | 1968 | C | 186 | 295-548 | 0.1-39.3 |
| Mamedov *et al.*[35] | 1975 | C | 136 | 295-548 | 0.1-40 |
| Dhillon and Chugh[36] | 1976 | C | 2 | 298-308 | 0.1 |
| 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 | 0.1-4.3 |
| Al-Madfai *et al.*[40] | 1985 | C | 1 | 298 | 0.1 |
| Oshmyansky *et al.*[41] | 1986 | C | 4 | 298-358 | 0.1 |
| Ramanjaneyulu *et al.*[42] | 1987 | C | 1 | 303 | 0.1 |
| Serrano *et al.*[43] | 1990 | C | 8 | 273-303 | 0.1 |
| Schumpe andLuehring[44] | 1990 | C | 1 | 293 | 0.1 |
| Assael *et al.*[45] | 1991 | VW | 23 | 303-323 | 0.1-56.3 |
| Aralaguppi *et al.*[46] | 1992 | C | 3 | 298-308 | 0.1 |
| Et-Tahir *et al.*[47] | 1995 | C | 5 | 298-363 | 0.1 |
| Et-Tahir *et al.*[47] | 1995 | FB | 19 | 298-353 | 0.1-100 |
| Ramachandran *et al.*[48] | 1995 | C | 1 | 303 | 0.1 |
| Singh *et al.*[49] | 1995 | C | 1 | 298 | 0.1 |
| Goud *et al.*[50] | 1999 | C | 1 | 308 | 0.1 |
| Moumouzias *et al.*[51] | 1999 | C | 4 | 293-308 | 0.1 |
| Prasad *et al.*[52] | 1999 | FB | 4 | 293-323 | 0.1 |
| Wegner *et al.*[53] | 1999 | - | 1 | 298 | 0.1 |
| Katritzky *et al.*[54] | 2000 | - | 1 | 293 | 0.1 |
| Gupta and Singh[55] | 2001 | C | 1 | 298 | 0.1 |
| George and Sastry[56] | 2003 | C | 2 | 298-308 | 0.1 |
| Lark *et al.*[57] | 2003 | C | 2 | 298-303 | 0.1 |
| Caudwell[58] | 2004 | VW | 114 | 298-473 | 0.1-198.5 |
| Singh *et al.*[59] | 2004 | C | 1 | 298 | 0.1 |
| Yang *et al.*[60] | 2004 | C | 3 | 298-323 | 0.1 |
| Rathnam *et al.*[61] | 2005 | C | 2 | 303-313 | 0.1 |

| | | | | | |
|---|---|---|---|---|---|
| Saleh et al.[62] | 2005 | C | 5 | 303-323 | 0.1 |
| Singh et al.[63] | 2005 | C | 1 | 298 | 0.1 |
| Ali et al.[64] | 2006 | C | 1 | 308 | 0.1 |
| Ali et al.[65] | 2006 | C | 5 | 298-318 | 0.1 |
| Al-Kandary et al.[66] | 2006 | RC | 4 | 288-303 | 0.1 |
| Nain et al.[67] | 2007 | C | 4 | 288-318 | 0.1 |
| Yang et al.[68] | 2007 | C | 7 | 298-353 | 0.1 |
| Rathnam et al.[69] | 2008 | C | 1 | 303 | 0.1 |
| Song et al.[70] | 2008 | C | 7 | 303-333 | 0.1 |
| Caudwell et al.[71] | 2009 | VW | 81 | 298-473 | 0.1-198.5 |
| Das et al.[72] | 2009 | C | 3 | 303-323 | 0.1 |
| Dominguez-Perez et al.[73] | 2009 | C | 1 | 298 | 0.1 |
| Nain et al.[74] | 2009 | C | 1 | 298 | 0.1 |
| Rathnam et al.[75] | 2009 | C | 2 | 303-313 | 0.1 |
| Sastry et al.[76] | 2009 | C | 2 | 298-308 | 0.1 |
| Yang et al.[77] | 2009 | C | 3 | 298-318 | 0.1 |
| Habibullah et al.[78] | 2010 | C | 2 | 308-318 | 0.1 |
| Rathnam et al.[79] | 2010 | C | 2 | 303-313 | 0.1 |
| Bhatia et al.[80] | 2011 | C | 2 | 298-308 | 0.1 |
| Rathnam et al.[81] | 2011 | C | 2 | 303-313 | 0.1 |
| Hamzehlouia and Asfour[82] | 2012 | C | 2 | 308-313 | 0.1 |
| Zarei and Salami[83] | 2012 | C | 1 | 298 | 0.1 |
| Bhalodia and Sharma[84] | 2013 | C | 3 | 303-313 | 0.1 |
| Dikio et al.[85] | 2013 | RC | 4 | 293-323 | 0.1 |
| Hamzehlouia and Asfour[86] | 2013 | C | 2 | 308-313 | 0.1 |
| Dikio[87] | 2014 | RC | 4 | 293-323 | 0.1 |
| Meng et al.[88] | 2016 | VW | 88 | 273-373 | 0.1-30 |
| | | | | | |
| **Tables of collected data** | | | | | |
| Golubev[89] | 1970 | - | 14 | 273-403 | 0.1 |
| NIST/TRC database 2008[90] | 2003 | - | 29 | 273-413 | 0.1 |

[a] C, capillary; FB, falling body; TC, torsional crystal; VW, vibrating wire; RB, rolling body; RC, rotating cylinder.