

Reference Correlation of the Viscosity of Toluene from the Triple Point to 675 K and up to 500 MPa

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S. Avgeri, M. J. Assael, M. L. Huber, and R. A. Perkins



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Reference Correlation of the Viscosity of Toluene from the Triple Point to 675 K and up to 500 MPa

S. Avgeri and M. J. Assael^{a)}

Laboratory of Thermophysical Properties and Environmental Processes, Chemical Engineering Department, Aristotle University, Thessaloniki 54124, Greece

M. L. Huber and R. A. Perkins

Applied Chemicals and Materials Division, National Institute of Standards and Technology, 325 Broadway, Boulder, Colorado 80305, USA

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This paper contains new, representative reference equations for the viscosity of toluene. The equations are based in part upon a body of experimental data that have been critically assessed for internal consistency and for agreement with theory whenever possible. The correlations are valid from the triple point (178.0 K) to 675 K, and at pressures up to 500 MPa. The estimated uncertainty at a 95% confidence level varies depending on the region of temperature and pressure from a low of 0.3% for the low-density gas at temperatures from 305 to 640 K at pressures to 0.3 MPa (essentially the uncertainty of the best experimental data) to 0.7% for the saturated liquid at temperatures from 263 to 373 K, to 5% for the low-temperature liquid from 187 to 210 K at pressures to 15 MPa. © 2015 by the U.S. Secretary of Commerce on behalf of the United States. All rights reserved. [<http://dx.doi.org/10.1063/1.4926955>]

Key words: reference correlation; toluene; transport properties; viscosity.

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^{a)}Author to whom correspondence should be addressed; electronic mail: assael@auth.gr.

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1. Introduction

In a series of recent papers, new reference correlations for the thermal conductivity of a series of fluids^{1–9} and the viscosity of water,¹⁰ *n*-hexane,¹¹ *n*-heptane,¹² and benzene¹³ covering a wide range of conditions of temperature and pressure were reported. In this paper, the methodology adopted for the viscosity of *n*-hexane,¹¹ *n*-heptane,¹² and benzene¹³ is extended to developing a new reference correlation for the viscosity of toluene.

Toluene was the first viscosity reference liquid to be proposed (after water), as it is widely used as a basic compound for chemical synthesis and as an organic solvent. Furthermore, its unusually wide temperature range in the liquid phase (178 to 384 K) makes it an ideal reference liquid for viscosity calibration purposes and apparatus validation. Thus in 2001, under the auspices of the Subcommittee on Transport Properties (presently known as the International Association for Transport Properties) of the International Union of Pure and Applied Chemistry (IUPAC), a correlation for the viscosity of liquid toluene as a function of temperature and density was proposed by Assael *et al.*¹⁴ The temperature range covered was from 213 to 373 K, and the pressure range from atmospheric up to 250 MPa. The standard deviation of the proposed correlation was 2.7% (within a 95% confidence limit). In the same paper, following a critical assessment of density measurements, a density correlation was also proposed.

In 2006, a new correlation for the viscosity of liquid toluene along the saturation line was published by Vieira dos Santos *et al.*¹⁵ Recommended values were proposed with uncertainties of 0.5% (at the 95% confidence level) for temperatures from 260 to 370 K, and 2% for 210 to 260 K and 370 to 400 K. Furthermore, the value of (554.2 ± 3.3) $\mu\text{Pa s}$ was proposed for the viscosity of liquid toluene at 298.15 K and 0.1 MPa.

In 2006, an equation of state for toluene was published by Lemmon and Span,¹⁶ thus making possible the development of a wide-range viscosity correlation for toluene. Hence, in this work, based on critically assessed literature data, a new wide-ranging correlation for the viscosity of toluene valid not only for the liquid phase as the aforementioned two correlations, but also over gas, liquid, and supercritical states, is proposed.

The new correlation incorporates densities provided by the equation of state of Lemmon and Span,¹⁶ and is consistent with our recent reference correlation for the thermal conductivity of toluene,³ published in 2012.

2. Methodology

The viscosity η can be expressed^{11–13,17} as the sum of four independent contributions, as

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

where ρ is the molar density, T is the absolute temperature, and the first term, $\eta_0(T) = \eta(0, T)$, is the contribution to the viscosity in the dilute-gas limit, where only two-body molecular interactions occur. The linear-in-density term, $\eta_1(T)\rho$, known as the initial density dependence term, can be separately established with the development of the Rainwater-Friend theory^{17–19} for the transport properties of moderately dense gases. The critical enhancement term, $\Delta\eta_c(\rho, T)$, arises from the long-range density fluctuations that occur in a fluid near its critical point, which contributes to divergence of the viscosity at the critical point. Finally, $\Delta\eta(\rho, T)$, the residual term, represents the contribution of all other effects to the viscosity of the fluid at elevated densities including many-body collisions, molecular-velocity correlations, and collisional transfer.

The identification of these four separate contributions to the viscosity and to transport properties in general is useful because it is possible, to some extent, to treat $\eta_0(T)$, $\eta_1(T)$, and $\Delta\eta_c(\rho, T)$ theoretically. In addition, it is possible to derive information about both $\eta_0(T)$ and $\eta_1(T)$ from experiment. In contrast, there is little theoretical guidance concerning the residual contribution, $\Delta\eta(\rho, T)$, and therefore its evaluation is based entirely on an empirical equation obtained by fitting experimental data.

The analysis described above should be applied to the best available experimental data for the viscosity. Thus, a prerequisite to the analysis is a critical assessment of the experimental data. For this purpose, two categories of experimental data are defined: primary data, employed in the development of the correlation, and secondary data, used simply for comparison purposes. According to the recommendation adopted by the Subcommittee on Transport Properties (now known as The International Association for Transport Properties) of IUPAC, the primary data are identified by a well-established set of criteria.²⁰ These criteria have been successfully employed to establish standard reference values for the viscosity and thermal conductivity of fluids over wide ranges of conditions, with uncertainties in the range of 1%. However, in many cases, such a narrow definition unacceptably limits the range of 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 a poorer accuracy, provided they are consistent with other more accurate data or with theory. In all cases, the accuracy claimed for the final recommended data must reflect the estimated uncertainty in the primary information.

3. The Correlation

Table 1 summarizes, to the best of our knowledge, the experimental measurements^{21–214} of the viscosity of toluene including sample purity and the uncertainties ascribed by the original authors. One hundred and ninety four sets are included in the table. From these sets, 26 were considered as primary data. These can be discussed in four categories.

- (a) Measurements employed in the 2001 viscosity reference correlation of Assael *et al.*¹⁴ (temperature range covered was from 213 to 373 K, and pressure range from atmospheric up to 250 MPa).

These measurements constitute part of our primary data and in Table 1 they are designated by a superscript “c” after the first author’s name (Harris,²⁸ Assael *et al.*,²⁹ Dymond and Simoiu,³⁰ Vieira dos Santos and Nieto de Castro,³¹ Krall and Sengers,³² Oliveira and Wakeham,³³ Assael *et al.*,³⁵ Dymond *et al.*,³⁶ Kaiser *et al.*,³⁷ Goncalves *et al.*,³⁹ Dymond and Robertson,⁴⁰ Bauer and Mehlender,⁴¹ and Kashiwagi and Makita⁴³).

- (b) Measurements employed in the 2006 viscosity reference correlation of Vieira dos Santos *et al.*¹⁵ along the saturation line (temperature range covered was from 210 to 400 K).

These measurements also constitute part of our primary data and in Table 1 they are designated by a superscript “b” after the first author’s name (Froba and Leipertz,²⁷ Assael *et al.*,²⁹ Dymond and Simoiu,³⁰ Krall and Sengers,³² Dymond *et al.*,³⁶ Kaiser *et al.*,³⁷ Goncalves *et al.*,³⁹ Dymond and Robertson,⁴⁰ and Bauer and Mehlender⁴¹).

- (c) New measurements taken after the publication of the aforementioned two correlations.

The measurements of Caetano *et al.*²⁵ and Avelino *et al.*²⁶ were both obtained in vibrating-wire instruments and extended to low temperatures and moderate pressures. These measurements, obtained with 1.5% and 2% uncertainty (rising to 3% at the lowest temperatures) correspondingly, were backed by a full theory and were thus included in the primary data set. The measurements of Meng *et al.*²¹ were also performed in a vibrating-wire instrument, the measurements of Baylaucq *et al.*²² in a falling-body instrument and a capillary viscometer, while Pensado *et al.*²⁴ employed a rolling-ball viscometer. The last three sets quote an uncertainty of 2%. Measurements from these three groups have been employed successfully in previous reference correlations, and thus are also included in the present correlation but with slightly inferior weight.

- (d) Other measurements that extend the temperature and pressure ranges of the two previous reference correlations.

The measurements of Vogel and Hendl³⁴ were performed in an oscillating-disk instrument in the vapor phase with an uncertainty of 0.15% at room temperature, rising to 0.3% at the highest temperatures. These are absolute measurements, backed by a full theory. Furthermore, measurements from this research group have been the basis of the vapor-phase correlation of many viscosity reference correlations. Hence, these measurements are part of the primary data set.

Two publications in Table 1 contain data that extend below 200 K. The measurements of Barlow *et al.*⁴⁶ were performed in a capillary viscometer with a 1% uncertainty, while the measurements of Karbanov and Geller,⁴⁴ also in a capillary viscometer, were performed with a 1.8% uncertainty. Both these sets are well documented and formed part of the primary data set.

In relation to higher temperatures, there are three publications in Table 1, all by the same group:

- (1) Akhundov *et al.*⁴⁵ in 1970 published measurements of the viscosity of toluene extending up to 548 K and 40 MPa,
- (2) Akhundov *et al.*⁴² in 1983 published measurements of the viscosity of toluene extending up to 673 K and 399 MPa, and,
- (3) Akhundov *et al.*,³⁸ in 1989, published 111 viscosity measurements very near the critical point, from 594 to 603 K. However, the apparent enhancements of these measurements do not make physical sense in the critical region, so only the isotherm at 603.15 K (where the enhancement is not apparent) was employed.

These three sets of measurements were also included in the primary data set, but with a reduced weight. The measurements of Fang *et al.*²³ were performed in a rolling-ball viscometer up to 473 K with a quoted uncertainty of 0.8%; these measurements also formed part of the primary data set, but with inferior weight.

Figures 1 and 2 show the ranges of the primary measurements outlined in Table 1, and the phase boundary may be seen in Fig. 2 as well. Temperatures for all data were converted to the ITS-90 temperature scale.²¹⁵ The development of the correlation requires densities; Lemmon and Span¹⁶ in 2006 reviewed the thermodynamic properties of toluene and developed an accurate, wide-ranging equation of state up to 675 K and 500 MPa. The approximate uncertainties of the density calculated with this equation are 0.05% in the liquid state below 540 K, 0.5% up to the critical temperature, 1% at higher temperatures, 0.5% at pressures from 100 to 500 MPa, and 0.2% in the vapor phase. The uncertainty for the saturated liquid density is as low as 0.01% at temperatures near 300 K. The uncertainty in heat capacities is generally 0.5% and rises to 3% in the critical region. We also adopt the values for the critical point and triple point employed in their equation of state; the critical temperature, T_c , and the critical density, ρ_c , were taken to be equal to 591.75 K and 291.987 kg m⁻³, respectively. The triple-point temperature is 178 K.

3.1. The dilute-gas limit and the initial-density dependence terms

The dilute-gas limit viscosity, $\eta_0(T)$ in $\mu\text{Pa s}$, can be analyzed independent of all other contributions in Eq. (1). According to the kinetic theory, the viscosity of a pure polyatomic gas may be related to an effective collision cross section, which contains all the dynamic and statistical information about the binary collision. For practical purposes, this relation is formally identical to that of monatomic gases

TABLE 1. Viscosity measurements of toluene

First author	Year of publication	Technique employed ^a	Purity (%)	Uncertainty (%)	No. of data	Temperature range (K)	Pressure range (MPa)
Primary data							
Meng ²¹	2013	VW	99.50	2	25	273–363	1–30
Baylaucq ²²	2009	FB/Cap	99.90	2	24	293–353	0.1–100
Fang ²³	2008	RB	99.95	0.8	20	313–473	0.1–3.2
Pensado ²⁴	2005	RB	99.80	2	84	303–353	0.1–60
Caetano ²⁵	2004	VW	99.80	1.5	79	213–298	0.1–20
Avelino ²⁶	2003	VW	99.80	2–3	54	248–323	0.1–80
Froba ^{27,b}	2003	SLS	99.90	1	13	263–383	0.0005–0.1
Harris ^{28,c}	2000	FB	99.80	1	196	255–323	0.1–400
Assael ^{29,b,c}	1999	VW	99.90	0.5	107	210–370	0.1–24
Dymond ^{30,b,c}	1998	Cap	99.90	0.5–2	10	259–318	0.1
Vieira dos Santos ^{31,c}	1997	OQ	99.99	0.5	31	298–348	0.1–207
Krall ^{32,b,c}	1992	OD	99.90	0.5	60	298–426	0.1–30
Oliveira ^{33,c}	1992	VW	99.95	0.5	46	303–348	0.1–252
Vogel ³⁴	1992	OD	99.99	0.15–0.3	99	305–630	0.005–0.23
Assael ^{35,c}	1991	VW	99.50	0.5	34	303–323	0.1–71
Dymond ^{36,b,c}	1991	FB	99.90	4	40	298–373	0.1–519
Kaiser ^{37,b,c}	1991	Cap	99.00	1.38	18	218–378	0.1
Akhundov ³⁸	1989	Cap	99.98	1.5–5	16	603	1.4–39.3
Goncalves ^{39,b,c}	1987	Cap	99.90	0.3	6	298–345	0.1
Dymond ^{40,b,c}	1985	Cap	99.95	0.5	7	288–393	0.1–0.13
Bauer ^{41,b,c}	1984	Cap	99.50	0.2	3	293–298	0.1
Akhundov ⁴²	1983	Cap	99.98	2–4	129	383–673	0.1–399
Kashiwagi ^{43,c}	1982	OQ	99.00	2	28	298–348	0.1–110
Karbanov ⁴⁴	1975	Cap	High purity	1.8	63	194–363	0.1–50
Akhundov ⁴⁵	1970	FB	99.96	1.2	153	297–548	0.1–40
Barlow ⁴⁶	1966	Cap	na	1	7	187–303	0.1
Secondary data							
Prak ⁴⁷	2014	RCC	99.7	1.7	7	293–363	0.1
Vijayalakshmi ⁴⁸	2014	Cap	99.7	1	2	303–313	0.1
Assael ⁴⁹	2013	VW	99.9	0.5	24	293–332	0.1–18
Bhalodia ⁵⁰	2013	Cap	99.00	0.1	3	303–313	0.1
Narendra ⁵¹	2012	Cap	na	0.2	4	303–318	0.1
Sarkar ⁵²	2012	Cap	99	0.6	1	298	0.1
Yadava ⁵³	2012	Cap	99	na	2	303–308	0.1
Daridon ⁵⁴	2011	OQ	99.50	5	30	293–332	0.1–80
Meng ⁵⁵	2011	VW	99.50	2.8	24	248–348	1–40
Pradhan ⁵⁶	2011	Cap	na	0.03	1	298	0.1
Yadava ⁵⁷	2011	Cap	99	na	1	308	0.1
Dubey ⁵⁸	2010	Cap	na	0.54	1	298	0.1
Rajagopal ⁵⁹	2010	Cap	99.7	1	3	298–308	0.1
Rajagopal ⁶⁰	2010	Cap	na	na	3	298–308	0.1
El-Sayed ⁶¹	2009	Cap	99.04	0.35	2	308–313	0.1
Sastry ⁶²	2009	Cap	99.98	0.57	2	298–308	0.1
Silva ⁶³	2009	RCC	99	1	5	283–323	0.1
Alonso ⁶⁴	2008	Cap	99.50	0.5	1	298	0.1
Awwad ⁶⁵	2008	Cap	99.00	0.61	4	298–323	0.1
Baskaran ⁶⁶	2008	Cap	99.50	0.05	1	298	0.1
Song ⁶⁷	2008	Cap	99.5	0.6	7	303–333	0.1
Hasan ⁶⁸	2007	Cap	99.50	0.57	2	298–308	0.1
Nain ⁶⁹	2007	Cap	99.80	na	4	288–318	0.1
Ren ⁷⁰	2007	Cap	na	0.67	6	298–343	0.1
Song ⁷¹	2007	Cap	99.80	0.7	7	298–353	0.1
Tomida ⁷²	2007	RB	99.50	3	6	293–313	0.1
Xu ⁷³	2007	VW	99.9	1	7	303–363	0.1
Yang ⁷⁴	2007	Cap	99.3	0.6	6	303–353	0.1
Al-Gherwi ⁷⁵	2006	Cap	99.90	na	2	308–313	0.1
Al-Kandary ⁷⁶	2006	Cap	99.5	0.4	2	298–303	0.1
Al-Kandary ⁷⁷	2006	VT	99.80	0.52	4	288–303	0.1
Baragi ⁷⁸	2006	Cap	99.50	0.19	3	298–308	0.1
Goodwin ⁷⁹	2006	VP-MEMS	99.80	10	11	323–373	0.1–68
Han ⁸⁰	2006	Cap	99.90	na	1	298	0.1
Hasan ⁸¹	2006	Cap	99.50	0.16	2	303–313	0.1

TABLE 1. Viscosity measurements of toluene—Continued

First author	Year of publication	Technique employed ^a	Purity (%)	Uncertainty (%)	No. of data	Temperature range (K)	Pressure range (MPa)
Tsierkezos ⁸²	2006	Cap	99.80	0.2	3	278–293	0.1
Yang ⁸³	2006	Cap	99.80	0.73	8	298–363	0.1
Varshney ⁸⁴	2006	Cap	99.50	0.02	1	303	0.1
Iloukhani ⁸⁵	2005	Cap	99.00	na	1	289	0.1
Kandil ⁸⁶	2005	VW	na	3	33	298–348	0.1–40
Knothe ⁸⁷	2005	Cap	99.00	na	1	313	0.1
Nikam ⁸⁸	2005	Cap	99.50	0.59	4	298–313	0.1
Oswal ⁸⁹	2005	Cap	99.00	0.39	1	303	0.1
Agarwal ⁹⁰	2004	Cap	99.00	0.53	1	298	0.1
Caudwell ⁹¹	2004	VW	99.90	2–5	38	323–373	0.01–90.1
Jain ⁹²	2004	Cap	99.00	0.57	1	303	0.1
Oswal ⁹³	2004	Cap	99.5	0.4	1	303	0.1
Wu ⁹⁴	2004	Cap	99.99	10	4	308–323	0.1
Yang ⁹⁵	2004	Cap	99.3	0.6	3	298–323	0.1
George ⁹⁶	2003	Cap	99.5	0.4	2	298–308	0.1
George ⁹⁷	2003	Cap	na	0.4	2	298–308	0.1
Lark ⁹⁸	2003	Cap	na	0.37	2	298–303	0.1
Oswal ⁹⁹	2003	Cap	99.5	na	1	303	0.1
Akhtar ¹⁰⁰	2002	Cap	99.00	0.13	5	303–323	0.1
Cruz ¹⁰¹	2002	Cap	99.50	0.35	2	293–298	0.1
Nayak ¹⁰²	2002	Cap	99.70	0.94	3	298–308	0.1
Peng ¹⁰³	2002	Cap	99.60	0.80	1	298	0.1
Rattan ¹⁰⁴	2002	Cap	na	na	2	293–313	0.1
Kapadi ¹⁰⁵	2001	Cap	na	0.7	1	293	0.1
Roos ¹⁰⁶	2001	Cap	99.70	0.5	1	298	0.1
Swain ¹⁰⁷	2001	Cap	98.00	na	5	298–318	0.1
Assael ¹⁰⁸	2000	VW	99.9	0.5	16	213–363	0–0.05
Nhaesi ¹⁰⁹	2000	Cap	99.00	na	2	293–298	0.1
Nikam ¹¹⁰	2000	Cap	99	0.6	3	303–313	0.1
Tsierkezos ¹¹¹	2000	Cap	99.5	0.1	1	293	0.1
Aminabhavi ¹¹²	1999	Cap	99.70	0.21	4	298–309	0.1
Aralaguppi ¹¹³	1999	Cap	99.70	0.19	3	298–308	0.1
Swain ¹¹⁴	1999	Cap	98	0.1	5	298–318	0.1
George ¹¹⁵	1998	Cap	na	5	1	293	0.1
Swain ¹¹⁶	1998	Cap	98	0.1	4	303–318	0.1
Abdulagatov ¹¹⁷	1996	Cap	na	1.2	6	436	5–30
Ramadevi ¹¹⁸	1996	Cap	na	na	2	303–313	0.1
Et Tahir ¹¹⁹	1995	FB/Cap	99.50	2	30	298–363	0.1–30
Exarchos ¹²⁰	1995	Cap	99.50	na	5	293–313	0.1
Dymond ¹²¹	1995	FB	99.9	4	23	298–323	0.1–492
Krishnan ¹²²	1995	Cap	99.95	0.01	1	303	0.1
Petrino ¹²³	1995	Cap	na	0.1	1	298	0.1
Singh ¹²⁴	1995	Cap	na	0.54	1	298	0.1
Pandey ¹²⁵	1994	Cap	na	0.01	1	298	0.1
Shastri ¹²⁶	1993	Cap	99.00	0.2	1	293	0.1
Aralaguppi ¹²⁷	1992	Cap	99+	0.2	3	298–308	0.1
Klofutar ¹²⁸	1992	Cap	na	0.62	6	293–333	0.1
Liu ¹²⁹	1992	Cap	na	na	2	293–298	0.1
Moumouzias ¹³⁰	1992	Cap	99.50	na	5	288–308	0.1
Aminabhavi ¹³¹	1991	Cap	na	na	8	298–313	0.1
Assael ¹³²	1991	VW	99.5	0.5	4	305–335	0.1
Das ¹³³	1991	Cap	na	1	1	302	0.1
Vavanellos ¹³⁴	1991	Cap	99.70	0.2	2	308–313	0.1
Asfour ¹³⁵	1990	Cap	na	na	2	293–298	0.1
Chevalier ¹³⁶	1990	Cap	99.95	0.1	1	298	0.1
Fermeglia ¹³⁷	1990	Cap	99.00	na	1	298	0.1
Schumpe ¹³⁸	1990	na	na	na	1	293	0.1
Singh ¹³⁹	1990	Cap	na	na	5	298–333	0.1
Sivaramprasad ¹⁴⁰	1990	Cap	na	0.5	1	298	0.1
Mamagakis ¹⁴¹	1989	Cap	99.80	na	1	298	0.1
Singh ¹⁴²	1989	Cap	na	na	5	298–333	0.1
Chandrasekhar ¹⁴³	1988	Cap	na	1	1	298	0.1
Rao ¹⁴⁴	1988	Cap	na	na	1	298	0.1
Ramanjaneyulu ¹⁴⁵	1987	Cap	na	na	1	303	0.1

TABLE 1. Viscosity measurements of toluene—Continued

First author	Year of publication	Technique employed ^a	Purity (%)	Uncertainty (%)	No. of data	Temperature range (K)	Pressure range (MPa)
Byers ¹⁴⁶	1987	Cap	99.00	0.8	8	298–368	0.1
Trumpakaj ¹⁴⁷	1986	Cap	na	0.5	30	242–382	0.1
Singh ¹⁴⁸	1986	Cap	na	na	1	298	0.1
Ritzoulis ¹⁴⁹	1986	Cap	na	na	3	288–308	0.1
Craubner ¹⁵⁰	1986	Cap	na	na	1	293	0.1
Singh ¹⁵¹	1985	Cap	na	na	5	298–333	0.1
Al-Madfai ¹⁵²	1985	Cap	99.50	na	1	298	0.1
Singh ¹⁵³	1984	Cap	na	0.1	4	303–333	0.1
Oswal ¹⁵⁴	1984	Cap	99+	0.2	1	303	0.1
Albright ¹⁵⁵	1983	Cap	99.50	na	1	298	0.1
Baldauf ¹⁵⁶	1983	Cap	na	1	3	283–303	0.1
Martin ¹⁵⁷	1983	Cap	na	3	5	303–343	0.1
Nath ¹⁵⁸	1983	Cap	na	0.19	1	303	0.1
Singh ¹⁵⁹	1982	na	na	na	1	298	0.1
Rabe ¹⁶⁰	1981	Cap	na	2.5	53	183–295	0.1–10
Teja ¹⁶¹	1981	Cap	na	1	3	298–323	0.1
Asfour ¹⁶²	1981	Cap	99+	1	1	298	0.1
Gouel ¹⁶³	1978	RB	na	na	53	297–392	0.1–40
Medani ¹⁶⁴	1977	RB	na	na	12	353–463	0.04–0.6
Dhillon ¹⁶⁵	1976	Cap	na	1	2	298–308	0.1
Hafez ¹⁶⁶	1976	Cap	na	0.19	4	293–318	0.1
Mussche ¹⁶⁷	1975	FB	na	1	2	293–298	0.1
Pugachevich ¹⁶⁸	1975	na	na	0.02	5	303–363	0.1
Wilbur ¹⁶⁹	1975	RB/Cap	na	na	41	238–473	0.1–350
Shikhaliev ¹⁷⁰	1974	Cap	99.95	na	14	223–353	0.1
Alms ¹⁷¹	1973	Cap	na	na	1	298	0.1
Katz ¹⁷²	1971	Cap	na	na	4	298–313	0.1
Konobeev ¹⁷³	1970	Cap	na	na	4	293–384	0.1
Neduzhii ¹⁷⁴	1968	Cap	99.74	1.5	15	220–360	0.1
Blank ¹⁷⁵	1968	na	na	na	1	298	0.1
Ling ¹⁷⁶	1958	Cap	na	2	5	303–384	0.1
Ling ¹⁷⁷	1958	Cap	na	na	2	403–423	0.2–0.3
Hammond ¹⁷⁸	1958	Cap	na	0.2	8	293–384	0.1
Ledneva ¹⁷⁹	1956	Cap	na	na	10	293–473	0.1
Toropov ¹⁸⁰	1956	na	na	na	3	293–333	0.1
Belinskaya ¹⁸¹	1955	Cap	na	0.5	11	233–333	0.1
Hammond ¹⁸²	1955	Cap	na	1	1	298	0.1
Khoskin ¹⁸³	1955	na	na	na	13	213–333	0.1
Mamedov ¹⁸⁴	1955	Cap	na	0.35	11	253–353	0.1
Richardson ¹⁸⁵	1954	na	na	na	4	283–313	0.1
Mukherjee ¹⁸⁶	1953	Cap	na	na	6	308–333	0.1
Lima ¹⁸⁷	1952	Cap	na	na	3	298–308	0.1
Teitelbaum ¹⁸⁸	1950	Cap	na	na	1	298	0.100
Geist ¹⁸⁹	1946	Cap	na	0.5	3	273–313	0.1
Zeidler ¹⁹⁰	1942	na	na	na	3	293–313	0.1
Linke ¹⁹¹	1941	FB	na	na	5	286–323	0.1
Litkenhous ¹⁹²	1940	na	na	na	1	298	0.1
Kyropoulos ¹⁹³	1939	Cap	na	na	2	306–383	0.1
Lemond ¹⁹⁴	1938	Cap	na	na	1	288	0.1
Bratton ¹⁹⁵	1936	Cap	na	na	1	363	0.1
Ilin ¹⁹⁶	1935	Pend	na	na	1	293	0.1
Houseman ¹⁹⁷	1931	Cap	na	na	1	298	0.1
Tausz ¹⁹⁸	1930	Cap	na	na	1	293	0.1
Lowry ¹⁹⁹	1929	na	na	na	2	298–369	0.07–0.1
Puschin ²⁰⁰	1929	na	na	na	1	303	0.1
Nasini ²⁰¹	1929	Cap	na	na	10	334–525	0.02–1.7
Timmermans ²⁰²	1926	na	na	na	3	288–333	0.1
Desart ²⁰³	1926	na	na	na	2	288–303	0.1
Bridgman ²⁰⁴	1926	FB	na	4	2	288–303	0.1
Kolossowsky ²⁰⁵	1925	Cap	na	na	9	287–306	0.1
Lewis ²⁰⁶	1925	Cap	na	na	1	298	0.1
Miller ²⁰⁷	1924	Cap	na	na	2	282–293	0.1
Schaaf ²⁰⁸	1923	Cap	na	na	1	290	0.1
Kendall ²⁰⁹	1917	na	na	0.1	1	298	0.1

TABLE 1. Viscosity measurements of toluene—Continued

First author	Year of publication	Technique employed ^a	Purity (%)	Uncertainty (%)	No. of data	Temperature range (K)	Pressure range (MPa)
Batschinski ²¹⁰	1913	na	na	na	11	273–373	0.1
Dunstan ²¹¹	1913	na	na	na	1	298	0.1
Linebarger ²¹²	1896	Cap	na	na	1	298	0.1
Heydweiller ²¹³	1896	Cap	na	0.2	27	273–463	0.1–0.6
Thorpe ²¹⁴	1894	Cap	na	na	12	273–380	0.1

^aCap, Capillary; FB, Falling Body; na, not available; OD, Oscillating Disk; OQ, Oscillating Quartz; Pend, Pendulum viscometer; RB, Rolling Ball; RCC, Rotating Concentric Cylinder; SLS, Surface Light Scattering; VW, Vibrating Wire; VP-MEMS, Vibrating-edge Plate by Micro ElectroMechanical Systems; VT, Vibrating Tube.

^bIncluded in the correlation of 2006 by Vieira dos Santos *et al.*¹⁵

^cIncluded in the correlation of 2001 by Assael *et al.*¹⁴

and can be written as²¹⁶

$$\eta_0(T) = 0.021357 \frac{\sqrt{MT}}{\sigma^2 S_{\eta}^*(T^*)}, \quad (2)$$

where $S_{\eta}^* = S(2000)/(\pi\sigma^2 f_{\eta})$ is a reduced effective cross section, M is the molar mass in g mol^{-1} , σ is the length scaling parameter in nm, f_{η} is a dimensionless higher-order correction factor according to Chapman and Cowling,^{217,218} and $S(2000)$ is a generalized cross section that includes all of the information about the dynamics of the binary collisions that govern transport properties, and in turn are governed by the intermolecular potential energy surface.²¹⁶ The reduced effective cross section is usually expressed in the functional form,

$$\ln S_{\eta}^*(T^*) = \sum_{i=0}^3 \alpha_i (\ln T^*)^i, \quad (3)$$

$$T^* = k_B T / \varepsilon, \quad (4)$$

where T^* is the reduced temperature, ε/k_B is an energy scaling parameter in K, and k_B is Boltzmann's constant.

The temperature dependence of the linear-in-density coefficient of the viscosity $\eta_1(T)$ in Eq. (1) is very large at subcritical temperatures and must be taken into account to obtain an accurate representation of the viscosity in the vapor phase. It changes sign from positive to negative as the temperature decreases. Therefore, the viscosity along an isotherm should first decrease in the vapor phase and subsequently increase with increasing density.²¹⁶ Vogel *et al.*²¹⁹ have shown that fluids exhibit the same general behavior of the initial density dependence of viscosity, which can also be expressed by means of

the second viscosity virial coefficient $B_{\eta}(T)$ in $\text{m}^3 \text{kg}^{-1}$, as

$$B_{\eta}(T) = \frac{\eta_1(T)}{\eta_0(T)}. \quad (5)$$

Note that in Eq. (5), if the dilute-gas limit viscosity, $\eta_0(T)$, is expressed in $\mu\text{Pa s}$, then the first-density viscosity, $\eta_1(T)$, will be expressed in $\mu\text{Pa s m}^3 \text{kg}^{-1}$. The second viscosity virial coefficient can be obtained according to the theory of Rainwater and Friend^{18,19} as a function of a reduced second viscosity virial coefficient, $B_{\eta}^*(T^*)$, as

$$B_{\eta}^*(T^*) = \frac{B_{\eta}(T) M}{N_A \sigma^3}, \quad (6)$$

where¹⁹

$$B_{\eta}^*(T^*) = \sum_{i=0}^6 b_i (T^*)^{-0.25i} + b_7 (T^*)^{-2.5} + b_8 (T^*)^{-5.5}. \quad (7)$$

In Eq. (6), M is the molar mass in g mol^{-1} given in Table 2 and N_A is the Avogadro constant. The coefficients b_i from Ref. 216 are given in Table 2.

Equations (2)–(7) present a consistent scheme for the correlation of the dilute-gas limit viscosity, $\eta_0(T)$, and the initial density dependence term, $\eta_1(T)$. In the case of toluene, very accurate dilute-gas limit and initial-density-dependence viscosity values have been presented by Vogel and Hendl.³⁴ These values have been used with the regression package ODRPACK (Ref. 220), in order to fit the coefficients α_i in Eq. (3) and the scaling parameters σ and ε/k_B . Values obtained are shown in Table 2. This procedure was also employed previously in correlating successfully the dilute-gas limit and

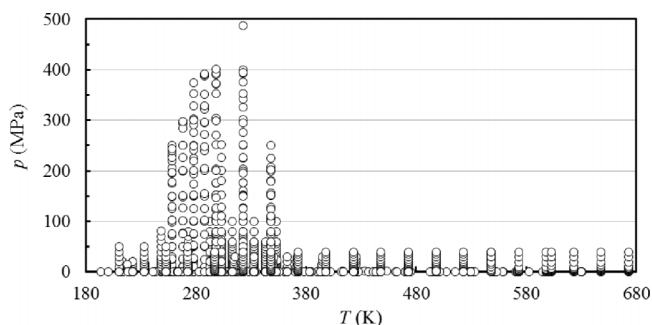


FIG. 1. Temperature-pressure ranges of the primary experimental viscosity data for toluene.

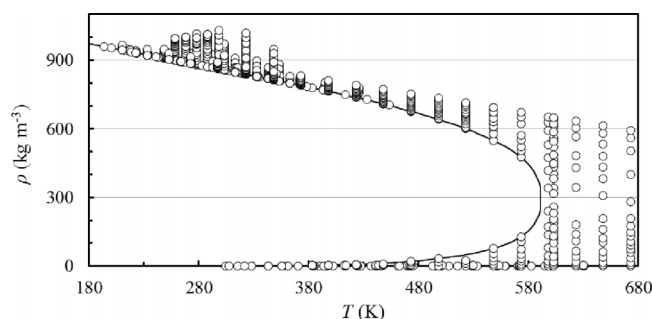


FIG. 2. Temperature-density ranges of the primary experimental viscosity data for toluene.

TABLE 2. Coefficients and parameters for Eqs. (2), (3), and (7)

Molar mass 92.138 42 g mol ⁻¹		
Critical parameters $\rho_c = 291.987 \text{ kg m}^{-3}$ $T_c = 591.75 \text{ K}$		
Scaling parameters $\varepsilon/k_B = 472.0 \text{ K}$ $\sigma = 0.524 \text{ nm}$		
Coefficients α_i for Eq. (3)		
$\alpha_0 = 0.401\ 080$	$\alpha_1 = -0.476\ 409$	
$\alpha_2 = 0.0$	$\alpha_3 = 0.069\ 442$	
Coefficients b_i for Eq. (7) ²¹⁶		
$b_0 = -19.572\ 881$	$b_1 = 219.739\ 99$	$b_2 = -1015.322\ 6$
$b_3 = 2471.012\ 5$	$b_4 = -3375.171\ 7$	$b_5 = 2491.659\ 7$
$b_6 = -787.260\ 86$	$b_7 = 14.085\ 455$	$b_8 = -0.346\ 641\ 58$

the initial density dependence viscosity values of *n*-hexane⁹ and *n*-heptane.¹² We note that the optimum values for the scaling parameters σ and ε/k_B were not the same as those employed in the calculation of the dilute-gas limit contribution in the thermal conductivity reference correlation for toluene,³ as these were optimized for that property.

Figures 3 and 4 show the percentage deviations between the viscosity at low density, $\Delta\eta_0 = \eta_0 + \eta_1\rho$, (calculated with Eqs. (2)–(7) and the parameters in Table 2) and the experimental viscosity values of Vogel and Hendl,³⁴ as a function of temperature and density. Although Eq. (7) was originally developed for propane, the agreement is excellent, as in its recent application to *n*-hexane,¹¹ *n*-heptane,¹² and benzene.¹³ Figure 5 shows a comparison of the initial density dependence, η_1 , viscosity data of Vogel and Hendl³⁴ with the values calculated with Eqs. (2)–(7). Again the agreement is good. Based on comparisons with the data of Vogel and Hendl,³⁴ we estimate the uncertainty of the correlation for the low-density gas viscosity at temperatures from 305 to 640 K to be 0.3%, at a 95% confidence level. Therefore, Eqs. (2)–(7) can be employed for the calculation of the dilute-gas limit viscosity, $\eta_0(T)$, and the initial density dependence term, $\eta_1(T)$.

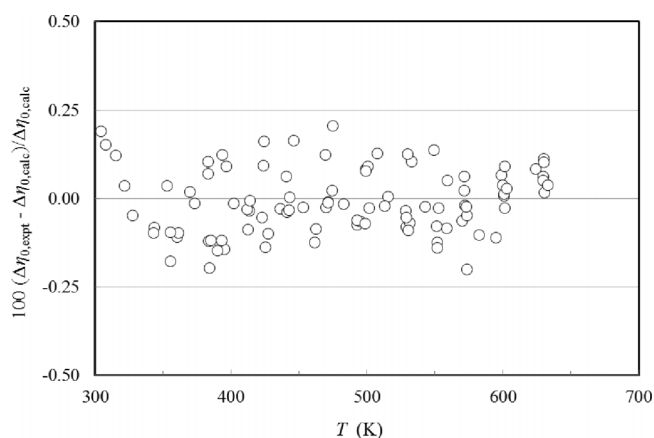


FIG. 3. Percentage deviations of the experimental low-density viscosity of toluene from those calculated with Eqs. (2)–(7) with the parameters in Table 2, as a function of temperature. (○) Vogel and Hendl.³⁴

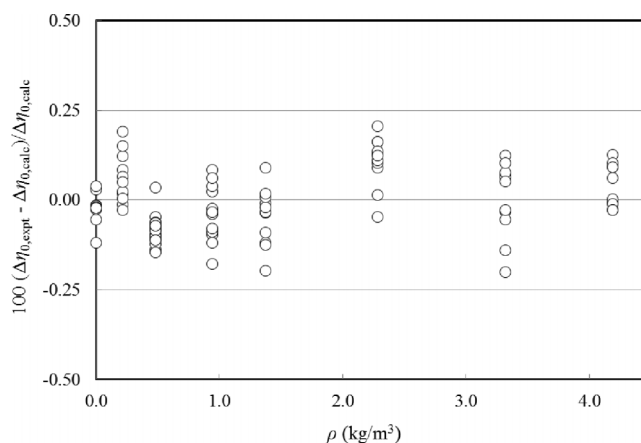


FIG. 4. Percentage deviations of the experimental low-density viscosity of toluene from those calculated with Eqs. (2)–(7) with the parameters in Table 2, as a function of density. (○) Vogel and Hendl.³⁴

3.2. The critical enhancement term

The critical enhancement for viscosity is only significant very close to the critical point (see the International Association for the Properties of Water and Steam (IAPWS) viscosity correlation for water¹⁰).^{221,222} The only data that are close enough to the critical point are due to Akhundov *et al.*³⁸ in 1989, with 111 viscosity measurements very near the critical point, from 594 to 603 K. However, the apparent enhancement of viscosity indicated by these measurements does not make physical sense in the critical region, so only the isotherm at 603.15 K (where the enhancement is not apparent) was employed. Since no reliable data were available to characterize the enhancement for the viscosity of toluene, this term ($\Delta\eta_c$ in Eq. (1)) is set to zero in the present correlation.

3.3. The residual term

As stated in Sec. 2, the residual viscosity term $\Delta\eta(\rho, T)$ represents the contribution of all other effects to the viscosity of the fluid at elevated densities, including many-body collisions, molecular-velocity correlations, and collisional transfer.

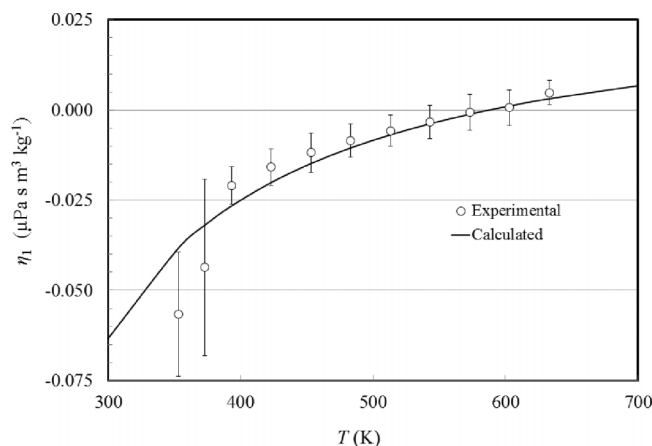


FIG. 5. Initial density-dependence viscosity as a function of the temperature. (○) Vogel and Hendl,³⁴ (—) values calculated with Eqs. (2)–(7) with the parameters in Table 2.

Because there is little theoretical guidance concerning this term, its evaluation here is based entirely on experimentally obtained data.

The procedure adopted for this analysis used symbolic regression software²²³ to fit all the primary data to the residual viscosity. Symbolic regression is a type of genetic programming that allows the exploration of arbitrary functional forms to regress data. The functional form is obtained by use of a set of operators, parameters, and variables as building blocks. Most recently, this method has been used to obtain correlations for the viscosity of *n*-hexane,¹¹ *n*-heptane,¹² benzene,¹³ and hydrogen.²²⁴ In the present work, we restricted the operators to the set (+, −, *, /) and the operands (constant, T_r , ρ_r), with $T_r = T/T_c$ and $\rho_r = \rho/\rho_c$. Various choices of a scaling factor for density were tested, but the best results were obtained using the critical density. In addition, we found the best results when we adopted a form suggested from the hard-sphere model employed by Assael *et al.*,²²⁵ $\Delta\eta(\rho_r, T_r) = (\rho_r^{2/3} T_r^{1/2}) F(\rho_r, T_r)$, where the symbolic regression method was used to determine the functional form for $F(\rho_r, T_r)$. For this task, the dilute-gas limit and the initial density dependence terms were calculated for each experimental point (employing Eqs. (2)–(7)) and subtracted from the experimental viscosity to obtain the residual term. The density values employed were obtained by the equation of state of Lemmon and Span.¹⁶ The final equation obtained was

$$\Delta\eta(\rho, T) = (\rho_r^{2/3} T_r^{1/2}) \times \left\{ \frac{c_0 \rho_r + c_1 \rho_r^4}{T_r} + \frac{c_2 \rho_r^3}{\rho_r^2 + c_3 + c_4 T_r} + c_5 \rho_r \right\}. \quad (8)$$

Coefficients c_i are given in Table 3.

Table 4 summarizes comparisons of the primary data with the correlation. We have defined the percent deviation as $\text{PCTDEV} = 100 * (\eta_{\text{exp}} - \eta_{\text{fit}}) / \eta_{\text{fit}}$, where η_{exp} is the experimental value of the viscosity and η_{fit} is the value calculated from the correlation. Thus, the average absolute percent deviation (AAD) is found with $\text{AAD} = (\sum |\text{PCTDEV}|) / n$, where the summation is over all n points, and the bias percent is found with $\text{BIAS} = (\sum \text{PCTDEV}) / n$. The average absolute percent deviation of the fit is 1.04, and its bias is −0.04.

Figure 6 shows the percentage deviations of all primary viscosity data from the values calculated by Eqs. (1)–(8) as a function of temperature, while Figs. 7 and 8 show the same deviations but as a function of the pressure and the density.

In Fig. 9, the percentage deviations of all primary viscosity data with uncertainty less than 1%, from the values calculated by Eqs. (1)–(8), are shown as a function of temperature. The majority of the data are within 1% of the correlation. The few points of Oliveira and Wakeham³³ that show a larger deviation are some very high-pressure measurements that showed a similar trend in the 2001 Assael *et al.*¹⁴ correlation.

TABLE 3. Coefficients c_i for Eq. (8)

$c_0 = 19.919\ 216$	$c_1 = -2.655\ 790\ 5$	$c_2 = -135.904\ 211$
$c_3 = -7.996\ 271\ 9$	$c_4 = -11.014\ 795$	$c_5 = -10.113\ 817$

TABLE 4. Evaluation of the toluene viscosity correlation for the primary data

First author	Year of Publication	AAD (%)	BIAS (%)
Meng ²¹	2013	0.46	−0.44
Baylaucq ²²	2009	0.33	0.24
Fang ²³	2008	1.30	−0.17
Pensado ²⁴	2005	0.48	0.22
Caetano ²⁵	2004	0.66	−0.02
Avelino ²⁶	2003	1.89	−1.84
Froba ²⁷	2003	1.11	0.83
Harris ²⁸	2000	0.88	0.20
Assael ²⁹	1999	0.72	−0.62
Dymond ³⁰	1998	0.71	0.67
Vieira dos Santos ³¹	1997	1.07	0.98
Krall ³²	1992	0.30	0.00
Oliveira ³³	1992	1.20	0.13
Vogel ³⁴	1992	0.08	−0.03
Assael ³⁵	1991	0.75	−0.54
Dymond ³⁶	1991	1.86	0.70
Kaiser ³⁷	1991	1.03	0.64
Akhundov ³⁸	1989	2.51	−0.52
Goncalves ³⁹	1987	0.59	0.59
Dymond ⁴⁰	1985	0.39	0.34
Bauer ⁴¹	1984	0.06	0.04
Akhundov ⁴²	1983	2.33	0.30
Kashiwagi ⁴³	1982	0.99	−0.79
Karbanov ⁴⁴	1975	1.15	0.81
Akhundov ⁴⁵	1970	1.37	−0.40
Barlow ⁴⁶	1966	1.42	1.51
Entire data set		1.04	−0.04

To establish estimates of the uncertainty (at a 95% confidence level) for the correlation, we looked at comparisons with the primary data sets with the lowest uncertainty in various regions of the T, p surface. Figure 10 shows the estimated uncertainties for the correlation. At temperatures below 210 K, there are few measurements. Based on the primary data sets of Karbanov and Geller⁴⁴ and Barlow *et al.*,⁴⁶ we estimate the

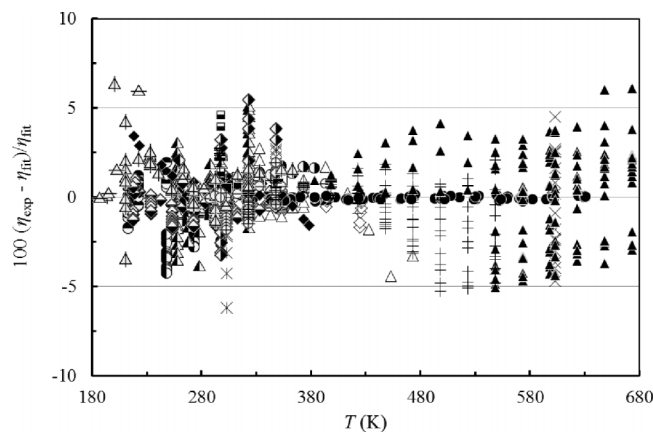


FIG. 6. Percentage deviations of primary experimental data of toluene from the values calculated by the present model as a function of temperature. Meng *et al.*²¹ (●), Baylaucq *et al.*²² (○), Fang *et al.*²³ (Δ), Pensado *et al.*²⁴ (□), Caetano *et al.*²⁵ (●), Avelino *et al.*²⁶ (●), Froba and Leipertz²⁷ (●), Harris²⁸ (Δ), Assael *et al.*²⁹ (◇), Dymond and Simoiu³⁰ (◇), Vieira dos Santos and Nieto de Castro³¹ (■), Krall and Sengers³² (◇), Oliveira and Wakeham³³ (*), Vogel and Hendi³⁴ (●), Assael *et al.*³⁵ (◇), Dymond *et al.*³⁶ (◇), Kaiser *et al.*³⁷ (◇), Akhundov *et al.*³⁸ (X), Goncalves *et al.*³⁹ (■), Dymond and Robertson⁴⁰ (Θ), Bauer and Meerlender⁴¹ (Φ), Akhundov *et al.*⁴² (▲), Kashiwagi and Makita⁴³ (Φ), Karbanov and Geller⁴⁴ (Φ), Akhundov *et al.*⁴⁵ (+), Barlow *et al.*⁴⁶ (Δ).

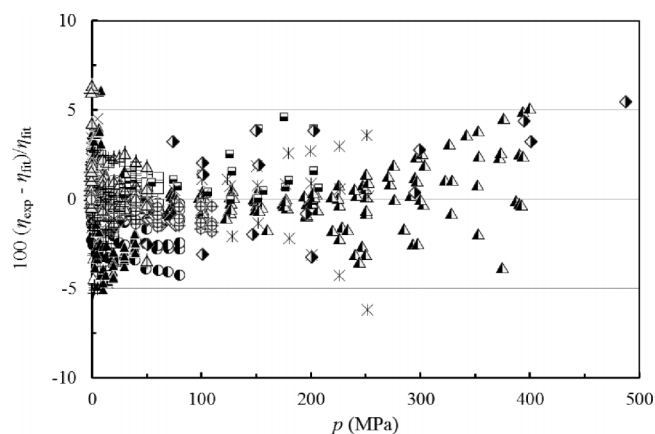


FIG. 7. Percentage deviations of primary experimental data of toluene from the values calculated by the present model as a function of pressure. Meng *et al.*²¹ (●), Baylaucq *et al.*²² (○), Fang *et al.*²³ (△), Pensado *et al.*²⁴ (□), Caetano *et al.*²⁵ (●), Avelino *et al.*²⁶ (●), Froba and Leipertz²⁷ (●), Harris²⁸ (△), Assael *et al.*²⁹ (◇), Dymond and Simoiu³⁰ (◇), Vieira dos Santos and Nieto de Castro³¹ (■), Krall and Sengers³² (◇), Oliveira and Wakeham³³ (*), Vogel and Hendl³⁴ (●), Assael *et al.*³⁵ (◇), Dymond *et al.*³⁶ (◇), Kaiser *et al.*³⁷ (◇), Akhundov *et al.*³⁸ (X), Gonçalves *et al.*³⁹ (■), Dymond and Robertson⁴⁰ (○), Bauer and Meerlender⁴¹ (Φ), Akhundov *et al.*⁴² (▲), Kashiwagi and Makita⁴³ (Φ), Karbanov and Geller⁴⁴ (▲), Akhundov *et al.*⁴⁵ (+), Barlow *et al.*⁴⁶ (△).

uncertainty for the range 187 to 210 K at atmospheric pressure up to 15 MPa to be 5%. An additional data set with low-temperature measurements¹⁶⁰ was excluded from the primary set as it appeared to deviate significantly from the other two low-temperature data sets. Below 187 K, the correlation behaves in a physically reasonable manner, but due to the lack of reliable data and the steep increase in viscosity as the triple point is approached, we can only estimate that the uncertainty exceeds 5%. Additional measurements are necessary to

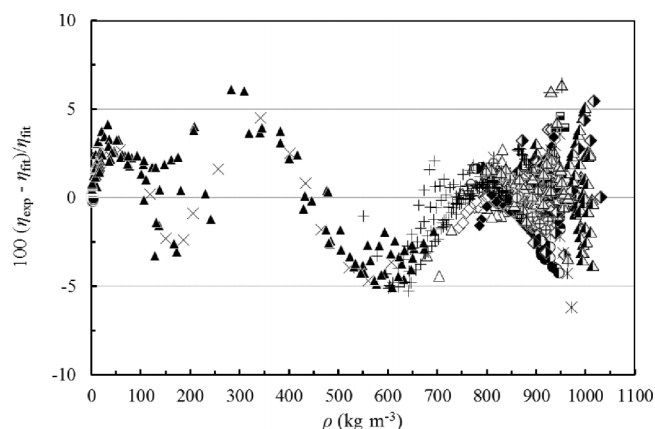


FIG. 8. Percentage deviations of primary experimental data of toluene from the values calculated by the present model as a function of density. Meng *et al.*²¹ (●), Baylaucq *et al.*²² (○), Fang *et al.*²³ (△), Pensado *et al.*²⁴ (□), Caetano *et al.*²⁵ (●), Avelino *et al.*²⁶ (●), Froba and Leipertz²⁷ (●), Harris²⁸ (△), Assael *et al.*²⁹ (◇), Dymond and Simoiu³⁰ (◇), Vieira dos Santos and Nieto de Castro³¹ (■), Krall and Sengers³² (◇), Oliveira and Wakeham³³ (*), Vogel and Hendl³⁴ (●), Assael *et al.*³⁵ (◇), Dymond *et al.*³⁶ (◇), Kaiser *et al.*³⁷ (◇), Akhundov *et al.*³⁸ (X), Gonçalves *et al.*³⁹ (■), Dymond and Robertson⁴⁰ (○), Bauer and Meerlender⁴¹ (Φ), Akhundov *et al.*⁴² (▲), Kashiwagi and Makita⁴³ (Φ), Karbanov and Geller⁴⁴ (▲), Akhundov *et al.*⁴⁵ (+), Barlow *et al.*⁴⁶ (△).

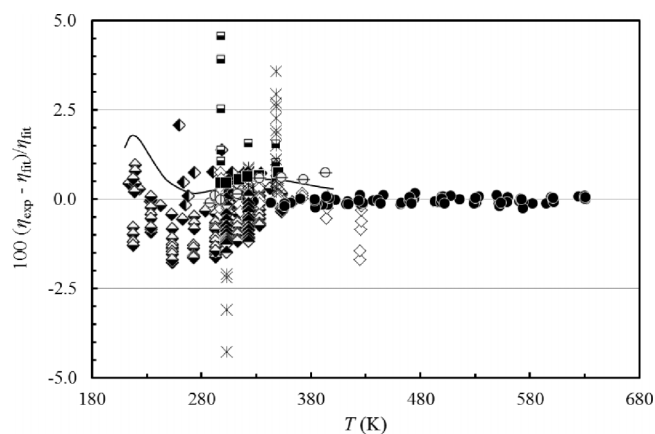


FIG. 9. Percentage deviations of primary experimental data of toluene (with uncertainty <1%) from the values calculated by the present model as a function of temperature. Assael *et al.*²⁹ (◇), Dymond and Simoiu³⁰ (◇), Vieira dos Santos and Nieto de Castro³¹ (■), Krall and Sengers³² (◇), Oliveira and Wakeham³³ (*), Vogel and Hendl³⁴ (●), Assael *et al.*³⁵ (◇), Gonçalves *et al.*³⁹ (■), Dymond and Robertson⁴⁰ (○), Bauer and Meerlender⁴¹ (Φ), Vieira dos Santos *et al.*¹⁵ correlation (—).

quantify the uncertainty further, and we recommend that additional measurements be made to supplement the sparse coverage in this region.

In the temperature range 210 K < T < 263 K and pressures to 20 MPa, we assess the uncertainty based on the measurements of Caetano *et al.*,²⁵ Assael *et al.*,²⁹ and Harris,²⁸ and estimate the uncertainty to be 2%. The atmospheric-pressure measurements of Kaiser *et al.*³⁷ in this region show a slightly different temperature dependency than the other data sets and also have slightly larger deviations, but generally are represented to within 3% in this region. For the region 210 K < T < 263 K and pressures from 20 to 50 MPa, the uncertainty is assessed based on the measurements of Harris²⁸ and Karbanov and Geller,⁴⁴ and is estimated to be 2%; for the region 255 K < T < 263 K, the estimated uncertainty is 2% for 50 to 200 MPa, rising to 3% at 250 MPa.

For the liquid phase at pressures from saturation to 0.1 MPa and at temperatures from 263 to 373 K, the uncertainty is

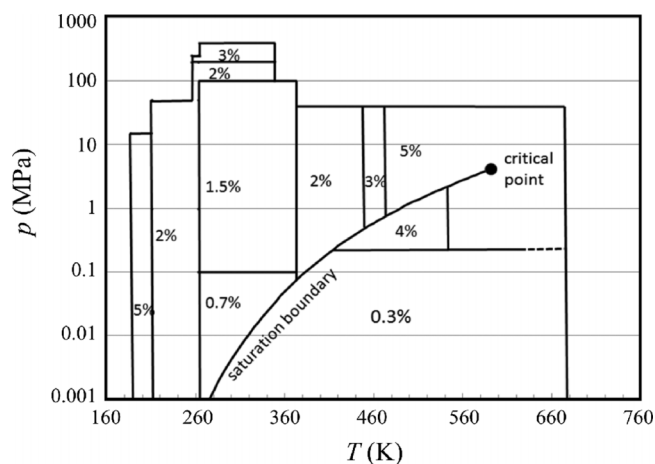


FIG. 10. Estimated uncertainties for the correlation.

TABLE 5. Viscosity values along the saturation line, calculated by the present scheme

T (K)	p (MPa)	ρ (kg m ⁻³)	η (μPa s)	ρ (kg m ⁻³)	η (μPa s)
Saturated liquid			Saturated vapor		
200.00	0.000 001 083 3	953.54	4582	0.000 060 025	4.91
220.00	0.000 011 479	934.64	2236	0.000 578 26	5.32
240.00	0.000 077 542	916.00	1374	0.003 581 0	5.73
260.00	0.000 373 12	897.50	946.0	0.015 913	6.16
280.00	0.001 382 9	879.01	697.6	0.054 825	6.58
300.00	0.004 177 4	860.44	539.7	0.154 93	7.01
320.00	0.010 727	841.66	432.4	0.374 49	7.44
340.00	0.024 170	822.57	355.9	0.799 45	7.87
360.00	0.048 980	803.05	299.2	1.545 1	8.30
380.00	0.090 988	782.98	255.7	2.757 0	8.72
400.00	0.157 31	762.19	221.3	4.612 5	9.14
420.00	0.256 22	740.49	193.3	7.327 3	9.57
440.00	0.396 98	717.63	169.9	11.169	10.01
460.00	0.589 74	693.30	149.8	16.482	10.48
480.00	0.845 59	667.03	132.1	23.741	10.98
500.00	1.176 6	638.14	116.0	33.644	11.55
520.00	1.596 4	605.52	100.9	47.328	12.22
540.00	2.120 7	567.23	86.1	66.883	13.10
560.00	2.769 1	519.05	70.8	96.968	14.42
580.00	3.568 8	446.99	53.0	153.00	17.17

based on primary measurements all with uncertainties less than 1%^{29–32,39–41} and is estimated to be 0.7%. The computed value at 298.15 K and 0.1 MPa is (552.2 ± 3.8) μPa s, which agrees with the value (554.2 ± 3.3) μPa s recommended by Vieira dos Santos *et al.*¹⁵ to within their mutual uncertainties.

For pressures from 0.1 to 30 MPa over the temperature range $263\text{ K} < T < 373\text{ K}$, the data sets of Harris,²⁸ Assael *et al.*,^{29,35} Caetano *et al.*,²⁵ Krall and Sengers,³² Vieira dos Santos and Nieto de Castro,³¹ and Fang *et al.*²³ (all with uncertainty less than 2%) were used to estimate the uncertainty level to be 1.5%. For this temperature range at higher pressures from 30 to 100 MPa, we used data from Harris,²⁸ Assael,²⁹ Vieira dos Santos and Nieto de Castro,³¹ and Akhundov *et al.*⁴⁵ to develop an uncertainty estimate of 1.5%. For 263 to 348 K at pressures from 100 to 200 MPa, the estimated uncertainty based on the data of Harris,²⁸ Vieira dos Santos and Nieto de Castro,³¹ and Kashiwagi and Makita⁴³ is 3%. Finally, at the highest pressures, 200 to 400 MPa for $263\text{ K} < T < 348\text{ K}$, the estimated uncertainty rises to 4% based on comparison with the data sets of Harris,²⁸ Vieira dos Santos and Nieto de Castro,³¹ and Dymond *et al.*³⁶ There are only three data points

between 400 MPa and 500 MPa, all from Dymond *et al.*³⁶ at 298 to 323 K, and they are represented to within 5%.

For the liquid from 373 to 448 K at pressures from saturation to 40 MPa, the estimated uncertainty is 2%, based on comparisons with the data of Kaiser *et al.*,³⁷ Froba and Leipertz,²⁷ Krall and Sengers,³² Dymond and Robertson,⁴⁰ Akhundov *et al.*,⁴⁵ and Fang *et al.*²³ For the liquid phase from saturation up to 40 MPa over the temperature range 448 to 473 K, the estimated uncertainty is 3%, and for the liquid from saturation to 40 MPa from 473 to 548 K, the estimated uncertainty is 5%, based on the data of Akhundov *et al.*⁴⁵ For the supercritical fluid, the estimated uncertainty is 5% based on two data sets from Akhundov.^{38,42} Finally, as mentioned earlier, the estimated uncertainty for the dilute gas over the temperature range 305–640 K at pressures up to 0.3 MPa is 0.3%. The correlation behaves in a physically reasonable manner over the entire range from the triple point up to 675 K, at pressures up to 500 MPa (the limits of the equation of state of Lemmon and Span¹⁶), but due to a lack of data for comparison, we cannot ascribe estimated uncertainties over this entire region.

TABLE 6. Viscosity values in μPa s, as a function of temperature and pressure

p (MPa)	T (K)									
	200	250	300	350	400	450	500	550	600	650
0.1	4589	1129	540.1	325.8	9.2	10.3	11.5	12.6	13.7	14.8
10	5267	1232	586.4	354.8	243.2	178.6	135.1	101.8	73.5	48.6
50	9827	1705	784.5	472.5	326.8	245.8	194.8	159.8	134.1	114.3
100		2475	1066	628.9	431.2	323.4	257.3	213.0	181.2	157.3
150		3551	1399	801.6	541.3	402.3	318.1	262.6	223.3	194.2
200		5142	1797	994.4	659.7	484.7	380.2	311.9	264.3	229.3
250		7716	2279	1211	788.1	571.9	444.6	362.3	305.4	263.9
300			2871	1456	927.9	664.6	511.9	414.2	347.2	298.7
350			3612	1734	1080	763.6	582.6	468.0	390.1	334.1
400			4556	2051	1247	869.3	657.0	524.0	434.2	370.1
450			5810	2416	1429	982.3	735.3	582.3	479.8	407.1

TABLE 7. Evaluation of the toluene viscosity correlation for the secondary data

First author	Year of publication	AAD (%)	BIAS (%)
Prak ⁴⁷	2014	1.52	-0.61
Vijayalakshmi ⁴⁸	2014	0.58	0.58
Assael ⁴⁹	2013	0.56	0.51
Bhalodia ⁵⁰	2013	0.29	0.29
Narendra ⁵¹	2012	2.49	2.49
Sarkar ⁵²	2012	0.41	0.41
Yadava ⁵³	2012	0.46	0.46
Daridon ⁵⁴	2011	1.74	-1.32
Meng ⁵⁵	2011	0.46	-0.02
Pradhan ⁵⁶	2011	4.85	4.85
Yadava ⁵⁷	2011	0.22	0.22
Dubey ⁵⁸	2010	0.69	0.69
Rajagopal ⁵⁹	2010	2.84	2.84
Rajagopal ⁶⁰	2010	2.76	2.76
El-Sayed ⁶¹	2009	0.48	0.48
Sastry ⁶²	2009	0.85	0.85
Silva ⁶³	2009	2.99	2.84
Alonso ⁶⁴	2008	4.49	4.49
Awwad ⁶⁵	2008	0.64	0.64
Baskaran ⁶⁶	2008	0.51	0.51
Song ⁶⁷	2008	1.38	1.38
Hasan ⁶⁸	2007	0.61	0.61
Nain ⁶⁹	2007	1.55	1.18
Ren ⁷⁰	2007	0.93	0.93
Song ⁷¹	2007	0.53	0.53
Tomida ⁷²	2007	10.10	-10.10
Xu ⁷³	2007	1.54	1.19
Yang ⁷⁴	2007	1.27	1.27
Al-Gherwi ⁷⁵	2006	0.15	-0.01
Al-Kandary ⁷⁶	2006	0.40	0.40
Al-Kandary ⁷⁷	2006	0.50	0.50
Baragi ⁷⁸	2006	1.13	1.13
Goodwin ⁷⁹	2006	1.58	-0.05
Han ⁸⁰	2006	0.69	0.69
Hasan ⁸¹	2006	1.05	1.05
Tsierkezos ⁸²	2006	4.50	-4.50
Yang ⁸³	2006	1.23	0.18
Varshney ⁸⁴	2006	0.46	0.46
Iloukhani ⁸⁵	2005	0.04	-0.04
Kandil ⁸⁶	2005	0.41	0.15
Knothe ⁸⁷	2005	3.91	3.91
Nikam ⁸⁸	2005	1.00	1.00
Oswal ⁸⁹	2005	0.09	-0.09
Agarwal ⁹⁰	2004	2.15	2.15
Caudwell ⁹¹	2004	1.44	-1.33
Jain ⁹²	2004	1.00	1.00
Oswal ⁹³	2004	0.64	0.64
Wu ⁹⁴	2004	0.16	0.16
Yang ⁹⁵	2004	0.79	0.79
George ⁹⁶	2003	0.85	0.53
George ⁹⁷	2003	0.85	0.45
Lark ⁹⁸	2003	0.15	-0.15
Oswal ⁹⁹	2003	0.64	0.64
Akhtar ¹⁰⁰	2002	1.99	1.99
Cruz ¹⁰¹	2002	0.67	0.67
Nayak ¹⁰²	2002	2.41	2.41
Peng ¹⁰³	2002	0.75	-0.75
Rattan ¹⁰⁴	2002	0.32	0.32
Kapadi ¹⁰⁵	2001	0.06	-0.06
Roos ¹⁰⁶	2001	0.50	0.50
Swain ¹⁰⁷	2001	1.78	1.78
Assael ¹⁰⁸	2000	0.26	0.05
Nhaesi ¹⁰⁹	2000	0.38	0.38
Nikam ¹¹⁰	2000	1.14	1.14

TABLE 7. Evaluation of the toluene viscosity correlation for the secondary data—Continued

First author	Year of publication	AAD (%)	BIAS (%)
Tsierkezos ¹¹¹	2000	0.91	0.91
Aminabhavi ¹¹²	1999	8.06	-8.06
Aralaguppi ¹¹³	1999	1.20	1.20
Swain ¹¹⁴	1999	1.85	1.85
George ¹¹⁵	1998	8.6	8.6
Swain ¹¹⁶	1998	19.51	19.51
Abdulagatov ¹¹⁷	1996	5.73	5.73
Ramadevi ¹¹⁸	1996	1.76	1.76
Et-Tahir ¹¹⁹	1995	1.29	-0.16
Exarchos ¹²⁰	1995	0.24	0.24
Dymond ¹²¹	1995	1.65	0.54
Krishnan ¹²²	1995	0.09	-0.09
Petrino ¹²³	1995	1.00	-1.00
Singh ¹²⁴	1995	0.04	-0.04
Pandey ¹²⁵	1994	6.97	6.97
Shastri ¹²⁶	1993	4.24	4.24
Aralaguppi ¹²⁷	1992	0.14	0.13
Klofutar ¹²⁸	1992	0.96	-0.96
Liu ¹²⁹	1992	0.66	0.66
Moumouzias ¹³⁰	1992	0.99	0.99
Aminabhavi ¹³¹	1991	3.08	2.82
Assael ¹³²	1991	0.68	0.68
Das ¹³³	1991	81.80	81.80
Vavanellos ¹³⁴	1991	0.37	0.37
Asfour ¹³⁵	1990	0.10	0.10
Chevalier ¹³⁶	1990	1.00	-1.00
Fermeglia ¹³⁷	1990	0.32	0.32
Schumpe ¹³⁸	1990	0.56	0.56
Singh ¹³⁹	1990	2.46	2.44
Sivaramprasad ¹⁴⁰	1990	6.84	6.84
Mamagakis ¹⁴¹	1989	0.08	0.08
Singh ¹⁴²	1989	2.51	2.51
Chandrasekhar ¹⁴³	1988	0.93	0.93
Rao ¹⁴⁴	1988	1.58	1.58
Ramanjaneyulu ¹⁴⁵	1987	0.17	0.17
Byers ¹⁴⁶	1987	0.27	-0.04
Trumpakaj ¹⁴⁷	1986	14.62	-14.62
Singh ¹⁴⁸	1986	0.04	0.04
Ritzoulis ¹⁴⁹	1986	0.39	0.10
Craubner ¹⁵⁰	1986	2.10	2.10
Singh ¹⁵¹	1985	2.51	2.51
Al-Madfai ¹⁵²	1985	0.05	-0.05
Singh ¹⁵³	1984	3.13	3.13
Oswal ¹⁵⁴	1984	0.60	-0.60
Albright ¹⁵⁵	1983	0.06	-0.06
Baldauf ¹⁵⁶	1983	1.19	0.91
Martin ¹⁵⁷	1983	0.23	0.08
Nath ¹⁵⁸	1983	0.29	0.29
Singh ¹⁵⁹	1982	0.04	0.04
Rabe ¹⁶⁰	1981	4.04	0.51
Teja ¹⁶¹	1981	0.59	0.42
Asfour ¹⁶²	1981	0.15	0.15
Gouel ¹⁶³	1978	10.13	10.13
Medani ¹⁶⁴	1977	1.92	-1.58
Dhillon ¹⁶⁵	1976	1.46	1.46
Hafez ¹⁶⁶	1976	0.21	0.10
Mussche ¹⁶⁷	1975	0.76	0.76
Pugachevich ¹⁶⁸	1975	0.34	-0.10
Wilbur ¹⁶⁹	1975	6.21	5.08
Shikhaliev ¹⁷⁰	1974	4.97	3.57
Alms ¹⁷¹	1973	0.05	-0.05
Katz ¹⁷²	1971	1.10	1.10
Konobeev ¹⁷³	1970	0.50	-0.14
Neduzhii ¹⁷⁴	1968	2.99	-2.99

TABLE 7. Evaluation of the toluene viscosity correlation for the secondary data—Continued

First author	Year of publication	AAD (%)	BIAS (%)
Blank ¹⁷⁵	1968	0.04	0.04
Ling ¹⁷⁶	1958	16.03	16.03
Ling ¹⁷⁷	1958	0.25	-0.25
Hammond ¹⁷⁸	1958	0.69	0.69
Ledneva ¹⁷⁹	1956	10.80	-10.80
Toropov ¹⁸⁰	1956	0.41	0.05
Belinskaya ¹⁸¹	1955	1.97	0.54
Hammond ¹⁸²	1955	0.59	-0.59
Khoskin ¹⁸³	1955	1.86	1.33
Mamedov ¹⁸⁴	1955	1.22	-0.85
Richardson ¹⁸⁵	1954	0.34	0.05
Mukherjee ¹⁸⁶	1953	1.06	-0.26
Lima ¹⁸⁷	1952	0.69	0.12
Teitelbaum ¹⁸⁸	1950	1.57	-1.57
Geist ¹⁸⁹	1946	0.32	0.01
Zeidler ¹⁹⁰	1942	8.88	8.88
Linke ¹⁹¹	1941	5.81	5.81
Litkenhous ¹⁹²	1940	0.23	-0.23
Kyropoulos ¹⁹³	1939	2.39	2.39
Lemond ¹⁹⁴	1938	0.77	-0.77
Bratton ¹⁹⁵	1936	2.04	-2.04
Ilin ¹⁹⁶	1935	4.63	-4.63
Houseman ¹⁹⁷	1931	1.64	1.64
Tausz ¹⁹⁸	1930	0.21	0.21
Lowry ¹⁹⁹	1929	2.94	0.72
Puschin ²⁰⁰	1929	1.04	1.04
Nasini ²⁰¹	1929	2.50	2.27
Timmermans ²⁰²	1926	0.96	0.71
Desart ²⁰³	1926	0.44	-0.44
Bridgman ²⁰⁴	1926	0.46	0.00
Kolosowsky ²⁰⁵	1925	0.57	0.23
Lewis ²⁰⁶	1925	0.20	-0.20
Miller ²⁰⁷	1924	1.45	-1.45
Schaaf ²⁰⁸	1923	8.33	8.33
Kendall ²⁰⁹	1917	0.05	-0.05
Batschinski ²¹⁰	1913	0.45	-0.01
Dunstan ²¹¹	1913	0.78	-0.78
Linebarger ²¹²	1896	2.04	-2.04
Heydweiller ²¹³	1896	1.62	-0.69
Thorpe ²¹⁴	1894	0.16	0.01

In general, the present correlation

- (1) represents the data employed in the 2001 Assael *et al.*¹⁴ viscosity correlation, developed with a 2.7% uncertainty (for a 95% confidence level), to within its uncertainty.
- (2) In Fig. 9, the 2006 Vieira dos Santos *et al.*¹⁵ viscosity correlation is also shown. That correlation was along the saturation line with uncertainties of 0.5% (at the 95% confidence level) for temperatures between 260 and 370 K, and 2% for 210 to 260 K and 370 to 400 K. The agreement is excellent.
- (3) Finally, the 2006 Vieira dos Santos *et al.*¹⁵ viscosity correlation proposed the value of (554.2 ± 3.3) $\mu\text{Pa s}$ for the viscosity of toluene at 298.15 K. The value calculated by the present correlation is (552.2 ± 3.8) $\mu\text{Pa s}$, which is within the mutual uncertainties of the two correlations.

Hence, the present correlation extends the range of the previous two correlations from the triple point to 675 K and

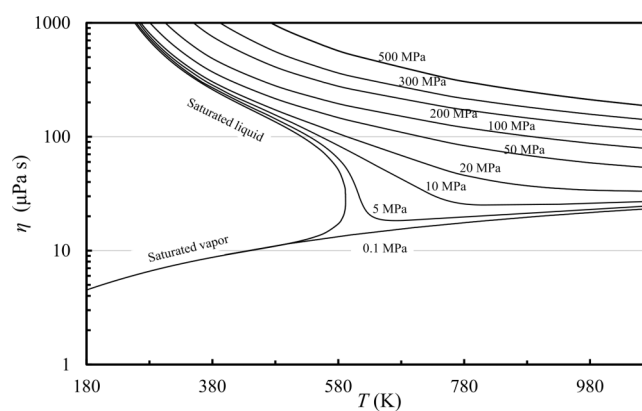


FIG. 11. Viscosity of toluene as a function of temperature for different pressures.

TABLE 8. Sample points for computer verification of the correlating equation

T (K)	ρ (kg m^{-3})	η ($\mu\text{Pa s}$)
300.00	0.00	7.023
400.00	0.00	9.243
550.00	0.00	12.607
300.00	865.00	566.78
400.00	770.00	232.75
550.00	550.00	80.267

can be used up to 500 MPa, including vapor, liquid, and supercritical phases, while still agreeing well with the previous two limited-range correlations over their range of applicability.

In Table 5, values are given along the saturation line, while in Table 6 values at specific temperatures and pressures are given, calculated from the present proposed correlation.

Table 7 shows the AAD and the bias for the secondary data. Finally, Fig. 11 shows the viscosity of toluene as a function of temperature for different pressures.

4. Computer-Program Verification

Table 8 is provided to assist the user in computer-program verification. The viscosity calculations are based on the tabulated temperatures and densities.

5. Conclusion

A new wide-ranging correlation for the viscosity of toluene was developed based on critically evaluated experimental data. The correlation is valid from the triple point to 675 K, and at pressures up to 500 MPa, and thus covers a much wider range than the previous two viscosity reference correlations (Assael *et al.*¹⁴ at saturation and Vieira dos Santos *et al.*¹⁵ for a narrower liquid range). The correlation is expressed in terms of temperature and density, with the density calculated from the equation of state of Lemmon and Span.¹⁶ The estimated uncertainty at a 95% confidence level varies depending on the region of temperature and pressure from 0.3% for the low-density gas at temperatures

from 305 to 640 K at pressures to 0.3 MPa (essentially the uncertainty of the best experimental data), to 0.7% for the saturated liquid at temperatures from 263 to 373 K, to 5% for the low-temperature liquid from 187 to 210 K at pressures to 15 MPa.

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