

Reference Correlation of the Viscosity of Benzene from the Triple Point to 675 K and up to 300 MPa

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Reference Correlation of the Viscosity of Benzene from the Triple Point to 675 K and up to 300 MPa

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This paper contains new, representative reference equations for the viscosity of benzene. The equations are based in part upon a body of experimental data that has been critically assessed for internal consistency and for agreement with theory whenever possible. The correlation is valid from the triple point (278.647 K) to 675 K, and at pressures up to 300 MPa, with the exception of temperatures lower than 350 K where the pressure is restricted to 200 MPa. For the liquid phase, at temperatures from 288 to 373 K at pressures up to 80 MPa, we estimate the uncertainty (at a 95% confidence level) to be 1.8%, increasing to 3.4% at 200 MPa, and 5% at pressures up to the correlation maximum. For the liquid at temperatures from 373 to 523 K, the uncertainty is 2.7% at pressures from saturation to 50 MPa, rising to 3.6% at 300 MPa. For temperatures above 523 K, we estimate the uncertainty in the liquid phase to be 5%. The uncertainty for the low-density fluid phase at temperatures from 305 to 640 K and pressures to 0.3 MPa is estimated to be 0.2%. © 2014 by the U.S. Secretary of Commerce on behalf of the United States. All rights reserved. [http://dx.doi.org/10.1063/1.4892935]

Key words: benzene; critical phenomena; transport properties; viscosity.

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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 and *n*-heptane¹² covering a wide range of conditions of temperature and pressure, were reported. In this paper, the methodology adopted for the viscosity of *n*-hexane¹¹ and *n*-heptane¹² is extended to developing a new reference correlation for the viscosity of benzene.

The goal of this work is to critically assess the available literature data, and provide a wide-ranging correlation for the viscosity of benzene that is valid over gas, liquid, and supercritical states, incorporating densities provided by the recent equation of state of Thol *et al.*,¹³ while maintaining consistency with our recent reference correlation for the thermal conductivity of benzene.⁴

2. Methodology

The viscosity η can be expressed^{11,12,14} 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^{14–16} 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 contribute to divergence of the viscosity at the critical point. Finally, the residual 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.

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. Finally, it should be stated that, relative to other types of viscosity models commonly used in engineering calculations, this viscosity model has a strong phenomenological basis and is best suited for providing a high precision correlation of pure-component viscosity over a very broad temperature and pressure space.

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 the International Union of Pure and Applied Chemistry, the primary data are identified by a well-established set of criteria.¹⁷ 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 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 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^{18–167} of the viscosity of benzene including sample purity and the uncertainties ascribed by the authors. 150 sets are included in the table. From these sets, 11 were considered as primary data. Table 1 shows that most of the secondary data sets consist of a few measurements over a limited temperature range near ambient pressure.

The measurements of Vogel *et al.*²² were performed in the very-low-density vapor range in an absolute oscillating-disk viscometer designed exactly for that region. These measurements were obtained with an uncertainty of 0.15% rising to 0.3% at the highest temperatures, and were part of the primary dataset. Knapstad *et al.*²¹ performed very accurate viscosity measurements at atmospheric pressure in an absolute oscillating-cup viscometer with an uncertainty of 0.33%,

TABLE 1. Viscosity measurements of benzene

1st author	Year Publ.	Technique employed ^a	Purity (%)	Uncertainty (%)	No. of data	Temperature range (K)	Pressure range (MPa)
Primary data							
dos Santos ¹⁸	1997	TCr	99.99	0.5	30	298–348	0.1–178
Matsuo ¹⁹	1993	Cap	99.5	2	20	298–313	0.1–49
Assael ²⁰	1991	VBW	99.80	0.5	28	303–323	0.1–70
Knapstad ²¹	1989	OCup	99.5	0.33	6	288–332	0.1
Vogel ²²	1986	OD	99.92	0.15	75	305–637	0–0.3
Bauer ²³	1984	Cap	99.7	0.1	2	293, 298	0.1
Abdullaev ^{24b}	1983	Cap	99.98	1.2	303	353–673	0.3–40
Kashiwagi ²⁵	1982	TCr	99	2	28	298–348	0.1–110
Dymond ²⁶	1981	FB	99.5	2	27	298–373	0.1–402
Parkhurst ²⁷	1975	RB	na	2.5	35	303–433	0.1–400
Mamedov ²⁸	1971	FB	na	1	130	293–548	0.1–41
Secondary data							
Bhalodia ²⁹	2013	Cap	na	0.1	3	303–313	0.1
Bhatia ³⁰	2013	Cap	99.7	0.53	3	298–308	0.1
de Doz ³¹	2011	Cap	99.8	0.35	1	298	0.1
Mariano ³²	2011	Cap	99.7	0.8	3	283–303	0.1
Pradhan ³³	2011	Cap	na	0.03	1	298	0.1
Rahman ³⁴	2011	Cap	99	1	3	303–323	0.1
Shukla ³⁵	2011	Cap	99	1.7	4	298–313	0.1
Dubey ³⁶	2010	Cap	na	0.5	1	298	0.1
Rathnam ³⁷	2010	Cap	99.5	0.7	3	303–313	0.1
Yadava ³⁸	2010	Cap	99.7	na	1	308	0.1
Ali ³⁹	2009	Cap	99	0.3	1	298	0.1
El-Sayed ⁴⁰	2009	Cap	99.95	0.34	2	308–313	0.1
Sastray ⁴¹	2009	Cap	99.98	0.53	2	298–308	0.1
Awwad ⁴²	2008	Cap	99.8	0.76	4	298–323	0.1
Song ⁴³	2008	Cap	99.5	0.64	7	303–333	0.1
Wankhede ⁴⁴	2008	Cap	na	na	3	288–308	0.1
Hernandez ⁴⁵	2007	RB	99.9	2	40	313–393	0.69–60
Kharat ⁴⁶	2007	Cap	99	0.55	4	298–313	0.1
Nain ⁴⁷	2007	Cap	99.8	na	3	298–318	0.1
Reddy ⁴⁸	2007	Cap	99.8	0.18	1	303	0.1
Ren ⁴⁹	2007	Cap	na	0.64	6	298–343	0.1
Song ⁵⁰	2007	Cap	99.8	0.6	5	298–333	0.1
Yang ⁵¹	2007	Cap	99.5	0.64	4	303–333	0.1
Ali ⁵²	2006	Cap	99	0.9	1	303	0.1
Al-Kandary ⁵³	2006	Cap	99.5	0.47	4	288–303	0.1
Baragi ⁵⁴	2006	Cap	99.80	na	3	298–308	0.1
Han ⁵⁵	2006	Cap	na	na	1	298	0.1
Varshney ⁵⁶	2006	Cap	99.3	0.02	1	303	0.1
Agarwal ⁵⁷	2004	Cap	99	0.49	1	298	0.1
Jain ⁵⁸	2004	Cap	99	0.56	1	313	0.1
Ma ⁵⁹	2004	VBW	99.5	1.60	22	303–445	0.1–6.1
Oswal ⁶⁰	2004	Cap	99.5	0.38	2	303–313	0.1
George ⁶¹	2003	Cap	99.5	0.5	2	298–308	0.1
Lark ⁶²	2003	Cap	na	0.35	2	298–303	0.107
Nikam ⁶³	2003	Cap	99	0.55	4	298–313	0.1
Nayak ⁶⁴	2002	Cap	99.9	0.88	3	298–308	0.1
Chowdhury ⁶⁵	2001	Cap	99	0.05	3	303–323	0.1
Pandey ⁶⁶	2001	Cap	na	0.02	1	298	0.1
Swain ⁶⁷	2001	Cap	98	na	5	298–318	0.1
Tsierkezos ⁶⁸	2000	Cap	99.5	0.15	1	293	0.1
Viswanathan ⁶⁹	2000	na	99.5	na	3	288–298	0.1
Aminabhavi ⁷⁰	1999	Cap	99.8	0.19	3	298–308	0.1
Aralaguppi ⁷¹	1999	Cap	99.8	0.18	3	298–308	0.1
Guzman ⁷²	1999	Cap	99.9	na	3	283–313	0.1
Sastray ⁷³	1999	Cap	99.8	0.2	2	308–318	0.1
Casas ⁷⁴	1998	Cap	99.5	0.08	1	298	0.1
Emmerling ⁷⁵	1998	Cap	99	na	4	293–323	0.1
Exarchos ⁷⁶	1995	Cap	99.5	0.3	4	293–308	0.1
Krishnan ⁷⁷	1995	Cap	99.95	0.1	1	303	0.105
Petrino ⁷⁸	1995	Cap	na	0.1	1	298	0.1
Rived ⁷⁹	1995	Cap	99.7	0.15	1	303	0.1
Singh ⁸⁰	1995	Cap	na	0.5	1	298	0.1

TABLE 1. Viscosity measurements of benzene—Continued

1st author	Year Publ.	Technique employed ^a	Purity (%)	Uncertainty (%)	No. of data	Temperature range (K)	Pressure range (MPa)
Lafuente ⁸¹	1994	Cap	99.9	na	2	298, 313	0.106
Rout ⁸²	1994	Cap	na	0.53	5	298–318	0.1
Shastri ⁸³	1993	Cap	99.8	0.2	1	293	0.1
Klofutar ⁸⁴	1992	Cap	na	0.58	6	293–333	0.102
Tasioula-Margari ⁸⁵	1992	Cap	99.7	na	5	298–308	0.1
Papaioannou ⁸⁶	1991	Cap	99.7	0.25	1	298	0.1
Zhang ⁸⁷	1991	FB	na	1.5	21	298–348	0.1–30
Chevalier ⁸⁸	1990	Cap	99.95	na	1	298	0.1
Joshi ⁸⁹	1990	Cap	na	0.13	5	298–313	0.1
Schumpe ⁹⁰	1990	Cap	na	na	1	293	0.1
Sekar ⁹¹	1990	Cap	na	0.5	1	303	0.1
Sivaramprasad ⁹²	1990	Cap	na	0.5	1	298	0.1
Kouris ⁹³	1989	Cap	99.7	0.25	1	298	0.1
Ruiz ⁹⁴	1989	Cap	99.7	0.2	3	303–323	0.1
Schrodt ⁹⁵	1989	Cap	na	na	1	297	0.1
Shah ⁹⁶	1989	Cap	na	0.55	3	298–319	0.1
Chandrasekhar ⁹⁷	1988	Cap	na	na	1	303	0.1
Rao ⁹⁸	1988	Cap	na	na	1	298	0.1
Manjeshwar ⁹⁹	1987	Cap	na	1.5	2	298–318	0.1
Ramanjaneyulu ¹⁰⁰	1987	Cap	na	na	1	303	0.1
Fischer ¹⁰¹	1986	Cap	99.7	na	7	286–343	0.1
Al-Mandfai ¹⁰²	1985	Cap	99.5	na	1	298	0.1
Albright ¹⁰³	1983	Cap	99.94	na	1	298	0.1
Martin ¹⁰⁴	1983	Cap	na	3	5	303–343	0.1
Nath ¹⁰⁵	1983	Cap	na	0.18	1	303	0.1
Asfour ¹⁰⁶	1981	Cap	99	0.13	1	298	0.1
Teja ¹⁰⁷	1981	Cap	na	0.1	3	298–323	0.1
Yadava ¹⁰⁸	1981	Cap	na	0.19	1	307	0.1
Bich ¹⁰⁹	1979	OD	na	na	47	307–628	0.01–0.1
Gouel ¹¹⁰	1978	Cap	na	5	51	292–392	0.1–40
Medani ¹¹¹	1977	RB	na	na	12	353–463	0.1–1.2
Vyunnik ¹¹²	1977	Cap	na	na	5	278–328	0.1
Dhillon ¹¹³	1976	Cap	na	1	2	298–308	0.1
Bulanov ¹¹⁴	1974	Cap	na	2	12	293–402	0.1–0.37
Mekhtiev ¹¹⁵	1974	Cap	99.98	0.5	7	283–343	0.1
Alms ¹¹⁶	1973	Cap	na	na	1	298	0.1
Collings ¹¹⁷	1971	TCr	na	1	19	303–323	0.1–171
Konobeev ¹¹⁸	1970	Cap	na	na	5	288–333	0.1
Heric ¹¹⁹	1967	Cap	na	0.1	1	298	0.1
Ridgway ¹²⁰	1967	Cap	na	na	1	298	0.1
Fort ¹²¹	1966	Cap	na	0.2	1	298	0.1
Katti ¹²²	1966	Cap	na	na	1	298	0.1
Bagdasarian ¹²³	1964	na	na	na	9	293–453	0.1–1
Howard ¹²⁴	1959	Cap	na	0.1	6	293–343	0.1
Teller ¹²⁵	1959	Cap	na	na	2	283–299	0.1
Ling ¹²⁶	1958	Cap	na	na	7	303–423	0.01–0.58
Rabinovich ¹²⁷	1958	Ultr	na	na	12	288–343	0.1
Airapetova ¹²⁸	1956	na	na	na	3	298–338	0.1
Heiks ¹²⁹	1956	na	na	na	12	363–561	0.2–5
Toropov ¹³⁰	1956	na	na	na	3	293–333	0.1
Belinskaya ¹³¹	1955	Cap	na	0.5	11	279–333	0.1
Koshkin ¹³²	1955	na	na	na	5	283–323	0.1
Kuss ¹³³	1955	Cap	na	na	7	293–343	0.1
Mamedov ¹³⁴	1955	Cap	na	0.04	7	283–343	0.1
Dixon ¹³⁵	1954	Cap	na	na	3	293–333	0.1
Grunberg ¹³⁶	1954	Cap	na	0.2	1	298	0.1
Keeling ¹³⁷	1954	Cap	na	na	3	303–348	0.1
Mukherjee ¹³⁸	1953	Cap	na	na	6	298–323	0.1
Subnis ¹³⁹	1952	Cap	na	na	6	293–323	0.1
Craven ¹⁴⁰	1951	Pend	na	1	4	308–351	0.1
Jobling ¹⁴¹	1951	FB	na	na	10	303–363	0.1
Golik ¹⁴²	1950	Cap	na	na	7	293–303	0.1–0.4
Teitelbaum ¹⁴³	1950	Cap	98	na	1	298	0.1
Geist ¹⁴⁴	1946	Cap	na	0.1	2	293–313	0.1
Linke ¹⁴⁵	1941	FB	na	na	13	286–353	0.1

TABLE 1. Viscosity measurements of benzene—Continued

1st author	Year Publ.	Technique employed ^a	Purity (%)	Uncertainty (%)	No. of data	Temperature range (K)	Pressure range (MPa)
Udovenko ¹⁴⁶	1940	na	na	na	1	298	0.1
Khalilov ¹⁴⁷	1939	na	na	na	18	293–483	0.1–1.7
Salceanu ¹⁴⁸	1939	Cap	na	na	1	293	0.1
Lemonde ¹⁴⁹	1938	Cap	na	na	2	284, 288	0.1
Adzumi ¹⁵⁰	1937	Cap	na	na	1	293	0.1
Kireev ¹⁵¹	1936	Cap	na	na	3	293–333	0.1
Titani ¹⁵²	1933	Cap	na	na	7	404–586	0.1
Piatti ¹⁵³	1931	na	na	na	7	273–333	0.1
Madge ¹⁵⁴	1930	na	na	na	7	283–343	0.1
Tausz ¹⁵⁵	1930	Cap	na	na	2	293	0.1
Lowry ¹⁵⁶	1929	na	na	na	2	293–373	0.1
Nasini ¹⁵⁷	1929	Cap	na	na	15	288–519	0.008–3
Bridgman ¹⁵⁸	1926	FB	na	na	6	303–348	0.1–98
Kolossowsky ¹⁵⁹	1925	Cap	na	na	8	285–313	0.1
Lewis ¹⁶⁰	1925	Cap	na	na	2	298	0.1
Bingham ¹⁶¹	1920	na	na	na	5	288–348	0.1
Faust ¹⁶²	1912	Cap	na	na	4	273–323	0.1
Rappenecker ¹⁶³	1910	Cap	na	na	2	373, 485	0.2, 1.8
Findlay ¹⁶⁴	1909	Cap	na	na	1	352	0.1
Dunstan ¹⁶⁵	1907	Cap	na	na	1	298	0.1
Heydweiller ¹⁶⁶	1896	Cap	na	na	38	288–463	0.1–1.2
Thorpe ¹⁶⁷	1894	Cap	na	na	12	280–348	0.1

^aAbs, Absolute; Cap, Capillary; FB, Falling Body; na, not available; OCup, Oscillating Cup; OD, Oscillating Disk; Pend, Pendulum; RB, Rolling Ball; TCR, Torsional Crystal; Ultr, Ultrasonic; VBW, Vibrating Wire.

^bLow-density points were excluded from the primary data set.

and these measurements were also included in the primary data set. A capillary viscometer was employed by Bauer and Meerlender²³ for two very-low-uncertainty absolute measurements of the viscosity of benzene at atmospheric pressure. The uncertainty was 0.1% and these measurements were also part of the primary set. An absolute vibrating-wire instrument was employed by Assael *et al.*²⁰ These measurements, backed by a full theoretical analysis, extend up to 70 MPa pressure with an uncertainty of 0.5%, and thus are primary data. Also of similar low uncertainty were the torsional-crystal viscosity measurements of dos Santos and Nieto de Castro,¹⁸ performed up to 178 MPa; these were also part of the primary data set. The remaining sets included in the primary data were of slightly inferior uncertainty. Capillary viscometers were employed by Matsuo and Makita¹⁹ and Abdullaev *et al.*²⁴ with quoted uncertainties of 2% and 1.2%, respectively. In the low-density fluid region where the zero-density and first viscosity virial terms contribute more than 99% of the total viscosity, we excluded points from Abdullaev *et al.*²⁴ from the primary data set (about 20 points in total) and exclusively used the measurements of Vogel *et al.*²² The measurements of Kashiwagi and Makita,²⁵ Dymond *et al.*,²⁶ and Parkhurst and Jonas²⁷ were also included as they extend to high pressures, and they seem to agree adequately with each other. They employed a torsional-crystal viscometer, a falling-body and a rolling-body viscometer, with corresponding uncertainties of 2%, 2%, and 2.5%. Finally, the measurements of Mamedov *et al.*,²⁸ performed in a falling-body viscometer with a 1% uncertainty, were also included as they extend to higher temperatures.

Figures 1 and 2 show the ranges of the primary measurements outlined in Table 1, and the phase boundary may be seen as well in Fig. 2. Examining Fig. 1 it can be seen that above 300 MPa pressure, only very few measurements exist. Hence it was preferred to restrict the pressure range of the present correlation to 300 MPa. Furthermore, below 350 K, pressure measurements exist only up to 200 MPa. As this is a range where the viscosity increases sharply with pressure, extrapolation of the correlation in this region should be avoided. Temperatures for all data were converted to the ITS-90 (Ref. 168) temperature scale. The development of the correlation requires densities; recently, Thol *et al.*¹³ reviewed the thermodynamic properties of benzene and developed an accurate, wide-ranging equation of state up to 725 K and 500 MPa. The approximate uncertainties of the density (at a coverage factor of 2) calculated with this

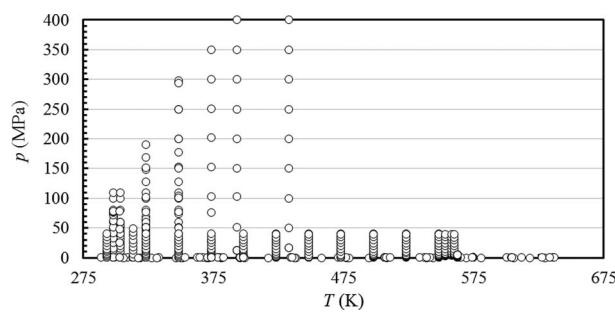


Fig. 1. Temperature-pressure ranges of the primary experimental viscosity data for benzene.

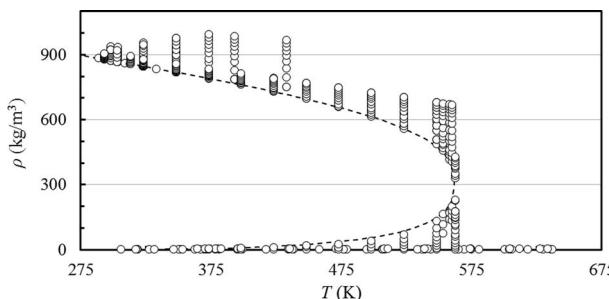


FIG. 2. Temperature-density ranges of the primary experimental viscosity data for benzene. Saturation line (---).

equation are 0.1% below 350 K and 0.2% above 350 K for liquid densities, 1% for saturated vapor densities, 0.1% for densities up to 350 K and 100 MPa, and 0.1%–0.5% in density above 350 K. Uncertainties in the critical region are higher for the above properties. We also adopt the values for the critical point and triple point from their equation of state;¹³ the critical temperature, T_c , and the critical density, ρ_c , were taken to be equal to 562.02 K and 304.792 kg m⁻³, respectively. The triple-point temperature is 278.674 K.¹³

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

The dilute-gas limit viscosity, $\eta_0(T)$, can be analyzed independently 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 and can be written as¹⁶⁹

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

where η_0 is in $\mu\text{Pa s}$, $S_\eta^* = S(2000)/(\pi\sigma^2 f_\eta)$ is a reduced effective cross section, M is the molar mass in g mol^{-1} , σ is the length scaling parameter in nm, and f_η is a dimensionless higher-order correction factor according to Chapman and Cowling.^{170,171} In the definition of S_η^* , $S(2000)$ 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.¹⁶⁹ The 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 behavior 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.¹⁶⁹ Vogel *et al.*²² 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 $B_\eta(T)$ as

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

The second viscosity virial coefficient can be obtained according to the theory of Rainwater and Friend^{15,16} as a function of a reduced second viscosity virial coefficient, $B_\eta^*(T^*)$, as

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

where¹⁶⁹

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

In Eq. (6), N_A is Avogadro's constant. The coefficients b_i from Ref. 169 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 particular case of benzene, very accurate dilute-gas limit and initial-density-dependence viscosity values have been presented by Vogel *et al.*²² These values have been used with the regression package ODRPACK (Ref. 172), in order to fit the coefficients a_i in Eq. (3). The scaling parameters σ and ε/k_B were the same as those employed in the calculation of the dilute-gas limit contribution in the recent thermal conductivity reference correlation for benzene.⁴ This procedure was also employed previously in correlating successfully the dilute-gas limit and

TABLE 2. Coefficients and parameters for Eqs. (2)–(4) and (7)

Molar mass	78.11184 g/mol
Scaling parameters	
$\varepsilon/k_B = 412.0 \text{ K}$	$\sigma = 0.540 \text{ nm}$
Coefficients a_i for Eq. (3)	
$a_0 = 0.234\ 018$	$a_1 = -0.476\ 136$
$a_2 = 0.0$	$a_3 = -0.015\ 269$
Coefficients b_i for Eq. (7) (Ref. 169)	
$b_0 = -19.572\ 881$	$b_1 = 219.739\ 99$
$b_3 = 2471.012\ 5$	$b_4 = -3375.171\ 7$
$b_6 = -787.260\ 86$	$b_5 = 2491.659\ 7$
	$b_7 = 14.085\ 455$
	$b_8 = -0.346\ 641\ 58$

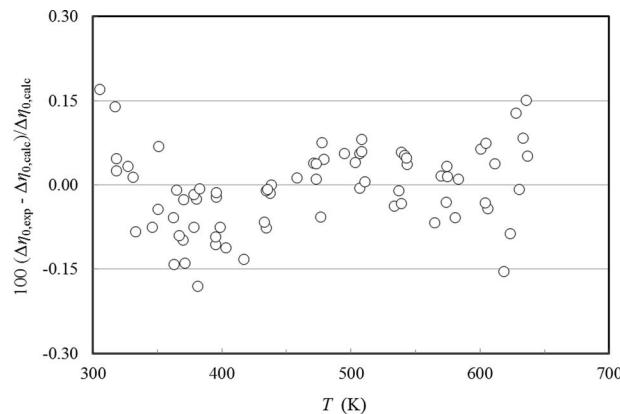


FIG. 3. Percentage deviations of the experimental low-density viscosity, $\eta_0 + \eta_1\rho$, of benzene, from those calculated with Eqs. (2)–(7) with the parameters in Table 2, as a function of temperature. (o) Vogel *et al.*²²

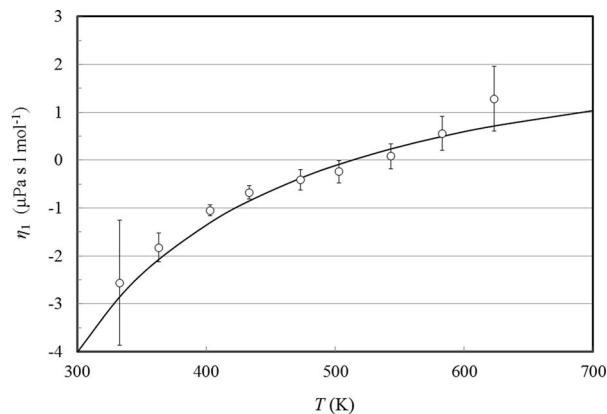


FIG. 5. Initial density dependence viscosity, η_1 , as a function of the temperature. (o) Vogel *et al.*²², (—) values calculated with Eqs. (2)–(7) with the parameters in Table 2.

the initial density dependence viscosity values of *n*-hexane¹¹ and *n*-heptane.¹²

The values obtained are shown in Table 2. Figures 3 and 4 show the percentage deviations of the viscosity at low density $\eta_0 + \eta_1\rho$, (calculated with Eqs. (2)–(7) and the parameters in Table 2) with the experimental viscosity values of Vogel *et al.*,²² as a function of temperature and density. Although Eq. (7) was originally developed for propane, as in its recent application to *n*-hexane¹¹ and *n*-heptane,¹² the agreement is excellent. Figure 5 shows a comparison of the initial density dependence, η_1 , viscosity data of Vogel *et al.*²² with the values calculated with Eqs. (2)–(7). Again, the agreement is good. Based on comparisons with the data of Vogel *et al.*,²² we estimate the uncertainty of the correlation for the low-density gas viscosity at temperatures from 305 to 640 K to be 0.2%, 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, $\eta_1(T)$.

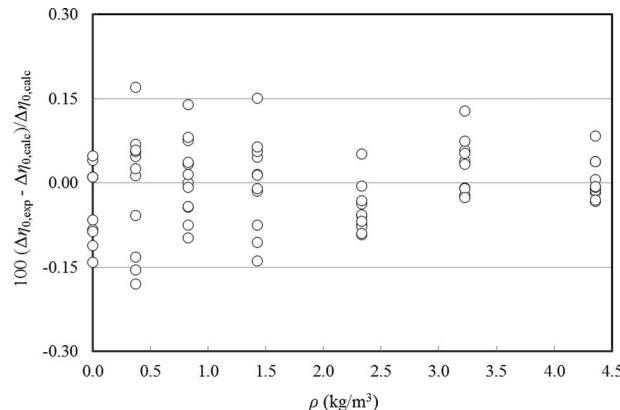


FIG. 4. Percentage deviations of the experimental low-density viscosity, $\eta_0 + \eta_1\rho$, of benzene, from those calculated with Eqs. (2)–(7) with the parameters in Table 2, as a function of density. (o) Vogel *et al.*²²

3.2. The critical enhancement term

Viscosity and thermal conductivity of pure fluids diverge at the critical point due to long-range fluctuations. The critical enhancements can be described by theoretical crossover models originally developed by Bhattacharjee *et al.*¹⁷³ and Olchowy and Sengers¹⁷⁴ and modified by Luettmer-Strathmann *et al.*¹⁷⁵ Unlike the critical enhancement in thermal conductivity, the enhancement in viscosity is confined to a small region, becoming relevant only at temperatures and densities very close to the critical point. For some fluids,^{176,177} the ratio $\Delta\eta_c(\rho, T)/\eta(\rho, T)$ exceeds 1% only within $\pm 1\%$ of the critical temperature of the fluid. There are only very few reliable data for benzene in the critical region. The study by Abdullaev *et al.*²⁴ has data along a subcritical isotherm near 560.20 K and supercritical isotherms near 562.65, 563.20, 564.20, and 566.20 K where the viscosity critical enhancement is significant near the critical density. These viscosity isotherms are shown in Fig. 6, after the reported temperatures were shifted by +0.09 K. This temperature shift is required to center the viscosity maximum in the data near the

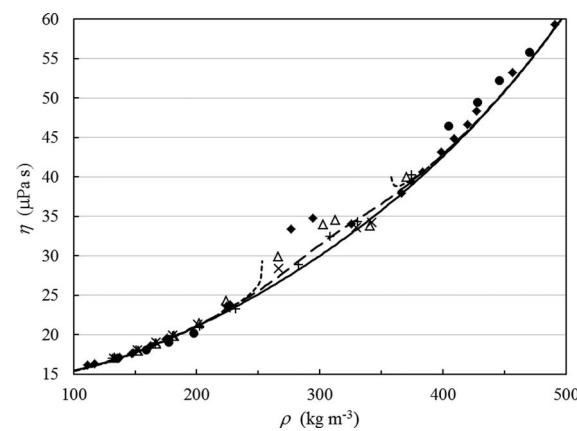


FIG. 6. Selected isotherms showing viscosity in the near-critical region. 562.65 K (♦), 562.65 K theoretical calculation (—), 563.20 K (Δ), 564.20 K (×), 566.20 K (+), 560.20 K (●), 560.20 K theoretical calculation (- - -), background (—).

critical density of $304.792 \text{ kg m}^{-3}$ as expected based on the theory. Even though the claimed temperature stability was $\pm 0.01 \text{ K}$, this temperature shift could be due to a temperature gradient in the viscometer or uncertainty in the temperature that was measured with a thermocouple. It is the temperature difference between the experimental temperature and the actual sample critical point that is important for the critical enhancement. The apparent critical temperature of the sample studied might also have been different from the critical point of pure benzene due to small concentrations ($\sim 0.02\%$) of impurities.

The critical enhancement model for viscosity of Bhattacharjee *et al.*¹⁷³ requires knowledge of the critical temperature, pressure, and density, and several critical parameters that are available from our earlier correlation for the thermal conductivity of benzene,⁴ along with the derivative $(\partial p/\partial T)_T$ from the equation of state of Thol *et al.*¹³ The viscosity model¹⁷³ additionally requires the wave number q_C that is calculated from the critical properties and knowledge of $(\partial p/\partial T)$ at the critical density from Thol *et al.*¹³ and the background values for the viscosity (this work) and thermal conductivity⁴ at the critical point. We calculate $q_C = 1.66 \times 10^{-8} \text{ m}^{-1}$ and assume that the only remaining adjustable parameter, the wave number cutoff $q_D = 1.63 \times 10^{-8} \text{ m}^{-1}$, is the same as that found for the thermal conductivity critical enhancement of benzene.⁴ In general, the values for the wave number cutoff are different for the viscosity and thermal conductivity models, but this is a reasonable estimate to calculate theoretical values for the viscosity critical enhancement. Figure 6 shows curves calculated for the critical enhancement of viscosity along the nearest subcritical isotherm at 560.20 K and the nearest supercritical isotherm at 562.65 K relative to the background viscosity and the data of Abdullaev *et al.*²⁴

It is apparent in Fig. 6 that the experimental data have much more critical enhancement relative to the background viscosity than that expected from the theoretically based model. Our theoretical estimates indicate a 4.6% critical enhancement for viscosity at the critical density along the 562.65 K isotherm of Abdullaev *et al.*²⁴ This is the maximum critical enhancement that is expected for any of the available experimental viscosity data. Figure 6 also shows that the scatter in the experimental data in the critical region exceeds the magnitude of the calculated critical enhancement, so our recommendation is to simply set the critical enhancement $\Delta\eta_c = 0$. Hence, the critical enhancement is considered negligible and it is not further taken into consideration in this work.

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

The procedure adopted during this analysis used symbolic regression software¹⁷⁸ to fit all the primary data to the residual viscosity. It should be noted that, according to the discussion in

TABLE 3. Coefficients of Eq. (8)

$c_0 = -9.989\ 45$	$c_1 = 86.062\ 60$	$c_2 = 2.748\ 72$
$c_3 = 1.111\ 30$	$c_4 = -1.0$	$c_5 = -134.133\ 0$
$c_6 = -352.473$	$c_7 = 6.609\ 89$	$c_8 = 88.417\ 4$

Sec. 3.2, the measurements of Abdullaev *et al.*²⁴ performed very near the critical temperature were not included in the correlation. To obtain the residual viscosity, symbolic regression was employed. 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 and hydrogen.¹⁷⁹ 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.*,¹⁸⁰ $\Delta\eta(\rho_r, T_r) = (\rho_r^{2/3} T_r^{1/2}) F(\rho_r, T_r)$, 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 Thol *et al.*¹³ The final equation obtained was

$$\Delta\eta(\rho, T) = (\rho_r^{2/3} T_r^{1/2}) \times \left\{ c_0 \rho_r^2 + \frac{c_1 \rho_r}{c_2 + c_3 T_r + c_4 \rho_r} + \frac{c_5 \rho_r + c_6 \rho_r^2}{c_7 + c_8 \rho_r^2} \right\}. \quad (8)$$

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

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

1st Author	Year Publ.	AAD (%)	BIAS (%)
dos Santos ¹⁸	1997	1.66	0.82
Matsuo ¹⁹	1993	0.57	-0.42
Assael ²⁰	1991	0.25	-0.16
Knapstad ²¹	1989	0.33	-0.27
Vogel ²²	1986	0.06	-0.01
Bauer ²³	1984	0.36	0.36
Abdullaev ²⁴	1983	1.56	-0.14
Kashiwagi ²⁵	1982	0.58	0.05
Dymond ²⁶	1981	1.26	0.84
Parkhurst ²⁷	1975	1.75	-0.10
Mamedov ²⁸	1971	1.31	0.42
Entire data set		1.23	-0.14

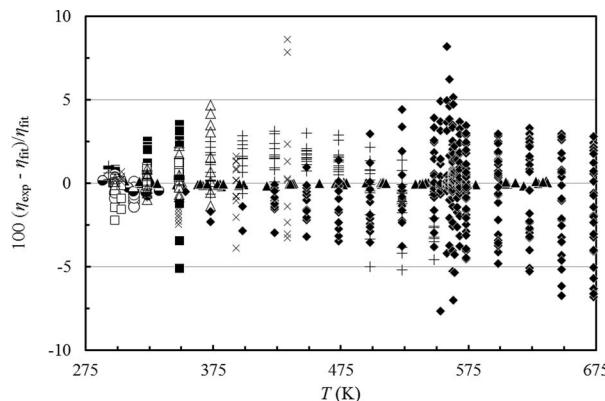


Fig. 7. Percentage deviations of primary experimental data of benzene from the values calculated by the present model as a function of temperature, dos Santos and Nieto de Castro¹⁸ (■), Matsuo and Makita¹⁹ (○), Assael *et al.*²⁰ (●), Knapstad *et al.*²¹ (◐), Vogel *et al.*²² (▲), Bauer and Meerlender²³ (◊), Abdulaev *et al.*²⁴ (◆), Kashiwagi and Makita²⁵ (□), Dymond *et al.*²⁶ (Δ), Parkhurst and Jonas²⁷ (×), Mamedov *et al.*²⁸ (+).

correlation. Thus, the average absolute percent deviation (AAD) is found with the expression $AAD = (\sum|PCTDEV|)/n$, where the summation is over all n points, the bias percent is found with the expression $BIAS = (\sum PCTDEV)/n$. The average absolute percent deviation of the fit is 1.34, and its bias is -0.02. For the liquid phase, at temperatures from 288 to 373 K at pressures up to 80 MPa, we estimate the uncertainty (at a 95% confidence level) to be 1.8%, increasing to 3.4% at 200 MPa, and 5% at pressures up to the correlation maximum. For the liquid at temperatures from 373 to 523 K, the uncertainty is 2.7% at pressures from saturation to 50 MPa, rising to 3.6% at 300 MPa. For temperatures above 523 K, we estimate the uncertainty in the liquid to be 5%. As mentioned previously, we estimate the expanded uncertainty of the correlation at a 95% confidence level for the low-density gas at temperatures from 305 to 640 K and pressures to 0.3 MPa to be 0.2%.

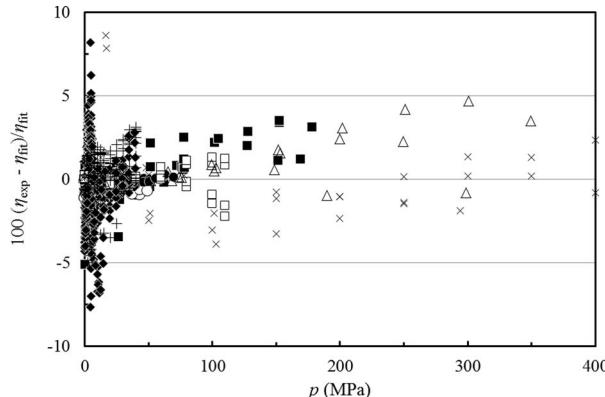


Fig. 8. Percentage deviations of primary experimental data of benzene from the values calculated by the present model as a function of pressure. dos Santos and Nieto de Castro¹⁸ (■), Matsuo and Makita¹⁹ (○), Assael *et al.*²⁰ (●), Knapstad *et al.*²¹ (◐), Vogel *et al.*²² (▲), Bauer and Meerlender²³ (◊), Abdulaev *et al.*²⁴ (◆), Kashiwagi and Makita²⁵ (□), Dymond *et al.*²⁶ (Δ), Parkhurst and Jonas²⁷ (×), Mamedov *et al.*²⁸ (+).

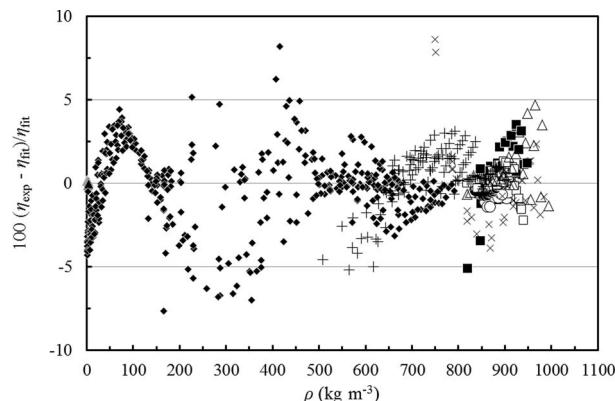


Fig. 9. Percentage deviations of primary experimental data of benzene from the values calculated by the present model as a function of density. dos Santos and Nieto de Castro¹⁸ (■), Matsuo and Makita¹⁹ (○), Assael *et al.*²⁰ (●), Knapstad *et al.*²¹ (◐), Vogel *et al.*²² (▲), Bauer and Meerlender²³ (◊), Abdulaev *et al.*²⁴ (◆), Kashiwagi and Makita²⁵ (□), Dymond *et al.*²⁶ (Δ), Parkhurst and Jonas²⁷ (×), Mamedov *et al.*²⁸ (+).

Figure 7 shows the percentage deviations of all primary viscosity data from the values calculated by Eqs. (1)–(8) as a function of temperature, while Figs. 8 and 9 show the same deviations but as a function of the pressure and the density.

In Table 5, values are given for the viscosity along the saturation line, calculated from the present proposed correlation between 250 and 360 K. Values of the viscosity as a function of temperature and pressure are also given in Table 6.

Table 7 shows the AAD and the bias for the secondary data. It can be seen that, except for a few isolated cases, most of the secondary data agree very well with the proposed correlation. Finally, Fig. 10 shows a plot of the viscosity of benzene as a function of the temperature for different pressures. Figure 10 should be employed only within the limits of the correlation.

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

T (K)	ρ (kg m ⁻³)	η (μ Pa s)
280.00	892.702	795.3
300.00	871.470	586.4
320.00	849.999	455.2
340.00	828.145	365.1
360.00	805.753	299.4
380.00	782.656	249.3
400.00	758.650	209.9
420.00	733.477	178.1
440.00	706.783	151.8
460.00	678.042	129.6
480.00	646.421	110.5
500.00	610.458	93.57
520.00	567.192	77.93
540.00	508.839	62.26

TABLE 6. Viscosity values in $\mu\text{Pa s}$, as a function of temperature and pressure

<i>p</i> (MPa)	<i>T</i> (K)										
	300	320	340	360	380	400	450	500	550	600	675
0	7.62	8.12	8.62	9.11	9.61	10.1	11.3	12.6	13.8	15.0	16.9
0.1	588.2	456.4	365.8	9.04	9.55	10.1	11.3	12.6	13.8	15.0	16.9
0.5	590.3	458.0	367.2	300.9	250.4	210.6	11.2	12.6	13.8	15.1	17.0
1	592.9	460.0	368.9	302.4	251.8	211.8	140.5	12.5	13.9	15.1	17.0
2	598.3	464.1	372.3	305.4	254.4	214.3	142.9	12.5	13.9	15.3	17.2
5	614.2	476.4	382.4	314.2	262.3	221.6	149.8	101.7	60.4	17.5	18.3
10	641.2	497.1	399.3	328.7	275.2	235.3	160.4	113.1	79.1	51.5	27.5
20	696.8	539.0	433.1	357.3	300.4	256.2	179.8	131.6	99.0	76.1	54.0
50	879.9	671.8	537.3	443.3	374.1	321.1	231.0	175.4	138.5	112.9	87.6
100	1268.3	931.6	729.9	595.5	499.8	428.1	309.5	237.7	190.1	156.8	123.1
200	2763.6	1734.3	1253.9	976.0	794.9	667.7	470.2	357.1	284.3	233.6	181.8
300				1552.1	1200.0	974.1	653.8	484.8	380.3	309.3	237.7

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

1st author	Year Publ.	AAD (%)	BIAS (%)
Bhalodia ²⁹	2013	1.53	1.53
Bhatia ³⁰	2013	0.76	0.14
de Doz ³¹	2011	0.15	0.15
Mariano ³²	2011	1.40	1.40
Pradhan ³³	2011	0.52	-0.52
Rahman ³⁴	2011	0.55	0.55
Shukla ³⁵	2011	0.43	-0.43
Dubey ³⁶	2010	0.31	0.31
Rathnam ³⁷	2010	1.02	1.02
Yadava ³⁸	2010	0.51	-0.51
Ali ³⁹	2009	0.15	0.15
El-Sayed ⁴⁰	2009	0.09	0.01
Sastray ⁴¹	2009	0.14	0.01
Awwad ⁴²	2008	0.28	-0.22
Song ⁴³	2008	0.53	0.31
Wankhede ⁴⁴	2008	2.99	-1.83
Hernandez ⁴⁵	2007	1.85	0.72
Kharat ⁴⁶	2007	0.77	0.77
Nain ⁴⁷	2007	0.86	0.55
Reddy ⁴⁸	2007	0.66	0.66
Ren ⁴⁹	2007	0.90	-0.90
Song ⁵⁰	2007	0.44	-0.44
Yang ⁵¹	2007	0.62	-0.62
Ali ⁵²	2006	0.39	0.39
Al-Kandary ⁵³	2006	0.93	0.93
Baragi ⁵⁴	2006	0.37	-0.37
Han ⁵⁵	2006	0.31	0.31
Varshney ⁵⁶	2006	0.30	0.30
Agarwal ⁵⁷	2004	0.98	0.98
Jain ⁵⁸	2004	4.14	-4.14
Ma ⁵⁹	2004	1.66	0.26
Oswal ⁶⁰	2004	0.27	-0.23
George ⁶¹	2003	0.07	-0.07
Lark ⁶²	2003	0.63	-0.56
Nikam ⁶³	2003	0.77	0.77
Nayak ⁶⁴	2002	1.23	1.23
Chowdhury ⁶⁵	2001	0.73	0.73
Pandey ⁶⁶	2001	1.00	-1.00
Swain ⁶⁷	2001	14.78	14.78
Tsierkezos ⁶⁸	2000	1.57	1.57
Viswanathan ⁶⁹	2000	6.28	6.28
Aminabhavi ⁷⁰	1999	7.53	-7.53
Aralaguppi ⁷¹	1999	0.46	0.46
Guzman ⁷²	1999	0.83	0.62
Sastray ⁷³	1999	1.46	1.46
Casas ⁷⁴	1998	1.68	-1.68
Emmerling ⁷⁵	1998	0.47	0.47
Exarchos ⁷⁶	1995	0.50	0.03

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

1st author	Year Publ.	AAD (%)	BIAS (%)
Krishnan ⁷⁷	1995	0.05	-0.05
Petrino ⁷⁸	1995	0.73	-0.73
Rived ⁷⁹	1995	1.41	-1.41
Singh ⁸⁰	1995	0.15	0.15
Lafuente ⁸¹	1994	1.60	-1.60
Rout ⁸²	1994	7.74	7.74
Shastri ⁸³	1993	0.13	-0.13
Klofutai ⁸⁴	1992	1.07	-1.07
Tasioula-Margari ⁸⁵	1992	0.49	0.49
Papaioannou ⁸⁶	1991	0.45	0.45
Zhang ⁸⁷	1991	1.83	1.73
Chevalier ⁸⁸	1990	0.20	0.20
Joshi ⁸⁹	1990	1.96	-1.04
Schumpe ⁹⁰	1990	0.88	0.88
Sekar ⁹¹	1990	2.08	2.08
Sivaramprasad ⁹²	1990	6.96	6.96
Kouris ⁹³	1989	0.43	0.43
Ruiz ⁹⁴	1989	0.89	-0.89
Schrodt ⁹⁵	1989	0.09	0.09
Shah ⁹⁶	1989	1.73	1.73
Chandrasekhar ⁹⁷	1988	1.32	1.32
Rao ⁹⁸	1988	1.79	1.79
Manjeshwar ⁹⁹	1987	1.28	1.08
Ramanjaneyulu ¹⁰⁰	1987	0.06	-0.06
Fischer ¹⁰¹	1986	10.74	10.74
Al-Mandfai ¹⁰²	1985	0.20	-0.20
Albright ¹⁰³	1983	0.18	0.18
Martin ¹⁰⁴	1983	0.72	-0.72
Nath ¹⁰⁵	1983	0.47	0.47
Asfour ¹⁰⁶	1981	0.08	0.08
Teja ¹⁰⁷	1981	0.63	-0.63
Yadava ¹⁰⁸	1981	0.41	-0.41
Bich ¹⁰⁹	1979	0.54	0.10
Gouel ¹¹⁰	1978	6.08	6.01
Medani ¹¹¹	1977	2.21	-2.21
Vyunnik ¹¹²	1977	0.58	-0.36
Dhillon ¹¹³	1976	0.16	0.16
Bulanov ¹¹⁴	1974	1.17	-1.02
Mekhtiev ¹¹⁵	1974	0.82	-0.54
Alms ¹¹⁶	1973	0.80	0.80
Collings ¹¹⁷	1971	1.60	0.68
Konobeev ¹¹⁸	1970	0.67	-0.02
Heric ¹¹⁹	1967	0.34	0.34
Ridgway ¹²⁰	1967	0.61	0.61
Fort ¹²¹	1966	0.03	-0.03
Katti ¹²²	1966	0.43	-0.43

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

1st author	Year Publ.	AAD (%)	BIAS (%)
Bagdasarian ¹²³	1964	2.10	-2.05
Howard ¹²⁴	1959	0.51	-0.22
Teller ¹²⁵	1959	2.73	2.73
Ling ¹²⁶	1958	1.07	-1.07
Rabinovich ¹²⁷	1958	0.52	0.48
Airapetova ¹²⁸	1956	1.04	-0.64
Heiks ¹²⁹	1956	9.31	8.19
Toropov ¹³⁰	1956	0.88	-0.88
Belinskaya ¹³¹	1955	1.83	1.83
Koshkin ¹³²	1955	0.74	0.74
Kuss ¹³³	1955	0.39	0.11
Mamedov ¹³⁴	1955	0.80	-0.64
Dixon ¹³⁵	1954	0.45	0.09
Grunberg ¹³⁶	1954	0.43	-0.43
Keeling ¹³⁷	1954	0.60	-0.60
Mukherjee ¹³⁸	1953	1.10	-0.89
Subnis ¹³⁹	1952	4.31	2.16
Craven ¹⁴⁰	1951	1.48	0.82
Jobling ¹⁴¹	1951	1.68	-0.60
Golik ¹⁴²	1950	10.96	-10.96
Teitelbaum ¹⁴³	1950	7.27	7.27
Geist ¹⁴⁴	1946	0.43	-0.11
Linke ¹⁴⁵	1941	9.33	9.33
Udovenko ¹⁴⁶	1940	0.05	0.05
Khalilov ¹⁴⁷	1939	2.53	-1.54
Salceanu ¹⁴⁸	1939	0.32	0.32
Lemonde ¹⁴⁹	1938	0.44	0.44
Adzumi ¹⁵⁰	1937	2.33	2.33
Kireev ¹⁵¹	1936	1.68	1.18
Titani ¹⁵²	1933	1.53	1.53
Piatti ¹⁵³	1931	63.39	40.69
Madge ¹⁵⁴	1930	0.48	-0.26
Tausz ¹⁵⁵	1930	0.43	0.28
Lowry ¹⁵⁶	1929	0.92	-0.15
Nasini ¹⁵⁷	1929	1.76	0.44
Bridgman ¹⁵⁸	1926	2.31	1.61
Kolossowsky ¹⁵⁹	1925	1.11	0.06
Lewis ¹⁶⁰	1925	1.16	-1.16
Bingham ¹⁶¹	1920	0.81	-0.60
Faust ¹⁶²	1912	3.44	-3.22
Rappenecker ¹⁶³	1910	1.67	1.39
Findlay ¹⁶⁴	1909	1.58	-1.58
Dunstan ¹⁶⁵	1907	0.27	0.27
Heydweiller ¹⁶⁶	1896	3.30	-2.28
Thorpe ¹⁶⁷	1894	0.44	-0.24

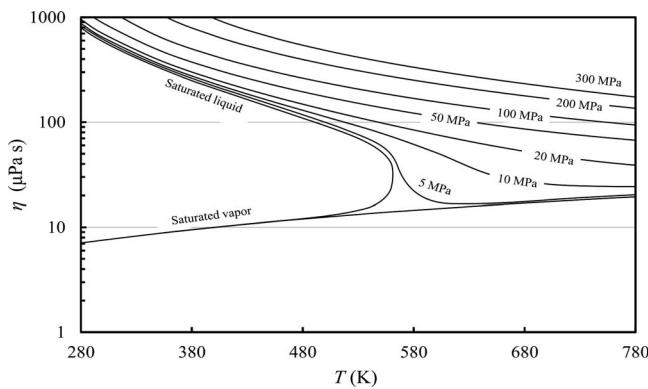


FIG. 10. Viscosity of benzene as a function of temperature for different pressures.

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

T (K)	ρ (kg m^{-3})	η ($\mu\text{Pa s}$)
300.00	0.00	7.625
400.00	0.00	10.102
550.00	0.00	13.790
300.00	875.00	608.52
400.00	760.00	211.74
550.00	500.00	60.511

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 benzene was developed based on critically evaluated experimental data. It consists of Eqs. (1)–(8), the coefficients found in Tables 2 and 3, and the equation of state of Thol *et al.*¹³ to calculate density. The correlation is valid from the triple point to 675 K, and at pressures up to 300 MPa. The correlation is expressed in terms of temperature and density, with the density calculated from the equation of state of Thol *et al.*¹³ The uncertainty estimate for the liquid phase at a 95% confidence level varies from 1.8% to 5%, and the uncertainty of the low-density gas at temperatures from 305 to 640 K and pressures to 0.3 MPa is estimated to be 0.2%.

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