



Reference Correlation for the Viscosity of Ethanol from the Triple Point to 620 K and Pressures Up to 102 MPa

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Abstract

We present a wide-ranging correlation expressed in terms of temperature and density for the viscosity of ethanol based on critically evaluated experimental data. The correlation is designed to be used with an existing equation of state from the triple point (159 K) to 620 K and at pressures up to 102 MPa. Comparisons with experimental data indicate the estimated uncertainty of the correlation is 4.2 % (at the 95 % confidence level) for the liquid and supercritical phase at pressures up to 102 MPa, and 2 % in the gas phase. Furthermore, for calculating viscosity values at 0.1 MPa, an additional correlation is proposed, valid from the triple point to the boiling point with an estimated uncertainty of 2.3 % (at the 95 % confidence level).

Keywords Ethanol · Transport properties · Viscosity

1 Introduction

Ethanol (IUPAC name), also known as ethyl alcohol, has the molecular formula of C_2H_5OH . Ethanol is an important chemical with numerous uses; it is used as a solvent, in the synthesis of other organic chemicals, as an additive to automotive gasoline, as a renewable transportation fuel, and as an intoxicating ingredient of many alcoholic beverages and distilled spirits. It is also used as a topical agent to prevent skin infections, in pharmaceutical preparations (e.g., lotions, colognes, etc.), in cosmetics, and in perfumes.

In 2013, a new reference correlation for the thermal conductivity of ethanol was presented by Assael et al. [1], covering for the first time a temperature range from

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the triple point to 600 K and up to 245 MPa. This was made possible following the development of an accurate equation of state for ethanol by Schroeder et al. [2]. This correlation is currently employed in REFPROP 10.0 [3].

The current ethanol viscosity correlation employed in REFPROP 10.0 [3], was developed in 2005 by Kiselev et al. [4], and is based on a generalized SAFT-DFT/DMT model for the thermodynamic, interfacial, and transport properties of associating fluids applied to n-alkanols. Its estimated uncertainty in the liquid phase along the saturation boundary is approximately 3 %, increasing to 10 % at pressures up to 100 MPa, and estimated as 10 % in the vapor phase.

In a series of recent papers, reference correlations for the viscosity of common fluids [1, 5–14] were developed that cover a wide range of temperature and pressure conditions, including the gas, liquid, and supercritical phases. In this paper, the methodology adopted in the aforementioned papers is extended to developing a new reference correlation for the viscosity of ethanol.

The analysis we use is based on the best available experimental viscosity data. A prerequisite to the analysis is a critical assessment of the experimental data. Here we define two categories of experimental data: 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 [15]. 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 higher uncertainty, provided they are consistent with other lower uncertainty data or with theory. In all cases, the uncertainty claimed for the final recommended data must reflect the estimated uncertainty in the primary information.

2 The Correlation

The viscosity η can be expressed [1, 5–14] 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 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 use of the Rainwater–Friend theory [16–18] 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. This term for viscosity is significant only in the region very near the critical point, as shown in Vesovic et al. [19] and Hendl et al. [20]. For CO_2 , Vesovic et al. [19] showed that the enhancement contributes greater than 1 % to the viscosity only in the small region bounded by $0.986 < T_r < 1.019$ and $0.642 < \rho_r < 1.283$ (where T_r and ρ_r denote the reduced temperature and density). Since data close to the critical point are unavailable, $\Delta\eta_c(\rho, T)$ will be set to zero in Eq. 1 and not discussed further. Finally, the term $\Delta\eta(\rho, T)$, 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.

Identification of these four separate contributions to the viscosity allows one, to some extent, to treat $\eta_0(T)$, and $\eta_1(T)$ 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 its evaluation is usually based entirely on an empirical equation obtained by fitting experimental data.

Table 1 summarizes, to the best of our knowledge, all the available experimental measurements of the viscosity of ethanol reported in the literature. Table 1 displays the experimental technique, purity, uncertainty as reported by the original authors, number of measurements, as well as the range of temperatures and pressures investigated. From the 275 measurement sets shown in total, 14 were performed at pressures above atmospheric, while the remaining 261 were performed at 0.1 MPa (or near saturation pressure), and mostly over a limited temperature range, at about room temperature.

In this particular case, and because of the very large number of measurements at 0.1 MPa, the primary data were separated into two subcategories: (a) primary data above atmospheric pressure, and (b) primary data at 0.1 MPa.

In the first data set, we included all measurements performed above atmospheric pressure, the only exceptions being the very high-pressure measurements of (a) Yusa et al. [253] performed in a falling-cylinder viscometer in 1977, and (b) the 1926 Bridgman [282] and 1914 Faust [286] measurements performed in a capillary viscometer, as they deviate more than 20 % from the remaining measurements. Therefore, the primary data set at pressures above atmospheric consists of 11 sets.

In relation to the primary data set of measurements at 0.1 MPa presented in Table 1, the following criteria were employed for selection. As already mentioned in the introduction, ethanol is extensively employed in experimental studies on volumetric and viscometric properties of binary and ternary mixtures, phase equilibria studies, or even acoustical studies. In such studies, although the viscosity of pure ethanol is also measured, the emphasis is on the properties of the mixture, the solution, and the effect of the change in concentration. Hence, in recent literature, there are a very large number of papers that include a single measurement of the viscosity of ethanol at room temperature with inadequate assessments of uncertainty. Therefore, we did not include in the primary data set such articles with a single viscosity measurement at room temperature or near it. Furthermore, as water is the only liquid whose viscosity is known to an uncertainty as low as 0.17 % (at the 95 % confidence level) [15], all measurements in which the authors

Table 1 Viscosity measurements of ethanol

Investigators/reference	Publ. Year	Technique employed ^a	Purity ^b (%)	Uncertainty (%)	No. of data	Temperature range (K)	Pressure range (MPa)
<i>Primary data—above atmospheric pressure</i>							
Mendo-Sanchez et al. [21]	2020	Cap	99.90	1.6	95	293 to 333	2.0 to 50
Zhu et al. [22]	2020	Cap	99.99	0.5	28	308 to 338	15.0 to 45
Ono et al. [23]	2017	Cap	99.95	1.8 to 3.1*	9	523 to 618	20.0 to 40
Ono et al. [24]	2016	Cap	HPLC	1.1	12	350 to 476	10.0 to 40
Pimentel-Rodas et al. [25]	2016	Cap	99.90	0.7	27	298 to 334	0.6 to 30
Zéberg-Mikkelsen et al. [26]	2005	FCyl	99.80	2.0	23	293 to 353	20.0 to 100
Assael and Polimatiidou [27]	1994	VW	99.50	0.5	27	298 to 328	0.1 to 28
Papatoannou and Panayiotou [28]	1994	FCyl	99.50	1 to 2.5	12	298	0.1 to 52
Papatoannou et al. [29]	1993	FCyl	99.50	2.5	11	298	0.1 to 72
Tanaka et al. [30]	1987	FCyl	99.50	2.0	16	298, 323	0.1 to 78
Golubev [31] [†]	1953	RCyl	na	na	114	273 to 534	0.1 to 102
<i>Primary data—0.1 MPa</i>							
Bhagat and Maken [32]	2021	RBall	99.80	0.3	3	298 to 318	0.1
Cai et al. [33]	2020	RBall	99.90	0.5	6	298 to 323	0.1
Jangir et al. [34]	2020	Cap	99.00	0.5	3	303 to 313	0.1
Wei et al. [35]	2020	RBall	99.90	0.3	7	288 to 318	0.1
Yang and Fang. [36]	2019	RBall	99.50	2.0	5	293 to 333	0.1
Alam et al. [37]	2018	RBall	99.90	0.5	11	293 to 343	0.1
Bian et al. [38]	2017	RBall	99.71	1.5	9	293 to 333	0.1
Li et al. [39]	2017	Cap	99.80	0.3	3	298 to 308	0.1
Liu et al. [40]	2017	Cap	99.80	1.0	4	293 to 323	0.1
Shan et al. [41]	2017	FBall	99.70	1.0	2	293, 298	0.1
Xing et al. [42]	2017	Cap	99.80	0.6	7	288 to 318	0.1
Lai and Tu [43]	2016	RBall	99.90	0.5	2	298, 318	0.1

Table 1 (continued)

Investigators/reference	Publ. Year	Technique employed ^a	Purity ^b (%)	Uncertainty (%)	No. of data	Temperature range (K)	Pressure range (MPa)
Mrad et al. [44]	2016	Cap	99.80	1.0	3	283 to 313	0.1
Sas et al. [45]	2016	RBall	99.90	0.5	3	298 to 318	0.1
Cano-Gomez et al. [46]	2015	RBall	99.80	1.0	8	293 to 328	0.1
Chen et al. [47]	2015	RBall	99.80	0.5	5	293 to 313	0.1
Lu et al. [48]	2015	RBall	99.80	0.5	7	293 to 323	0.1
Salinas et al. [49]	2015	RBall	99.90	0.2	4	278 to 338	0.1
Castro et al. [50]	2014	Cap	99.80	0.5	7	278 to 338	0.1
Faria et al. [51]	2013	Cap	99.80	2.0 *	4	283 to 313	0.1
Quijada-Maldonado et al. [52]	2013	Cap	99.50	0.3	7	298 to 328	0.1
Xu et al. [53]	2013	RBall	99.80	0.2	5	293 to 313	0.1
Cano-Gomez et al. [54]	2012	RBall	99.80	0.4	8	293 to 328	0.1
Chen et al. [55]	2012	RBall	99.90	0.8	5	293 to 323	0.1
Garcia-Mardones et al. [56]	2012	Cap	99.50	1.0	4	293 to 323	0.1
Han et al. [57]	2012	Cap	99.70	1.0	5	293 to 333	0.1
Quijada-Maldonado et al. [58]	2012	Cap	99.50	0.34	4	298 to 343	0.1
Shao et al. [59]	2012	RBall	99.70	0.5	4	298 to 313	0.1
Hasan et al. [60]	2011	Cap	99.50	0.3	4	298 to 313	0.1
Hoga and Torres [61]	2011	RCyl	99.90	0.2	4	293 to 308	0.1
Hou et al. [62]	2010	Cap	99.50	0.6 *	8	278 to 313	0.1
Yang et al. [63]	2010	Cap	99.80	0.6	8	278 to 313	0.1
Feitosa et al. [64]	2009	RCyl	98.50	0.35	2	293, 298	0.1
Wang et al. [65]	2009	Cap	99.80	0.3	6	303 to 328	0.1
Yan et al. [66]	2009	Cap	99.50	0.3	4	298 to 328	0.1

Table 1 (continued)

Investigators/reference	Publ. Year	Technique employed ^a	Purity ^b (%)	Uncertainty (%)	No. of data	Temperature range (K)	Pressure range (MPa)
Ali et al. [67]	2008	Cap	99.80	0.3	2	298, 303	0.1
Rehman and Ansari [68]	2008	Cap	99.00	1.0	12	268 to 323	0.1
Zafarani-Moattar and Tohidifar [69]	2008	Cap	99.50	0.5	4	288 to 328	0.1
Zafarani-Moattar and Magdan-Cegincara [70]	2008	Cap	99.80	0.5	4	298 to 328	0.1
Zafarani-Moattar and Khoshshima [71]	2008	Cap	99.80	0.5	3	298 to 318	0.1
Yang et al. [72]	2008	Cap	99.50	0.3	6	293 to 333	0.1
Sun and Ma [73]	2007	Cap	99.90	0.3	7	293 to 343	0.1
Gomez et al. [74]	2006	Cap	99.80	1.0	3	288 to 328	0.1
Kadam et al. [75]	2006	Cap	99.00	0.3	2	298, 308	0.1
Sheu and Tu [76]	2006	Cap	99.90	0.6	4	288 to 318	0.1
Chen and Tu [77]	2005	Cap	99.80	0.6	3	288 to 308	0.1
Djojoputro and Ismadji [78]	2005	RBall	99.00	0.4	3	293 to 313	0.1
Djojoputro and Ismadji [79]	2005	RBall	99.50	0.4	3	298 to 318	0.1
Ku and Tu [80]	2005	Cap	99.80	0.8	3	298 to 318	0.1
Wang et al. [81]	2005	RBall	99.80	0.6	3	298 to 318	0.1
Wankhede et al. [82]	2005	Cap	98.00	0.2	3	298 to 308	0.1
Ye and Tu [83]	2005	Cap	99.90	0.5	3	298 to 308	0.1
Rodriguez et al. [84]	2004	RBall	99.90	0.2	4	293 to 313	0.1
Peng and Tu [85]	2002	Cap	99.60	0.7	3	288 to 308	0.1
Tu et al. [86]	2001	Cap	99.60	0.8	3	298 to 318	0.1
Tu et al. [87]	2001	Cap	99.60	0.7	3	293 to 313	0.1
Tu et al. [88]	2000	Cap	99.50	0.7	3	293 to 313	0.1
Ali and Nain [89]	1999	Cap	Anal	0.3	5	298 to 318	0.1

Table 1 (continued)

Investigators/reference	Publ. Year	Technique employed ^a	Purity ^b (%)	Uncertainty (%)	No. of data	Temperature range (K)	Pressure range (MPa)
Kumagai and Yokoyama [90]	1998	Cap	99.50	1.3	4	273 to 333	0.1
Lee and Lin [91]	1995	FBall	99.80	1.5	3	303 to 323	0.1
Sivaramprasad et al. [92]	1990	Cap	Lab	0.5	4	303 to 333	0.1
Komarenko et al. [93]	1967	Cap	Lab	1.5	16	160 to 298	0.1
Reid and Belenyessy [94] ^v	1960	Cap	na	na	1	423	0.1
Titani [95] ^v	1933	Cap	Lab	na	7	403 to 581	0.1
Vogel [96] ^v	1914	OsD	na	0.5	1	273	0.1
Rappenecker [97] ^v	1910	Cap	na	na	2	373, 485	0.1
Pedersen [98] ^v	1907	Cap	na	na	1	373	0.1
<i>Secondary data</i>							
Skonieczny and Krolikowska [99]	2022	Cone	99.80	1.0	10	293 to 338	0.1
Correa et al. [100]	2021	Cap	99.90	3.0	1	318	0.08
Fatima et al. [101]	2021	RBall	99.00	20.0	6	298 to 323	0.1
Krolikowska et al. [102]	2021	Cone	99.80	3.0	10	293 to 338	0.1
Lladosa et al. [103]	2021	FBall	99.90	3.0	5	283–323	0.1
Mohammadi et al. [104]	2021	FBall	99.80	3.0	1	298	0.1
Satheesh et al. [105]	2021	Cap	99.90	na	3	298 to 308	0.1
Wei et al. [106]	2021	RBall	99.00	2.7	7	288 to 318	0.1
Yoshimura et al. [107]	2021	na	99.50	0.1	1	298	0.1
Ariba et al. [108]	2020	RBall	99.00	3.0	5	283 to 323	0.1
Fernandez et al. [109]	2020	Cap	99.90	5.0	5	293 to 313	0.1
Goncalves et al. [110]	2020	FBall	99.50	0.7	1	298	0.1
Kumari et al. [111]	2020	RCyl	99.90	1.0 ^{NP}	3	293 to 303	0.1

Table 1 (continued)

Investigators/reference	Publ. Year	Technique employed ^a	Purity ^b (%)	Uncertainty (%)	No. of data	Temperature range (K)	Pressure range (MPa)
Liu et al. [112]	2020	RBall	99.80	2.3	6	288 to 308	0.1
Mousavi et al. [113]	2020	RBall	99.90	0.18	3	293 to 303	0.1
Naessesms et al. [114]	2020	RCyl	99.80	0.1	1	298	0.1
Touazi et al. [115]	2020	RCyl	99.80	2.45	3	293 to 313	0.1
Zhang et al. [116]	2020	RBall	99.50	0.01	3	303 to 313	0.1
Bittencourt et al. [117]	2019	Cone	99.90	9.0 *	5	293 to 313	0.1
Hema et al. [118]	2019	Cap	99.00	0.1 NP	4	283 to 333	0.1
Koshima et al. [119]	2019	FBall	99.81	10.0	1	298	0.1
Lin et al. [120]	2019	Cap	99.81	3.0	3	303 to 323	0.1
Lu et al. [121]	2019	RBall	99.80	4.0 *	7	293 to 323	0.1
Mirheydari et al. [122]	2019	Cap	99.20	2.5	7	288 to 318	0.1
Paiva et al. [123]	2019	RCyl	99.50	2.4	4	293 to 323	0.1
Verma et al. [124]	2019	RBall	na	0.3	1	298	0.1
Alcalde et al. [125]	2018	MovP	99.80	2.0	5	293 to 323	0.1
Goncalves et al. [126]	2018	FBall	99.90	0.7	1	298	0.1
Hoga et al. [127]	2018	Cone	99.90	14.0 *	4	293 to 308	0.1
Ozturk et al. [128]	2018	FBall	98.00	6.0	1	298	0.1
Shekaari et al. [129]	2018	RBall	99.80	10.0	4	288 to 318	0.1
Verma et al. [130]	2018	na	na	0.3	1	298	0.1
Budeanu and Dumitrescu [131]	2017	Cap	99.30	0.1	5	288 to 308	0.1
Sawhney et al. [132]	2017	Cap	na	0.1	3	298 to 308	0.1
Zarei et al. [133]	2017	Cap	99.80	0.6	1	298	0.1
Babavali et al. [134]	2016	Cap	99.00	0.1	4	303 to 318	0.1

Table 1 (continued)

Investigators/reference	Publ. Year	Technique employed ^a	Purity ^b (%)	Uncertainty (%)	No. of data	Temperature range (K)	Pressure range (MPa)
Liu and Liu [135]	2016	Cap	99.80	3.0	5	298 to 318	0.1
Yang et al. [136]	2016	Cap	98.00	0.15	3	293 to 333	0.1
Zhang et al. [137]	2016	RBall	99.80	4.0	7	293 to 322	0.1
Cao et al. [138]	2015	RBall	99.70	0.5	1	298	0.1
Dalai et al. [139]	2015	Cap	99.90	0.3	1	303	0.1
Neyband et al. [140]	2015	Cap	99.80	0.3	1	298	0.1
Florido et al. [141]	2014	FBall	99.81	na	1	298	0.1
Gonçalves et al. [142]	2014	FBall	98.00	0.65	1	298	0.1
Moosavi et al. [143]	2014	RCyl	98.00	0.1	6	298 to 323	0.1
Moosavi et al. [144]	2014	Cap	99.68	25.0	3	298 to 308	0.1
Zhang et al. [145]	2014	Cap	99.90	0.5 ^{NP}	7	293 to 323	0.1
Zhu et al. [146]	2014	Cap	99.70	0.1	5	293 to 333	0.1
Caro et al. [147]	2013	Cap	99.80	na	5	283 to 313	0.1
Estrada-Baltazar et al. [148]	2013	Cap	99.90	na	7	293 to 323	0.1
Kondaiah et al. [149]	2013	Cap	99.50	na	3	303 to 323	0.1
Yang et al. [150]	2013	Cone	99.50	2.0	4	293 to 308	0.1
Blanco et al. [151]	2012	Cap	99.50	0.26	1	298	0.1
Cui et al. [152]	2012	Cap	na	na	5	293 to 333	0.1
Gong et al. [153]	2012	RBall	99.70	0.5 ^{NP}	9	293 to 333	0.1
Khattab et al. [154]	2012	Cap	99.90	0.01	7	293 to 323	0.1
Li et al. [155]	2012	RBall	99.70	0.005	1	298	0.1
Qian et al. [156]	2012	RBall	99.80	0.1	5	293 to 313	0.1
Sreekanth et al. [157]	2012	Cap	99.00	na	3	308 to 318	0.1

Table 1 (continued)

Investigators/reference	Publ. Year	Technique employed ^a	Purity ^b (%)	Uncertainty (%)	No. of data	Temperature range (K)	Pressure range (MPa)
Yao et al. [158]	2012	FBall	99.80	na	7	293 to 323	0.1
Xu et al. [159]	2012	RBall	99.00	na	5	293 to 313	0.1
Garcia-Abuin et al. [160]	2011	Cap	99.50	na	4	293 to 323	0.1
Kurmia and Mutalib [161]	2011	RCyl	99.70	na	5	293 to 323	0.1
Lui et al. [162]	2011	Cap	99.50	7.0	5	293 to 333	0.1
Sadeghi and Azizpour [163]	2011	Cap	99.90	0.1	5	293 to 313	0.1
Anouti et al. [164]	2010	Cone	99.00	0.1	7	293 to 323	0.1
Bhattacharjee and Roy [165]	2010	Cap	99.90	0.02	1	298	0.1
Goncalves et al. [166]	2010	Cap	99.80	0.1	23	273 to 346	0.1
Li et al. [167]	2010	Cap	99.50	0.6 ^{NP}	5	298 to 318	0.1
Rilo et al. [168]	2010	FBall	99.50	na	4	298 to 318	0.1
Andreatta et al. [169]	2009	Cap	99.90	0.5	1	298	0.1
Domanska and Laskowska [170]	2009	RBall	99.80	0.3 ^{NP}	6	298 to 348	0.1
Mokhtarani et al. [171]	2009	RBall	na	20.0	11	283 to 333	0.1
Roy et al. [172]	2009	Cap	99.50	0.02	3	298 to 318	0.1
Roy et al. [173]	2009	Cap	99.00	0.02	3	298 to 318	0.1
Tsierkezos and Molinou [174]	2009	Cap	99.90	0.1	1	293	0.1
Zarei et al. [175]	2009	Cap	99.80	0.4	1	303	0.08
Alkindi et al. [176]	2008	Cap	99.99	1.0	1	294	0.1
Arce et al. [177]	2008	Cap	99.80	0.5	1	298	0.1
Awwad et al. [178]	2008	Cap	99.90	0.3 ^{NP}	4	293 to 323	0.1
Gomez et al. [179]	2008	Cap	99.80	na	3	298 to 328	0.1
Nain [180]	2008	Cap	99.50	na	6	293 to 318	0.1

Table 1 (continued)

Investigators/reference	Publ. Year	Technique employed ^a	Purity ^b (%)	Uncertainty (%)	No. of data	Temperature range (K)	Pressure range (MPa)
Sih et al. [181]	2008	FCyl	99.70	5.0	4	298 to 313	0.1
Bhuiyan and Uddin [182]	2007	Cap	99.90	na	5	303 to 323	0.1
Gurung and Roy [183]	2007	Cap	99.50	0.03	3	298 to 318	0.1
Mehta et al. [184]	2007	Cap	na	0.1	3	303 to 313	0.1
Pires et al. [185]	2007	FBall	99.80	0.1	2	298, 318	0.1
Alvarez et al. [186]	2006	Cap	99.70	na	6	298 to 323	0.1
Aralaguppi and Baragi [187]	2006	Cap	99.90	na	3	298 to 308	0.1
Arce et al. [188]	2006	Cap	99.90	na	1	298	0.1
Das and Roy [189]	2006	Cap	99.00	0.02	1	298	0.1
Gonzalez et al. [190]	2006	Cap	99.80	na	3	298 to 328	0.1
Gonzalez et al. [191]	2006	Cap	99.80	0.1	3	298 to 303	0.1
Iloukhani et al. [192]	2006	Cap	99.00	0.1	1	298	0.1
Mutalik et al. [193]	2006	Cap	99.90	na	3	298 to 308	0.1
Rodriguez et al. [194]	2006	Cap	99.90	0.1	1	298	0.1
Roy and Sinha [195]	2006	Cap	99.90	na	1	303	0.1
Bhat and Sreelatha [196]	2005	Cap	99.90	na	4	288 to 318	0.1
Calvar et al. [197]	2005	na	99.80	na	1	298	0.1
Chen et al. [198]	2005	Cap	99.80	na	3	298 to 303	0.1
Gonzalez et al. [199]	2005	Cap	99.90	0.1	1	298	0.1
Oswal et al. [200]	2005	Cap	99.50	0.2	1	303	0.1
Agarwal and Singh [201]	2004	Cap	99.00	0.3	1	298	0.1
Belda et al. [202]	2004	Cap	99.50	na	7	293 to 343	0.1
Chen et al. [203]	2004	Cap	na	0.6	3	288 to 308	0.1

Table 1 (continued)

Investigators/reference	Publ. Year	Technique employed ^a	Purity ^b (%)	Uncertainty (%)	No. of data	Temperature range (K)	Pressure range (MPa)
Herraez and Belda [204]	2004	Cap	99.00	na	1	298	0.1
Ouyang et al. [205]	2004	RCyl	99.90	1.0	1	298	0.1
Rattan et al. [206]	2004	Cap	99.80	na	2	298, 308	0.1
Saleh et al. [207]	2004	Cap	99.00	0.06	5	303, 323	0.1
Romano et al. [208]	2003	Cap	99.60	0.4 ^{NP}	5	298 to 313	0.1
Marrigliano and Solimo [209]	2002	Cap	100.0	5.0	6	298 to 323	0.1
Prasad et al. [210]	2002	FBall	99.90	na	3	293 to 313	0.1
Henni et al. [211]	2000	Cap	99.50	na	1	313	0.1
Nikam et al. [212]	2000	Cap	na	na	3	303 to 313	0.1
Pan et al. [213]	2000	Cap	99.50	0.3	1	303	0.1
Ali et al. [214]	1999	Cap	Anal	0.3	1	303	0.1
Aralaguppi et al. [215]	1999	Cap	99.00	0.1	3	298 to 308	0.1
Haraschta et al. [216]	1999	Cap	99.80	0.2	1	298	0.1
Prasad et al. [217]	1999	FBall	na	na	4	293 to 323	0.1
Aminabhavi and Banerjee [218]	1998	Cap	99.80	0.1	3	298 to 308	0.1
Aminabhavi and Patil [219]	1998	Cap	99.60	0.1	3	298 to 308	0.1
Canosa et al. [220]	1998	RBall	99.80	0.02	1	298	0.1
Oswal and Desai [221]	1998	Cap	99.50	na	2	303, 313	0.1
El-Banna [222]	1997	Cap	99.80	0.05	1	298	0.1
Orge et al. [223]	1997	RBall	99.80	na	1	298	0.1
Ali et al. [224]	1996	Cap	Anal	na	5	298 to 318	0.1
Aucejo et al. [225]	1996	Cap	99.00	0.05	1	298	0.1
García et al. [226]	1996	RBall	99.00	na	1	298	0.1

Table 1 (continued)

Investigators/reference	Publ. Year	Technique employed ^a	Purity ^b (%)	Uncertainty (%)	No. of data	Temperature range (K)	Pressure range (MPa)
Lang and Jun [227]	1996	Cap	99.50	na	1	303	0.1
Nikam et al. [228]	1996	Cap	99.70	0.1	3	298 to 308	0.1
El-Banna and Ramadan [229]	1995	Cap	na	0.008	3	298 to 318	0.1
Nikam et al., [230]	1995	Cap	99.70	0.1	2	298, 303	0.1
Rived et al. [231]	1995	Cap	99.80	na	1	303	0.1
Rodriguez et al. [232]	1994	FBall	99.80	0.1	8	278 to 313	0.1
Aminabhavi et al. [233]	1993	Cap	99.00	0.1	3	298 to 308	0.1
Crabtree and O'Brien [234]	1991	Cap	na	na	3	303 to 319	0.1
Das and Jha [235]	1991	Cap	Anal	0.5 ^{NP}	1	298?	0.1
Garcia et al. [236]	1991	Cap	na	na	5	298 to 333	0.1
Papaoannou et al. [237]	1991	Cap	99.50	0.15	1	298	0.1
Papanastasiou and Ziogas [238]	1991	Cap	Abs	na	5	288 to 308	0.1
Ramakanth et al. [239]	1991	na	99.90	na	1	298	0.1
Ramprasad et al. [240]	1991	na	na	na	1	293	0.1
Aminabhavi et al. [241]	1990	Cap	99.90	0.5	4	298 to 313	0.1
Brunson and Byers [242]	1989	DLS	na	na	49	293 to 503	0.006 to 5.2
Papanastasiou et al. [243]	1987	Cap	Abs	na	5	288 to 308	0.1
Barbetova [244]	1984	Cap	na	0.02	4	283 to 318	0.1
Bavadekar et al. [245]	1984	Cap	na	na	1	303	0.1
Noda et al. [246]	1983	Cap	na	2.0	1	298	0.1
Rauf et al. [247]	1983	Cap	na	0.1	5	288 to 328	0.1
Dizechi and Marschall [248]	1982	Cap	na	na	5	283 to 323	0.1
Kumar et al. [249]	1981	Cap	na	na	1	298	0.1

Table 1 (continued)

Investigators/reference	Publ. Year	Technique employed ^a	Purity ^b (%)	Uncertainty (%)	No. of data	Temperature range (K)	Pressure range (MPa)
Won et al. [250]	1981	Cap	na	na	1	298	0.1
Baykut and Tanrikulu [251]	1980	Cap	na	na	1	293	0.1
Pikkariainen [252]	1980	Cap	na	na	2	303, 333	0.1
Yusa et al. [253]	1977	Cap	99.90	0.37	1	298	0.1
Yusa et al. [253]	1977	FCyl	99.90	1.25	6	298	36 to 203
Lee et al. [254]	1976	Cap	Abs	na	6	303 to 313	0.1
Mussche and Verhoeve [255]	1975	FBall	na	1.0	2	293, 298	0.1
Janelli et al. [256]	1974	Cap	na	na	3	303 to 313	0.1
Ratkovics et al. [257]	1974	FBall	na	na	12	233 to 343	0.1
Shikhhaliev et al. [258]	1974	Cap	na	na	13	223 to 343	0.1
Mamedov et al. [259]	1973	na	na	na	1	293	0.1
Ratcliff and Khan [260]	1971	Cap	na	na	1	298	0.1
Blank and Popova [261]	1970	na	na	na	1	293	0.1
Konobejev and Lyapin [262]	1970	Cap	99.80	3	3	303 to 323	0.1
Phillips and Murphy [263]	1970	Cap	99.90	na	16	273 to 348	0.1
Tommila et al. [264]	1969	Cap	na	na	5	293 to 323	0.1
Kikuchi and Oikawa [265]	1967	Cap	na	na	8	288 to 323	0.1
Bamelis et al. [266]	1965	Cap	na	na	4	298 to 328	0.1
Misra and Varshni [267]	1961	Cap	na	na	8	273 to 343	0.1
Mukherjee and Grunwald [268]	1958	Cap	na	na	1	298	0.1
Ling and van Winkle [269]	1958	Cap	na	na	3	303 to 348	0.1
Hammond and Stokes [270]	1955	Cap	na	na	1	298	0.1
Chang and Wilke [271]	1955	Cap	na	na	2	298, 313	0.1

Table 1 (continued)

Investigators/reference	Publ. Year	Technique employed ^a	Purity ^b (%)	Uncertainty (%)	No. of data	Temperature range (K)	Pressure range (MPa)
Uchiyama [272] ^v	1955	na	na	na	4	373 to 673	0.1
Mukherjee [273]	1953	Cap	na	na	6	298 to 323	0.1
Teitel'baum [274]	1950	Cap	na	na	1	293	0.1
Vierk [275]	1950	Cap	na	na	1	293	0.1
Hatem [276]	1949	Cap	na	na	1	293	0.1
Jones et al. [277]	1948	Cap	na	na	1	298	0.1
Submis et al. [278]	1948	Na	na	na	3	303 to 323	0.1
Khalilov [279] ^{sat}	1939	Cap	99.80	na	37	293 to 513	0.01 to 6
Dolian and Briscoe [280]	1937	Cap	na	na	2	298	0.1
Titani [281] ^{sat}	1927	Cap	Lab	0.1	14	303 to 423	0.01 to 1.0
Bridgman [282]	1926	FCyl	na	na	18	303 to 348	0.1 to 1175
Mizushima [283]	1926	na	na	na	9	213 to 293	0.1
Parks and Kelly [284]	1925	Cap	na	na	1	298	0.1
Herz and Schuftan [285]	1922	Cap	na	na	1	298	0.1
Faust [286]	1914	Cap	na	1.5	22	273 to 326	0.1 to 295
Bingham et al. [287]	1913	Cap	na	na	11	298 to 348	0.1
Muchin [288]	1913	Cap	na	na	1	293	0.1
Thole [289]	1910	Cap	na	na	1	298	0.1
Findlay [290]	1909	Cap	na	na	1	350	0.1
Dunstan and Stubbs [291]	1908	Cap	na	na	2	298	0.1
Dunstan et al. [292]	1907	Cap	na	na	1	298	0.1
Jones and McMaster [293]	1906	Cap	na	na	2	273, 298	0.1
Dunstan [294]	1904	Cap	na	na	2	298	0.1

Table 1 (continued)

Investigators/reference	Publ. Year	Technique employed ^a	Purity ^b (%)	Uncertainty (%)	No. of data	Temperature range (K)	Pressure range (MPa)
Thorpe and Rodger [295]	1894	Cap	Lab	0.1	12	280 to 347	0.1

^aCap, Capillary; Cone, Cone and Plate; DLS, Dynamic Light Scatter; FBall, Balling Ball; FCyl, Falling Cylinder; MovP, Moving Piston; OsD, Oscillating Disk; RBall, Rolling Ball; RCyl, Rotating Cylinder; VW, Vibrating Wire

^bAbs, Absolute purity; Anal, Analar (Analytical Reagent) purity; HPLC, High-Pressure Liquid Chromatography purity; Lab, grade purified in the Laboratory but specific purity level not provided

^{Sat}Under saturation conditions measurements

^VVapor-phase measurements

*Uncertainty quoted at the 95 % confidence level. Others are not specified

[†]Data as presented by Golubev [296]

^{NP}Not in the primary data set, due to deviations far in excess of quoted uncertainties—see also text

na not available

quote uncertainties of less than 0.2 % (e.g., 0.005 %!), characteristic of investigators that do not understand how to assess their measurement uncertainty, have been placed in the secondary data set. Since we are also interested in low-uncertainty measurements, we also did not consider for the primary data set measurements with quoted uncertainty larger than 2 %.

In conclusion, the viscosity measurements in 0.1 MPa, to be included in the primary data set,

1. must not be a single measurement at room temperature,
2. their quoted uncertainty must be between 0.2 % and 2 %, and
3. the purity of the sample and the technique employed must be stated.

Additionally, we included the vapor-measurements of Reid and Belenyessy [94], Titani [95], Vogel [96], Rappenecker [97] and Pedersen [98] as they are the only ones in the vapor phase. Here we note that Uchiyama [272] reported also 4 measurements in the vapor phase, but they were more than 20 % lower than the aforementioned values, so they were not considered as part of the primary dataset.

We also did not include in the primary data set at 0.1 MPa measurements performed by the cone and plate technique as this is an excellent technique for non-Newtonian fluids, but not particularly accurate for Newtonian ones. We also did not include the one set performed in a moving piston viscometer, as this technique is not fully backed by theory. Moreover, we also excluded 9 sets of measurements that, although satisfied the above criteria, showed very large, unexplainable deviations which were higher than the quoted uncertainty, from the remaining sets: Kumari et al. [111] 10 % deviation, Hema et al. [118] 10 %, Zhang et al. [145] 7 %, Gong et al. [153] 5 %, Li et al. [167] 10 %, Domanska and Laskowska [170] 10 %, Awwad et al. [178] 8 %, Romano et al. [208] 5 %, and Das and Jha [235] 48 %.

In conclusion, from the 275 sets of measurements shown in Table 1, the primary set is composed of 11 sets under pressure, and 67 sets at 0.1 MPa. Figures 1 and 2 show the ranges of the primary measurements outlined in Table 1, and the phase boundary.

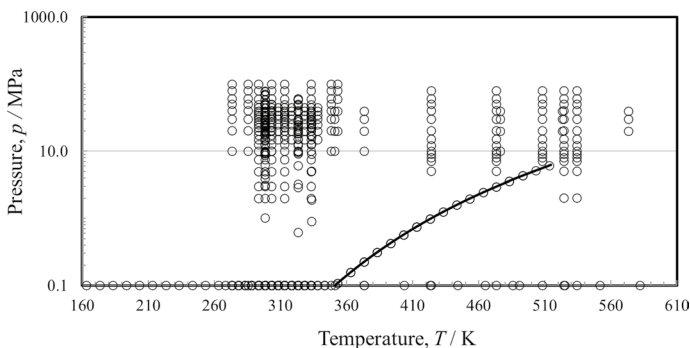


Fig. 1 Temperature–pressure ranges of the primary experimental viscosity data for ethanol. (–) saturation curve

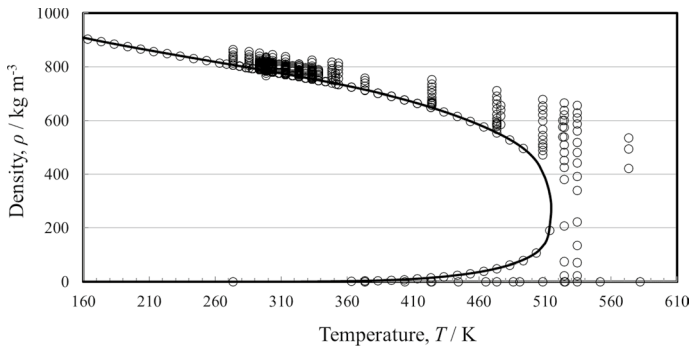


Fig. 2 Temperature–density ranges of the primary experimental viscosity data for ethanol. (–) saturation curve

The development of the correlation requires densities; Schroeder et al. [2] in 2014 reviewed the thermodynamic properties of ethanol and developed an accurate, wide-ranging equation of state valid for single-phase and saturation states from 160 K to 650 K at pressures up to 280 MPa, with an uncertainty in density of 0.2 %. We also adopt the values for the critical point and triple point from his equation of state; the critical temperature, T_c , and the critical density, ρ_c , were taken to be equal to 514.71 K and 273.186 $\text{kg}\cdot\text{m}^{-3}$, respectively [2]. The triple point temperature is 159.0 K [2].

2.1 The Dilute-Gas Limit Viscosity Term

The dilute-gas limit viscosity, $\eta_0(T)$ is a function only of temperature and can be analyzed independently of all other contributions in Eq. 1. Employing the Chapman-Enskog theory [297], the dilute-gas limit viscosity of a gas of spherical molecules is given as

$$\eta_0(T) = 0.02669 \frac{\sqrt{MT}}{\sigma^2 \Omega^{(2,2)}}, \tag{2}$$

where M ($46.0684 \text{ g}\cdot\text{mol}^{-1}$) is the molar mass, the collision diameter σ in nm is the smallest separation distance where the intermolecular potential function is equal to zero, T is the temperature in K, and the resulting viscosity is in $\mu\text{Pa}\cdot\text{s}$. $\Omega^{(2,2)}$ is a collision integral that depends upon the potential function.

In the case of nonpolar gases, Neufeld et al. [298] developed an empirical correlation for the Lennard–Jones (12-6), $\Omega^{(2,2)}$ collision integral, as a function of the dimensionless temperature $T^* = T/(\epsilon/k_B)$ (where k_B is Boltzmann’s constant and ϵ is the Lennard–Jones energy parameter), as

$$\Omega_{\text{LJ}}^{(2,2)}(T^*) = 1.16145(T^*)^{-0.14874} + 0.52487 e^{-0.7732T^*} + 2.16178 e^{-2.43787T^*} - 6.435 \times 10^{-4}(T^*)^{0.14874} \sin [18.0323(T^*)^{-0.7683} - 7.27371]. \tag{3}$$

The subscript LJ refers to the Lennard–Jones potential.

For polar gases, it is more appropriate [299] to employ the Stockmayer (12-6-3) potential $\varphi_{SM}(r)$

$$\varphi_{SM}(r) = 4\epsilon \left[\left(\frac{\sigma}{r} \right)^{12} - \left(\frac{\sigma}{r} \right)^6 + \delta \left(\frac{\sigma}{r} \right)^3 \right]. \quad (4)$$

Here, δ , accounts for the anisotropic charge distribution from which the polarity of a particle characterized by its dipole moment μ arises, as well as the angles of inclination of the dipole axis to the line joining the centers of the two molecules and the azimuthal angle between them [299].

Xiang et al. [300] fitted the values for the Stockmayer (12-6-3) collision integral, $\Omega_{SM}^{(2,2)}$, tabulated by Monchick and Mason [301], to an empirical function that reduces to the Lennard–Jones (12-6) form when the dipole moment, μ , is zero and obtained.

$$\Omega_{SM}^{(2,2)} = \Omega_{LJ}^{(2,2)} \left[1 + \frac{\delta^2}{1 + a_1 \delta^6} \Omega_{\delta}^{(2,2)} \right], \quad (5)$$

$$\text{with } \Omega_{\delta}^{(2,2)} = a_2(T^*)^{a_3} + a_4 \exp(a_5 T^*) + a_6 \exp(a_7 T^*), \quad (6)$$

with coefficients $a_1 - a_7$, given in Table 2.

In Eq. 5, the parameter δ can be obtained by the expression [301]

$$\delta = \frac{3.6220\mu^2}{\sigma^3(\epsilon/k_B)}, \quad (7)$$

where the dipole moment μ is in Debyes, σ in nm, and ϵ/k_B in K.

Equations 2, 3, 5 to 7, form a consistent scheme for the calculation of the dilute-gas limit viscosity as a function of the temperature. The only unknowns (as $\mu = 1.6909$ Debyes [302]), are the σ and ϵ parameters, which can be obtained by fitting all the available experimental vapor viscosity data at very low pressures (Reid and Belenyessy [94], Golubev [31], Titani [95], Vogel [96], Rappenecker [97], Pedersen [98]), and also the vapor-measurements of Khalilov [279] from the secondary set). The values obtained are $\sigma = 0.479$ nm and $\epsilon/k_B = 265$ K (also shown in Table 2). Figure 3 shows the gas phase low-pressure data and the calculated results for η_0 using Eqs. 2, 3, 5 to 7. The values calculated by the correlation of Kiselev et al. [4], as presented in REFPROP 10 [3], agree very well within the range of the experimental data, but deviate by up to 5 % outside this range—see also Fig. 4). The dilute-gas contribution in the Kiselev et al. [4] correlation was developed by fitting a polynomial to the experimental data. As the range of experimental data is limited, having theoretical guidance provides physically reasonable behavior upon extrapolation outside of the range of data.

Table 2 Coefficients and parameters for Eqs. 5, 6, 8, and 11

M (g·mol ⁻¹)	46.0684	ϵ/k_B (K)	265
T_c (K)	514.71	σ (nm)	0.479
ρ_c (kg·m ⁻³)	273.186	μ (D)	1.6909
Coefficients α_i (-) for Eqs. 5 and 6 [300]		Coefficients c_i (-) for Eq. 8	
1	0.95976×10^{-3}	0	- 0.0281703
2	0.10225	1	1.00
3	- 0.97346		
4	0.10657	Coefficients d_i (-) for Eq. 11 [304]	
5	- 0.34528	0	- 1.9572881×10^1
6	- 0.44557	1	2.1973999×10^2
7	- 2.58055	2	- 1.0153226×10^3
		3	2.4710125×10^3
Coefficients b_i (μPa·s) for Eq. 8		4	- 3.3751717×10^3
0	0.422373	5	2.4916597×10^3
1	- 3.78868	6	- 7.8726086×10^2
2	23.8708	7	1.4085455×10^1
3	- 7.89204	8	- 3.4664158×10^{-1}
4	2.09783		
5	- 0.247702		

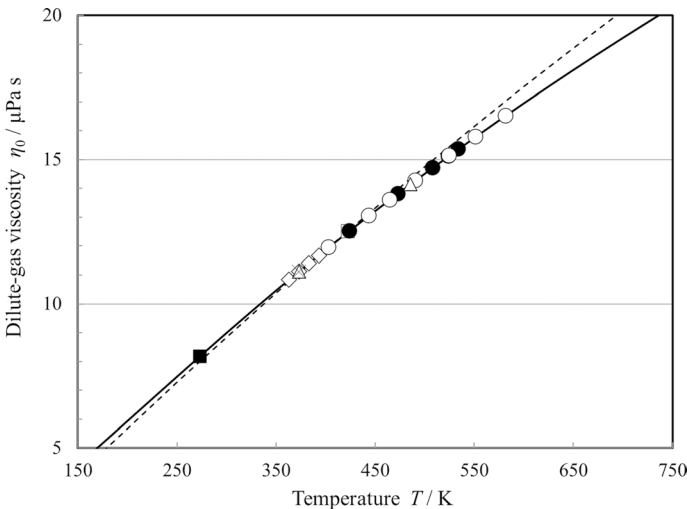


Fig. 3 Dilute-gas viscosity, η_0 , as a function of the temperature: Reid and Belenyessy [94] (□), Golubev [31] (●),Titani [95] (○), Vogel [96] (■), Rappenecker [97] (Δ), Pedersen [98] (×), Khalilov [279] (◇), and correlation of Kiselev et al. [4] (- -), Eqs. 2, 3, 5 to 7 (—)

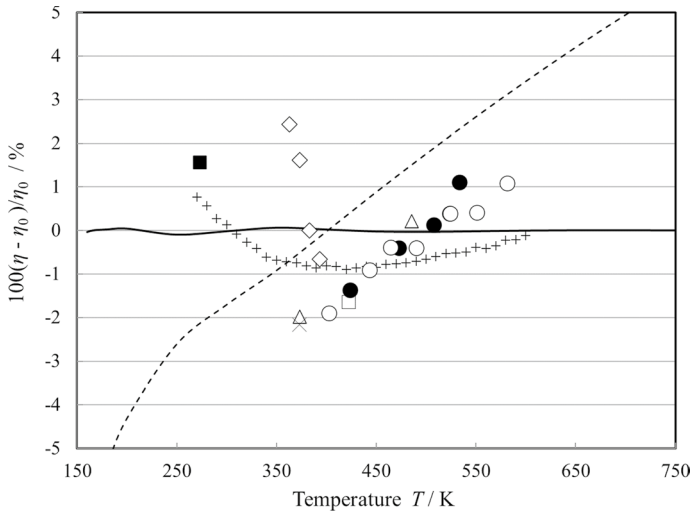


Fig. 4 Dilute-gas viscosity deviations from the values obtained by the scheme of Eqs. 2, 3, 5 to 7, as a function of the temperature: Reid and Belenyessy [94] (□), Golubev [31] (●), Titani [95] (○), Vogel [96] (■), Rappenecker [97] (Δ), Pedersen [98] (×), Touloukian et al. [303] (+), Khalilov [279] (◇), and values calculated from Eq. 8 (■), and correlation of Kiselev et al. [4] (- -)

For ease of use in calculations, η_0 was fitted as:

$$\eta_0(T_r) = \frac{\sum_{i=0}^5 b_i T_r^i}{\sum_{i=0} c_i T_r^i}, \tag{8}$$

where the units for η_0 are $\mu\text{Pa}\cdot\text{s}$, the reduced temperature is $T_r = (T/T_c)$, and the coefficients b_i and c_i are in Table 2. Equation 8 reproduces the values calculated by Eqs. 2, 3, 5 to 7 to within 0.05 % up to 1000 K, and thus it will be employed hereafter. Figure 4 shows the deviations of the measurements from the scheme of Eqs. 2, 3, 5 to 7. In the same figure the values obtained by Eq. 8 are shown, as well as the values proposed in 1975 by Touloukian et al. [303]. The values in Touloukian et al. [303] are tabulated recommended values based on analysis of experimental data. The agreement in the range of existing data, is within 2 %.

2.2 The Initial-Density Dependence Viscosity Term

To represent the initial-density dependence of viscosity term, $\eta_1\rho$, in Eq. 1, we use the model proposed by Vogel et al. [305] which expresses the second viscosity virial coefficient $B_\eta(T)$ in $\text{m}^3\cdot\text{kg}^{-1}$, as

$$B_{\eta}(T) = \frac{\eta_1(T)}{\eta_0(T)}. \quad (9)$$

In Eq. 9, when the dilute-gas limit viscosity, $\eta_0(T)$, is expressed in $\mu\text{Pa}\cdot\text{s}$, the initial-density dependence viscosity term, $\eta_1(T)$, has units $\mu\text{Pa}\cdot\text{s}\cdot\text{m}^3\cdot\text{kg}^{-1}$. The second viscosity virial coefficient can be obtained according to the theory of Rainwater and Friend [16, 17] as a function of a reduced second viscosity virial coefficient, $B_{\eta}^*(T^*)$, as

$$B_{\eta}^*(T^*) = \frac{B_{\eta}(T) M}{N_A \sigma^3}, \quad (10)$$

$$\text{where } B_{\eta}^*(T^*) = \sum_{i=0}^6 d_i(T^*)^{-0.25i} + d_7(T^*)^{-2.5} + d_8(T^*)^{-5.5}. \quad (11)$$

In Eq. 10, M is the molar mass $46.0684 \text{ g}\cdot\text{mol}^{-1}$, the scaled temperature is $T^* = T/(\epsilon/k_B)$, and N_A is the Avogadro constant. The coefficients d_i from Vogel et al. [304] are given in Table 2.

2.3 The Residual Term

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. An attempt to employ the hard-sphere model proposed by Assael et al. [306] was not very successful, as the present data cover the gas, liquid, and supercritical regions. Hence, it was preferred to evaluate this term almost entirely on experimentally obtained data, as discussed in the next paragraph.

The procedure adopted during this analysis used symbolic regression software [307] to fit all the primary data to the residual viscosity as a function of the reduced temperature, $T_r = T/T_c$ and reduced density, $\rho_r = \rho/\rho_c$. In addition, we adopted a form suggested by the hard-sphere model employed by Assael et al. [306] $\Delta\eta(\rho_r, T_r) = (\rho_r^{2/3} T_r^{1/2}) F(\rho_r, T_r)$, where the fitting software 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 term were calculated for each experimental point, employing Eqs. 8 to 11, and subtracted from the experimental viscosity to obtain the residual term, $\Delta\eta(\rho_r, T_r)$. The density values were obtained by the Schroeder et al. [2] equation of state. The final equation was

$$\Delta\eta(\rho, T) = (\rho_r^{2/3} T_r^{1/2}) \left\{ 8.32575272\rho_r + 9.66535242 \times 10^{-2} \frac{\rho_r^8}{T_r^4(1 + \rho_r^2) - T_r^2} \right\}, \quad (12)$$

where $\Delta\eta$ is in $\mu\text{Pa}\cdot\text{s}$.

2.4 Comparison with Data

The final correlation model consists of Eqs. 1, and 8 to 12 with the critical enhancement term set to zero. Tables 3 and 4 summarize comparisons of the primary data with the correlation—Table 3 for the primary data under pressure, and Table 4 for the primary data at 0.1 MPa. We define the percent deviation as $PCTDEV = 100(\eta_{exp} - \eta_{fit})/\eta_{fit}$, where η_{exp} is the experimental value of the viscosity and η_{fit} is the value calculated from the correlation. 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 percentage deviation of the fit for the primary data under pressure is 1.46 %, with a bias of 0.44 %, while for the primary data at 0.1 MPa is 1.12 %, with a bias of 0.07 %, respectively. The estimated uncertainty of the correlation in the temperature range 160 to 620 K and up to 102 MPa is 4.2 % (at the 95 % confidence level). Due to the omission of a critical enhancement term, in the near vicinity of the critical point the uncertainty can be very large since the viscosity becomes infinite at the critical point.

As the primary dataset is composed of 11 sets under pressure and 67 sets at 0.1 MPa, we decided to show only the primary datasets under pressure in figure form. Hence, Fig. 5 shows the relative deviations of the primary viscosity data under pressure, of ethanol from the values calculated by Eqs. 1, 8 to 12, as a function of temperature, while Figs. 6 and 7 show the same deviations but as a function of the pressure and the density. It should be noted that in these three figures we also included the measurements at 0.1 MPa of Komarenko et al. [93] as they are the only ones going down to 160 K.

Table 5 shows the average absolute percent deviation (AAD) and the bias for the secondary data. In most cases the agreement is within the uncertainty of the

Table 3 Evaluation of the ethanol viscosity correlation for the primary data at pressures above atmospheric

Investigators/reference	Year publ	AAD (%)	BIAS (%)
Mendo-Sanchez et al. [21]	2020	0.96	0.70
Zhu et al. [22]	2020	0.73	− 0.45
Ono et al. [23]	2017	4.43	1.07
Ono et al. [24]	2016	1.71	0.84
Pimentel-Rodas et al. [25]	2016	0.68	0.50
Zéberg-Mikkelsen et al. [26]	2005	2.46	2.40
Assael and Polimatiidou [27]	1994	0.61	0.29
Papaioannou and Panayiotou [28]	1994	1.28	0.89
Papaioannou et al. [29]	1993	1.38	1.31
Tanaka et al. [30]	1987	2.66	2.00
Golubev [31]	1953	2.76	− 0.17
Data set		1.46	0.44

Table 4 Evaluation of the ethanol viscosity correlation for the primary data at 0.1 MPa

Investigators/reference	Year Publ	AAD (%)	BIAS (%)	Investigators/reference	Year Publ	AAD (%)	BIAS (%)
Bhagat and Maken [32]	2021	1.83	- 1.83	Yan et al. [66]	2009	0.49	0.49
Cai et al. [33]	2020	1.63	1.63	Ali et al. [67]	2008	0.58	0.00
Jangir et al. [34]	2020	1.57	1.57	Rehman and Ansari [68]	2008	1.68	0.81
Wei et al. [35]	2020	0.56	0.17	Zafarani-Moattar and Tohidifar [69]	2008	1.06	- 1.06
Yang and Fang. [36]	2019	1.05	0.85	Zafarani-Moattar and Magdan-Cegincara [70]	2008	0.72	0.72
alAlam et al. [37]	2018	0.62	- 0.33	Zafarani-Moattar and Khoshshima [71]	2008	0.59	0.45
Bian et al. [38]	2017	0.83	0.60	Yang et al. [72]	2008	2.04	2.04
Li et al. [39]	2017	0.50	- 0.24	Sun and Ma [73]	2007	0.65	0.20
Liu et al. [40]	2017	2.64	- 1.55	Gomez et al. [74]	2006	0.79	0.35
Shan et al. [41]	2017	2.57	- 1.67	Kadam et al. [75]	2006	0.25	- 0.24
Xing et al. [42]	2017	2.79	- 1.77	Sheu and Tu [76]	2006	1.34	1.34
Lai and Tu [43]	2016	1.41	- 0.30	Chen and Tu [77]	2005	0.33	- 0.50
Mrad et al. [44]	2016	1.79	- 0.87	Djojoputro and Ismadji [78]	2005	2.25	- 2.25
Sas et al. [45]	2016	1.12	0.00	Djojoputro and Ismadji [79]	2005	0.85	0.41
Cano-Gomez et al. [46]	2015	2.62	- 1.49	Ku and Tu [80]	2005	0.57	0.49
Chen et al. [47]	2015	1.31	- 0.27	Wang et al. [81]	2005	0.42	0.16
Lu et al. [48]	2015	1.71	- 0.60	Wankhede et al. [82]	2005	0.46	- 0.46
Salinas et al. [49]	2015	2.20	0.83	Ye and Tu [83]	2005	0.71	- 0.41
Castro et al. [50]	2014	1.49	- 0.44	Rodriguez et al. [84]	2004	1.05	- 0.16
Faria et al. [51]	2013	0.77	0.70	Peng and Tu [85]	2002	0.72	- 0.42
Quijada-Maldonado et al. [52]	2013	0.82	0.94	Tu et al. [86]	2001	0.58	- 0.44
Xu et al. [53]	2013	1.13	2.09	Tu et al. [87]	2001	0.60	- 0.28
Cano-Gomez et al. [54]	2012	2.56	- 1.44	Tu et al. [88]	2000	0.40	- 0.40
Chen et al. [55]	2012	1.36	- 0.28	Ali and Nain [89]	1999	0.91	0.89
Garcia-Mardones et al. [56]	2012	1.35	- 0.21	Kumagai and Yokoyama [90]	1998	1.16	- 0.73

Table 4 (continued)

Investigators/reference	Year Publ	AAD (%)	BIAS (%)	Investigators/reference	Year Publ	AAD (%)	BIAS (%)
Han et al. [57]	2012	0.72	0.45	Lee and Lin [91]	1995	0.99	0.97
Quijada-Maldonado et al. [58]	2012	0.49	0.77	Sivaramprasad et al. [92]	1990	1.61	1.61
Shao et al. [59]	2012	0.47	1.05	Komarenko et al. [93]	1967	3.16	-0.10
Hasan et al. [60]	2011	1.79	-0.70	Reid and Belenyessy [94]	1960	1.75	-1.75
Hoga and Torres [61]	2011	1.12	-0.12	Titani [95]	1933	0.80	-0.37
Hou et al. [62]	2010	0.38	0.51	Vogel [96]	1914	1.48	1.48
Yang et al. [63]	2010	0.78	-0.76	Rappenecker [97]	1910	1.03	-0.96
Feitosa et al. [64]	2009	0.84	0.84	Pedersen [98]	1907	2.18	-2.18
Wang et al. [65]	2009	2.31	-2.31	Data set		1.12	-0.07

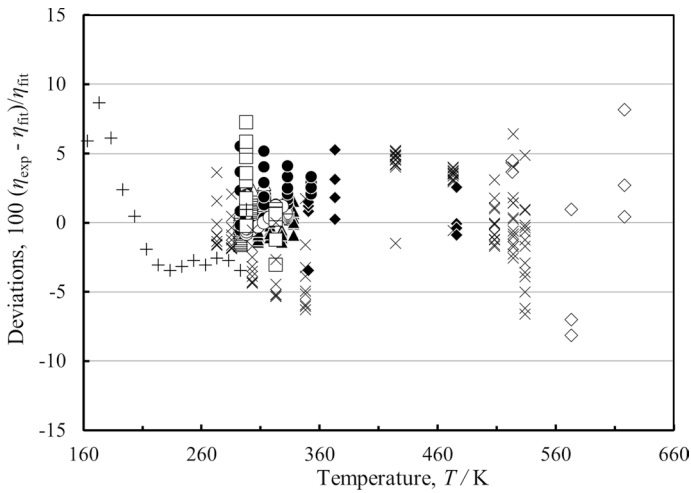


Fig. 5 Relative deviations of primary experimental data under pressure of ethanol from the values calculated by the present model, Eqs. 1, 8 to 12, as a function of temperature. Mendo-Sanchez et al. [21] (Δ), Zhu et al. [22] (\blacktriangle), Ono et al. [23] (\diamond), Ono et al. [24] (\blacklozenge), Pimentel-Rodas et al. [25] (\oplus), Zéberg-Mikkelsen et al. [26] (\bullet), Assael and Polimatidou [27] (\circ), Papaioannou and Panayiotou [28] (\bullet), Papaioannou et al. [29] (\bullet), Tanaka et al. [30] (\square), Golubev [31] (\times). The values of Komarenko et al. [93] (+) at 0.1 MPa are also included

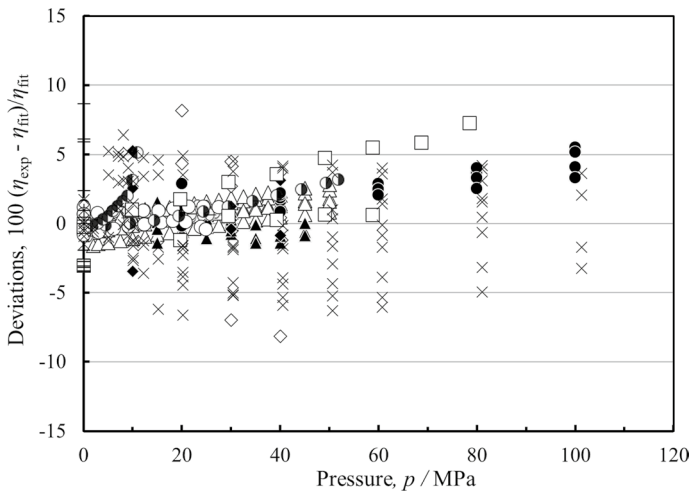


Fig. 6 Relative deviations of primary experimental data under pressure of ethanol from the values calculated by the present model, Eqs. 1, 8 to 12, as a function of pressure. Mendo-Sanchez et al. [21] (Δ), Zhu et al. [22] (\blacktriangle), Ono et al. [23] (\diamond), Ono et al. [24] (\blacklozenge), Pimentel-Rodas et al. [25] (\oplus), Zéberg-Mikkelsen et al. [26] (\bullet), Assael and Polimatidou [27] (\circ), Papaioannou and Panayiotou [28] (\bullet), Papaioannou et al. [29] (\bullet), Tanaka et al. [30] (\square), Golubev [31] (\times). The values of Komarenko et al. [93] (+) at 0.1 MPa are also included

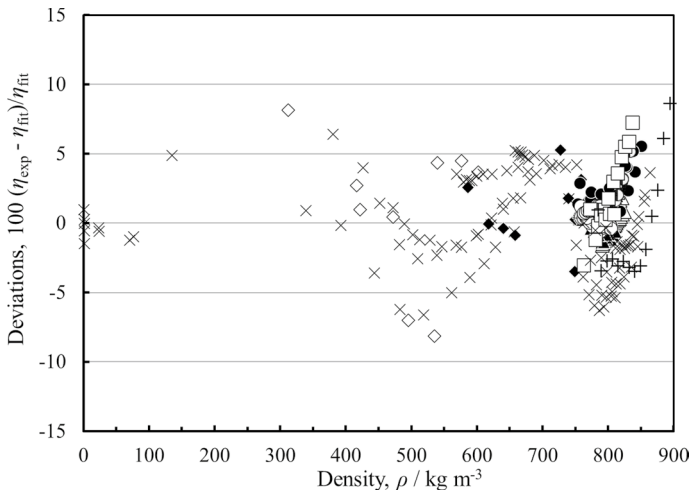


Fig. 7 Relative deviations of primary experimental data under pressure of ethanol from the values calculated by the present model, Eqs. 1, 8 to 12, as a function of density. Mendo-Sanchez et al. [21] (Δ), Zhu et al. [22] (\blacktriangle), Ono et al. [23] (\diamond), Ono et al. [24] (\blacklozenge), Pimentel-Rodas et al. [25] (\oplus), Zéberg-Mikkelsen et al. [26] (\bullet), Assael and Polimatidou [27] (\circ), Papaioannou and Panayiotou [28] (\ominus), Papaioannou et al. [29] (\odot), Tanaka et al. [30] (\square), Golubev [31] (\times). The values of Komarenko et al. [93] (+) at 0.1 MPa are also included

proposed correlation. Finally, Fig. 8 shows a plot of the viscosity of ethanol as a function of the temperature for different pressures. The plot demonstrates the physically reasonable extrapolation behavior at pressures higher than 102 MPa, and at temperatures that exceed the 620 K limit of the current measurements.

2.5 A Correlation for the Primary Data at 0.1 MPa

As the viscosity of ethanol at 0.1 MPa, $\eta(T, 0.1 \text{ MPa})$, is very often used, the primary data at 0.1 MPa were fitted to the following equation

$$\eta(T, 0.1 \text{ MPa}) = \exp(-0.721846 \theta^4 + 5.91281 \theta^3 - 15.0092 \theta^2 + 20.9305 \theta - 3.62716), \quad (13)$$

where the viscosity is in ($\mu\text{Pa}\cdot\text{s}$) and $\theta = 273.15/T$. The above equation is valid from the triple point (159 K) to the 0.1 MPa boiling temperature of 351.57 K, with an estimated uncertainty of 2.3 % (at the 95 % confidence level). Figure 9 shows the relative deviations of primary experimental data at 0.1 MPa of ethanol from the values calculated by Eq. 13, as a function of temperature.

3 Recommended Values

In Table 6, viscosity values are given along the saturated liquid and vapor curves, calculated from the full correlation given by Eq. 1 and Eqs. 8 to 12 between 160 K and 510 K, while in Table 7 viscosity values are given for temperatures between 180 K and 600 K at selected pressures. Saturation pressure and saturation density values for

Table 5 Evaluation of the ethanol viscosity correlation for the secondary data

Investigators/reference	Year publ	AAD (%)	BIAS (%)	Investigators/reference	Year publ	AAD (%)	BIAS (%)
Skonieczny and Krolikowska [99]	2022	1.70	0.73	Chen et al. [198]	2005	1.46	- 1.46
Correa et al. [100]	2021	2.37	2.37	Gonzalez et al. [199]	2005	0.67	- 0.67
Fatima et al. [101]	2021	2.97	2.97	Oswal et al. [200]	2005	0.29	0.29
Krolikowska et al. [102]	2021	0.54	- 0.39	Agarwal and Singh [201]	2004	2.08	2.08
Lladosa et al. [103]	2021	1.42	- 0.50	Belda et al. [202]	2004	3.31	1.41
Mohammadi et al. [104]	2021	0.66	0.66	Chen et al. [203]	2004	0.39	- 0.38
Satheesh et al. [105]	2021	2.16	1.71	Herraez and Belda [204]	2004	1.22	- 1.22
Wei et al. [106]	2021	0.39	- 0.13	Ouyang et al. [205]	2004	2.69	- 2.69
Yoshimura et al. [107]	2021	0.04	- 0.04	Rattan et al. [206]	2004	3.10	3.10
Ariba et al. [108]	2020	3.15	- 3.15	Saleh et al. [207]	2004	0.80	0.80
Fernandez et al. [109]	2020	0.34	1.34	Romano et al. [208]	2003	1.66	1.24
Goncalves et al. [110]	2020	3.93	3.93	Marigliano and Solimo [209]	2002	4.12	- 4.10
Kumari et al. [111]	2020	10.55	- 6.42	Prasad et al. [210]	2002	10.00	- 10.00
Liu et al. [112]	2020	0.88	0.88	Henni et al. [211]	2000	1.06	1.06
Mousavi et al. [113]	2020	0.42	- 0.42	Nikam et al. [212]	2000	2.36	- 2.36
Naessens et al. [114]	2020	0.67	- 0.67	Pan et al. [213]	2000	0.48	- 0.48
Touazi et al. [115]	2020	2.28	1.78	Ali et al. [214]	1999	1.90	1.90
Zhang et al. [116]	2020	0.53	- 0.53	Aralaguppi et al. [215]	1999	0.61	0.61
Hema et al. [118]	2019	6.20	- 6.20	Haraschta et al. [216]	1999	0.70	0.39
Koshima et al. [119]	2019	1.08	1.08	Prasad et al. [217]	1999	15.00	- 11.64
Lin et al. [120]	2019	0.44	0.03	Aminabhavi and Banerjee [218]	1998	3.95	- 3.95
Lu et al. [121]	2019	1.12	- 0.82	Aminabhavi and Patil [219]	1998	3.95	- 3.95
Mirheydari et al. [122]	2019	2.46	2.46	Canosa et al. [220]	1998	1.43	- 3.19
Paiva et al. [123]	2019	2.90	2.90	Oswal and Desai [221]	1998	0.50	0.50
Verma et al. [124]	2019	0.58	- 0.58	El-Banna [222]	1997	0.32	0.11

Table 5 (continued)

Investigators/reference	Year publ	AAD (%)	BIAS (%)	Investigators/reference	Year publ	AAD (%)	BIAS (%)
Alcalde et al. [125]	2018	2.44	2.08	Orge et al. [223]	1997	2.76	- 0.22
Bittencourt et al. [117]	2018	1.45	1.45	Ali et al. [224]	1996	0.87	0.87
Goncalves et al. [126]	2018	2.97	- 2.97	Aucejo et al. [225]	1996	1.83	- 1.83
Hoga et al. [127]	2018	0.17	0.17	Garcia et al. [226]	1996	0.74	0.74
Ozturk et al. [128]	2018	4.44	- 4.44	Lang and Jun [227]	1996	0.23	0.23
Shekaari et al. [129]	2018	2.80	- 2.80	Nikam et al. [228]	1996	0.63	- 0.63
Verma et al. [130]	2018	0.58	- 0.58	El-Banna and Ramadan [229]	1995	2.21	1.88
Budeanu and Dumitrescu [131]	2017	2.02	2.02	Nikam et al., [230]	1995	0.66	- 1.33
Sawhney et al. [132]	2017	1.60	- 1.60	Rived et al. [231]	1995	1.55	- 1.55
Zarei et al. [133]	2017	0.35	0.16	Rodriguez et al. [232]	1994	3.29	1.02
Babavali et al. [134]	2016	3.37	- 2.09	Aminabhavi et al. [233]	1993	1.18	- 1.18
Liu and Liu [135]	2016	1.21	1.21	Crabtree and O'Brien [234]	1991	0.94	- 0.94
Yang et al. [136]	2016	1.66	- 1.34	Das and Jha [235]	1991	47.16	47.16
Zhang et al. [137]	2016	1.06	- 0.60	Garcia et al. [236]	1991	3.40	- 3.40
Cao et al. [138]	2015	0.58	- 0.58	Papaioannou et al. [237]	1991	0.63	0.63
Dalai et al. [139]	2015	0.73	- 0.73	Papanastasiou and Ziogas [238]	1991	0.31	0.31
Neyband et al. [140]	2015	1.26	1.26	Ramakanth et al. [239]	1991	21.93	21.93
Florido et al. [141]	2014	3.28	3.28	Ramprasad et al. [240]	1991	23.57	23.57
Gonçaves et al. [142]	2014	9.03	9.03	Aminabhavi et al. [241]	1990	0.56	0.56
Moosavi et al. [143]	2014	2.36	- 2.34	Brunson and Byers [242]	1989	13.32	12.93
Moosavi et al. [144]	2014	2.36	- 2.34	Papanastasiou et al. [243]	1987	0.64	- 0.51
Zhang et al. [145]	2014	3.29	3.29	Barbetova [244]	1984	0.35	- 0.31
Zhu et al. [146]	2014	2.29	- 2.29	Bavadekar et al. [245]	1984	0.66	0.66
Caro et al. [147]	2013	0.79	0.49	Noda et al. [246]	1983	0.14	0.14
Estrada- Baltazar et al. [148]	2013	0.86	0.86	Rauf et al. [247]	1983	2.05	- 2.05

Table 5 (continued)

Investigators/reference	Year publ	AAD (%)	BIAS (%)	Investigators/reference	Year publ	AAD (%)	BIAS (%)
Kondaiah et al. [149]	2013	3.27	1.68	Dizechi and Marschall [248]	1982	1.06	0.57
Yang et al. [150]	2013	0.78	-0.78	Kumar et al. [249]	1981	4.15	4.15
Bianco et al. [151]	2012	0.16	0.16	Won et al. [250]	1981	0.91	0.91
Cui et al. [152]	2012	0.91	-0.22	Baykut and Tamrikulu [251]	1980	4.07	4.07
Gong et al. [153]	2012	3.37	-3.37	Pikkarainen [252]	1980	0.59	0.59
Khattab et al. [154]	2012	3.97	3.60	Yusa et al. [253] (0.1 MPa)	1977	0.87	0.87
Li et al. [155]	2012	4.80	-4.80	Yusa et al. [253]	1977	20.17	-19.92
Qian et al. [156]	2012	2.09	2.09	Lee et al. [254]	1976	0.98	0.98
Sreekanth et al. [157]	2012	4.51	3.92	Mussche and Verhoeve [255]	1975	0.57	-0.48
Yao et al. [158]	2012	1.50	1.21	Janelli et al. [256]	1974	0.34	0.34
Xu et al. [159]	2012	3.02	3.02	Ratkovics et al. [257]	1974	1.08	-0.29
García-Abuin et al. [160]	2011	5.94	-5.94	Shikhaliev et al. [258]	1974	2.19	-2.03
Kurnia and Mutalib [161]	2011	2.05	1.36	Mamedov et al. [259]	1973	0.39	-0.39
Lui et al. [162]	2011	0.59	0.45	Ratcliff and Khan [260]	1971	0.97	0.97
Sadeghi and Azizpour [163]	2011	0.59	0.59	Blank and Popova [261]	1970	0.10	-0.10
Anouti et al. [164]	2010	2.81	-1.54	Konobeov and Lyapin [262]	1970	1.00	1.00
Bhattacharjee and Roy [165]	2010	1.29	-1.29	Phillips and Murphy [263]	1970	1.39	0.82
Goncalves et al. [166]	2010	1.79	1.69	Tommila et al. [264]	1969	0.24	0.20
Li et al. [167]	2010	4.38	4.38	Kikuchi and Oikawa [265]	1967	0.48	0.46
Rilo et al. [168]	2010	1.69	0.52	Bamelis et al. [266]	1965	0.64	0.64
Andreata et al. [169]	2009	3.24	-3.24	Misra and Varshni [267]	1961	1.33	0.64
Domanska and Laskowska [170]	2009	5.13	5.13	Mukherjee and Grunwald [268]	1958	1.13	1.13
Mokhtarami et al. [171]	2009	2.01	-1.81	Ling and van Winkle [269]	1958	1.53	1.36
Roy et al. [172]	2009	0.70	0.44	Hammond and Stokes [270]	1955	0.21	0.21

Table 5 (continued)

Investigators/reference	Year publ	AAD (%)	BIAS (%)	Investigators/reference	Year publ	AAD (%)	BIAS (%)
Roy et al. [173]	2009	0.70	0.44	Chang and Wilke [271]	1955	1.29	-1.29
Tsierkezos and Molinou [174]	2009	0.25	0.25	Uchiyama [272]	1955	14.09	-14.09
Zarei et al. [175]	2009	0.40	0.40	Mukherjee [273]	1953	2.38	2.38
Alkindi et al. [176]	2008	2.79	2.79	Teitel'baum [274]	1950	1.69	-1.69
Arce et al. [177]	2008	1.22	-1.22	Vierk [275]	1950	2.62	2.62
Awwad et al. [178]	2008	3.11	2.51	Hatem [276]	1949	0.11	-0.11
Gomez et al. [179]	2008	0.79	0.35	Jones et al. [277]	1948	0.33	0.33
Nain [180]	2008	0.59	0.57	Subnis et al. [278]	1948	1.60	0.26
Sih et al. [181]	2008	0.87	-0.87	Khalilov [279]	1939	5.51	1.63
Bhuiyan and Uddin [182]	2007	7.75	7.75	Dolian and Briscoe [280]	1937	1.38	-0.41
Gurung and Roy [183]	2007	0.57	0.50	Titani [281]	1927	2.46	2.46
Mehta et al. [184]	2007	27.30	-27.30	Bridgman [282] (limited to 200 MPa)	1926	5.52	3.78
Pires et al. [185]	2007	0.84	0.33	Mizushima [283]	1926	4.10	0.71
Alvarez et al. [186]	2006	3.78	-3.72	Parks and Kelly [284]	1925	0.87	-0.87
Aralaguppi and Baragi [187]	2006	0.61	-0.61	Herz and Schuftan [285]	1922	11.59	11.59
Arce et al. [188]	2006	1.13	-2.75	Faust [286]	1914	12.42	6.86
Das and Roy [189]	2006	0.01	-2.20	Bingham et al. [287]	1913	3.82	2.34
Gonzalez et al. [190]	2006	0.69	-0.16	Muchin [288]	1913	4.32	4.32
Gonzalez et al. [191]	2006	0.69	-0.16	Thole [289]	1910	3.24	3.24
Iloukhani et al. [192]	2006	0.34	0.34	Findlay [290]	1909	0.08	-0.08
Mutalik et al. [193]	2006	1.62	-1.62	Dunstan and Stubbs [291]	1908	2.98	0.93
Rodriguez et al. [194]	2006	1.44	1.44	Dunstan et al. [292]	1907	2.98	0.93

Table 5 (continued)

Investigators/reference	Year publ	AAD (%)	BIAS (%)	Investigators/reference	Year publ	AAD (%)	BIAS (%)
Roy and Sinha [195]	2006	2.29	- 2.29	Jones and McMaster [293]	1906	1.83	1.83
Bhat and Sreelatha [196]	2005	3.40	3.40	Dunstan [294]	1904	4.62	4.62
Calvar et al. [197]	2005	0.67	- 0.67	Thorpe and Rodger [295]	1894	1.11	0.37

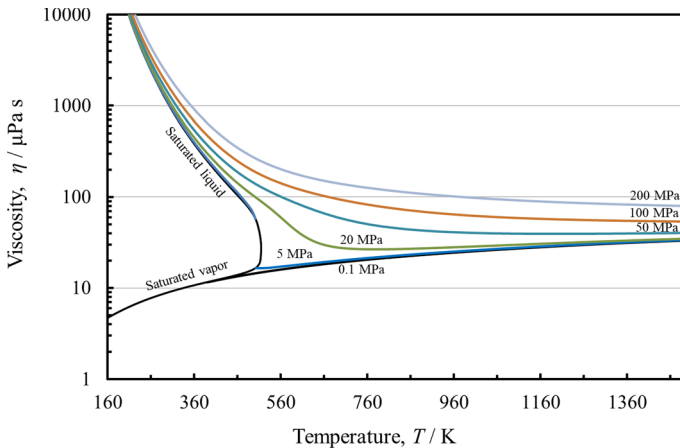


Fig. 8 Viscosity of ethanol as a function of the temperature for different pressures

selected temperatures, as well as the density values for the selected temperature and pressure, are obtained from the equation of state of Schroeder et al. [2]. The calculations in Tables 6 and 7 are performed at the given temperatures and densities. For computer verification of values, the following points may be used for the given T, ρ conditions: $T=300$ K, $\rho=0$ kg·m⁻³, $\eta=8.9893$ μPa·s, $T=300$ K, $\rho=10.0$ kg·m⁻³, $\eta=8.9382$ μPa·s, $T=300$ K, $\rho=850.0$ kg·m⁻³, $\eta=1682.72$ μPa·s.

4 Conclusions

A new wide-ranging correlation for the viscosity of ethanol was developed based on critically evaluated experimental data and theoretical results. The average absolute percentage deviation of the fit for the primary data under pressure is 1.46 %, with a bias of 0.44 %, while for the primary data at 0.1 MPa is 1.12 %, with a bias of 0.07 %, respectively. The estimated uncertainty of the correlation in the liquid and supercritical regions for the temperature range 160 K to 620 K and up to 102 MPa is 4.2 % (at the 95 % confidence level). The estimated uncertainty in the gas phase at atmospheric pressure is 2 %. Furthermore, for calculating viscosity values at 0.1 MPa, an additional correlation is proposed, valid from the triple point (159 K) to the boiling point (351.57 K), at 0.1 MPa, with an estimated uncertainty of 2.3 % (at the 95 % confidence level).

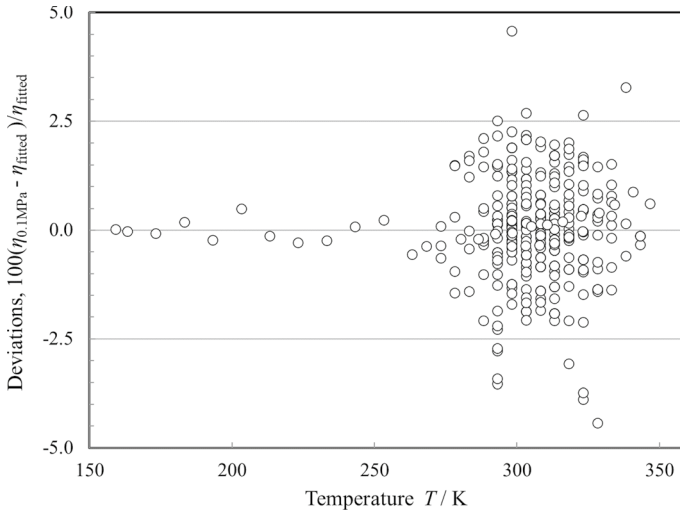


Fig. 9 Relative deviations of primary experimental data at 0.1 MPa of ethanol from the values calculated by Eq. 13, as a function of temperature

Table 6 Viscosity values of ethanol along the saturation curve, calculated by the present scheme

T (K)	p (MPa)	ρ_{liq} (kg·m ⁻³)	ρ_{vap} (kg·m ⁻³)	η_{liq} (μPa·s)	η_{vap} (μPa·s)
160	9.0145×10^{-10}	907.9	3.1217×10^{-8}	112802	4.716
180	4.8122×10^{-8}	887.9	1.4813×10^{-6}	30896	5.316
200	1.1018×10^{-6}	869.5	3.0523×10^{-5}	13,445	5.929
220	1.3694×10^{-5}	851.8	3.4489×10^{-4}	6971	6.548
240	1.0804×10^{-4}	834.5	2.4948×10^{-3}	3989	7.166
260	6.0233×10^{-4}	817.5	0.012846	2439	7.780
280	2.5697×10^{-3}	800.5	0.05078	1569	8.388
300	8.7679×10^{-3}	783.5	0.1629	1051	8.988
320	2.5238×10^{-2}	765.9	0.4426	728.3	9.582
340	6.3033×10^{-2}	747.6	1.052	520.1	10.17
360	0.14003	727.9	2.246	381.1	10.75
380	0.28215	706.4	4.393	285.7	11.33
400	0.52368	682.1	8.010	218.1	11.93
420	0.90636	654.2	13.80	168.9	12.55
440	1.4776	621.8	22.77	132.3	13.21
460	2.2890	584.0	36.47	104.4	13.97
480	3.3976	537.8	57.90	81.94	14.91
500	4.8720	467.4	96.62	59.51	16.41
510	5.7767	386.1	141.9	42.35	18.31

Table 7 Viscosity values of ethanol at selected temperatures and pressures, calculated by the present scheme

T (K)	ρ	η	ρ	η	ρ	η	ρ	η
	($\text{kg}\cdot\text{m}^{-3}$)	($\mu\text{Pa}\cdot\text{s}$)	($\text{kg}\cdot\text{m}^{-3}$)	($\mu\text{Pa}\cdot\text{s}$)	($\text{kg}\cdot\text{m}^{-3}$)	($\mu\text{Pa}\cdot\text{s}$)	($\text{kg}\cdot\text{m}^{-3}$)	($\mu\text{Pa}\cdot\text{s}$)
	0.1 MPa		25 MPa		50 MPa		75 MPa	
180	887.9	30,901	899.5	31,955				
200	869.5	13448	882.0	14,286	893.1	15,090	903.2	15869
220	851.8	6974	865.5	7550	877.5	8095	888.2	8617
240	834.6	3990	849.6	4394	862.6	4772	874.1	5133
260	817.5	2441	834.2	2732	848.2	3003	860.6	3260
280	800.6	1570	818.9	1785	834.1	1985	847.3	2174
300	783.5	1051	803.7	1216	820.2	1366	834.3	1509
320	766.0	728.7	788.4	857.0	806.2	973.6	821.3	1083
340	747.6	520.2	772.6	622.9	791.9	715.2	808.1	801.5
360	1.584	10.75	756.1	465.4	777.3	540.1	794.6	609.4
380	1.490	11.32	738.6	356.5	761.9	418.3	780.6	475.2
400	1.409	11.88	719.6	279.3	745.7	331.6	766.1	379.3
420	1.337	12.42	699.0	223.3	728.4	268.7	750.7	309.4
440	1.272	12.96	676.3	181.8	709.8	222.1	734.5	257.6
460	1.215	13.49	651.6	150.7	690.1	187.1	717.5	218.6
480	1.162	14.01	624.9	127.1	669.4	160.5	699.7	188.9
500	1.114	14.53	596.4	108.6	647.8	140.1	681.4	166.0
520	1.070	15.03	565.4	93.67	625.6	124.1	662.7	148.2
540	1.030	15.53	531.2	80.90	602.8	111.1	643.7	133.9
560	0.9926	16.01	493.1	69.58	579.4	100.5	624.6	122.4
580	0.9579	16.49	451.7	59.62	555.4	91.38	605.3	112.8
600	0.9256	16.97	409.9	51.36	531.1	83.54	586.0	104.6

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Declarations

Conflict of interest The authors declare no competing interests.

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References

1. M.J. Assael, E.A. Sykioti, M.L. Huber, R.A. Perkins, *J. Phys. Chem. Ref. Data* **42**, 023102 (2013)
2. J.A. Schroeder, S.G. Penoncello, J.S. Schroeder, *J. Phys. Chem. Ref. Data* **43**, 043102 (2014)
3. E.W. Lemmon, I.H. Bell, M.L. Huber, M.O. McLinden, NIST Standard Reference Database 23, NIST Reference Fluid Thermodynamic and Transport Properties Database (REFPROP): Version 10.0 (2018)
4. S.B. Kiselev, J.F. Ely, I.M. Abdulagatov, M.L. Huber, *Ind. Eng. Chem. Res.* **44**, 6916 (2005)
5. M.J. Assael, T.B. Papalas, M.L. Huber, *J. Phys. Chem. Ref. Data* **46**, 033103 (2017)
6. S. Avgeri, M.J. Assael, M.L. Huber, R.A. Perkins, *J. Phys. Chem. Ref. Data* **43**, 033103 (2014)
7. S. Avgeri, M.J. Assael, M.L. Huber, R.A. Perkins, *J. Phys. Chem. Ref. Data* **44**, 033101 (2015)
8. M. Mebelli, D. Velliadou, M.J. Assael, M.L. Huber, *Int. J. Thermophys.* **42**, 116 (2021)
9. E.K. Michailidou, M.J. Assael, M.L. Huber, I.M. Abdulagatov, R.A. Perkins, *J. Phys. Chem. Ref. Data* **43**, 023103 (2014)
10. E.K. Michailidou, M.J. Assael, M.L. Huber, R.A. Perkins, *J. Phys. Chem. Ref. Data* **42**, 033104 (2013)
11. S.A. Monogenidou, M.J. Assael, M.L. Huber, *J. Phys. Chem. Ref. Data* **47**, 023102 (2018)
12. D. Velliadou, K.D. Antoniadis, M.J. Assael, M.L. Huber, *Int. J. Thermophys.* **43**, 129 (2022)
13. D. Velliadou, M.J. Assael, M.L. Huber, *Int. J. Thermophys.* **43**, 105 (2022)
14. D. Velliadou, K.A. Tasidou, K.D. Antoniadis, M.J. Assael, R.A. Perkins, M.L. Huber, *Int. J. Thermophys.* **42**, 73 (2021)
15. M.J. Assael, A.E. Kalyva, S.A. Monogenidou, M.L. Huber, R.A. Perkins, D.G. Friend, E.F. May, *J. Phys. Chem. Ref. Data* **47**, 021501 (2018)
16. D.G. Friend, J.C. Rainwater, *Chem. Phys. Lett.* **107**, 590 (1984)
17. J.C. Rainwater, D.G. Friend, *Phys. Rev. A* **36**, 4062 (1987)
18. E. Bich, E. Vogel, in *Transport Properties of Fluids. Their Correlation, Prediction and Estimation* (Cambridge University Press, Cambridge, 1996)
19. V. Vesovic, W.A. Wakeham, G.A. Olchoway, J.V. Sengers, J.T.R. Watson, J. Millat, *J. Phys. Chem. Ref. Data* **19**, 763 (1990)
20. S. Hendl, J. Millat, E. Vogel, V. Vesovic, W.A. Wakeham, J. Luettmer-Strathmann, J.V. Sengers, M.J. Assael, *Int. J. Thermophys.* **15**, 1 (1994)
21. R.P. Mendo-Sanchez, C.A. Arroyo-Hernandez, A. Pimentel-Rodas, L.A. Galicia-Luna, *Fluid Phase Equilib.* **514**, 112559 (2020)
22. T. Zhu, H. Gong, M. Dong, *J. Chem. Eng. Data* **65**, 3820 (2020)
23. T. Ono, M. Kyoda, R. Ameszawa, M. Ota, Y. Sato, H. Inomata, *Fluid Phase Equilib.* **453**, 13 (2017)
24. T. Ono, R. Ameszawa, A. Igarashi, M. Ota, Y. Sato, H. Inomata, *Fluid Phase Equilib.* **407**, 198 (2016)
25. A. Pimentel-Rodas, L.A. Galicia-Luna, J.J. Castro-Arellano, *J. Chem. Eng. Data* **61**, 45 (2016)
26. C.K. Zeberg-Mikkelsen, A. Baylaucq, G. Watson, C. Boned, *Int. J. Thermophys.* **26**, 1289 (2005)
27. M.J. Assael, S.K. Polimatidou, *Int. J. Thermophys.* **15**, 95 (1994)
28. D. Papaioannou, C. Panayiotou, *J. Chem. Eng. Data* **39**, 463 (1994)
29. D. Papaioannou, M. Bridakis, C.G. Panayiotou, *J. Chem. Eng. Data* **38**, 370 (1993)
30. Y. Tanaka, Y. Matsuda, H. Fujiwara, H. Kubota, T. Makita, *Int. J. Thermophys.* **8**, 147 (1987)
31. I.F. Golubev, V.A. Petrov, *Trudy Gosudarst Nauch-Issledovatel Proekt. Inst. Azot. Prom.* **2**, 5 (1953)
32. P. Bhagat, S. Maken, *J. Mol. Liq.* **326**, 115240 (2021)
33. G. Cai, S. Yang, X. Wang, Q. Zhou, J. Xu, X. Lu, *J. Solution Chem.* **49**, 423 (2020)
34. A.K. Jangir, H. Mandviwala, P. Patel, S. Sharma, K. Kuperkar, *J. Mol. Liq.* **317**, 113923 (2020)
35. J. Wei, D. Lu, C. Jiang, D. Fang, X. Hu, *J. Mol. Liq.* **313**, 113538 (2020)
36. X. Yang, Y. Fang, *J. Chem. Eng. Data* **64**, 722 (2019)
37. M.S. Alam, B. Ashokkumar, A.M. Siddiq, *J. Mol. Liq.* **251**, 458 (2018)
38. Y. Bian, Y. Zhao, S. Shen, *J. Chem. Eng. Data* **62**, 3169 (2017)
39. Y. Li, C. Li, L. Chen, *J. Mol. Liq.* **225**, 517 (2017)
40. Q. Liu, C. Zhu, T. Fu, Y. Ma, *J. Chem. Eng. Data* **62**, 3261 (2017)
41. Y. Shan, B. Asadzadeh, W. Yan, *J. Chem. Eng. Data* **62**, 3229 (2017)
42. N. Xing, L. Yang, J. Wei, C. Gu, Z. Li, W. Guan, *J. Chem. Thermodyn.* **115**, 171 (2017)
43. G.H. Lai, C.H. Tu, *J. Chem. Eng. Data* **61**, 3048 (2016)

44. S. Mrad, C. Lafuente, M. Hichri, I. Khattech, *J. Chem. Eng. Data* **61**, 2946 (2016)
45. O.G. Sas, R. Fidalgo, I. Dominguez, E.A. Macedo, B. Gonzalez, *J. Chem. Eng. Data* **61**, 4191 (2016)
46. J.J. Cano-Gomez, G.A. Iglesias-Silva, E.O. Castrejon-Gonzalez, M. Ramos-Estrada, K.R. Hall, *J. Chem. Eng. Data* **60**, 1945 (2015)
47. J. Chen, L. Chen, Y. Xu, *J. Chem. Thermodyn.* **88**, 110 (2015)
48. X. Lu, D. Wu, D. Ye, Y. Wang, Y. Guo, W. Fang, *J. Chem. Eng. Data* **60**, 2618 (2015)
49. R. Salinas, J. Pla-Franco, E. Lladosa, J. Monton, *J. Chem. Eng. Data* **60**, 525 (2015)
50. M.C. Castro, H. Rodriguez, A. Arce, A. Soto, *Ind. Eng. Chem. Res.* **53**, 11850 (2014)
51. M.A.F. Faria, R.J. Martins, M.J.E.M. Cardoso, O.E. Barcia, *J. Chem. Eng. Data* **58**, 3405 (2013)
52. E. Quijada-Maldonado, G.W. Meindersma, A.B. De Haan, *J. Chem. Thermodyn.* **57**, 500 (2013)
53. Y. Xu, B. Chen, W. Qian, H. Li, *J. Chem. Thermodyn.* **58**, 449 (2013)
54. J.J. Cano-Gomez, G.A. Iglesias-Silva, *J. Chem. Eng. Data* **57**, 2560 (2012)
55. K.D. Chen, Y.F. Lin, C.H. Tu, *J. Chem. Eng. Data* **57**, 1118 (2012)
56. M. Garcia-Mardones, I. Gascon, M.C. Lopez, F.M. Royo, C. Lafuente, *J. Chem. Eng. Data* **57**, 3549 (2012)
57. S. Han, C. Zhu, Y. Ma, *J. Chem. Eng. Data* **57**, 1396 (2012)
58. E. Quijada-Maldonado, S. van der Boogaart, J.H. Lijbers, G.W. Meindersma, A.B. de Haan, *J. Chem. Thermodyn.* **51**, 51 (2012)
59. D. Shao, X. Lu, W. Fang, G. Yongsheng, L. Xu, *J. Chem. Eng. Data* **57**, 937 (2012)
60. M. Hasan, A.P. Hiray, U.B. Kadam, D.F. Shirude, K.J. Kurhe, A.B. Sawant, *J. Solution Chem.* **40**, 415 (2011)
61. H.E. Hoga, R.B. Torres, *J. Chem. Thermodyn.* **43**, 1104 (2011)
62. C. Hou, Z. Jiang, B. Ren, *J. Chem. Eng. Data* **55**, 4943 (2010)
63. L. Yang, T.L. Luo, H.L. Lian, G.J. Liu, *J. Chem. Eng. Data* **55**, 1364 (2010)
64. F.X. Feitosa, A.C.R. Caetano, T.B. Cidade, H.B. de Sant Ana, *J. Chem. Eng. Data* **54**, 2957 (2009)
65. Y. Wang, H.L. Lian, T.L. Luo, G.J. Liu, *J. Chem. Eng. Data* **54**, 1158 (2009)
66. J.H. Yan, L.Y. Dai, X.Z. Wang, Y.Q. Chen, *J. Chem. Eng. Data* **54**, 1147 (2009)
67. A. Ali, F. Nabi, F.A. Itoo, S. Tasneem, *J. Mol. Liq.* **143**, 141 (2008)
68. H. Rehman, M.S. Ansari, *J. Chem. Eng. Data* **53**, 2072 (2008)
69. M.T. Zafarani-Moattar, N. Tohidifar, *J. Chem. Eng. Data* **53**, 785 (2008)
70. M.T. Zafarani-Moattar, R. Majdan-Cegincara, *J. Chem. Eng. Data* **53**, 2211 (2008)
71. M.T. Zafarani-Moattar, Z. Khoshshima, *J. Chem. Thermodyn.* **40**, 1569 (2008)
72. C. Yang, Y. Sun, Y. He, P. Ma, *J. Chem. Eng. Data* **53**, 293 (2008)
73. Y. Sun, P. Ma, *Gaoxiao Huaxue Gongcheng Xuebao* **21**, 511 (2007)
74. E. Gomez, N. Calvar, I. Dominguez, A. Dominguez, *Phys. Chem. Liq.* **44**, 409 (2006)
75. U.B. Kadam, A.P. Hiray, A.B. Sawant, M. Hasan, *J. Chem. Thermodyn.* **38**, 1675 (2006)
76. Y.W. Sheu, C.H. Tu, *J. Chem. Eng. Data* **51**, 496 (2006)
77. H.W. Chen, C.H. Tu, *J. Chem. Eng. Data* **50**, 1262 (2005)
78. H. Djojoputro, S. Ismadji, *J. Chem. Eng. Data* **50**, 1343 (2005)
79. H. Djojoputro, S. Ismadji, *J. Chem. Eng. Data* **50**, 2003 (2005)
80. H.C. Ku, C.H. Tu, *J. Chem. Eng. Data* **50**, 608 (2005)
81. C.C. Wang, H.W. Chen, C.H. Tu, *J. Chem. Eng. Data* **50**, 1687 (2005)
82. N. Wankhede, M.K.K. Lande, B.R.R. Arbad, *J. Chem. Eng. Data* **50**, 969 (2005)
83. J.D. Ye, C.H. Tu, *J. Chem. Eng. Data* **50**, 1060 (2005)
84. A. Rodriguez, J. Canosa, A. Dominguez, J. Tojo, *J. Chem. Eng. Data* **49**, 157 (2004)
85. I.H. Peng, C.H. Tu, *J. Chem. Eng. Data* **47**, 1457 (2002)
86. C.H. Tu, H.C. Ku, W.F. Wang, Y.T. Chou, *J. Chem. Eng. Data* **46**, 317 (2001)
87. C.H. Tu, S.L. Lee, I.H. Peng, *J. Chem. Eng. Data* **46**, 151 (2001)
88. C.H. Tu, C.Y. Liu, W.F. Wang, Y.T. Chou, *J. Chem. Eng. Data* **45**, 450 (2000)
89. A. Ali, A.K. Nain, *Phys. Chem. Liq.* **37**, 161 (1999)
90. A. Kumagai, C. Yokoyama, *Int. J. Thermophys.* **19**, 3 (1998)
91. M.J. Lee, T.K. Lin, *J. Chem. Eng. Data* **40**, 336 (1995)
92. G. Sivaramprasad, M.V. Rao, D.H.L. Prasad, *J. Chem. Eng. Data* **35**, 122 (1990)
93. V.G. Komarenko, V.G. Manzhelii, A.V. Radtsig, *Ukr. Fiz. Zh.* **12**, 676 (1967)
94. R.C. Reid, L.I. Belenyessy, *J. Chem. Eng. Data* **5**, 150 (1960)
95. T. Titani, *Bull. Chem. Soc. Jpn.* **8**, 255 (1933)
96. H. Vogel, *Ann. Phys.* **43**, 1235 (1914)

97. K. Rappenecker, *Z. Phys. Chem.* **72**, 695 (1910)
98. F.M. Pedersen, *Phys. Rev.* **25**, 225 (1907)
99. M. Skonieczny, M. Krolikowska, *J. Chem. Eng. Data* **67**, 869 (2022)
100. M.L. Correa, L.F. Cardona, J.A. Velasquez, L.A. Forero, *J. Chem. Eng. Data* **66**, 1089 (2021)
101. U. Fatima, Riyazuddeen, P. Dhakal, J.K. Shah, *J. Chem. Eng. Data* **66**, 101 (2021)
102. M. Krolikowska, K. Grzeszyk, M. Skonieczny, *Fluid Phase Equilib.* **547**, 113175 (2021)
103. E. Lladosa, S. Loras, H. Poy, L. Caballero, *J. Chem. Eng. Data* **66**, 968 (2021)
104. M.D. Mohammadi, M. Hamzehloo, H.Y. Abdullah, *J. Solution Chem.* **50**, 576 (2021)
105. B. Satheesh, D. Sreenu, T.S. Jyostna, *J. Solution Chem.* **50**, 615 (2021)
106. J. Wei, A. Yi, J. Miao, J. Liu, D. Fang, Z. Zhang, *J. Chem. Thermodyn.* **154**, 106320 (2021)
107. Y. Yoshimura, S. Hattori, K. Kitawaki, T. Mori, K. Kaneko, T. Takekiyo, A. Shimizu, *J. Solution Chem.* **50**, 995 (2021)
108. H. Ariba, Y. Wang, C. Devouge-Boyer, R.P. Stateva, S. Leveneur, *J. Chem. Eng. Data* **65**, 3008 (2020)
109. R.L. Fernandes, H.E. Hoga, R.B. Torres, *J. Chem. Thermodyn.* **148**, 106140 (2020)
110. D. Goncalves, C. Panzarin, C.B. Goncalves, C.E.d.C. Rodrigues, *Fluid Phase Equilib.* **521**, 112730 (2020)
111. L. Kumari, S. Gupta, I. Singh, O. Prasad, L. Sinha, M. Gupta, *J. Mol. Liq.* **299**, 112237 (2020)
112. J. Liu, X. Qi, L. Li, N. Chang, J. Wei, D. Fang, Z. Zhang, *J. Chem. Eng. Data* **65**, 5176 (2020)
113. Z. Mousavi, M. Pirdashti, A.A. Rostami, E.N. Dragoi, *Int. J. Thermophys.* **41**, 19 (2020)
114. R.M. Naessesms, R.A. Clara, A.C.G. Marigliano, *Chem. Data Collect.* **28**, 100428 (2020)
115. A.A. Touazi, P. Saeda Didaoui, P. Kamel Khimeche, D.H. Mokhtar Benziane, *Int. J. Thermophys.* **41**, 130 (2020)
116. S. Zhang, Y. Wang, X. Wang, J. Yao, H. Li, *Ind. Eng. Chem. Res.* **59**, 897 (2020)
117. S.S. Bittencourt, H.E. Hoga, R.B. Torres, J.V.H. d'Angelo, *J. Therm. Anal. Calorim.* **135**, 2519 (2019)
118. T. Hema, T. Bhatt, C.C. Pant, H. Dhondiyal, Tiwari, *Asian J. Chem.* **32**, 167 (2019)
119. C.C. Koshima, D. Goncalves, K.T. Nakamoto, T.K. Umeda, C.B. Goncalves, C.E.C. Rodrigues, *J. Chem. Eng. Data* **64**, 1873 (2019)
120. M.-J. Lin, C.-S. Su, T.-M. Yang, J.-S. Li, *J. Chin. Inst. Eng.* **42**, 420 (2019)
121. X. Lu, H. Xie, Q. Lei, W. Fang, *J. Chem. Thermodyn.* **136**, 44 (2019)
122. S.N. Mirheydari, M. Barzegar-Jalali, B. Golmohamadi, H. Shekaari, F. Martinez, A. Jouyban, *J. Chem. Eng. Data* **64**, 1425 (2019)
123. C.L. Paiva, R.S. Pinheiro, F.X. Feitosa, H.B.d. Sant'Ana, *J. Chem. Eng. Data* **64**, 594 (2019)
124. S. Verma, S. Gahlyan, J. Kaur, S. Maken, *J. Mol. Liq.* **292**, 111359 (2019)
125. R. Alcalde, M. Atilhan, S. Aparicio, *J. Mol. Liq.* **258**, 1 (2018)
126. D. Goncalves, M.F. Paludetti, P.M. Florido, C. Tonetti, C.B. Goncalves, C.E.C. Rodrigues, *J. Chem. Eng. Data* **63**, 2718 (2018)
127. H.E. Hoga, R.B. Torres, P.L.O. Volpe, *J. Chem. Thermodyn.* **122**, 38 (2018)
128. B. Ozturk, J. Esteban, M. Gonzalez-Miquel, *J. Chem. Eng. Data* **63**, 2384 (2018)
129. H. Shekaari, M.T. Zafarani-Moattar, S. Faraji, M. Mokhtarpour, *J. Mol. Liq.* **269**, 547 (2018)
130. S. Verma, S. Gahlyan, M. Rani, S. Maken, *J. Mol. Liq.* **265**, 468 (2018)
131. M.M. Budeanu, V. Dumitrescu, *J. Serb. Chem. Soc.* **82**, 891 (2017)
132. N. Sawhney, M. Kumar, R. Lal, A.K. Sharma, M. Sharma, *J. Mol. Liq.* **236**, 422 (2017)
133. H. Zarei, F. Bohloor, A. Omid, *J. Chem. Thermodyn.* **107**, 163 (2017)
134. S.F. Babavali, D. Punyaseshudu, K. Narendra, C.S. Yesaswi, C. Srinivasu, *J. Mol. Liq.* **224**, 47 (2016)
135. B. Liu, Y. Liu, *J. Chem. Thermodyn.* **92**, 1 (2016)
136. J. Yang, A. Gong, Y. Li, Z. Liu, R. Jiang, H. Sun, L. Qiu, *Fluid Phase Equilib.* **429**, 113 (2016)
137. L. Zhang, X. Lu, D. Ye, Y. Guo, W. Fang, *J. Chem. Eng. Data* **61**, 1023 (2016)
138. Q. Cao, X. Lu, X. Wu, Y. Guo, L. Xu, W. Fang, *J. Chem. Eng. Data* **60**, 455 (2015)
139. B. Dalai, S.K. Dash, S.K. Singh, B.B. Swain, *J. Mol. Liq.* **208**, 151 (2015)
140. R.S. Neyband, A. Yousefi, H. Zarei, *J. Chem. Eng. Data* **60**, 2291 (2015)
141. P.M. Florido, I.M.G. Andrade, M.C. Capellini, F.H. Carvalho, K.K. Aracava, C.C. Koshima, C.E.C. Rodrigues, C.B. Goncalves, *J. Chem. Thermodyn.* **72**, 152 (2014)
142. D. Goncalves, C.C. Koshima, K.T. Nakamoto, T.K. Umeda, K.K. Aracava, C.B. Goncalves, C.E.d.C. Rodrigues, *J. Chem. Thermodyn.* **69**, 66 (2014)
143. M. Moosavi, A. Daneshvar, E. Sedghamiz, E. Momtaz, A. Joharian, *J. Mol. Liq.* **199**, 257 (2014)

144. M. Moosavi, A. Omrani, A.A. Rostami, A. Motahari, *J. Chem. Thermodyn.* **68**, 205 (2014)
145. Z. Zhang, Q. Zhou, X. Lu, C. Qiao, S. Zhang, *J. Chem. Eng. Data* **59**, 2377 (2014)
146. C. Zhu, S. Han, J. Liu, Y. Ma, *J. Chem. Eng. Data* **59**, 880 (2014)
147. M.N. Caro, J.L. Trenzado, S. Galvan, E. Romano, E. Gonzalez, R. Alcalde, S. Aparicio, *J. Chem. Eng. Data* **58**, 909 (2013)
148. A. Estrada-Baltazar, G.A. Iglesias-Silva, C. Caballero-Ceron, *J. Chem. Eng. Data* **58**, 3351 (2013)
149. M. Kondaiah, K. Srekanth, D.S. Kumar, D.K. Rao, *J. Solution Chem.* **42**, 494 (2013)
150. Q. Yang, K. Yu, H. Xing, B. Su, Z. Bao, Y. Yang, Q. Ren, *J. Ind. Eng. Chem. (Amst.Neth.)* **19**, 1708 (2013)
151. A. Blanco, A. Garcia-Abuin, D. Gomez-Diaz, J.M. Navaza, *J. Chem. Eng. Data* **57**, 1009 (2012)
152. T.B. Cui, C. Zhang, L. Xu, G.J. Liu, Henan Shifan Daxue Xuebao. *Ziran Kexueban* **40**, 98 (2012)
153. Y.h. Gong, C. Shen, Y.Z. Lu, H. Meng, C.X. Li, *J. Chem. Eng. Data* **57**, 33 (2012)
154. I.S. Khattab, F. Bandarkar, M.A.A. Fakhree, A. Jouyban, *Korean J. Chem. Eng.* **29**, 812 (2012)
155. X.-M. Li, C. Shen, C.-X. Li, *J. Chem. Thermodyn.* **53**, 167 (2012)
156. W. Qian, Y. Xu, H. Zhu, C. Yu, *J. Chem. Thermodyn.* **49**, 87 (2012)
157. K. Srekanth, M. Kondaiah, D.S. Kumar, D.K. Rao, *J. Therm. Anal. Calorim.* **110**, 1341 (2012)
158. H. Yao, S. Zhang, J. Wang, Q. Zhou, H. Dong, X. Zhang, *J. Chem. Eng. Data* **57**, 875 (2012)
159. Y.J. Xu, J. Yao, C. Wang, H. Li, *J. Chem. Eng. Data* **57**, 298 (2012)
160. A. Garcia-Abuin, D. Gomez-Diaz, M.D. La Rubia, J.M. Navaza, *J. Chem. Eng. Data* **56**, 646 (2011)
161. K.A. Kurnia, M.I.A. Mutalib, *J. Chem. Eng. Data* **56**, 79 (2011)
162. J. Liu, C. Zhu, Y. Ma, *J. Chem. Eng. Data* **56**, 2095 (2011)
163. R. Sadeghi, S. Azizpour, *J. Chem. Eng. Data* **56**, 240 (2011)
164. M. Anouti, J. Jacquemin, D. Lemordant, *J. Chem. Eng. Data* **55**, 5719 (2010)
165. A. Bhattacharjee, M.N. Roy, *Phys. Chem. Liq.* **48**, 618 (2010)
166. F.A.M.M. Goncalves, A.R. Trindade, C.S.M.F. Costa, J.C.S. Bernardo, I. Johnson, I.M.A. Fonseca, A.G.M. Ferreira, *J. Chem. Thermodyn.* **42**, 1039 (2010)
167. H. Li, X. Chen, Z. Zhang, *J. Chem. Eng. Data* **55**, 3441 (2010)
168. E. Rilo, J. Vila, M. Garcia, L.M. Varela, O. Cabeza, *J. Chem. Eng. Data* **55**, 5156 (2010)
169. A.E. Andreatta, A. Arce, E. Rodil, A. Soto, *J. Chem. Eng. Data* **54**, 1022 (2009)
170. U. Domanska, M. Laskowska, *J. Chem. Eng. Data* **54**, 2113 (2009)
171. B. Mokhtarani, A. Sharifi, H.R. Mortaheb, M. Mirzaei, M. Mafi, F. Sadeghian, *J. Chem. Thermodyn.* **41**, 1432 (2009)
172. M.N. Roy, A. Banerjee, A. Choudhury, *Phys. Chem. Liq.* **47**, 412 (2009)
173. M.N. Roy, R. Chandra, G. Ghosh, *Zh. Fiz. Khim.* **83**, 1499 (2009)
174. N.G. Tsierkezos, I.E. Molinou, *Phys. Chem. Liq.* **47**, 505 (2009)
175. H.A. Zarei, N. Mirhidari, Z. Zangeneh, *J. Chem. Eng. Data* **54**, 847 (2009)
176. A.S. Alkindi, Y.M. Al-Wahaibi, A.H. Muggeridge, *J. Chem. Eng. Data* **53**, 2793 (2008)
177. A. Arce, A. Soto, J. Ortega, G. Sabater, *J. Chem. Eng. Data* **53**, 770 (2008)
178. A.M. Awwad, H.A. Alsyouri, K.A. Jbara, *J. Chem. Eng. Data* **53**, 1655 (2008)
179. E. Gomez, B. Gonzalez, N. Calvar, A. Dominguez, *J. Chem. Thermodyn.* **40**, 1208 (2008)
180. A.K. Nain, *J. Mol. Liq.* **140**, 108 (2008)
181. R. Sih, M. Armenti, R. Mammucari, F. Dehghani, N.R. Foster, *J. Supercrit. Fluids* **43**, 460 (2008)
182. M.M.H. Bhuiyan, J. Ferdaush, M.H. Uddin, *J. Chem. Thermodyn.* **39**, 675 (2007)
183. B.B. Gurung, M.N. Roy, *Phys. Chem. Liq.* **45**, 331 (2007)
184. N.M. Mehta, F.D. Karia, P.H. Parsania, *Fluid Phase Equilib.* **262**, 61 (2007)
185. R.M. Pires, H.F. Costa, A.G.M. Ferreira, I.M.A. Fonseca, *J. Chem. Eng. Data* **52**, 1240 (2007)
186. E. Alvarez, A. Cancela, R. Maceiras, J.M. Navaza, R. Taboas, *J. Chem. Eng. Data* **51**, 940 (2006)
187. M.I. Aralaguppi, J.G. Baragi, *J. Chem. Thermodyn.* **38**, 434 (2006)
188. A. Arce, E. Rodil, A. Soto, *J. Solution Chem.* **35**, 63 (2006)
189. M. Das, M.N. Roy, *Phys. Chem. Liq.* **444**, 663 (2006)
190. E.J. Gonzalez, L. Alonso, A. Dominguez, *J. Chem. Eng. Data* **51**, 1446 (2006)
191. B. Gonzalez, A. Dominguez, J. Tojo, *J. Chem. Thermodyn.* **38**, 1172 (2006)
192. H. Iloukhani, B. Samiey, M.A. Moghaddasi, *J. Chem. Thermodyn.* **38**, 190 (2006)
193. V. Mutalik, L.S. Manjeshwar, M. Sairam, T.M. Aminabhavi, *J. Chem. Thermodyn.* **38**, 1620 (2006)
194. A. Rodriguez, A.B. Pereiro, J. Canosa, J. Tojo, *J. Chem. Thermodyn.* **38**, 505 (2006)
195. M.N. Roy, A. Sinha, *Fluid Phase Equilib.* **243**, 133 (2006)

196. J.I. Bhat, T.N. Sreelantha, *J. Mol. Liq.* **116**, 175 (2005)
197. N. Calvar, A. Dominguez, J. Tojo, *Fluid Phase Equilib.* **235**, 215 (2005)
198. S. Chen, Q. Lei, W. Fang, *Fluid Phase Equilib.* **234**, 22 (2005)
199. B. Gonzalez, A. Dominguez, J. Tojo, M.J.C. Esteves, M.J.E.d.M. Cardoso, O.E. Barcia, *J. Chem. Eng. Data* **0**, 109 (2005)
200. S.L. Oswal, K.D. Prajapati, P. Oswal, N.Y. Ghael, S.P. Ijardar, *J. Mol. Liq.* **116**, 73 (2005)
201. D. Agarwal, M. Singh, *J. Chem. Eng. Data* **49**, 1218 (2004)
202. R. Belda, J.V. Herraes, O. Diez, *Phys. Chem. Liq.* **42**, 467 (2004)
203. H.W. Chen, C.C. Wen, C.H. Tu, *J. Chem. Eng. Data* **49**, 347 (2004)
204. J.V. Herraes, R. Belda, *J. Sol. Chem.* **33**, 117 (2004)
205. G. Ouyang, G. Lu, Y. Yang, Z.Q. Huang, *Acta Sci. Nat. Univ. Sunyatseni* **43**, 44 (2004)
206. V.K. Rattan, S. Singh, B.P.S. Sethi, *J. Chem. Eng. Data* **49**, 1074 (2004)
207. M.A. Saleh, S. Akhtar, S. Begum, M.S. Ahmed, S.K. Begum, *Phys. Chem. Liq.* **42**, 615 (2004)
208. E. Romano, J.L. Trenzado, E. González, J.S. Matos, L. Segade, E. Jiménez, *Fluid Phase Equilib.* **211**, 219 (2003)
209. A.C.G. Marigliano, H.N. Solimo, *J. Chem. Eng. Data* **47**, 796 (2002)
210. T.E.V. Prasad, R. Mythili, G.S. Nirmala, D.H.L. Prasad, *J. Chem. Eng. Data* **47**, 68 (2002)
211. A. Henni, Y. Maham, P. Tontiwachwuthkul, A. Chakma, A.E. Mather, *J. Chem. Eng. Data* **45**, 247 (2000)
212. P.S. Nikam, B.S. Jagdale, A.B. Sawant, M. Hasan, *J. Chem. Eng. Data* **45**, 559 (2000)
213. I.C. Pan, M. Tang, Y.P. Chen, *J. Chem. Eng. Data* **45**, 1012 (2000)
214. A. Ali, S. Hyder, A.K. Nain, *J. Mol. Liq.* **79**, 89 (1999)
215. M.I. Aralaguppi, C.V. Jadar, T.M. Aminabhavi, *J. Chem. Eng. Data* **44**, 216 (1999)
216. P. Haraschta, A. Heintz, J.K. Lehmann, A. Peters, *J. Chem. Eng. Data* **44**, 932 (1999)
217. T.E.V. Prasad, K. Chandrika, M. Haritha, N.B. Geetha, D.H.L. Prasad, *Phys. Chem. Liq.* **1999**, 429 (1999)
218. T.M. Aminabhavi, K. Banerjee, *J. Chem. Eng. Data* **43**, 509 (1998)
219. T.M. Aminabhavi, V.B. Patil, *J. Chem. Eng. Data* **43**, 504 (1998)
220. J. Canosa, A. Rodriguez, J. Tojo, *J. Chem. Eng. Data* **43**, 961 (1998)
221. S.L. Oswal, H.S. Desai, *Fluid Phase Equilib.* **149**, 359 (1998)
222. M.M. El-Banna, *J. Chem. Eng. Data* **42**, 31 (1997)
223. B. Orge, M. Iglesias, A. Rodriguez, J.M. Canosa, J. Tojo, *Fluid Phase Equilib.* **133**, 213 (1997)
224. A. Ali, A.K. Nain, M. Kamil, *Thermochim. Acta* **274**, 209 (1996)
225. A. Aucejo, M.C. BURGUE, R. Munoz, *J. Chem. Eng. Data* **41**, 1131 (1996)
226. B. Garcia, R. Alcalde, J.M. Leal, J.S. Matos, *J. Chem. Soc. Faraday Trans.* **92**, 3347 (1996)
227. Z.H. Lang, H.S. Jun, *Phys. Chem. Liq.* **31**, 49 (1996)
228. P.S. Nikam, T.R. Mahale, M. Hasan, *J. Chem. Eng. Data* **41**, 1055 (1996)
229. M.M. El-Banna, M.S. Ramadan, *J. Chem. Eng. Data* **40**, 367 (1995)
230. P.S. Nikam, M.C. Jadhav, M. Hasan, *J. Chem. Eng. Data* **40**, 931 (1995)
231. F. Rived, M. Roses, E. Bosch, *J. Chem. Eng. Data* **40**, 1111 (1995)
232. M. Rodriguez, M. Galan, M.J. Munoz, R. Martin, *J. Chem. Eng. Data* **39**, 102 (1994)
233. T.M. Aminabhavi, M.I. Aralaguppi, S.B. Harogoppad, R.H. Balundgi, *J. Chem. Eng. Data* **38**, 31 (1993)
234. A.M. Crabtree, J.F. O'Brien, *J. Chem. Eng. Data* **36**, 140 (1991)
235. A.K. Das, B.L. Jha, *J. Mol. Liq.* **50**, 155 (1991)
236. B. Garcia, C. Herrera, J.M. Leal, *J. Chem. Eng. Data* **36**, 269 (1991)
237. D. Papaioannou, T. Evangelou, C. Panayiotou, *J. Chem. Eng. Data* **36**, 43 (1991)
238. G.E. Papanastasiou, I.I. Ziogas, *J. Chem. Eng. Data* **36**, 46 (1991)
239. C. Ramakanth, A.K. Mukherjee, T.R. Das, *J. Chem. Eng. Data* **36**, 384 (1991)
240. G. Ramprasad, A.K. Mukherjee, T.R. Das, *J. Chem. Eng. Data* **36**, 124 (1991)
241. V.A. Aminabhavi, T.M. Aminabhavi, R.H. Balundgi, *Ind. Eng. Chem. Res.* **29**, 2106 (1990)
242. R.R. Brunson, C.H. Byers, *J. Chem. Eng. Data* **34**, 46 (1989)
243. G.E. Papanastasiou, A.D. Papoutsis, I. Kokkinidis, *J. Chem. Eng. Data* **32**, 377 (1987)
244. L.P. Barbetova, Solubility of N₂, O₂, Ar in mixtures of water, methanol, ethanol with ethylene glycol, propylene glycol, glycerol, and Et₄NBr in ethylene glycol; their densities and viscosities at 283–318 K. (Ph.D. Thesis, Ivanovo Chem. Tech. Inst., Ivanovo: Russia, 1984)
245. V.K. Bavadekar, B.D. Bamane, A.A. Nadkarni, D.S. Datar, *Bioviyanam*. **10**, 189 (1984)
246. K. Noda, Y. Aono, K. Ishida, *Kagaku Rogaku Ronbunshu* **9**, 237 (1983)

247. M.A. Rauf, G.H. Stewart, A. Farhat, J. Chem. Eng. Data **28**, 324 (1983)
248. M. Dizechi, E. Marschall, J. Chem. Eng. Data **27**, 358 (1982)
249. A. Kumar, O. Prakash, S. Prakash, J. Chem. Eng. Data **26**, 64 (1981)
250. Y.S. Won, D.K. Chung, A.F. Mills, J. Chem. Eng. Data **26**, 141 (1981)
251. S. Baykut, M. Tanrikulu, Chim. Acta Turc. **8**, 69 (1980)
252. L. Pikkarainen, Finn. Chem. Lett., 185 (1980)
253. M. Yusa, G.P. Mathur, R.A. Stager, J. Chem. Eng. Data **22**, 32 (1977)
254. F.M. Lee, L.E. Lahti, C.E. Stoops, J. Chem. Eng. Data **21**, 36 (1976)
255. M.J. Mussche, L.A. Verhoeve, J. Chem. Eng. Data **20**, 46 (1975)
256. L. Janelli, A.K. Rakshit, A. Sacco, Z. Naturforsch. **29**, 355 (1974)
257. F. Ratkovich, T. Salamon, L. Domonkos, Acta Chim. Acad. Sci. Hung. **83**, 71 (1974)
258. Y.A. Shikhaliev, A.A. Mamedov, M.A. Aleskerov, S.K. Khalilov, Zh. Fiz. Khim. **48**, 1696 (1974)
259. A.A. Mamedov, M.A. Aleksperov, Y.A. Shikhaliev, S.K. Khalilov, Deposited Document VINITI, 6334 (1973)
260. G.A. Ratcliff, M.A. Khan, Can. J. Chem. Eng. **49**, 125 (1971)
261. M.G. Blank, T.V. Popova, Ukr. Khim. Zh. **36**, 563 (1970)
262. B.I. Konobeev, V.V. Lyapin, Zh. Prikl. Khim. **43**, 803 (1970)
263. T.W. Phillips, K.P. Murphy, J. Chem. Eng. Data **15**, 304 (1970)
264. E. Tommila, E. Lindell, M.L. Virtalaime, R. Laakso, Suom. Kemistil. B **42**, 95 (1969)
265. M. Kikuchi, E. Oikawa, Nippon Kagaku Zasshi **88**, 1259 (1967)
266. P. Bamelis, P. Huyskens, E. Meussen, J. Chim. Phys. Phys.-Chim. Biol. **62**, 158 (1965)
267. B.N. Misra, Y.P. Varshni, J. Chem. Eng. Data **6**, 194 (1961)
268. L.M. Mukherjee, E. Grunwald, J. Phys. Chem. **62**, 1311 (1958)
269. T.D. Ling, M. Van Winkle, Ind. Eng. Chem. Chem. Eng. Data Ser. **3**, 88 (1958)
270. B.R. Hammond, R.H. Stokes, Trans. Faraday Soc. **51**, 1641 (1955)
271. P. Chang, C.R. Wilke, J. Phys. Chem. **59**, 592 (1955)
272. H. Uchiyama, Kagaku Kogaku **19**, 342 (1955)
273. A.K. Mukherjee, Ind. Chem. Soc. **30**, 670 (1953)
274. B.Y. Teitel'baum, T.A. Gortalova, S.G. Ganelina, Zh. Obshch. Khim. **20**, 1422 (1950)
275. A.L. Vierk, Z. Anorg. Chem. **261**, 283 (1950)
276. S. Hatem, Bull. Soc. Chim. Fr., 599 (1949)
277. W.J. Jones, S.T. Bowden, W.W. Yarnold, W.H. Jones, J. Phys. Colloid Chem. **52**, 753 (1948)
278. S.W. Subnis, W.V. Bhagwat, R.B. Kanugo, J. Indian Chem. Soc. **25**, 575 (1948)
279. K.M. Khalilov, Zh. Eksp. Teor. Fiz. **9**, 335 (1939)
280. F.E. Dolian, H.T. Briscoe, J. Phys. Chem. **41**, 1129 (1937)
281. T. Titani, Bull. Chem. Soc. Jpn. **2**, 95 (1927)
282. P.W. Bridgman, Proc. Am. Acad. Arts Sci. **61**, 57 (1926)
283. S. Mizushima, Bull. Chem. Soc. Jpn. **1**, 143 (1926)
284. G.S. Parks, K.K. Kelley, J. Phys. Chem. **29**, 727 (1925)
285. W. Herz, P. Schuftan, Z. Phys. Chem. Stoechiom. Verwandtschaftsl. **101**, 269 (1922)
286. O. Faust, Z. Phys. Chem. **86**, 479 (1914)
287. E.C. Bingham, G.F. White, A. Thomas, J.L. Cadwell, Z. Phys. Chem. (Leipzig) **83**, 641 (1913)
288. G. Muchin, Z. Elektrochem. Angew. Phys. Chem. **19**, 819 (1913)
289. F.B. Thole, J. Chem. Soc. **97**, 2596 (1910)
290. A. Findlay, Z. Phys. Chem. **69**, 203 (1909)
291. A.E. Dunstan, J.A. Stubbs, J. Chem. Soc. Trans. **93**, 1919 (1908)
292. A.E. Dunstan, B.T. Thole, J.S. Hunt, J. Chem. Soc. **91**, 1728 (1907)
293. C.H. Jones, L. McMaster, Am. Chem. J. **36**, 325 (1906)
294. A.E. Dunstan, J. Chem. Soc. **85**, 817 (1904)
295. T.E. Thorpe, J.W. Rodger, Philos. Trans. R. Soc. London, Ser. A **185**, 397 (1894)
296. I.F. Golubev, in *Viscosity of Gases and Gas Mixtures* - translated from Russian, Ed. Slutzkin, D. (Israel Program for Scientific Translations, Jerusalem, Israel, 1970)
297. R.C. Reid, J.M. Prausnitz, B.E. Poling, *The Properties of Gases and Liquids*, 4th edn (McGraw-Hill, New York, 1987)
298. P.D. Neufeld, A.R. Janzen, R.A. Aziz, J. Chem. Phys. **57**, 1100 (1972)
299. J.O. Hirschfelder, C.F. Curtiss, R.B. Bird, *Molecular Theory of Gases and Liquids* (Wiley, New York, 1964)
300. H.W. Xiang, A. Laesecke, M.L. Huber, J. Phys. Chem. Ref. Data **35**, 1597 (2006)

301. L. Monchick, E.A. Mason, *J. Chem. Phys.* **35**, 1676 (1961)
302. R.D. Nelson, D.R. Lide, A.A. Maryott, *NSRDS 10* (National Bureau of Standards, Washington, D.C., 1967)
303. Y.S. Touloukian, S.C. Saxena, P. Hestermans, *Thermophysical Properties of Matter*, vol. 11 (Plenum, New York, 1975)
304. E. Vogel, C. Küchenmeister, E. Bich, A. Laesecke, *J. Phys. Chem. Ref. Data* **27**, 947 (1998)
305. E. Vogel, E. Bich, R. Nimz, *Physica A* **139**, 188 (1986)
306. M.J. Assael, J.H. Dymond, M. Papadaki, P.M. Patterson, *Int. J. Thermophys.* **13**, 269 (1992)
307. EUREQA Formulize v.098.1, Commercial equipment, instruments, or materials are identified only in order to adequately specify certain procedures. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the products identified are necessarily the best available for the purpose (Nutionian Inc, Cambridge, 2012)

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