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Reference Correlation of the Thermal Conductivity of Nitrogen from the Triple Point to High Temperatures and Pressures

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Abstract

A new wide-ranging correlation for the thermal conductivity of nitrogen, based on the most recent ab initio dilute gas theoretical calculations, a simplified crossover critical enhancement contribution, and critically evaluated experimental data, is presented. The correlation is designed to be used with a high-accuracy Helmholtz equation of state over the range of temperatures from the triple-point temperature to 1000 K, and at pressures up to 2200 MPa. The estimated expanded uncertainty (at the 95 % confidence level) in the range of validity of the correlation ranges from a minimum of 1 % in the gas phase for temperatures from 102 K to 700 K at pressures up to 1 MPa, to 4 % in the high temperature, high pressure region covering 500 K $< T <$ 744 K at pressures from 1 MPa to 40 MPa. In the gas and supercritical region 112 K $< T <$ 475 K for pressures 1 MPa $< p <$ 1000 MPa the estimated uncertainty is 2.2 %, and for the liquid from 81 K to 122 K at pressures up to 70 MPa the estimated uncertainty is 3 %. The correlation behaves in a physically reasonable manner when extrapolated to temperatures below the triple point and is suitable for use in certain corresponding-states applications. However, care should be taken when using the correlation outside of the experimentally validated range.

Keywords Nitrogen · Thermal conductivity · Transport properties

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1 Introduction

Nitrogen is an important industrial fluid that has many uses. Accurate representation of its thermophysical properties, including thermal conductivity, is of technological importance. One application of nitrogen is as a calibration gas in the production of semiconductors. Many gases are used in the production of semiconductors, and it is common to calibrate flow meters with one gas, such as nitrogen, and then obtain calibration constants for other fluids using gas-property data [1]. Thermal conductivity is a property incorporated in some flow-meter models [2, 3] and therefore lower uncertainties in the thermal conductivity can lead to better models for laminar flow meters.

Recent advances in quantum-chemical ab initio computations allow improvement in the representation of the dilute-gas viscosity and thermal conductivity of nitrogen [4]. Recently, ab initio computations were used to develop an improved correlation for the viscosity of nitrogen [5]. It is our goal to similarly incorporate ab initio results to develop an improved correlation for the thermal conductivity of nitrogen that can not only be used for gas-calibration purposes, but that is valid over the entire fluid range incorporating gas, liquid, and supercritical regions.

Although there are a couple of wide-ranging correlations for the thermal conductivity of nitrogen developed in the 1980's [6, 7], the correlation published in 2004 by Lemmon and Jacobsen [8] is the most widely used and is considered a standard. It is valid over liquid, vapor, and supercritical states and includes a simplified crossover model to describe the critical region. According to Lemmon and Jacobsen [8], the uncertainty for the dilute-gas thermal conductivity (defined in their manuscript as $p < 1$ MPa) is generally within about 2 %, increasing near the triple point. For the non-dilute gas, the uncertainty is 2 % for temperatures greater than 150 K, while it rises to 3 % below the critical point and 5 % in the critical region, except for states near the critical point. The uncertainties above 100 MPa are not known because of the lack of experimental data on which to base estimates.

In 2013, Hellmann [4] published a new four-dimensional intermolecular potential-energy hypersurface for two rigid nitrogen molecules, determined from highly accurate quantum-chemical ab initio computations. Subsequently, he computed values of the thermal conductivity in the dilute-gas limit for temperatures between 70 and 3000 K using the kinetic theory of molecular gases and the classical trajectory method. Hellmann [4] reported that the computed thermal conductivity values were in very good agreement with the experimental data for temperatures below 500 K. However, at higher temperatures most of the experimental data show large negative deviations (up to 9 %) from the theoretically calculated values. Considering the very good agreement between theory and experiment for the thermal conductivity below 500 K as well as for the virial coefficients and shear viscosity, it is highly unlikely that the theoretically calculated values for the thermal conductivity were characterized by such large uncertainties. Therefore, Hellmann [4] concluded that the computed values were recommended as reference values for the complete temperature range.

Consequently, Hellmann et al. [9] proposed that the combined expanded uncertainty (95 % confidence level) of the computed thermal conductivity values, based on extensive comparisons with experimental data, is 1 % between 300 K and 700 K, increasing to 2 % at both 70 K and 1200 K.

Hence, the goal of this work is to develop a new wider range thermal-conductivity correlation, that will incorporate the new dilute-gas limit ab initio calculations for the thermal conductivity lowering its uncertainty in that region, while extending its temperature range and also correcting the high-temperature extrapolation of the 2004 correlation of Lemmon and Jacobsen [8]. In addition, our new correlation will incorporate critically assessed available literature data that became available after 2004, and an improved viscosity correlation [5] (viscosity is incorporated in the critical enhancement).

Over the last decade, we reported new reference correlations valid over wide ranges of temperature and pressure for hydrocarbons [10–20], alcohols [21, 22], refrigerants [23–26] and some simple fluids [27–33]. In this paper, this same methodology is employed to develop a new correlation for the thermal conductivity of nitrogen. We use an analysis based on the best available experimental data. A prerequisite to this analysis is 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 [32]. 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.

The form of correlation we use expresses the thermal conductivity as a function of temperature and density. Since experimental data are generally reported in terms of pressure and temperature, an equation of state (EOS) is needed to obtain densities. We first convert temperatures to ITS-90 [34, 35] if necessary, then use the Helmholtz EOS published by Span et al. [36] to obtain the density for a given T, p state point. We also use the critical and triple points associated with this EOS; the critical point and other constants for this EOS are given in Table 1. The uncertainty in density of this EOS is 0.02 % from the triple point up to temperatures of 523 K, and pressures up to 12 MPa and from temperatures of 240 K to 523 K at pressures less than 30 MPa. In the range from 270 K to 350 K at pressures less than 12 MPa, the uncertainty in density is 0.01 %.

Table 1 Critical point and fixed constants for the EOS of Span et al. [36]

Property	Symbol	Units	Value
Critical temperature	T_c	K	126.192
Critical pressure	p_c	MPa	3.3958
Critical density	ρ_c	mol/dm^3	11.1839
Triple-point temperature	T_{tp}	K	63.151
Molar mass	M	g/mol	28.01348

2 The Correlation

The thermal conductivity λ is expressed [10–33], as the sum of three independent contributions, as

$$\lambda(\rho, T) = \lambda_0(T) + \Delta\lambda(\rho, T) + \Delta\lambda_c(\rho, T) \quad (1)$$

where ρ is the density, T is the temperature, and the first term, $\lambda_0(T) = \lambda(0,T)$, is the contribution to the thermal conductivity in the dilute-gas limit, where only two-body molecular interactions occur. The final term, $\Delta\lambda_c(\rho,T)$, the critical enhancement, arises from the long-range density fluctuations that occur in a fluid near its critical point, which contribute to divergence of the thermal conductivity at the critical point. Finally, the term $\Delta\lambda(\rho,T)$, the residual term, represents the contribution of all other effects to the thermal conductivity of the fluid at elevated densities.

In addition to performing literature searches and utilizing content in previous correlations, we made extensive use of the NIST ThermoData Engine [134] to identify data sources. Table 2 summarizes, to the best of our knowledge, the experimental measurements of the thermal conductivity of nitrogen reported in the literature. Data sources in italics indicate that the particular set was also employed in the development of the correlation of Lemmon and Jacobsen [8]. We only included in the primary dataset measurements where the technique employed, the purity of the sample, and the uncertainty of the technique, are specified. Very few data sets specifically call out if the uncertainty is on a $k = 1$ or $k = 2$ basis; we assume $k = 2$ when no information is given. Furthermore, with the exceptions discussed below, we preferred measurements with uncertainty less than 1.5 %. Hence, the following datasets were included in the primary sets:

- Clifford et al. [53, 56], Assael and Wakeham [52], Haran et al. [50], Imaishi et al. [49], Johns et al. [46, 47] Millat et al. [44], Mostert et al. [43], Richard and Shankland [45] (even though there is no purity given), as well as the more recent measurements of Patek et al. [40], were all performed in two-wire transient hot-wire instruments, with a full theory, and with uncertainties from 0.1 % to 0.5 % (the measurements of Patek et al. [40] are quoted at 1 % but at the 95 % confidence level). These are the most accurate measurements today.
- The measurements of Perkins et al. [41, 42], Sun and Venart [39], and Wang et al. [38], were also performed in a two-wire transient hot-wire instrument with a full theory, but with 1 % uncertainty, while the measurements of Roder [54]

Table 2 Thermal conductivity measurements of nitrogen

Investigators/reference	Publ. Year	Technique employed[a]	Purity (%)	Uncertainty (%)	No. of data	Temperature range (K)	Pressure range (MPa)
Primary data							
Harvey et al. [37]	2011	2THW	99.9995	4.0[c]	310	503–744	7.6–41
Harvey et al. [37]	2011	2HW	99.9995	4.0[c]	135	502–742	0.1–9.9
Wang et al. [38]	2006	2THW	99.9995	1.0	19	235–326	0.7–5.4
Sun and Venart [39]	2005	2THW	99.99	1.0	36	300–340	0.3–7
Patek et al. [40]	2003	2THW	99.999	1.0[c]	60	300–425	0.7–18
Perkins et al. [41]	1991	2THW	99.999	1.0	65	425–428	3–58
Perkins et al. [42]	1991	2THW	99.999	1.0	377	81–303	0.3–71
Mostert et al. [43]	1990	2THW	99.9997	0.5	20	308	1.1–20
Millat et al. [44]	1989	2THW	99.998	0.3	48	177–270	0.3–11
Richard and Shankland [45]	1989	2THW	na	0.4	6	310–352	0
Johns et al. [46]	1988	2THW	99.999	0.2	12	471–476	1–28
Johns et al. [47]	1986	2THW	99.999	0.2	14	426–479	1–30
Tarzimanov et al. [48]	1985	PHHW	na	1.0	4	373, 473	30
Imaishi et al. [49]	1984	2THW	99.9	0.3	19	300	0.7–12
Haran et al. [50]	1983	2THW	99.9992	0.3	45	308–429	0.4–10
Shashkov et al. [51]	1983	HW	na	1.5	8	305–361	0.02–0.1
Assael and Wakeham [52]	1981	2THW	99.999	0.2	18	307–309	1–9.3
Clifford et al. [53]	1981	2THW	99.999	0.2	40	341–389	0.5–25
Roder [54]	1981	2THW	na	1.5	93	297–302	1–69
Tufeu and Le Neindre [55]	1980	CC	na	1.0	13	298	0.1–1000
Clifford et al. [56]	1979	2THW	99.9995	0.1	34	299–303	0.5–36
Dijkema et al. [57]	1972	CC	na	0.5	3	293–333	0.1
Le Neindre et al. [58]	1968	CC	na	1.5	50	297–304	0.1–118

Table 2 (continued)

Investigators/reference	Publ. Year	Technique employed[a]	Purity (%)	Uncertainty (%)	No. of data	Temperature range (K)	Pressure range (MPa)
Secondary data							
Yao et al. [59]	2014	THW	99.99	2.0–3.0	49	321–340	0.6–4.3
Gauthier et al. [60]	2013	3ω	na	5.0	1	298	0.1
Duan et al. [61]	1997	2THW	99.95	3.0	10	296	0.4–2
Roder et al. [62]	1988	2THW	na	na	1423	80–254	0.3–70
Zheng et al. [63]	1984	CC	99.50	3.0	21	298, 323	0.1–9.8
Tret'yakov et al. [64]	1983	HW	na	4.0	52	64–124	0.01–3.06
Yorizane et al. [65]	1983	CC	99.99	3.0	34	298–324	0.1–15.2
Tufeu and Le Neindre [66]	1979	CC	na	1.0	18	481–683	0.01–18.7
Slushar et al. [67]	1975	HW	na	3.5	31	64–300	0.01–111
Vasilkovskaya and Golubev [68]	1975	CC	na	na	12	295–570	1.0–38.7
Carey et al. [69]	1974	ACres	99.995	1.0	44	299–992	0.1–53
Chen and Saxena [70]	1973	HW	99.999	1.5	221	373–2473	0.01–0.04
Haarman [71]	1973	THW	na	0.3	8	328–468	0.1
Shashkov and Kamchatov [72]	1973	HW	na	na	9	309–395	0.1
Faubert and Springer [73] [b]	1972	HW	na	3.0	4	800–2000	0.1
Parkinson and Gray [74]	1971	2THW	99.997	2.0	2	323, 373	0.1
Peterson et al. [75]	1971	CC	99.996	2.5	11	348	5–284
Saxena [76]	1971	HW	99.95	2.0	24	350–1500	0.1
Tondon and Saxena [77]	1970	HW	99.95	2.0	6	313–448	0.1
Barua et al. [78]	1968	HW	99.5	1.0	5	273–473	0.1
Ibele and Briggs [79] [b]	1968	Pr	na	na	6	300–623	0.1
van Dael and Cauvenbergh [80]	1968	THR	99.85	na	1	296	0.1
Brain [81]	1967	CC	99.90	1.5	14	421–552	0.1

Table 2 (continued)

Investigators/reference	Publ. Year	Technique employed[a]	Purity (%)	Uncertainty (%)	No. of data	Temperature range (K)	Pressure range (MPa)
Mukhopadhyay et al. [82]	1967	HW	99.95	1.0	7	258–473	0.1
Gilmore and Comings [83]	1966	HCC	99.996	3.0	12	348	0.1–304
Baker and Brakow [84]	1965	HW	na	na	15	299–474	0.1
Keyes and Vines [85]	1965	CC	na	na	31	412–621	0.4–44
Misic and Thodos [86]	1965	CC	na	na	21	295,323	6–32
Baker and Brokaw [87]	1964	HW	na	na	4	381–525	0.1
Golubev and Kalsina [88]	1964	HW	99.995	na	322	78–273	0.1–50
Schramm [89]	1964	HW	na	3.0	10	275–1394	0.1
Vargaftik and Zhimina [90]	1964	HF	na	na	11	304–1134	0.1
Venart [91] [b]	1964	RHF	na	2.0	11	295–346	0.1
Pereira and Raw [92]	1963	HW	na	2.0	5	305–453	0.1
Cheung et al. [93]	1962	CC	na	1.2	2	377, 590	0.1
Westenberg and de Haas [94]	1962	HW	99.00	na	4	300–1000	0.1
Geier and Schaeper [95]	1961	HW	na	2.0	12	273–1373	0.1
Kramer and Comings [96]	1960	CC	99.996	na	8	348	10–104
Vines [97]	1960	CC	na	na	4	533–1173	0.1
Barua [98]	1959	HW	na	na	7	303, 318	0.1
Srivastava and Srivastava [99]	1959	HW	na	na	1	311	0.1
Ziebland and Burton [100]	1958	CC	99.50	na	86	80–202	0.1–13.6
Johannin and Vodar [101]	1957	CC	na	1.0	50	348–573	0.1–132
Nuttall and Ginnings [102]	1957	PP	99.99	0.5	18	323–773	0.07–10
Schäfer and Reiter [103]	1957	HW	na	2.0	12	273–1373	0.1
Keyes [104]	1955	CC	na	na	4	92, 273	0.1–1

Table 2 (continued)

Investigators/reference	Publ. Year	Technique employed[a]	Purity (%)	Uncertainty (%)	No. of data	Temperature range (K)	Pressure range (MPa)
Kulakov [105]	1955	HW	na	na	2	338, 603	0.1
Rothman and Bromley [106]	1955	CC	99.7	3.0	4	639–951	0.1
Ziebland and Burton [107]	1955	CC	na	na	1	80	3.4
Powers et al. [108]	1954	PP	na	1.5	12	68–88	0.03–0.3
Davidson and Music [109]	1953	CC	na	5.0	1	273	0.1
Lenoir et al. [110]	1953	CC	na	3.0	13	325	0.1–22
Michels and Botzen [111]	1953	PP	na	1.0	115	298–348	0.1–252
Senftleben [112]	1953	Ht	na	na	1	303	0.1
Keyes [113]	1952	CC	na	na	5	273–623	0.1
Schottky [114]	1952	HW	na	1.0	9	373–773	0.1
Uhlir [115]	1952	CC	na	2.5	22	76–184	0.5–6.8
Wirth and Klemene [116]	1952	HW	na	na	1	273	0.1
Franck [117]	1951	HW	na	na	20	93–787	0.07
Keyes et al. [118]	1951	CC	na	na	13	273–423	0.1–15
Lenoir and Comings [119]	1951	CC	na	3.0	13	314	0.1–21
Stoliarov et al. [120]	1950	CC	99.0	3.0	23	298–565	0.1–49
Keyes [121]	1949	CC	na	na	41	273–674	0.1–15
Borovick [122]	1947	HW	99.8	3.0	21	90–170	1.1–10
Borovick et al. [123]	1940	HW	99.8	0.7	6	77–112	0.1
Hammann [124]	1938	PP	na	2.0	6	64–73	0.1
Vargaftik [125, 126]	1937	HW	na	na	18	313–326	0.1–9.1
Shushpanov [127]	1935	HHW	na	na	14	373–493	0.1
Dickins [128]	1934	2HW	na	0.15	2	273, 296	0.1

Table 2 (continued)

Investigators/reference	Publ. Year	Technique employed[a]	Purity (%)	Uncertainty (%)	No. of data	Temperature range (K)	Pressure range (MPa)
Ibbs and Hirst [129]	1929	Kath	na	na	1	288	0.1
Gregory and Marshall [130] [b]	1928	HW	na	na	5	277–285	0.1
Weber [131]	1917	na	na	na	1	273	0.1
Eucken [132]	1911	HW	na	0.2	4	90–373	0.1
Winkelmann [133]	1875	na	na	na	1	280	0.02

Data sources in italics indicate that the particular set was also employed in the development of the correlation of Lemmon and Jacobsen [8]

[a]3-ω, 3-omega method; ACres, Acoustic Cavity resonator; CC, Concentric Cylinders; HHW, Horizontal Hot Wire; HCC, Horizontal Concentric Cylinders; Ht, Heat transfer experiment; Kath, Katharometer; PHHW, Pulse-Heated Hot Wire; PP, Parallel Plates; Pr, Based on Pr number; RHF, Radial Heat Flow; THR, Thermistors technique; THW, Transient Hot Wire; 2THW, 2-Wires Transient Hot Wire; 2HW, 2-hot wires, steady state

[b]Measurements presented only graphically

[c]Uncertainties given by the author are specified at the 95 % confidence level

na Not available

(even though purity is not given) were performed with a 1.5 % uncertainty. These sets were also included in the primary data set.
- The group of Tufeu and Le Neindre [55, 58] employed a concentric-cylinders instrument to reach very high temperatures and pressures, with an uncertainty of 1 %–1.5 %. We note that we did not include in the primary dataset the measurements of Tufeu and Le Neindre [66] as they were performed to investigate Knudsen effects and their uncertainty obtained from a graph was about 10 %.
- We also included in the primary datasets the recent high-temperature measurements of Harvey et al. [37] performed in a two-wire transient hot-wire instrument as well as a two-wire steady-state instrument, both with an uncertainty of 4 % (at the 95 % confidence level).
- Finally, we included in the primary data set three more investigators (although they did not quote sample purity). These are Tarzimanov et al. [48] and Shashkov et al. [51] that employed a hot wire with uncertainties of 1 % and 1.5 %, and Dijkema et al. [57] that employed a concentric-cylinders instrument with a 0.5 % uncertainty.

All remaining measurements were considered as secondary as they did not satisfy the criteria. Furthermore, measurements performed by unproven techniques (e.g., acoustic cavity resonator, Carey et al. [69]), or that show unusually large deviations from the rest (e.g., Slushar et al. [67], Chen and Saxena [70], Barua et al. [78]), were also not included in the primary data set. Measurements prior to 1965 were not regarded as primary, as we focused exclusively on the most reliable data—significant advancements in digital electronics, counters, and related technologies occurred after that period, marking a substantial improvement in measurement precision.

We finally note that in cases where measurements are superseded by more recent ones at the same conditions, we use only the latest (e.g., the measurements of Vargaftik and Smirnova [135] were superseded by Vargaftik and Zhimina [90], the measurements of Le Neindre [136] and Le Neindre [137], both were superseded by Tufeu and Le Neindre [55], while the measurements of Saxena and Gupta [138] and Tondon and Saxena [139] both were superseded by Tondon and Saxena [77]).

Figures 1 and 2 show the ranges of the primary measurements outlined in Table 2.

As shown in both figures, there is a large amount of data covering a wide range of temperatures and pressures.

2.1 The Dilute-Gas Term

The dilute-gas limit thermal conductivity, $\lambda_0(T)$ is a function only of temperature and can be analyzed independently of all other contributions in Eq. 1. As stated in the introduction, in 2013 Hellmann [4] published a new four-dimensional intermolecular potential energy hypersurface for two rigid nitrogen molecules, determined from highly accurate quantum-chemical ab initio computations. The computed thermal-conductivity values in the dilute-gas limit covered a temperature range between 70 K and 3000 K.

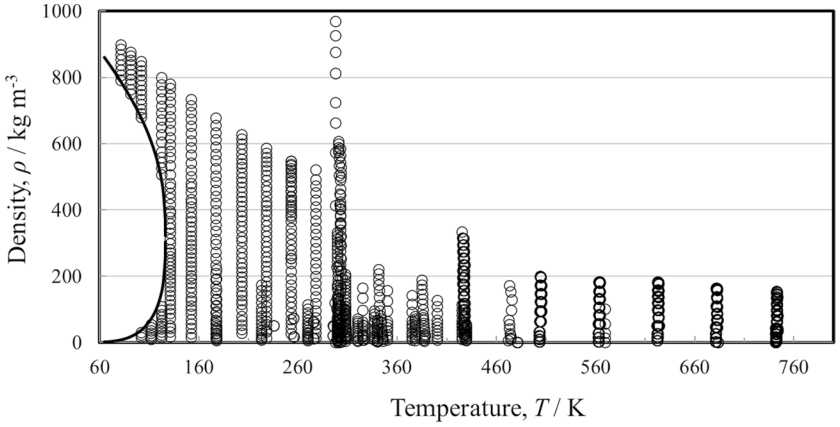

Fig. 1 Temperature-density ranges of the primary experimental viscosity data for nitrogen, (—) saturation curve

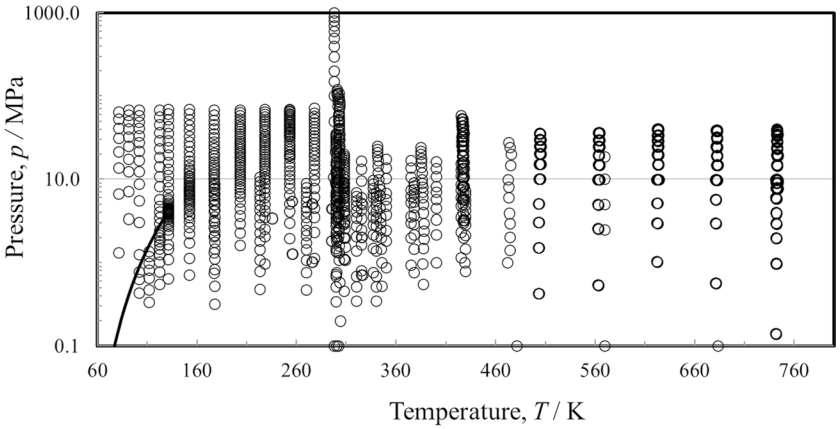

Fig. 2 Temperature–pressure ranges of the primary experimental viscosity data for nitrogen, (—) saturation curve

For ease of use in calculations, the λ_0 values calculated by Hellmann [4] over the temperature range 70 K to 3000 K were fitted using a commercial program [140] to a rational polynomial:

$$\lambda_0(\mathrm{T}) = \frac{-50.4059 + 1457.09T_\mathrm{r} - 2580.5T_\mathrm{r}^2 + 3616.59T_\mathrm{r}^3 - 695.367T_\mathrm{r}^4 + 129.796T_\mathrm{r}^5 + 4.03114T_\mathrm{r}^6}{99.3852 - 151.972T_\mathrm{r} + 229.102T_\mathrm{r}^2 - 22.9451T_\mathrm{r}^3 + 6.0789T_\mathrm{r}^4 + T_\mathrm{r}^5} \tag{2}$$

where the units for λ_0 are $\mathrm{mW{\cdot}m^{-1}{\cdot}K^{-1}}$, and the reduced temperature is $T_\mathrm{r} = (T/T_\mathrm{c})$. Equation 2 reproduces the values calculated by Hellmann [4] to within 0.04 % over the entire temperature range from 70 K to 3000 K, and will be used to represent the

dilute-gas thermal conductivity. As discussed earlier, the uncertainty is 1 % between 300 K and 700 K, increasing to 2 % at both 70 K and 1200 K.

In Fig. 3 the new dilute-gas thermal conductivity correlation of Hellmann [4], and the correlation of Lemmon and Jacobsen [8] are shown. The difference at high temperatures is apparent. Lemmon and Jacobsen [8] did not have access to the more accurate ab initio values and their correlation was based solely on experimental data available at the time. In Fig. 4, the deviations of the dilute-gas thermal conductivity from the values calculated by Eq. 2, as a function of the temperature, are shown. Dilute-gas thermal conductivity values shown in Fig. 4, are those given by the investigators, or values that could easily be extrapolated to zero density. As expected all measurements agree with the values calculated by Hellmann [4] within their mutual uncertainty (even the values of Harvey et al. [37] as they are quoted with a 4 % uncertainty at the 95 % confidence level). Data that were not included in our primary set show even larger deviations than those shown in Fig. 4, some approaching 9 % (see Fig. 6 in Hellmann [4]).

2.2 The Residual Term

The thermal conductivities of pure fluids exhibit an enhancement over a large range of densities and temperatures around the critical point and become infinite at the critical point. This behavior can be described by models that produce a smooth crossover from the singular behavior of the thermal conductivity

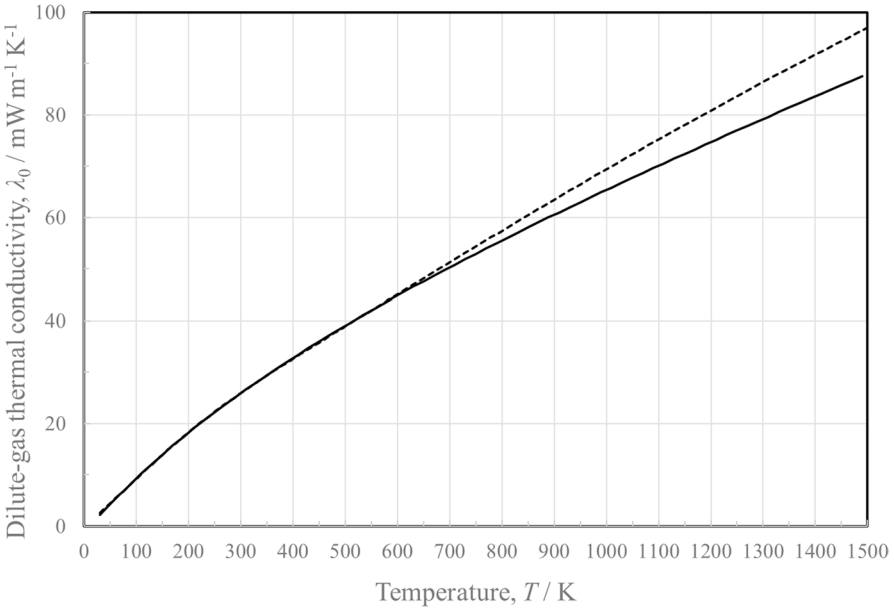

Fig. 3 Dilute-gas thermal conductivity as a function of temperature. Hellmann [4] (---), Lemmon and Jacobsen [8] (▬)

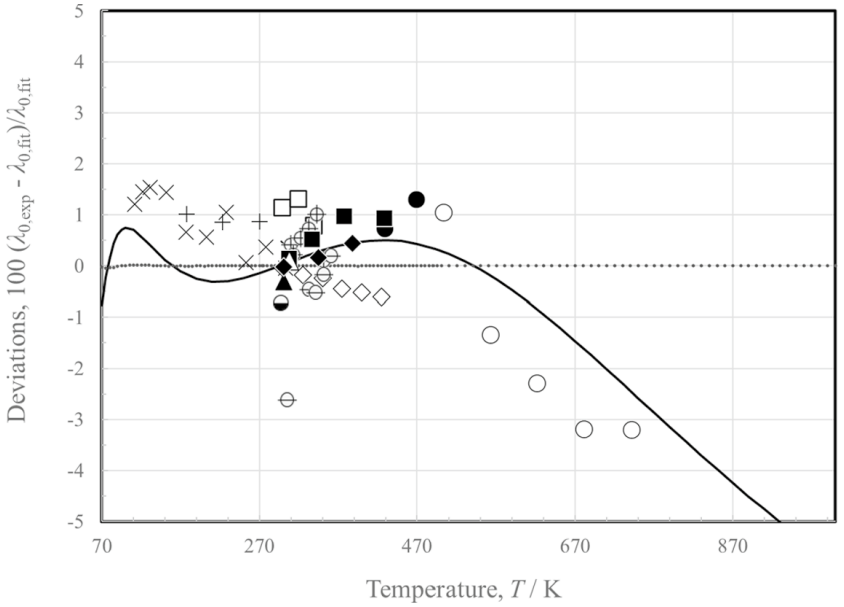

Fig. 4 Deviations of the dilute-gas thermal conductivity from the values calculated by Eq. 2, as a function of the temperature. Hellmann [4] (…), Lemmon and Jacobsen [8] (▬), Harvey et al. [37] (○), Sun and Venart [39] (□), Patek et al. [40] (◊), Perkins et al. [42] (×), Mostert et al. [43] (⚹), Millat et al. [44] (+), Richard and Shankland [45] (⊕), Johns et al. [47] (●), Imaishi et al. [49] (▲), Haran et al. [50] (■). Shashkov et al. [51] (⊖), Assael and Wakeham [52] (Δ), Clifford et al. [53] (♦), Le Neindre et al. [58] (◒)

asymptotically close to the critical point to the residual values far away from the critical point [41, 141, 142]. The density-dependent terms for thermal conductivity can be grouped according to Eq. 1 as $[\Delta\lambda(\rho,T)+\Delta\lambda_c(\rho,T)]$. To assess the critical enhancement theoretically, we need to evaluate, in addition to the dilute-gas thermal conductivity, the residual thermal-conductivity contribution. The procedure adopted during this analysis used ODRPACK (Ref. [143]) to fit all the primary data simultaneously to the residual thermal conductivity and the critical enhancement, while maintaining the values of the dilute-gas thermal-conductivity data already obtained. The density values employed were obtained by the equation of state of Span et al. [36]. The primary data were weighted in inverse proportion to the square of their uncertainty.

The residual thermal conductivity was represented with a polynomial in temperature and density:

$$\Delta\lambda(\rho,T)=\sum_{i=1}^{5}\left(B_{1,i}+B_{2,i}(T/T_c)\right)\left(\rho/\rho_c\right)^i. \tag{3}$$

Coefficients $B_{1,i}$ and $B_{2,i}$ are shown in Table 3.

Table 3 Coefficients of Eq. 3 for the residual thermal conductivity of nitrogen

i	$B_{1,i}$ (mW·m^{-1}·K^{-1})	$B_{2,i}$ (mW·m^{-1}·K^{-1})
1	0.111638×10^{-1}	0.888313×10^{-4}
2	0.176473×10^{-1}	-0.196140×10^{-2}
3	-0.165839×10^{-1}	0.280261×10^{-2}
4	0.932251×10^{-2}	-0.116666×10^{-2}
5	-0.121718×10^{-2}	0.168200×10^{-3}

2.3 The Critical-Enhancement Term

The theoretically based crossover model proposed by Olchowy and Sengers [41, 141, 142] is complex and requires solution of a quartic system of equations in terms of complex variables. A simplified crossover model has also been proposed by Olchowy and Sengers [144]. The critical enhancement of the thermal conductivity from this simplified model is given by.

$$\Delta\lambda_c = \frac{\rho c_p R_D k_B T}{6\pi\overline{\eta}\xi}\left(\overline{\Omega}-\overline{\Omega}_0\right) \tag{4}$$

with

$$\overline{\Omega} = \frac{2}{\pi}\left[\left(\frac{c_p - c_v}{c_p}\right)\arctan\left(\overline{q}_D\xi\right) + \frac{c_v}{c_p}\overline{q}_D\xi\right] \tag{5}$$

and

$$\overline{\Omega}_0 = \frac{2}{\pi}\left[1-\exp\left(-\frac{1}{(\overline{q}_D\xi)^{-1}+(\overline{q}_D\xi\rho_c/\rho)^2/3}\right)\right]. \tag{6}$$

In Eqs. 4–6, k_B is the Boltzmann constant, $\overline{\eta}$ (Pa s) is the viscosity, and c_p and c_v (J kg^{-1} K^{-1}) are the isobaric and isochoric specific heat obtained from the equation of state. The correlation length ξ (m) is given by

$$\xi = \xi_0\left(\frac{p_c\rho}{\Gamma\rho_c^2}\right)^{\nu/\gamma}\left[\left.\frac{\partial\rho(T,\rho)}{\partial p}\right|_T - \left(\frac{T_{ref}}{T}\right)\left.\frac{\partial\rho(T_{ref},\rho)}{\partial p}\right|_T\right]^{\nu/\gamma}. \tag{7}$$

This crossover model requires the universal amplitude, $R_D = 1.02$, and the universal critical exponents, $\nu = 0.63$ and $\gamma = 1.239$, and the system–dependent amplitudes Γ and ξ_0. For this work, we adopted the values $\Gamma = 0.058$ (−), $\xi_0 = 0.163\times10^{-9}$ m, using the universal representation of the critical enhancement of the thermal conductivity by Perkins et al. [145]. We also used this method to estimate the effective cutoff wavelength $\overline{q}_D^{-1}$(m), and obtained 4.33×10^{-10} m. The viscosity required for Eq. 4 was obtained from the recent viscosity correlation [5]. The reference temperature T_{ref}, far above the critical temperature where the critical enhancement is negligible, was calculated by $T_{ref} = (^3/_2)\,T_c$ [146], which for nitrogen is 189.29 K. Thus, the

present critical enhancement calculation is consistent with the equation of state of Span et al. [36] and should provide reasonable estimates of the thermal conductivity critical enhancement, although the uncertainty is larger in this area.

3 Comparison with Data

The final correlation consists of Eqs. 1–7. Table 4 summarizes comparisons of the primary data with the present work and also with the correlation of Lemmon and Jacobsen [8], and Table 5 gives comparisons with the present work for the secondary data. We define the percent deviation as $\mathrm{PCT} = 100(\lambda_{\mathrm{exp}} - \lambda_{\mathrm{fit}})/\lambda_{\mathrm{fit}}$, where λ_{exp} is the experimental value of the thermal conductivity and λ_{fit} is the value calculated from the correlation. The average absolute percent deviation (AAD) is found with the expression $\mathrm{AAD} = (\sum \left| \mathrm{PCT} \right|)/n$, where the summation is over all n points, the bias percent is found with the expression $\mathrm{BIAS} = (\sum \mathrm{PCT})/n$ and $\mathrm{STDEV} = \mathrm{sqrt}((\sum (\mathrm{PCT\text{-}BIAS})^2)/(n-1))$.

Figure 5 shows the relative deviations of the primary thermal conductivity data from the values calculated by Eqs. 1–7 as a function of temperature, while Figs. 6 and 7 show the same deviations but as a function of the pressure and the density. There are analogous figures for the model of Lemmon and Jacobsen [8] in the Supplemental information. The deviation plots and the statistics in Table 5 show that the two models are very similar. The major difference is in the dilute-gas region mentioned earlier, where the present model has superior high-temperature performance due to its incorporation of the theoretical results. Examination of Fig. 5 indicates that there are two temperature regions to consider, one region below 500 K and the other above. The data are generally represented better below 500 K, and there are more data sources for comparison. Above 500 K, there is only one primary data source—the measurements by Harvey et al. [37] that cover the temperature range from 502 K to 744 K at pressures from 0.1 MPa to 41 MPa. There are no trends with respect to pressure for this data set. The measurements were made with 2 different measurement techniques, but the expanded uncertainty is the same for both, 4 %. For all measurements of Harvey et al. [37] the AAD is 1.28 %, the BIAS is 0.30 % and the STDEV is 1.59 %. However, since the expanded uncertainty of the measurements is 4 %, using solely the experimental data we can only claim the correlation in this region has the same uncertainty as the underlying measurements, or 4 %. For temperatures below 500 K, covering the range $112\ \mathrm{K} < T < 475\ \mathrm{K}$ and pressures $1\ \mathrm{MPa} < p < 1000\ \mathrm{MPa}$, the AAD, BIAS, and STDEV for all primary data excluding the liquid phase is 0.82 %, − 0.12 %, and 1.08 % respectively and based on comparisons with experimental data we estimate the uncertainty at the $k = 2$ level to be 2.2 %.

Figure 6 shows deviations with respect to pressure. There are no systematic trends. In addition, one data set was omitted from the figure, that of Tufeu and Le Neindre [55]. These data extend up to 1000 MPa but are limited to one temperature, 298 K. For all points in that set, at pressures up to 1000 MPa, the deviations do not exceed 1.3 %.

Table 4 Evaluation of the nitrogen thermal-conductivity correlation for the primary data

Investigators/ reference	Publ. Year	This work			Lemmon and Jacobsen (2004)		
		AAD (%)	BIAS (%)	STDEV (%)	AAD (%)	BIAS (%)	STDEV (%)
Harvey et al. [37] (2THW)	2011	1.19	0.11	1.54	1.87	0.71	2.37
Harvey et al. [37] (2HW)	2011	1.48	0.64	1.61	2.43	2.20	1.83
Wang et al. [38]	2006	0.80	− 0.76	0.63	0.74	− 0.28	0.80
Sun and Venart [39]	2005	1.09	1.09	0.35	1.31	1.31	0.38
Patek et al. [40]	2003	0.48	− 0.46	0.34	0.56	− 0.44	0.51
Perkins et al. [41]	1991	0.35	− 0.18	0.36	0.76	− 0.69	0.41
Perkins et al. [42]	1991	0.87	− 0.14	1.17	0.65	0.08	0.91
Mostert et al. [43]	1990	0.70	0.68	0.47	1.17	1.17	0.39
Millat et al. [44]	1989	1.57	1.57	0.48	2.25	2.25	0.43
Richard and Shankland [45]	1989	0.50	0.50	0.30	0.38	0.31	0.30
Johns et al. [46]	1988	1.02	1.02	0.21	0.71	0.71	0.37
Johns et al. [47]	1986	0.33	0.32	0.26	0.28	0.00	0.34
Tarzimanov et al. [48]	1985	1.63	− 1.60	1.06	1.96	− 1.96	0.81
Imaishi et al. [49]	1984	0.61	− 0.61	0.36	0.28	− 0.16	0.30
Haran et al. [50]	1983	0.81	0.79	0.50	0.84	0.84	0.34
Shashkov et al. [51]	1983	1.45	− 1.45	1.14	1.54	− 1.54	0.99
Assael and Wakeham [52]	1981	0.67	− 0.67	0.16	0.31	− 0.31	0.14
Clifford et al. [53]	1981	0.39	− 0.22	0.43	0.37	− 0.25	0.38
Roder [54]	1981	1.51	− 1.51	0.75	0.99	− 0.99	0.55
Tufeu and Le Neindre [55]	1980	0.48	− 0.06	0.58	0.87	− 0.31	1.02
Clifford et al. [56]	1979	0.25	− 0.06	0.29	0.41	0.40	0.22
Dijkema et al. [57]	1972	1.47	− 0.91	1.26	1.36	− 0.92	1.15
Le Neindre et al. [58]	1968	0.75	0.39	0.78	0.78	0.64	0.62
Total		0.98	0.02	1.28	1.18	0.42	1.63

Table 5 Evaluation of the nitrogen thermal-conductivity correlation for the secondary data

Investigators/reference	Publ. Year	AAD (%)	BIAS (%)	Investigators/reference	Publ. Year	AAD (%)	BIAS (%)
Yao et al. [59]	2014	1.91	− 1.87	Kramer and Comings [96]	1960	2.32	2.32
Gauthier et al. [60]	2013	4.68	4.68	Vines [97]	1960	4.16	− 3.51
Duan et al. [61]	1997	0.50	0.45	Barua [98]	1959	2.17	− 2.17
Roder et al. [62]	1988	1.15	0.08	Srivastava and Srivastava [99]	1959	5.42	− 5.42
Zheng et al. [63]	1984	0.91	0.31	Ziebland and Burton [100]	1958	3.24	0.27
Tret'yakov et al. [64]	1983	3.84	− 2.75	Johannin and Vodar [101]	1957	1.23	− 0.92
Yorizane et al. [65]	1983	0.84	− 0.59	Nuttall and Ginnings [102]	1957	1.11	0.43
Tufeu and Le Neindre [66]	1979	3.81	− 3.74	Schäfer and Reiter [103]	1957	10.4	− 10.4
Slushar et al. [67]	1975	14.4	10.3	Keyes [104]	1955	0.97	0.97
Vasilkovskaya and Golubev [68]	1975	1.35	− 0.21	Kulakov [105]	1955	2.34	− 2.34
Carey et al. [69]	1974	4.27	− 0.91	Rothman and Bromley [106]	1955	4.00	− 4.00
Chen and Saxena [70]	1973	6.54	− 6.52	Ziebland and Burton [107]	1955	3.38	− 3.38
Haarman [71]	1973	0.16	− 0.11	Powers et al. [108]	1954	2.97	− 2.20
Shashkov and Kamchatov [72]	1973	1.59	− 1.35	Davidson and Music [109]	1953	0.65	0.65
Faubert and Springer [73]	1972	6.79	− 6.79	Lenoir et al. [110]	1953	0.72	0.65
Parkinson and Gray [74]	1971	0.33	− 0.19	Michels and Botzen [111]	1953	6.31	6.31
Peterson et al. [75]	1971	1.60	− 1.60	Senftleben [112]	1953	3.24	− 3.24
Saxena [76]	1971	9.08	− 8.40	Keyes [113]	1952	1.26	0.86
Tondon and Saxena [77]	1970	1.33	1.33	Schottky [114]	1952	6.03	− 6.03
Barua et al. [78]	1968	4.34	− 3.97	Uhlir [115]	1952	3.57	− 1.51
Ibele and Briggs [79]	1968	0.56	− 0.30	Wirth and Klemene [116]	1952	0.81	− 0.81
van Dael and Cauvenbergh [80]	1968	0.60	0.60	Franck [117]	1951	4.20	− 4.00
Brain [81]	1967	1.61	− 1.40	Keyes et al. [118]	1951	1.18	0.81
Mukhopadhyay et al. [82]	1967	3.23	− 2.80	Lenoir and Comings [119]	1951	0.44	0.25
Gilmore and Comings [83]	1966	1.69	− 1.43	Stoliarov et al. [120]	1950	5.24	− 3.48

Table 5 (continued)

Investigators/reference	Publ. Year	AAD (%)	BIAS (%)	Investigators/reference	Publ. Year	AAD (%)	BIAS (%)
Baker and Brakow [84]	1965	3.16	− 3.16	Keyes [121]	1949	5.77	− 5.43
Keyes and Vines [85]	1965	0.56	− 0.27	Borovick [122]	1947	6.77	− 2.36
Misic and Thodos [86]	1965	1.18	− 0.34	Borovick et al. [123]	1940	20.0	9.81
Baker and Brokaw [87]	1964	2.49	− 2.49	Hammann [124]	1938	23.6	23.6
Golubev and Kalsina [88]	1964	3.86	− 2.90	Vargaftik [125, 126]	1937	0.57	0.38
Schramm [89]	1964	6.86	− 6.86	Shushpanov [127]	1935	0.32	− 0.18
Vargaftik and Zhimina [90]	1964	4.17	− 3.57	Dickins [128]	1934	1.64	− 0.47
Venart [91]	1964	0.97	0.07	Ibbs and Hirst [129]	1929	9.20	− 9.20
Pereira and Raw [92]	1963	0.97	− 0.72	Gregory and Marshall [130]	1928	0.94	0.9
Cheung et al. [93]	1962	0.16	0.15	Weber [131]	1917	1.46	− 1.46
Westenberg and de Haas [94]	1962	2.65	− 2.65	Eucken [132]	1911	1.45	− 0.47
Geier and Schaeper [95]	1961	8.92	− 8.92	Winkelmann [133]	1875	31.3	31.3

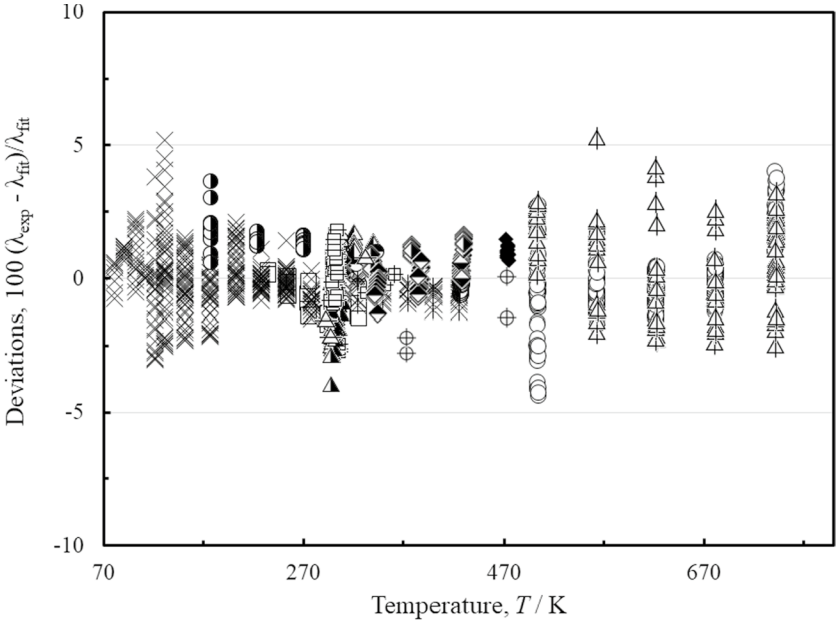

Fig. 5 Percentage deviations of primary thermal conductivity experimental data of nitrogen from the values calculated by the present scheme, Eqs. 1–7, as a function of temperature. Harvey et al. [37] (2THW) (○), Harvey et al. [37] (2HW) (△), Wang et al. [38] (□), Sun and Venart [39] (◭), Patek et al. [40] (⋆), Perkins et al. [41] (◐), Perkins et al. [42] (×), Mostert et al. [43] (◒), Millat et al. [44] (◑), Richard and Shankland [45] (◓), Johns et al. [46] (◆), Johns et al. [47] (◒), Tarzimanov et al. [48] (⊕), Imaishi et al. [49] (▲), Haran et al. [50] (◑), Shashkov et al. [51] (⊞), Assael and Wakeham [52] (◐), Clifford et al. [53] (◓), Roder [54] (◭), Tufeu and Le Neindre [55] (◒), Clifford et al. [56] (△), Dijkema et al. [57] (⧋), Le Neindre et al. [58] (⊟)

Figure 7 displays the deviations with respect to density. Note that although the range from 0 kg·m^{-3} to 1000 kg·m^{-3} is covered, there is only one data set that has liquid-phase data, Perkins et al. [42]. The other high-density data shown in Fig. 7 are the very-high pressure (up to 1000 MPa) data of Tufeu and Le Neindre [55]. The Perkins et al. [42] data include 46 points taken at four isotherms at 81 K, 91 K, 102 K, and 122 K at pressures up to ~ 70 MPa. Based on comparisons with these points, the uncertainty in the liquid region is 3 %.

As discussed earlier the dilute-gas limit values proposed by Hellmann et al. [9], have an uncertainty (95 % confidence level) of 1 % between 300 K and 700 K, increasing to 2 % at both 70 K and 1200 K. We can compare the most accurate experimental data at low pressure ($p < 1$ MPa) to assess the uncertainty of the correlation in the low-pressure region. Comparing with the data at pressures less than 1 MPa from the data sets of Clifford et al. [53, 56], Haran et al. [50], Imaishi et al. [49], Johns et al. [46, 47], Patek et al.[40], and Perkins et al. [42] that all have uncertainties of 1 % or less, we estimate the uncertainty in this region is 1 %. The temperature range covered by the data is 102 K to 472 K. At temperatures above 472 K, the thermal conductivity is less sensitive to small changes in pressure, and we estimate

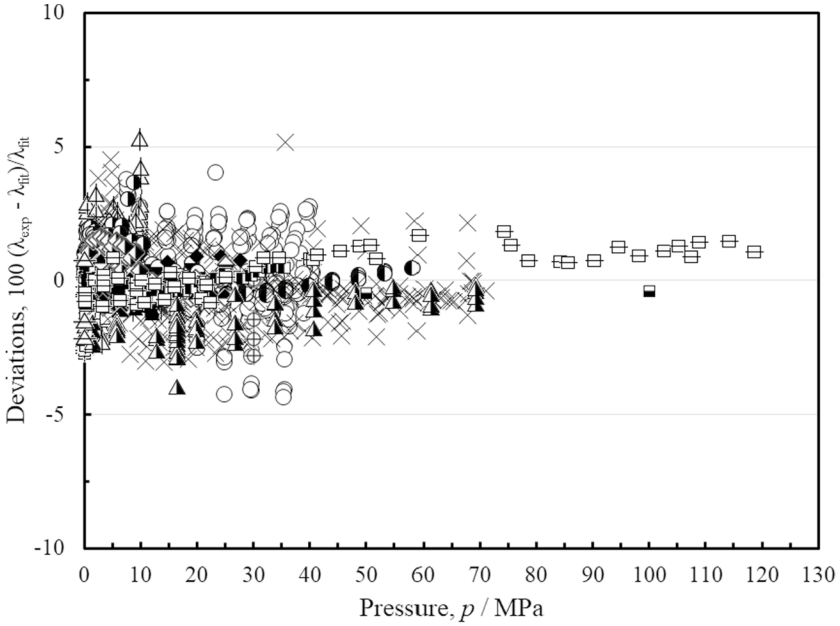

Fig. 6 Percentage deviations of primary thermal conductivity experimental data of nitrogen from the values calculated by the present scheme, Eqs. 1 - 7, as a function of pressure, for pressures up to 130 MPa. Harvey et al. [37] (2THW) (○), Harvey et al. [37] (2HW) (△), Wang et al. [38] (□), Sun and Venart [39] (◭), Patek et al. [40] (⊛), Perkins et al. [41] (◐), Perkins et al. [42] (×), Mostert et al. [43] (◒), Millat et al. [44] (◑), Richard and Shankland [45] (◓), Johns et al. [46] (♦), Johns et al. [47] (◈), Tarzimanov et al. [48] (⊕), Imaishi et al. [49] (▲), Haran et al. [50] (◗), Shashkov et al. [51] (⊞), Assael and Wakeham [52] (◖), Clifford et al. [53] (♠), Roder [54] (◮), Tufeu and Le Neindre [55] (⬓), Clifford et al. [56] (△), Dijkema et al. [57] (△), Le Neindre et al. [58] (⊟)

that the uncertainty for temperatures up to 700 K is also 1 %. However, at temperatures below 102 K the uncertainty may be larger than 1 % due to the strong initial density dependence of thermal conductivity at low temperatures.

The correlation developed by Lemmon and Jacobsen [8] was designed to ensure that the thermal conductivity correlation extrapolated well below the triple point and at high temperatures and pressures would exhibit physically reasonable behavior so that the correlation could be used in corresponding-states models as a reference fluid, even though these extrapolations may not correspond to physically accessible points. We also developed our correlation with these requirements in mind. Figure 8 shows a plot of the thermal conductivity of nitrogen as a function of the temperature for different pressures. The plot demonstrates the reasonable extrapolation behavior at pressures up to 3200 MPa and at temperatures to 3000 K, well exceeding the 745 K limit of the current measurements. As discussed by Lemmon and Jacobsen [8], the extrapolation behavior to well below the triple-point temperature within the 2-phase region is important for extended corresponding states and some mixture models. We ensured that the extrapolation behavior down to 30 K (the triple-point temperature is 63.151 K) does not contain any large loops in the 2-phase

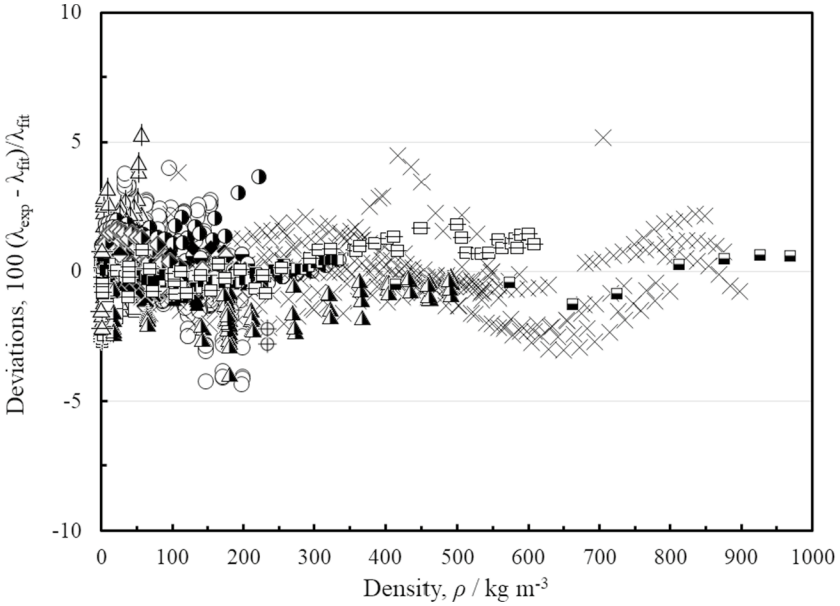

Fig. 7 Percentage deviations of primary thermal conductivity experimental data of nitrogen from the values calculated by the present scheme, Eqs. 1–7, as a function of density. Harvey et al. [37] (2THW) (○), Harvey et al. [37] (2HW) (△), Wang et al. [38] (□), Sun and Venart [39] (◭), Patek et al. [40] (⋆), Perkins et al. [41] (◐), Perkins et al. [42] (×), Mostert et al. [43] (◒), Millat et al. [44] (◑), Richard and Shankland [45] (◓), Johns et al. [46] (♦), Johns et al. [47] (◒), Tarzimanov et al. [48] (⊕), Imaishi et al. [49] (▲), Haran et al. [50] (◆), Shashkov et al. [51] (⊞), Assael and Wakeham [52] (◆), Clifford et al. [53] (◓), Roder [54] (◭), Tufeu and Le Neindre [55] (⬓), Clifford et al. [56] (△), Dijkema et al. [57] (△), Le Neindre et al. [58] (⊟)

region. Following Lemmon and Jacobsen [8], in Fig. 9 we plot the behavior of the correlation (without the critical enhancement contribution) as a function of density for selected isotherms including the 2-phase region. There are no large bumps or unusual behavior when extrapolated as low as 30 K. Finally, in Fig. 10, we show the behavior as a function of density for isotherms in the critical region.

4 Recommended Values

In Table 6, thermal conductivity values are given along the saturation boundary, calculated from the present proposed correlation between 70 K and 120 K, while in Table 7, thermal conductivity values are given for temperatures between 150 K and 600 K and at selected pressures. Saturation density values for selected temperatures, as well as the density values for the selected temperature and pressure, are obtained from the equation of state of Span et al. [36] as calculated with REFPROP v10 [147] using the supplementary file included with this work. The values in the tables are calculated from the given temperatures and densities according to Eqs. 1–7 for thermal conductivity.

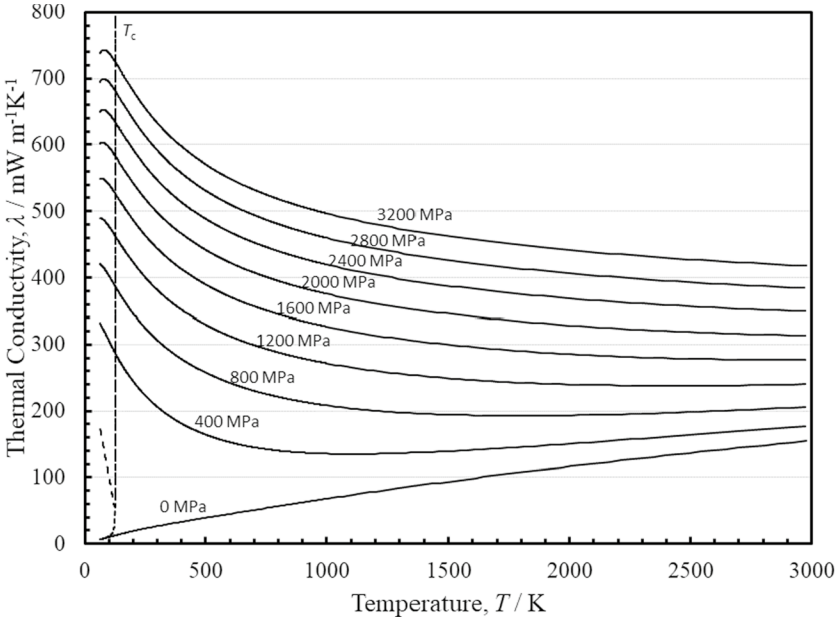

Fig. 8 The thermal conductivity of nitrogen as a function of temperature at different pressures. The saturation boundary is indicated by the dashed lines

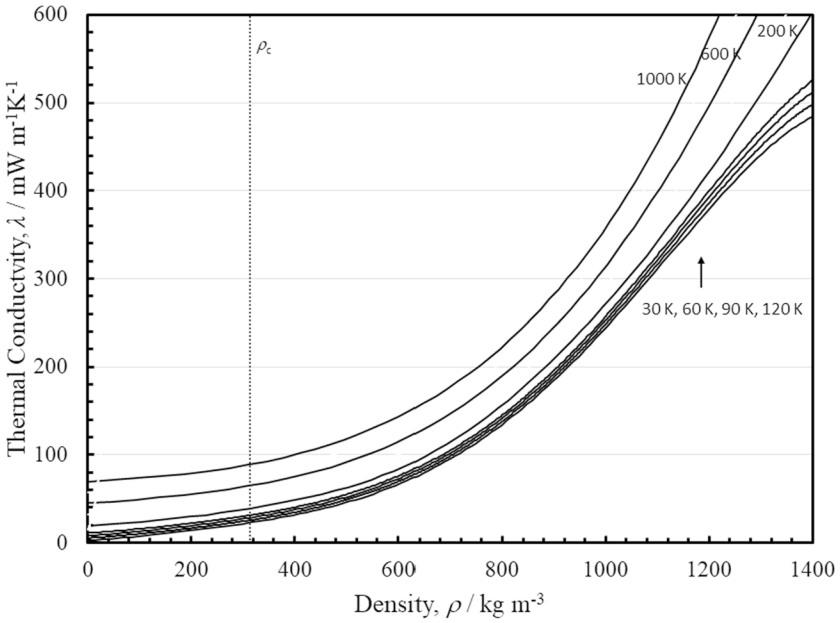

Fig. 9 Thermal conductivity versus density including 2-phase behavior for selected isotherms

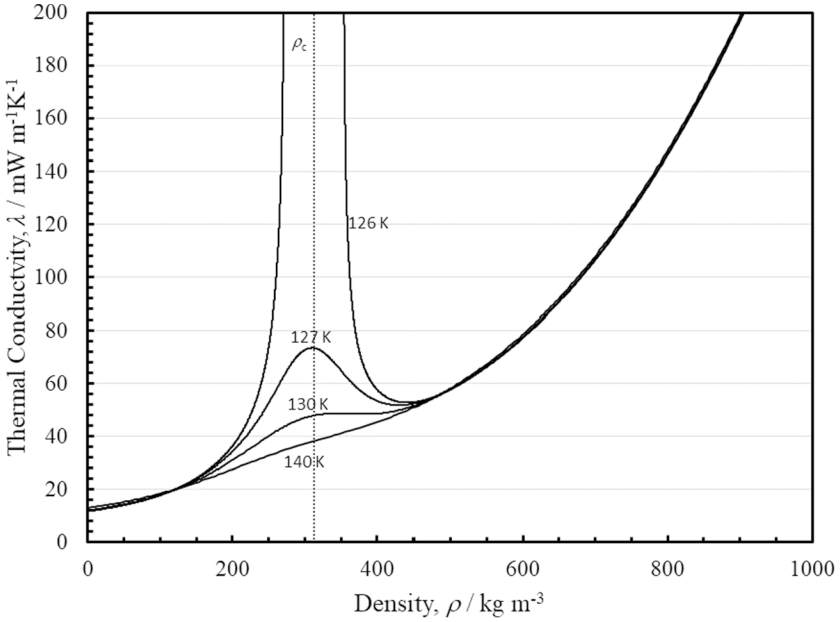

Fig. 10 The thermal conductivity of nitrogen as a function of density at different temperatures illustrating the critical enhancement

Table 6 Thermal conductivity values of nitrogen along the saturation boundary, calculated by the present scheme

T (K)	ρ_{liq} (kg·m^{-3})	ρ_{vap} (kg·m^{-3})	λ_{liq} (mW·m^{-1}·K^{-1})	λ_{vap} (mW·m^{-1}·K^{-1})
70	838.51	1.8960	157.7	6.416
80	793.94	6.0894	138.1	7.527
90	745.02	15.079	118.9	8.875
100	689.35	31.961	100.1	10.71
110	621.45	62.579	81.24	13.75
120	523.36	125.09	61.51	21.81

We note that Table 7 includes more values at 0.1 MPa as these are very near the dilute-gas limit values, obtained as discussed, by highly accurate quantum-chemical ab initio computations showing an uncertainty (95 % confidence level) of 1 % between 300 K and 700 K.

Table 7 Thermal conductivity values of nitrogen at selected temperatures and pressures,calculated by the present scheme

p (MPa)	T (K)	ρ (kg·m^{-3})	λ (mW·m^{-1}·K^{-1})
0.1	100	3.4366	9.33
	150	2.2592	14.00
	200	1.6882	18.35
	225	1.4994	20.37
	250	1.3488	22.31
	275	1.2257	24.18
	300	1.1233	25.97
	325	1.0367	27.71
	350	0.96252	29.39
	375	0.89827	31.04
	400	0.84208	32.66
	425	0.79250	34.25
	450	0.74845	35.82
	475	0.70904	37.38
	500	0.67358	38.93
	600	0.56130	45.11
10	100	733.61	115.68
	150	419.17	47.38
	200	199.44	29.37
	250	140.59	29.40
	300	111.73	31.29
	350	93.741	33.68
	400	81.186	36.25
	450	71.813	38.92
	500	64.498	41.66
	600	53.738	47.31
50	100	827.06	155.74
	150	693.50	106.82
	200	576.24	78.23
	250	482.36	63.83
	300	411.72	57.12
	350	358.96	54.21
	400	318.73	53.27
	450	287.16	53.44
	500	261.74	54.29
	600	223.19	57.28
100	100	890.63	188.5
	150	789.70	144.4
	200	703.71	115.3
	250	631.37	96.98
	300	570.89	85.53

Table 7 (continued)

p (MPa)	T (K)	ρ (kg·m^{-3})	λ (mW·m^{-1}·K^{-1})
	350	520.38	78.45
	400	478.03	74.17
	450	442.22	71.72
	500	411.64	70.51
	600	362.27	70.46
150	100	935.28	214.1
	150	849.02	172.6
	200	775.82	143.6
	250	713.64	123.7
	300	660.41	110.0
	350	614.50	100.5
	400	574.62	94.01
	450	539.75	89.60
	500	509.06	86.71
	600	457.62	84.02
200	100	970.58	235.7
	150	893.33	196.3
	200	827.58	167.4
	250	771.48	146.7
	300	722.99	131.6
	350	680.60	120.7
	400	643.19	112.6
	450	609.92	106.8
	500	580.14	102.6
	600	529.09	97.67
500	150	1051.7	297.1
	200	1003.7	270.9
	250	962.00	249.4
	300	925.47	231.9
	350	892.95	217.5
	400	863.65	205.6
	450	836.95	195.8
	500	812.40	187.6
	600	768.52	175.1
1000	150	1195.4	403.1
	200	1156.6	383.6
	250	1122.2	365.4
	300	1091.8	349.2
	350	1064.7	334.9
	400	1040.2	322.3
	450	1017.8	311.2
	500	997.13	301.3

Table 7 (continued)

p (MPa)	T (K)	ρ (kg·m^{-3})	λ (mW·m^{-1}·K^{-1})
	600	960.01	285.0

Table 8 Data points for computer verification of the correlation

T (K)	ρ (kg·m^{-3})	λ (mW·m^{-1}·K^{-1})
126.2	0.0	11.7110
126.2	320.0	385.931
500.0	0.0	38.9095
500.0	320.0	59.6387
500.0	500.0	84.9555

5 Computer-Program Verification

Table 8 is provided for checking computer implementations of the correlation. Note that the point at 126.2 K and 320.0 kg·m^{-3} is very near the critical point and has a significant critical enhancement contribution of 353.3371 mW·m^{-1}·K^{-1}.

6 Conclusions

A new wide-ranging correlation for the thermal conductivity of nitrogen, incorporating the most recent ab initio dilute-gas theoretical calculations, a simplified crossover critical enhancement contribution, and critically evaluated experimental data, is presented. The correlation is designed to be used with the high-accuracy Helmholtz equation of state of Span et al. [36], whose range of application is from the triple-point temperature to 1000 K and pressures to 2200 MPa. The correlation has been designed to display reasonable extrapolation behavior to temperatures as low as 30 K so that it may be used in corresponding- states applications, and reasonable extrapolation behavior to high pressures. The high-temperature behavior is guided by the theoretical results of Hellmann [4], improving upon the previous correlation of Lemmon and Jacobsen [8]. For temperatures between 102 K and 700 K at pressures up to 1 MPa the estimated uncertainty (at $k=2$) is 1 %, rising to 2 % at 1200 K. For the high-temperature region 500 K $< T <$ 744 K at pressures from 1 MPa $< p <$ 40 MPa the estimated uncertainty is 4 %. In the gas and supercritical region 112 K $< T <$ 475 K for pressures 1 MPa $< p <$ 1000 MPa the estimated uncertainty is 2.2 %, and for the liquid from 81 K to 122 K at pressures up to 70 MPa the estimated uncertainty is 3 %. The uncertainties will be larger near the critical point and in other regions not covered by experimental data.

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Data Availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest Marc J. Assael is the Editor-in-Chief and Marcia L. Huber is on the Editorial Advisory Board of the International Journal of Thermophysics.

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