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Reference Values and Reference Correlations for the Thermal Conductivity and Viscosity of Fluids

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In this paper, reference values and reference correlations for the thermal conductivity and viscosity of pure fluids are reviewed. Reference values and correlations for the thermal conductivity and the viscosity of pure fluids provide thoroughly evaluated data or functional forms and serve to help calibrate instruments, validate or extend models, and underpin some commercial transactions or designs, among other purposes. The criteria employed for the selection of thermal conductivity and viscosity reference values are also discussed; such values, which have the lowest uncertainties currently achievable, are typically adopted and promulgated by international bodies. Similar criteria are employed in the selection of reference correlations, which cover a wide range of conditions, and are often characterized by low uncertainties in their ranges of definition. © *2018 by the U.S. Secretary of Commerce on behalf of the United States. All rights reserved.* https://doi.org/10.1063/1.5036625

Key words: calibration; reference correlations; reference values; thermal conductivity; viscosity.

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1. Introduction

In this work, we review reference values and correlations for two important fluid transport properties: thermal conductivity and viscosity. Internationally accepted "reference values" (known also as "standard reference values") serve two primary purposes. First, they can provide a means of confirming the operation and experimental uncertainty of any new absolute apparatus and the stability and reproducibility of existing absolute measurement equipment. Second, in the case of instruments operating in a relative way, they provide the basis to calibrate one or more unknown constants in the working equation. Reference values refer to the properties specified at a fixed state condition (specific temperature, pressure, and composition) or at a small number of such states. These values are often characterized by the lowest uncertainty possible at the time of their acceptance.

"Reference correlations" for pure-fluid transport properties often cover a wide range of conditions—typically from the triple-point temperature to 1000 K and up to 100 MPa pressure—and are developed to achieve the lowest possible uncertainties (although perhaps higher than those of reference values). In between these two categories, there exist "restricted reference correlations" that refer to a limited range of conditions, often with lower uncertainty than wide-range reference correlations and that may be of specific industrial or scientific interest. When appropriate, the reference correlations or restricted reference correlations are constrained to agree with any reference values that may have been established for the fluid of interest.

The current paper emphasizes the work of three main bodies that remain active in the field of reference values and correlations for transport properties. The National Institute of Standards and Technology (NIST) in Boulder, CO, has been involved in the development of wide-range reference correlations for thermal conductivity and viscosity to extend the capabilities of the reference software they develop. The International Association for Transport Properties (IATP), formerly known as the Subcommittee on Transport Properties of the International Union of Pure and Applied Chemistry (IUPAC), has been proposing mostly reference values. Finally, we should also mention the International Association for the Properties of Water and Steam (IAPWS), which since 1929 has been the body that proposes the reference correlations and values for the properties of water and steam, including transport properties. These three organizations often collaborate on both reference data and correlations for transport properties.

2. Reference Values

2.1. Thermal conductivity

The thermal conductivity of a fluid, λ, has proven to be one of the most difficult thermophysical properties to measure accurately. It is important to recall that the thermal conductivity, $\lambda(T, P)$, is the state-dependent proportionality constant in Fourier's law relating heat flow to an infinitesimally small temperature gradient. It was not until 1951 that any proposal was made for standard reference values for this fluid property. At that time, Riedel[1] suggested that the thermal conductivity of liquid toluene (a liquid that can easily be obtained at high purity) be adopted as a reference value at 293.15 K and 0.1 MPa.

The inherent difficulty in the measurement of the thermal conductivity for both liquids and gases arises from the impossibility of decoupling the processes associated with heat transfer: conduction, convection, and radiation. The absence of a gravitational field (e.g., space-based measurements) can mitigate convective heat flow, and radiative heat flow is generally less of a problem at low temperatures.

In 1986, in view of the rapid developments in the measurement of the thermal conductivity, primarily of fluids in the liquid phase, Nieto de Castro *et al.*[2] proposed a complete reappraisal of reference values for thermal conductivity. The work was carried out under the auspices of the Subcommittee on Transport Properties (since 2001 known as the IATP) of IUPAC.

The reappraisal took the form of a critical analysis of the experimental measurements of the thermal conductivity of a number of important liquids, which permitted the available data to be characterized as **primary or secondary** according to their estimated uncertainty. The following recommendations were employed as a means of identifying primary data:[2]

(i) Measurements must have been made with a primary experimental apparatus, i.e., an essentially complete working equation must be available.

(ii) The form of the working equation should be such that the sensitivity of thermal conductivity to the principal variables does not magnify the random errors of measurement.

(iii) All principal variables should be measurable to a high degree of precision.

(iv) The published work should include some description of purification methods for pure fluids and a validated assessment of purity (or an appropriate characterization of a mixture).

(v) The data reported must be unsmoothed data. While graphs and fitted equations are useful summaries for the reader, they are not sufficient for standardization purposes.

(vi) Explicit quantitative estimates of the uncertainty of reported values should be given, based on the extant guidelines for the expression of uncertainty in measurements (GUM)[3] and taking into account all sources of uncertainty of the experimental measurements, including possible systematic components of uncertainty.

(vii) Owing to the desire to produce high accuracy reference values, limits are usually imposed on the two-sigma expanded relative uncertainty of the primary data sets; these are usually required to be better than 1.5%.

Only primary data are used, when adequate, to develop a reference correlation or to develop recommended reference values. These recommendations for assessing literature data for transport properties have continued to guide the subsequent work by the IATP on both reference data and correlations.

2.1.1. Reference values for the thermal conductivity of liquids

Toluene and water have been proposed as thermal-conductivity reference liquids. Nieto de Castro *et al.*[2] recommended in 1986 the following reference values, which are still valid today:

For toluene, at 298.15 K and 0.1 MPa,

$$\lambda = 0.1311 \pm 0.0026\ \mathrm{W\,m^{-1}K^{-1}}, \tag{1}$$

and for water, at 298.15 K and 0.1 MPa,

$$\lambda = 0.6067 \pm 0.0122\ \mathrm{W\,m^{-1}K^{-1}}. \tag{2}$$

Uncertainties were reported at the 95% confidence level.

The temperature dependence of the thermal conductivity of liquid toluene at 0.1 MPa was represented[2] by the following equations, still valid today, where $T^* = (T/298.15\ \mathrm{K})$, and $\lambda^* = (\lambda(T)/\lambda(298.15\ \mathrm{K}))$:

In the temperature range $230\ \mathrm{K} \leq T \leq 360\ \mathrm{K}$,

$$\lambda^* = 1.68182 - 0.682022\,T^*, \tag{3}$$

and in the extended range $189\ \mathrm{K} \leq T \leq 360\ \mathrm{K}$,

$$\lambda^* = 1.45210 - 0.224229\,T^* - 0.225873\,T^{*2}. \tag{4}$$

Considering the uncertainty of the primary experimental data, the relative expanded uncertainty of the thermal conductivity from Eq. (3) is 2.2% and from Eq. (4) is 2.6%, at the 95% confidence level.

In the case of water, the IAPWS recommendation of 2012[4] proposed the following equation as a function of temperature, valid at 0.1 MPa, over the temperature range of $273.15\ \mathrm{K} \leq T \leq 383.15\ \mathrm{K}$:

$$\lambda(T)/\left(1\ \mathrm{mW\ m^{-1}K^{-1}}\right) = 1.663T_{\mathrm{r}}^{-1.15} - 1.7781T_{\mathrm{r}}^{-3.4} + 1.1567T_{\mathrm{r}}^{-6} - 0.432115T_{\mathrm{r}}^{-7.6}, \tag{5}$$

where $T_{\mathrm{r}} = T/(300\ \mathrm{K})$. The expanded relative uncertainty in thermal conductivity from Eq. (5) was 1.5% at the 95% confidence level.

Other liquid thermal-conductivity reference values and limited correlations are of slightly higher uncertainty, e.g., *n*-heptane[2] and benzene.[5]

2.1.2. Reference values for the thermal conductivity of gases

Significant progress has been made over the last two decades in establishing reference values for the thermal conductivity of the noble gases at low densities. This is principally a result of theoretical advances in the *ab initio* determination of intermolecular pair potential energy surfaces for the noble gases, which have been made possible by rapid increases in computational power. Cencek *et al.*[6] developed the most accurate pair potential energy surface to date and used it to calculate the thermophysical properties of helium in the dilute-gas state over the temperature range from 1 to 10^4 K with uncertainties up to nearly two orders of magnitude smaller than those of the most accurate measurements. The calculations of Cencek *et al.*[6] lead to a reference value for the thermal conductivity of helium at 25 °C and 0.1 MPa, $\lambda_{\mathrm{He}} = (0.155\,000\,8 \pm 0.000\,001\,5)\ \mathrm{W\ m^{-1}\ K^{-1}}$. May *et al.*[7,8] have shown that for noble gases the *ratio* of the thermal conductivity to the viscosity can be calculated very accurately using a modern *ab initio* pair potential function with classical kinetic theory. Thus, by combining reference experimental viscosity ratios with accurate (λ/η) ratios calculated using the potentials of Hellmann and coworkers,[9–12] the *ab initio* properties of helium can be leveraged to determine recommended values for the thermal conductivity of neon, argon, krypton, and xenon at 25 °C, 0.1 MPa, which we present in Table 1. In Table 1 the error bounds correspond to the expanded ($k = 2$) uncertainty at a 95% confidence interval.

Table 1. Reference values for the thermal conductivity of selected gases at 25 °C and 0.1 MPa based on experimental viscosity ratios with accurate (λ/η) ratios

Gas	λ ($\mathrm{W\ m^{-1}\ K^{-1}}$)	$U(\lambda)$ ($\mathrm{W\ m^{-1}\ K^{-1}}$)
He	0.155 000 8	0.000 003 0
Ar	0.017 668	0.000 010
Xe	0.005 505	0.000 012
Ne	0.049 193	0.000 032
Kr	0.009 457	0.000 006

Dilute-gas transport properties evaluated from *ab initio* pair potential functions are strictly evaluated in the limit of zero density. For comparisons with experiment, values obtained from theory should be adjusted to match the pressure at which the measurement was made using the initial density dependence of that transport property. This initial density dependence is temperature dependent and can be estimated using the Rainwater-Friend corresponding-states theory;[13] such adjustments are negligible at 0.1 MPa for helium at 25 °C. The values of λ_{Ne}, λ_{Ar}, λ_{Kr}, and λ_{Xe} at 25 °C listed in Table 1 have already had this adjustment applied using the initial density dependence from Bich *et al.*,[9] which amounts to approximately 0.04%, 0.23%, 0.41%, and 0.71%, respectively.

Remarkably, the modern reference values for the noble gases at 25 °C and 0.1 MPa listed above differ from values for the thermal conductivity of noble gases (Table 2) recommended by Kestin *et al.*[14] in 1980 by less than 0.42%. This is

Table 2. Values recommended by Kestin *et al.*[14] in 1980 for the thermal conductivity of noble gases at 0.1 MPa. These are consistent with the modern reference values anchored to the properties of helium calculated *ab initio* at the level of the uncertainty estimated by Kestin *et al.*[14]

	Thermal conductivity ($\mathrm{W\ m^{-1}\ K^{-1}}$)				
t (°C)	Helium	Neon	Argon	Krypton	Xenon
25	0.1553	0.049 24	0.017 67	0.009 451	0.005 482
100	0.1811	0.057 84	0.021 36	0.011 63	0.006 852
200	0.2139	0.067 43	0.025 59	0.014 18	0.008 534
300	0.2447	0.076 79	0.029 60	0.016 50	0.010 07
400	0.2741	0.085 34	0.033 14	0.018 64	0.011 49
500	0.3020	0.093 39	0.036 50	0.020 64	0.012 81

essentially within the expanded relative uncertainty estimated by Kestin *et al.*[14] (0.6% in the range 25–200 °C and 1% in the range 200–500 °C, at the 95% confidence level). We recommend using the values presented in Table 1 for the thermal conductivity of gases at 298.15 K and 0.1 MPa. For higher temperatures, Table 2 can still be employed directly to obtain the thermal conductivity of the gas.

For higher pressures, up to 30 MPa and at a temperature of 27.5 °C, the thermal conductivity of argon gas is represented by the following equation[14] (corrected for the current reference equation of state for argon[15]):

$$\lambda = 17.743 + 21.440 \times 10^{-3}\rho + 28.321 \times 10^{-6}\rho^2, \qquad (6)$$

where λ is measured in mW m^{-1} K^{-1} and ρ is measured in kg m^{-3}.

Wide-range reference correlations for these gases will yield slightly different values when evaluated at the fixed points of these reference values. At 25 °C and 0.1 MPa, the correlations in the NIST REFerence fluid PROPerties (REFPROP) version 10 database[16] yield 0.155 31 W m^{-1} K^{-1} for helium[17] and 0.017 745 W m^{-1} K^{-1} for argon.[18] Compared to Table 1, we note differences of 0.2% and 0.4%, respectively, for these noble gases. While these comparisons indicate mutual agreement within the stated uncertainties, they serve to re-emphasize several points. Reference values are often more accurate than reference correlations, and reference values are preferred for calibrations when they are sufficient. The dates and sources associated with a specific reference value and reference correlation are important considerations when selecting the best source for application.

2.2. Viscosity

In this work, we only consider the dynamic Newtonian viscosity—the coefficient of the linear response to an infinitesimally small shear velocity.

2.2.1. Reference values for the viscosity of liquids

The viscosity of water is one of the most important standards for viscometry, and IAPWS maintains the current international consensus standards for the fluid. Consistent with the IAPWS reference correlation, ISO/TR 3666: 1998[19] provides the internationally agreed standard value for the viscosity of liquid water at 20 °C and atmospheric pressure (0.101 325 MPa); the consensus reference value is

$$\eta = 1.0016\ \text{mPa s}. \qquad (7)$$

This value has an expanded relative uncertainty of 0.17% (at the 95% confidence level). The reference value is largely based on the experimental value of 1.0019 mPa s reported by Swindells *et al.*[20] in 1952, which was also the basis of ISO/TR 3666:1977. The standard value given in Eq. (7) accounts for the difference between the ITS-48 and ITS-90 temperature scales.

The 2009 IAPWS reference equation[21] for liquid water at 0.1 MPa from 253.15 K to 383.15 K is

$$\eta/(1\,\mu\text{Pa s}) = 280.68T_\text{r}^{-1.9} + 511.45T_\text{r}^{-7.7} + 61.131T_\text{r}^{-19.6} + 0.45903T_\text{r}^{-40.0}, \qquad (8)$$

with $T_\text{r} = T/(300\ \text{K})$. The expanded relative uncertainty of this equation is 1.5% at the 95% confidence level. This reference correlation gives a value of 1.0016 mPa s at 20 °C and 0.1 MPa that is consistent with the ISO/TR 3666:1998[19] standard reference value.

In a recent paper,[22] a reference correlation for toluene was proposed. In the specific range of 263 K to 373 K and 0.1 MPa, the viscosity values proposed had an uncertainty of 0.7% (at the 95% confidence level). The following equation fits those values with an uncertainty of less than 0.1%:

$$\eta/(1\,\mu\text{Pa s}) = 47.53 - 304.968T_\text{r} + 75.285T_\text{r}^2 - 838.095T_\text{r}^3 + 353.120T_\text{r}^4, \qquad (9)$$

where in this case $T_\text{r} = T/T_\text{c}$ and T_c is the critical temperature of toluene[22] (=591.75 K).

2.2.2. Reference values for the viscosity of gases

In the case of the viscosity of gases, the theoretical advances discussed in Sec. 2.1.2 allow the calculation of helium's thermophysical properties at low densities and result in the most accurately known viscosity standard, with a relative uncertainty around 10^{-5} at ambient temperatures.[6] By combining reference values for viscosity ratios derived from measurements with the *ab initio* viscosity of helium, the viscosities of H_2, CH_4, Ne, N_2, C_2H_6, Ar, C_3H_8, Kr, Xe, and SF_6 can also be determined at 25 °C and 0.1 MPa (using the initial density dependencies reported by Berg and Moldover[23]) and are listed in Table 3.

Reference values for the viscosity of the noble gases at a pressure of 0.1 MPa and temperatures up to 500 °C recommended by Wakeham *et al.*[24] are shown in Table 4. These values differ from the viscosity values listed for the noble gases at 25 °C and 0.1 MPa in Table 3 by less than 0.33%, which is essentially consistent with the uncertainty estimates reported by Wakeham *et al.*[24] (0.2% in the range 25–200 °C and 0.4% in the range 200–500 °C). In principle, the uncertainty of these values could be reduced several fold by

Table 3. Reference values for the viscosity of 11 gases at 25 °C and 0.1 MPa[23] and their expanded uncertainty at the 95% confidence level, $U(\eta)$

Gas	η (μPa s)	$U(\eta)$ (μPa s)
He	19.8249	0.0009
N_2	17.7620	0.0099
Ar	22.5844	0.0125
CH_4	11.0769	0.0075
Xe	23.0514	0.0152
Ne	31.7124	0.0200
Kr	25.3371	0.0182
C_2H_6	9.2398	0.0075
H_2	8.9011	0.0060
C_3H_8	8.1327	0.0081
SF_6	15.2288	0.0216

Table 4. Reference values for the viscosity of noble gases at 0.1 MPa[24]

	Viscosity (μPa s)				
t (°C)	Helium	Neon	Argon	Krypton	Xenon
25	19.86	31.76	22.62	25.39	23.09
100	23.16	37.06	27.32	31.22	28.84
200	27.35	43.47	32.85	38.06	35.91
300	31.28	49.50	37.83	44.28	42.38
400	35.04	55.00	42.35	49.99	48.32
500	38.60	60.19	46.63	55.34	53.84

combining the reference values listed in Table 3 with the ratio of the gas viscosity at temperature T to that at 25 °C calculated using an *ab initio* pair potential,[9,10] together with a small correction for the initial density dependence from Bich *et al.*[11]

Finally, we note that the NIST REFPROP[16] program discussed in Sec. 3 uses a variety of individual wide-ranging correlations from different authors, developed at different times, to compute viscosity values and does not necessarily reproduce the recommended values in Table 3 to within the stated uncertainty in Table 3. For instrument calibration, the values in Table 3 are preferable to those found in the correlations in REFPROP,[16] and one should always check to see if there are newer recommendations in place.

Gas viscosities at slightly higher pressures, with uncertainties comparable to those now achievable at 0.1 MPa, could in principle be obtained using an adaptation of the two-capillary viscometer method as described by Berg *et al.*[25] This proposed approach exploits helium's small viscosity virial coefficient, which means the value at pressure differs only marginally from the dilute-gas value calculated *ab initio*. At 20 °C, the viscosity of helium is 19.598 μPa s with an expanded relative uncertainty of 0.3% at pressures up to 10 MPa and an expanded relative uncertainty of 0.5% at higher pressures up to 25 MPa.[26]

For now, more empirical correlations are needed for other gases at higher pressures: for example, up to 30 MPa and at a temperature of 25 °C, the viscosity of nitrogen can be employed to produce reference values by the following equation:[24]

$$\eta = 0.17763 \times 10^{-4} + 0.86870 \times 10^{-8}\rho + 0.14240 \times 10^{-9}\rho^2, \tag{10}$$

where η is measured in Pa s and ρ is measured in kg m^{-3}. Note that Eq. (10) does not yield the exact reference value given in Table 3.

3. Reference Correlations

Since wide-ranging reference correlations are often connected with the work on thermophysical properties at NIST, it is worthwhile presenting some historical information. The National Bureau of Standards (NBS) was founded in 1901 and in 1988 became NIST. NIST began producing and distributing tabulations of thermophysical properties early in its history, but the dissemination of computerized databases for thermophysical properties dates to the 1980s with the release of programs[27] such as REFPROP (NIST23), DDMIX (NIST14), MIPROPS (NIST12), and Supertrapp (NIST4). The roots of such computer programs follow from earlier work on property tabulations and collaborations with NASA which included both thermodynamic and transport properties of hydrogen.

In 1989, NBS/NIST released the computer program REFPROP,[16] which stood for REFrigerant PROPerties. It was limited to refrigerants, while the other NIST thermophysical properties program at the time covered hydrocarbon fluids and cryogens, in support of the NASA space programs, the natural gas sector, and the more general petrochemical industry. In 1991, the program grew to include the calculation of transport properties (viscosity and thermal conductivity) with an extended corresponding-states model. The usage of "reference equations or correlations" for transport properties appears to have arisen from the ability to use a correlation as a reference fluid in the context of a corresponding-states model. In 2002, the acronym for REFPROP[16] was changed to stand for REFerence fluid PROPerties, since by that time the program contained more than just refrigerants and had expanded to include reference-quality equations of state and transport correlations for many industrial fluids such as constituents of natural gas and cryogens.

In Tables 5 and 6, we summarize wide-ranging correlations for viscosity and thermal conductivity, many of which have appeared in the Journal of Physical and Chemical Reference Data and are also implemented in REFPROP. These correlations are typically formulated in terms of a dilute-gas contribution that is a function only of temperature, a residual term that is a function of both temperature and density, and a critical enhancement term. The critical enhancement term is also a function of temperature and density; for viscosity correlations, it often is ignored since it is significant only in a small region very near the critical point. For thermal conductivity correlations, it is typically included since it is active over a wider region. Since these correlations are expressed in terms of temperature and density, a high-accuracy equation of state is typically used to provide the density for a given temperature and pressure. The publication containing the correlation should state what method is used to obtain density, and if an alternative method is used, care should be taken to check that the results are not changed significantly. The viscosity at low temperatures near the triple point and the thermal conductivity near the critical region are especially sensitive to changes in density.

4. Restricted Reference Correlations

As already mentioned, restricted reference correlations refer to representations over a limited range of conditions, but which have specific industrial or scientific interest. We present reference correlations as examples, developed for the

(a) viscosity and thermal conductivity of molten metals and
(b) viscosity of high-viscosity liquids.

TABLE 5. Wide-ranging reference correlations for viscosity

Fluid	First author	Year	T_{range} (K)	P_{max} (MPa)
Ammonia	Monogenidou[28]	2018	195.46–725	50
Argon	Lemmon[18]	2004	55–2000	1000
Benzene	Avgeri[29]	2014	278.67–675	300
n-butane	Herrmann[30]	2018	134.9–650	100
Carbon dioxide	Laesecke[31]	2017	100–2000	8000
Cyclohexane	Tariq[32]	2014	279.47–873	110
Cyclopentane	Vassiliou[33]	2015	240–455	250
n-decane	Huber[34]	2004	243.5–574	300
Dimethylether	Meng[35]	2012	233–373	30
n-dodecane	Huber[36]	2004	263.6–800	200
Ethane	Vogel[37]	2015	210–675	100
Ethanol	Kiselev[38]	2005	273–538	100
Ethylbenzene	Meng[39]	2016	178.2–673	110
Ethylene	Holland[40]	1983	110–500	50
Heavy water	Kestin[41]	1984	276.97–775	100
Helium-4	Arp[42]	1998	0.8–1500	2000
n-heptane	Michailidou[43]	2014	100.20–600	248
n-hexane	Michailidou[44]	2013	177.83–600	100
Hydrogen	Muzny[45]	2013	13.96–1000	200
Hydrogen sulfide	Schmidt[46]	2008	190–600	100
Isobutane	Vogel[47]	2000	113.55–600	35
Krypton	Hanley[48]	1974	125–500	20
Methane	Quiñones-Cisneros[49]	2011	90.69–625	1000
Methanol	Xiang[50]	2006	175.61–630	8000
m-xylene	Cao[51]	2016	273–673	200
Nitrogen	Lemmon[18]	2004	50–2000	2200
n-nonane	Huber[34]	2004	219.7–524	69
Novec 649[a]	Wen[52]	2017	165–500	50
n-octane	Quiñones-Cisneros[53]	2006	280–600	149
Oxygen	Lemmon[18]	2004	54.36–1000	82
o-xylene	Cao[54]	2016	273–673	110
parahydrogen	Muzny[45]	2013	13.80–2000	200
n-pentane	Quiñones-Cisneros[53]	2006	300–550	151
Propane	Vogel[55]	2016	90–625	62
p-xylene	Balogun[56]	2015	286.40–673	110
R123	Tanaka[57]	1996	253–373	30
R1234yf	Huber[58]	2016	220–410	30
R1234ze(E)	Huber[58]	2016	169–420	100
R125	Huber[59]	2006	172.52–500	60
R134a	Quiñones-Cisneros[53]	2006	200–425	100
R152a	Krauss[60]	1996	240–440	20
R161	Tsolakidou[61]	2017	243–363	30
R23	Shan[62]	2000	153–570	60
R245fa	Perkins[63]	2016	233–413	40
Sulfur hexafluoride	Quiñones-Cisneros[64]	2012	223.55–1000	50
Toluene	Avgeri[22]	2015	178–675	500
n-undecane	Assael[65]	2017	247.54–700	500
Water	Huber[21]	2009	273.16–1173	1000
Xenon	Hanley[48]	1974	170–500	20

[a] Commercial equipment, instruments, or materials are identified only in order to adequately specify certain procedures. In no case does such an 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.

4.1. Reference correlations for the viscosity and thermal conductivity of molten metals

Following the need for reference values of the viscosity and thermal conductivity of liquid metals identified over several years, a project was initiated by the IATP in 2006 to critically evaluate the density, the viscosity, and the thermal conductivity of selected liquid metals. Reference correlations developed so far based on critically evaluated experimental data are shown in Tables 7 and 8.

4.2. Reference correlations for the viscosity of high-viscosity liquids

For higher-viscosity liquids, a correlating equation for the representation of the viscosity of squalane as a function of temperature at atmospheric pressure has recently been proposed in conjunction with the IATP.[100,101] Note that the measurements of Schmidt *et al.*,[102] published in 2015, were incorporated in the correlation of Mylona *et al.*[101] as part of the unpublished data of Trusler. The viscosity of squalane covers

TABLE 6. Wide-ranging reference correlations for thermal conductivity

Fluid	First author	Year	T_{range} (K)	$P_{\max}$ (MPa)
Ammonia	Tufeu[66]	1984	195.46–550	80
Argon	Lemmon[18]	2004	55–2000	1000
Benzene	Assael[67]	2012	278.67–725	500
n-butane	Perkins[68]	2002	134.86–600	70
Carbon dioxide	Huber[69]	2016	216.59–1100	200
Cyclohexane	Koutian[70]	2017	279.86–640	175
Cyclopentane	Vassiliou[33]	2015	240–455	250
n-decane	Huber[71]	2005	243–678	400
n-dodecane	Huber[36]	2004	263.6–800	200
Ethane	Friend[72]	1991	90.35–600	70
Ethanol	Assael[73]	2013	159–600	245
Ethylbenzene	Mylona[74]	2014	178.2–700	60
Ethylene	Assael[75]	2016	110–680	200
Heavy water	Kestin[41]	1984	276.97–825	100
Helium-4	Hands[17]	1981	2.18–830	127
n-heptane	Assael[76]	2013	100.20–600	250
n-hexadecane	Monogenidou[77]	2018	291.33–700	50
n-hexane	Assael[78]	2013	177.83–600	500
Hydrogen	Assael[79]	2011	13.96–1000	100
Isobutane	Perkins[80]	2002	114–600	70
Isopentane	Vassiliou[33]	2015	273–673	400
Krypton	Hanley[48]	1974	125–500	20
Methane	Friend[81]	1989	91–700	100
Methanol	Sykioti[82]	2013	175.61–660	245
Methyl linoleate	Perkins[83]	2011	302–505	42
Methyl oleate	Perkins[83]	2011	302–508	42
Methyl cyclohexane	Perkins[84]	2008	300–600	60
m-xylene	Mylona[74]	2014	225.3–700	200
Nitrogen	Lemmon[18]	2004	50–2000	2200
n-nonane	Huber[71]	2005	219.7–678	503
n-octane	Huber[71]	2005	216.37–678	591
Oxygen	Lemmon[18]	2004	54.36–2000	82
o-xylene	Mylona[74]	2014	247.98–700	70
parahydrogen	Assael[79]	2011	13.80–1000	100
n-pentane	Vassiliou[33]	2015	143.47–624	70
Propane	Marsh[85]	2002	85.47–600	70
Propylcyclohexane	Perkins[84]	2008	300–600	60
Propylene	Assael[75]	2016	180–625	50
p-xylene	Mylona[74]	2014	286.40–700	200
R113	Krauss[86]	1989	240–500	30
R114	Krauss[86]	1989	280–500	20
R12	Krauss[86]	1989	200–600	60
RC318	Krauss[86]	1989	240–450	60
R123	Laesecke[87]	1996	180–480	67
R1233zd(E)	Perkins[88]	2017	204–453	67
R1234yf	Perkins[89]	2011	242–344	23
R1234ze(E)	Perkins[89]	2011	203–344	23
R125	Perkins[59]	2006	190–512	70
R134a	Perkins[90]	2000	200–450	70
R152a	Krauss[60]	1996	240–440	20
R161	Tsolakidou[61]	2017	234–374	20
R23	Shan[62]	2000	170–433	60
R245fa	Perkins[63]	2016	172–416	70.5
Sulfur hexafluoride	Assael[91,92]	2012	223.55–1000	150
Toluene	Assael[93]	2012	178–1000	1000
n-undecane	Assael[65]	2017	247.54–700	500
Water	Huber[4]	2012	273.16–1173	1000
Xenon	Hanley[48]	1974	170–500	20

a range of 0.5–140 mPa s. The temperature and pressure range covered is 273 K–473 K with pressures to 200 MPa, and the uncertainty is 4.75% at the 95% confidence level.[101]

Very recently, a new reference correlation for the viscosity of tris(2-ethylhexyl) trimellitate (TOTM) was proposed.[103] The new correlation was designed to serve in industrial applications for the calibration of viscometers at elevated temperatures and pressures such as those encountered in the exploration of oil reservoirs and in lubrication. The correlation covers temperatures from 303 to 477 K, pressures from

TABLE 7. Reference correlations for the viscosity of molten metals at 0.1 MPa

Fluid	First author	Year	T_{range} (K)
Aluminum	Assael[94]	2006	950–1200
Antimony	Assael[95]	2012	900–1300
Bismuth	Assael[95]	2012	545–1500
Cadmium	Assael[96]	2012	900–1300
Cobalt	Assael[96]	2012	1768–2100
Copper	Assael[97]	2010	1356–1950
Gallium	Assael[96]	2012	304–800
Indium	Assael[96]	2012	429–1000
Iron	Assael[94]	2006	1850–2500
Lead	Assael[95]	2012	601–2000
Mercury	Assael[96]	2012	234–600
Nickel	Assael[95]	2012	1728–2500
Silicon	Assael[96]	2012	1685–1900
Silver	Assael[95]	2012	1235–1600
Thallium	Assael[96]	2012	577–800
Tin	Assael[97]	2010	506–1280
Zinc	Assael[96]	2012	695–1100

TABLE 8. Reference correlations for the thermal conductivity of molten metals at 0.1 MPa

Fluid	First author	Year	T_{range} (K)
Bismuth	Assael[98]	2017	545–1110
Cobalt	Assael[98]	2017	1769–1903
Copper	Assael[99]	2017	1358–1700
Gallium	Assael[99]	2017	303–850
Germanium	Assael[98]	2017	1212–1473
Indium	Assael[99]	2017	430–1300
Iron	Assael[99]	2017	1815–2050
Lead	Assael[99]	2017	602–1150
Nickel	Assael[99]	2017	1730–2000
Silicon	Assael[98]	2017	1690–1945
Tin	Assael[99]	2017	507–2000

0.1 to 200 MPa, and viscosities from 1.6 to 760 mPa s. The uncertainty in the data provided is on the order of 3.2% at a 95% confidence level, which was proposed by the IATP as adequate for most industrial applications.

5. Conclusions

In this paper, we discussed and presented reference values and reference correlations for the thermal conductivity and viscosity of many important fluids. The criteria employed for the development of thermal conductivity and viscosity reference values and reference correlations were also discussed.

Although it seems that there exist reference correlations for many fluids covering a very wide range of conditions, a lot of work still needs to be done. In particular, consistency and consensus for reference quantities should be established. New measurements should concentrate in extreme conditions of temperatures and pressures and in fluids not covered in the tables presented in this work to meet modern industrial demands. For low-pressure gases, theoretical advances in the ability to calculate *ab initio* pair potentials will become increasingly important for an increasingly wide range of substances. Theoretical progress is needed, however, to extend these results to higher pressures by considering, for example, the effects of three-body collisions on transport properties and to establish and validate more general liquid-state predictive models. Similarly, theoretical advances are needed to extend the use of *ab initio* calculations of thermal conductivity beyond the noble gases and/or to higher densities.

Acknowledgments

Wide-ranging reference correlations cover the zero-density, the critical, and the residual contributions. The work of E. Vogel and his co-workers in the zero-density viscosity region, as well as the work of J. V. Sengers and his co-workers in the critical region of thermal conductivity and viscosity, is gratefully acknowledged—without them, developing low-uncertainty reference correlations would have been much more difficult. The resulting theoretical basis in the zero-density and critical regions constrains reference correlations, allowing for more reliable extrapolation behavior.

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