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Reference Values and Reference Correlations for the Thermal Conductivity and Viscosity of Fluids[a)]

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Abstract

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.

Keywords

reference correlations; reference values; thermal conductivity; viscosity

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

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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 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 IUPAC, has been proposing mostly reference values. Finally, we should also mention the International Association for the Properties of Water and Steam that 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., spacebased 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 International Association for Transport Properties, IATP) of the International Union of Pure and Applied Chemistry, 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 measureable 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 subsequent work by 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 thermalconductivity 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,

$$\lambda = 0.1311 \pm 0.0026\ \mathrm{W\ m^{-1}\ K^{-1}}. \quad (1)$$

and for water, at 298.15 K and 0.1 MPa,

$$\lambda = 0.6067 \pm 0.0122 \text{ W m}^{-1} \text{ K}^{-1}. \quad (2)$$

These expanded 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 $T^* = (T/298.15 \text{ K})$, and $\lambda^* = (\lambda(T)/\lambda(298.15 \text{ K}))$: temperature range 230 K ≤ T ≤ 360 K,

$$\lambda^* = 1.68182 - 0.682022\, T^* \quad (3)$$

, and extended range 189 K ≤ T ≤ 360 K,

$$\lambda^* = 1.45210 - 0.224229\, \mathrm{T}^* - 0.225873\, T^*2 \quad (4)$$

.

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 K ≤ T ≤ 383.15 K, as

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

where $T_\mathrm{r} = T/(300 \text{ K})$. The expanded relative uncertainty thermal conductivity from this equation 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 thermosphysical properties of helium in the dilute-gas state over the temperature range from (1 to 104) 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 the following reference value for the thermal conductivity of helium at 25 °C, 0.1 MPa, $\lambda_{\mathrm{He}} = 0.155\,000\,8 \pm 0.000\,001\,5$ $\mathrm{Wm}^{-1}\,\mathrm{K}^{-1}$. 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, that we present in Table 1. In Table 1 the error bounds correspond to the expanded ($k = 2$) uncertainty at a 95% confidence interval.

Dilute-gas transport properties evaluated from *abinitio* 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 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 above 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 equation,[14] (corrected for the current valid equation of state for argon[15])

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

where λ is measured in mW $\mathrm{m}^{-1}\,\mathrm{K}^{-1}$ and ρ 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 REFPROP version 10 database[16] yield (0.15531 and 0.017745) W $\mathrm{m}^{-1}\,\mathrm{K}^{-1}$ for helium[17] and argon[18], respectively. 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 the International Association for the Properties of Water and Steam (IAPWS) maintains current international consensus standards for the fluid. Consistent with the IAPWS reference correlation, ISO/TR 3666:199819 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

$$\eta \;=\; 1.0016\ \mathrm{mPa\ s} \qquad (7)$$

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

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

with $T_{\mathrm{r}} = T/(300\ \mathrm{K})$. 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 3666:199819 standard reference value.

In a recent paper,[22] a reference correlation for toluene was proposed. In the specific range of 263 to 273 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 then 0.1%.

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

where, in this case, $T_{\mathrm{r}} = T/T_{\mathrm{c}}$ 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 Section 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 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 *abinitio* 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 the next section 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 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 equation[24]

$$\eta = 0.17763 \times 10^{-4} + 0.86870 \times 10^{-8}\rho + 0.14240 \times 10^{-9}\rho^2 \quad (10)$$

where η is measured in Pa s and ρ in kg m^{-3}. Note that this equation 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 the

National Institute of Standards and Technology (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 1980's 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 (REFrigerant PROPerties).[16] Its scope was 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 included 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 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 if often is ignored since it is significant only in a small region very near the critical point. For thermal conductivity correlations it typically is 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

b. Viscosity of high-viscosity liquids

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 International Association for Transport Properties, IATP, in 2006 to critically evaluate the density, the viscosity, and the thermal conductivity of selected liquid metals. Reference correlations developed based on critically evaluated experimental data so far, 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 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 M. Trusler. The viscosity of squalane covers a range of 0.5 to 140 mPa s. The temperature and pressure range covered is 273 K to 473 K with pressures to 200 MPa, and an uncertainty of 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 (0.1 to 200) MPa and viscosities from (1.6 to 760) mPa s. The uncertainty in the data provided is of the order of 3.2 % at a 95 % confidence level which was proposed by 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.

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Wide-ranging reference correlations cover the zerodensity, the critical, and the residual contributions. The work of E. Vogel and his coworkers in the zero-density viscosity region, as well as the work of J.V. Sengers and his coworkers in the critical region of thermal conductivity and viscosity, are 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.

6. References

1. Riedel L, Chem. lng. Tech. 23, 21 (1951).
2. Nieto de Castro CA, Li SFY, Nagashima A, Trengove RD, and Wakeham WA, J. Phys. Chem. Ref. Data 15, 1073 (1986).
3. Taylor BN and Kuyatt CE, Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results , NIST Technical Note 1297 (1994).
4. Huber ML, Perkins RA, Friend DG, Sengers JV, Assael MJ, Metaxa IN, Miyagawa K, Hellmann R, and Vogel E, J. Phys. Chem. Ref. Data 41, 033102 (2012).
5. Assael MJ, Ramires MLV, Nieto de Castro CA, and Wakeham WA, J. Phys. Chem. Ref. Data 19, 113 (1990).
6. Cencek W, Przybytek M, Komasa J, Mehl JB, Jeziorski B, and Szalewicz K, J. Chem. Phys. 136, 224303 (2012). [PubMed: 22713043]
7. May EF, Moldover MR, Berg RF, and Hurly JJ, Metrologia 43, 247 (2006).
8. May EF, Moldover MR, and Berg RF, Int. J. Thermophys. 28, 1085 (2007).
9. Bich E, Hellmann R, and Vogel E, Mol. Phys. 106, 1107 (2008).
10. Vogel E, Jager B, Hellmann R, and Bich E, Mol. Phys. 108, 3335 (2010).
11. Jäger B, Hellmann R, Bich E, and Vogel E, J. Chem. Phys. 144, 114304 (2016). [PubMed: 27004873]
12. Hellmann R, Jäger B, and Bich E, J. Chem. Phys. 147, 034304 (2017). [PubMed: 28734299]
13. Rainwater JC and Friend DG, Phys. Rev. A 36, 4062 (1987).
14. Kestin J, Paul R, Clifford AA, and Wakeham WA, Physica 100A, 349 (1980).
15. Tegeler C, Span R, and Wagner W, J. Phys. Chem. Ref. Data 28, 779 (1999).
16. Lemmon EW, Bell IH, Huber ML, and McLinden MO, NIST Standard Reference Database 23: Reference Fluid Thermodynamic and Transport Properties -REFPROP, Version 10.0, National Institute of Standards and Technology (2018).
17. Hands BA and Arp VD, Cryogenics 21, 697 (1981).
18. Lemmon EW and Jacobsen RT, Int. J. Thermophys. 25, 21 (2004).
19. Viscosity of Water, ISO/TR Technical Report 3666 (International Organization for Standardization (ISO), Geneva, 1998(E), 1998).
20. Swindells JF, Coe JR Jr., and Godfrey TB, J. Res. NBS 48, 1 (1952).
21. Huber ML, Perkins RA, Laesecke A, Friend DG, Sengers JV, Assael MJ, Metaxa IN, Vogel E, Mares R, and Miyagawa K, J. Phys. Chem. Ref. Data 38, 101 (2009).
22. Avgeri S, Assael MJ, Huber ML, and Perkins RA, J. Phys. Chem. Ref. Data 44, 033101 (2015).
23. Berg RF and Moldover MR, J. Phys. Chem. Ref. Data 41, 043104 (2012).
24. Experimental Thermodynamics Vol. III Measurement of the Transport Properties of Fluids, edited by Wakeham WA, Nagashima A, and Sengers JV (Blackwell Scientific Publications, Oxford, 1991).
25. Berg RF, May EF, and Moldover MR, J. Chem. Eng. Data 59, 116 (2014).
26. Seibt D, Herrmann S, Vogel E, Bich E, and Hassel E, J. Chem. Eng. Data 54, 2626 (2009).
27. Friend DG and Huber ML, Int. J. Thermophys. 15, 1279 (1994).
28. Monogenidou SA, Assael MJ, and Huber ML, J.Phys. Chem. Ref. Data(in press).
29. Avgeri S, Assael MJ, Huber ML, and Perkins RA, J. Phys. Chem. Ref. Data 43, 033103 (2014).

30. Herrmann S and Vogel E, J. Phys. Chem. Ref. Data 47, 013104 (2018).
31. Laesecke A and Muzny CD, J. Phys. Chem. Ref. Data 46, 013107 (2017). [PubMed: 28736460]
32. Tariq U, Jusoh ARB, Riesco N, and Vesovic V, J.Phys. Chem. Ref. Data 43, 033101 (2014).
33. Vassiliou C-M, Assael MJ, Huber ML, and Perkins RA, J. Phys. Chem. Ref. Data 44, 033102 (2015).
34. Huber ML, Laesecke A, and Xiang HW, Fluid Phase Equilib. 224, 263 (2004).
35. Meng X, Zhang J, Wu J, and Liu Z, J. Chem. Eng. Data 57, 988 (2012).
36. Huber ML, Laesecke A, and Perkins RA, Energy & Fuels 18, 968 (2004).
37. Vogel E, Span R, and Herrmann S, J. Phys. Chem. Ref. Data 44, 043101 (2015).
38. Kiselev SB, Ely JF, Abdulagatov IM, and Huber ML, Ind. Eng. Chem. Res. 44, 6916 (2005).
39. Meng X, Cao FL, Wu JT, and Vesovic V, J. Phys. Chem. Ref. Data 46, 013101 (2017).
40. Holland PM, Eaton BE, and Hanley HJM, J. Phys. Chem. Ref. Data 12, 917 (1983).
41. Kestin J, Sengers JV, Kamgar-Parsi B, and Levelt Sengers JMH, J. Phys. Chem. Ref. Data 13, 601 (1984).
42. Arp VD, McCarty RD, and Friend DG, Thermophysical Properties of Helium-4 from 0.8 to 1500 K with Pressures to 2000 MPa, NIST Technical Note 1334 (revised), 1998.
43. Michailidou EK, Assael MJ, Huber ML, Abdulagatov IM, and Perkins RA, J. Phys. Chem. Ref. Data 43, 023103 (2014).
44. Michailidou EK, Assael MJ, Huber ML, and Perkins RA, J. Phys. Chem. Ref. Data 42, 033014 (2013).
45. Muzny CD, Huber ML, and Kazakov AF, J. Chem. Eng. Data 58, 969 (2013).
46. Schmidt KAG, Quiñones-Cisneros SE, Carroll JJ, and Kvamme B, Energy & Fuels 22, 3424 (2008).
47. Vogel E, Kuchenmeister C, and Bich E, Int. J. Thermophys. 21, 343 (2000).
48. Hanley HJM, McCarty RD, and Haynes WM, J.Phys. Chem. Ref. Data 3, 979 (1974).
49. Quiñones-Cisneros SE, Huber ML, and Deiters UK, Reference correlation for the viscosity of methane, unpublished work, . (2011).
50. Xiang HW, Laesecke A, and Huber ML, J. Phys. Chem. Ref. Data 35, 1597 (2006).
51. Cao FL, Meng XY, Wu JT, and Vesovic V, J. Phys. Chem. Ref. Data 45, 013103 (2016).
52. Wen C, Meng X, Huber ML, and Wu J, J. Chem. Eng. Data 62, 3603 (2017). [PubMed: 29311751]
53. Quiñones-Cisneros SE and Deiters UK, J. Phys. Chem. B 110, 12820 (2006). [PubMed: 16800618]
54. Cao FL, Meng XY, Wu JT, and Vesovic V, J. Phys. Chem. Ref. Data 45, 023102 (2016).
55. Vogel E and Herrmann S, J. Phys. Chem. Ref. Data 45, 043103 (2016).
56. Balogun B, Riecso N, and Vesovic V, J. Phys. Chem. Ref. Data 44, 013103 (2015).
57. Tanaka Y and Sotani T, Int. J. Thermophys. 17, 293 (1996).
58. Huber ML and Assael MJ, Int. J. Refrig.-Rev. Int. du Froid 71, 39 (2016).
59. Perkins RA and Huber ML, J. Chem. Eng. Data 51, 898 (2006).
60. Krauss R, Weiss VC, Edison TA, Sengers JV, and Stephan K, Int. J. Thermophys. 17, 731 (1996).
61. Tsolakidou CM, Assael MJ, Huber ML, and Perkins RA, J. Phys. Chem. Ref. Data 46, 023103 (2017). [PubMed: 28785120]
62. Shan Z, Penoncello SG, and Jacobsen RT, ASHRAE Trans. 106, 1 (2000).
63. Perkins RA, Huber ML, and Assael MJ, J. Chem. Eng. Data 61, 3286 (2016).
64. Quiñones-Cisneros SE, Huber ML, and Deiters UK, J. Phys. Chem. Ref. Data 41, 023102 (2012).
65. Assael MJ, Papalas TB, and Huber ML, J. Phys. Chem. Ref. Data 46, 033103 (2017). [PubMed: 29230074]
66. Tufeu R, Ivanov DY, Garrabos Y, and Leneindre B, Ber. Bunsen-Ges. Phys. Chem. 88, 422 (1984).
67. Assael MJ, Mihailidou EK, Huber ML, and Perkins RA, J. Phys. Chem. Ref. Data 41, 043102 (2012).
68. Perkins RA, Ramires MLV, Nieto de Castro CA, and Cusco L, J. Chem. Eng. Data 47, 1263 (2002).

69. Huber ML, Sykioti EA, Assael MJ, and Perkins RA, J. Phys. Chem. Ref. Data 45, 013102 (2016). [PubMed: 27064300]
70. Koutian A, Assael MJ, Huber ML, and Perkins RA, J. Phys. Chem. Ref. Data 46, 013102 (2017). [PubMed: 28584386]
71. Huber ML and Perkins RA, Fluid Phase Equilib. 227, 47 (2005).
72. Friend DG, Ingham H, and Ely JF, J. Phys. Chem. Ref. Data 20, 275 (1991).
73. Assael MJ, Sykioti EA, Huber ML, and Perkins RA, J. Phys. Chem. Ref. Data 42, 023102 (2013).
74. Mylona SK, Antoniadis KD, Assael MJ, Huber ML, and Perkins RA, J. Phys. Chem. Ref. Data 43, 043104 (2014).
75. Assael MJ, Koutian A, Huber ML, and Perkins RA, J. Phys. Chem. Ref. Data 45, 033104 (2016). [PubMed: 27818536]
76. Assael MJ, Bogdanou I, Mylona SK, Huber ML, Perkins RA, and Vesovic V, J. Phys. Chem. Ref. Data 42, 023101 (2013).
77. Monogenidou SA, Assael MJ, and Huber ML, J.Phys. Chem. Ref. Data 47, 013103 (2018).
78. Assael MJ, Mylona SK, Tsiglifisi CA, Huber ML, and Perkins RA, J. Phys. Chem. Ref. Data 42, 013106 (2013).
79. Assael MJ, Assael JAM, Huber ML, Perkins RA, and Takata Y, J. Phys. Chem. Ref. Data 40, 033101 (2011).
80. Perkins RA, J. Chem. Eng. Data 47, 1272 (2002).
81. Friend DG, Ely JF, and Ingham H, Tables for the Thermophysical Properties of Methane, NIST Technical Note 1325, 1989.
82. Sykioti EA, Assael MJ, Huber ML, and Perkins RA, J. Phys. Chem. Ref. Data 42, 043101 (2013).
83. Perkins RA and Huber ML, Energy & Fuels 25, 2383 (2011).
84. Perkins RA, Hammerschmidt U, and Huber ML, J.Chem. Eng. Data 53, 2120 (2008).
85. Marsh KN, Perkins RA, and Ramires MLV, J. Chem. Eng. Data 47, 932 (2002).
86. Krauss R and Stephan K, J. Phys. Chem. Ref. Data 18, 43 (1989).
87. Laesecke A, Perkins RA, and Howley JB, Int. J. Refrig.-Rev. Int. du Froid 19, 231 (1996).
88. Perkins RA, Huber ML, and Assael MJ, J. Chem. Eng. Data 62, 2659 (2017). [PubMed: 29230068]
89. Perkins RA and Huber ML, J. Chem. Eng. Data 56, 4868 (2011).
90. Perkins RA, Laesecke A, Howley JB, Ramires MLV, Gurova AN, and Cusco L, Experimental thermal conductivity values for the IUPAC roundrobin sample of 1,1,1,2-tetrafluoroethane (R134a), NISTIR 6605, 2000.
91. Assael MJ, Koini IA, Antoniadis KD, Huber ML, Abdulagatov IM, and Perkins RA, J. Phys. Chem. Ref. Data 41, 023104 (2012).
92. Assael MJ, Koini IA, Antoniadis KD, Huber ML, Abdulagatov IM, and Perkins RA, J. Phys. Chem. Ref. Data 43, 039901 (2014).
93. Assael MJ, Mylona SK, Huber ML, and Perkins RA, J. Phys. Chem. Ref. Data 41, 023101 (2012).
94. Assael MJ, Kakosimos K, Bannish M, Brillo J, Egry I, Brooks R, Quested PN, Mills KC, Nagashima A, Sato Y, and Wakeham WA, J. Phys. Chem. Ref. Data 35, 285 (2006).
95. Assael MJ, Kalyva AE, Antoniadis KE, Banish RM, Egry I, Wu J, Kaschnitz E, and Wakeham WA, High Temp. - High Press. 41, 161 (2012).
96. Assael MJ, Armyra IJ, Brillo J, Stankus S, Wu J, and Wakeham WA, J. Phys. Chem. Ref. Data 41, 033101 (2012).
97. Assael MJ, Kalyva AE, Antoniadis KE, Banish RM, Egry I, Quested PN, Wu J, Kaschnitz E, and Wakeham WA, J. Phys. Chem. Ref. Data 39, 033105 (2010).
98. Assael MJ, Antoniadis KD, Wakeham WA, Huber ML, and Fukuyama H, J. Phys. Chem. Ref. Data 46, 033101 (2017). [PubMed: 28970643]
99. Assael MJ, Chatzimichailidis A, Antoniadis KD, Wakeham WA, Huber ML, and Fukuyama H, High Temp. - High Press. 46, 391 (2017). [PubMed: 29353915]
100. Comuñas MJP, Paredes X, Gaciño FM, Fernández J, Bazile JP, Boned C, Daridon JL, Galliero DG, Pauly J, Harris K, Assael MJ, and Mylona SK, J. Phys. Chem. Ref. Data 42, 033101 (2013).

101. Mylona SK, Assael MJ, Comunas MJP, Paredes X, Gacino FM, Fernandez J, Bazile JP, Boned C, Daridon JL, Galliero G, Pauly J, and Harris K, J. Phys. Chem. Ref. Data 43, 013104 (2014).

102. Schmidt KAG, Pagnutti D, Curran MD, Singh A, Trusler JPM, Maitland GC, and McBride-Wright M, J. Chem. Eng. Data 60, 137 (2015).

103. Wakeham WA, Assael MJ, Avelino H, Bair S, Baled HO, Bamgbade B, Bazile JP, Caetano F, Communas M, Daridon J-L, Diogo J, Enick R, Fareleira J, Fernandez J, Oliveira MC, Santos T, and Tsolakidou CM, J. Chem. Eng. Data 62, 2884 (2017).

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 / W m^{-1} K^{-1}	$U(\lambda)$ / W m^{-1} K^{-1}
He	0.1550008	0.0000030
Ar	0.017668	0.000010
Xe	0.005505	0.000012
Ne	0.049193	0.000032
Kr	0.009457	0.000006

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 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	0.04924	0.01767	0.009451	0.005482
100	0.1811	0.05784	0.02136	0.01163	0.006852
200	0.2139	0.06743	0.02559	0.01418	0.008534
300	0.2447	0.07679	0.02960	0.01650	0.01007
400	0.2741	0.08534	0.03314	0.01864	0.01149
500	0.3020	0.09339	0.03650	0.02064	0.01281

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 /μ Pa 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

TABLE 5.

Wide-ranging Reference Correlations for Viscosity

Fluid	1st Author	Year	T_{range} (K)	P_{max} (MPa)
ammonia	Monogenidou[28]	1995	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	Quinones-Cis[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-Cis[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-Cis[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

Fluid	**1st Author**	**Year**	**T_{range} (K)**	**P_{max} (MPa)**
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-Cis[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	223–1000	50
toluene	Avgeri[22]	2015	178–675	500
n-undecane	Assael[65]	2017	247.54–700	500
water	Huber[21]	2009	273–1173	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 identification imply recommendation or endorsement by the National Institute of Standards and technology, no does it imply that the products identified are necessarily the best available for the purpose.

TABLE 6.

Wide-ranging Reference Correlations for Thermal Conductivity

Fluid	**1st 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	216–1100	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

Fluid	1st Author	Year	T_{range} (K)	P_{max} (MPa)
propylcyclohe xane	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	Assael91, 92	2012	223–1000	150
toluene	Assael[93]	2012	178–1000	1000
n-undecane	Assael[65]	2017	247.54–700	500
water	Huber[4]	2012	273–1173	1000
xenon	Hanley[48]	1974	170–500	20

TABLE 7.

Reference Correlations for the Viscosity of Molten Metals at 0.1 MPa.

Fluid	**1st Author**	**Year**	**T_{range} (K)**
aluminium	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	**1st 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