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Thermal conductivity, viscosity, isobaric specific heat capacity and Prandtl number of gases at low pressure: Aliphatic hydrocarbons – alkanes

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THE PREPARATION OF THIS DATA ITEM

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THERMAL CONDUCTIVITY, VISCOSITY, ISOBARIC SPECIFIC HEAT CAPACITY AND PRANDTL NUMBER OF GASES AT LOW PRESSURE: ALIPHATIC HYDROCARBONS – ALKANES

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Data sheets for each of the gases are given in the following order:-

	Formula	Name	Alternative Name(s)	
1.	CH ₄	Methane		11
2.	C ₂ H ₆	Ethane		13
3.	C ₃ H ₈	Propane		15
4.	C ₄ H ₁₀	Butane		17
5.	(CH ₃) ₃ CH	2-Methylpropane	Isobutane	19
6.	C ₅ H ₁₂	Pentane		20
7.	(CH ₃) ₂ CHCH ₂ CH ₃	2-Methylbutane	Isopentane	22

	Formula	Name	Alternative Name(s)	
8.	$(\text{CH}_3)_4\text{C}$	2,2-Dimethylpropane	Neopentane	23
9.	C_6H_{14}	Hexane		24
10.	$(\text{CH}_3)_3\text{CCH}_2\text{CH}_3$	2,2-Dimethylbutane	Neohexane	26
11.	C_7H_{16}	Heptane		27
12.	$(\text{CH}_3)_2\text{CHCH}_2\text{CH}(\text{CH}_3)_2$	2,4-Dimethylpentane		29
13.	C_8H_{18}	Octane		30
14.	$(\text{CH}_3)_3\text{CCH}_2\text{CH}(\text{CH}_3)_2$	2,2,4-Trimethylpentane	Isooctane	32
15.	C_9H_{20}	Nonane		33
16.	$\text{C}_{10}\text{H}_{22}$	Decane		35
17.	$\text{C}_{11}\text{H}_{24}$	Undecane		37
18.	$\text{C}_{12}\text{H}_{26}$	Dodecane		39
19.	$\text{C}_{13}\text{H}_{28}$	Tridecane		41
20.	$\text{C}_{14}\text{H}_{30}$	Tetradecane		43
21.	$\text{C}_{15}\text{H}_{32}$	Pentadecane		45
22.	$\text{C}_{16}\text{H}_{34}$	Hexadecane		47
23.	$\text{C}_{18}\text{H}_{38}$	Octadecane		49

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THERMAL CONDUCTIVITY, VISCOSITY, ISOBARIC SPECIFIC HEAT CAPACITY AND PRANDTL NUMBER OF GASES AT LOW PRESSURE: ALIPHATIC HYDROCARBONS – ALKANES

1. INTRODUCTION

This Item presents in tabular form values of thermal conductivity, viscosity, isobaric specific heat capacity and Prandtl number of the vapours of alkanes at or below atmospheric pressure. The range covered is in general from below the normal boiling point to at least 603 K. Previous Data Items in this group were restricted to thermal conductivity but the importance of the Prandtl number for chemical engineering design makes the inclusion of the isobaric specific heat capacity and viscosity desirable.

The data on which these values are based are believed to be the most reliable available and have been reviewed and suitably extended. Sections 4, 5 and 6 describe, respectively, the procedures used to obtain the values of thermal conductivity, viscosity and isobaric specific heat capacity and indicate the effects of pressure. Section 7 gives an explanation of the Tables, the Prandtl number equation and indicates the uncertainties in the values presented.

References to sources of supplementary information are given in Section 8. Appendix A provides a full bibliography of relevant data sources for viscosity, specific heat capacity and thermal conductivity. The data sources for each particular compound are listed with the appropriate table.

2. NOTATION AND UNITS

The units of each property are based on SI units. The SI units of thermal conductivity, viscosity and specific heat capacity are the watt per metre kelvin (W/m K), the newton second per square metre (N s/m²) and the joule per kilogram kelvin (J/kg K) respectively. Convenient units for the properties in this Item are: thermal conductivity, the milliwatt per metre kelvin (mW/m K); viscosity, the micronewton second per square metre (μN s/m²); isobaric specific heat capacity, the kilojoule per kilogram kelvin (kJ/kg K). Conversion factors are given in Section 3. The correlation parameters are not dimensionless but take the units listed in Tables 9.1, 9.2 and 9.3.

b_1, b_2, b_3, b_4	constants for each fluid in Equation (4.1), (5.1), (6.1)	*
c	specific heat capacity	kJ/kg K
M	molecular weight (relative molecular mass)	—
p	pressure	kPa
Pr	Prandtl number	—
T	kelvin temperature	K
t	Celsius temperature, $T - 273.15$	°C
η	dynamic viscosity	μN s/m ²
λ	thermal conductivity	mW/m K
Γ	correlation parameter for thermal conductivity	—
ξ	correlation parameter for viscosity	—

* See footnote at end of this section.

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Superscripts

id	denotes ideal gas
(o)	denotes dilute gas

Subscripts

c	denotes value at critical point
p	denotes constant pressure
r	denotes reduced quantity, for example $T_r = T/T_c$

* The units of these constants for thermal conductivity, viscosity and ideal gas heat capacity can be found in Tables 9.1, 9.2 and 9.3 respectively.

3. CONVERSION FACTORS

Thermal conductivity

$$\begin{aligned}
 1 \text{ mW/m K} &= 0.8598 \times 10^{-3} \text{ kcal/m h } ^\circ\text{C} \\
 &= 2.3885 \times 10^{-6} \text{ cal/cm s } ^\circ\text{C} \\
 &= 0.5778 \times 10^{-3} \text{ Chu/ft h } ^\circ\text{C} \\
 &= 0.5778 \times 10^{-3} \text{ Btu/ft h } ^\circ\text{F} \\
 &= 6.9335 \times 10^{-3} \text{ Btu in/ft}^2 \text{ h } ^\circ\text{F}
 \end{aligned}$$

Viscosity

$$\begin{aligned}
 1 \text{ } \mu\text{N s/m}^2 &= 10^{-3} \text{ cP} \\
 &= 145.04 \times 10^{-12} \text{ lbf s/in}^2 \\
 &= 101.972 \times 10^{-9} \text{ kgf s/m}^2 \\
 &= 10^{-6} \text{ kg/m s}
 \end{aligned}$$

Specific heat capacity

$$\begin{aligned}
 1 \text{ kJ/kg K} &= 0.239 \text{ cal/g K} \\
 &= 0.239 \text{ Btu/lb } ^\circ\text{F}
 \end{aligned}$$

Pressure

$$\begin{aligned}
 10^5 \text{ Pa} &= 1 \text{ bar} \\
 &= 14.5038 \text{ lbf/in}^2 \\
 &= 1.0197 \text{ kgf/cm}^2 \\
 &= 0.9869 \text{ atm} \\
 &= 750.062 \text{ mmHg.}
 \end{aligned}$$

4. THERMAL CONDUCTIVITY OF GASES

4.1 Thermal Conductivity at Low Pressure (Dilute Gas)

A comprehensive survey of the literature on the thermal conductivity of dilute gases (at atmospheric pressure or below) was prepared with the assistance of the National Engineering Laboratory (NEL), East Kilbride, UK. Data for the normal alkanes up to octadecane and a few branched alkanes have been studied and a correlation of the data has been obtained using a modification of the scheme proposed by Thodos and co-workers (Reference 1). The correlation reduces the thermal conductivity by means of a parameter $\Gamma = M^{1/2} T_c^{1/6} / p_c^{2/3}$ and relates the value of $\Gamma \lambda / c_p$ to the reduced temperature. Since the critical

constants are reliable (Data Sources A1.: 10, 11, 12) and the heat capacity data are well established (Data Source A1.: 21), the values of λ can be calculated back with confidence from a smooth line drawn through a $\Gamma\lambda/c_p$ vs T_r plot.

Close agreement of the data among the numerous authors and differing methods was found and it was possible to extend the range of results to between at least 293 and 603 K in all cases. Measurements on methane, ethane, propane and butane have been made for temperatures up to at least 740 K. Where measurements have been reported at high temperatures, a tendency for the thermal conductivity versus temperature gradient to increase unexpectedly has been assumed to indicate breakdown of the molecule into simpler constituents with higher values of the property. These values were therefore ignored in the correlation.

The correlated data are represented by the equation

$$\lambda^{(o)} = b_1 + b_2(1 - T_r) + b_3(1 - T_r)^2 + b_4(1 - T_r)^3. \quad (4.1)$$

The derived values of the constants given in Table 9.1 give the best fits to the experimental data, not only as individual compounds but also as members of their chemical series.

Using these values with the values of T_c given in Table 9.1 (Data Sources A1.: 10, 11, 12), values of $\lambda^{(o)}$ in mW/m K have been calculated at 20 K and at 20 degree Celsius intervals for each compound.

4.2 Effect of Pressure

The thermal conductivity of all gases increases with pressure but the effect is small at low pressures from 0.1 to 1000 kPa (approximately 1% per 100 kPa). At higher pressures it is difficult to generalise. However, there is a considerable literature available for the lower hydrocarbons. The correlations of Stiel and Thodos (Reference 4) remain the best method of evaluating the pressure effect in terms of the density and critical properties. Tables for the effect of pressure for the alkanes have been published in Data Sources A1.:16 and A2.: 871. Data sources providing tables for specific compounds are marked with an asterisk in Appendix A2.

Near the critical point, the thermal conductivity increases asymptotically and at the critical point tends to infinity. This phenomenon, the so-called critical enhancement implies that, in the critical region the thermal conductivity is very sensitive to temperature and pressure and cannot be predicted reliably. As a rough guide, for the subcritical vapour for $0.9 \leq T_r \leq 1$, the critical enhancement takes effect at pressures exceeding $\approx 0.5p_c$ and is greatest at saturation. For values of T_r in the range $1 \leq T_r \leq 1.1$, the thermal conductivity at any specified temperature passes through a maximum at values of $p_r > 1$; the maximum declines and shifts to higher pressures with increasing temperature. A useful discussion of the anomalous behaviour of thermal conductivity near the critical point is given in References 14 and 16 and Data Source A2.: 7512. For example, Le Neindre (Data Source A2.: 811) measured values for propane of 100 mW/m K above the dilute gas value – a fivefold increase.

5. VISCOSITY OF GASES

5.1 Viscosity at Low Pressure (Dilute Gas)

Well-documented and correlated data are available for the normal alkanes up to octane. Where necessary, these data were extended to lower and/or higher temperatures by prediction using either the Chapman-Enskog theory or Reichenberg's method (Data Source A1.: 7). Data for the isomeric compounds

were extended adequately by the Chapman-Enskog theory, with the values of critical temperature, critical pressure and acentric factor published by ESDU (Data Source A1.: 10, 11, 12).

For the higher carbon number alkanes, the Reichenberg method (Data Source A1.: 7) appeared to give adequate agreement with any available data. Confirmation of this was obtained by correlating any reliable values of $\eta^{(o)}$ on a reduced basis using the parameter, ξ , suggested by Stiel and Thodos (Reference 2), where

$$\xi = T_c^{1/6} / (M^{1/2} p_c^{2/3}).$$

From a plot of $\xi \eta^{(o)}$ against T_r , values of $\eta^{(o)}$ were estimated for temperature ranges for which the data were otherwise inadequate.

The experimental and estimated dilute gas viscosities are adequately represented by the following equation of the same form as that used for thermal conductivity and it is valid over the same temperature range.

$$\eta^{(o)} = b_1 + b_2(1 - T_r) + b_3(1 - T_r)^2 + b_4(1 - T_r)^3. \quad (5.1)$$

The derived values of the constants given in Table 9.2 give the best fit to the data. Using these values with the value of T_c given in Table 9.2, values of $\eta^{(o)}$ in $\mu\text{N s/m}^2$ have been calculated at 20 K and at 20 degree Celsius intervals for each compound.

5.2 Effect of Pressure

The viscosity of gases increases with pressure, but the effect is small at low pressures (0.1 to 1000 kPa). The correlation of Stiel and Thodos (Reference 3) may be used to evaluate the pressure effect in terms of the density and critical properties. Near the critical point, however, the pressure effect is greater and cannot be predicted reliably but is less significant than in the case of thermal conductivity.

The effect of pressure on the principal alkanes has been evaluated in three of the listed Data Sources (A1.: 9, 15, 16) and in the specific sources marked with an asterisk.

6. ISOBARIC SPECIFIC HEAT CAPACITY

6.1 Isobaric Specific Heat Capacity at Low Pressure (Ideal Gas)

The isobaric specific heat capacity approaches the ideal gas value as the pressure tends to zero and these are the values tabulated in this Data Item.

Data for the isobaric specific heat capacity of the ideal gas were taken from the sources listed on the individual compound data sheets. Over the temperature ranges covered by this Data Item, they can be adequately represented by the following simple polynomial in reduced temperature:

$$c_p^{\text{id}} = b_1 + b_2 T_r + b_3 T_r^2 + b_4 T_r^3. \quad (6.1)$$

The values of the constants given in Table 9.3 were derived from the best fit to the selected data over the given temperature range. Using these values with the value of T_c given in Table 9.3, values of c_p^{id} in kJ/kg K have been calculated at 20 K and at 20 degree Celsius intervals for each compound.

6.2 Effect of Pressure

For non-reacting non-associating vapours far from the critical point, the effect of pressure is small. At the critical point, c_p tends to infinity and large effects in the critical region will occur. Estimates may be obtained from general equations of state such as the Soave-Redlich-Kwong, Lee-Kesler and Peng-Robinson (References 8, 9, 11). Fortran programs for the Soave-Redlich-Kwong and the Peng-Robinson equations may be found in Reference 14. For more accurate calculations, fluid specific equations of state should be used. References to these for methane, ethane, propane, butane and 2-methylpropane may be found in a review article by de Reuck, Craven and Elhassan (Reference 15).

7. EXPLANATION OF TABLES AND THE PRANDTL NUMBER EQUATION

For each compound the constants in Equations (4.1), (5.1) and (6.1) are given in Tables 9.1, 9.2 and 9.3 respectively, together with the critical temperature and the range of applicability.

Within the compound tables, values of thermal conductivity and viscosity that are supported by experimental data are presented in bold type. Isobaric specific heat capacity values from Data Source A1.: 21 are also given in bold type.

Experimental data for thermal conductivity from the most reliable individual sources have a repeatability of about $\pm 2\%$. However, differences in methods and technique increase the uncertainty of the absolute values to $\pm 3\%$ or more. Such reliable data are not available for all the compounds considered, however, nor over the whole temperature range covered.

Although it is considered that the procedure adopted for thermal conductivity keeps the errors in the values presented to a minimum, the user should allow for an uncertainty of $\pm 5\%$ in all values, except those unsupported by experimental data (presented in plain type) where the uncertainty increases to $\pm 10\%$.

Experimental data for the viscosity of most of the gases have been reviewed by the author cited, and may be assumed to have an uncertainty of about $\pm 3\%$. For values unsupported by experiment the uncertainty is greater. Although it is considered that the procedure adopted here keeps the errors in the values presented to a minimum, the user should allow for an uncertainty of $\pm 5\%$ in values not supported by experimental data. The equation represents the results over the given temperature range within $\pm 1.0\%$.

The isobaric specific heat capacity values are based on theoretical considerations and are represented by the equation to within $\pm 0.5\%$ over the given temperature range. In general an uncertainty of $\pm 2\%$ should be allowed for in all cases.

At any specific temperature, the Prandtl number entry was calculated from Equations (4.1), (5.1), (6.1) and the relation

$$Pr^{(o)} = \frac{c_p^{id(o)} \eta}{\lambda^{(o)}} \quad (7.1)$$

No attempt was made to smooth the values thus obtained. Rounding errors, which may affect the last significant figure may produce differences between the tabulated values and those calculated directly from the tabulated entries for thermal conductivity, viscosity and isobaric specific heat capacity.

8. REFERENCES

The references given are recommended sources of information supplementary to that in this Data Item.

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9. TABLES

TABLE 9.1 Dilute Gas Thermal Conductivity; Constants for Equation (4.1)

Compound	T_c K	b_1 mW/m K	b_2 mW/m K	b_3 mW/m K	b_4 mW/m K	Range of applicability °C
1. Methane	190.56	20.74	-23.24	3.72	0.13	-173 to 730
2. Ethane	305.4	21.97	-37.84	16.18	3.55	-73 to 630
3. Propane	369.9	27.40	-50.98	19.92	8.66	-73 to 630
4. Butane	425.25	31.26	-59.02	21.48	11.53	-73 to 630
5. 2-Methylpropane	407.85	28.96	-57.74	26.43	20.72	-73 to 330
6. Pentane	469.8	34.04	-64.21	22.17	13.08	-73 to 630
7. 2-Methylbutane	460.45	32.88	-63.07	25.56	16.10	-73 to 430
8. 2,2-Dimethylpropane	433.75	32.20	-62.89	25.99	5.49	-73 to 430
9. Hexane	507.9	36.12	-67.70	22.43	13.85	20 to 727
10. 2,2-Dimethylbutane	489.35	36.29	-71.08	30.78	6.01	-73 to 430
11. Heptane	540.15	37.72	-70.11	22.44	14.13	-73 to 730
12. 2,4-Dimethylpentane	519.75	38.70	-72.18	21.27	15.81	20 to 427
13. Octane	568.95	38.98	-71.77	22.29	14.09	20 to 727
14. 2,2,4-Trimethylpentane	543.85	39.10	-72.93	28.23	6.51	20 to 527
15. Nonane	594.65	39.96	-72.88	22.04	13.82	20 to 627
16. Decane	617.65	40.73	-73.56	21.71	13.39	20 to 627
17. Undecane	638.85	41.31	-73.90	21.34	12.84	20 to 627
18. Dodecane	658.65	41.73	-73.94	20.92	12.19	20 to 627
19. Tridecane	676.15	42.01	-73.74	20.47	11.47	20 to 627
20. Tetradecane	693.15	42.16	-73.32	20.00	10.70	20 to 627
21. Pentadecane	708.13	42.18	-72.70	19.51	9.87	20 to 627
22. Hexadecane	722.15	42.09	-71.90	19.01	9.01	20 to 627
23. Octadecane	749.15	41.58	-69.81	17.96	7.20	20 to 627

TABLE 9.2 Dilute Gas Viscosity; Constants for Equation (5.1)

Compound	T_c K	b_1 $\mu\text{N s/m}^2$	b_2 $\mu\text{N s/m}^2$	b_3 $\mu\text{N s/m}^2$	b_4 $\mu\text{N s/m}^2$	Range of applicability $^{\circ}\text{C}$
1. Methane	190.56	7.419	-6.989	-0.793	-0.063	-173 to 730
2. Ethane	305.4	9.479	-9.168	-1.217	-0.139	-73 to 630
3. Propane	369.9	10.080	-9.488	-0.947	0.079	-73 to 630
4. Butane	425.25	10.571	-10.002	-1.341	0.093	-73 to 630
5. 2-Methylpropane	407.85	10.230	-9.828	-1.011	0.716	-73 to 330
6. Pentane	469.8	10.643	-10.110	-1.268	0.640	-73 to 630
7. 2-Methylbutane	460.45	11.038	-10.931	-0.256	-0.677	-73 to 430
8. 2,2-Dimethylpropane	433.75	10.199	-9.696	-0.260	0.019	-73 to 430
9. Hexane	507.9	10.682	-10.603	-0.079	1.433	20 to 727
10. 2,2-Dimethylbutane	489.35	11.062	-9.653	-1.241	-2.252	-73 to 430
11. Heptane	540.15	10.567	-10.117	-0.818	0.517	-73 to 730
12. 2,4-Dimethylpentane	519.75	10.854	-9.416	-0.913	-3.634	20 to 427
13. Octane	568.95	10.866	-9.501	-1.133	-0.088	20 to 727
14. 2,2,4-Trimethylpentane	543.85	11.517	-11.305	-0.475	0.522	20 to 527
15. Nonane	594.65	10.507	-10.015	-0.821	0.726	20 to 627
16. Decane	617.65	10.404	-10.144	0.202	0.376	20 to 627
17. Undecane	638.85	10.356	-10.031	-0.801	1.133	20 to 627
18. Dodecane	658.65	10.258	-9.877	-0.340	0.337	20 to 627
19. Tridecane	676.15	10.178	-9.764	-0.868	0.774	20 to 627
20. Tetradecane	693.15	10.115	-9.710	-1.006	0.937	20 to 627
21. Pentadecane	708.13	10.006	-9.515	-0.944	0.564	20 to 627
22. Hexadecane	722.15	9.936	-9.536	-0.735	0.485	20 to 627
23. Octadecane	749.15	9.729	-9.296	-0.342	-0.262	20 to 627

TABLE 9.3 Ideal Gas Isobaric Specific Heat Capacity; Constants for Equation (6.1)

Compound	T_c K	b_1 kJ/kg K	b_2 kJ/kg K	b_3 kJ/kg K	b_4 kJ/kg K	Range of applicability °C
1. Methane	190.56	2.1851	-0.4131	0.3503	-0.03555	-173 to 730
2. Ethane	305.4	0.7036	0.9144	0.2513	-0.06775	-73 to 630
3. Propane	369.9	0.3763	1.5992	0.1096	-0.0815	-73 to 630
4. Butane	425.25	0.4570	1.7408	0.1817	-0.1321	-73 to 630
5. 2-Methylpropane	407.85	0.6234	0.6836	1.4246	-0.5597	-73 to 330
6. Pentane	469.8	0.5114	1.6616	0.4651	-0.2433	-73 to 630
7. 2-Methylbutane	460.45	0.1819	2.2810	0.0984	-0.1844	-73 to 430
8. 2,2-Dimethylpropane	433.75	-0.2766	3.4706	-1.0469	0.1700	-73 to 430
9. Hexane	507.9	-0.0760	3.4255	-0.8730	0.0731	20 to 727
10. 2,2-Dimethylbutane	489.35	0.2286	2.2162	0.3695	-0.3038	-73 to 430
11. Heptane	540.15	0.3291	2.5491	-0.0837	-0.1513	-73 to 730
12. 2,4-Dimethylpentane	519.75	-0.3057	4.3664	-1.6720	0.2925	20 to 427
13. Octane	568.95	-0.1215	3.9554	-1.2001	0.1200	20 to 727
14. 2,2,4-Trimethylpentane	543.85	-0.0460	3.4727	-0.6560	-0.0357	20 to 527
15. Nonane	594.65	-0.1550	4.2730	-1.4782	0.1914	20 to 627
16. Decane	617.65	-0.1601	4.4140	-1.5387	0.1850	20 to 627
17. Undecane	638.85	-0.1248	4.4141	-1.4503	0.1231	20 to 627
18. Dodecane	658.65	-0.1381	4.5915	-1.5798	0.1429	20 to 627
19. Tridecane	676.15	-0.0285	4.2302	-1.0016	-0.1345	20 to 627
20. Tetradecane	693.15	-0.1548	4.8839	-1.8006	0.1758	20 to 627
21. Pentadecane	708.13	-0.1616	5.0143	-1.9103	0.1973	20 to 627
22. Hexadecane	722.15	-0.1704	5.1460	-2.0233	0.2197	20 to 627
23. Octadecane	749.15	-0.1755	5.3545	-2.1935	0.2453	20 to 627

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CH₄ METHANE

$M = 16.04$

$$\lambda^{(o)} \text{ and } \eta^{(o)} = b_1 + b_2 (1 - T_r) + b_3 (1 - T_r)^2 + b_4 (1 - T_r)^3,$$

$$c_p^{\text{id}} = b_1 + b_2 T_r + b_3 T_r^2 + b_4 T_r^3,$$

$$T_r = T/T_c, \quad T = \text{temperature (K)}, \quad T_c = \text{critical temperature} = 190.56 \text{ K } (= -82.59 \text{ }^\circ\text{C})$$

	b_1	b_2	b_3	b_4	Equation
Thermal conductivity of dilute gas, $\lambda^{(o)}$ (mW/m K)	20.74	-23.24	3.72	0.13	(4.1)
Viscosity of dilute gas, $\eta^{(o)}$ ($\mu\text{N s/m}^2$)	7.419	-6.989	-0.793	-0.063	(5.1)
Specific heat capacity of ideal gas, c_p^{id} (kJ/kg K)	2.1851	-0.4131	0.3503	-0.03555	(6.1)

T K	$\lambda^{(o)}$ mW/m K	$\eta^{(o)}$ $\mu\text{N s/m}^2$	c_p^{id} kJ/kg K	$Pr^{(o)}$ -	t $^\circ\text{C}$	$\lambda^{(o)}$ mW/m K	$\eta^{(o)}$ $\mu\text{N s/m}^2$	c_p^{id} kJ/kg K	$Pr^{(o)}$ -
100	10.5	3.9	2.060	0.76	-170	10.9	4.0	2.058	0.76
120	12.7	4.7	2.055	0.77	-150	13.0	4.8	2.055	0.77
140	14.8	5.5	2.057	0.76	-130	15.2	5.6	2.057	0.76
160	17.1	6.3	2.064	0.76	-110	17.5	6.4	2.066	0.76
180	19.5	7.0	2.077	0.75	-90	19.8	7.1	2.080	0.75
200	21.9	7.8	2.096	0.74	-70	22.3	7.9	2.100	0.74
220	24.4	8.5	2.120	0.74	-50	24.8	8.6	2.125	0.74
240	27.0	9.2	2.149	0.73	-30	27.4	9.3	2.154	0.73
260	29.7	9.9	2.183	0.73	-10	30.1	10.0	2.189	0.72
280	32.5	10.5	2.222	0.72	10	32.9	10.6	2.228	0.72
300	35.3	11.2	2.264	0.72	30	35.7	11.3	2.271	0.72
320	38.2	11.8	2.311	0.72	50	38.7	11.9	2.319	0.71
340	41.2	12.4	2.361	0.71	70	41.7	12.5	2.370	0.71
360	44.3	13.1	2.415	0.71	90	44.7	13.1	2.424	0.71
380	47.4	13.6	2.472	0.71	110	47.9	13.7	2.482	0.71
400	50.6	14.2	2.533	0.71	130	51.1	14.3	2.542	0.71
420	53.9	14.8	2.596	0.71	150	54.4	14.9	2.606	0.71
440	57.2	15.4	2.661	0.71	170	57.8	15.4	2.672	0.71
460	60.7	15.9	2.729	0.71	190	61.2	16.0	2.740	0.72
480	64.2	16.4	2.799	0.72	210	64.7	16.5	2.810	0.72
500	67.7	16.9	2.871	0.72	230	68.3	17.0	2.882	0.72
520	71.4	17.5	2.944	0.72	250	71.9	17.5	2.956	0.72
540	75.1	18.0	3.018	0.72	270	75.7	18.0	3.030	0.72
560	78.8	18.4	3.094	0.72	290	79.4	18.5	3.106	0.72
580	82.7	18.9	3.171	0.73	310	83.3	19.0	3.183	0.73
600	86.6	19.4	3.248	0.73	330	87.2	19.5	3.260	0.73
620	90.5	19.9	3.325	0.73	350	91.1	19.9	3.337	0.73
640	94.5	20.3	3.402	0.73	370	95.2	20.4	3.414	0.73
660	98.6	20.8	3.479	0.73	390	99.3	20.8	3.492	0.73
680	102.8	21.2	3.556	0.73	410	103.4	21.3	3.568	0.73

(continued)

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T K	$\lambda^{(o)}$ mW/m K	$\eta^{(o)}$ $\mu\text{N s/m}^2$	c_p^{id} kJ/kg K	$Pr^{(o)}$ -	t °C	$\lambda^{(o)}$ mW/m K	$\eta^{(o)}$ $\mu\text{N s/m}^2$	c_p^{id} kJ/kg K	$Pr^{(o)}$ -
700	107.0	21.6	3.632	0.73	430	107.6	21.7	3.644	0.73
720	111.2	22.1	3.708	0.74	450	111.9	22.1	3.719	0.74
740	115.6	22.5	3.782	0.74	470	116.2	22.6	3.793	0.74
760	119.9	22.9	3.854	0.74	490	120.6	23.0	3.866	0.74
780	124.4	23.3	3.925	0.74	510	125.1	23.4	3.936	0.74
800	128.9	23.7	3.994	0.74	530	129.6	23.8	4.005	0.74
820	133.4	24.1	4.061	0.73	550	134.1	24.2	4.072	0.73
840	138.0	24.5	4.126	0.73	570	138.7	24.6	4.136	0.73
860	142.7	24.9	4.188	0.73	590	143.4	25.0	4.197	0.73
880	147.4	25.3	4.247	0.73	610	148.1	25.4	4.256	0.73
900	152.1	25.7	4.303	0.73	630	152.9	25.8	4.311	0.73
920	156.9	26.1	4.355	0.72	650	157.7	26.1	4.363	0.72
940	161.8	26.5	4.404	0.72	670	162.5	26.5	4.411	0.72
960	166.7	26.9	4.449	0.72	690	167.4	26.9	4.456	0.72
980	171.6	27.2	4.490	0.71	710	172.4	27.3	4.496	0.71
1000	176.6	27.6	4.527	0.71	730	177.4	27.7	4.532	0.71

Data Sources (see Appendix A)

Thermal conductivity – A2.: 311, 401, 461, 501, 512, 521, 522, 531, 532, 542, 551, 553, 603, 604, 611, 621, 631, 633, 651, 652, 664, 665, 672, 702, 721, 722, 724, 741, 761, 771, 811, 832, 842, 851, 871, 881, 901

Viscosity – A1.: 13, 14, 15

Specific heat capacity – A1.: 21

C₂H₆ ETHANE

$M = 30.07$

$$\lambda^{(o)} \text{ and } \eta^{(o)} = b_1 + b_2 (1 - T_r) + b_3 (1 - T_r)^2 + b_4 (1 - T_r)^3,$$

$$c_p^{id} = b_1 + b_2 T_r + b_3 T_r^2 + b_4 T_r^3,$$

$$T_r = T/T_c, \quad T = \text{temperature (K)}, \quad T_c = \text{critical temperature} = 305.4 \text{ K} (= 32.25 \text{ }^\circ\text{C})$$

	b_1	b_2	b_3	b_4	Equation
Thermal conductivity of dilute gas, $\lambda^{(o)}$ (mW/m K)	21.97	-37.84	16.18	3.55	(4.1)
Viscosity of dilute gas, $\eta^{(o)}$ ($\mu\text{N s/m}^2$)	9.479	-9.168	-1.217	-0.139	(5.1)
Specific heat capacity of ideal gas, c_p^{id} (kJ/kg K)	0.7036	0.9144	0.2513	-0.06775	(6.1)

T K	$\lambda^{(o)}$ mW/m K	$\eta^{(o)}$ $\mu\text{N s/m}^2$	c_p^{id} kJ/kg K	$Pr^{(o)}$ -	t $^\circ\text{C}$	$\lambda^{(o)}$ mW/m K	$\eta^{(o)}$ $\mu\text{N s/m}^2$	c_p^{id} kJ/kg K	$Pr^{(o)}$ -
200	11.0	6.2	1.391	0.78	-70	11.2	6.3	1.403	0.78
220	12.7	6.8	1.467	0.79	-50	13.0	6.9	1.479	0.79
240	14.6	7.5	1.544	0.79	-30	15.0	7.6	1.557	0.79
260	16.7	8.1	1.622	0.79	-10	17.1	8.2	1.635	0.78
280	18.9	8.7	1.701	0.78	10	19.3	8.8	1.713	0.78
300	21.3	9.3	1.780	0.78	30	21.7	9.4	1.793	0.78
320	23.8	9.9	1.860	0.77	50	24.2	10.0	1.872	0.77
340	26.5	10.5	1.940	0.77	70	26.9	10.6	1.952	0.77
360	29.2	11.1	2.020	0.77	90	29.7	11.2	2.032	0.76
380	32.1	11.6	2.100	0.76	110	32.6	11.7	2.113	0.76
400	35.1	12.2	2.180	0.76	130	35.6	12.3	2.193	0.76
420	38.3	12.8	2.260	0.75	150	38.8	12.8	2.273	0.75
440	41.5	13.3	2.340	0.75	170	42.0	13.4	2.353	0.75
460	44.8	13.8	2.420	0.75	190	45.3	13.9	2.432	0.75
480	48.2	14.3	2.499	0.74	210	48.8	14.4	2.511	0.74
500	51.7	14.9	2.577	0.74	230	52.3	14.9	2.589	0.74
520	55.3	15.4	2.655	0.74	250	55.9	15.4	2.667	0.74
540	59.0	15.9	2.732	0.73	270	59.6	15.9	2.744	0.73
560	62.7	16.4	2.808	0.73	290	63.3	16.4	2.819	0.73
580	66.5	16.8	2.882	0.73	310	67.1	16.9	2.894	0.73
600	70.3	17.3	2.956	0.73	330	71.0	17.4	2.968	0.73
620	74.2	17.8	3.029	0.73	350	74.9	17.9	3.040	0.73
640	78.2	18.2	3.100	0.72	370	78.8	18.3	3.111	0.72
660	82.2	18.7	3.170	0.72	390	82.8	18.8	3.180	0.72
680	86.2	19.1	3.238	0.72	410	86.8	19.2	3.248	0.72

(continued)

T K	$\lambda^{(o)}$ mW/m K	$\eta^{(o)}$ $\mu\text{N s/m}^2$	c_p^{id} kJ/kg K	$Pr^{(o)}$ -	t °C	$\lambda^{(o)}$ mW/m K	$\eta^{(o)}$ $\mu\text{N s/m}^2$	c_p^{id} kJ/kg K	$Pr^{(o)}$ -
700	90.2	19.6	3.304	0.72	430	90.9	19.7	3.314	0.72
720	94.3	20.0	3.368	0.72	450	94.9	20.1	3.378	0.72
740	98.4	20.5	3.431	0.71	470	99.0	20.5	3.441	0.71
760	102.4	20.9	3.491	0.71	490	103.1	21.0	3.501	0.71
780	106.5	21.3	3.550	0.71	510	107.2	21.4	3.558	0.71
800	110.6	21.7	3.605	0.71	530	111.3	21.8	3.614	0.71
820	114.7	22.1	3.659	0.71	550	115.3	22.2	3.667	0.71
840	118.7	22.5	3.710	0.70	570	119.4	22.6	3.718	0.70
860	122.8	22.9	3.758	0.70	590	123.4	23.0	3.766	0.70
880	126.8	23.3	3.804	0.70	610	127.4	23.4	3.811	0.70
900	130.8	23.7	3.847	0.70	630	131.4	23.8	3.853	0.70

Data Sources (see Appendix A)

Thermal conductivity – A2.: 311, 401, 491, 531, 541, 542, 553, 571, 611, 631, 632, 652, 662, 724, 744, 772, 791, 811, 841, 852, 871

Viscosity – A1.: 13, 15, 19

Specific heat capacity – A1.: 21

C₃H₈ PROPANE

$M = 44.10$

$$\lambda^{(o)} \text{ and } \eta^{(o)} = b_1 + b_2 (1 - T_r) + b_3 (1 - T_r)^2 + b_4 (1 - T_r)^3,$$

$$c_p^{\text{id}} = b_1 + b_2 T_r + b_3 T_r^2 + b_4 T_r^3,$$

$$T_r = T/T_c, \quad T = \text{temperature (K)}, \quad T_c = \text{critical temperature} = 369.9 \text{ K} (= 96.75 \text{ }^\circ\text{C})$$

	b_1	b_2	b_3	b_4	Equation
Thermal conductivity of dilute gas, $\lambda^{(o)}$ (mW/m K)	27.40	-50.98	19.92	8.66	(4.1)
Viscosity of dilute gas, $\eta^{(o)}$ ($\mu\text{N s/m}^2$)	10.080	-9.488	-0.947	0.079	(5.1)
Specific heat capacity of ideal gas, c_p^{id} (kJ/kg K)	0.3763	1.5992	0.1096	-0.0815	(6.1)

T K	$\lambda^{(o)}$ mW/m K	$\eta^{(o)}$ $\mu\text{N s/m}^2$	c_p^{id} kJ/kg K	$Pr^{(o)}$ -	t °C	$\lambda^{(o)}$ mW/m K	$\eta^{(o)}$ $\mu\text{N s/m}^2$	c_p^{id} kJ/kg K	$Pr^{(o)}$ -
200	9.0	5.5	1.260	0.77	-70	9.3	5.6	1.274	0.77
220	10.6	6.1	1.349	0.78	-50	10.9	6.2	1.363	0.78
240	12.3	6.6	1.438	0.77	-30	12.6	6.7	1.452	0.77
260	14.2	7.2	1.526	0.77	-10	14.6	7.3	1.540	0.77
280	16.3	7.7	1.614	0.76	10	16.7	7.8	1.628	0.76
300	18.5	8.3	1.702	0.76	30	18.9	8.3	1.716	0.76
320	20.9	8.8	1.789	0.75	50	21.3	8.9	1.803	0.75
340	23.4	9.3	1.876	0.75	70	23.8	9.4	1.889	0.74
360	26.1	9.8	1.961	0.74	90	26.5	9.9	1.975	0.74
380	28.8	10.3	2.046	0.73	110	29.3	10.4	2.060	0.73
400	31.7	10.8	2.131	0.73	130	32.1	10.9	2.144	0.73
420	34.6	11.3	2.214	0.73	150	35.1	11.4	2.227	0.72
440	37.7	11.8	2.296	0.72	170	38.2	11.9	2.309	0.72
460	40.9	12.3	2.378	0.72	190	41.4	12.4	2.390	0.72
480	44.1	12.8	2.458	0.71	210	44.6	12.9	2.470	0.71
500	47.4	13.3	2.537	0.71	230	47.9	13.4	2.549	0.71
520	50.8	13.8	2.615	0.71	250	51.3	13.8	2.627	0.71
540	54.2	14.2	2.691	0.71	270	54.8	14.3	2.703	0.71
560	57.7	14.7	2.766	0.70	290	58.2	14.8	2.777	0.70
580	61.2	15.1	2.839	0.70	310	61.8	15.2	2.851	0.70
600	64.7	15.6	2.911	0.70	330	65.3	15.7	2.922	0.70
620	68.3	16.0	2.981	0.70	350	68.9	16.1	2.992	0.70
640	71.9	16.5	3.049	0.70	370	72.4	16.5	3.060	0.70
660	75.5	16.9	3.116	0.70	390	76.0	17.0	3.126	0.70
680	79.0	17.3	3.180	0.70	410	79.6	17.4	3.190	0.70

(continued)

T K	$\lambda^{(o)}$ mW/m K	$\eta^{(o)}$ $\mu\text{N s/m}^2$	c_p^{id} kJ/kg K	$Pr^{(o)}$ -	t °C	$\lambda^{(o)}$ mW/m K	$\eta^{(o)}$ $\mu\text{N s/m}^2$	c_p^{id} kJ/kg K	$Pr^{(o)}$ -
700	82.6	17.7	3.243	0.70	430	83.2	17.8	3.252	0.70
720	86.2	18.1	3.303	0.70	450	86.7	18.2	3.313	0.70
740	89.7	18.5	3.362	0.70	470	90.2	18.6	3.371	0.70
760	93.2	18.9	3.418	0.69	490	93.7	19.0	3.426	0.69
780	96.6	19.3	3.472	0.69	510	97.1	19.4	3.480	0.69
800	100.0	19.7	3.523	0.69	530	100.5	19.8	3.531	0.69
820	103.3	20.1	3.572	0.69	550	103.8	20.1	3.580	0.69
840	106.6	20.4	3.619	0.69	570	107.1	20.5	3.626	0.69
860	109.8	20.8	3.663	0.69	590	110.3	20.9	3.669	0.69
880	112.9	21.2	3.704	0.69	610	113.4	21.2	3.710	0.69
900	115.9	21.5	3.742	0.69	630	116.3	21.6	3.748	0.69

Data Sources (see Appendix A)

Thermal conductivity – A2.: 311, 491, 522, 541, 553, 571, 604, 621, 631, 652, 661, 681, 692, 744, 761, 781, 792, 811, 871, 872

Viscosity – A1.: 15, 20

Specific heat capacity – A1.: 21