

Thermal conductivity of liquids: Alicyclic compounds – cycloalkanes, alkenes, alkanols, alkanones and alkylamines

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Mr J.T.R. Watson	— Independent.

* Emeritus Member.

[†] Corresponding Member.

The technical work involved in the assessment of the available information and the construction and subsequent development of the Data Item was undertaken (under contract to ESDU) by

Dr. D.T. Jamieson — Independent.

The person with overall responsibility for the work in this subject area is Mr S.J. Pugh, Head of Thermofluids Group.

THERMAL CONDUCTIVITY OF LIQUIDS: ALICYCLIC COMPOUNDS – CYCLOALKANES, ALKENES, ALKANOLS, ALKANONES AND ALKYLAMINES

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

Formula	Name	Alternative Name(s)
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CYCLOALKANES

1. $c\text{-C}_5\text{H}_{10}$	Cyclopentane	Pentamethylene	7
2. $c\text{-C}_6\text{H}_{12}$	Cyclohexane	Hexamethylene	9
3. $c\text{-C}_7\text{H}_{14}$	Cycloheptane	Heptamethylene	11
4. $c\text{-C}_8\text{H}_{16}$	Cyclooctane	Octamethylene	12
5. $c\text{-C}_9\text{H}_{18}$	Cyclononane	Nonamethylene	13
6. $c\text{-C}_{10}\text{H}_{20}$	Cyclodecane	Decamethylene	14

METHYLCYCLOALKANES

7. $c\text{-C}_5\text{H}_9\text{CH}_3$	Methylcyclopentane	Cyclopentylmethane	15
8. $c\text{-C}_6\text{H}_{11}\text{CH}_3$	Methylcyclohexane	Cyclohexylmethane	16
9. $c\text{-C}_7\text{H}_{13}\text{CH}_3$	Methylcycloheptane	Cycloheptylmethane	18
10. $c\text{-C}_8\text{H}_{15}\text{CH}_3$	Methylcyclooctane	Cyclooctylmethane	19
11. $cis\text{-}1,2\text{-}c\text{-C}_6\text{H}_{10}(\text{CH}_3)_2$	$cis\text{-}1,2\text{-Dimethylcyclohexane}$	1, $cis\text{-}2\text{-Dimethylcyclohexane}$	20
12. $trans\text{-}1,2\text{-}c\text{-C}_6\text{H}_{10}(\text{CH}_3)_2$	$trans\text{-}1,2\text{-Dimethylcyclohexane}$	1, $trans\text{-}2\text{-Dimethylcyclohexane}$	21

Formula	Name	Alternative Name(s)		
CYCLOALKENES				
13. <i>c</i> -C ₅ H ₈	Cyclopentene			22
14. <i>c</i> -C ₆ H ₁₀	Cyclohexene			23
15. <i>c</i> -C ₇ H ₁₂	Cycloheptene			25
16. <i>c</i> -C ₈ H ₁₄	Cyclooctene			26
CYCLOALKADIENES				
17. <i>c</i> -1,3-C ₆ H ₈	Cyclohexa-1,3-diene	1,3-Cyclohexadiene		27
18. <i>c</i> -1,4-C ₆ H ₈	Cyclohexa-1,4-diene	1,4-Cyclohexadiene		28
CYCLOALKANOLS				
19. <i>c</i> -C ₅ H ₉ OH	Cyclopentanol	Cyclopentyl alcohol		29
20. <i>c</i> -C ₆ H ₁₁ OH	Cyclohexanol	Cyclohexyl alcohol	Hexalin Hexahydrophenol	30
21. <i>c</i> -C ₇ H ₁₃ OH	Cycloheptanol	Cycloheptyl alcohol	Suberol	32
22. <i>c</i> -C ₈ H ₁₅ OH	Cyclooctanol	Cyclooctyl alcohol		33
CYCLOALKANONES				
23. <i>c</i> -C ₅ H ₈ O	Cyclopentanone	Ketocyclopentane	Adipic ketone	34
24. <i>c</i> -C ₆ H ₁₀ O	Cyclohexanone	Ketocyclohexane	Pimelic ketone	35
25. <i>c</i> -C ₇ H ₁₂ O	Cycloheptanone	Ketocycloheptane	Suberone	37
26. <i>c</i> -C ₈ H ₁₄ O	Cyclooctanone	Ketocyclooctane		38
CYCLOALKYLAMINES				
27. <i>c</i> -C ₅ H ₉ NH ₂	Cyclopentanamine	Cyclopentylamine	Aminocyclopentane	39
28. <i>c</i> -C ₆ H ₁₁ NH ₂	Cyclohexanamine	Cyclohexylamine	Aminocyclohexane	40
29. <i>c</i> -C ₇ H ₁₃ NH ₂	Cycloheptanamine	Cycloheptylamine	Aminocycloheptane	41
30. <i>c</i> -C ₈ H ₁₅ NH ₂	Cyclooctanamine	Cyclooctylamine	Aminocyclooctane	42

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THERMAL CONDUCTIVITY OF LIQUIDS: ALICYCLIC COMPOUNDS – CYCLOALKANES, ALKENES, ALKANOLS, ALKANONES AND ALKYLAMINES

1. INTRODUCTION

This Item presents values of thermal conductivity at saturation pressure, in tabular form, for liquid cycloalkanes, methylcycloalkanes, cycloalkenes, cycloalkadienes, cycloalkanols, cycloalkanones and cycloalkylamines.

The data on which these recommended values of thermal conductivity are based are the most reliable available and the temperature range covered for most compounds is from the melting temperature to approximately 0.9 of the critical temperature. Quantities are expressed in SI units and conversion factors to other units are provided in Section 3.

Section 4 describes the procedure used to obtain the values of thermal conductivity presented and indicates the effect of pressure. Section 5 gives an explanation of the Tables and indicates the uncertainties in the values presented in them.

References to sources of supplementary information are given in Section 6. The data sources for each particular compound are listed on the appropriate data sheet.

2. NOTATION AND UNITS

The SI unit of thermal conductivity is the watt per metre kelvin (W/m K). A convenient submultiple SI unit for the range of thermal conductivity in this Item is the milliwatt per metre kelvin (mW/m K); hence that is the unit adopted here.

A	constant for each liquid in Equation (4.2)	mW/m K
A'	constant for each liquid in Equation (4.1)	mW/m K
B, C, D	non-dimensional constants for each liquid in Equation (4.2)	–
p	pressure	N/m ² (Pa)
T	kelvin temperature	K
t	Celsius temperature, $T - 273.15$	°C
λ	thermal conductivity	mW/m K

Subscripts

c	denotes value at the critical point
p	denotes value at pressure p
r	denotes reduced quantity, <i>e.g.</i> $T_r = T/T_c$.

3. CONVERSION FACTORS

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

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

* The values used for the calorie and British Thermal Unit are International Table values.

4. THERMAL CONDUCTIVITY

4.1 Thermal Conductivity at Saturation Pressure

In Reference 2 Riedel showed that the experimental data for the thermal conductivity of normal (that is unassociated) liquids along the saturation line could be represented by the equation:

$$\lambda = A' [1 + (20/3)(1 - T_r)^{2/3}]. \quad (4.1)$$

The range of applicability of Equation (4.1) is limited for most compounds. For the liquids considered in this Item a good representation of the data* between the melting temperature and $T_r \approx 0.9$ is obtained from the equation:

$$\lambda = A [1 + B(1 - T_r)^{1/3} + C(1 - T_r)^{2/3} + D(1 - T_r)]. \quad (4.2)$$

Measurements of thermal conductivity have been made for relatively few liquids at $T_r > 0.9$ and so, because of the uncertain variation of thermal conductivity in the critical region, data are presented only for temperatures up to $T_r = 0.9$. The equation extrapolates in a physically realistic manner to within a few kelvin of the critical point.

The critical temperatures for these compounds have either been taken from ESDU 82016, 93009, 97012. (References 7, 10 and 11) or estimated from correlations of ESDU values with chemical structure. In this Item, the critical temperatures should be regarded as correlating parameters only and should not be taken as a source of accurate values.

The derived values of A , B , C and D given in Table 7.1 are a correlated set of values giving the best fit to the experimental data, not only as individual compounds but also as members of their chemical series. This method of correlating data for a series of compounds has been described in References 5 and 6. The cycloalkanols and cycloalkylamines in this Item have B , C and D values† typical of hydrogen bonded

* Experimental data at temperatures below the normal boiling temperature, t_b are often at 1 atm pressure. As indicated in Section 4.2 the difference between values of λ at 1 atm pressure and at saturation pressure below t_b is not significant.

† $B = 3.0$, $C = -6.5$ for cycloalkanols and cycloalkylamines. $D = 4.4$ for cyclopentanol, cyclopentanamine; 5.4 for the other cycloalkanols and cycloalkanamines.

compounds such as the aliphatic alcohols and amines. For the cycloalkanes, methylcycloalkanes, cycloalkenes, cycloalkadienes and cycloalkanones in this Item, it was found that C and D are directly related to B^* , as was observed for other non-hydrogen-bonded compounds such as the alkanes. Correlated values of the constants A , B , C and D were used to estimate constants for liquids for which no experimental data exist. Using these values with the values of T_c given in Table 7.1, values of λ in mW/m K have been calculated for each compound from Equation (4.2) and are presented in the data sheets.

4.2 Effect of Pressure

At temperatures up to the normal boiling point, the effect of pressure from the saturation pressure to $50 \times 10^5 \text{ N/m}^2$ (up to 50 atm) is to increase the thermal conductivity by approximately 1 per cent and, for most practical purposes, values at saturation pressure may be taken as equal to those at atmospheric pressure.

Reference 1 gives measurements of thermal conductivity for a number of liquids up to $12\,000 \times 10^5 \text{ N/m}^2$ ($\approx 12\,000 \text{ atm}$) at 30°C and 75°C . A generalised correlation of these results is given in Reference 3, but a knowledge of the critical pressure of the substance is required for its use.

For pressures up to $500 \times 10^5 \text{ N/m}^2$ ($\approx 500 \text{ atm}$) between the melting temperature and the normal boiling point a very approximate relationship:

$$\lambda_p/\lambda \approx 1 + 0.2p \times 10^{-8}, \quad (4.3)$$

may be used where λ_p is the thermal conductivity at pressure p and λ is the thermal conductivity at a pressure of 10^5 N/m^2 ($\approx 1 \text{ atm}$), both at the same temperature.

5. EXPLANATION OF TABLES

The constants of Equation (4.2) are given in Table 7.1 and on the data sheets. Values of the thermal conductivity are given in the data sheets at 10 kelvin intervals in K and $^\circ\text{C}$, from within 10 kelvin of the melting temperature, or an appropriate starting temperature where the melting temperature is unknown, to a temperature corresponding with $T_r \approx 0.9$.

The sources are given in the data sheets and extrapolated values are indicated in parentheses.

For uniformity and ease of interpolation the data are presented and can be read to more significant digits than is warranted by their estimated accuracy.

The experimental data from the most reliable individual sources have a repeatability of about ± 1 per cent although differences in technique used by different workers (and possibly also in the purity of samples) can increase the uncertainty in the absolute values to about ± 2 per cent. However, such reliable data are not available for all the compounds considered, nor over the whole temperature range covered. Although it is considered that the correlation procedures adopted keep the errors in the values presented to a minimum, the user should in general allow for an uncertainty of ± 5 per cent unless the value in the data sheet is truncated to a whole number. Where whole numbers are given the uncertainty increases to ± 10 per cent.

Some fluids have poor thermal stability coupled with a high critical temperature. Values have been tabulated for all fluids up to $T_r \approx 0.9$ but many of these fluids will decompose at elevated temperatures. As most compounds will decompose rapidly at temperatures above about 300°C , uncertainties of greater than ± 10 per cent may occur for temperatures $\geq 573 \text{ K}$.

* $C = 1 - 3B$ and $D = 3B$ for cycloalkanes, methylcycloalkanes, cycloalkenes, cycloalkadienes and cycloalkanones.

The structural formulae of all the compounds in this Item are given in Appendix A.

6. REFERENCES

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

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7. TABLES

TABLE 7.1 Constants for Equation (4.2)

Compound		T_c	A	B	C	D	Range of Applicability °C		
		K	mW/m K						
1.	Cyclopentane	511.7	52.0	2.8	-7.4	8.4	-100	to	200
2.	Cyclohexane	553.5	46.0	2.8	-7.4	8.4	0	to	230
3.	Cycloheptane	604.3	43.0	2.8	-7.4	8.4	-10	to	280
4.	Cyclooctane	647.2	41.0	2.8	-7.4	8.4	0	to	320
5.	Cyclononane	682.75	40.3	2.8	-7.4	8.4	0	to	350
6.	Cyclodecane	712.75	39.9	2.8	-7.4	8.4	0	to	380
7.	Methylcyclopentane	532.8	45.3	2.8	-7.4	8.4	-140	to	210
8.	Methylcyclohexane	572.2	42.4	2.8	-7.4	8.4	-130	to	250
9.	Methylcycloheptane	615.15	40.3	2.8	-7.4	8.4	-50	to	290
10.	Methylcyclooctane	646.15	39.9	2.8	-7.4	8.4	-50	to	320
11.	cis-1,2-Dimethylcyclohexane	603.	39.0	2.8	-7.4	8.4	-50	to	280
12.	trans-1,2-Dimethylcyclohexane	594.	39.0	2.8	-7.4	8.4	-90	to	270
13.	Cyclopentene	506.	54.9	2.8	-7.4	8.4	-140	to	190
14.	Cyclohexene	560.5	49.0	2.8	-7.4	8.4	-110	to	240
15.	Cycloheptene	601.75	44.9	2.8	-7.4	8.4	-60	to	280
16.	Cyclooctene	639.15	42.4	2.8	-7.4	8.4	-20	to	310
17.	Cyclohexa-1,3-diene	559.	50.0	2.8	-7.4	8.4	-90	to	240
18.	Cyclohexa-1,4-diene	567.	54.0	2.8	-7.4	8.4	-50	to	250
19.	Cyclopentanol	619.5	96.0	3.0	-6.5	4.4	-20	to	290
20.	Cyclohexanol	650.	65.2	3.0	-6.5	5.4	0	to	320
21.	Cycloheptanol	653.15	59.2	3.0	-6.5	5.4	0	to	320
22.	Cyclooctanol	666.15	55.4	3.0	-6.5	5.4	0	to	330
23.	Cyclopentanone	624.5	72.9	1.0	-2.0	3.0	-60	to	300
24.	Cyclohexanone	653.	65.9	1.0	-2.0	3.0	-50	to	320
25.	Cycloheptanone	680.	59.4	1.0	-2.0	3.0	-50	to	350
26.	Cyclooctanone	701.	55.6	1.0	-2.0	3.0	-50	to	370
27.	Cyclopentanamine	589.	95.7	3.0	-6.5	4.4	-90	to	270
28.	Cyclohexanamine	625.	65.7	3.0	-6.5	5.4	-20	to	300
29.	Cycloheptanamine	654.15	59.7	3.0	-6.5	5.4	-20	to	320
30.	Cyclooctanamine	678.15	55.9	3.0	-6.5	5.4	-20	to	350

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c-C₅H₁₀ CYCLOPENTANE (PENTAMETHYLENE)

$$\lambda = A[1 + B(1 - T_r)^{1/3} + C(1 - T_r)^{2/3} + D(1 - T_r)]$$

where

λ = thermal conductivity at saturation pressure (mW/m K)

$T_r = T/T_c$, T = temperature (K)

$T_c = 511.7$ K

$A = 52.0$, $B = 2.8$, $C = -7.4$, $D = 8.4$

T K	λ mW/m K	T K	λ mW/m K	t °C	λ mW/m K	t °C	λ mW/m K
170	(177.)	330	117.3	-100	(176.)	60	116.2
180	(173.)	340	113.9	-90	(172.)	70	112.9
190	(169.)	350	110.7	-80	(167.7)	80	109.7
200	(165.0)	360	(107.5)	-70	(163.7)	90	(106.5)
210	(161.1)	370	(104.4)	-60	(159.8)	100	(103.4)
220	(157.2)	380	(101.3)	-50	156.0	110	(100.4)
230	153.3	390	(98.4)	-40	152.1	120	(97.5)
240	149.5	400	(96.)	-30	148.3	130	(95.)
250	145.7	410	(93.)	-20	144.6	140	(92.)
260	142.0	420	(90.)	-10	140.8	150	(89.)
270	138.3	430	(87.)	0	137.2	160	(87.)
280	134.7	440	(85.)	10	133.6	170	(84.)
290	131.1	450	(83.)	20	130.0	180	(82.)
300	127.6	460	(80.)	30	126.4	190	(80.)
310	124.1	470	(78.)	40	123.0	200	(78.)
320	120.6			50	119.6		

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c-C₆H₁₂ CYCLOHEXANE (HEXAMETHYLENE)

$$\lambda = A[1 + B(1 - T_r)^{1/3} + C(1 - T_r)^{2/3} + D(1 - T_r)]$$

where

λ = thermal conductivity at saturation pressure (mW/m K)

$$T_r = T/T_c, \quad T = \text{temperature (K)}$$

$$T_c = 553.5 \text{ K}$$

$$A = 46.0, \quad B = 2.8, \quad C = -7.4, \quad D = 8.4$$

T K	λ mW/m K	T K	λ mW/m K	t °C	λ mW/m K	t °C	λ mW/m K
270	(129.)	390	94.9	0	(128.1)	120	94.1
280	(126.0)	400	92.4	10	125.0	130	91.6
290	123.0	410	89.9	20	122.0	140	89.1
300	120.0	420	87.	30	119.1	150	87.
310	117.0	430	85.	40	116.1	160	84.
320	114.1	440	83.	50	113.2	170	82.
330	111.3	450	81.	60	110.4	180	80.
340	108.4	460	78.	70	107.5	190	78.
350	105.6	470	76.	80	104.8	200	76.
360	102.9	480	74.	90	102.0	210	74.
370	100.2	490	73.	100	99.3	220	72.
380	97.5	500	71.	110	96.7	230	70.

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- HIDEYUKI, K.

$c\text{-C}_7\text{H}_{14}$ CYCLOHEPTANE (HEPTAMETHYLENE, SUBERANE)

$$\lambda = A[1 + B(1 - T_r)^{1/3} + C(1 - T_r)^{2/3} + D(1 - T_r)]$$

where

λ = thermal conductivity at saturation pressure (mW/m K)

$$T_r = T/T_c, \quad T = \text{temperature (K)}$$

$$T_c = 604.3 \text{ K}$$

$$A = 43.0, \quad B = 2.8, \quad C = -7.4, \quad D = 8.4$$

T K	λ mW/m K	T K	λ mW/m K	t °C	λ mW/m K	t °C	λ mW/m K
260	(130.)	410	(92.)	-10	129.1	140	(92.)
270	127.2	420	(90.)	0	126.4	150	(89.)
280	124.5	430	(88.)	10	123.7	160	(87.)
290	121.9	440	(86.)	20	121.1	170	(85.)
300	119.3	450	(84.)	30	118.4	180	(83.)
310	116.7	460	(81.)	40	115.9	190	(81.)
320	114.1	470	(79.)	50	113.3	200	(79.)
330	111.5	480	(77.)	60	110.7	210	(77.)
340	109.0	490	(76.)	70	108.2	220	(75.)
350	(106.5)	500	(74.)	80	(105.8)	230	(73.)
360	(104.)	510	(72.)	90	(103.)	240	(71.)
370	(102.)	520	(70.)	100	(101.)	250	(70.)
380	(99.)	530	(69.)	110	(99.)	260	(68.)
390	(97.)	540	(67.)	120	(96.)	270	(67.)
400	(95.)	550	(66.)	130	(94.)	280	(65.)

WATANABE, H.
HIDEYUKI, K.

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JAMIESON, D.T.

Unpublished data, National Engineering Laboratory, East Kilbride, UK.