

Thermal conductivity of liquids: Glycols, glycerol and their aqueous solutions

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THERMAL CONDUCTIVITY OF LIQUIDS: GLYCOLS, GLYCEROL AND THEIR AQUEOUS SOLUTIONS

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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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ETHYLENE GLYCOLS

1. HO[CH ₂] ₂ OH	Ethylene glycol	Ethane-1,2-diol 1,2-Dihydroxyethane 1,2-Ethanediol Monoethylene glycol Glycol	9
2. HO[CH ₂] ₂ O[CH ₂] ₂ OH	Diethylene glycol	Bis(2-hydroxyethyl) ether 2,2'-Oxydiethanol 2,2'-Dihydroxyethyl ether 3-Oxapentane-1,5-diol 3-Oxa-1,5-pentanediol Diglycol Digol	12
3. HO([CH ₂] ₂ O) ₂ [CH ₂] ₂ OH	Triethylene glycol	1,2-Bis(2-hydroxyethoxy)ethane 3,6-Dioxaoctane-1,8-diol 3,6-Dioxa-1,8-octanediol Triglycol Trigol	14

Formula	Name	Alternative Name(s)	
4. $\text{HO}[(\text{CH}_2)_2\text{O}]_3[\text{CH}_2]_2\text{OH}$	Tetraethylene glycol	Bis(2-(2-hydroxyethoxy)ethyl) ether 3,6,9-Trioxaundecane-1,11-diol 3,6,9-Trioxa-1,11-undecanediol Tetraglycol Tetragol	16
5. $\text{HO}[(\text{CH}_2)_2\text{O}]_4[\text{CH}_2]_2\text{OH}$	Pentaethylene glycol	1,2-Bis(2-(2-hydroxyethoxy)ethoxy)ethane 3,6,9,12-Tetraoxatetradecane-1,14-diol 3,6,9,12-Tetraoxa-1,14-tetradecanediol Pentaglycol Pentagol	18
6. $\text{HO}[(\text{CH}_2)_2\text{O}]_5[\text{CH}_2]_2\text{OH}$	Hexaethylene glycol	Bis(2-(2-(2-hydroxyethoxy)ethoxy)ethyl) ether 3,6,9,12,15-Pentaoxaheptadecane-1,17-diol 3,6,9,12,15-Pentaoxa-1,17-heptadecanediol Hexaglycol Hexagol	20
7. $\text{HO}[(\text{CH}_2)_2\text{O}]_6[\text{CH}_2]_2\text{OH}$	Heptaethylene glycol	1,2-Bis(2-(2-(2-hydroxyethoxy)ethoxy)ethoxy)ethane 3,6,9,12,15,18-Hexaoxaicosane-1,20-diol 3,6,9,12,15,18-Hexaoxa-1,20-eicosanediol Heptaglycol Heptagol	22
C₃ to C₅ ALKANEDIOLS			
8. $\text{CH}_3\text{CH}(\text{OH})\text{CH}_2\text{OH}$	Propylene glycol	Propane-1,2-diol 1,2-Dihydroxypropane 1,2-Propanediol	24
9. $\text{HO}[\text{CH}_2]_3\text{OH}$	Trimethylene glycol	Propane-1,3-diol 1,3-Dihydroxypropane 1,3-Propanediol	26
10. $\text{CH}_3\text{CH}_2\text{CH}(\text{OH})\text{CH}_2\text{OH}$	α -Butylene glycol	Butane-1,2-diol 1,2-Dihydroxybutane 1,2-Butanediol	27
11. $\text{CH}_3\text{CH}(\text{OH})[\text{CH}_2]_2\text{OH}$	β -Butylene glycol	Butane-1,3-diol 1,3-Dihydroxybutane 1,3-Butanediol	28
12. $\text{HO}[\text{CH}_2]_4\text{OH}$	Tetramethylene glycol	Butane-1,4-diol 1,4-Dihydroxybutane 1,4-Butanediol	29
13. $\text{HO}[\text{CH}_2]_5\text{OH}$	Pentamethylene glycol	Pentane-1,5-diol 1,5-Dihydroxypentane 1,5-Pentanediol	30
14. $(\text{CH}_3)_2\text{C}(\text{OH})\text{CH}_2\text{CH}(\text{OH})\text{CH}_3$	Hexylene glycol	2-Methylpentane-2,4-diol 2,4-Dihydroxy-2-methylpentane 2-Methyl-2,4-pentanediol	31
DIPROPYLENE GLYCOLS			
15. $(\text{CH}_3\text{CH}(\text{OH})\text{CH}_2)_2\text{O}$	Di- α -propylene glycol	2,2'-Dihydroxypropyl ether 4-Oxaheptane-2,6-diol 4-Oxa-2,6-heptanediol	32
ALKANETRIOLS			
16. $\text{HOCH}_2\text{CH}(\text{OH})\text{CH}_2\text{OH}$	Glycerol	Propane-1,2,3-triol 1,2,3-Trihydroxypropane 1,2,3-Propanetriol Glycerine	33

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THERMAL CONDUCTIVITY OF LIQUIDS: GLYCOLS, GLYCEROL AND THEIR AQUEOUS SOLUTIONS

1. INTRODUCTION

This Item presents values of thermal conductivity at saturation pressure, in tabular form, for liquid glycols, glycerol and their aqueous solutions.

The data on which these recommended values of thermal conductivity are based are the most reliable available and the temperature range covered 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
w	weight fraction	–
α	non-dimensional mixing parameter for binary mixtures in Equation (4.3)	–
λ	thermal conductivity	mW/m K

Subscripts

1, 2	denote mixture component with lower (1) and higher (2) thermal conductivity
b	denotes value at the normal boiling point
c	denotes value at the critical point
m	denotes value at the normal melting temperature
mix	denotes mixture
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 $T_r = 0.9$ 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 $T_r = 0.9^\dagger$. 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 95002 (Reference 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 6 and 7. For the diols, glycols and triols in this Item, it was found that C is directly related to $B^\ddagger$ and D is constant. For ethylene glycol, diethylene glycol, propane-1,2-diol, butane-1,2-, -1,3- and -1,4-diols and glycerol, it

* Experimental data at temperatures below the normal boiling temperature, t_b are often at 1 atm pressure. As indicated in Section 4.3 the difference between values of λ at 1 atm pressure and at saturation pressure below t_b is not significant.

[†] Most fluids in this Item will decompose at temperatures considerably below $T_r = 0.9$.

[‡] $C = 1 - 2.6B$ and $D = -12.5$.

was found that B , C and D could be held constant as was observed for other hydrogen bonded compounds such as the aliphatic alcohols and amines*. 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 Aqueous Solutions

For most liquid mixtures measurements have been made at a small number of concentrations and/or over a small temperature range. This makes graphical interpolation or extrapolation difficult or even impossible. However, data for the thermal conductivity of mixtures can be represented by equations and the NEL equation, Equation (4.3) (References 4, 5 and 9) was found to be the simplest and most accurate:

$$\lambda_{\text{mix}} = \lambda_1 w_1 + \lambda_2 w_2 - \alpha(\lambda_2 - \lambda_1)(1 - \sqrt{w_2})w_2 \quad (4.3)$$

where λ and w refer to the thermal conductivity and weight fraction composition respectively. Subscript 2 refers to the component with the higher thermal conductivity, namely water.

For prediction purposes α may be set to unity and the resultant predictions reproduce experiment to within ± 7 per cent (for a 95 per cent confidence limit) for all binary mixtures. This figure for accuracy applies whenever accurate data exist for the pure components but if the uncertainty in one or both of the pure component thermal conductivities is large, the mixture uncertainty must be revised upwards.

There exist experimental data for six polyhydric alcohols in aqueous solution. More accurate predictions can be obtained by using these data to determine individual values for α in Equation (4.3). These fitted values are given in Table 7.2 and were used to generate thermal conductivity values for aqueous solutions of the glycols and glycerol in the Data Sheets.

To compute values of λ_{mix} at temperatures below the freezing temperature of the pure component of higher melting temperature, values of thermal conductivity of that component had to be estimated at those temperatures. The estimated values were obtained by extrapolating pure component data with respect to temperature and were confirmed by extrapolating mixture data to zero concentration. These extrapolated values of λ_2 are given in the data sheets for aqueous solutions. Above 0 °C values of λ for water have been taken from Reference 12; values below 0 °C have been obtained by extrapolation both as a function of temperature and mixture composition.

4.3 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:

$$\lambda_p/\lambda \approx 1 + 0.2p \times 10^{-8}, \quad (4.4)$$

* $B = -7.00$, $C = 19.20$, $D = -12.5$.

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. For pure components, values of the thermal conductivity are given in the data sheets at 10 kelvin intervals in K and °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 $T_r \approx 0.9$. For aqueous mixtures values of thermal conductivity are given with temperatures in °C only.

The sources are given in the data sheets and, for pure components extrapolated values are indicated in parentheses on the pure component data sheets.

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 most 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 $\geq 573 \text{ K}$.

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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 K	A mW/m K	B	C	D	Range of Applicability °C
1. Ethylene glycol	725.	201.0	-7.00	19.20	-12.5	-10 to 390
2. Diethylene glycol	760.	161.0	-7.00	19.20	-12.5	-10 to 420
3. Triethylene glycol	795.	133.0	-7.20	19.72	-12.5	-10 to 450
4. Tetraethylene glycol	820.	102.0	-7.60	20.76	-12.5	-10 to 470
5. Pentaethylene glycol	865.	90.5	-7.80	21.28	-12.5	-20 to 510
6. Hexaethylene glycol	905.	84.0	-7.95	21.67	-12.5	-20 to 550
7. Heptaethylene glycol	940.	81.5	-8.00	21.80	-12.5	-20 to 580
8. Propylene glycol	670.	158.0	-7.00	19.20	-12.5	-60 to 340
9. Trimethylene glycol	735.	188.6	-6.90	18.94	-12.5	-30 to 400
10. α -Butylene glycol	675.	134.3	-7.00	19.20	-12.5	-50 to 340
11. β -Butylene glycol	700.	147.0	-7.00	19.20	-12.5	-50 to 360
12. Tetramethylene glycol	745.	164.0	-7.00	19.20	-12.5	20 to 410
13. Pentamethylene glycol	750.	147.0	-7.10	19.46	-12.5	-20 to 410
14. Hexylene glycol	675.	92.0	-7.10	19.46	-12.5	-50 to 340
15. Di- α -propylene glycol	700.	112.0	-7.20	19.72	-12.5	-50 to 360
16. Glycerol	765.	233.0	-7.00	19.20	-12.5	20 to 420

TABLE 7.2 Normal melting and boiling temperatures for aqueous glycol and glycerol solutions and values of α for Equation (4.3)

Aqueous solutions of:	w_2 —	t_m °C	t_b °C	α —
Ethylene glycol	0.8	-9	102	0.70
	0.6	-24	104	
	0.4	-54	111	
	0.2	-46	124	
Diethylene glycol	0.8	-4	102	0.46
	0.6	-16	103	
	0.4	-44	107	
	0.2	-41	117	
Triethylene glycol	0.8	-3	100	0.83
	0.6	-12	101	
	0.4	-37	104	
	0.2	-38	112	
Propylene glycol	0.8	-7	102	0.62
	0.6	-20	104	
	0.4	-60	109	
	0.2	-80	120	
Di- α -propylene glycol*	0.8	-3	101	0.82
	0.6	-14	103	
	0.4	-48	106	
	0.2	-70	114	
Glycerol	0.8	-5	102	0.42
	0.6	-15	104	
	0.4	-35	109	
	0.2	-20	121	

* The normal melting and normal boiling point data for di- α -propylene glycol are estimated.

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HO[CH₂]₂OH ETHYLENE GLYCOL (ETHANE-1,2-DIOL, 1,2-DIHYDROXYETHANE, 1,2-ETHANEDIOL, MONOETHYLENE GLYCOL, GLYCOL)

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

where

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

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

$$T_c = 725. \text{ K}$$

$$A = 201.0, \quad B = -7.00, \quad C = 19.20, \quad D = -12.5$$

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	(246.3)	470	247.1	-10	(247.0)	200	246.2
270	248.4	480	(244.)	0	249.1	210	(243.)
280	250.4	490	(241.)	10	251.0	220	(240.)
290	252.1	500	(238.)	20	252.7	230	(236.)
300	253.7	510	(234.)	30	254.2	240	(233.)
310	255.1	520	(230.)	40	255.5	250	(228.)
320	256.3	530	(225.)	50	256.7	260	(224.)
330	257.3	540	(220.)	60	257.6	270	(218.)
340	258.1	550	(215.)	70	258.3	280	(213.)
350	258.7	560	(209.)	80	258.9	290	(207.)
360	259.1	570	(202.)	90	259.2	300	(200.)
370	259.3	580	(196.)	100	259.3	310	(193.)
380	259.2	590	(188.)	110	259.1	320	(186.)
390	258.9	600	(180.)	120	258.7	330	(178.)
400	258.3	610	(172.)	130	258.1	340	(169.)
410	257.5	620	(163.)	140	257.2	350	(160.)
420	256.5	630	(153.)	150	256.1	360	(150.)
430	255.2	640	(142.)	160	254.7	370	(139.)
440	253.6	650	(131.)	170	253.0	380	(127.)
450	251.7	660	(119.)	180	251.0	390	(115.)
460	249.5			190	248.8		

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