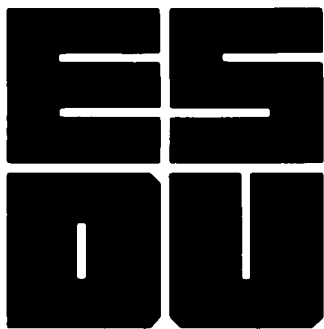


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Engineering Sciences Data
Item Number

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Thermal conductivity of carbon dioxide gas and liquid

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The Physical Data and Reaction Kinetics Committee, which first met in May 1966, has the co-operation of many engineers and scientists in industry, research establishments and universities from whom much assistance and information are being received. For this particular Item the initial assessment of the available information, the correlations and the tables calculated from them were prepared by the National Engineering Laboratory. The work was undertaken by Mr J.T.R.Watson of the Properties of Fluids Division and was sponsored by ESDU. The Item was accepted for inclusion in the Physical Data, Mechanical Engineering Sub-series by committee members representing the interests of mechanical engineers on behalf of the Institution of Mechanical Engineers.

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(Continued on inside back cover)

THERMAL CONDUCTIVITY OF CARBON DIOXIDE GAS AND LIQUID

1. INTRODUCTION

This Item presents equations and values in SI units of the thermal conductivity of carbon dioxide for temperatures between 240 K and 1500 K and for pressures from 1 to 1000 bar. The data are presented in the form of Tables generated by computer.

Table I gives the variation of the thermal conductivity of carbon dioxide with temperature along the saturation line and Table II gives the variation with temperature and pressure in the single-phase region. The detailed variation of the thermal conductivity of carbon dioxide in the critical region is given in Table III as a function of density and temperature; Table IV lists the pressures corresponding to the thermal conductivity entries of Table III.

The tabulated values of thermal conductivity in Tables I and II have been calculated at specific values of temperature and pressure from a single representative equation for the thermal conductivity of liquid and gaseous carbon dioxide as a function of density and temperature. The values of the thermodynamic properties used both for the correlation of the original experimental data and for the preparation of the Tables have been calculated from the 1973 IUPAC formulation for the thermodynamic properties of carbon dioxide, Reference 7.

2. NOTATION AND UNITS

Equations are written in terms of thermodynamic temperature T ; for most purposes the thermodynamic scale is interchangeable with the International Practical Temperature Scale of 1968 (Reference 1) and all numerical values are given as International Practical Kelvin Temperatures, T_{68} .

$F(\rho, T)$	factor in Equation (3) giving enhancement of thermal conductivity at density ρ and temperature T over thermal conductivity of dilute gas at same temperature	
p	pressure	bar
T	thermodynamic temperature	K
T_r	reduced temperature, $T/T_c = T/304.21$	
T_{68}	International Practical Kelvin temperature	K
$\Delta_c \lambda$	enhancement to thermal conductivity in critical region	mW/m K
η	dynamic viscosity	$\mu\text{Ns/m}^2$
λ	thermal conductivity	mW/m K
λ_{id}	value of λ at critical point as given by Equation (3) without $\Delta_c \lambda(\rho, T)$ term	mW/m K
$\lambda(0, T)$	thermal conductivity in the limit of low pressures at temperature T	mW/m K
ρ	density	kg/m^3
ρ_r	reduced density, $\rho/\rho_c = \rho/466.0$	

Suffixes

- c* denotes value at critical point
- g* denotes value for saturated vapour
- l* denotes value for saturated liquid

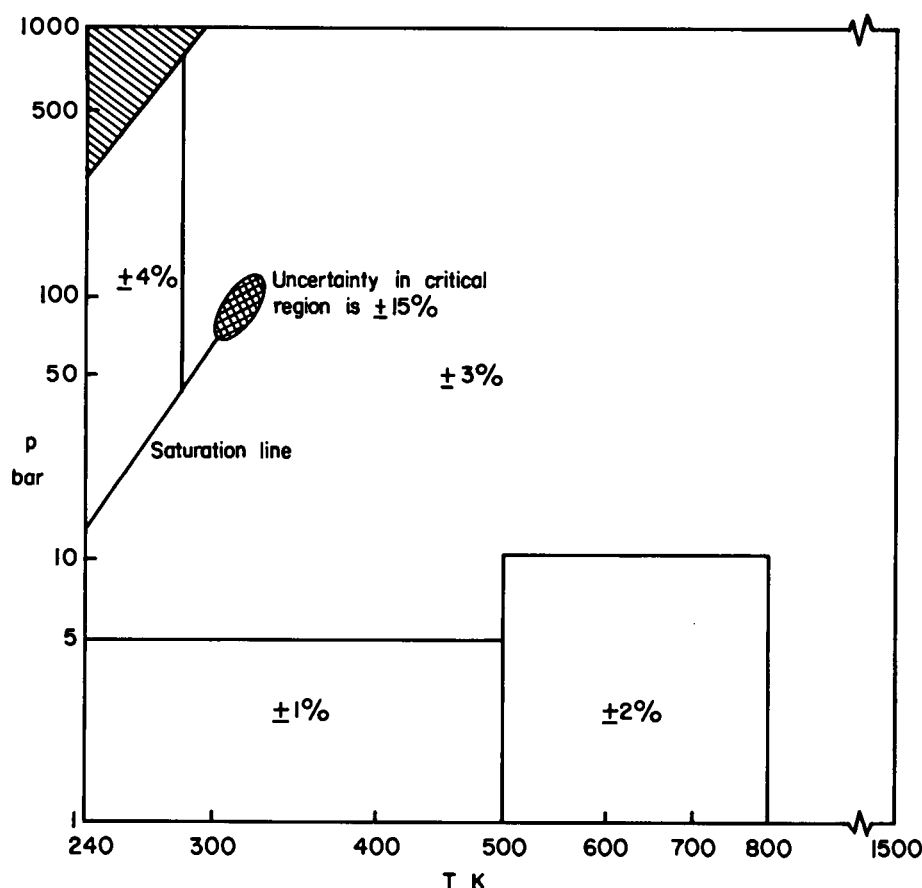
3. CONVERSION FACTORS

<i>To convert from</i>	<i>to</i>	<i>multiply by</i>
Thermal conductivity in mW/m K	thermal conductivity in W/m K	10^{-3}
	thermal conductivity in J/cm s K	10×10^{-6}
	thermal conductivity in cal/cm s K	$2.388\ 46 \times 10^{-6}$
	thermal conductivity in kcal/m h K	859.845×10^{-6}
	thermal conductivity in Btu/in h °F	$48.148\ 9 \times 10^{-6}$
	thermal conductivity in Btu/ft s °F	160.496×10^{-9}
	thermal conductivity in Btu/ft min °F	$9.629\ 78 \times 10^{-6}$
	thermal conductivity in Btu/ft h °F	577.787×10^{-6}
	thermal conductivity in Btu in/ft ² h °F	$6.933\ 45 \times 10^{-3}$
Pressure in bar	pressure in N/m ²	100×10^3
	pressure in atm	986.923×10^{-3}
	pressure in lbf/in ²	14.503 8
	pressure in kgf/cm ²	1.019 72
	pressure in mmHg	750.062

4. USE AND ACCURACY OF TABLES

In general the last figure, and on occasions the penultimate figure, are not significant but are included to reduce errors in interpolation. Linear interpolation between adjacent tabulated values will usually be sufficient in Table II except for the range of temperatures and pressures as covered in Table IV, and in Table III except for a region close to the critical point.

The estimated uncertainties in the tabulated values of thermal conductivity are shown in Sketch (i) and are based largely on the spread of experimental results. For data at a boundary dividing one region from another the lower value of the uncertainty may be taken to apply.



Sketch (i) Tolerance diagram for thermal conductivity

5. AUXILIARY EQUATIONS FOR SATURATION LINE

Values obtained by interpolation from Table I will be adequate for most purposes. However, if the data are required in a design program it may be convenient to have the data in functional form. Equation (3), given for the thermal conductivity in Section 6, is not ideally suited for use in this way because of the complexity of the calculations involved, the need for density data, and for a wide range of conditions around the critical point the need for the first partial derivatives of pressure with respect to temperature and density respectively. The following, more convenient forms of equation, which represent the tabulated values well (to within rms percentage deviations of 0.075 and 0.20 for the saturated liquid and vapour respectively), are recommended for the saturation line values between 240 K and the critical point.

For the saturated liquid

$$\ln(\lambda_1/\lambda_{id}) = \sum_{i=1}^6 a_i (1 - T_r)^{(i-3)/3}, \quad (1)$$

where $\lambda_{id} = 56.5702 \text{ mW/m K}$, and the numerical values of the coefficients are

$$\begin{aligned} a_1 &= 27.86052 \times 10^{-3}, & a_4 &= -16.69428, \\ a_2 &= -501.9150 \times 10^{-3}, & a_5 &= 31.11670, \\ a_3 &= 4.530751, & a_6 &= -18.59093, \end{aligned}$$

and for the saturated vapour,

$$\ln(\lambda_{id}/\lambda_g) = \sum_{i=1}^8 b_i(1-T_r)^{(i-3)/3}, \quad (2)$$

where the value of λ_{id} is as given for Equation (1), and the numerical values of the coefficients are

$$\begin{aligned} b_1 &= -527.529\,83 \times 10^{-3}, & b_5 &= -1.545\,8024 \times 10^3, \\ b_2 &= 11.225\,434, & b_6 &= 2.658\,2979 \times 10^3, \\ b_3 &= -105.099\,57, & b_7 &= -2.483\,0210 \times 10^3, \\ b_4 &= 529.673\,12, & b_8 &= 971.495\,91. \end{aligned}$$

6. DERIVATION OF THE THERMAL CONDUCTIVITY EQUATION

References 2 and 4 together form a reasonably complete bibliography on the thermal conductivity of carbon dioxide to 1973. A careful assessment of these and other more recent sources was made and the data of Derivations 10 to 29 selected for this work.

A statistical analysis of the data away from the critical region shows that the variation of thermal conductivity with density and temperature can be best represented by the general equation

$$\lambda = \lambda(\rho, T) = \lambda(0, T) \cdot F(\rho, T) + \Delta_c \lambda(\rho, T), \quad (3)$$

where $\lambda(0, T)$ is the value of thermal conductivity in the limit of low pressures, $F(\rho, T)$ is an enhancement factor relating the thermal conductivity at density ρ to the thermal conductivity of the dilute gas at the same temperature, and $\Delta_c \lambda(\rho, T)$ is the additional enhancement to the thermal conductivity in the critical region.

For carbon dioxide the various functions in Equation (3) are given by the following expressions (Equations (3a), (3b) and (3c)):

$$\lambda(0, T) = T^{1/2} \sum_{i=0}^3 b_i \left(\frac{100}{T} \right)^i, \quad (3a)$$

where the numerical values of the coefficients are

$$\begin{aligned} b_0 &= 323.537 \times 10^{-3}, & b_2 &= 6.181\,15, \\ b_1 &= 771.034 \times 10^{-3}, & b_3 &= -6.138\,48; \end{aligned}$$

$$F(\rho, T) = \exp \left\{ \sum_{i=1}^6 \sum_{j=0}^2 a_{ij} \cdot \rho_r^i \cdot T_r^{-j} \right\}, \quad (3b)$$

with $a_{5,2} = 0.0$, $a_{6,2} = 0.0$,

and where the remaining coefficients, each fully significant at a 99.9 per cent confidence level, are

$$\begin{aligned} a_{1,0} &= 2.177\,518\,14, & a_{1,1} &= -6.498\,944\,20, \\ a_{2,0} &= -5.038\,233\,45, & a_{2,1} &= 14.294\,837\,5, \\ a_{3,0} &= 5.740\,162\,66, & a_{3,1} &= -13.980\,486\,9, \\ a_{4,0} &= -3.383\,987\,10, & a_{4,1} &= 7.723\,337\,29, \\ a_{5,0} &= 1.023\,180\,80, & a_{5,1} &= -2.245\,918\,32, \\ a_{6,0} &= -129.016\,578 \times 10^{-3}, & a_{6,1} &= 273.746\,572 \times 10^{-3}, \end{aligned}$$

$$a_{1,2} = 5.012\,667\,85,$$

$$a_{2,2} = -5.768\,313\,54,$$

$$a_{3,2} = 2.389\,987\,12,$$

$$a_{4,2} = -387.403\,274 \times 10^{-3};$$

$$\Delta_c \lambda(\rho, T) = 5.2135 \frac{T^2}{\eta \rho} \left(\frac{\partial p}{\partial T} \right)_\rho^2 \left[\frac{1}{\rho} \left(\frac{\partial \rho}{\partial p} \right)_T \right]^{1/2} \exp \left\{ -18.66(T_r - 1)^2 \right\} \exp \left\{ -4.25(\rho_r - 1)^4 \right\}. \quad (3c)$$

The coefficients of Equation (3a) were obtained from an analysis of experimental data in Derivations 10 to 14, 17 to 20, 23 to 25 and 28, 29, supplemented at high temperatures with values calculated from the theoretical methods of Reference 3 and 6. Values calculated from Equation (3a) are estimated to be accurate to within ± 1 per cent from 200 to 500 K, ± 2 per cent from 500 to 800 K, and ± 3 per cent from 800 to 1500 K.

The coefficients of Equation (3b) were obtained from a statistical analysis of the best available data outside the critical region in Derivations 15, 16, 21, 22, 26 and 27. Density values required in the analysis were calculated from a computer package based on the 1973 IUPAC Formulation for the thermodynamic properties of carbon dioxide, Reference 7. The agreement obtained with the selected sources of data in this area is shown in the following Table.

<i>Derivation</i>	<i>Author</i>	<i>*No. of points</i>	<i>Mean percentage deviation</i>	<i>Mean absolute percentage deviation</i>	<i>rms percentage deviation</i>
15	Keyes	6 (6)	0.363	1.336	1.773
16	Shingarev	22 (22)	-0.599	2.579	3.188
21	Guildner	9 (9)	0.051	1.774	1.949
22	Michels, et al.	103 (33)	0.258	0.861	1.360
26	Tarzmanov	60 (60)	-0.073	0.834	1.022
27	Le Neindre, et al.	507 (456)	-0.129	0.897	1.205

* Number of points used in final analyses are in brackets.

Equation (3c) is based on a semi-theoretical expression developed by Sengers⁵ to represent the critical enhancement in the thermal conductivity of carbon dioxide. Values of the thermodynamic derivatives required in this expression were calculated by numerical differentiation of the IUPAC equation of state for carbon dioxide. Likewise, viscosity values were obtained from the formulation given in Reference 8.

Full details of the experimental data selection, assessment and weighting, together with the development of Equation (3) are available in Reference 9. The equation applies in the range of temperatures from 240 to 1500 K and the range of pressures from 0 to 1000 bar with the exception of part of the dense liquid region, shown as the shaded area in Sketch (i). Approximations to the formulation may be introduced in the following areas:

- at low pressures, below 2 bar at 240 K rising to some 20 bar at 1500 K, Equation (3a) may be used alone with little loss of accuracy, and
- outside the ranges $290 < T < 375$ and $0.5 < \rho_r < 1.5$ the $\Delta_c \lambda(\rho, T)$ term may be omitted from Equation (3) with little loss of accuracy.

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