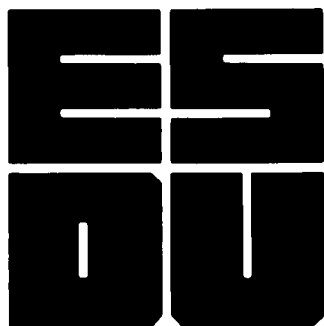


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Dynamic viscosity of carbon dioxide gas and liquid

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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)

DYNAMIC VISCOSITY OF CARBON DIOXIDE GAS AND LIQUID

1. INTRODUCTION

This Item presents equations and values in SI units of the dynamic viscosity 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 dynamic and kinematic viscosity of carbon dioxide with temperature and pressure along the saturation line and Table II gives the variation of the dynamic viscosity with temperature and pressure in the single-phase region.

The tabulated values have been calculated at specific values of temperature and pressure from a single representative equation for the viscosity of liquid and gaseous carbon dioxide as a function of temperature and density. Density values, 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 2.

2. NOTATION AND UNITS

Equations are written in terms of thermodynamic temperatures 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} .

p	pressure	bar
T	thermodynamic temperature	K
T_r	reduced temperature, $T/T_c = T/304.21$	
T_{68}	International Practical Kelvin temperature	K
η	dynamic viscosity	$\mu\text{Ns/m}^2$
ν	kinematic viscosity	$\mu\text{m}^2/\text{s}$
ρ	density	kg/m^3
ρ_r	reduced density, $\rho/\rho_c = \rho/466.0$	
<i>Suffixes</i>		
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>
Dynamic viscosity in $\mu\text{Ns/m}^2$	dynamic viscosity in g/cm s (= Poise)	10×10^{-6}
	dynamic viscosity in kg/m s	10^{-6}
	dynamic viscosity in lb/ft h	$2.419\,09 \times 10^{-3}$
	dynamic viscosity in lb/ft s	671.971×10^{-9}
	dynamic viscosity in kgf s/m^2	101.972×10^{-9}
	dynamic viscosity in lbf s/in^2	145.038×10^{-12}
Kinematic viscosity in $\mu\text{m}^2/\text{s}$	kinematic viscosity in cm^2/s (= Stoke)	10×10^{-3}
	kinematic viscosity in m^2/s	10^{-6}
	kinematic viscosity in m^2/h	3.60×10^{-3}
	kinematic viscosity in ft^2/s	$10.763\,9 \times 10^{-6}$
	kinematic viscosity in ft^2/h	$38.750\,1 \times 10^{-3}$
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 except in the critical region, that is for temperatures above 300 K in Table I and for temperatures between 300 and 305 K and pressures between 65 and 100 bar in Table II.

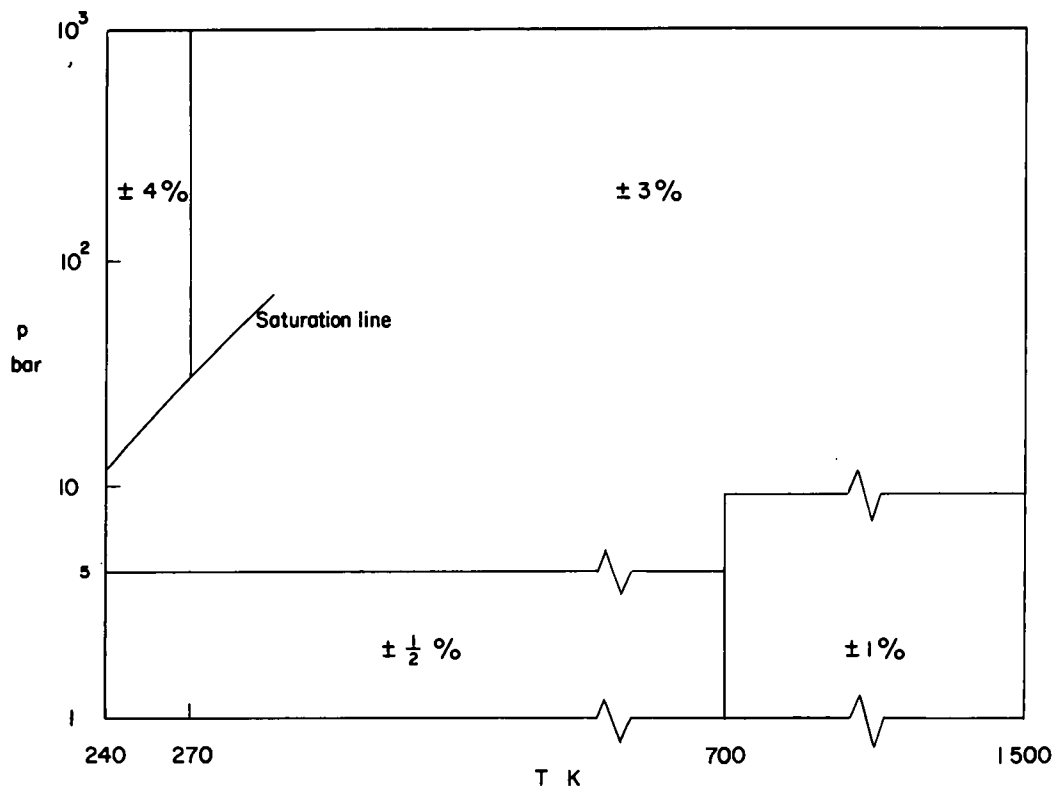
The estimated uncertainties in the tabulated values of dynamic viscosity are shown in Sketch (i) and are based on the spread of experimental results. For data at a boundary dividing one region from another the lower value of the uncertainty may be taken to apply. The uncertainties in the tabulated values of kinematic viscosity in Table I correspond to the uncertainties in the values of dynamic viscosity: these are

± 3 per cent for the saturated vapour from 240 K to T_c

± 4 per cent for the saturated liquid from 240 K to 270 K, and

± 3 per cent for the saturated liquid from 270 K to T_c .

* $1 \mu\text{m}^2/\text{s} = 10^{-6} \text{ m}^2/\text{s}$.



Sketch (i) Tolerance diagram for dynamic viscosity

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 dynamic viscosity in Section 6, is not ideally suited for use in this way because of the complexity of the calculations involved and the need for density data. The following, more convenient forms of equation, which represent the tabulated values well (within a maximum percentage deviation of ± 0.025), are recommended for the saturation line values between 240 K and the critical point.

For the saturated liquid

$$\ln(\eta_l/\eta_c) = a_0(1 - T_r)^{0.40} + \sum_{i=1}^4 a_i(1 - T_r)^{(i+1)/3}, \quad (1)$$

where $\eta_c = 32.595 \mu\text{Ns/m}^2$, $T_c = 304.21 \text{ K}$ and the numerical values of the coefficients are

$$a_0 = 3.499\,977,$$

$$a_1 = -5.339\,064,$$

$$a_2 = 14.946\,93,$$

$$a_3 = -20.638\,40,$$

$$a_4 = 14.506\,07,$$

and for the saturated vapour

$$\ln(\eta_c/\eta_g) = b_0(1 - T_r)^{0.35} + \sum_{i=1}^4 b_i(1 - T_r)^{(i+1)/3}, \quad (2)$$

where η_c and T_c are as defined earlier, and the numerical values of the coefficients are

$$\begin{aligned} b_0 &= 1.882\,465, \\ b_1 &= 0.150\,027\,7, \\ b_2 &= 0.396\,762\,4, \\ b_3 &= -5.202\,870, \\ b_4 &= 5.448\,607. \end{aligned}$$

The corresponding auxiliary equations, for the density of saturated liquid and vapour as a function of temperature, given in Reference 2, may be used in conjunction with these expressions to compute values of kinematic viscosity on the saturation line.

6. DERIVATION OF VISCOSITY EQUATION

A careful assessment was made of the available experimental data for the viscosity of carbon dioxide given in Derivations 4 to 20. The constants in Equation (3) (representing the dynamic viscosity of the liquid and the gas) were obtained by fitting the equation to those data. For the dense fluid state, it was necessary to express the dynamic viscosity as a function of density and temperature; densities corresponding to the temperatures and pressures of the source data points were calculated from a computer package based on the 1973 IUPAC Formulation for the thermodynamic properties of carbon dioxide. Full details of the experimental data selection, assessment and weighting, together with the development of the correlation equation, are available in Reference 3.

The equation for the dynamic viscosity of carbon dioxide is

$$\eta = \eta(\rho, T) = \eta(0, T) \cdot \exp \left[\sum_{i=1}^5 \sum_{j=0}^1 a_{ij} \rho_r^i T_r^{-j} \right] \quad \mu\text{Ns/m}^2, \quad (3)$$

where $a_{50} = 0$ and where the remaining coefficients, each fully significant at a 99.9 per cent confidence level, are:

$$\begin{aligned} a_{1,0} &= 187.907\,23 \times 10^{-3}, & a_{1,1} &= -113.311\,51 \times 10^{-3}, \\ a_{2,0} &= -531.582\,00 \times 10^{-3}, & a_{2,1} &= 1.971\,878\,0, \\ a_{3,0} &= 596.747\,00 \times 10^{-3}, & a_{3,1} &= -1.706\,279\,6, \\ a_{4,0} &= -131.569\,27 \times 10^{-3}, & a_{4,1} &= 549.508\,07 \times 10^{-3}, \\ & & a_{5,1} &= -57.400\,364 \times 10^{-3}. \end{aligned}$$

The zero density viscosity (see Reference 3) term $\eta(0, T)$ is given by the expression

$$\eta(0, T) = T^{1/2} \left[\sum_{i=0}^4 b_i \left(\frac{100}{T} \right)^i \right]^{-1} \quad \mu\text{Ns/m}^2,$$

where the numerical values of the coefficients are:

$$b_0 = 629.068\,31 \times 10^{-3},$$

$$b_1 = 1.255\,549\,5,$$

$$b_2 = 1.295\,180\,9,$$

$$b_3 = -71.773\,558 \times 10^{-3},$$

$$b_4 = -2.843\,672\,9.$$

Equation (3) applies in the range of temperatures from 240 to 1500 K and the range of pressures from 0 to 1000 bar. The agreement obtained with the selected sources of data at elevated pressure 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>
5	Golubev and Petrov	144 (141)	0.764	1.519	2.123
6	Michels, Botzen and Schuurman	144 (125)	-0.692	0.859	1.101
7	Kestin and Leidenfrost	7 (7)	-0.170	0.170	0.187
8	Kestin and Whitelaw	43 (43)	0.210	1.008	1.333
9	Kestin, Whitelaw and Zien	103 (49)	-0.589	0.717	0.957
10	Kestin, Kobayashi and Wood	33 (33)	0.044	0.101	0.134
11	Breetveld, DiPippo and Kestin	8 (8)	-0.009	0.066	0.086
17	Golubev, Gnezdilov and Brodskaja	72 (72)	-1.060	1.167	1.519
18	Golubev and Shepleva	107 (107)	-0.019	0.821	1.136
20	Kurin and Golubev	44 (44)	-0.62	1.528	2.305

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

The zero density expression applies in the range of temperatures from 200 to 1500 K and represents the best available data (Derivations 4, 12, 13, 14, 15, 16 and 19) to within ± 0.5 per cent between 200 and 700 K and to within ± 1.0 per cent between 700 and 1500 K.

Very close to the critical point Equation (3) gives values that deviate from measured data, the deviation increasing logarithmically as the critical point is approached. However, the magnitude of the effect is small and can only be noticed in the immediate vicinity of the critical point. For most engineering purposes the effect may be neglected.

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