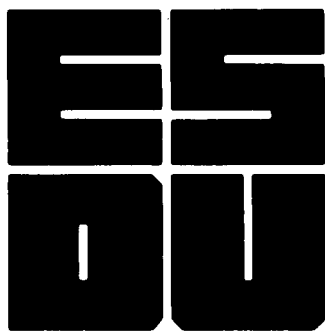




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Thermal conductivity, viscosity, heat capacity, density and Prandtl number of sea water and its concentrates

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ENGINEERING SCIENCES DATA ITEM No. 77024

Physical Data, Chemical Engineering Sub-series

Physical Data, Mechanical Engineering Sub-series

Engineering Sciences Data Items provide evaluated data and authoritative information for use in engineering design. The results of much valuable work, both theoretical and practical, are frequently not applied because they are not readily available or because the form in which they are available is not suitable for use directly in design. Accordingly, the Engineering Sciences Data Unit has for many years issued Data Sheets and Memoranda in numerous Sub-series. This work is sponsored by the following Institutions: the Royal Aeronautical Society, the Institution of Mechanical Engineers, the Institution of Chemical Engineers and the Institution of Structural Engineers. Crucial support for this work is provided voluntarily by industrial companies, government research laboratories, universities and others through the attendance at Technical Committees (see below) of their leading experts.

The work of the permanent professional staff of the Engineering Sciences Data Unit on this particular Item was monitored and guided by the Physical Data and Reaction Kinetics Committee which has the following constitution:

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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 Properties of Fluids Division at the National Engineering Laboratory. The work was supervised by Dr J.D.Isdale and Dr D.T.Jamieson, 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.

In order to assist the preparation of new work, and particularly to assist the periodic review and revision of work already issued, users are encouraged to make known their experience in using the information and procedures and to notify the Unit of any additional information which they can provide or to which reference can be made. Prepaid reply service cards are available for this purpose. Whenever an Item is revised, users who are Associates of ESDU (i.e. have a standing

(Continued on inside back cover)

* Corresponding Member

THERMAL CONDUCTIVITY, VISCOSITY, HEAT CAPACITY, DENSITY AND PRANDTL NUMBER OF SEA WATER AND ITS CONCENTRATES

1. INTRODUCTION

This Item presents values of thermal conductivity, dynamic viscosity, heat capacity, density and Prandtl number for sea water and its concentrates both in tabular form and as equations. The data on which these recommended values are based are the most reliable available and cover a wide range of both temperature and concentration.

The concentration of sea water samples is normally defined by a single term, either salinity or chlorinity. This is possible since for all practical purposes the relative composition of sea water is constant. This does not imply that all samples have the same composition but merely that all ions are present in the same ratios and that the only variation is the amount of pure water present. Thus if the concentration of any one ion is measured then the amount of all other ions can be accurately found by calculation.

Salinity was originally defined as the weight in grammes of the dissolved inorganic matter in 1 kg of sea water, after all bromide and iodide have been replaced by an equivalent amount of chloride and all carbonate converted to oxide. Chlorinity is in effect the halide concentration of sea water. The two are related by

$$S_{\text{‰}} = 1.80655 Cl_{\text{‰}} \quad (1)$$

(The symbol ‰ denotes parts per thousand of sea water.) Chlorinity and salinity are now more accurately found by measuring the ratio of the electrical conductivity of the unknown sample to that of a "Standard Sea Water" sample*.

Table I gives the major components of sea water at its "normal" salinity of 35‰ though samples from different seas may vary by more than the range 32–40‰. Samples reported at other salinities in this Item may be considered merely as having more or less pure water but at the highest concentrations reported some salts (notably calcium sulphates) will have exceeded their solubilities and precipitated from solutions.

2. NOTATION

The following SI units or multiples of SI units are adopted here.

Cl	chlorinity	g/kg
c_p	heat capacity at constant pressure	kJ/kg K
Pr	Prandtl number, $c_p \eta / \lambda$	
S	salinity	g/kg
T	thermodynamic temperature	K
t	Celsius temperature, $T - 273.15$	°C

* Samples are available from IAPSO Standard Sea Water Service, Brook Road, Wormley, Godalming, Surrey, UK.

η	dynamic viscosity of sea water solution of salinity $S\%$ at $t^\circ\text{C}$	mN s/m^2 or cP
λ	thermal conductivity	mW/m K
ρ	density	kg/m^3

3. CONVERSION FACTORS

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

$$\begin{aligned}
 1 \text{ kJ/kg K} &= 0.239006 \text{ cal/g } ^\circ\text{C} \\
 &= 0.238846 \text{ Btu/lb } ^\circ\text{F}
 \end{aligned}$$

$$\begin{aligned}
 1 \text{ kg/m}^3 &= 1.0 \times 10^{-3} \text{ g/cm}^3 \\
 &= 62.428 \times 10^{-3} \text{ lb/ft}^3
 \end{aligned}$$

$$\begin{aligned}
 1 \text{ mN s/m}^2 &= 1.0 \text{ cP} \\
 &= 671.97 \times 10^{-6} \text{ lb/ft s} \\
 &= 20.885 \times 10^{-6} \text{ slug/ft s}
 \end{aligned}$$

4. PROPERTIES

The properties given in the following Sections are based on data taken from the sources listed in Section 5. These data were correlated in equation form and the Tables were generated from these equations.

Values obtained by linear interpolation from the Tables will be adequate for most purposes but since data are often required in a computerized design program the equation forms are also given.

4.1 Thermal Conductivity

Values given in Table II were calculated from the equation

$$\ln \lambda = \ln (\lambda_c + X) + \left(2.3 - \frac{G}{T} \right) \left(1 - \frac{T}{T_c + Y} \right)^{0.333} \quad (2)$$

where λ_c = thermal conductivity of distilled water extrapolated to the critical point (240 mW/m K),

T_c = critical temperature of distilled water (647.27 K),

$X = 0.2S$,

$Y = 0.03S$,

$G = 343.5 + 0.37S$.

The pseudocritical temperature of the test liquid ($T_c + Y$) was obtained from the boiling points of water and sea water solutions assuming that the ratio boiling point temperature/critical temperature is constant.

The values in the Table calculated from Equation (2) are estimated to be accurate to within ± 3 per cent.

4.2 Dynamic Viscosity

Values given in Tables III and IV were calculated from the equation

$$\log_{10} \eta = \log_{10} \eta_{20} - \left[\frac{t-20}{t+109} \right] [A(1 + a_1 S + a_2 S^2) + B(1 + b_1 S + b_2 S^2)(t-20)] \quad (3)$$

where η_{20} = viscosity of the sea water solution at 20°C in cP
 $= 1.002 + c_1 S + c_2 S^2 + c_3 S^3$,

$$\begin{aligned} A &= 1.3706 & B &= 8.32 \times 10^{-4} & C_1 &= 1.851\,896\,1 \times 10^{-3} \\ a_1 &= -6.19 \times 10^{-4} & b_1 &= 1.43 \times 10^{-4} & C_2 &= 3.082\,369\,7 \times 10^{-6} \\ a_2 &= 1.2 \times 10^{-6} & b_2 &= 1.0 \times 10^{-5} & C_3 &= 3.010\,305\,2 \times 10^{-8} \end{aligned}$$

The values in the Tables calculated from Equation (3) are estimated to be accurate to ± 1 per cent.

4.3 Heat Capacity

Values given in Tables V and VI were calculated from Equation (4) which can be evaluated using the Fortran IV computer program given in Appendix A.

$$c_p = \sum_{i=0}^2 \sum_{j=0}^2 C_{ij} \cdot E_j(x_C) \cdot E_i(x_{C1}) \text{ kJ/kg K} \quad (4)$$

where Σ' denotes a summation the first term of which is halved, $E_j(x_C)$ is the Chebyshev polynomial in x_C of degree j and

$$x_C = (2S - 180)/180,$$

$$x_{C1} = (2t - 180)/180.$$

The Chebyshev coefficients C_{ij} are:

$i \backslash j$	0	1	2
0	15.328	0.1583	0.0436
1	-0.7775	-0.0221	-0.0123
2	0.064	-0.006	0.017

The values in the Tables calculated from Equation (4) are estimated to be accurate to ± 0.3 per cent.

4.4 Density

Values given in Tables VII and VIII between 20 °C and 180 °C were calculated from Equation (5) which can be evaluated using the Fortran IV computer program given in Appendix A.

$$\rho = 10^3 \cdot \sum_{i=0}^3 \sum_{j=0}^2 D_{ij} \cdot E_j(x_D) \cdot E_i(x_{D1}) \text{ kg/m}^3 \quad (5)$$

where Σ' denotes a summation the first term of which is halved, $E_j(x_D)$ is the Chebyshev polynomial in x_D of degree j and

$$x_D = (2S - 150)/150,$$

$$x_{D1} = (2t - 200)/160.$$

The Chebyshev coefficients D_{ij} are:

$j \backslash i$	0	1	2	3
0	4.032 219	-0.108 199	-0.012 247	0.000 692
1	0.115 313	0.001 571	0.001 74	-0.000 087
2	0.000 326	-0.000 423	-0.000 009	-0.000 053

The values in the Tables between 20 °C and 180 °C calculated from Equation (5) are estimated to be accurate to ± 0.05 per cent.

The values at temperatures of less than 20 °C in Tables VII and VIII are the best representation of the experimental data but are not given by Equation (5).

4.5 Prandtl Number

For convenience, values of Prandtl number have been evaluated from the tabulated values of c_p , η and λ and are presented in Table IX.

5. DERIVATION

The derivation lists selected sources that have assisted in the preparation of this Item.

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