second edition

TABLES on the THERMOPHYSICAL PROPERTIES of LIQUIDS and GASES

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In Normal and Dissociated States

N. B. Vargaftik

With a Foreword by

Y. S. Touloukian

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SECOND EDITION

BY

N. B. VARGAFTIK

WITH A FOREWORD TO THE ENGLISH EDITION BY

Y. S. Touloukian
PURDUE UNIVERSITY

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FOREWORD TO THE ENGLISH TRANSLATION–SECOND EDITION

I am indeed pleased to write a foreword to this extensive work. This book is a translation of the second, most recent edition of Professor Vargaftik's "Spravochnik po Teplofizicheskim Svoitstvam Gazov i Zhidkostey," which first appeared in this format in 1963. The primary contribution of the translated version comes from the author's extensive presentation, primarily from the Russian literature, on a wide range of materials of technological importance, in the liquid, vapor, gaseous, dissociated, and ionized states. The thermodynamic and transport properties presented, often over a wide range of temperatures and pressures, are basically reproductions from other data sources. In several instances, the tabular material is unique, and this reasonably up-to-date compendium would be most welcome by many in the English-speaking world to whom much of the data would otherwise remain unobtainable.

In the absence of any evaluative commentary in the presentation of the data, those who use this work will have to rely at this time on the author's judgment in the selection of the data and his internationally acknowledged reputation for his many valuable and original contributions to the field. I very much hope, however, that this work, together with others, may constitute the basis for future cooperative endeavors for the generation of an internationally agreed-upon set of thermophysical properties tables for gases and liquids such as that currently sponsored by special Task Groups within CODATA/ICSU, IUPAC, and the International Association for the Properties of Steam.

In this translation the corrections found on the errata page of the original work have been incorporated as have additional corrections noted since it was published. As an added feature the translated edition presents a thorough index to both the substances and the properties covered in the volume. The reader will find these conveniences most helpful in using this extensive reference work.

Y. S. Touloukian, Director
Center for Information and
Numerical Data Analysis and Synthesis
and
Distinguished Atkins Professor of Engineering
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West Lafayette, Indiana

FOREWORD TO THE SECOND EDITION

Since the publication of the first edition of this Handbook (in 1963) a large amount of material on thermophysical properties of different substances has been published. The following changes and additions have been incorporated in the present edition:

1. New, detailed data are given for two types of hydrogen, both in the liquid and in the gaseous states. The present tables contain data up to 6,000°K and 1,000 bar, that is, the data include the region of high temperatures where hydrogen exists in a dissociated state. New tables of transport properties of hydrogen have been provided for both the liquid and the gaseous states at different pressures up to a temperature of 2,000°K.

2. The thermophysical properties of nitrogen, oxygen, air and argon are given over a much wider range of parameters. Detailed new data at high temperatures are given for these substances, for both the liquid as well as for the gaseous states, ranging from extremely low to very high pressures (up to 1,000 bar).

3. The tables of thermophysical properties of carbon dioxide (CO_2) have been reworked, expanded and rendered more accurate. This section contains new detailed data for liquid carbon dioxide at high temperatures (up to 4,000°K) in the critical region, where it exists in the dissociated state.

4. More detailed tables are given for alkali metals and mercury. Thermodynamic properties have been determined on the basis of new, more accurate data on the dissociation energy of diatomic molecules of alkali metals. The thermodynamic properties tables have been expanded to 3,000°K, taking into account both dissociation and ionization. Thermodynamic properties for ionized lithium at high temperatures are given in a separate set of tables. Viscosity and thermal conductivity of alkali metals in the gas phase are reported here for the first time.

5. Information on thermophysical properties of monatomic substances has been significantly expanded. In particular, new tables for helium include data for both liquid and gas phases at extremely low and high temperatures (up to 3,000°K) at different pressures. Thermophysical properties of neon, krypton and xenon are given for a wide range of temperatures and pressures.

6. Thermophysical properties of water and steam are given here on the basis of new international tables adapted in 1963–1964. For dissociated steam, data are given up to 6,000°K and 1,000 bar taking into account true properties of dissociated steam.

7. New data are given on diffusion in binary gas mixtures, on viscosity and thermal conductivity of mixtures and solutions; data at different pressures are included.

8. The majority of tables for the remaining substances cite more accurate and newer data over a wider range of parameters.

9. The editors have not included in the present edition data on thermophysical properties of compounds of boron, nitrogen oxide, gallium, deuterium and individual hydrocarbons, due to the fact almost no new information for these substances has been published since the appearance of the original edition of this handbook.

10. All thermophysical properties are given in SI units, with the exception of the data for ionized lithium, argon and nitrogen.

The author is grateful to the entire faculty of the Department of Physics at Moscow Institute of Aviation for their help in the preparation of this handbook. The author was helped in many aspects in the preparation of the present edition by Prof. P. M. Kesselman, Docents L. D. Volyak, Y. K. Vinogradov and N. D. Kosov and Assistant E. L. Studnikov, to whom he wishes to express his appreciation.

The author is very grateful to Academician A. S. Predvoditelev and Professor L. P. Filippov for valuable comments and to E. I. Gaydul for great help in the preparation of the manuscript.

N. B. Vargaftik

FOREWORD TO THE FIRST EDITION

The requirements of modern science and technology necessitate the knowledge of thermophysical properties of gases and liquids.

This area of science, in addition to experimental work, centers on research in diffusion, thermal conductivity and viscosity of gases, as well as on the derivation of equations of state for real gases. Over the recent years, a large amount of data on thermophysical properties of gases and liquids have been collected; these data are of great practical interest.

The present book attempts to provide a systematic presentation of data obtained over the last 5–10 years. Most reliable data for pure substances, gas mixtures and solutions are presented. The data are essentially based on experimental results. Most often, the data are given for whole-number temperatures and pressures, and in the cases of mixtures for concentrations convenient for practical calculations.

The handbook gives data for thermophysical properties of a number of gases: hydrogen, lithium, nitrogen, argon and steam; data are given at high temperatures and take into account the dissociation of the given gas. Data on thermophysical properties of vapors of lithium, sodium and potassium up to 2,000°K take into account the dimerization of these substances in the gaseous state. The book gives I-S [entropy-enthalpy] charts for these substances in the range of high temperatures.

In the compilation of this handbook, data reported in both monographic and periodical literature has been cited.

The author would like to express his appreciation to the entire faculty of the Department of Physics at the Moscow Institute of Aviation for their help in the preparation of this book.

Special thanks are due to Docent L. D. Volyak who arranged and correlated the data and compiled the tables on thermodynamic properties of potassium in the gas phase, to Assistant Yu. D. Vasilevskaya who worked on diffusion in binary mixtures, to V. V. Rybakov for thermodynamic properties of lithium at high temperatures in the gas phase. Candidate of Technical Sciences L. S. Zaytseva prepared the graphical presentation of thermodynamic properties of air at high temperatures.

The author is deeply grateful to Academician A. S. Predvoditelev and Candidate of Physical-Mathematical Sciences L. P. Filippov for their very valuable comments, and to E. I. Gaydul for great help in the preparation of the manuscript.

N. B. Vargaftik

CONTENTS

PART I
PURE SUBSTANCES

PART II
MIXTURES

USEFUL CONVERSION TABLES AND SYMBOLS

Dimensionless Groups

Group*	Symbol	Name
$\Delta p/\rho V^2$	Eu	Euler number
$\alpha t/r_0^2$	Fo	Fourier number
$(L/d)(k/Vd\rho c_p)$	Gz [= (L/d)/RePr]	Graetz number
$g\beta(\Delta T)L^3\rho^2/\mu^2$	Gr	Grashof number
λ/L	Kn	Knudsen number
α/D	Le	Lewis number
V/V_{sound}	Ma	Mach number
hL/k, hd/k	Nu	Nusselt number
$Vd\rho c_p/k$	Pe (= RePr)	Peclet number
$c_p\mu/k$	Pr	Prandtl number
$g\beta(\Delta T)L^3\rho^2 c_p/\mu k$	Ra (= GrPr)	Rayleigh number
$\rho VD/u$, $\rho VL/\mu$	Re	Reynolds number
$\mu/\rho D$	Sc	Schmidt number
$h_p d/D$	Sh	Sherwood number
$h/c_p G$	St (= Nu/RePr)	Stanton number
$V_\infty^2/C_p(\Delta T)_0$	E	Eckert number
V^2/gL	Fr	Froude number
$f_r d/V$	St	Strouhal number
$\rho V^2 L/\sigma$	We	Weber number

*f_r = frequency of oscillation
σ = surface tension.

Conversion Table

	To convert number of	To	Multiply by
Length	inch	cm	2.540
	ft	m	0.3048
Area	ft^2	m^2	0.0929
Volume	ft^3	m^3	0.02832
Mass	lbm	kg	0.45359
	Slugs	kg	14.594
Force	lbf	Newtons	4.4482
Density	lbm/ft^3	kg/m^3	16.02
Work	ft-lbf	mkg	0.1383
	hp-hr	mkg	273,700
Heat	Btu	kcal	0.2520
	Chu	Btu	1.800
	Btu	Joules	1054.35
	Btu	ft-lbf	778.26
	kw-hr	Btu	3412.75
Specific heat	Btu/lbm-°F	cal/gC	1.000
	Btu/lbm-°F	Wsec/kgmC	4184.0
Pressure	lbf/in^2, psi	kgf/cm^2	0.070309
	psi	atm	0.068046
	psi	bars	0.068948
	psi	$dynes/cm^2$	68947.0
Surface tension	lbf/ft	dynes/cm	6.8519×10^{-5}

Heat Flux, q/A

Multiply number of → by ↘ To obtain ↓	$\frac{Btu}{ft^2\text{-}hr}$	$\frac{W}{cm^2}$	$\frac{kcal}{hr\text{-}m^2}$	$\frac{cal}{sec\text{-}cm^2}$
Btu/ft^2-hr	1	3,170.75	0.36865	13,277.26
W/cm^2	3.154×10^{-4}	1	1.163×10^{-4}	4.1868
$kcal/hr\text{-}m^2$	2.7126	8,600	1	2.778×10^{-5}
$cal/sec\text{-}cm^2$	7.536×10^{-5}	0.2389	36,000	1

Heat Transfer Coefficient, h

Multiply number of → by ↘ To obtain ↓	$\frac{Btu}{hr\text{-}ft^2\text{-}°F}$	$\frac{W}{cm^2\text{-}°C}$	$\frac{cal}{sec\text{-}cm^2\text{-}°C}$	$\frac{kcal}{hr\text{-}m^2\text{-}°C}$
$Btu/hr\text{-}ft^2\text{-}°F$	1	1761	7376	0.20489
$W/cm^2\text{-}°C$	5.6785×10^{-4}	1	4.186	1.163×10^{-4}
$cal/sec\text{-}cm^2\text{-}°C$	1.356×10^{-4}	0.2391	1	2.778×10^{-5}
$kcal/hr\text{-}m^2\text{-}°C$	4.8826	8600	36000	1

Thermal Conductivity, k

Multiply number of → by ↘ To obtain ↓	$\frac{Btu}{hr\text{-}ft\text{-}°F}$	$\frac{W}{cm\text{-}°C}$	$\frac{cal}{sec\text{-}cm\text{-}°C}$	$\frac{kcal}{hr\text{-}m\text{-}°C}$	$\frac{Btu\ in}{hr\text{-}ft^2\text{-}°F}$
Btu/hr-ft-°F	1	57.793	241.9	0.6722	0.08333
W/cm-°C	0.01730	1	4.186	0.01171	1.442×10^{-3}
cal/sec-cm-°C	4.134×10^{-3}	0.2389	1	2.778×10^{-3}	3.445×10^{-4}
kcal/hr-m-°C	1.488	86.01	360	1	0.1240
Btu in./$hr\text{-}ft^2\text{-}°F$	12	693.5	2903	8.064	1

Viscosity, μ

Multiply number of → by ↘ To obtain ↓	$\frac{lbm}{ft\text{-}hr}$	$\frac{lbf\text{-}sec}{ft^2}$	Centipoise	$\frac{kgm}{m\text{-}hr}$	$\frac{kgf\text{-}sec}{m^2}$
lbm/ft-hr	1	116,000	2.42	0.672	23733
$lbf\text{-}sec/ft^2$	0.00000862	1	0.00002086	0.00000579	0.2048
Centipoise	0.413	47,880	1	0.278	9807
kgm/m-hr	1.49	172,000	3.60	1	35305
$kgf\text{-}sec/m^2$	0.0000421	4.882	0.0001020	0.0000284	1

100 centipoise = 1 Poise = 1g/sec-cm = 1 dyne sec/cm^2.

Kinematic Viscosity, υ

Multiply number of → by ↘ To obtain ↓	$\frac{ft^2}{hr}$	Stokes	$\frac{m^2}{hr}$	$\frac{m^2}{sec}$
ft^2/hr	1	3.875	10.764	38,751
Stokes	0.25806	1	2.778	10^4
m^2/hr	0.092903	0.3599	1	3600
m^2/sec	0.00002581	10^{-4}	0.0002778	1

Conversion Factors

The following tables of conversion factors are convenient. In order to convert the numerical value of a property expressed in one of the units in the left-hand column of the table to the numerical value of the same property expressed in one of the units in the tow row of the table, multiply the former vvalue by the factor in the block common to both units.

In tables involving energy, *cal* denotes the thermochemical calorie; *IT cal* denotes the International Steam Table calorie. The thermochemical calorie (cal) equals 4.184 joule. The International Steam Table calorie (IT cal) equals 4.186 joule. The Btu is the International Steam Table Btu and it equals 1055.04 joule.

Conversion Factors for Mass

	lbm	slugs	gm	kg	ton
1 lbm =	1	0.03108	453.59	0.45359	0.0005
1 slug =	32.174	1	1.4594×10^4	14.594	0.016087
1 gm =	2.2046×10^{-3}	6.8521×10^{-5}	1	10^{-3}	1.1023×10^{-6}
1 kg =	2.2046	6.8521×10^{-3}	10^3	1	1.1023×10^{-3}
1 ton =	2000	61.162	9.0718×10^5	907.18	1

SOURCE: Modified and extended from "Selected Values of Properties of Hydrocarbons," National Bureau of Standards.

Conversion Factors for Density

	lbm/ft³	slug/ft³	lbm/in.³	lbm/gal	gm/cc
1 lbm/ft^3 =	1	0.03108	5.787×10^{-4}	0.13368	0.01602
1 $slug/ft^3$ =	32.174	1	0.1862	4.3010	0.51543
1 $lbm/in.^3$ =	1728	53.706	1	231	27.680
1 lbm/gal =	7.4805	0.2325	4.329×10^{-3}	1	0.11983
1 gm/cc =	62.428	1.9403	0.03613	8.345	1

SOURCE: Modified and extended from "Selected Values of Properties of Hydrocarbons," National Bureau of Standards.

Conversion Factors for Pressure

	lbf/ft^2	lbf/in.^{2}	atm	in. Hg	in. H_2O	mm Hg	bar
1 lbf/ft^2 =	1	0.006944	4.726×10^{-4}	0.014139	0.19243	0.3591	4.788×10^{-4}
1 lbf/in.^{2} =	144	1	0.06805	2.036	27.71	51.715	0.06895
1 atm =	2116.2	14.696	1	29.921	407.18	760	1.01325
1 in. Hg =	70.726	0.49116	0.033421	1	13.608	25.40	0.03386
1 in. H_2O =	5.197	0.036092	0.002456	0.07348	1	1.8665	0.002488
1 mm Hg =	2.7845	0.019337	1.315×10^{-3}	0.03937	0.53577	1	1.333×10^{-3}
1 mm H_2O =	2.0886×10^4	14.504	0.98692	29.530	401.85	750.06	1

Conversion Factors for Energy

	abs joule	cal	IT cal	Btu	int. kw-hr	hp-hr	ft-lb	liter-atm
1 abs joule =	1	0.239005	0.238848	0.947827×10^{-3}	2.77731×10^{-7}	3.72505×10^{-7}	0.737561	9.86896×10^{-3}
1 cal =	4.18401	1	0.999344	3.96572×10^{-3}	1.162028×10^{-6}	1.558566×10^{-6}	3.08596	4.12918×10^{-2}
1 IT cal =	4.18676	1.000657	1	3.96832×10^{-3}	1.162791×10^{-6}	1.559590×10^{-6}	3.08799	4.13189×10^{-2}
1 Btu =	1055.045	252.161	251.996	1	2.93018×10^{-4}	3.93010×10^{-4}	778.16	10.41220
1 int. kw-hr =	3,600,612	860,565	860,000	3412.76	1	1.341247	2,655,669	35534.3
1 hp-hr =	2,684,525	641.615	641.194	2544.46	0.745575	1	1,980,000	26493.5
1 ft-lb =	1.355821	0.324048	0.323836	1.285083×10^{-3}	3.76553×10^{-7}	5.05051×10^{-7}	1	1.338054×10^{-2}
1 liter-atm =	101.3278	24.2179	24.2020	0.0960412	2.81418×10^{-5}	3.77452×10^{-5}	74.7354	1

Conversion Factors for Specific Energy

	abs joule/gm	cal/gm	IT cal/gm	Btu/lb	ft-lbf/lbm	int. kw-hr/gm	hp-hr/lb	ft^2/sec^2
abs joule/gm =	1	0.2390	0.2388	0.4299	334.53	2.777×10^{-7}	1.690×10^{-4}	10763
cal/gm =	4.184	1	0.9993	1.7988	1399.75	1.162×10^{-6}	7.069×10^{-4}	4.504×10^4
IT cal/gm =	4.186	1.0007	1	1.8	1400.69	1.163×10^{-6}	7.074×10^{-4}	4.506×10^4
Btu/lb =	2.326	0.5559	0.5556	1	778.16	6.460×10^{-7}	3.930×10^{-4}	25,037
ft-lbf/lbm =	2.989×10^{-3}	7.144×10^{-4}	7.139×10^{-4}	1.285×10^{-3}	1	8.302×10^{-10}	5.051×10^{-7}	32.174
int. kw-hr/gm =	3.610×10^6	860,565	860,000	1.548×10^6	1.2046×10^9	1	608.4	3.876×10^{10}
hp-hr/lb =	5919	1414.5	1413.6	2545	1.980×10^6	0.001644	1	6.370×10^7
ft^2/sec^2 =	9.291×10^{-5}	2.220×10^{-5}	2.219×10^{-5}	3.994×10^{-5}	0.03108	2.580×10^{-11}	1.567×10^{-8}	1

Conversion Factors for Specific Energy per Degree

	abs joule/gm-°K	cal/gm-°K	IT cal/gm-°K	Btu/lb-°R	w-sec/kg-°K
abs joule/gm-°K =	1	0.2390	0.2388	0.2388	10^3
cal/gm-°K =	4.184	1	0.9993	0.9993	4184
IT cal/gm-°K =	4.186	1.0007	1	1	4186
Btu/lb-°R =	4.186	1.0007	1	1	4186
w-sec/kg-°K =	10^{-3}	2.390×10^{-4}	2.388×10^{-4}	2.388×10^{-4}	1

Conversion Factors for Thermal Conductivity

	cal/sec-cm-°C	Btu/hr-ft-°F	Btu/hr-ft^2-°F/in.	w/cm-°C
1 cal/sec-cm-°C =	1	241.9	2903	4.183
1 Btu/hr-ft-°F =	4.13×10^{-3}	1	12	0.0173
1 Btu/hr-ft^2-°F/in.=	3.45×10^{-4}	0.0833	1	1.44×10^{-3}
1 w/cm^2-°C =	0.239	57.8	694	1

Conversion Factors for Dynamic Viscosity

	poise or g/cm-sec, or dyn-sec/cm^2	lbm/ft-hr or pdl-hr/ft^2	lbm/ft-sec or pdl-sec/ft^2
1 poise =	1	242	0.0672
1 lbm/ft-hr =	4.13×10^{-3}	1	2.78×10^{-4}
1 lbm/ft-sec =	14.87	3600	1

Conversion Factors for Kinematic Viscosity

	ft^2/hr	stokes	m^2/hr	m^2/sec
ft^2/hr =	1	0.25806	0.092903	2.58×10^{-5}
stokes =	3.885	1	0.36	10^{-4}
m^2/hr =	10.764	2.778	1	2.778×10^{-4}
m^2/sec =	38,750	10^4	3600	1

CONVERSION OF UNITS FROM SI TO OTHER SYSTEMS

Quantity	Symbol	Units, in SI	Units, in other systems	To convert from SI to other system, multiply by
Pressure	P	N/m^2	$dyne/cm^2$	10
			bar	10^{-5}
			atm (phys)	$0.9869 \cdot 10^{-5}$
		$bar = 10^5\ N/m^2$	atm (phys)	0.9869
			kg/cm^2 (atm. abs)	1.0197
			mm Hg	750
Density	ϱ	kg/m^3	g/cm^3	10^{-3}
Specific volume	V	m^3/kg	cm^3/g	10^3
Heat capacity	C	kJ/kg · deg	Kcal/kg · deg	0.2388
Enthalpy	i	kJ/kg	Kcal/kg	0.2388
Entropy	S	kJ/kg · deg	Kcal/kg · deg	0.2388
Latent heat of vaporization	r	kJ/kg	Kcal/kg	0.2388
Thermal conductivity	λ	W/m · deg	cal/cm · s · deg	$2.388 \cdot 10^{-3}$
			Kcal/m · hr · deg	0.86
Viscosity	η	$N \cdot s/m^2$ (kg/m ·)		
			g/cm · s (poise)	10
			$kg \cdot s/m^2$	0.102
Kinematic viscosity	$\nu = \frac{\eta}{\varrho}$	m^2/s	cm^2/s (stokes)	10^4
Surface tension	δ	N/m	dyne/cm (erg/cm^2)	10^3

NOTATION

a — thermal diffusivity
C_p, c_p — heat capacity at constant pressure
C_v — heat capacity at constant volume
D — diffusion coefficient
I, i — enthalpy
K_T — thermodiffusion ratio
p — pressure
Pr — prandtl number
q — heat of melting
R, r — heat of vaporization
r_i, X_i — volumetric component fractions in a gas mixture
S, s — entropy
u — velocity of sound
V — specific volume
z — compressibility factor (pV/RT)
α — volumetric expansion coefficient $\left(\frac{1}{V}\frac{\delta V}{\delta T}\right)_p$
β — coefficient of thermal compressibility $\left(-\frac{1}{V}\frac{\delta V}{\delta p}\right)_T$
η — viscosity
λ — thermal conductivity
$\Delta\lambda$ — coefficient of thermodiffusional separation of the gas mixture
ν — kinematic viscosity
ϱ — density
σ — surface tension, electrical conductivity

Subscript *cr* and superscript *o* refer, respectively, to critical and ideal states of the gas. A prime and a double prime refer, respectively, to liquid and vapor at saturation. In all tables a horizontal line indicates the separation of liquid and vapor states.