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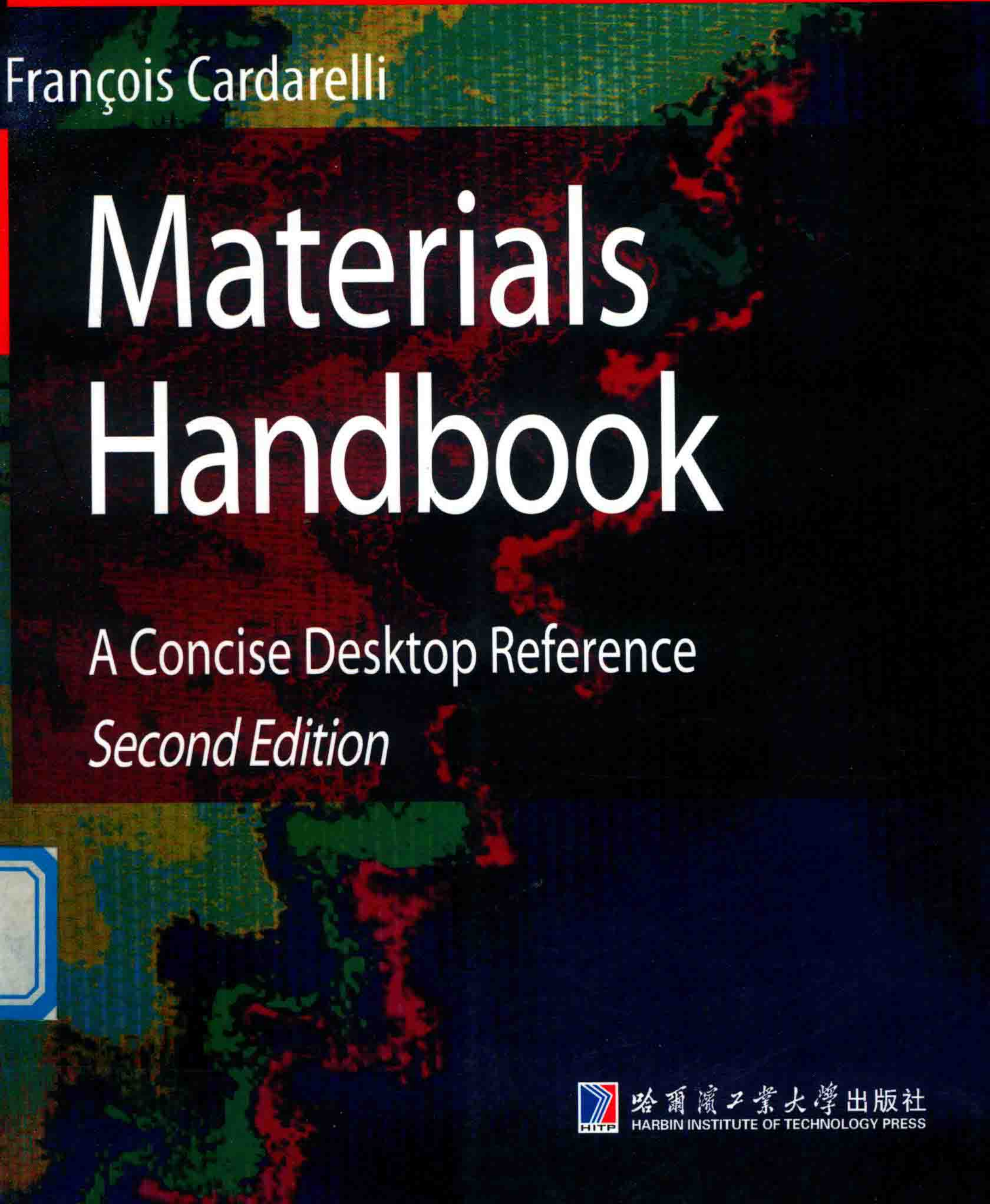

François Cardarelli

Materials Handbook

A Concise Desktop Reference

Second Edition

哈爾濱工業大學出版社
HARBIN INSTITUTE OF TECHNOLOGY PRESS

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原版影印说明

《材料手册》（8册）是 Springer ***Materials Handbook*** *A Concise Desktop Reference*（2nd Edition）的影印版。为使用方便，由原版1卷分为8册：

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8 气体 液体

本手册提供各种材料的物理和化学性质，是一本简洁的手边工具书。第二版与第一版的差别是扩充了新的家用材料，但重点是每一类常见的工业材料。

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François Cardarelli

Materials Handbook

A Concise Desktop Reference

2nd Edition

Springer

Dedication for the First Edition

The ***Materials Handbook*: *A Concise Desktop Reference*** is dedicated to my father, Antonio, and my mother, Claudine, to my sister, Elsa, and to my spouse Louise Saint-Amour for their love and support. I want also to express my thanks to my two parents and my uncle Consalvo Cardarelli, which in close collaboration have provided valuable financial support when I was a teenager to contribute to my first fully equipped geological and chemical laboratory and to my personal comprehensive scientific library. This was the starting point of my strong and extensive interest in both science and technology, and excessive consumption of scientific and technical literature.

François Cardarelli

Dedication for the Second Edition

The ***Materials Handbook: A Concise Desktop Reference*** is dedicated to my father, Antonio, and my mother, Claudine, to my sister, Elsa, and to my wife Elizabeth I.R. Cardarelli for their love and support. I want also to express my thanks to my two parents and my uncle Consalvo Cardarelli, which in close collaboration have provided valuable financial support when I was a teenager to contribute to my first fully equipped geological and chemical laboratory and to my personal comprehensive scientific library. This was the starting point of my strong and extensive interest in both science and technology, and excessive consumption of scientific and technical literature.

François Cardarelli

Acknowledgements for the First Edition

Mr. Nicholas Pinfield (engineering editor, London), Mr. Jean-Étienne Mittelmann (editor,Paris), Mrs. Alison Jackson (editorial assistant, London), and Mr. Nicolas Wilson (senior production controller, London) are gratefully acknowledged for their valued assistance,patience, and advice.

Acknowledgements for the Second Edition

Mr. Anthony Doyle (senior engineering editor), Mr. Oliver Jackson (associate engineering editor), and Mr. Nicolas Wilson (editorial coordinator) are gratefully acknowledged for their valued assistance, patience, and advice.

Units Policy

In this book the only units of measure used for describing physical quantities and properties of materials are those recommended by the *Système International d'Unités* (SI). For accurate conversion factors between these units and the other non-SI units (e.g., cgs, fps, Imperial, and US customary), please refer to the reference book by the same author:

Cardarelli, F. (2005) *Encyclopaedia of Scientific Units, Weights, and Measures. Their SI Equivalences and Origins*. Springer, London New York. ISBN 978-1-85233-682-1.

Author Biography

Dr. François Cardarelli (Ph.D.)
Born in Paris (France) February 17, 1966
Canadian citizen

Academic Background

- Ph.D., chemical engineering (Université Paul Sabatier, Toulouse, France, 1996)
- Postgraduate degree (DEA) in electrochemistry (Université Pierre et Marie Curie, Paris, 1992)
- M.Sc. (Maîtrise), physical chemistry (Université Pierre et Marie Curie, Paris, 1991)
- B.Sc. (Licence), physical chemistry (Université Pierre et Marie Curie, Paris, 1990)
- DEST credits in nuclear sciences and technologies (Conservatoire National des Arts et Métiers, Paris, 1988)

- Associate degree (DEUG B) in geophysics and geology (Université Pierre et Marie Curie, Paris, 1987)
- Baccalaureate C (mathematics, physics, and chemistry) (CNED, Versailles, France, 1985)

Fields of Professional Activity

The author has worked in the following areas (in chronological order) since 1990.

(1) Research scientist at the Laboratory of Electrochemistry (Université Pierre & Marie Curie, Paris, France) for the development of a nuclear detector device for electrochemical experiments involving radiolabeled compounds;

(2) research scientist at the Institute of Marine Biogeochemistry (CNRS & École Normale Supérieure, Paris, France) for the environmental monitoring of heavy-metal pollution by electroanalytical techniques;

(3) research scientist for the preparation by electrochemistry in molten salts of tantalum protective thin coatings for the chemical-process industries (sponsored by Electricité de France);

(4) research scientist for the preparation and characterization of iridium-based industrial electrodes for oxygen evolution in acidic media at the Laboratory of Electrochemical Engineering (Université Paul Sabatier, Toulouse, France);

(5) registered consultant in chemical and electrochemical engineering (Toulouse, France);

(6) battery product leader in the technology department of ARGOTECH Productions, Boucherville (Québec), Canada, in charge of electric-vehicle, stationary, and oil-drilling applications of lithium polymer batteries;

(7) materials expert and industrial electrochemist in the lithium department of ARGOTECH Productions, involved in both the metallurgy and processing of lithium metal anodes and the recycling of spent lithium polymer batteries;

(8) materials expert and industrial electrochemist in the technology department of AVESTOR, Boucherville (Quebec), Canada, in charge of all strategic raw materials entering into the fabrication of lithium polymer batteries, as well as being in charge of the recycling process of spent lithium batteries;

(9) principal chemist, materials, in the technology department of RIO TINTO Iron and Titanium, Sorel–Tracy (Québec), Canada working on the electrowinning of titanium metal from titania-rich slags and on other novel electrochemical processes;

(10) principal electrochemist at Materials and Electrochemical Research (MER) Corp., Tuscon (Arizona, USA) working on the electrowinning of titanium metal powder from composite anodes and other materials related projects.

Introduction

Despite the wide availability of several comprehensive series in materials sciences and metallurgy, it is difficult to find grouped properties either on metals and alloys, traditional and advanced ceramics, refractories, polymers and elastomers, composites, minerals and rocks, soils, woods, cement, and building materials in a single-volume source book.

Actually, the purpose of this practical and concise reference book is to provide key scientific and technical materials properties and data to materials scientists, metallurgists, engineers, chemists, and physicists as well as to professors, technicians, and students working in a broad range of scientific and technical fields.

The classes of materials described in this handbook are as follows:

(i) metals and their alloys;
(ii) semiconductors;
(iii) superconductors;
(iv) magnetic materials;
(v) dielectrics and insulators;
(vi) miscellaneous electrical materials (e.g., resistors, thermocouples, and industrial electrode materials);
(vii) ceramics, refractories, and glasses;
(viii) polymers and elastomers;
(ix) minerals, ores, and gemstones;
(x) rocks and meteorites;
(xi) soils and fertilizers;
(xii) timbers and woods;
(xiii) cement and concrete;
(xiv) building materials;
(xv) fuels, propellants, and explosives;

(xvi) composites;
(xvii) gases;
(xviii) liquids.

Particular emphasis is placed on the properties of the most common industrial materials in each class. The physical and chemical properties usually listed for each material are as follows:

(i) physical (e.g., density, viscosity, surface tension);
(ii) mechanical (e.g., elastic moduli, Poisson's ratio, yield and tensile strength, hardness, fracture toughness);
(iii) thermal (e.g., melting and boiling point, thermal conductivity, specific heat capacity, coefficients of thermal expansion, spectral emissivities);
(iv) electrical (e.g., resistivity, relative permittivity, loss tangent factor);
(v) magnetic (e.g., magnetization, permeability, retentivity, coercivity, Hall constant);
(vi) optical (e.g., refractive indices, reflective index, dispersion, transmittance);
(vii) electrochemical (e.g., Nernst standard electrode potential, Tafel slopes, specific capacity, overpotential);
(viii) miscellaneous (e.g., relative abundances, electron work function, thermal neutron cross section, Richardson constant, activity, corrosion rate, flammability limits).

Finally, detailed appendices provide additional information (e.g., properties of the pure chemical elements, thermochemical data, crystallographic calculations, radioactivity calculations, prices of metals, industrial minerals and commodities), and an extensive bibliography completes this comprehensive guide. The comprehensive index and handy format of the book enable the reader to locate and extract the relevant information quickly and easily. Charts and tables are all referenced, and tabs are used to denote the different sections of the book. It must be emphasized that the information presented here is taken from several scientific and technical sources and has been meticulously checked and every care has been taken to select the most reliable data.

Contents

19

Gases

19.1 Properties of Gases

The state of a gas is defined by the values of its volume (V), its absolute thermodynamic temperature (T), its absolute pressure (P) and the amount of substance or number of moles (n). An equation of state is a mathematical relationship between these four physical quantities: $f = (P, V, T, n)$. The equation is obtained from knowledge of the experimental behavior of a system.

Ideal gases. The ideal gas assumption is an ideal state, where the size of the microscopic entities (i.e., atoms or molecules) constitutive of the gas is negligible and the interatomic or intermolecular forces existing between them are neglected in a first approximation. Therefore, the ideal gas assumption is suitable for assessing properties of common gases under low pressure or at high temperature.

Real gases. In real gases, non-ideality arises from either atomic or molecular size or intermolecular interactions caused by electrostatic attraction or repulsion (i.e., Coulomb's forces). The departure from ideal behavior of a gas is particularly noticeable under high pressure or at cryogenic temperatures. Under high pressure, the volume occupied by the atoms or molecules of gas is no longer negligible compared with the overall volume and electrostatic attractions are more important so the equation of state of the actual gas must take additional parameters into account.

19.1.1 Pressure

The pressure of a fluid (e.g., liquid, gas) is a scalar physical quantity, denoted P, and is expressed in the SI in pascals (Pa), corresponding to the force F expressed in newtons (N), exerted uniformly onto a surface having cross-sectional area *A* expressed in square meters (m^2) according to the following equation:

$$P = F/A$$

Important notes

(i) Pressure is an intensive quantity, that is, it does not depend on the size of the system (i.e., volume, mass, etc.).

(ii) The pressure is a scalar quantity by contrast with the stress which is a tensor.

(iii) For an ideal fluid, i.e., without viscosity and incompressible (i.e., a constant mass density), the forces exerted onto the wall of a container are normal (i.e., orthogonal) to the surface. Actually, if the forces were not normal, they could be decomposed into two vectors

   (1) a normal component; and

   (2) a tangential component.

   Under the tangential force, the liquid would move alone along the wall.

As discussed previously the pressure is a scalar physical quantity with the following dimensional equation: $[P] = [ML^{-1}T^{-2}]$. In the *Système International d'unités* (SI), the pressure unit is a derived unit having a special name pascal[1], with the symbol Pa, hence 1 Pa = $1 N.m^{-2}$ = $1 kg.m^{-1}.s^{-2}$. However, there also exist several obsolete units of pressure relative to different systems or used in particular scientific, and technical fields. Although these obsolete units should be discontinued their remanence exists for practical uses and they are listed in Table 19.1.

Table 19.1. Non-SI units of pressure listed by alphabetical order

Pressure unit	System	SI conversion factor
atmosphere (standard)	–	1 atm =101,325 Pa (E)
atmosphere (technical)	metric	1 at = 10^5 Pa (E)
bar	metric technical system	1 bar =10^5 Pa (E)
barye	cgs	1 barye = 1 μbar (E) = 1 dyne/cm^2 (E) = 10^{-1} Pa (E)
foot of water (39.2°F)	FPS	1 ftH_2O (4°C) = 2.988983226×10^3 Pa
inch of mercury (32°F)	UK, US	1 in Hg (0°C) = 3.38638816×10^3 Pa
kilogram-force per square centimeter	MKpS	1 $kg_f/cm^2 = 9.80665 \times 10^4$ Pa (E)
meter of water (4°C)	metric	1 mH_2O (4°C) = 9.8063754×10^3 Pa
millimeter of mercury (0°C) centimeter of mercury (0°C)	obsolete	1 mmHg (0°C) = 133.322368421 Pa 1 cmHg (0°C) = 1333.22368421 Pa
ounce-force per square inch (osi)	UK, US	1 oz_f/in^2 = 430.922330823 Pa
pièze (pz)	MTS	1 Pz = 1 sthène/m^2 (E) = 10^3 Pa (E)
pound-force per square inch (psi)	US, UK technical system	1 lb_f/in^2 = 1 psi (E) = $6.89475729317 \times 10^3$Pa
poundal per square foot (pdsf)	FPS	1 pdl/ft^2 = 1 pdsf (E) = 1.4881639437 Pa
torr[2] (Torr)	obsolete	1 Torr = 1 mmHg (0°C) (E) = 133.322368421 Pa

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[1] Unit name after the French mathematician, physicist and scientist Blaise Pascal [Clermont-Ferrand (1623), Paris (1662)].

[2] Named after the Italian scientist Evangelista Torricelli (1608–1647).

Table 19.2. Pressure of the standard atmosphere in numerous practical units

1 atm	= 101,325 kg.m^{-1}.s^{-1} (E) = 101,325 Pa (E) = 101,325 N.m^{-2} (E) = 101,325 J.m^{-3} (E).
	= 1.01325 bar = 1013.25 mbar = 1.01325 × 10^6 μbar = 1.01325 × 10^6 barye
	= 101.325 pz (E) = 1.01325 hpz (E)
	= 1.033227453 kg$_f$.cm^{-2}
	= 760 Torr (E) = 760 mmHg(0°C) (E) = 76 cmHg(0°C) (E) = 29.9212598425 in Hg (32°F)
	= 10.33256384 mH$_2$O (4°C) = 33.89948766 ftH$_2$O (39.2°F) = 406.793852 inH$_2$O (32°F)
	= 14.69594878 psi$_a$ = 235.135180 osi$_a$

However, the best way to remember all these numerous conversion factors is to remember the exact value of the standard atmosphere in all these units or the relationships between them, as listed in Table 19.2.

19.1.2 The Boyle–Mariotte Law

For a fixed mass of gas under isothermal (i.e., constant temperature) conditions, the product of absolute pressure, p times the volume, V, occupied by the gas is a constant. The constant increases with increasing temperature.

$$PV = P_1V_1 = P_2V_2 = \ldots = P_kV_k = \ldots = P_nV_n = \text{constant}$$

Therefore, in a PV diagram they form hyperbolic curves (see Figure 19.1)

Example: A commercial gas cylinder supplied by a gas manufacturer contains a volume $V = 10$ liters of compressed gas at a pressure $P = 200$ bar. What is the total volume of gas that can be delivered under atmospheric pressure? Since 1 bar = 10^5 Pa (E) and $P_{\text{atm}} = 101.325$ kPa, the volume delivered in cubic decimeters is then $V_{\text{atm}} = PV/P_{\text{atm}} = [(2 \times 10^7 \times 10)/101{,}325]$ m^3 = 1974 dm^3.

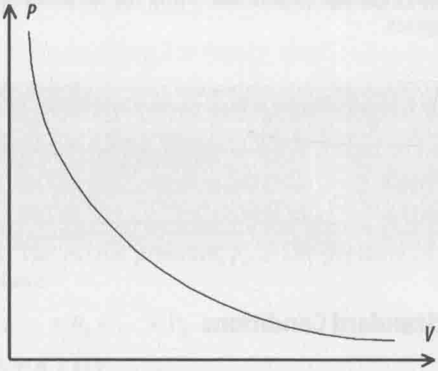

Figure 19.1. PV diagram

19.1.3 Charles and Gay-Lussac's Law

For a given mass of gas under isobaric (i.e., constant pressure) conditions, the ratio of the volume occupied by the gas to the absolute thermodynamic temperature is a constant (see Figure 19.2). This constant changes with changing pressure

$$V/T = V_1/T_1 = V_2/T_2 = \dots = V_k/T_k = \dots = V_n/T_n = \text{constant}$$

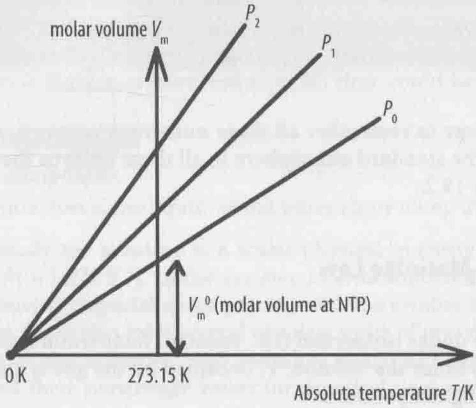

Figure 19.2. VT diagram

19.1.4 The Avogadro–Ampere Law

Under isothermal and isobaric conditions (i.e., at constant T and P), equal volumes of gases contain equal numbers of atoms or molecules.

The proportionality constant is independent of the identity of the gas. Some examples of molar volumes of an ideal gas at various T and P conditions are presented in Table 19.3.

One important practical consequence is that mole fraction and volume fraction are identical quantities for ideal gases.

Table 19.3. Molar volumes of ideal gas vs. T and P ($/10^{-3}\ m^3.mol^{-1}$)

	$P_0 = 101.325$ kPa	$P_0 = 1$ bar
$T = 273.15$ K	22.4135	22.7105
$T = 298.15$ K	24.4649	24.7891

19.1.5 Normal and Standard Conditions

Since the properties of gases strongly depend on both pressure and temperature, it is important to define standardized conditions of T and P. Unfortunately there is a great variety of adopted conventions, academic, industrial and even commercial. In both theory and practice, the conditions recommended by the *International Union of Pure and Applied Chemistry*