

MECHANICAL ENGINEERS' HANDBOOK

Volume

Energy and Power »

4

MYER KUTZ EDITOR

FOURTH EDITION

WILEY

Mechanical Engineers' Handbook

Fourth Edition

Energy and Power

Edited by
Myer Kutz

WILEY

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Mechanical Engineers' Handbook

To Arthur and Bess, Tony and Mary-Ann, for all the good times

Preface

The fourth volume of the fourth edition of the *Mechanical Engineers' Handbook* comprises 32 chapters divided into two parts, the first on energy and the second on power. Part 1 begins with a chapter on thermophysical properties of fluids, then proceeds to cover fundamentals of mechanics of incompressible fluids, thermodynamics (including a chapter on exergy and entropy generation minimization), heat transfer, and temperature and heat flux measurements. Additional heat transfer topics in this volume include heat exchangers, heat pipes, air heating, and electronic equipment cooling. There are chapters on refrigeration and cryogenic engineering. One chapter deals with environmental issues: indoor environmental control. A chapter on thermal systems optimization rounds out this part of this volume.

Part 2 opens with a chapter on combustion. This part also includes chapters on conventional energy sources—gaseous and liquid fuels and coal (one chapter on properties of coals, lignite, and peat and a second chapter on clean power generation from coal)—and alternative energy sources—biofuels, solar, geothermal and fuel cells. There are, in addition, chapters on cogeneration and hydrogen energy. There are six chapters on power machinery: one on fans, blowers, compressors, and pumps; one each on gas, wind, and steam turbines; one on internal combustion engines and one on fluid power.

Two chapters—on cryogenic engineering and steam turbines—replace the old versions of the chapters on these important topics. To provide greater emphasis on sustainability than in earlier editions, I have included four chapters—on clean power generation from coal, wind power generation, cogeneration, and hydrogen energy—from my book, *Environmentally Conscious Alternative Energy Production* (chapters updated as contributors found necessary) and one chapter on biofuels from *Environmentally Conscious Transportation*. I have also included three chapters—on temperature, heat flux, and solar energy measurements—from my *Handbook of Measurement in Science and Engineering* and one on mechanics of incompressible fluids from the current edition of *Eshbach's Handbook of Engineering Fundamentals*, which I edited. Inclusion of these chapters enriches this handbook. All told, more than half the chapters in this volume contain material new to this handbook.

Vision for the Fourth Edition

Basic engineering disciplines are not static, no matter how old and well established they are. The field of mechanical engineering is no exception. Movement within this broadly based discipline is multidimensional. Even the classic subjects, on which the discipline was founded, such as mechanics of materials and heat transfer, keep evolving. Mechanical engineers continue to be heavily involved with disciplines allied to mechanical engineering, such as industrial and manufacturing engineering, which are also constantly evolving. Advances in other major disciplines, such as electrical and electronics engineering, have significant impact on the work of mechanical engineers. New subject areas, such as neural networks, suddenly become all the rage.

In response to this exciting, dynamic atmosphere, the Mechanical Engineers' Handbook expanded dramatically, from one to four volumes for the third edition, published in November 2005. It not only incorporated updates and revisions to chapters in the second edition, published seven years earlier, but also added 24 chapters on entirely new subjects, with updates and revisions to chapters in the Handbook of Materials Selection, published in 2002, as well as to chapters in Instrumentation and Control, edited by Chester Nachtigal and published in 1990, but never updated by him.

The fourth edition retains the four-volume format, but there are several additional major changes. The second part of Volume I is now devoted entirely to topics in engineering mechanics, with the addition of five practical chapters on measurements from the Handbook of Measurement in Science and Engineering, published in 2013, and a chapter from the fifth edition of Eshbach's Handbook of Engineering Fundamentals, published in 2009. Chapters on mechanical design have been moved from Volume I to Volumes II and III. They have been augmented with four chapters (updated as needed) from Environmentally Conscious Mechanical Design, published in 2007. These chapters, together with five chapters (updated as needed, three from Environmentally Conscious Manufacturing, published in 2007, and two from Environmentally Conscious Materials Handling, published in 2009) in the beefed-up manufacturing section of Volume III, give the handbook greater and practical emphasis on the vital issue of sustainability.

Prefaces to the handbook's individual volumes provide further details on chapter additions, updates and replacements. The four volumes of the fourth edition are arranged as follows:

Volume 1: Materials and Engineering Mechanics—27 chapters

Part 1. Materials—15 chapters

Part 2. Engineering Mechanics—12 chapters

Volume 2: Design, Instrumentation and Controls—25 chapters

Part 1. Mechanical Design—14 chapters

Part 2. Instrumentation, Systems, Controls, and MEMS —11 chapters

Volume 3: Manufacturing and Management—28 chapters

Part 1. Manufacturing—16 chapters

Part 2. Management, Finance, Quality, Law, and Research—12 chapters

Volume 4: Energy and Power—35 chapters

Part 1: Energy—16 chapters

Part 2: Power—19 chapters

The mechanical engineering literature is extensive and has been so for a considerable period of time. Many textbooks, reference works, and manuals as well as a substantial number of journals exist. Numerous commercial publishers and professional societies, particularly in the United States and Europe, distribute these materials. The literature grows continuously, as applied mechanical engineering research finds new ways of designing, controlling, measuring, making, and maintaining things, as well as monitoring and evaluating technologies, infrastructures, and systems.

Most professional-level mechanical engineering publications tend to be specialized, directed to the specific needs of particular groups of practitioners. Overall, however, the mechanical engineering audience is broad and multidisciplinary. Practitioners work in a variety of organizations, including institutions of higher learning, design, manufacturing, and consulting firms, as well as federal, state, and local government agencies. A rationale for a general mechanical engineering handbook is that every practitioner, researcher, and bureaucrat cannot be an expert on every topic, especially in so broad and multidisciplinary a field, and may need an authoritative professional summary of a subject with which he or she is not intimately familiar.

Starting with the first edition, published in 1986, my intention has always been that the Mechanical Engineers' Handbook stand at the intersection of textbooks, research papers, and design manuals. For example, I want the handbook to help young engineers move from the college classroom to the professional office and laboratory where they may have to deal with issues and problems in areas they have not studied extensively in school.

With this fourth edition, I have continued to produce a practical reference for the mechanical engineer who is seeking to answer a question, solve a problem, reduce a cost, or improve a system or facility. The handbook is not a research monograph. Its chapters offer design techniques, illustrate successful applications, or provide guidelines to improving performance, life expectancy, effectiveness, or usefulness of parts, assemblies, and systems. The purpose is to show readers what options are available in a particular situation and which option they might choose to solve problems at hand.

The aim of this handbook is to serve as a source of practical advice to readers. I hope that the handbook will be the first information resource a practicing engineer consults when faced with a new problem or opportunity—even before turning to other print sources, even officially sanctioned ones, or to sites on the Internet. In each chapter, the reader should feel that he or she is in the hands of an experienced consultant who is providing sensible advice that can lead to beneficial action and results.

Can a single handbook, even spread out over four volumes, cover this broad, interdisciplinary field? I have designed the Mechanical Engineers' Handbook as if it were serving as a core for an Internet-based information source. Many chapters in the handbook point readers to information sources on the Web dealing with the subjects addressed. Furthermore, where appropriate, enough analytical techniques and data are provided to allow the reader to employ a preliminary approach to solving problems.

The contributors have written, to the extent their backgrounds and capabilities make possible, in a style that reflects practical discussion informed by real-world experience. I would like readers to feel that they are in the presence of experienced teachers and consultants who know about the multiplicity of technical issues that impinge on any topic within mechanical engineering. At the same time, the level is such that students and recent graduates can find the handbook as accessible as experienced engineers.

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PART 1

ENERGY

CHAPTER 1

THERMOPHYSICAL PROPERTIES OF FLUIDS

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In this chapter, information is usually presented in the System International des Unités, called in English the International System of Units and abbreviated SI. Various tables of conversion factors from other unit systems into the SI system and vice versa are available. The following table is intended to enable rapid conversion to be made with moderate, that is, five significant figure, accuracy, usually acceptable in most engineering calculations. The references listed should be consulted for more exact conversions and definitions.

Table 1 Conversion Factors

| |
|--|
| Density: $1 \text{ kg/m}^3 = 0.06243 \text{ lb}_m/\text{ft}^3 = 0.01002 \text{ lb}_m/\text{U.K. gallon} = 8.3454 \times 10^{-3} \text{ lb}_m/\text{U.S. gallon} = 1.9403 \times 10^{-3} \text{ slug/ft}^3 = 10^{-3} \text{ g/cm}^3$ |
| Energy: $1 \text{ kJ} = 737.56 \text{ ft} \cdot \text{lb}_f = 239.01 \text{ cal}_{\text{th}} = 0.94783 \text{ Btu} = 3.7251 \times 10^{-4} \text{ hp h} = 2.7778 \times 10^{-4} \text{ kWh}$ |
| Specific energy: $1 \text{ kJ/kg} = 334.54 \text{ ft} \cdot \text{lb}_f/\text{lb}_m = 0.4299 \text{ Btu/lb}_m = 0.2388 \text{ cal/g}$ |
| Specific energy per degree: $1 \text{ kJ/kg} \cdot \text{K} = 0.23901 \text{ Btu}_{\text{th}}/\text{lb} \cdot ^\circ\text{F} = 0.23901 \text{ cal}_{\text{th}}/\text{g} \cdot ^\circ\text{C}$ |
| Mass: $1 \text{ kg} = 2.20462 \text{ lb}_m = 0.06852 \text{ slug} = 1.1023 \times 10^{-3} \text{ U.S. ton} = 10^{-3} \text{ tonne} = 9.8421 \times 10^{-4} \text{ U.K. ton}$ |
| Pressure: $1 \text{ bar} = 10^5 \text{ N/m}^2 = 10^5 \text{ Pa} = 750.06 \text{ mm Hg at } 0^\circ\text{C} = 401.47 \text{ in. H}_2\text{O at } 32^\circ\text{F} = 29.530 \text{ in. Hg at } 0^\circ\text{C} = 14.504 \text{ lb/in.}^2 = 14.504 \text{ psia} = 1.01972 \text{ kg/cm}^2 = 0.98692 \text{ atm} = 0.1 \text{ MPa}$ |
| Temperature: $T(\text{K}) = T(^{\circ}\text{C}) + 273.15 = [T(^{\circ}\text{F}) + 459.69]/1.8 = T(^{\circ}\text{R})/1.8$ |
| Temperature difference: $\Delta T(\text{K}) = \Delta T(^{\circ}\text{C}) = \Delta T(^{\circ}\text{F})/1.8 = \Delta T(^{\circ}\text{R})/1.8$ |
| Thermal conductivity: $1 \text{ W/m} \cdot \text{K} = 0.8604 \text{ kcal/m} \cdot \text{h} \cdot ^\circ\text{C} = 0.5782 \text{ Btu/ft} \cdot \text{h} \cdot ^\circ\text{F} = 0.01 \text{ W/cm} \cdot \text{K} = 2.390 \times 10^{-3} \text{ cal/cm} \cdot \text{s} \cdot ^\circ\text{C}$ |
| Thermal diffusivity: $1 \text{ m}^2/\text{s} = 38,750 \text{ ft}^2/\text{h} = 3600 \text{ m}^2/\text{h} = 10.764 \text{ ft}^2/\text{s}$ |
| Viscosity, dynamic: $1 \text{ N} \cdot \text{s/m}^2 = 1 \text{ Pa} \cdot \text{s} = 10^7 \text{ } \mu\text{P} = 2419.1 \text{ lb}_m/\text{ft} \cdot \text{h} = 10^3 \text{ cP} = 75.188 \text{ slug/ft} \cdot \text{h} = 10 \text{ P} = 0.6720 \text{ lb}_m/\text{ft} \cdot \text{s} = 0.02089 \text{ lb}_f \cdot \text{s/ft}^2$ |
| Viscosity, kinematic (<i>see</i> thermal diffusivity) |

Source: E. Lange, L. F. Sokol, and V. Antoine, *Information on the Metric System and Related Fields*, 6th ed., G. C. Marshall Space Flight Center, AL (exhaustive bibliography); B. N. Taylor, *The International System of Units*, NBS S.P. 330, Washington, D.C., 2001; E. A. Mechtly, *The International System of Units. Physical Constants and Conversion Factors*, NASA S.P. 9012, 1973, numerous revisions periodically appear: see, for example, *Pure Appl. Chem.*, **51**, 1–41 (1979) and later issues.

Table 2 Phase Transition Data for Elements^a

| Name | Symbol | Formula Weight | T_m (K) | Δh_{fus} (kJ/kg) | T_b (K) | T_c (K) |
|-----------|-----------------|----------------|-----------|---------------------------------|-----------|-----------|
| Actinium | Ac | 227.028 | 1323 | 63 | 3,475 | |
| Aluminum | Al | 26.9815 | 933.5 | 398 | 2,750 | 7,850 |
| Antimony | Sb | 121.75 | 903.9 | 163 | 1,905 | 5,700 |
| Argon | Ar | 39.948 | 83 | 30 | 87.2 | 151 |
| Arsenic | As | 74.9216 | 885 | — | — | 2,100 |
| Barium | Ba | 137.33 | 1,002 | 55.8 | — | 4,450 |
| Beryllium | Be | 9.01218 | 1,560 | 1,355 | 2,750 | 6,200 |
| Bismuth | Bi | 208.980 | 544.6 | 54.0 | 1,838 | 4,450 |
| Boron | B | 10.81 | 2,320 | 1,933 | 4,000 | 3,300 |
| Bromine | Br | 159.808 | 266 | 66.0 | 332 | 584 |
| Cadmium | Cd | 112.41 | 594 | 55.1 | 1,040 | 2,690 |
| Calcium | Ca | 40.08 | 1,112 | 213.1 | 1,763 | 4,300 |
| Carbon | C | 12.011 | 3,810 | — | 4,275 | 7,200 |
| Cerium | Ce | 140.12 | 1,072 | 390 | — | 9,750 |
| Cesium | Cs | 132.905 | 301.8 | 16.4 | 951 | 2,015 |
| Chlorine | Cl ₂ | 70.906 | 172 | 180.7 | 239 | 417 |

Table 2 (Continued)

| Name | Symbol | Formula Weight | T_m (K) | Δh_{fus} (kJ/kg) | T_b (K) | T_c (K) |
|--------------|----------------|----------------|-----------|--------------------------|-----------|-----------|
| Chromium | Cr | 51.996 | 2,133 | 325.6 | 2,950 | 5,500 |
| Cobalt | Co | 58.9332 | 1,766 | 274.7 | 3,185 | 6,300 |
| Copper | Cu | 63.546 | 1,357 | 206.8 | 2,845 | 8,280 |
| Dysprosium | Dy | 162.50 | 1,670 | 68.1 | 2,855 | 6,925 |
| Erbium | Er | 167.26 | 1,795 | 119.1 | 3,135 | 7,250 |
| Europium | Eu | 151.96 | 1,092 | 60.6 | 1,850 | 4,350 |
| Fluorine | F ₂ | 37.997 | 53.5 | 13.4 | 85.0 | 144 |
| Gadolinium | Gd | 157.25 | 1,585 | 63.8 | 3,540 | 8,670 |
| Gallium | Ga | 69.72 | 303 | 80.1 | 2,500 | 7,125 |
| Germanium | Ge | 72.59 | 1,211 | 508.9 | 3,110 | 8,900 |
| Gold | Au | 196.967 | 1,337 | 62.8 | 3,130 | 7,250 |
| Hafnium | Hf | 178.49 | 2,485 | 134.8 | 4,885 | 10,400 |
| Helium | He | 4.00260 | 3.5 | 2.1 | 4.22 | 5.2 |
| Holmium | Ho | 164.930 | 1,744 | 73.8 | 2,968 | 7,575 |
| Hydrogen | H ₂ | 2.0159 | 14.0 | — | 20.4 | — |
| Indium | In | 114.82 | 430 | 28.5 | 2,346 | 6,150 |
| Iodine | I ₂ | 253.809 | 387 | 125.0 | 457 | 785 |
| Iridium | Ir | 192.22 | 2,718 | 13.7 | 4,740 | 7,800 |
| Iron | Fe | 55.847 | 1,811 | 247.3 | 3,136 | 8,500 |
| Krypton | Kr | 83.80 | 115.8 | 19.6 | 119.8 | 209.4 |
| Lanthanum | La | 138.906 | 1,194 | 44.6 | 3,715 | 10,500 |
| Lead | Pb | 207.2 | 601 | 23.2 | 2,025 | 5,500 |
| Lithium | Li | 6.941 | 454 | 432.2 | 1,607 | 3,700 |
| Lutetium | Lu | 174.967 | 1,937 | 106.6 | 3,668 | — |
| Magnesium | Mg | 24.305 | 922 | 368.4 | 1,364 | 3,850 |
| Manganese | Mn | 54.9380 | 1,518 | 219.3 | 2,334 | 4,325 |
| Mercury | Hg | 200.59 | 234.6 | 11.4 | 630 | 1,720 |
| Molybdenum | Mo | 95.94 | 2,892 | 290.0 | 4,900 | 1,450 |
| Neodymium | Nd | 144.24 | 1,290 | 49.6 | 3,341 | 7,900 |
| Neon | Ne | 20.179 | 24.5 | 16.4 | 27.1 | 44.5 |
| Neptunium | Np | 237.048 | 910 | — | 4,160 | 12,000 |
| Nickel | Ni | 58.70 | 1,728 | 297.6 | 3,190 | 8,000 |
| Niobium | Nb | 92.9064 | 2,740 | 283.7 | 5,020 | 12,500 |
| Nitrogen | N ₂ | 28.013 | 63.2 | 25.7 | 77.3 | 126.2 |
| Osmium | Os | 190.2 | 3,310 | 150.0 | 5,300 | 12,700 |
| Oxygen | O ₂ | 31.9988 | 54.4 | 13.8 | 90.2 | 154.8 |
| Palladium | Pd | 106.4 | 1,826 | 165.0 | 3,240 | 7,700 |
| Phosphorus | P | 30.9738 | 317 | — | 553 | 995 |
| Platinum | Pt | 195.09 | 2,045 | 101 | 4,100 | 10,700 |
| Plutonium | Pu | 244 | 913 | 11.7 | 3,505 | 10,500 |
| Potassium | K | 39.0983 | 336.4 | 60.1 | 1,032 | 2,210 |
| Praseodymium | Pr | 140.908 | 1,205 | 49 | 3,785 | 8,900 |
| Promethium | Pm | 145 | 1,353 | — | 2,730 | — |
| Protactinium | Pa | 231 | 1,500 | 64.8 | 4,300 | — |
| Radium | Ra | 226.025 | 973 | — | 1,900 | — |
| Radon | Rn | 222 | 202 | 12.3 | 211 | 377 |
| Rhenium | Re | 186.207 | 3,453 | 177.8 | 5,920 | 18,900 |
| Rhodium | Rh | 102.906 | 2,236 | 209.4 | 3,980 | 7,000 |
| Rubidium | Rb | 85.4678 | 312.6 | 26.4 | 964 | 2,070 |
| Ruthenium | Ru | 101.07 | 2,525 | 256.3 | 4,430 | 9,600 |
| Samarium | Sm | 150.4 | 1,345 | 57.3 | 2,064 | 5,050 |
| Scandium | Sc | 44.9559 | 1,813 | 313.6 | 3,550 | 6,410 |

(continued)