

Handbook of Smoke Control Engineering

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Dr. John Klote is known throughout the world as an expert in smoke control due to his many books on the topic and his 19 years of fire research conducted at the U.S. National Institute of Standards and Technology (NIST) in Gaithersburg, Maryland. For 11 years, he operated his own consulting company specializing in analysis of smoke control systems. Klote developed a series of smoke control seminars that he teaches for the Society of Fire Protection Engineers. The primary author of the 2007 ICC book *A Guide to Smoke Control in the 2006 IBC* and the 2002 ASHRAE book *Principles of Smoke Management*, Dr. Klote is also the primary author of two other ASHRAE books about smoke control, and he has written chapters about smoke control in a number of books, as well as over 80 papers and articles on smoke control, smoke movement, CFD fire simulations, and other aspects of fire protection. He is a licensed professional engineer in Washington, DC. Klote earned his doctorate in mechanical engineering from George Washington University. Klote is a member of NFPA, a fellow of SFPE and a fellow of ASHRAE. He is a member and past chair of ASHRAE Technical Committee 5.6, Fire and Smoke Control, and a member of the NFPA Smoke Management Committee.

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DEDICATION

This book is dedicated to the memory of Harold (Bud) Nelson. Because of his many significant contributions when he worked at the General Services Administration (GSA) and the National Institute of Standards and Technology (NIST), Bud Nelson was recognized as one of the great pioneers of fire protection engineering. Bud Nelson also was the first chairman of the NFPA Smoke Management Committee.

HOW TO USE THIS BOOK

This book is organized in the classic handbook format to help engineers and other professionals who need to get information about a topic quickly. The Table of Contents and the Index can be used so readers can go directly to their topic of interest. The handbook format has no introductory chapter, and the most fundamental material is in the first chapters and applied material is in later chapters. To help readers get information quickly, the chapters do not include derivations of equations. Unlike textbooks, some redundancy is needed in handbooks so that the chapters can be relatively independent. This redundancy is minimized, and in some places readers are referred to another section or chapter for more information. This book includes all the information in my earlier smoke control books plus a number of other topics, and there are many example calculations. This handbook can be used as a textbook with the teacher selecting the chapters and parts of chapters to be taught. The only departure from the handbook format is that derivations of equations are in an appendix included to make the book more useful to scholars, teachers, and students.

John H. Klotz

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PREFACE

In 1983, ASHRAE published *Design of Smoke Control Systems for Buildings* by John Fothergill and me. This book was the first attempt to consolidate and present practical information about smoke control design. Judging by the many favorable comments and suggestions about this first book, I feel that it was a success. The first publication was limited to systems that control smoke by means of the physical mechanisms of pressurization and airflow.

In 1992, ASHRAE and SFPE jointly published *Design of Smoke Management Systems* by James Milke and me. The term *smoke management* was used in the title of this publication to indicate that the physical mechanisms were expanded from pressurization and airflow to include compartmentation, dilution, and buoyancy. Based on heightened concerns about supplying combustion air to the fire, a caution was added about the use of airflow for smoke management.

In 2002, ASHRAE and SFPE jointly published *Principles of Smoke Management* by James Milke and me. This publication included the material of the two earlier books plus people movement in fire, hazard analysis, scale modeling, and computational fluid dynamics.

This new publication is in handbook form that is intended to make the book more useful to practicing engineers. The earlier books were aimed at both practicing engineers and students, and derivations of equations were included in many of the chapters. To make the handbook easier to use for engineers who want information on a specific topic quickly, the derivations are not included in the chapters. However, to make the book useful to students and teachers, the derivations are in an appendix.

This new book addresses the material of the earlier books plus (1) controls, (2) fire and smoke control in transport tunnels, and (3) full scale fire testing. For those getting started with the computer models CONTAM and CFAST, there are simplified instructions with examples. As with the other books, this new book is primarily intended for designers, but it is expected that it will be of interest to other professionals (architects, code officials, researchers, etc.).

In this book, the term *smoke control system* is used to mean an engineered system that includes all methods that can be used singly or in combination to modify smoke movement. This usage is consistent with that of the 2009 NFPA 92A, 2012 NFPA 92, and most codes including the International Building Code. This usage is a departure from the earlier ASHRAE smoke control books and earlier versions of NFPA 92A. The meaning of the term *smoke management system* was completely changed in the 2009 NFPA 92A, and this term is almost never used in this handbook. Because these terms have different meanings in many publications, readers are cautioned to be careful about this terminology when reading different books, research papers, and articles.

This book and its predecessors are different from other design books in a number of respects. This book is written in both English units (also called I-P for inch-pound) and SI units so that it can be used by a wide audience. Physical descriptions are worked into the text as simple explanations of how particular mechanisms, processes or events happen. Many example calculations are included. As with the earlier book, I hope that this book is of value to the engineering community. Further, I invite readers to mail their suggestions and comments to me at the address below.

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ACKNOWLEDGMENTS

This project would not have been possible without the support of ASHRAE. In addition to publishing books about smoke control, ASHRAE has funded a considerable body of smoke control research from the 1980s to the present time. A debt is owed to my coauthors: James A. Milke, Paul G. Turnbull, Ahmed Kashef, and Michael J. Ferreira. Each of them has authored a chapter or more, and they have provided valuable advice during development of this handbook.

Acknowledgement is made to the members of the ASHRAE Smoke Control Monitoring Committee for their generous support and constructive criticism. The members of this subcommittee are: William A. Webb (Chair), Jeffrey S. Tubbs, and Douglas Evans. Gary D. Lougheed, Paul G. Turnbull, John A. Clark, John Breen, and W. Stuart Dols also provided constructive criticism.

Special thanks are due to Gary Lougheed for his insightful comments regarding fluid flow, design fires, and full scale fire testing. Paul Turnbull made valuable comments about practically every aspect of the book. John Clark provided helpful comments in a number of areas. John Breen, who is a student at the Department of Fire Protection Engineering at the University of Maryland, made valuable comments regarding the computer program CONTAM. W. Stuart Dols, who is in charge of the development of CONTAM at NIST, made helpful comments about a number of aspects of CONTAM. In addition to chairing the review subcommittee, Bill Webb made practical comments on subjects in every chapter of the book.

Acknowledgement must be made to the many engineers and scientists who have conducted the research that is the foundation of modern smoke control technology. These researchers are too many to mention here, but many of their efforts are referenced in the text. It should be mentioned that I personally owe much to the National Institute of Standards and Technology in Gaithersburg, MD for the opportunity of being able to do fire research there for nineteen years.

The content of this book is heavily dependent on extensive smoke control research conducted at the National Research Council of Canada (NRCC). Much of this research has been conducted at NRCC's Experimental Fire Tower near Ottawa.

John H. Klote

NOTE ON SUSTAINABILITY

Sustainability has attracted considerable attention in recent years, and the design of green buildings requires ingenuity and understanding of the technology. This handbook does not explicitly address sustainability, but it can be thought of as a treatment of sustainability to the extent that designers can develop sustainable smoke control systems based on information provided herein.

In one sense, smoke control systems can be thought of as sustainable systems in that they can minimize the extent of smoke damage to building components during fires. However, the amount of materials used in some smoke control systems can be minimized or even eliminated.

The use of natural smoke venting for smoke control in atria and other large volume spaces eliminates the fans and ductwork used in conventional smoke exhaust systems. The only equipment needed for this kind of venting is a roof vent that opens in the event of a fire. Natural smoke venting has been used for many decades in the United Kingdom, Australia, and Japan. An algebraic equation in Chapter 15 can be used as a starting point for analysis of a natural venting system. Wind effects are a special concern with natural smoke venting, and these systems should be analyzed with computational fluid dynamic (CFD) modeling (Chapter 20).

Smoke filling is the simplest form of smoke control for atria and other large volume spaces, because it eliminates the need for any equipment. This approach consists of allowing smoke to fill the large volume space without any smoke exhaust or other smoke removal. For very large spaces, the smoke filling time can be long enough for evacuation. Smoke filling time can be calculated by algebraic equations or with the use of computer models as discussed in Chapter 15. It is essential that calculations of evacuation time include the times needed for recognition, validation, and premovement as discussed in Chapter 4.

For some applications, passive smoke control using smoke barriers has the potential to be used in place of pressurization smoke control systems. This can reduce or eliminate the fans and ductwork of the pressurization systems. Such systems need to provide equivalent life-safety protection as that of the pressurization systems. The tenability of such passive systems can be analyzed with CFD modeling or with a combination of CONTAM and zone fire modeling as discussed in Chapter 19.

Stairwell ventilation systems have the potential to maintain tenability in stairwells at reduced fan capacity compared to stairwell pressurization. The idea of these ventilation systems is to supply air to and exhaust air from the stairwell so that any smoke leaking into the stairwell is diluted to maintain tenable conditions in the stairwell. The amount of air needed for stairwell pressurization is proportional to the number of floors served by the stairwell, but the amount of air needed for stairwell ventilation, is almost independent of the number of floors. This means that the greatest savings in fan capacity are for stairwells in very tall buildings. For stairwell ventilation the most important location is the landing of the fire floor, and tenability here can be analyzed by CFD modeling as discussed in Chapter 20.

The extent to which smoke control systems can be more sustainable depends on the ingenuity, creativity, and knowledge of the design team. Some old ideas (such as smoke shafts and smoke venting with exterior wall vents) may be reevaluated and revised to become sustainable systems or parts of sustainable systems. It is essential that the alternate smoke control systems provide protection that is equivalent to that of conventional systems.

CHAPTER 1

Units and Properties

John H. Klotz

The international system (SI) of units is used for almost all applications outside the U.S. and for many applications inside the U.S. In the U.S., a collection of mostly old English units are used for many applications. These old style units are referred to here as inch-pound (I-P) units. This chapter deals with units of measurement and physical properties.

DUAL UNITS

Most equations in this handbook are presented in dual units, but exceptions are noted at the beginning of some chapters. The equation below for the Reynolds number is an example of these dual units.

$$R_e = \frac{1.39 \times 10^{-3} D_h U}{\nu} \quad (1.1)$$
$$R_e = \frac{D_h U}{\nu} \text{ for SI}$$

where

- R_e = Reynolds number, dimensionless,
- D_h = hydraulic diameter of flow path, in. (m),
- U = average velocity in flow path, fpm (m/s),
- ν = kinematic viscosity, ft²/s (m²/s).

This equation consists of an I-P version followed by an SI version. The “where” list below the equation contains the variable names, followed by the I-P units with the SI units in parentheses. For example, the I-P units of average velocity in flow path are fpm, and the SI units for this variable are m/s.

The I-P units are used in the following systems: (1) the pound-mass and pound-force system, (2) the slug and pound system, and (3) the pound-mass and poundal

system. Each version has its own rules for dealing with units, but these are not discussed here. The approach taken here is to focus on the SI system, and to provide conversions between the I-P units and SI units.

THE SI SYSTEM

Today’s SI system is based on the metric system that was first adopted in France in 1791. This section is a general discussion of the SI system. More detailed information is available from NIST (Thompson and Taylor 2008) and IEEE/ASTM (IEEE/ASTM 2002). The NIST publication can be downloaded over the Internet at no cost.

The SI system consists of base units and derived units which together form what is called a coherent system of SI units. Such a coherent system needs no additional factors in equations to adjust for the units, and the advantage of this is illustrated later. The seven base quantities upon which the SI system is founded are length, mass, time, thermodynamic temperature, electric current, amount of substance, and luminous intensity. Table 1.1 lists the names and symbols of the units for these base quantities.

Derived units are expressed algebraically in terms of base units or other derived units. The symbols for derived units are obtained by means of the mathematical operations of multiplication and division. For example, the derived unit for the derived quantity mass flow (mass divided by time) is the kilogram per second, and the symbol for mass flow is kg/s. Other examples of derived units expressed in terms of SI base units are given in Table 1.2.

There are a number of coherent derived units that have special names and symbols. For example, the pascal

is the special unit for pressure, and the symbol Pa is the special symbol for the pascal. Table 1.3 lists some of these units with special names and symbols. When it is stated that an equation is valid for the SI system, it is meant that the equation is valid for variables that are the coherent units of the SI system.

Prefixes are listed in Table 1.4. For example, the prefix kilo (k) means a multiplication factor of one thousand, and a kilometer (km) is a thousand meters (m). Conversions between I-P and SI units are listed in Table 1.5.

Chapters in SI Only

Some of the chapters in this handbook are only in SI units. This was done because the equations in these chapters are intended primarily for explanation. These equations can also be used to write computer programs, and most computer programs are written in SI units because they are based on equations from research done in SI units. All of the variables in an SI equation are in base units or coherent derived units (Tables 1.1 to 1.3).

Care needs to be taken because units with a prefix are not coherent except for the kilogram, which is an exception. For example, the following is an SI equation for the pressure difference between two nodes:

$$\Delta p_{ij} = p_i - p_j + \rho_i g (z_i - z_j) \quad (1.2)$$

where

- Δp_{ij} = pressure difference from node i to node j ,
- p_i = pressure at node i ,
- p_j = pressure at node j ,
- ρ_i = density of gas at node i ,
- z_i = elevation of node i ,
- z_j = elevation of node j ,
- g = acceleration of gravity.

It can be seen from Table 1.3 that the pressures and the pressure difference are in the units of pascals (Pa). Elevations are quantities of length, and they are in meters (m) as can be seen from Table 1.1. From Table 1.2, it can be seen that the acceleration term has units of meter per second squared (m/s^2).

Table 1.1: Base Units of the SI System

Base Quantity	Unit	Symbol
Length	meter	m
Mass	kilogram	kg
Time	second	s
Thermodynamic temperature ¹	kelvin	K
Electric current	ampere	A
Amount of substance	mole	mole
Luminous intensity	candela	cd

¹This is also called absolute temperature. Kelvin is also the unit for temperature difference and temperature rise.

Table 1.2: Some Coherent Derived Units

Quantity	Name	Symbol
Acceleration	meter per second squared	m/s^2
Area	square meter	m^2
Density	kilogram per cubic meter	kg/m^3
Mass flow	mass per second	kg/s
Velocity	meter per second	m/s
Volume	cubic meter	m^3
Volumetric flow	cubic meter per second	m^3/s

Table 1.3: Some Coherent Derived Units with Special Names and Symbols

Quantity	Special Name	Special Symbol	Expression in other SI Units	Expression in SI Base Units
Electrical charge	coulomb	C	–	s A
Electric potential difference	volt	V	W/A	$m^2 kg s^{-3} A^{-1}$
Energy, heat, and work	joule	J	N m	$m^2 kg s^{-3}$
Force	newton	N	–	$m kg s^{-2}$
Frequency	hertz	Hz	–	s^{-1}
Power, heat release rate	watt	W	J/s	$m^2 kg s^{-3}$
Pressure, pressure difference	pascal	Pa	N/m^2	$m^{-1} kg s^{-2}$

TEMPERATURE CONVERSION

The SI unit of absolute temperature is kelvin, and the I-P unit of absolute temperature is Rankine. In addition, temperature is frequently measured in the Celsius or the Fahrenheit scale. The following equations can be used to convert between temperature scales:

$$\begin{aligned}
 T_F &= T_R - 459.67 \\
 T_R &= T_F + 459.67 \\
 T_C &= T_K - 273.15 \\
 T_K &= T_C + 273.15 \\
 T_F &= 1.8T_C + 32 \\
 T_C &= \frac{T_F - 32}{1.8}
 \end{aligned}
 \tag{1.3}$$

where

- T_F = temperature in degrees Fahrenheit,
- T_R = temperature in degrees Rankin,
- T_C = temperature in degrees Celsius,
- T_K = temperature in kelvin.

Temperature Difference

This section deals with temperature difference, temperature rise, and temperature drop. All of these are handled the same way, and they are referred to here in a generic sense as temperature difference. The following equations can be used for temperature difference conversions:

$$\begin{aligned}
 \Delta T_F &= 1.8\Delta T_C \\
 \Delta T_F &= \Delta T_R \\
 \Delta T_C &= \frac{\Delta T_F}{1.8} \\
 \Delta T_C &= \Delta T_K
 \end{aligned}
 \tag{1.4}$$

where

- ΔT_F = temperature difference in degrees Fahrenheit,
- ΔT_C = temperature difference in degrees Celsius,
- ΔT_K = temperature difference in kelvin,
- ΔT_R = temperature difference in degrees Rankine.

SOFT AND HARD CONVERSIONS

Many people are confused by the terms soft conversion and hard conversion, because the terms seem backwards. Regarding conversions, *soft* means exact or nearly so, and *hard* means approximate. An example of a soft conversion is 810 ft equals exactly 246.888 m. What is

hard about a hard conversion is deciding how many digits should be kept in the rounded number. Should 810 ft be rounded to 250 m, 247 m, or something else? The answer depends on numerous considerations, some of which are unique to specific areas of engineering.

In this handbook, hard conversions are used. Often, values are rounded to three significant digits because calculations based on such rounding are equivalent for engineering purposes in both systems. Rounding is sometimes based on accuracy considerations of the original value. With most research work and some standards, the original value is in SI units. For consistency in this handbook, I-P units are listed first, followed by SI units in parentheses, regardless of the source of the data.

UNIT CONVERSIONS FOR EQUATIONS

Because almost all research is conducted in SI units, there is a need to convert SI equations to I-P equations. This section discusses a method that can be used for such conversions. For SI equations with temperature in degrees Celsius, the equation needs to be converted to one with temperature in kelvin.

The following is an equation in functional form:

$$y = f(x_1, x_2, \dots, x_n) \tag{1.5}$$

where y is a dependent variable, and x_i from $i = 1$ to n are independent variables. Equation 1.5 is in SI units, and it is desired to convert it to I-P units. The variables in this equation are related to the ones in the other unit system as follows:

$$\begin{aligned}
 y &= ay' \\
 x_i &= b_i x'_i
 \end{aligned}
 \tag{1.6}$$

Table 1.4: SI Prefixes

Prefix	Symbol	Multiplication Factor
giga	G	$10^9 = 1\,000\,000\,000$
mega	M	$10^6 = 1\,000\,000$
kilo	k	$10^3 = 1\,000$
centi ¹	c	$10^{-2} = 0.01$
milli	m	$10^{-3} = 0.001$
micro	μ	$10^{-6} = 0.000\,001$
nano	n	$10^{-9} = 0.000\,000\,001$

¹The prefix centi is to be avoided where possible.

Table 1.5: Factors for Unit Conversions

TO CONVERT FROM	TO	MULTIPLY BY
Acceleration		
foot per second squared (ft/s ²)	meter per second squared (m/s ²)	0.3048
meter per second squared (m/s ²)	foot per second squared (ft/s ²)	3.2808
standard gravity (g)	meter per second ² (m/s ²)	9.80665
standard gravity (g)	foot per second (ft/s ²)	32.174
Area		
foot squared (ft ²)	meter ² (m ²)	0.09290
foot squared (ft ²)	inch squared (in. ²)	144
meter squared (m ²)	foot squared (ft ²)	10.76
meter squared (m ²)	inch squared (in. ²)	1550
meter squared (m ²)	yard squared (yd ²)	1.196
yard squared (yd ²)	meter ² (m ²)	0.8361
yard squared (yd ²)	foot squared (ft ²)	9
yard squared (yd ²)	inch squared (in. ²)	1296
Density		
gram per cubic meter (g/m ³)	kilogram per cubic meter (kg/m ³)	0.001
kilogram per cubic meter (kg/m ³)	gram per cubic meter (g/m ³)	1000
gram per cubic meter (g/m ³)	pound per cubic foot (lb/ft ³)	6.2428E-5
kilogram per cubic meter (kg/m ³)	pound per cubic foot (lb/ft ³)	0.062428
pound per cubic foot (lb/ft ³)	kilogram per cubic meter (kg/m ³)	16.018
pound per cubic foot (lb/ft ³)	gram per cubic meter (g/m ³)	16,018
Energy (also Heat and Work)		
British thermal unit (Btu)	joule (J)	1055
British thermal unit (Btu)	foot pound (ft lb)	778
erg	joule (J)	1.000E-7
foot pound (ft lb)	joule (J)	1.356
joule (J)	British thermal unit (Btu)	9.479E-4
Flow, Mass		
kilogram per second (kg/s)	pound per hour (lb/h)	7937
kilogram per second (kg/s)	pound per minute (lb/min)	132.3
kilogram per second (kg/s)	pound per second (lb/s)	2.205
kilogram per second (kg/s)	standard cubic feet per min (scfm) at 68°F	1760
pound per hour (lb/h)	kilogram per second (kg/s)	0.0001260
pound per minute (lb/min)	kilogram per second (kg/s)	0.007560
pound per second (lb/s)	kilogram per second (kg/s)	0.4536
pound per second (lb/s)	standard cubic feet per min (scfm) at 68°F	798.5
standard cubic feet per min (scfm) at 68°F	kilogram per second (kg/s)	0.005680
standard cubic feet per min (scfm) at 68°F	pound per second (lb/s)	0.0012523

Table 1.5: Factors for Unit Conversions (Continued)

TO CONVERT FROM	TO	MULTIPLY BY
Flow, Volumetric		
foot cubed per minute (ft ³ /min or cfm)	meter cubed per second (m ³ /s)	4.719E-04
foot cubed per second (ft ³ /s)	meter cubed per second (m ³ /s)	0.02832
gallon per minute (gal/min or gpm)	meter cubed per second (m ³ /s)	6.309E-05
meter cubed per second (m ³ /s)	foot cubed per minute (ft ³ /min or cfm)	2119
meter cubed per second (m ³ /s)	foot cubed per second (ft ³ /s)	35.31
meter cubed per second (m ³ /s)	gallon per minute (gal/min or gpm)	15850
gallon per minute (gal/min or gpm)	foot cubed per minute (ft ³ /min or cfm)	0.1337
foot cubed per minute (ft ³ /min or cfm)	gallon per minute (gal/min or gpm)	7.481
Force		
kilogram-force (at sea level)	newton (N)	9.80665
pound-force (lb)	newton (N)	4.448
newton (N)	pound-force (lb)	0.2248
Heat (See Energy)		
Heat Release Density		
Btu/s ft ²	kW/m ²	11.36
kW/m ²	Btu/s ft ²	0.08806
Heat Release Rate (see Power)		
Length		
foot (ft)	meter (m)	0.3048
foot (ft)	inch (in.)	12
inch (in.)	meter (m)	0.02540
inch (in.)	centimeter (cm)	2.54
inch (in.)	foot (ft)	0.08333
meter (m)	foot (ft)	3.2808
meter (m)	inch (in)	39.3701
meter (m)	nautical mile (U.S.)	0.0005
meter (m)	mile	6.214E-4
meter (m)	yard	1.0936
mile	meter (m)	1609.3
mile	foot (ft)	5280
nautical mile (U.S.)	meter (m)	1852
yard	meter (m)	0.9144
yard	foot (ft)	3
yard	meter (m)	0.9144
Light		
footcandle	lux (lx)	10.764
lux (lx)	footcandle	0.0929
Mass		
gram (g)	kilogram (kg)	0.001

Table 1.5: Factors for Unit Conversions (Continued)

TO CONVERT FROM	TO	MULTIPLY BY
gram (g)	pound (lb)	0.002205
kilogram (kg)	gram (g)	1000
kilogram (kg)	pound (lb)	2.205
ounce (avoirdupois)	kilogram (kg)	0.03110
pound (lb)	kilogram (kg)	0.4536
pound (lb)	gram (g)	453.6
pound (lb)	slug	0.03108
slug	kilogram (kg)	14.60
slug	pound (lb)	32.174
ton (long, 2240 lb)	kilogram (kg)	1016
ton (metric)	kilogram (kg)	1000
ton (short, 2000 lb)	kilogram (kg)	907.2
Mass Flow (see Flow, Mass)		
Temperature (see equations in the text)		
Power (also Heat Release Rate)		
British thermal unit per hour (Btu/h)	kilowatt (kW)	2.931E-04
British thermal unit per hour (Btu/h)	watt (W)	0.293
British thermal unit per minute (Btu/min)	watt (W)	17.58
British thermal unit per minute (Btu/min)	kilowatt (kW)	0.01758
British thermal unit per second (Btu/s)	watt (W)	1055
British thermal unit per second (Btu/s)	kilowatt (kW)	1.055
horsepower	watt (W)	745.7
horsepower	foot pound per second (ft lb/s)	550.0
horsepower	kilowatt (kW)	0.7457
ton (refrigeration)	watt (W)	3517
ton (refrigeration)	kilowatt (kW)	3.517
Pressure		
atmosphere, standard (atm)	pascal (Pa)	101325
atmosphere, standard (atm)	pound per square inch (lb/in. ² or psi)	14.696
atmosphere, standard (atm)	pound per square foot (lb/ft ²)	2116.2
atmosphere, standard (atm)	inch of water (in. H ₂ O) at 60 °F	407.19
atmosphere, standard (atm)	foot of water (ft H ₂ O) at 60 °F	33.932
centimeter of mercury (cm Hg) at 0°C	pascal (Pa)	1333.22
centimeter of water (cm H ₂ O) 60°C	pascal (Pa)	97.97
foot of water (ft H ₂ O) at 60°F	pascal (Pa)	2986
inch of mercury (in. Hg)	pascal (Pa)	3386
inch of water (in. H ₂ O) at 60°F	pascal (Pa)	248.84
pascal (Pa)	inch of mercury (in. Hg)	2.953E-04
pascal (Pa)	inch of water (in. H ₂ O) at 60°F	0.004019
pascal (Pa)	foot of water (ft H ₂ O) at 60°F	3.349E-04
pascal (Pa)	centimeter of mercury (cm Hg) at 0°C	7.501E-04

Table 1.5: Factors for Unit Conversions (Continued)

TO CONVERT FROM	TO	MULTIPLY BY
pascal (Pa)	centimeter of water (cm H ₂ O) 60° C	0.01021
pascal (Pa)	pound per square foot (lbf/ft ²)	0.02089
pascal (Pa)	pound per square inch (lbf/in ² or psi)	1.450E-04
pound per square foot (lbf/ft ²)	pascal (Pa)	47.88
pound per square inch (lbf/in. ² or psi)	pascal (Pa)	6895
Velocity (also Speed)		
foot per hour (ft/h)	meter per second (m/s)	8.467E-05
foot per minute (ft/min or fpm)	meter per second (m/s)	0.005080
foot per second (ft/s)	meter per second (m/s)	0.3048
kilometer per hour (km/h)	meter per second (m/s)	0.2778
knot	meter per second (m/s)	0.5144
meter per second (m/s)	foot per minute (ft/min or fpm)	196.9
meter per second (m/s)	foot per second (ft/s)	3.281
meter per second (m/s)	foot per hour (ft/h)	11811
meter per second (m/s)	kilometer per hour (km/h)	3.600
meter per second (m/s)	knot	1.944
meter per second (m/s)	mile per hour (mi/h or mph)	2.237
mile per hour (mi/h or mph)	kilometer per hour (km/h)	1.609
Volume		
foot cubed (ft ³)	meter cubed (m ³)	0.02832
foot cubed (ft ³)	inch cubed (in. ³)	1728
foot cubed (ft ³)	gallon (U.S.)	7.4805428
foot cubed (ft ³)	yard cubed (yd ³)	0.03704
gallon (U.S.)	meter cubed (m ³)	0.003785412
gallon (U.S.)	foot cubed (ft ³)	0.1337
inch cubed (in. ³)	meter cubed (m ³)	1.639x10 ⁻⁵
inch cubed (in. ³)	foot cubed (ft ³)	0.0005787
liter	meter cubed (m ³)	0.001
liter	gallon (U.S.)	0.2642
meter cubed (m ³)	foot cubed (ft ³)	35.31
meter cubed (m ³)	inch cubed (in. ³)	61013
meter cubed (m ³)	gallon (U.S.)	264.2
meter cubed (m ³)	liter	1000
meter cubed (m ³)	yard cubed (yd ³)	1.308
yard cubed (yd ³)	meter cubed (m ³)	0.7646
yard cubed (yd ³)	foot cubed (ft ³)	27
Volumetric Flow (see Flow, Volumetric)		
Work (see Energy)		

Chapter 1—Units and Properties

where y' and x'_i are corresponding variables in I-P units, and a and b_i are conversion constants. Table 1.5 lists some conversion factors. Substituting Equations 1.6 into Equation 1.5 results in

$$ay' = f(b_1x'_1, b_2x'_2, \dots, b_nx'_n). \quad (1.7)$$

This equation is equivalent to Equation 1.6, but it is in I-P units. Equation 1.7 demonstrates that an alternate form of any equation can be developed. In practice, the coefficients of a function in the form of Equation 1.7 would be rearranged and rounded off. The resulting equation can be written as

$$y' = f'(x'_1, x'_2, \dots, x'_n) \quad (1.8)$$

where f' is a new function with rounded off coefficients. The level of agreement between Equations 1.7 and 1.8 can be expressed as

$$\epsilon = \frac{af'(x'_1, x'_2, \dots, x'_n) - f(x_1, x_2, \dots, x_n)}{f(x_1, x_2, \dots, x_n)} \quad (1.9)$$

where ϵ is the error in the function, f' , due to rounding. A positive value of ϵ means that f' is overpredicting in comparison to the predictions of f .

When rounding off the coefficients, the temptation of using a simple rule based on the accuracy of the original research needs to be avoided. For example, a person might mistakenly think that because the original

research has an accuracy of only two significant figures, all the coefficients should be rounded to two places. Some constants in a function can have a much greater impact than others, and using such a simple approach can result in error values ϵ , that are unacceptably high.

A more appropriate rule is to round coefficients to the smallest values that will result in values of ϵ that are within a predetermined limit. For many engineering applications, a value ϵ of 1% would be reasonable, and this value is used in Example 1.1.

PHYSICAL DATA

The values of some physical constants are listed in Table 1.6. The properties of air are listed in Tables 1.7 and 1.8. The thermal properties of a number of materials are listed in Tables 1.9 and 1.10.

U.S. STANDARD ATMOSPHERE

The barometric pressure and temperature of the air vary with altitude, local geographic conditions, and weather conditions. Altitude is the elevation above sea level. The standard atmosphere is a standard of reference for properties at various altitudes. At sea level, the standard temperature is 59°F (15°C) and the standard barometric pressure is 14.6959 psi (101.325 kPa). The barometric pressure and temperature decrease with increasing altitude. The temperature is considered to decrease linearly throughout the troposphere, which is the lowest portion of the earth's atmosphere. The standard barometric pressure varies with altitude as

$$p = 14.6959(1 - 6.87559 \times 10^{-6}z)^{5.2559} \quad (1.10)$$

$$p = 101.325(1 - 2.25577 \times 10^{-5}z)^{5.2559} \text{ for SI.}$$

The standard temperature varies with altitude as

$$T = 59 - 0.00357z \quad (1.11)$$

$$T = 15 - 0.0065z \text{ for SI}$$

where

- p = barometric pressure, psi (kPa),
- T = temperature, °F (°C),
- z = altitude, ft (m).

Example 1.2 shows how to calculate the standard barometric pressure. The climatic data listed in Chapter 2 lists the standard barometric pressure calculated from Equation 1.10 for locations throughout the world. The above equations for barometric pressure and temperature are accurate from -16,400 to 36,000 ft (-5000 to 11,000 m). For higher altitudes, see NASA (1976).

Table 1.6: Some Physical Constants

Acceleration of gravity at sea level, g	9.80665 m/s ²
	32.174 ft/s ²
Gas constant of air, R	287.0 J/kg K
	53.34 ft lbf/lbm/°R
	1716. ft lbf/slugg/°R
	0.06858 Btu/lbm/°R
Standard atmospheric pressure, P_{atm}	101,325 Pa
	14.696 psi
	2116.2 lb/ft ²
	407.19 in. H ₂ O (60°F)
	33.932 ft H ₂ O (60°F)
	1033.3 cm H ₂ O (4°C)
30.006 inch mercury (60°F)	
760.00 mm mercury (0°C)	