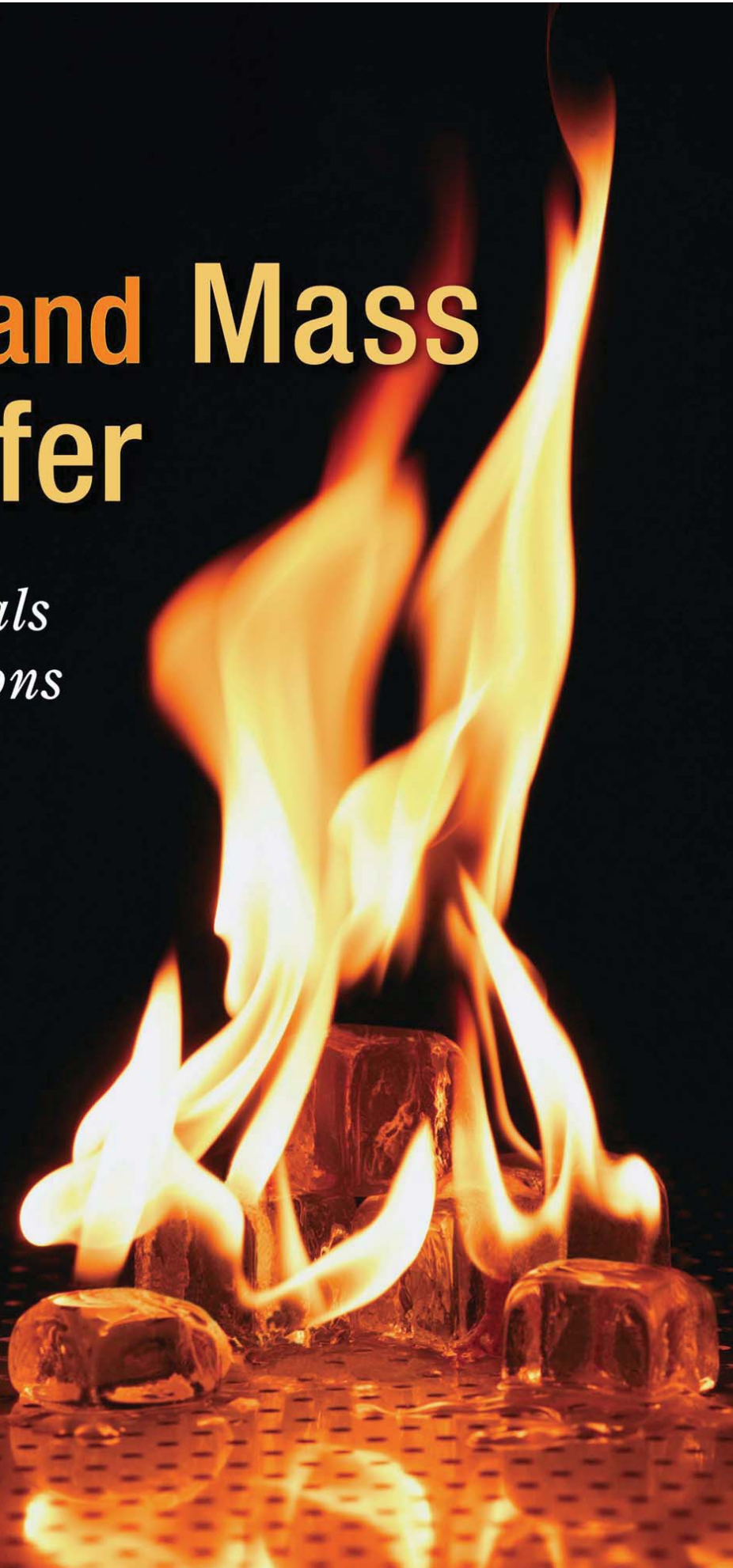


Fifth Edition

# Heat and Mass Transfer

*Fundamentals  
& Applications*

Yunus A. Çengel  
Afshin J. Ghajar



# HEAT AND MASS TRANSFER



FUNDAMENTALS & APPLICATIONS

## *Quotes on Ethics*

*Without ethics, everything happens as if we were all five billion passengers on a big machinery and nobody is driving the machinery. And it's going faster and faster, but we don't know where.*

*—Jacques Cousteau*

*Because you're able to do it and because you have the right to do it doesn't mean it's right to do it.*

*—Laura Schlessinger*

*A man without ethics is a wild beast loosed upon this world.*

*—Manly Hall*

*The concern for man and his destiny must always be the chief interest of all technical effort. Never forget it among your diagrams and equations.*

*—Albert Einstein*

*Cowardice asks the question, 'Is it safe?' Expediency asks the question, 'Is it politic?' Vanity asks the question, 'Is it popular?' But, conscience asks the question, 'Is it right?' And there comes a time when one must take a position that is neither safe, nor politic, nor popular but one must take it because one's conscience tells one that it is right.*

*—Martin Luther King, Jr*

*To educate a man in mind and not in morals is to educate a menace to society.*

*—Theodore Roosevelt*

*Politics which revolves around benefit is savagery.*

*—Said Nursi*

*The true test of civilization is, not the census, nor the size of the cities, nor the crops, but the kind of man that the country turns out.*

*—Ralph W. Emerson*

*The measure of a man's character is what he would do if he knew he never would be found out.*

*—Thomas B. Macaulay*

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FIFTH  
EDITION

**YUNUS A. ÇENGEL**

*University of Nevada,  
Reno*

**AFSHIN J. GHAJAR**

*Oklahoma State  
University, Stillwater*

**Mc  
Graw  
Hill**  
Education



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# ABOUT THE AUTHORS

**Yunus A. Çengel** is Professor Emeritus of Mechanical Engineering at the University of Nevada, Reno. He received his B.S. in mechanical engineering from Istanbul Technical University and his M.S. and Ph.D. in mechanical engineering from North Carolina State University. His areas of interest are renewable energy, energy efficiency, energy policies, heat transfer enhancement, and engineering education. He served as the director of the Industrial Assessment Center (IAC) at the University of Nevada, Reno, from 1996 to 2000. He has led teams of engineering students to numerous manufacturing facilities in Northern Nevada and California to perform industrial assessments, and has prepared energy conservation, waste minimization, and productivity enhancement reports for them. He has also served as an advisor for various government organizations and corporations.

Dr. Çengel is also the author or coauthor of the widely adopted textbooks *Thermodynamics: An Engineering Approach* (8th ed., 2015), *Fluid Mechanics: Fundamentals and Applications* (3rd ed., 2014), *Fundamentals of Thermal-Fluid Sciences* (3rd ed., 2008), *Introduction to Thermodynamics and Heat Transfer* (2nd ed., 2008), and *Differential Equations for Engineers and Scientists* (1st ed., 2013), all published by McGraw-Hill. Some of his textbooks have been translated into Chinese, Japanese, Korean, Thai, Spanish, Portuguese, Turkish, Italian, Greek, and French.

Dr. Çengel is the recipient of several outstanding teacher awards, and he has received the ASEE Meriam/Wiley Distinguished Author Award for excellence in authorship in 1992 and again in 2000. Dr. Çengel is a registered Professional Engineer in the State of Nevada, and is a member of the American Society of Mechanical Engineers (ASME) and the American Society for Engineering Education (ASEE).

**Afshin J. Ghajar** is *Regents Professor* and *John Brammer Professor* in the School of Mechanical and Aerospace Engineering at Oklahoma State University, Stillwater, Oklahoma, USA and a Honorary Professor of Xi'an Jiaotong University, Xi'an, China. He received his B.S., M.S., and Ph.D. all in Mechanical Engineering from Oklahoma State University. His expertise is in experimental heat transfer/fluid mechanics and development of practical engineering correlations. Dr. Ghajar has made significant contributions to the field of thermal sciences through his experimental, empirical, and numerical works in heat transfer and stratification in sensible heat storage systems, heat transfer to non-Newtonian fluids, heat transfer in the transition region, and non-boiling heat transfer in two-phase flow. His current research is in two-phase flow heat transfer/pressure drop studies in pipes with different orientations, heat transfer/pressure drop in mini/micro tubes, and mixed convective heat transfer/pressure drop in the transition region (plain and enhanced tubes). Dr. Ghajar has been a Summer Research Fellow at Wright Patterson AFB (Dayton, Ohio) and Dow Chemical Company (Freeport, Texas). He and his co-workers have published over 200 reviewed research papers. He has delivered numerous keynote and invited lectures at major technical conferences and institutions. He has received several outstanding teaching, research, advising, and service awards from College of Engineering at Oklahoma State University. His latest award is the 75th Anniversary Medal of the ASME Heat Transfer Division “in recognition of his service to the heat transfer community and contributions to the field”. Dr. Ghajar is a *Fellow* of the American Society of Mechanical Engineers (ASME), *Heat Transfer Series Editor* for CRC Press/Taylor & Francis and *Editor-in-Chief* of *Heat Transfer Engineering*, an international journal aimed at practicing engineers and specialists in heat transfer published by Taylor and Francis.

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# PREFACE

## BACKGROUND

**H**eat and mass transfer is a basic science that deals with the rate of transfer of thermal energy. It has a broad application area ranging from biological systems to common household appliances, residential and commercial buildings, industrial processes, electronic devices, and food processing. Students are assumed to have an adequate background in calculus and physics. The completion of first courses in thermodynamics, fluid mechanics, and differential equations prior to taking heat transfer is desirable. However, relevant concepts from these topics are introduced and reviewed as needed.

## OBJECTIVES

This book is intended for undergraduate engineering students in their sophomore or junior year, and as a reference book for practicing engineers. The objectives of this text are

- To cover the *basic principles* of heat transfer.
- To present a wealth of real-world *engineering examples* to give students a feel for how heat transfer is applied in engineering practice.
- To develop an *intuitive understanding* of heat transfer by emphasizing the physics and physical arguments.

It is our hope that this book, through its careful explanations of concepts and its use of numerous practical examples and figures, helps the students develop the necessary skills to bridge the gap between knowledge and the confidence for proper application of that knowledge.

In engineering practice, an understanding of the mechanisms of heat transfer is becoming increasingly important since heat transfer plays a crucial role in the design of vehicles, power plants, refrigerators, electronic devices, buildings, and bridges, among other things. Even a chef needs to have an intuitive understanding of the heat transfer mechanism in order to cook the food “right” by adjusting the rate of heat transfer. We may not be aware of it, but we already use the principles of heat transfer when seeking thermal comfort. We insulate our bodies by putting on heavy coats in winter, and we minimize heat gain by radiation by staying in shady places in summer. We speed up the cooling of hot food by blowing on it and keep warm in cold weather by cuddling up and thus minimizing the exposed surface area. That is, we already use heat transfer whether we realize it or not.



## GENERAL APPROACH

This text is the outcome of an attempt to have a textbook for a practically oriented heat transfer course for engineering students. The text covers the standard topics of heat transfer with an emphasis on physics and real-world applications. This approach is more in line with students' intuition, and makes learning the subject matter enjoyable.

The philosophy that contributed to the overwhelming popularity of the prior editions of this book has remained unchanged in this edition. Namely, our goal has been to offer an engineering textbook that

- Communicates directly to the minds of tomorrow's engineers in a *simple yet precise* manner.
- Leads students toward a clear understanding and firm grasp of the *basic principles* of heat transfer.
- Encourages *creative thinking* and development of a *deeper understanding* and *intuitive feel* for heat transfer.
- Is *read* by students with *interest* and *enthusiasm* rather than being used as an aid to solve problems.

Special effort has been made to appeal to students' natural curiosity and to help them explore the various facets of the exciting subject area of heat transfer. The enthusiastic response we received from the users of prior editions—from small colleges to large universities all over the world—indicates that our objectives have largely been achieved. It is our philosophy that the best way to learn is by practice. Therefore, special effort is made throughout the book to reinforce material that was presented earlier.

Yesterday's engineer spent a major portion of his or her time substituting values into the formulas and obtaining numerical results. However, now formula manipulations and number crunching are being left mainly to the computers. Tomorrow's engineer will have to have a clear understanding and a firm grasp of the *basic principles* so that he or she can understand even the most complex problems, formulate them, and interpret the results. A conscious effort is made to emphasize these basic principles while also providing students with a perspective at how computational tools are used in engineering practice.

## NEW IN THIS EDITION

Some of the primary changes in this fifth edition of the text include new and expanded coverage of heat transfer in biological systems, a new section on the general solutions to selected differential equations, and inclusion of example problems and end of chapter problems which incorporate the new Prevention through Design (PtD) concept. The concept of PtD involves proper use of design to promote safety and reduce accidents and injuries. We also have incorporated over 350 new problems. Each chapter, with the exception of Chapters 5 and 6, now contains one new solved example problem based on the concept of PtD, and a significant part of existing problems were modified. All the popular features of the previous editions are retained. The main body of all chapters, the organization of the text, and the tables and charts in the appendices remain mostly unchanged.



The fifth edition also includes **McGraw-Hill's Connect®** Engineering. This online homework management tool allows assignment of algorithmic problems for homework, quizzes and tests. It connects students with the tools and resources they'll need to achieve success. To learn more, visit [www.mcgrawhillconnect.com](http://www.mcgrawhillconnect.com)

**McGraw-Hill LearnSmart™** is also available as an integrated feature of McGraw-Hill Connect® Engineering. It is an adaptive learning system designed to help students learn faster, study more efficiently, and retain more knowledge for greater success. LearnSmart assesses a student's knowledge of course content through a series of adaptive questions. It pinpoints concepts the student does not understand and maps out a personalized study plan for success. Visit the following site for a demonstration: [www.mhlearnsmart.com](http://www.mhlearnsmart.com)

### FUNDAMENTALS OF ENGINEERING (FE) EXAM PROBLEMS

To prepare students for the Fundamentals of Engineering Exam and to facilitate multiple-choice tests, over 200 *multiple-choice problems* are included in the end-of-chapter problem sets of this edition also. They are placed under the title "Fundamentals of Engineering (FE) Exam Problems" for easy recognition. These problems are intended to check the understanding of fundamentals and to help readers avoid common pitfalls. The EES solutions of these problems are available for instructors for ease of facilitation and easy modification.

### PREVENTION THROUGH DESIGN (PtD) PROBLEMS

In 2007, the National Institute for Occupational Safety and Health launched the National Prevention through Design (PtD) initiative, with the mission to prevent or reduce work-related injuries, illnesses, and fatalities by including prevention considerations in all circumstances that impact individuals in the workplace. As such, the concept of PtD involves applying the means of reducing risks and preventing hazards in the design of equipment, tools, processes, and work facilities. The PtD concept is first introduced in Chapter 1. The idea of having example problems and end of chapter problems throughout the different chapters in the text is not only to simply provide discussions of interesting real world applications, but also to introduce the concepts of PtD to the minds of tomorrow's engineers whereby they may influence a change in culture toward more emphasis on safety designs.

### NEW COVERAGE OF HEAT TRANSFER IN BIOLOGICAL SYSTEMS

Thermal Comfort is presented as a Topic of Special Interest in Chapter 1. This section is expanded and the term *thermoregulation* is introduced in this section. Thermoregulation means the body has mechanisms to act as a thermostat, when the core body temperature deviates from the normal resting value. Thermoregulation in the human body is achieved by keeping a tight balance between heat gain and heat loss. The "Bioheat Transfer Equation" introduced in Chapter 3 is used to calculate the heat transfer between a human body and its surroundings. Thermoregulation can be adjusted by both behavioral changes and physiological changes. Behavioral changes could be relocating to a more desirable environment within the structure or putting on more clothing. Physiological changes include blood vessel diameter changes and the production of sweat. However, under normal conditions, few of these changes

are needed because of the efficient organization of arteries and veins; they are arranged as a counter-current heat exchanger. This concept is presented in Chapter 11 as a Topic of Special Interest “The Human Cardiovascular System as a Counter-Current Heat Exchanger”.

### EXPANDED COVERAGE OF MINI AND MICRO TUBES

Owing to the rapid advancement in fabrication techniques, the use of the miniaturized devices and components is ever increasing. Whether it is in the application of miniature heat exchangers, fuel cells, pumps, compressors, turbines, sensors, or artificial blood vessels, a sound understanding of fluid flow in micro-scale channels and tubes is essential. Microscale Heat Transfer is presented as a Topic of Special Interest in Chapter 6. This edition expands the coverage of plain mini and micro tubes to spiral micro-fin tubes in Chapter 8.

### THREE ONLINE APPLICATION CHAPTERS

The application chapters “Cooling of Electronic Equipment” (Chapter 15), “Heating and Cooling of Buildings” (Chapter 16), and “Refrigeration and Freezing of Foods” (Chapter 17) are available for download via the text website; go to [www.mhhe.com/cengel](http://www.mhhe.com/cengel) for detailed coverage of these topics.

### CONTENT CHANGES AND REORGANIZATION

With the exception of the changes already mentioned, minor changes are made in the main body of the text. Over 350 new problems are added, and a significant number of the existing problems are revised. The noteworthy changes in various chapters are summarized here for those who are familiar with the previous edition.

- In Chapter 1, the concept of Prevention through Design (PtD) has been introduced by Dr. Clement C. Tang of University of North Dakota. In addition, the coverage of Thermal Comfort presented as a Topic of Special Interest has been expanded by Dr. David A. Rubenstein of Stony Brook University.
- In Chapter 2, a new section “General Solution to Selected Differential Equations” is added.
- In Chapter 3, a new section “Bioheat Transfer Equation” is added.
- In Chapter 5, the section on “Interactive SS-T-CONDUCT Software” which introduced the software and demonstrated its use has been deleted and moved to text website. This information and the software are available from the online learning center ([www.mhhe.com/cengel](http://www.mhhe.com/cengel)) to the instructors and students. The software can be used to solve or to check the solutions of many of the one- and two-dimensional heat conduction problems with uniform energy generation in rectangular geometries.
- In Chapter 8, a new subsection “Fully Developed Transitional Flow Heat Transfer” is added. Also, the coverage of subsections on “Pressure Drop in the Transition Region” and “Heat Transfer in the Transition Region” of the Topic of Special Interest on Transitional Flow in Tubes has been expanded.
- In Chapter 10, the coverage of the Topic of Special Interest on “Non-Boiling Two-Phase Flow Heat Transfer” has been expanded and a new

subsection on “Application of Reynolds Analogy to Non-Boiling Two-Phase Flow” has been added.

- In Chapter 11, the coverage of Heat Exchangers has been expanded and this chapter now has the Topic of Special Interest “The Human Cardiovascular System as a Counter-Current Heat Exchanger” contributed by Dr. David A. Rubenstein of Stony Brook University.
- In Chapter 14, the section on Water Vapor Migration in Buildings has been expanded.

## LEARNING TOOLS

### EMPHASIS ON PHYSICS

The authors believe that the emphasis in undergraduate education should remain on *developing a sense of underlying physical mechanisms* and a *mastery of solving practical problems* that an engineer is likely to face in the real world.

### EFFECTIVE USE OF ASSOCIATION

An observant mind should have no difficulty understanding engineering sciences. After all, the principles of engineering sciences are based on our *everyday experiences and experimental observations*. The process of cooking, for example, serves as an excellent vehicle to demonstrate the basic principles of heat transfer.

### SELF-INSTRUCTING

The material in the text is introduced at a level that an average student can follow comfortably. It speaks *to* students, not *over* students. In fact, it is *self-instructive*. The order of coverage is from *simple* to *general*.

### EXTENSIVE USE OF ARTWORK

Art is an important learning tool that helps students “get the picture.” The fifth edition of *Heat and Mass Transfer: Fundamentals & Applications* contains more figures and illustrations than any other book in this category.

### LEARNING OBJECTIVES AND SUMMARIES

Each chapter begins with an *Overview* of the material to be covered and chapter-specific *Learning Objectives*. A *Summary* is included at the end of each chapter, providing a quick review of basic concepts and important relations, and pointing out the relevance of the material.

### NUMEROUS WORKED-OUT EXAMPLES WITH A SYSTEMATIC SOLUTIONS PROCEDURE

Each chapter contains several worked-out *examples* that clarify the material and illustrate the use of the basic principles. An *intuitive* and *systematic* approach is used in the solution of the example problems, while maintaining an informal conversational style. The problem is first stated, and the objectives are identified. The assumptions are then stated, together with their justifications. The properties needed to solve the problem are listed separately,

if appropriate. This approach is also used consistently in the solutions presented in the instructor's solutions manual.

## A WEALTH OF REAL-WORLD END-OF-CHAPTER PROBLEMS

The end-of-chapter problems are grouped under specific topics to make problem selection easier for both instructors and students. Within each group of problems are:

- **Concept Questions**, indicated by “C,” to check the students' level of understanding of basic concepts.
- **Review Problems** are more comprehensive in nature and are not directly tied to any specific section of a chapter—in some cases they require review of material learned in previous chapters.
- **Fundamentals of Engineering (FE) Exam Problems** are designed to help students prepare for the *Fundamentals of Engineering* exam, as they prepare for their Professional Engineering license.



These problems are “Prevention through Design” related problems.



These problems are solved using EES, and complete solutions together with parametric studies are included on the textbook's website.



These problems are comprehensive in nature and are intended to be solved with a computer, possibly using the EES software.

- **Design and Essay** are intended to encourage students to make engineering judgments, to conduct independent exploration of topics of interest, and to communicate their findings in a professional manner.

Several economics- and safety-related problems are incorporated throughout to enhance cost and safety awareness among engineering students. Answers to selected problems are listed immediately following the problem for convenience to students.

## A CHOICE OF SI ALONE OR SI/ENGLISH UNITS

In recognition of the fact that English units are still widely used in some industries, both SI and English units are used in this text, with an emphasis on SI. The material in this text can be covered using combined SI/English units or SI units alone, depending on the preference of the instructor. The property tables and charts in the appendices are presented in both units, except the ones that involve dimensionless quantities. Problems, tables, and charts in English units are designated by “E” after the number for easy recognition, and they can be ignored by SI users.

## TOPICS OF SPECIAL INTEREST

Most chapters contain a real world application, end-of-chapter optional section called “Topic of Special Interest” where interesting applications of heat transfer are discussed such as *Thermal Comfort* in Chapter 1, *Heat Transfer through the Walls and Roofs* in Chapter 3, *Microscale Heat Transfer* in Chapter 6, *Transitional Flow in Tubes* in Chapter 8, *Heat Transfer through Windows* in

Chapter 9, *Non-Boiling Two-Phase Flow Heat Transfer* in Chapter 10, *Human Cardiovascular System as a Counter-Current Heat Exchanger* in Chapter 11, and *Heat Transfer from the Human Body* in Chapter 13.

### CONVERSION FACTORS

Frequently used conversion factors and physical constants are listed on the inner cover pages of the text for easy reference.

### SUPPLEMENTS

The following supplements are available to the users of the book.

#### ENGINEERING EQUATION SOLVER (EES)

Developed by Sanford Klein and William Beckman from the University of Wisconsin—Madison, this software combines equation-solving capability and engineering property data. EES can do optimization, parametric analysis, and linear and nonlinear regression, and provides publication-quality plotting capabilities. Thermodynamics and transport properties for air, water, and many other fluids are built in, and EES allows the user to enter property data or functional relationships.

EES is a powerful equation solver with built-in functions and property tables for thermodynamic and transport properties as well as automatic unit checking capability. It requires less time than a calculator for data entry and allows more time for thinking critically about modeling and solving engineering problems. Look for the EES icons in the homework problems sections of the text.

The Limited Academic Version of EES is available for departmental license upon adoption of the Fifth Edition of *Heat and Mass Transfer: Fundamentals and Applications* (meaning that the text is required for students in the course). You may load this software onto your institution's computer system, for use by students and faculty related to the course, as long as the arrangement between McGraw-Hill Education and F-Chart is in effect. There are minimum order requirements stipulated by F-Chart to qualify.

#### TEXT WEBSITE

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Visit this website for general text information, errata, and author information. The site also includes resources for students including a list of helpful web links. The instructor side of the site includes the solutions manual, the text's images in PowerPoint form, and more!

#### COSMOS

(Available to Instructors Only)

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**Yunus A. Çengel**  
**Afshin J. Ghajar**

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## INTRODUCTION AND BASIC CONCEPTS

The science of thermodynamics deals with the *amount* of heat transfer as a system undergoes a process from one equilibrium state to another, and makes no reference to *how long* the process will take. But in engineering, we are often interested in the *rate* of heat transfer, which is the topic of the science of *heat transfer*.

We start this chapter with a review of the fundamental concepts of thermodynamics that form the framework for heat transfer. We first present the relation of heat to other forms of energy and review the energy balance. We then present the three basic mechanisms of heat transfer, which are conduction, convection, and radiation, and discuss thermal conductivity. *Conduction* is the transfer of energy from the more energetic particles of a substance to the adjacent, less energetic ones as a result of interactions between the particles. *Convection* is the mode of heat transfer between a solid surface and the adjacent liquid or gas that is in motion, and it involves the combined effects of conduction and fluid motion. *Radiation* is the energy emitted by matter in the form of electromagnetic waves (or photons) as a result of the changes in the electronic configurations of the atoms or molecules. We close this chapter with a discussion of simultaneous heat transfer.



### OBJECTIVES

When you finish studying this chapter, you should be able to:

- Understand how thermodynamics and heat transfer are related to each other,
- Distinguish thermal energy from other forms of energy, and heat transfer from other forms of energy transfer,
- Perform general energy balances as well as surface energy balances,
- Understand the basic mechanisms of heat transfer, which are conduction, convection, and radiation, and Fourier's law of heat conduction, Newton's law of cooling, and the Stefan–Boltzmann law of radiation,
- Identify the mechanisms of heat transfer that occur simultaneously in practice,
- Develop an awareness of the cost associated with heat losses, and
- Solve various heat transfer problems encountered in practice.



## 1-1 ■ THERMODYNAMICS AND HEAT TRANSFER

We all know from experience that a cold canned drink left in a room warms up and a warm canned drink left in a refrigerator cools down. This is accomplished by the transfer of *energy* from the warm medium to the cold one. The energy transfer is always from the higher temperature medium to the lower temperature one, and the energy transfer stops when the two mediums reach the same temperature.

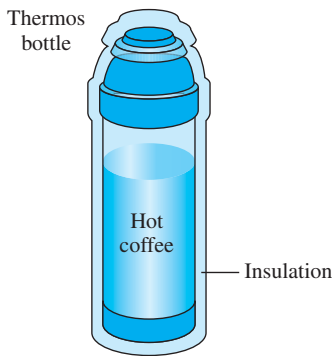
You will recall from thermodynamics that energy exists in various forms. In this text we are primarily interested in **heat**, which is *the form of energy that can be transferred from one system to another as a result of temperature difference*. The science that deals with the determination of the *rates* of such energy transfers is **heat transfer**.

You may be wondering why we need to undertake a detailed study on heat transfer. After all, we can determine the amount of heat transfer for any system undergoing any process using a thermodynamic analysis alone. The reason is that thermodynamics is concerned with the *amount* of heat transfer as a system undergoes a process from one equilibrium state to another, and it gives no indication about *how long* the process will take. A thermodynamic analysis simply tells us how much heat must be transferred to realize a specified change of state to satisfy the conservation of energy principle.

In practice we are more concerned about the rate of heat transfer (heat transfer per unit time) than we are with the amount of it. For example, we can determine the amount of heat transferred from a thermos bottle as the hot coffee inside cools from  $90^{\circ}\text{C}$  to  $80^{\circ}\text{C}$  by a thermodynamic analysis alone. But a typical user or designer of a thermos bottle is primarily interested in *how long* it will be before the hot coffee inside cools to  $80^{\circ}\text{C}$ , and a thermodynamic analysis cannot answer this question. Determining the rates of heat transfer to or from a system and thus the times of heating or cooling, as well as the variation of the temperature, is the subject of *heat transfer* (Fig. 1-1).

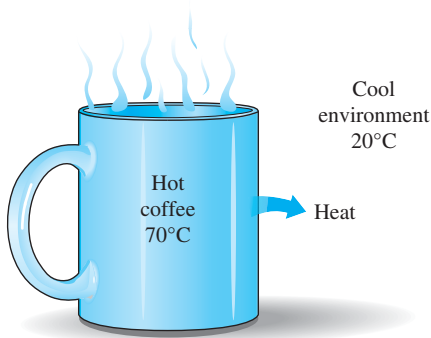
Thermodynamics deals with equilibrium states and changes from one equilibrium state to another. Heat transfer, on the other hand, deals with systems that lack thermal equilibrium, and thus it is a *nonequilibrium* phenomenon. Therefore, the study of heat transfer cannot be based on the principles of thermodynamics alone. However, the laws of thermodynamics lay the framework for the science of heat transfer. The *first law* requires that the rate of energy transfer into a system be equal to the rate of increase of the energy of that system. The *second law* requires that heat be transferred in the direction of decreasing temperature (Fig. 1-2). This is like a car parked on an inclined road must go downhill in the direction of decreasing elevation when its brakes are released. It is also analogous to the electric current flowing in the direction of decreasing voltage or the fluid flowing in the direction of decreasing total pressure.

The basic requirement for heat transfer is the presence of a *temperature difference*. There can be no net heat transfer between two bodies that are at the same temperature. The temperature difference is the *driving force* for heat transfer, just as the *voltage difference* is the driving force for electric current flow and *pressure difference* is the driving force for fluid flow. The rate of heat transfer in a certain direction depends on the magnitude of the *temperature gradient* (the temperature difference per unit length or the rate of change of temperature) in that direction. The larger the temperature gradient, the higher the rate of heat transfer.



**FIGURE 1-1**

We are normally interested in how long it takes for the hot coffee in a thermos bottle to cool to a certain temperature, which cannot be determined from a thermodynamic analysis alone.



**FIGURE 1-2**

Heat flows in the direction of decreasing temperature.

## Application Areas of Heat Transfer

Heat transfer is commonly encountered in engineering systems and other aspects of life, and one does not need to go very far to see some application areas of heat transfer. In fact, one does not need to go anywhere. The human body is constantly rejecting heat to its surroundings, and human comfort is closely tied to the rate of this heat rejection. We try to control this heat transfer rate by adjusting our clothing to the environmental conditions.

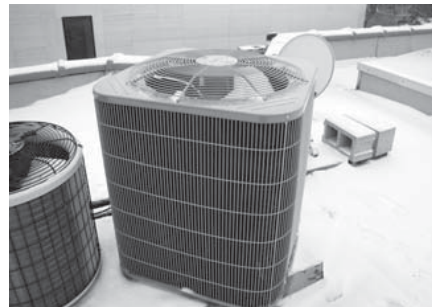
Many ordinary household appliances are designed, in whole or in part, by using the principles of heat transfer. Some examples include the electric or gas range, the heating and air-conditioning system, the refrigerator and freezer, the water heater, the iron, and even the computer, the TV, and the DVD player. Of course, energy-efficient homes are designed on the basis of minimizing heat loss in winter and heat gain in summer. Heat transfer plays a major role in the design of many other devices, such as car radiators, solar collectors, various components of power plants, and even spacecraft (Fig. 1–3). The optimal insulation thickness in the walls and roofs of the houses, on hot water or steam pipes, or on water heaters is again determined on the basis of a heat transfer analysis with economic consideration.

## Historical Background

Heat has always been perceived to be something that produces in us a sensation of warmth, and one would think that the nature of heat is one of the first



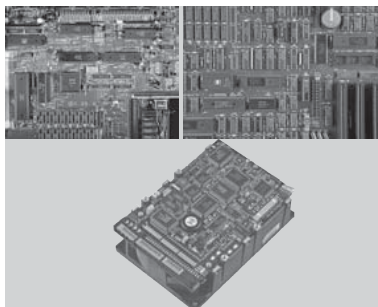
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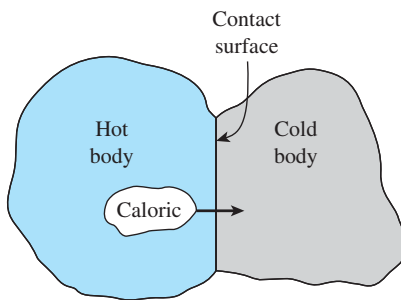
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**FIGURE 1–3**

Some application areas of heat transfer.



**FIGURE 1-4**

In the early nineteenth century, heat was thought to be an invisible fluid called the *caloric* that flowed from warmer bodies to the cooler ones.

things understood by mankind. But it was only in the middle of the nineteenth century that we had a true physical understanding of the nature of heat, thanks to the development at that time of the **kinetic theory**, which treats molecules as tiny balls that are in motion and thus possess kinetic energy. Heat is then defined as the energy associated with the random motion of atoms and molecules. Although it was suggested in the eighteenth and early nineteenth centuries that heat is the manifestation of motion at the molecular level (called the *live force*), the prevailing view of heat until the middle of the nineteenth century was based on the **caloric theory** proposed by the French chemist Antoine Lavoisier (1743–1794) in 1789. The caloric theory asserts that heat is a fluid-like substance called the **caloric** that is a massless, colorless, odorless, and tasteless substance that can be poured from one body into another (Fig. 1–4). When caloric was added to a body, its temperature increased; and when caloric was removed from a body, its temperature decreased. When a body could not contain any more caloric, much the same way as when a glass of water could not dissolve any more salt or sugar, the body was said to be saturated with caloric. This interpretation gave rise to the terms *saturated liquid* and *saturated vapor* that are still in use today.

The caloric theory came under attack soon after its introduction. It maintained that heat is a substance that could not be created or destroyed. Yet it was known that heat can be generated indefinitely by rubbing one's hands together or rubbing two pieces of wood together. In 1798, the American Benjamin Thompson (Count Rumford) (1753–1814) showed in his papers that heat can be generated continuously through friction. The validity of the caloric theory was also challenged by several others. But it was the careful experiments of the Englishman James P. Joule (Fig. 1–5) published in 1843 that finally convinced the skeptics that heat was not a substance after all, and thus put the caloric theory to rest. Although the caloric theory was totally abandoned in the middle of the nineteenth century, it contributed greatly to the development of thermodynamics and heat transfer.

## 1-2 ■ ENGINEERING HEAT TRANSFER

Heat transfer equipment such as heat exchangers, boilers, condensers, radiators, heaters, furnaces, refrigerators, and solar collectors are designed primarily on the basis of heat transfer analysis. The heat transfer problems encountered in practice can be considered in two groups: (1) *rating* and (2) *sizing* problems. The rating problems deal with the determination of the heat transfer rate for an existing system at a specified temperature difference. The sizing problems deal with the determination of the size of a system in order to transfer heat at a specified rate for a specified temperature difference.

An engineering device or process can be studied either *experimentally* (testing and taking measurements) or *analytically* (by analysis or calculations). The experimental approach has the advantage that we deal with the actual physical system, and the desired quantity is determined by measurement, within the limits of experimental error. However, this approach is expensive, timeconsuming, and often impractical. Besides, the system we are analyzing may not even exist. For example, the entire heating and plumbing systems of a building must usually be sized *before* the building is actually built on the basis of the specifications given. The analytical approach (including the

numerical approach) has the advantage that it is fast and inexpensive, but the results obtained are subject to the accuracy of the assumptions, approximations, and idealizations made in the analysis. In engineering studies, often a good compromise is reached by reducing the choices to just a few by analysis, and then verifying the findings experimentally.

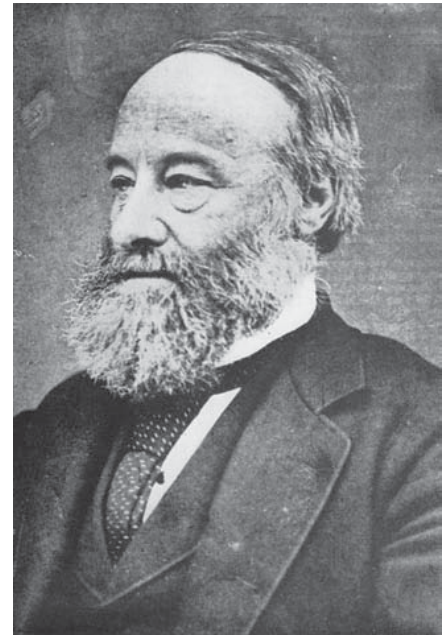
## Modeling in Engineering

The descriptions of most scientific problems involve equations that relate the changes in some key variables to each other. Usually the smaller the increment chosen in the changing variables, the more general and accurate the description. In the limiting case of infinitesimal or differential changes in variables, we obtain differential equations that provide precise mathematical formulations for the physical principles and laws by representing the rates of change as derivatives. Therefore, differential equations are used to investigate a wide variety of problems in sciences and engineering (Fig. 1–6). However, many problems encountered in practice can be solved without resorting to differential equations and the complications associated with them.

The study of physical phenomena involves two important steps. In the first step, all the variables that affect the phenomena are identified, reasonable assumptions and approximations are made, and the interdependence of these variables is studied. The relevant physical laws and principles are invoked, and the problem is formulated mathematically. The equation itself is very instructive as it shows the degree of dependence of some variables on others, and the relative importance of various terms. In the second step, the problem is solved using an appropriate approach, and the results are interpreted.

Many processes that seem to occur in nature randomly and without any order are, in fact, being governed by some visible or not-so-visible physical laws. Whether we notice them or not, these laws are there, governing consistently and predictably what seem to be ordinary events. Most of these laws are well defined and well understood by scientists. This makes it possible to predict the course of an event before it actually occurs, or to study various aspects of an event mathematically without actually running expensive and time-consuming experiments. This is where the power of analysis lies. Very accurate results to meaningful practical problems can be obtained with relatively little effort by using a suitable and realistic mathematical model. The preparation of such models requires an adequate knowledge of the natural phenomena involved and the relevant laws, as well as a sound judgment. An unrealistic model will obviously give inaccurate and thus unacceptable results.

An analyst working on an engineering problem often finds himself or herself in a position to make a choice between a very accurate but complex model, and a simple but not-so-accurate model. The right choice depends on the situation at hand. The right choice is usually the simplest model that yields adequate results. For example, the process of baking potatoes or roasting a round chunk of beef in an oven can be studied analytically in a simple way by modeling the potato or the roast as a spherical solid ball that has the properties of water (Fig. 1–7). The model is quite simple, but the results obtained are sufficiently accurate for most practical purposes. As another example, when we analyze the heat losses from a building in order to select the right size for a heater, we determine the heat losses under anticipated worst conditions and select a furnace that will provide sufficient energy to make up for those



**FIGURE 1–5**

**James Prescott Joule** (1818–1889) is a British physicist born in Salford, Lancashire, England. Joule is best

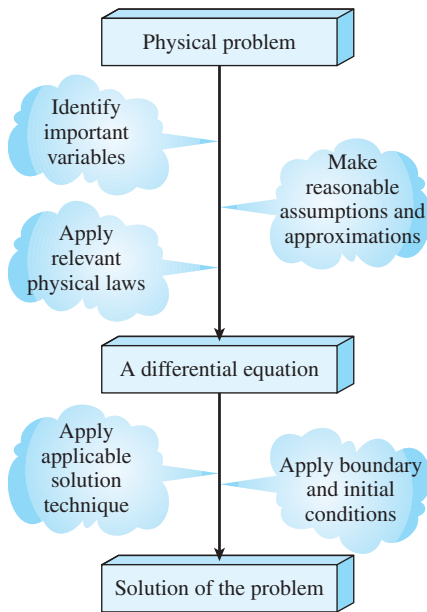
known for his work on the conversion of electrical and mechanical energy into heat and the first law of thermodynamics. The energy unit joule (J) is named after him. The Joule's law of electric heating that he formulated states that the rate of heat production in a conducting wire is proportional to the product of the resistance of the wire and the square of the electric current.

Through his experiments, Joule has demonstrated the mechanical equivalence of heat, i.e., the conversion of mechanical energy into an equivalent amount of thermal energy, which laid the foundation for the conservation of energy principle. Joule, together with William Thomson (later Lord Kelvin),

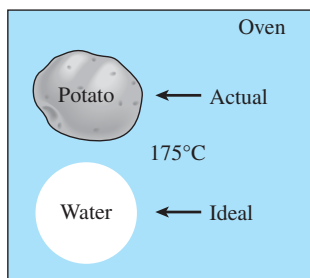
discovered the temperature drop of a substance during free expansion, a phenomenon known as the Joule-Thomson effect, which forms the foundation of the operation of the common vapor-compression refrigeration and air conditioning systems.

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**FIGURE 1-6**  
Mathematical modeling of physical problems.



**FIGURE 1-7**  
Modeling is a powerful engineering tool that provides great insight and simplicity at the expense of some accuracy.

losses. Often we tend to choose a larger furnace in anticipation of some future expansion, or just to provide a factor of safety. A very simple analysis is adequate in this case.

When selecting heat transfer equipment, it is important to consider the actual operating conditions. For example, when purchasing a heat exchanger that will handle hard water, we must consider that some calcium deposits will form on the heat transfer surfaces over time, causing fouling and thus a gradual decline in performance. The heat exchanger must be selected on the basis of operation under these adverse conditions instead of under new conditions.

Preparing very accurate but complex models is usually not so difficult. But such models are not much use to an analyst if they are very difficult and time-consuming to solve. At the minimum, the model should reflect the essential features of the physical problem it represents. There are many significant real-world problems that can be analyzed with a simple model. But it should always be kept in mind that the results obtained from an analysis are as accurate as the assumptions made in simplifying the problem. Therefore, the solution obtained should not be applied to situations for which the original assumptions do not hold.

A solution that is not quite consistent with the observed nature of the problem indicates that the mathematical model used is too crude. In that case, a more realistic model should be prepared by eliminating one or more of the questionable assumptions. This will result in a more complex problem that, of course, is more difficult to solve. Thus any solution to a problem should be interpreted within the context of its formulation.

### 1-3 ■ HEAT AND OTHER FORMS OF ENERGY

Energy can exist in numerous forms such as thermal, mechanical, kinetic, potential, electrical, magnetic, chemical, and nuclear, and their sum constitutes the **total energy**  $E$  (or  $e$  on a unit mass basis) of a system. The forms of energy related to the molecular structure of a system and the degree of the molecular activity are referred to as the *microscopic energy*. The sum of all microscopic forms of energy is called the **internal energy** of a system, and is denoted by  $U$  (or  $u$  on a unit mass basis).

The international unit of energy is *joule* (J) or *kilojoule* (1 kJ = 1000 J). In the English system, the unit of energy is the *British thermal unit* (Btu), which is defined as the energy needed to raise the temperature of 1 lbm of water at 60°F by 1°F. The magnitudes of kJ and Btu are almost identical (1 Btu = 1.055056 kJ). Another well known unit of energy is the *calorie* (1 cal = 4.1868 J), which is defined as the energy needed to raise the temperature of 1 gram of water at 14.5°C by 1°C.

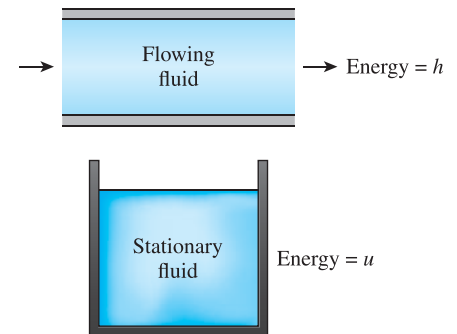
Internal energy may be viewed as the sum of the kinetic and potential energies of the molecules. The portion of the internal energy of a system associated with the kinetic energy of the molecules is called **sensible energy** or **sensible heat**. The average velocity and the degree of activity of the molecules are proportional to the temperature. Thus, at higher temperatures the molecules possess higher kinetic energy, and as a result, the system has a higher internal energy.

The internal energy is also associated with the intermolecular forces between the molecules of a system. These are the forces that bind the molecules to each

other, and, as one would expect, they are strongest in solids and weakest in gases. If sufficient energy is added to the molecules of a solid or liquid, they will overcome these molecular forces and simply break away, turning the system to a gas. This is a *phase change* process and because of this added energy, a system in the gas phase is at a higher internal energy level than it is in the solid or the liquid phase. The internal energy associated with the phase of a system is called **latent energy** or **latent heat**.

The changes mentioned above can occur without a change in the chemical composition of a system. Most heat transfer problems fall into this category, and one does not need to pay any attention to the forces binding the atoms in a molecule together. The internal energy associated with the atomic bonds in a molecule is called **chemical** (or **bond**) **energy**, whereas the internal energy associated with the bonds within the nucleus of the atom itself is called **nuclear energy**. The chemical and nuclear energies are absorbed or released during chemical or nuclear reactions, respectively.

In the analysis of systems that involve fluid flow, we frequently encounter the combination of properties  $u$  and  $Pv$ . For the sake of simplicity and convenience, this combination is defined as **enthalpy**  $h$ . That is,  $h = u + Pv$  where the term  $Pv$  represents the *flow energy* of the fluid (also called the *flow work*), which is the energy needed to push a fluid and to maintain flow. In the energy analysis of flowing fluids, it is convenient to treat the flow energy as part of the energy of the fluid and to represent the microscopic energy of a fluid stream by enthalpy  $h$  (Fig. 1–8).



**FIGURE 1–8**

The *internal energy*  $u$  represents the microscopic energy of a nonflowing fluid, whereas *enthalpy*  $h$  represents the microscopic energy of a flowing fluid.

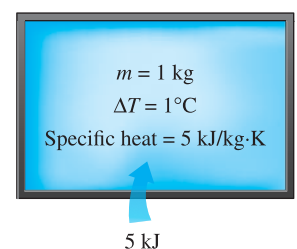
## Specific Heats of Gases, Liquids, and Solids

You may recall that an **ideal gas** is defined as a gas that obeys the relation

$$Pv = RT \quad \text{or} \quad P = \rho RT \quad (1-1)$$

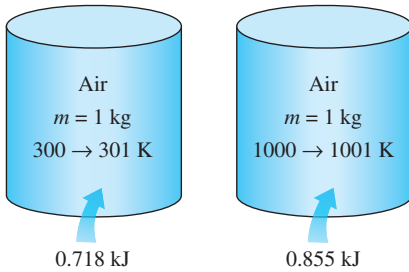
where  $P$  is the absolute pressure,  $v$  is the specific volume,  $T$  is the thermodynamic (or absolute) temperature,  $\rho$  is the density, and  $R$  is the gas constant. It has been experimentally observed that the ideal gas relation given above closely approximates the  $P$ - $v$ - $T$  behavior of real gases at low densities. At low pressures and high temperatures, the density of a gas decreases and the gas behaves like an ideal gas. In the range of practical interest, many familiar gases such as air, nitrogen, oxygen, hydrogen, helium, argon, neon, and krypton and even heavier gases such as carbon dioxide can be treated as ideal gases with negligible error (often less than one percent). Dense gases such as water vapor in steam power plants and refrigerant vapor in refrigerators, however, should not always be treated as ideal gases since they usually exist at a state near saturation.

You may also recall that **specific heat** is defined as *the energy required to raise the temperature of a unit mass of a substance by one degree* (Fig. 1–9). In general, this energy depends on how the process is executed. We are usually interested in two kinds of specific heats: specific heat at constant volume  $c_v$  and specific heat at constant pressure  $c_p$ . The **specific heat at constant volume**  $c_v$  can be viewed as the energy required to raise the temperature of a unit mass of a substance by one degree as the volume is held constant. The energy required to do the same as the pressure is held constant is the **specific heat at constant pressure**  $c_p$ . The specific heat at constant pressure  $c_p$  is greater



**FIGURE 1–9**

Specific heat is the energy required to raise the temperature of a unit mass of a substance by one degree in a specified way.



**FIGURE 1-10**

The specific heat of a substance changes with temperature.

than  $c_v$  because at constant pressure the system is allowed to expand and the energy for this expansion work must also be supplied to the system. For ideal gases, these two specific heats are related to each other by  $c_p = c_v + R$ .

A common unit for specific heats is  $\text{kJ/kg}\cdot^\circ\text{C}$  or  $\text{kJ/kg}\cdot\text{K}$ . Notice that these two units are *identical* since  $\Delta T(^\circ\text{C}) = \Delta T(\text{K})$ , and  $1^\circ\text{C}$  change in temperature is equivalent to a change of 1 K. Also,

$$1 \text{ kJ/kg}\cdot^\circ\text{C} \equiv 1 \text{ J/g}\cdot^\circ\text{C} \equiv 1 \text{ kJ/kg}\cdot\text{K} \equiv 1 \text{ J/g}\cdot\text{K}$$

The specific heats of a substance, in general, depend on two independent properties such as temperature and pressure. For an *ideal gas*, however, they depend on *temperature* only (Fig. 1-10). At low pressures all real gases approach ideal gas behavior, and therefore their specific heats depend on temperature only.

The differential changes in the internal energy  $u$  and enthalpy  $h$  of an ideal gas can be expressed in terms of the specific heats as

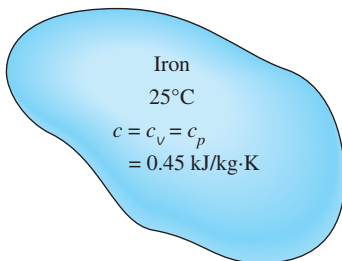
$$du = c_v dT \quad \text{and} \quad dh = c_p dT \quad (1-2)$$

The finite changes in the internal energy and enthalpy of an ideal gas during a process can be expressed approximately by using specific heat values at the average temperature as

$$\Delta u = c_{v, \text{avg}} \Delta T \quad \text{and} \quad \Delta h = c_{p, \text{avg}} \Delta T \quad (\text{J/g}) \quad (1-3)$$

or

$$\Delta U = mc_{v, \text{avg}} \Delta T \quad \text{and} \quad \Delta H = mc_{p, \text{avg}} \Delta T \quad (\text{J}) \quad (1-4)$$



**FIGURE 1-11**

The  $c_v$  and  $c_p$  values of incompressible substances are identical and are denoted by  $c$ .

where  $m$  is the mass of the system.

A substance whose specific volume (or density) does not change with temperature or pressure is called an **incompressible substance**. The specific volumes of solids and liquids essentially remain constant during a process, and thus they can be approximated as incompressible substances without sacrificing much in accuracy.

The constant-volume and constant-pressure specific heats are identical for incompressible substances (Fig. 1-11). Therefore, for solids and liquids the subscripts on  $c_v$  and  $c_p$  can be dropped and both specific heats can be represented by a single symbol,  $c$ . That is,  $c_p \cong c_v \cong c$ . This result could also be deduced from the physical definitions of constant-volume and constant-pressure specific heats. Specific heats of several common gases, liquids, and solids are given in the Appendix.

The specific heats of incompressible substances depend on temperature only. Therefore, the change in the internal energy of solids and liquids can be expressed as

$$\Delta U = mc_{\text{avg}} \Delta T \quad (\text{J}) \quad (1-5)$$

where  $c_{\text{avg}}$  is the average specific heat evaluated at the average temperature. Note that the internal energy change of the systems that remain in a single phase (liquid, solid, or gas) during the process can be determined very easily using average specific heats.

## Energy Transfer

Energy can be transferred to or from a given mass by two mechanisms: *heat transfer*  $Q$  and *work*  $W$ . An energy interaction is heat transfer if its driving force is a temperature difference. Otherwise, it is work. A rising piston, a rotating shaft, and an electrical wire crossing the system boundaries are all associated with work interactions. Work done *per unit time* is called **power**, and is denoted by  $\dot{W}$ . The unit of power is W or hp (1 hp = 746 W). Car engines and hydraulic, steam, and gas turbines produce work; compressors, pumps, and mixers consume work. Notice that the energy of a system decreases as it does work, and increases as work is done on it.

In daily life, we frequently refer to the sensible and latent forms of internal energy as **heat**, and we talk about the heat content of bodies (Fig. 1–12). In thermodynamics, however, those forms of energy are usually referred to as **thermal energy** to prevent any confusion with *heat transfer*.

The term *heat* and the associated phrases such as *heat flow*, *heat addition*, *heat rejection*, *heat absorption*, *heat gain*, *heat loss*, *heat storage*, *heat generation*, *electrical heating*, *latent heat*, *body heat*, and *heat source* are in common use today, and the attempt to replace *heat* in these phrases by *thermal energy* had only limited success. These phrases are deeply rooted in our vocabulary and they are used by both ordinary people and scientists without causing any misunderstanding. For example, the phrase *body heat* is understood to mean the *thermal energy content* of a body. Likewise, *heat flow* is understood to mean the *transfer of thermal energy*, not the flow of a fluid-like substance called *heat*, although the latter incorrect interpretation, based on the caloric theory, is the origin of this phrase. Also, the transfer of heat into a system is frequently referred to as *heat addition* and the transfer of heat out of a system as *heat rejection*.

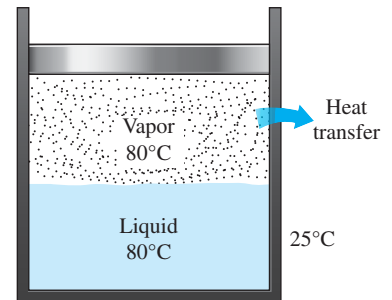
Keeping in line with current practice, we will refer to the thermal energy as *heat* and the transfer of thermal energy as *heat transfer*. The amount of heat transferred during the process is denoted by  $Q$ . The amount of heat transferred per unit time is called **heat transfer rate**, and is denoted by  $\dot{Q}$ . The overdot stands for the time derivative, or “per unit time.” The heat transfer rate  $\dot{Q}$  has the unit J/s, which is equivalent to W.

When the *rate* of heat transfer  $\dot{Q}$  is available, then the total amount of heat transfer  $Q$  during a time interval  $\Delta t$  can be determined from

$$Q = \int_0^{\Delta t} \dot{Q} dt \quad (\text{J}) \quad (1-6)$$

provided that the variation of  $\dot{Q}$  with time is known. For the special case of  $\dot{Q} = \text{constant}$ , the equation above reduces to

$$Q = \dot{Q} \Delta t \quad (\text{J}) \quad (1-7)$$



**FIGURE 1–12**

The sensible and latent forms of internal energy can be transferred as a result of a temperature difference, and they are referred to as *heat* or *thermal energy*.



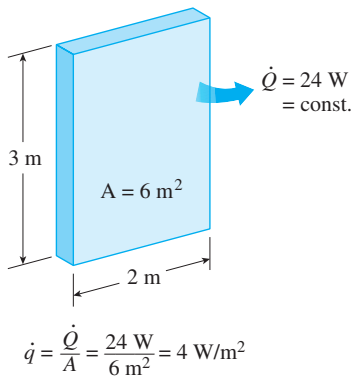


FIGURE 1–13

Heat flux is heat transfer *per unit time* and *per unit area*, and is equal to  $\dot{q} = \dot{Q}/A$  when  $\dot{Q}$  is uniform over the area  $A$ .

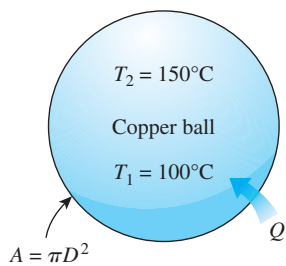


FIGURE 1–14

Schematic for Example 1–1.

The rate of heat transfer per unit area normal to the direction of heat transfer is called **heat flux**, and the average heat flux is expressed as (Fig. 1–13)

$$\dot{q} = \frac{\dot{Q}}{A} \quad (\text{W/m}^2) \quad (1-8)$$

where  $A$  is the heat transfer area. The unit of heat flux in English units is  $\text{Btu/h}\cdot\text{ft}^2$ . Note that heat flux may vary with time as well as position on a surface.

### EXAMPLE 1–1 Heating of a Copper Ball

A 10-cm-diameter copper ball is to be heated from  $100^\circ\text{C}$  to an average temperature of  $150^\circ\text{C}$  in 30 minutes (Fig. 1–14). Taking the average density and specific heat of copper in this temperature range to be  $\rho = 8950 \text{ kg/m}^3$  and  $c_p = 0.395 \text{ kJ/kg}\cdot^\circ\text{C}$ , respectively, determine (a) the total amount of heat transfer to the copper ball, (b) the average rate of heat transfer to the ball, and (c) the average heat flux.

**SOLUTION** The copper ball is to be heated from  $100^\circ\text{C}$  to  $150^\circ\text{C}$ . The total heat transfer, the average rate of heat transfer, and the average heat flux are to be determined.

**Assumptions** Constant properties can be used for copper at the average temperature.

**Properties** The average density and specific heat of copper are given to be  $\rho = 8950 \text{ kg/m}^3$  and  $c_p = 0.395 \text{ kJ/kg}\cdot^\circ\text{C}$ .

**Analysis** (a) The amount of heat transferred to the copper ball is simply the change in its internal energy, and is determined from

Energy transfer to the system = Energy increase of the system

$$Q = \Delta U = mc_{\text{avg}}(T_2 - T_1)$$

where

$$m = \rho V = \frac{\pi}{6}\rho D^3 = \frac{\pi}{6}(8950 \text{ kg/m}^3)(0.1 \text{ m})^3 = 4.686 \text{ kg}$$

Substituting,

$$Q = (4.686 \text{ kg})(0.395 \text{ kJ/kg}\cdot^\circ\text{C})(150 - 100)^\circ\text{C} = \mathbf{92.6 \text{ kJ}}$$

Therefore, 92.6 kJ of heat needs to be transferred to the copper ball to heat it from  $100^\circ\text{C}$  to  $150^\circ\text{C}$ .

(b) The rate of heat transfer normally changes during a process with time. However, we can determine the *average* rate of heat transfer by dividing the total amount of heat transfer by the time interval. Therefore,

$$\dot{Q}_{\text{avg}} = \frac{Q}{\Delta t} = \frac{92.6 \text{ kJ}}{1800 \text{ s}} = 0.0514 \text{ kJ/s} = \mathbf{51.4 \text{ W}}$$

(c) Heat flux is defined as the heat transfer per unit time per unit area, or the rate of heat transfer per unit area. Therefore, the average heat flux in this case is

$$\dot{q}_{\text{avg}} = \frac{\dot{Q}_{\text{avg}}}{A} = \frac{\dot{Q}_{\text{avg}}}{\pi D^2} = \frac{51.4 \text{ W}}{\pi(0.1 \text{ m})^2} = 1636 \text{ W/m}^2$$

**Discussion** Note that heat flux may vary with location on a surface. The value calculated above is the *average* heat flux over the entire surface of the ball.

## 1-4 ■ THE FIRST LAW OF THERMODYNAMICS

The **first law of thermodynamics**, also known as the **conservation of energy principle**, states that *energy can neither be created nor destroyed during a process; it can only change forms*. Therefore, every bit of energy must be accounted for during a process. The conservation of energy principle (or the energy balance) for *any system* undergoing *any process* may be expressed as follows: *The net change (increase or decrease) in the total energy of the system during a process is equal to the difference between the total energy entering and the total energy leaving the system during that process*. That is

$$\left( \begin{array}{c} \text{Total energy} \\ \text{entering the} \\ \text{system} \end{array} \right) - \left( \begin{array}{c} \text{Total energy} \\ \text{leaving the} \\ \text{system} \end{array} \right) = \left( \begin{array}{c} \text{Change in the} \\ \text{total energy of} \\ \text{the system} \end{array} \right) \quad (1-9)$$

Noting that energy can be transferred to or from a system by *heat*, *work*, and *mass flow*, and that the total energy of a simple compressible system consists of internal, kinetic, and potential energies, the **energy balance** for any system undergoing any process can be expressed as

$$\underbrace{E_{\text{in}} - E_{\text{out}}}_{\substack{\text{Net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{\Delta E_{\text{system}}}_{\substack{\text{Change in internal, kinetic,} \\ \text{potential, etc., energies}}} \quad (\text{J}) \quad (1-10)$$

or, in the **rate form**, as

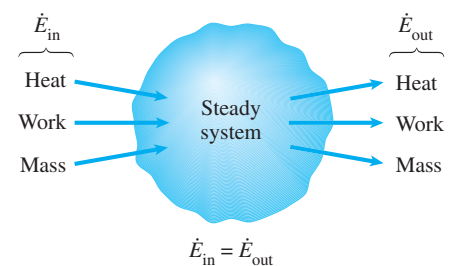
$$\underbrace{\dot{E}_{\text{in}} - \dot{E}_{\text{out}}}_{\substack{\text{Rate of net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{dE_{\text{system}}/dt}_{\substack{\text{Rate of change in internal} \\ \text{kinetic, potential, etc., energies}}} \quad (\text{W}) \quad (1-11)$$

Energy is a property, and the value of a property does not change unless the state of the system changes. Therefore, the energy change of a system is zero ( $\Delta E_{\text{system}} = 0$ ) if the state of the system does not change during the process, that is, the process is steady. The energy balance in this case reduces to (Fig. 1-15)

*Steady, rate form:*

$$\underbrace{\dot{E}_{\text{in}}}_{\substack{\text{Rate of net energy transfer in} \\ \text{by heat, work, and mass}}} = \underbrace{\dot{E}_{\text{out}}}_{\substack{\text{Rate of net energy transfer out} \\ \text{by heat, work, and mass}}} \quad (1-12)$$

In the absence of significant electric, magnetic, motion, gravity, and surface tension effects (i.e., for stationary simple compressible systems), the change



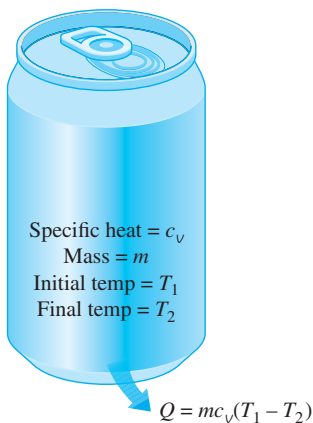
**FIGURE 1-15**

In steady operation, the rate of energy transfer to a system is equal to the rate of energy transfer from the system.

in the *total energy* of a system during a process is simply the change in its *internal energy*. That is,  $\Delta E_{\text{system}} = \Delta U_{\text{system}}$ .

In heat transfer analysis, we are usually interested only in the forms of energy that can be transferred as a result of a temperature difference, that is, heat or thermal energy. In such cases it is convenient to write a **heat balance** and to treat the conversion of nuclear, chemical, mechanical, and electrical energies into thermal energy as *heat generation*. The *energy balance* in that case can be expressed as

$$\underbrace{Q_{\text{in}} - Q_{\text{out}}}_{\text{Net heat transfer}} + \underbrace{E_{\text{gen}}}_{\text{Heat generation}} = \underbrace{\Delta E_{\text{thermal, system}}}_{\text{Change in thermal energy of the system}} \quad (\text{J}) \quad (1-13)$$



**FIGURE 1-16**

In the absence of any work interactions, the change in the energy content of a closed system is equal to the net heat transfer.

## Energy Balance for Closed Systems (*Fixed Mass*)

A closed system consists of a *fixed mass*. The total energy  $E$  for most systems encountered in practice consists of the internal energy  $U$ . This is especially the case for stationary systems since they don't involve any changes in their velocity or elevation during a process. The energy balance relation in that case reduces to

$$\text{Stationary closed system:} \quad E_{\text{in}} - E_{\text{out}} = \Delta U = mc_v\Delta T \quad (\text{J}) \quad (1-14)$$

where we expressed the internal energy change in terms of mass  $m$ , the specific heat at constant volume  $c_v$ , and the temperature change  $\Delta T$  of the system. When the system involves heat transfer only and no work interactions across its boundary, the energy balance relation further reduces to (Fig. 1-16)

$$\text{Stationary closed system, no work:} \quad Q = mc_v\Delta T \quad (\text{J}) \quad (1-15)$$

where  $Q$  is the net amount of heat transfer to or from the system. This is the form of the energy balance relation we will use most often when dealing with a fixed mass.

## Energy Balance for Steady-Flow Systems

A large number of engineering devices such as water heaters and car radiators involve mass flow in and out of a system, and are modeled as *control volumes*. Most control volumes are analyzed under steady operating conditions. The term *steady* means *no change with time* at a specified location. The opposite of steady is *unsteady* or *transient*. Also, the term *uniform* implies *no change with position* throughout a surface or region at a specified time. These meanings are consistent with their everyday usage (steady girlfriend, uniform distribution, etc.). The total energy content of a control volume during a *steady-flow process* remains constant ( $E_{\text{CV}} = \text{constant}$ ). That is, the change in the total energy of the control volume during such a process is zero ( $\Delta E_{\text{CV}} = 0$ ). Thus the amount of energy entering a control volume in all forms (heat, work, mass transfer) for a steady-flow process must be equal to the amount of energy leaving it.

The amount of mass flowing through a cross section of a flow device per unit time is called the **mass flow rate**, and is denoted by  $\dot{m}$ . A fluid may flow in and out of a control volume through pipes or ducts. The mass flow

rate of a fluid flowing in a pipe or duct is proportional to the cross-sectional area  $A_c$  of the pipe or duct, the density  $\rho$ , and the velocity  $V$  of the fluid. The mass flow rate through a differential area  $dA_c$  can be expressed as  $\delta\dot{m} = \rho V_n dA_c$  where  $V_n$  is the velocity component normal to  $dA_c$ . The mass flow rate through the entire cross-sectional area is obtained by integration over  $A_c$ .

The flow of a fluid through a pipe or duct can often be approximated to be *one-dimensional*. That is, the properties can be assumed to vary in one direction only (the direction of flow). As a result, all properties are assumed to be uniform at any cross section normal to the flow direction, and the properties are assumed to have *bulk average values* over the entire cross section. Under the one-dimensional flow approximation, the mass flow rate of a fluid flowing in a pipe or duct can be expressed as (Fig. 1–17)

$$\dot{m} = \rho VA_c \quad (\text{kg/s}) \quad (1-16)$$

where  $\rho$  is the fluid density,  $V$  is the average fluid velocity in the flow direction, and  $A_c$  is the cross-sectional area of the pipe or duct.

The volume of a fluid flowing through a pipe or duct per unit time is called the **volume flow rate**  $\dot{V}$ , and is expressed as

$$\dot{V} = VA_c = \frac{\dot{m}}{\rho} \quad (\text{m}^3/\text{s}) \quad (1-17)$$

Note that the mass flow rate of a fluid through a pipe or duct remains constant during steady flow. This is not the case for the volume flow rate, however, unless the density of the fluid remains constant.

For a steady-flow system with one inlet and one exit, the rate of mass flow into the control volume must be equal to the rate of mass flow out of it. That is,  $\dot{m}_{\text{in}} = \dot{m}_{\text{out}} = \dot{m}$ . When the changes in kinetic and potential energies are negligible, which is usually the case, and there is no work interaction, the energy balance for such a steady-flow system reduces to (Fig. 1–18)

$$\dot{Q} = \dot{m} \Delta h = \dot{m} c_p \Delta T \quad (\text{kJ/s}) \quad (1-18)$$

where  $\dot{Q}$  is the rate of net heat transfer into or out of the control volume. This is the form of the energy balance relation that we will use most often for steady-flow systems.

## Surface Energy Balance

As mentioned in the chapter opener, heat is transferred by the mechanisms of conduction, convection, and radiation, and heat often changes vehicles as it is transferred from one medium to another. For example, the heat conducted to the outer surface of the wall of a house in winter is convected away by the cold outdoor air while being radiated to the cold surroundings. In such cases, it may be necessary to keep track of the energy interactions at the surface, and this is done by applying the conservation of energy principle to the surface.

A surface contains no volume or mass, and thus no energy. Therefore, a surface can be viewed as a fictitious system whose energy content remains

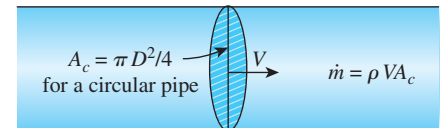


FIGURE 1–17

The mass flow rate of a fluid at a cross section is equal to the product of the fluid density, average fluid velocity, and the cross-sectional area.

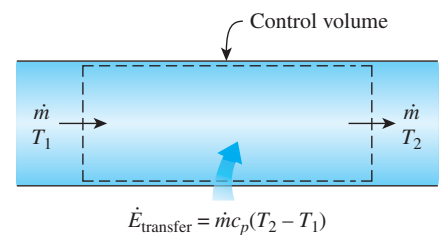


FIGURE 1–18

Under steady conditions, the net rate of energy transfer to a fluid in a control volume is equal to the rate of increase in the energy of the fluid stream flowing through the control volume.

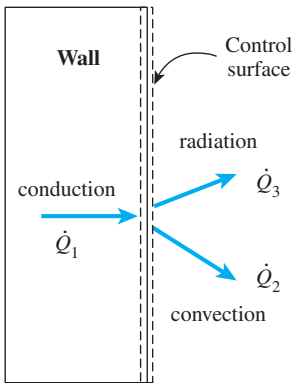


FIGURE 1-19

Energy interactions at the outer wall surface of a house.

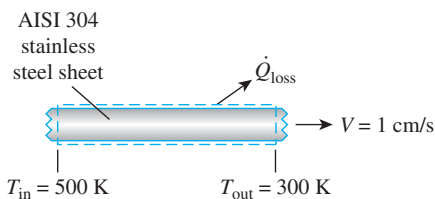


FIGURE 1-20

Schematic for Example 1-2.

constant during a process (just like a steady-state or steady-flow system). Then the energy balance for a surface can be expressed as

$$\text{Surface energy balance:} \quad \dot{E}_{\text{in}} = \dot{E}_{\text{out}} \quad (1-19)$$

This relation is valid for both steady and transient conditions, and the surface energy balance does not involve heat generation since a surface does not have a volume. The energy balance for the outer surface of the wall in Fig. 1-19, for example, can be expressed as

$$\dot{Q}_1 = \dot{Q}_2 + \dot{Q}_3 \quad (1-20)$$

where  $\dot{Q}_1$  is conduction through the wall to the surface,  $\dot{Q}_2$  is convection from the surface to the outdoor air, and  $\dot{Q}_3$  is net radiation from the surface to the surroundings.

When the directions of interactions are not known, all energy interactions can be assumed to be towards the surface, and the surface energy balance can be expressed as  $\sum \dot{E}_{\text{in}} = 0$ . Note that the interactions in opposite direction will end up having negative values, and balance this equation.

### EXAMPLE 1-2 Cooling of Stainless Steel Sheets

A heated continuous AISI 304 stainless steel sheet is being conveyed at a constant speed of 1 cm/s into a chamber to be cooled (Fig. 1-20). The stainless steel sheet is 5 mm thick and 2 m wide, and it enters and exits the chamber at 500 K and 300 K, respectively. Determine the rate of heat loss from the stainless steel sheet inside the chamber.

**SOLUTION** The rate of heat loss from a stainless steel sheet being conveyed inside a chamber is to be determined.

**Assumptions** 1 Steady operating conditions exist. 2 The stainless steel sheet has constant properties. 3 Changes in potential and kinetic energy are negligible.

**Properties** The constant pressure specific heat of AISI 304 stainless steel at the average temperature of  $(500 + 300)/2 = 400$  K is 515 J/kg·K. The density of AISI 304 stainless steel is 7900 kg/m<sup>3</sup> (Table A-3).

**Analysis** The mass of the stainless steel sheet being conveyed enters and exits the chamber at a rate of

$$\begin{aligned} \dot{m} &= \rho V w t \\ &= (7900 \text{ kg/m}^3)(0.01 \text{ m/s})(2 \text{ m})(0.005 \text{ m}) \\ &= 0.79 \text{ kg/s} \end{aligned}$$

The rate of heat loss from the stainless steel sheet in the chamber can be determined as

$$\begin{aligned} \dot{Q}_{\text{loss}} &= \dot{m} c_p (T_{\text{in}} - T_{\text{out}}) \\ &= (0.79 \text{ kg/s})(515 \text{ J/kg}\cdot\text{K})(500 - 300)\text{K} = 81370 \text{ J/s} \\ &= \mathbf{81.4 \text{ kW}} \end{aligned}$$

**Discussion** The stainless steel sheet being conveyed in and out of the chamber is treated as a control volume.

**EXAMPLE 1–3 Heat Loss from Heating Ducts in a Basement**

A 5-m-long section of an air heating system of a house passes through an unheated space in the basement (Fig. 1–21). The cross section of the rectangular duct of the heating system is 20 cm  $\times$  25 cm. Hot air enters the duct at 100 kPa and 60°C at an average velocity of 5 m/s. The temperature of the air in the duct drops to 54°C as a result of heat loss to the cool space in the basement. Determine the rate of heat loss from the air in the duct to the basement under steady conditions. Also, determine the cost of this heat loss per hour if the house is heated by a natural gas furnace that has an efficiency of 80 percent, and the cost of the natural gas in that area is \$1.60/therm (1 therm = 100,000 Btu = 105,500 kJ).

**SOLUTION** The temperature of the air in the heating duct of a house drops as a result of heat loss to the cool space in the basement. The rate of heat loss from the hot air and its cost are to be determined.

**Assumptions** 1 Steady operating conditions exist. 2 Air can be treated as an ideal gas with constant properties at room temperature.

**Properties** The constant pressure specific heat of air at the average temperature of  $(54 + 60)/2 = 57^\circ\text{C}$  is 1.007 kJ/kg $\cdot$ K (Table A–15).

**Analysis** We take the basement section of the heating system as our system, which is a steady-flow system. The rate of heat loss from the air in the duct can be determined from

$$\dot{Q} = \dot{m}c_p\Delta T$$

where  $\dot{m}$  is the mass flow rate and  $\Delta T$  is the temperature drop. The density of air at the inlet conditions is

$$\rho = \frac{P}{RT} = \frac{100 \text{ kPa}}{(0.287 \text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(60 + 273)\text{K}} = 1.046 \text{ kg/m}^3$$

The cross-sectional area of the duct is

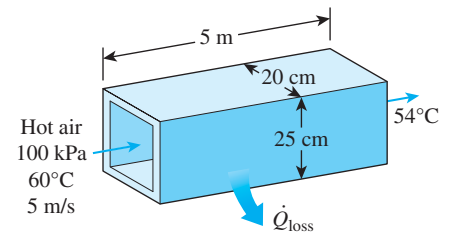
$$A_c = (0.20 \text{ m})(0.25 \text{ m}) = 0.05 \text{ m}^2$$

Then the mass flow rate of air through the duct and the rate of heat loss become

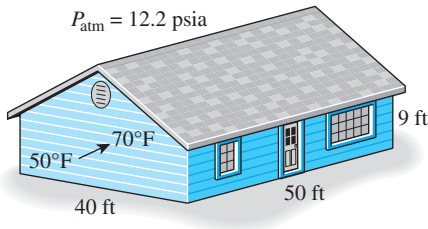
$$\dot{m} = \rho VA_c = (1.046 \text{ kg/m}^3)(5 \text{ m/s})(0.05 \text{ m}^2) = 0.2615 \text{ kg/s}$$

and

$$\begin{aligned}\dot{Q}_{\text{loss}} &= \dot{m}c_p(T_{\text{in}} - T_{\text{out}}) \\ &= (0.2615 \text{ kg/s})(1.007 \text{ kJ/kg}\cdot^\circ\text{C})(60 - 54)^\circ\text{C} \\ &= \mathbf{1.58 \text{ kJ/s}}\end{aligned}$$



**FIGURE 1–21**  
Schematic for Example 1–3.



**FIGURE 1-22**  
Schematic for Example 1-4.

or 5688 kJ/h. The cost of this heat loss to the home owner is

$$\begin{aligned}\text{Cost of heat loss} &= \frac{(\text{Rate of heat loss})(\text{Unit cost of energy input})}{\text{Furnace efficiency}} \\ &= \frac{(5688 \text{ kJ/h})(\$1.60/\text{therm}) \left( \frac{1 \text{ therm}}{105,500 \text{ kJ}} \right)}{0.80} \\ &= \mathbf{\$0.108/h}\end{aligned}$$

**Discussion** The heat loss from the heating ducts in the basement is costing the home owner 10.8 cents per hour. Assuming the heater operates 2000 hours during a heating season, the annual cost of this heat loss adds up to \$216. Most of this money can be saved by insulating the heating ducts in the unheated areas.

#### EXAMPLE 1-4 Electric Heating of a House at High Elevation

Consider a house that has a floor space of 2000 ft<sup>2</sup> and an average height of 9 ft at 5000 ft elevation where the standard atmospheric pressure is 12.2 psia (Fig. 1-22). Initially the house is at a uniform temperature of 50°F. Now the electric heater is turned on, and the heater runs until the air temperature in the house rises to an average value of 70°F. Determine the amount of energy transferred to the air assuming (a) the house is air-tight and thus no air escapes during the heating process and (b) some air escapes through the cracks as the heated air in the house expands at constant pressure. Also determine the cost of this heat for each case if the cost of electricity in that area is \$0.075/kWh.

**SOLUTION** The air in the house is heated by an electric heater. The amount and cost of the energy transferred to the air are to be determined for constant-volume and constant-pressure cases.

**Assumptions** 1 Air can be treated as an ideal gas with constant properties. 2 Heat loss from the house during heating is negligible. 3 The volume occupied by the furniture and other things is negligible.

**Properties** The specific heats of air at the average temperature of  $(50 + 70)/2 = 60^\circ\text{F}$  are  $c_p = 0.240 \text{ Btu/lbm}\cdot\text{R}$  and  $c_v = c_p - R = 0.171 \text{ Btu/lbm}\cdot\text{R}$  (Tables A-1E and A-15E).

**Analysis** The volume and the mass of the air in the house are

$$\begin{aligned}V &= (\text{Floor area})(\text{Height}) = (2000 \text{ ft}^2)(9 \text{ ft}) = 18,000 \text{ ft}^3 \\ m &= \frac{PV}{RT} = \frac{(12.2 \text{ psia})(18,000 \text{ ft}^3)}{(0.3704 \text{ psia}\cdot\text{ft}^3/\text{lbm}\cdot\text{R})(50 + 460)\text{R}} = 1162 \text{ lbm}\end{aligned}$$

(a) The amount of energy transferred to air at constant volume is simply the change in its internal energy, and is determined from

$$\begin{aligned}E_{\text{in}} - E_{\text{out}} &= \Delta E_{\text{system}} \\ E_{\text{in, constant volume}} &= \Delta U_{\text{air}} = mc_v \Delta T \\ &= (1162 \text{ lbm})(0.171 \text{ Btu/lbm}\cdot^\circ\text{F})(70 - 50)^\circ\text{F} \\ &= \mathbf{3974 \text{ Btu}}\end{aligned}$$



At a unit cost of \$0.075/kWh, the total cost of this energy is

$$\begin{aligned}\text{Cost of energy} &= (\text{Amount of energy})(\text{Unit cost of energy}) \\ &= (3974 \text{ Btu})(\$0.075/\text{kWh})\left(\frac{1 \text{ kWh}}{3412 \text{ Btu}}\right) \\ &= \mathbf{\$0.087}\end{aligned}$$

(b) The amount of energy transferred to air at constant pressure is the change in its enthalpy, and is determined from

$$\begin{aligned}E_{\text{in, constant pressure}} &= \Delta H_{\text{air}} = mc_p \Delta T \\ &= (1162 \text{ lbm})(0.240 \text{ Btu/lbm}\cdot^\circ\text{F})(70 - 50)^\circ\text{F} \\ &= \mathbf{5578 \text{ Btu}}\end{aligned}$$

At a unit cost of \$0.075/kWh, the total cost of this energy is

$$\begin{aligned}\text{Cost of energy} &= (\text{Amount of energy})(\text{Unit cost of energy}) \\ &= (5578 \text{ Btu})(\$0.075/\text{kWh})\left(\frac{1 \text{ kWh}}{3412 \text{ Btu}}\right) \\ &= \mathbf{\$0.123}\end{aligned}$$

**Discussion** It costs about 9 cents in the first case and 12 cents in the second case to raise the temperature of the air in this house from 50°F to 70°F. The second answer is more realistic since every house has cracks, especially around the doors and windows, and the pressure in the house remains essentially constant during a heating process. Therefore, the second approach is used in practice. This conservative approach somewhat overpredicts the amount of energy used, however, since some of the air escapes through the cracks before it is heated to 70°F.

## 1–5 ■ HEAT TRANSFER MECHANISMS

In Section 1–1, we defined *heat* as the form of energy that can be transferred from one system to another as a result of temperature difference. A thermodynamic analysis is concerned with the *amount* of heat transfer as a system undergoes a process from one equilibrium state to another. The science that deals with the determination of the *rates* of such energy transfers is the *heat transfer*. The transfer of energy as heat is always from the higher-temperature medium to the lower-temperature one, and heat transfer stops when the two mediums reach the same temperature.

Heat can be transferred in three different modes: *conduction*, *convection*, and *radiation*. All modes of heat transfer require the existence of a temperature difference, and all modes are from the high-temperature medium to a lower-temperature one. Below we give a brief description of each mode. A detailed study of these modes is given in later chapters of this text.

## 1–6 ■ CONDUCTION

**Conduction** is the transfer of energy from the more energetic particles of a substance to the adjacent less energetic ones as a result of interactions between the particles. Conduction can take place in solids, liquids, or gases.



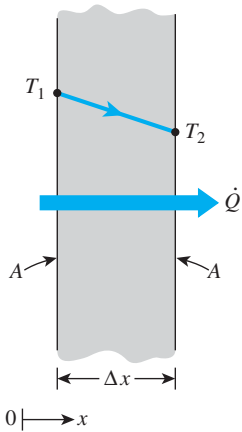


FIGURE 1-23

Heat conduction through a large plane wall of thickness  $\Delta x$  and area  $A$ .

In gases and liquids, conduction is due to the *collisions* and *diffusion* of the molecules during their random motion. In solids, it is due to the combination of *vibrations* of the molecules in a lattice and the energy transport by *free electrons*. A cold canned drink in a warm room, for example, eventually warms up to the room temperature as a result of heat transfer from the room to the drink through the aluminum can by conduction.

The *rate* of heat conduction through a medium depends on the *geometry* of the medium, its *thickness*, and the *material* of the medium, as well as the *temperature difference* across the medium. We know that wrapping a hot water tank with glass wool (an insulating material) reduces the rate of heat loss from the tank. The thicker the insulation, the smaller the heat loss. We also know that a hot water tank loses heat at a higher rate when the temperature of the room housing the tank is lowered. Further, the larger the tank, the larger the surface area and thus the rate of heat loss.

Consider steady heat conduction through a large plane wall of thickness  $\Delta x = L$  and area  $A$ , as shown in Fig. 1-23. The temperature difference across the wall is  $\Delta T = T_2 - T_1$ . Experiments have shown that the rate of heat transfer  $\dot{Q}$  through the wall is *doubled* when the temperature difference  $\Delta T$  across the wall or the area  $A$  normal to the direction of heat transfer is doubled, but is *halved* when the wall thickness  $L$  is doubled. Thus we conclude that *the rate of heat conduction through a plane layer is proportional to the temperature difference across the layer and the heat transfer area, but is inversely proportional to the thickness of the layer*. That is,

$$\text{Rate of heat conduction} \propto \frac{(\text{Area})(\text{Temperature difference})}{\text{Thickness}}$$

or,

$$\dot{Q}_{\text{cond}} = kA \frac{T_1 - T_2}{\Delta x} = -kA \frac{\Delta T}{\Delta x} \quad (\text{W}) \quad (1-21)$$

where the constant of proportionality  $k$  is the **thermal conductivity** of the material, which is a *measure of the ability of a material to conduct heat* (Fig. 1-24). In the limiting case of  $\Delta x \rightarrow 0$ , the equation above reduces to the differential form

$$\dot{Q}_{\text{cond}} = -kA \frac{dT}{dx} \quad (\text{W}) \quad (1-22)$$

which is called **Fourier's law of heat conduction** after J. Fourier (Fig. 1-25), who expressed it first in his heat transfer text in 1822. Here  $dT/dx$  is the **temperature gradient**, which is the slope of the temperature curve on a  $T$ - $x$  diagram (the rate of change of  $T$  with  $x$ ), at location  $x$ . The relation above indicates that the rate of heat conduction in a given direction is proportional to the temperature gradient in that direction. Heat is conducted in the direction of decreasing temperature, and the temperature gradient becomes negative when temperature decreases with increasing  $x$ . The *negative sign* in Eq. 1-22 ensures that heat transfer in the positive  $x$  direction is a positive quantity.

The heat transfer area  $A$  is always *normal* to the direction of heat transfer. For heat loss through a 5-m-long, 3-m-high, and 25-cm-thick wall, for example, the heat transfer area is  $A = 15 \text{ m}^2$ . Note that the thickness of the wall has no effect on  $A$  (Fig. 1-26).

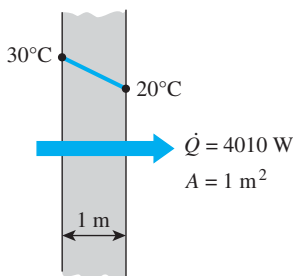
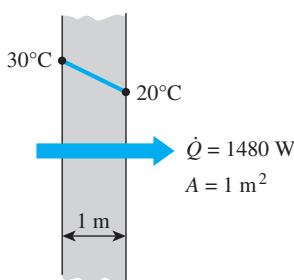
(a) Copper ( $k = 401 \text{ W/m}\cdot\text{K}$ )(b) Silicon ( $k = 148 \text{ W/m}\cdot\text{K}$ )

FIGURE 1-24

The rate of heat conduction through a solid is directly proportional to its thermal conductivity.

**EXAMPLE 1–5 The Cost of Heat Loss through a Roof**

The roof of an electrically heated home is 6 m long, 8 m wide, and 0.25 m thick, and is made of a flat layer of concrete whose thermal conductivity is  $k = 0.8 \text{ W/m}\cdot\text{K}$  (Fig. 1–27). The temperatures of the inner and the outer surfaces of the roof one night are measured to be  $15^\circ\text{C}$  and  $4^\circ\text{C}$ , respectively, for a period of 10 hours. Determine (a) the rate of heat loss through the roof that night and (b) the cost of that heat loss to the home owner if the cost of electricity is  $\$0.08/\text{kWh}$ .

**SOLUTION** The inner and outer surfaces of the flat concrete roof of an electrically heated home are maintained at specified temperatures during a night. The heat loss through the roof and its cost that night are to be determined.

**Assumptions** 1 Steady operating conditions exist during the entire night since the surface temperatures of the roof remain constant at the specified values. 2 Constant properties can be used for the roof.

**Properties** The thermal conductivity of the roof is given to be  $k = 0.8 \text{ W/m}\cdot\text{K}$ .

**Analysis** (a) Noting that heat transfer through the roof is by conduction and the area of the roof is  $A = 6 \text{ m} \times 8 \text{ m} = 48 \text{ m}^2$ , the steady rate of heat transfer through the roof is

$$\dot{Q} = kA \frac{T_1 - T_2}{L} = (0.8 \text{ K})(48 \text{ m}^2) \frac{(15 - 4)^\circ\text{C}}{0.25 \text{ m}} = \mathbf{1690 \text{ W} = 1.69 \text{ kW}}$$

(b) The amount of heat lost through the roof during a 10-hour period and its cost is

$$\begin{aligned} Q &= \dot{Q} \Delta t = (1.69 \text{ kW})(10 \text{ h}) = 16.9 \text{ kWh} \\ \text{Cost} &= (\text{Amount of energy})(\text{Unit cost of energy}) \\ &= (16.9 \text{ kWh})(\$0.08/\text{kWh}) = \mathbf{\$1.35} \end{aligned}$$

**Discussion** The cost to the home owner of the heat loss through the roof that night was  $\$1.35$ . The total heating bill of the house will be much larger since the heat losses through the walls are not considered in these calculations.

**FIGURE 1–25**

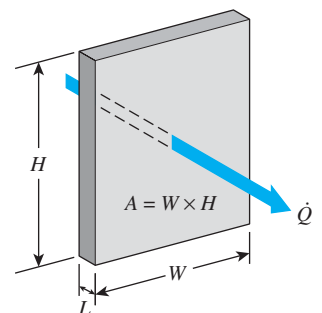
**Jean Baptiste Joseph Fourier** (1768–1830) was a French mathematician and physicist born in Auxerre, France. He is best known for his work on the infinite series of trigonometric functions that bear his name and for his development of the mathematical theory of heat conduction. Fourier established the partial differential equation governing heat diffusion, and he solved it by using the Fourier series. The Fourier transform, Fourier number, and the Fourier's law of heat conduction are named in his honor. Fourier is also credited with the discovery of the phenomenon of greenhouse effect in 1824.

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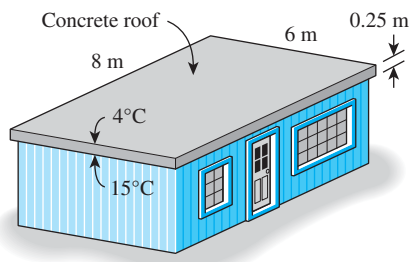
## Thermal Conductivity

We have seen that different materials store heat differently, and we have defined the property specific heat  $c_p$  as a measure of a material's ability to store thermal energy. For example,  $c_p = 4.18 \text{ kJ/kg}\cdot^\circ\text{C}$  for water and  $c_p = 0.45 \text{ kJ/kg}\cdot^\circ\text{C}$  for iron at room temperature, which indicates that water can store almost 10 times the energy that iron can per unit mass. Likewise, the thermal conductivity  $k$  is a measure of a material's ability to conduct heat. For example,  $k = 0.607 \text{ W/m}\cdot\text{K}$  for water and  $k = 80.2 \text{ W/m}\cdot\text{K}$  for iron at room temperature, which indicates that iron conducts heat more than 100 times faster than water can. Thus we say that water is a poor heat conductor relative to iron, although water is an excellent medium to store thermal energy.

Equation 1–21 for the rate of conduction heat transfer under steady conditions can also be viewed as the defining equation for thermal conductivity. Thus the **thermal conductivity** of a material can be defined as *the rate of*

**FIGURE 1–26**

In heat conduction analysis,  $A$  represents the area *normal* to the direction of heat transfer.



**FIGURE 1–27**  
Schematic for Example 1–5.

**TABLE 1–1**

The thermal conductivities of some materials at room temperature

Material	$k$ , W/m·K*
Diamond	2300
Silver	429
Copper	401
Gold	317
Aluminum	237
Iron	80.2
Mercury (l)	8.54
Glass	0.78
Brick	0.72
Water (l)	0.607
Human skin	0.37
Wood (oak)	0.17
Helium (g)	0.152
Soft rubber	0.13
Glass fiber	0.043
Air (g)	0.026
Urethane, rigid foam	0.026

\*Multiply by 0.5778 to convert to Btu/h·ft·°F.

heat transfer through a unit thickness of the material per unit area per unit temperature difference. The thermal conductivity of a material is a measure of the ability of the material to conduct heat. A high value for thermal conductivity indicates that the material is a good heat conductor, and a low value indicates that the material is a poor heat conductor or *insulator*. The thermal conductivities of some common materials at room temperature are given in Table 1–1. The thermal conductivity of pure copper at room temperature is  $k = 401 \text{ W/m}\cdot\text{K}$ , which indicates that a 1-m-thick copper wall will conduct heat at a rate of 401 W per  $\text{m}^2$  area per K temperature difference across the wall. Note that materials such as copper and silver that are good electric conductors are also good heat conductors, and have high values of thermal conductivity. Materials such as rubber, wood, and Styrofoam are poor conductors of heat and have low conductivity values.

A layer of material of known thickness and area can be heated from one side by an electric resistance heater of known output. If the outer surfaces of the heater are well insulated, all the heat generated by the resistance heater will be transferred through the material whose conductivity is to be determined. Then measuring the two surface temperatures of the material when steady heat transfer is reached and substituting them into Eq. 1–21 together with other known quantities give the thermal conductivity (Fig. 1–28).

The thermal conductivities of materials vary over a wide range, as shown in Fig. 1–29. The thermal conductivities of gases such as air vary by a factor of  $10^4$  from those of pure metals such as copper. Note that pure crystals and metals have the highest thermal conductivities, and gases and insulating materials the lowest.

Temperature is a measure of the kinetic energies of the particles such as the molecules or atoms of a substance. In a liquid or gas, the kinetic energy of the molecules is due to their random translational motion as well as their vibrational and rotational motions. When two molecules possessing different kinetic energies collide, part of the kinetic energy of the more energetic (higher-temperature) molecule is transferred to the less energetic (lower-temperature) molecule, much the same as when two elastic balls of the same mass at different velocities collide, part of the kinetic energy of the faster ball is transferred to the slower one. The higher the temperature, the faster the molecules move and the higher the number of such collisions, and the better the heat transfer.

The *kinetic theory* of gases predicts and the experiments confirm that the thermal conductivity of gases is proportional to the *square root of the thermodynamic temperature  $T$* , and inversely proportional to the *square root of the molar mass  $M$* . Therefore, for a particular gas (fixed  $M$ ), the thermal conductivity increases with increasing temperature and at a fixed temperature the thermal conductivity decreases with increasing  $M$ . For example, at a fixed temperature of 1000 K, the thermal conductivity of helium ( $M = 4$ ) is 0.343 W/m·K and that of air ( $M = 29$ ) is 0.0667 W/m·K, which is much lower than that of helium.

The thermal conductivities of *gases* at 1 atm pressure are listed in Table A-16. However, they can also be used at pressures other than 1 atm, since the thermal conductivity of gases is *independent of pressure* in a wide range of pressures encountered in practice.

The mechanism of heat conduction in a *liquid* is complicated by the fact that the molecules are more closely spaced, and they exert a stronger intermolecular force field. The thermal conductivities of liquids usually lie between those of

solids and gases. The thermal conductivity of a substance is normally highest in the solid phase and lowest in the gas phase. The thermal conductivity of liquids is generally insensitive to pressure except near the thermodynamic critical point. Unlike gases, the thermal conductivities of most liquids decrease with increasing temperature, with water being a notable exception. Like gases, the conductivity of liquids decreases with increasing molar mass. Liquid metals such as mercury and sodium have high thermal conductivities and are very suitable for use in applications where a high heat transfer rate to a liquid is desired, as in nuclear power plants.

In *solids*, heat conduction is due to two effects: the *lattice vibrational waves* induced by the vibrational motions of the molecules positioned at relatively fixed positions in a periodic manner called a lattice, and the energy transported via the *free flow of electrons* in the solid (Fig. 1–30). The thermal conductivity of a solid is obtained by adding the lattice and electronic components. The relatively high thermal conductivities of pure metals are primarily due to the electronic component. The lattice component of thermal conductivity strongly depends on the way the molecules are arranged. For example, diamond, which is a highly ordered crystalline solid, has the highest known thermal conductivity at room temperature.

Unlike metals, which are good electrical and heat conductors, *crystalline solids* such as diamond and semiconductors such as silicon are good heat conductors but poor electrical conductors. As a result, such materials find

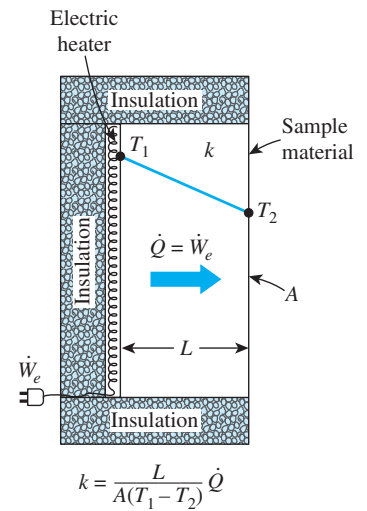


FIGURE 1–28

A simple experimental setup to determine the thermal conductivity of a material.

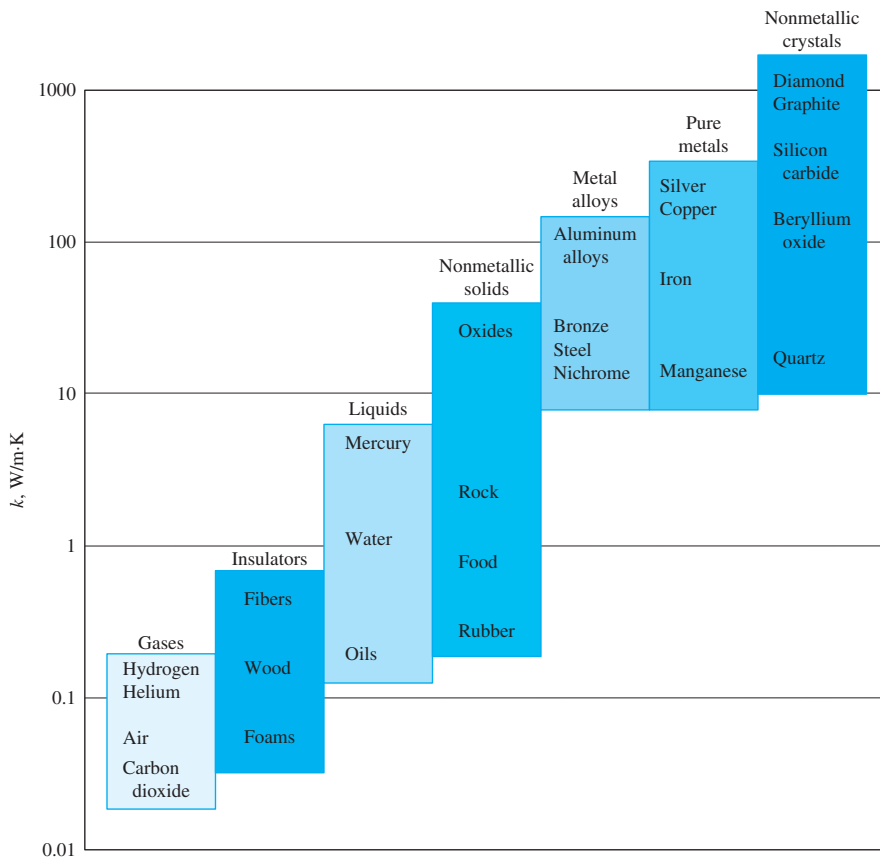


FIGURE 1–29

The range of thermal conductivity of various materials at room temperature.

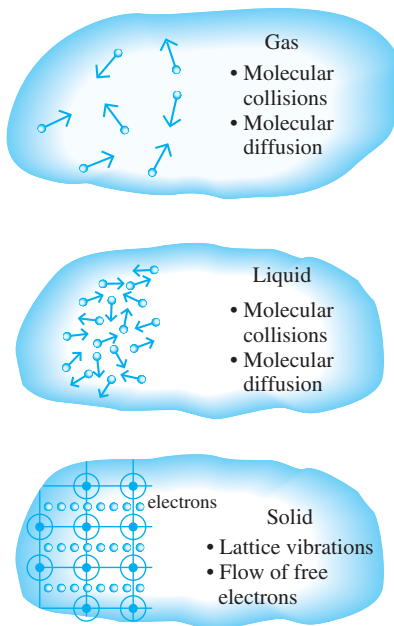


FIGURE 1-30

The mechanisms of heat conduction in different phases of a substance.

TABLE 1-2

The thermal conductivity of an alloy is usually much lower than the thermal conductivity of either metal of which it is composed

Pure metal or alloy	$k$ , W/m·K, at 300 K
Copper	401
Nickel	91
Constantan (55% Cu, 45% Ni)	23
Copper	401
Aluminum	237
Commercial bronze (90% Cu, 10% Al)	52

widespread use in the electronics industry. Despite their higher price, diamond heat sinks are used in the cooling of sensitive electronic components because of the excellent thermal conductivity of diamond. Silicon oils and gaskets are commonly used in the packaging of electronic components because they provide both good thermal contact and good electrical insulation.

Pure metals have high thermal conductivities, and one would think that *metal alloys* should also have high conductivities. One would expect an alloy made of two metals of thermal conductivities  $k_1$  and  $k_2$  to have a conductivity  $k$  between  $k_1$  and  $k_2$ . But this turns out not to be the case. The thermal conductivity of an alloy of two metals is usually much lower than that of either metal, as shown in Table 1-2. Even small amounts in a pure metal of “foreign” molecules that are good conductors themselves seriously disrupt the transfer of heat in that metal. For example, the thermal conductivity of steel containing just 1 percent of chrome is 62 W/m·K, while the thermal conductivities of iron and chromium are 83 and 95 W/m·K, respectively.

The thermal conductivities of materials vary with temperature (Table 1-3). The variation of thermal conductivity over certain temperature ranges is negligible for some materials, but significant for others, as shown in Fig. 1-31. The thermal conductivities of certain solids exhibit dramatic increases at temperatures near absolute zero, when these solids become *superconductors*. For example, the conductivity of copper reaches a maximum value of about 20,000 W/m·K at 20 K, which is about 50 times the conductivity at room temperature. The thermal conductivities and other thermal properties of various materials are given in Tables A-3 to A-17.

Values of thermal conductivity given in Tables A-3 to A-17 are appropriate when the physical dimensions of the material under consideration are relatively large. In some of the emerging areas of technology, such as microelectronics, the physical dimensions are typically in the order of micro or nano meters. For these applications the small physical dimensions most likely will influence the value of thermal conductivity in the solid and liquid states. In these situations, as the physical dimensions decrease, the average net distance traveled by the energy carriers typically decreases and this reduces the value of thermal conductivity.

The temperature dependence of thermal conductivity causes considerable complexity in conduction analysis. Therefore, it is common practice to evaluate the thermal conductivity  $k$  at the *average temperature* and treat it as a *constant* in calculations.

In heat transfer analysis, a material is normally assumed to be *isotropic*; that is, to have uniform properties in all directions. This assumption is realistic for most materials, except those that exhibit different structural characteristics in different directions, such as laminated composite materials and wood. The thermal conductivity of wood across the grain, for example, is different than that parallel to the grain.

## Thermal Diffusivity

The product  $\rho c_p$ , which is frequently encountered in heat transfer analysis, is called the **heat capacity** of a material. Both the specific heat  $c_p$  and the heat capacity  $\rho c_p$  represent the heat storage capability of a material. But  $c_p$  expresses it *per unit mass* whereas  $\rho c_p$  expresses it *per unit volume*, as can be noticed from their units J/kg·K and J/m<sup>3</sup>·K, respectively.



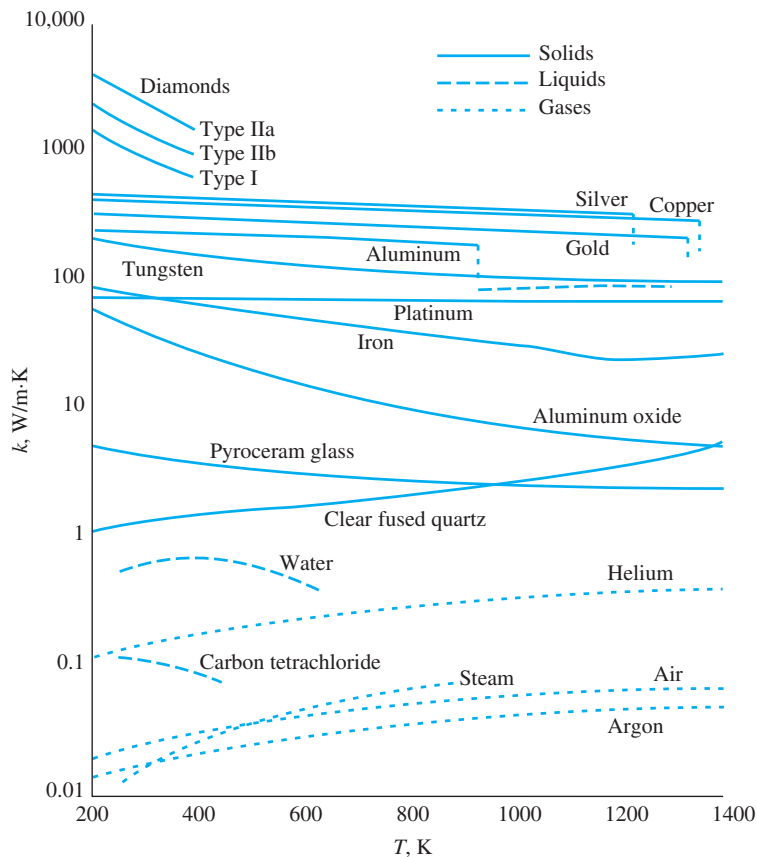


FIGURE 1-31

The variation of the thermal conductivity of various solids, liquids, and gases with temperature.

TABLE 1-3

Thermal conductivities of materials vary with temperature

T, K	k, W/m·K	
	Copper	Aluminum
100	482	302
200	413	237
300	401	237
400	393	240
600	379	231
800	366	218

TABLE 1-4

The thermal diffusivities of some materials at room temperature

Material	$\alpha$ , m <sup>2</sup> /s*
Silver	$149 \times 10^{-6}$
Gold	$127 \times 10^{-6}$
Copper	$113 \times 10^{-6}$
Aluminum	$97.5 \times 10^{-6}$
Iron	$22.8 \times 10^{-6}$
Mercury (l)	$4.7 \times 10^{-6}$
Marble	$1.2 \times 10^{-6}$
Ice	$1.2 \times 10^{-6}$
Concrete	$0.75 \times 10^{-6}$
Brick	$0.52 \times 10^{-6}$
Heavy soil (dry)	$0.52 \times 10^{-6}$
Glass	$0.34 \times 10^{-6}$
Glass wool	$0.23 \times 10^{-6}$
Water (l)	$0.14 \times 10^{-6}$
Beef	$0.14 \times 10^{-6}$
Wood (oak)	$0.13 \times 10^{-6}$

\*Multiply by 10.76 to convert to ft<sup>2</sup>/s.

Another material property that appears in the transient heat conduction analysis is the **thermal diffusivity**, which represents how fast heat diffuses through a material and is defined as

$$\alpha = \frac{\text{Heat conduction}}{\text{Heat storage}} = \frac{k}{\rho c_p} \quad (\text{m}^2/\text{s}) \quad (1-23)$$

Note that the thermal conductivity  $k$  represents how well a material conducts heat, and the heat capacity  $\rho c_p$  represents how much energy a material stores per unit volume. Therefore, the thermal diffusivity of a material can be viewed as the ratio of the *heat conducted* through the material to the *heat stored* per unit volume. A material that has a high thermal conductivity or a low heat capacity will obviously have a large thermal diffusivity. The larger the thermal diffusivity, the faster the propagation of heat into the medium. A small value of thermal diffusivity means that heat is mostly absorbed by the material and a small amount of heat is conducted further.

The thermal diffusivities of some common materials at 20°C are given in Table 1-4. Note that the thermal diffusivity ranges from  $\alpha = 0.14 \times 10^{-6}$  m<sup>2</sup>/s for water to  $149 \times 10^{-6}$  m<sup>2</sup>/s for silver, which is a difference of more than a thousand times. Also note that the thermal diffusivities of beef and water are the same. This is not surprising, since meat as well as fresh vegetables and fruits are mostly water, and thus they possess the thermal properties of water.



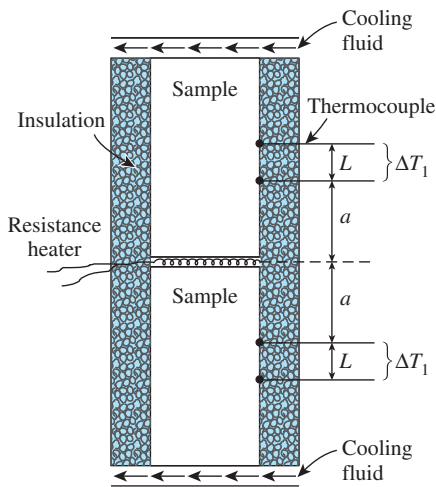


FIGURE 1–32

Apparatus to measure the thermal conductivity of a material using two identical samples and a thin resistance heater (Example 1–6).

### EXAMPLE 1–6 Measuring the Thermal Conductivity of a Material

A common way of measuring the thermal conductivity of a material is to sandwich an electric thermofoil heater between two identical samples of the material, as shown in Fig. 1–32. The thickness of the resistance heater, including its cover, which is made of thin silicon rubber, is usually less than 0.5 mm. A circulating fluid such as tap water keeps the exposed ends of the samples at constant temperature. The lateral surfaces of the samples are well insulated to ensure that heat transfer through the samples is one-dimensional. Two thermocouples are embedded into each sample some distance  $L$  apart, and a differential thermometer reads the temperature drop  $\Delta T$  across this distance along each sample. When steady operating conditions are reached, the total rate of heat transfer through both samples becomes equal to the electric power drawn by the heater.

In a certain experiment, cylindrical samples of diameter 5 cm and length 10 cm are used. The two thermocouples in each sample are placed 3 cm apart. After initial transients, the electric heater is observed to draw 0.4 A at 110 V, and both differential thermometers read a temperature difference of 15°C. Determine the thermal conductivity of the sample.

**SOLUTION** The thermal conductivity of a material is to be determined by ensuring one-dimensional heat conduction, and by measuring temperatures when steady operating conditions are reached.

**Assumptions** 1 Steady operating conditions exist since the temperature readings do not change with time. 2 Heat losses through the lateral surfaces of the apparatus are negligible since those surfaces are well insulated, and thus the entire heat generated by the heater is conducted through the samples. 3 The apparatus possesses thermal symmetry.

**Analysis** The electrical power consumed by the resistance heater and converted to heat is

$$\dot{W}_e = VI = (110 \text{ V})(0.4 \text{ A}) = 44 \text{ W}$$

The rate of heat flow through each sample is

$$\dot{Q} = \frac{1}{2} \dot{W}_e = \frac{1}{2} \times (44 \text{ W}) = 22 \text{ W}$$

since only half of the heat generated flows through each sample because of symmetry. Reading the same temperature difference across the same distance in each sample also confirms that the apparatus possesses thermal symmetry. The heat transfer area is the area normal to the direction of heat transfer, which is the cross-sectional area of the cylinder in this case:

$$A = \frac{1}{4} \pi D^2 = \frac{1}{4} \pi (0.05 \text{ m})^2 = 0.001963 \text{ m}^2$$

Noting that the temperature drops by 15°C within 3 cm in the direction of heat flow, the thermal conductivity of the sample is determined to be

$$\dot{Q} = kA \frac{\Delta T}{L} \rightarrow k = \frac{\dot{Q} L}{A \Delta T} = \frac{(22 \text{ W})(0.03 \text{ m})}{(0.001963 \text{ m}^2)(15^\circ\text{C})} = 22.4 \text{ W/m}\cdot\text{K}$$

**Discussion** Perhaps you are wondering if we really need to use two samples in the apparatus, since the measurements on the second sample do not give any additional information. It seems like we can replace the second sample by insulation. Indeed, we do not need the second sample; however, it enables us to verify the temperature measurements on the first sample and provides thermal symmetry, which reduces experimental error.

**EXAMPLE 1–7 Conversion between SI and English Units**

An engineer who is working on the heat transfer analysis of a brick building in English units needs the thermal conductivity of brick. But the only value he can find from his handbooks is  $0.72 \text{ W/m}\cdot^\circ\text{C}$ , which is in SI units. To make matters worse, the engineer does not have a direct conversion factor between the two unit systems for thermal conductivity. Can you help him out?

**SOLUTION** The situation this engineer is facing is not unique, and most engineers often find themselves in a similar position. A person must be very careful during unit conversion not to fall into some common pitfalls and to avoid some costly mistakes. Although unit conversion is a simple process, it requires utmost care and careful reasoning.

The conversion factors for W and m are straightforward and are given in conversion tables to be

$$\begin{aligned} 1 \text{ W} &= 3.41214 \text{ Btu/h} \\ 1 \text{ m} &= 3.2808 \text{ ft} \end{aligned}$$

But the conversion of  $^\circ\text{C}$  into  $^\circ\text{F}$  is not so simple, and it can be a source of error if one is not careful. Perhaps the first thought that comes to mind is to replace  $^\circ\text{C}$  by  $(^\circ\text{F} - 32)/1.8$  since  $T(^{\circ}\text{C}) = [T(^{\circ}\text{F}) - 32]/1.8$ . But this will be wrong since the  $^\circ\text{C}$  in the unit  $\text{W/m}\cdot^\circ\text{C}$  represents *per  $^\circ\text{C}$  change in temperature*. Noting that  $1^\circ\text{C}$  change in temperature corresponds to  $1.8^\circ\text{F}$ , the proper conversion factor to be used is

$$1^\circ\text{C} = 1.8^\circ\text{F}$$

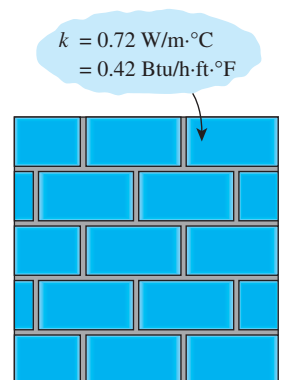
Substituting, we get

$$1 \text{ W/m}\cdot^\circ\text{C} = \frac{3.41214 \text{ Btu/h}}{(3.2808 \text{ ft})(1.8^\circ\text{F})} = 0.5778 \text{ Btu/h}\cdot\text{ft}\cdot^\circ\text{F}$$

which is the desired conversion factor. Therefore, the thermal conductivity of the brick in English units is

$$\begin{aligned} k_{\text{brick}} &= 0.72 \text{ W/m}\cdot^\circ\text{C} \\ &= 0.72 \times (0.5778 \text{ Btu/h}\cdot\text{ft}\cdot^\circ\text{F}) \\ &= \mathbf{0.42 \text{ Btu/h}\cdot\text{ft}\cdot^\circ\text{F}} \end{aligned}$$

**Discussion** Note that the thermal conductivity value of a material in English units is about half that in SI units (Fig. 1–33). Also note that we rounded the result to two significant digits (the same number in the original value) since expressing the result in more significant digits (such as 0.4160 instead of 0.42) would falsely imply a more accurate value than the original one.



**FIGURE 1–33** The thermal conductivity value in English units is obtained by multiplying the value in SI units by 0.5778.

**1–7 ■ CONVECTION**

**Convection** is the mode of energy transfer between a solid surface and the adjacent liquid or gas that is in motion, and it involves the combined effects of *conduction* and *fluid motion*. The faster the fluid motion, the greater the convection heat transfer. In the absence of any bulk fluid motion, heat transfer between a solid surface and the adjacent fluid is by pure conduction. The presence of bulk motion of the fluid enhances the heat transfer between the solid surface and the fluid, but it also complicates the determination of heat transfer rates.

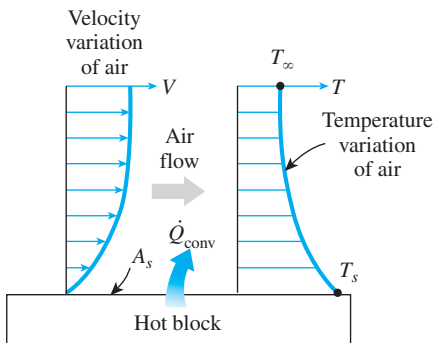


FIGURE 1-34

Heat transfer from a hot surface to air by convection.

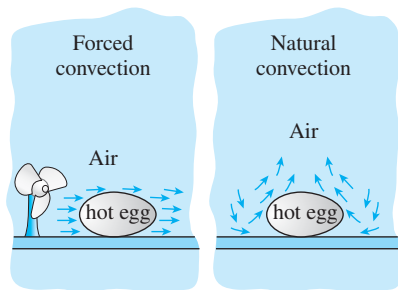


FIGURE 1-35

The cooling of a boiled egg by forced and natural convection.

TABLE 1-5

Typical values of convection heat transfer coefficient

Type of convection	$h$ , $W/m^2 \cdot K^*$
Free convection of gases	2–25
Free convection of liquids	10–1000
Forced convection of gases	25–250
Forced convection of liquids	50–20,000
Boiling and condensation	2500–100,000

\*Multiply by 0.176 to convert to  $Btu/h \cdot ft^2 \cdot ^\circ F$ .

Consider the cooling of a hot block by blowing cool air over its top surface (Fig. 1–34). Heat is first transferred to the air layer adjacent to the block by conduction. This heat is then carried away from the surface by convection, that is, by the combined effects of conduction within the air that is due to random motion of air molecules and the bulk or macroscopic motion of the air that removes the heated air near the surface and replaces it by the cooler air.

Convection is called **forced convection** if the fluid is forced to flow over the surface by external means such as a fan, pump, or the wind. In contrast, convection is called **natural (or free) convection** if the fluid motion is caused by buoyancy forces that are induced by density differences due to the variation of temperature in the fluid (Fig. 1–35). For example, in the absence of a fan, heat transfer from the surface of the hot block in Fig. 1–34 is by natural convection since any motion in the air in this case is due to the rise of the warmer (and thus lighter) air near the surface and the fall of the cooler (and thus heavier) air to fill its place. Heat transfer between the block and the surrounding air is by conduction if the temperature difference between the air and the block is not large enough to overcome the resistance of air to movement and thus to initiate natural convection currents.

Heat transfer processes that involve *change of phase* of a fluid are also considered to be convection because of the fluid motion induced during the process, such as the rise of the vapor bubbles during boiling or the fall of the liquid droplets during condensation.

Despite the complexity of convection, the rate of *convection heat transfer* is observed to be proportional to the temperature difference, and is conveniently expressed by **Newton’s law of cooling** as (Fig. 1–36)

$$\dot{Q}_{\text{conv}} = hA_s(T_s - T_\infty) \quad (W) \quad (1-24)$$

where  $h$  is the *convection heat transfer coefficient* in  $W/m^2 \cdot K$  or  $Btu/h \cdot ft^2 \cdot ^\circ F$ ,  $A_s$  is the surface area through which convection heat transfer takes place,  $T_s$  is the surface temperature, and  $T_\infty$  is the temperature of the fluid sufficiently far from the surface. Note that at the surface, the fluid temperature equals the surface temperature of the solid.

The convection heat transfer coefficient  $h$  is not a property of the fluid. It is an experimentally determined parameter whose value depends on all the variables influencing convection such as the surface geometry, the nature of fluid motion, the properties of the fluid, and the bulk fluid velocity. Typical values of  $h$  are given in Table 1–5.

Some people do not consider convection to be a fundamental mechanism of heat transfer since it is essentially heat conduction in the presence of fluid motion. But we still need to give this combined phenomenon a name, unless we are willing to keep referring to it as “conduction with fluid motion.” Thus, it is practical to recognize convection as a separate heat transfer mechanism despite the valid arguments to the contrary.

#### EXAMPLE 1-8 Measuring Convection Heat Transfer Coefficient

A 2-m-long, 0.3-cm-diameter electrical wire extends across a room at  $15^\circ C$ , as shown in Fig. 1–37. Heat is generated in the wire as a result of resistance heating, and the surface temperature of the wire is measured to be  $152^\circ C$  in

steady operation. Also, the voltage drop and electric current through the wire are measured to be 60 V and 1.5 A, respectively. Disregarding any heat transfer by radiation, determine the convection heat transfer coefficient for heat transfer between the outer surface of the wire and the air in the room.

**SOLUTION** The convection heat transfer coefficient for heat transfer from an electrically heated wire to air is to be determined by measuring temperatures when steady operating conditions are reached and the electric power consumed.

**Assumptions** 1 Steady operating conditions exist since the temperature readings do not change with time. 2 Radiation heat transfer is negligible.

**Analysis** When steady operating conditions are reached, the rate of heat loss from the wire equals the rate of heat generation in the wire as a result of resistance heating. That is,

$$\dot{Q} = \dot{E}_{\text{generated}} = VI = (60 \text{ V})(1.5 \text{ A}) = 90 \text{ W}$$

The surface area of the wire is

$$A_s = \pi DL = \pi(0.003 \text{ m})(2 \text{ m}) = 0.01885 \text{ m}^2$$

Newton's law of cooling for convection heat transfer is expressed as

$$\dot{Q}_{\text{conv}} = hA_s(T_s - T_\infty)$$

Disregarding any heat transfer by radiation and thus assuming all the heat loss from the wire to occur by convection, the convection heat transfer coefficient is determined to be

$$h = \frac{\dot{Q}_{\text{conv}}}{A_s(T_s - T_\infty)} = \frac{90 \text{ W}}{(0.01885 \text{ m}^2)(152 - 15)^\circ\text{C}} = \mathbf{34.9 \text{ W/m}^2\cdot\text{K}}$$

**Discussion** Note that the simple setup described above can be used to determine the average heat transfer coefficients from a variety of surfaces in air. Also, heat transfer by radiation can be eliminated by keeping the surrounding surfaces at the temperature of the wire.

## 1-8 ■ RADIATION

**Radiation** is the energy emitted by matter in the form of *electromagnetic waves* (or *photons*) as a result of the changes in the electronic configurations of the atoms or molecules. Unlike conduction and convection, the transfer of heat by radiation does not require the presence of an *intervening medium*. In fact, heat transfer by radiation is fastest (at the speed of light) and it suffers no attenuation in a vacuum. This is how the energy of the sun reaches the earth.

In heat transfer studies we are interested in *thermal radiation*, which is the form of radiation emitted by bodies because of their temperature. It differs from other forms of electromagnetic radiation such as x-rays, gamma rays, microwaves, radio waves, and television waves that are not related to temperature. All bodies at a temperature above absolute zero emit thermal radiation.

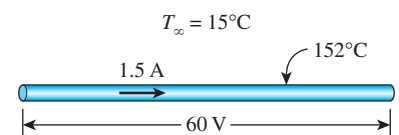
Radiation is a *volumetric phenomenon*, and all solids, liquids, and gases emit, absorb, or transmit radiation to varying degrees. However, radiation is



**FIGURE 1-36**

**Sir Isaac Newton** (1642–1727) was an English mathematician, physicist, and astronomer, born in Lincolnshire, England. Newton is regarded as one of the greatest scientists and mathematicians in history. His contributions to mathematics include the development of the binomial theorem, the differential calculus, and the integral calculus. He is said to have conceived the idea of the law of gravity upon the observation of the fall of an apple in 1665. With the three fundamental laws that bear his name and are described in *Philosophiæ Naturalis Principia Mathematica*, Newton is known as the father of classical mechanics. Newton showed that each of Kepler's three laws on the motion of planets and stars could be derived from the single law of gravity. Newton is also credited for the discovery of the composite nature of white light and the separation of different colors by a prism. The law of cooling that governs the rate of heat transfer from a hot surface to a cooler surrounding fluid is also attributed to Newton.

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**FIGURE 1-37**

Schematic for Example 1-8.

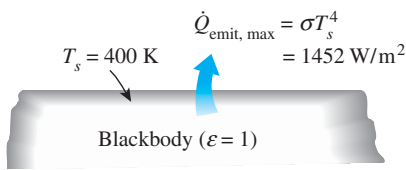


FIGURE 1–38

Blackbody radiation represents the maximum amount of radiation that can be emitted from a surface at a specified temperature.

TABLE 1–6

Emissivities of some materials at 300 K

Material	Emissivity
Aluminum foil	0.07
Anodized aluminum	0.82
Polished copper	0.03
Polished gold	0.03
Polished silver	0.02
Polished stainless steel	0.17
Black paint	0.98
White paint	0.90
White paper	0.92–0.97
Asphalt pavement	0.85–0.93
Red brick	0.93–0.96
Human skin	0.95
Wood	0.82–0.92
Soil	0.93–0.96
Water	0.96
Vegetation	0.92–0.96

usually considered to be a *surface phenomenon* for solids that are opaque to thermal radiation such as metals, wood, and rocks since the radiation emitted by the interior regions of such material can never reach the surface, and the radiation incident on such bodies is usually absorbed within a few microns from the surface.

The maximum rate of radiation that can be emitted from a surface at a thermodynamic temperature  $T_s$  (in K or R) is given by the **Stefan–Boltzmann law** as

$$\dot{Q}_{\text{emit, max}} = \sigma A_s T_s^4 \quad (\text{W}) \quad (1-25)$$

where  $\sigma = 5.670 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4$  or  $0.1714 \times 10^{-8} \text{ Btu/h} \cdot \text{ft}^2 \cdot \text{R}^4$  is the *Stefan–Boltzmann constant*. The idealized surface that emits radiation at this maximum rate is called a **blackbody**, and the radiation emitted by a blackbody is called **blackbody radiation** (Fig. 1–38). The radiation emitted by all real surfaces is less than the radiation emitted by a blackbody at the same temperature, and is expressed as

$$\dot{Q}_{\text{emit}} = \epsilon \sigma A_s T_s^4 \quad (\text{W}) \quad (1-26)$$

where  $\epsilon$  is the **emissivity** of the surface. The property emissivity, whose value is in the range  $0 \leq \epsilon \leq 1$ , is a measure of how closely a surface approximates a blackbody for which  $\epsilon = 1$ . The emissivities of some surfaces are given in Table 1–6.

Another important radiation property of a surface is its **absorptivity**  $\alpha$ , which is the fraction of the radiation energy incident on a surface that is absorbed by the surface. Like emissivity, its value is in the range  $0 \leq \alpha \leq 1$ . A blackbody absorbs the entire radiation incident on it. That is, a blackbody is a perfect absorber ( $\alpha = 1$ ) as it is a perfect emitter.

In general, both  $\epsilon$  and  $\alpha$  of a surface depend on the temperature and the wavelength of the radiation. **Kirchhoff's law** of radiation states that the emissivity and the absorptivity of a surface at a given temperature and wavelength are equal. In many practical applications, the surface temperature and the temperature of the source of incident radiation are of the same order of magnitude, and the average absorptivity of a surface is taken to be equal to its average emissivity. The rate at which a surface absorbs radiation is determined from (Fig. 1–39)

$$\dot{Q}_{\text{absorbed}} = \alpha \dot{Q}_{\text{incident}} \quad (\text{W}) \quad (1-27)$$

where  $\dot{Q}_{\text{incident}}$  is the rate at which radiation is incident on the surface and  $\alpha$  is the absorptivity of the surface. For opaque (nontransparent) surfaces, the portion of incident radiation not absorbed by the surface is reflected back.

The difference between the rates of radiation emitted by the surface and the radiation absorbed is the *net* radiation heat transfer. If the rate of radiation absorption is greater than the rate of radiation emission, the surface is said to be *gaining* energy by radiation. Otherwise, the surface is said to be *losing* energy by radiation. In general, the determination of the net rate of heat transfer by radiation between two surfaces is a complicated matter since it depends on the properties of the surfaces, their orientation relative to each other, and the interaction of the medium between the surfaces with radiation.

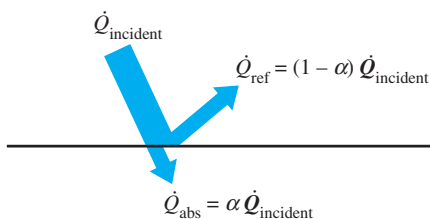


FIGURE 1–39

The absorption of radiation incident on an opaque surface of absorptivity  $\alpha$ .



When a surface of emissivity  $\varepsilon$  and surface area  $A_s$  at a *thermodynamic temperature*  $T_s$  is *completely enclosed* by a much larger (or black) surface at thermodynamic temperature  $T_{\text{surr}}$  separated by a gas (such as air) that does not intervene with radiation, the net rate of radiation heat transfer between these two surfaces is given by (Fig. 1–40)

$$\dot{Q}_{\text{rad}} = \varepsilon\sigma A_s (T_s^4 - T_{\text{surr}}^4) \quad (\text{W}) \quad (1-28)$$

In this special case, the emissivity and the surface area of the surrounding surface do not have any effect on the net radiation heat transfer.

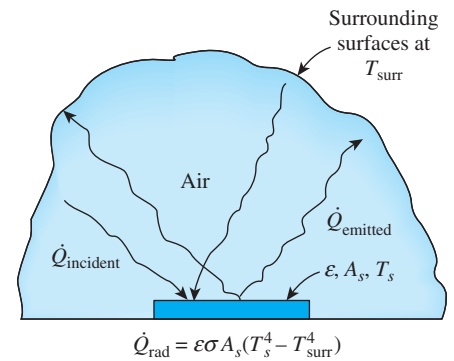
Radiation heat transfer to or from a surface surrounded by a gas such as air occurs *parallel* to conduction (or convection, if there is bulk gas motion) between the surface and the gas. Thus the total heat transfer is determined by *adding* the contributions of both heat transfer mechanisms. For simplicity and convenience, this is often done by defining a **combined heat transfer coefficient**  $h_{\text{combined}}$  that includes the effects of both convection and radiation. Then the *total* heat transfer rate to or from a surface by convection and radiation is expressed as

$$\begin{aligned} \dot{Q}_{\text{total}} &= \dot{Q}_{\text{conv}} + \dot{Q}_{\text{rad}} = h_{\text{conv}} A_s (T_s - T_{\text{surr}}) + \varepsilon\sigma A_s (T_s^4 - T_{\text{surr}}^4) \\ \dot{Q}_{\text{total}} &= h_{\text{combined}} A_s (T_s - T_{\infty}) \quad (\text{W}) \end{aligned} \quad (1-29)$$

$$h_{\text{combined}} = h_{\text{conv}} + h_{\text{rad}} = h_{\text{conv}} + \varepsilon\sigma (T_s + T_{\text{surr}})(T_s^2 + T_{\text{surr}}^2)$$

Note that the combined heat transfer coefficient is essentially a convection heat transfer coefficient modified to include the effects of radiation.

Radiation is usually significant relative to conduction or natural convection, but negligible relative to forced convection. Thus radiation in forced convection applications is usually disregarded, especially when the surfaces involved have low emissivities and low to moderate temperatures.



**FIGURE 1-40**  
Radiation heat transfer between a surface and the surfaces surrounding it.

### EXAMPLE 1-9 Radiation Effect on Thermal Comfort

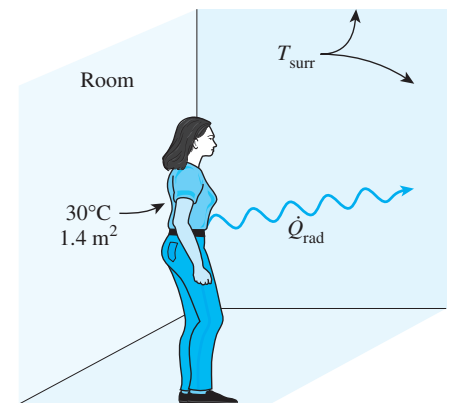
It is a common experience to feel “chilly” in winter and “warm” in summer in our homes even when the thermostat setting is kept the same. This is due to the so called “radiation effect” resulting from radiation heat exchange between our bodies and the surrounding surfaces of the walls and the ceiling.

Consider a person standing in a room maintained at 22°C at all times. The inner surfaces of the walls, floors, and the ceiling of the house are observed to be at an average temperature of 10°C in winter and 25°C in summer. Determine the rate of radiation heat transfer between this person and the surrounding surfaces if the exposed surface area and the average outer surface temperature of the person are 1.4 m<sup>2</sup> and 30°C, respectively (Fig. 1–41).

**SOLUTION** The rates of radiation heat transfer between a person and the surrounding surfaces at specified temperatures are to be determined in summer and winter.

**Assumptions** 1 Steady operating conditions exist. 2 Heat transfer by convection is not considered. 3 The person is completely surrounded by the interior surfaces of the room. 4 The surrounding surfaces are at a uniform temperature.

**Properties** The emissivity of a person is  $\varepsilon = 0.95$  (Table 1–6).



**FIGURE 1-41**  
Schematic for Example 1-9.



**Analysis** The net rates of radiation heat transfer from the body to the surrounding walls, ceiling, and floor in winter and summer are

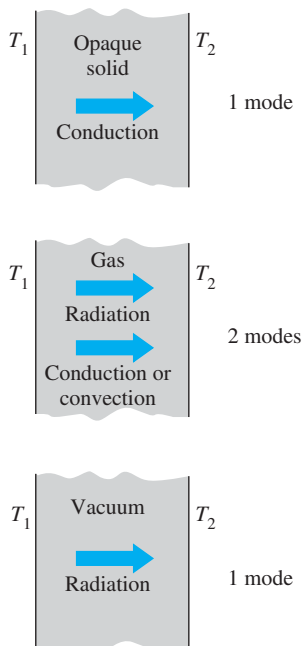
$$\begin{aligned}\dot{Q}_{\text{rad, winter}} &= \varepsilon\sigma A_s (T_s^4 - T_{\text{surr, winter}}^4) \\ &= (0.95)(5.67 \times 10^{-8} \text{ W/m}^2\cdot\text{K}^4)(1.4 \text{ m}^2) \\ &\quad \times [(30 + 273)^4 - (10 + 273)^4] \text{ K}^4 \\ &= \mathbf{152 \text{ W}}\end{aligned}$$

and

$$\begin{aligned}\dot{Q}_{\text{rad, summer}} &= \varepsilon\sigma A_s (T_s^4 - T_{\text{surr, summer}}^4) \\ &= (0.95)(5.67 \times 10^{-8} \text{ W/m}^2\cdot\text{K}^4)(1.4 \text{ m}^2) \\ &\quad \times [(30 + 273)^4 - (25 + 273)^4] \text{ K}^4 \\ &= \mathbf{40.9 \text{ W}}\end{aligned}$$

**Discussion** Note that we must use *thermodynamic* (i.e., *absolute*) temperatures in radiation calculations. Also note that the rate of heat loss from the person by radiation is almost four times as large in winter than it is in summer, which explains the “chill” we feel in winter even if the thermostat setting is kept the same.

## 1–9 ■ SIMULTANEOUS HEAT TRANSFER MECHANISMS



**FIGURE 1–42**

Although there are three mechanisms of heat transfer, a medium may involve only two of them simultaneously.

We mentioned that there are three mechanisms of heat transfer, but not all three can exist simultaneously in a medium. For example, heat transfer is only by conduction in *opaque solids*, but by conduction and radiation in *semitransparent solids*. Thus, a solid may involve conduction and radiation but not convection. However, a solid may involve heat transfer by convection and/or radiation on its surfaces exposed to a fluid or other surfaces. For example, the outer surfaces of a cold piece of rock will warm up in a warmer environment as a result of heat gain by convection (from the air) and radiation (from the sun or the warmer surrounding surfaces). But the inner parts of the rock will warm up as this heat is transferred to the inner region of the rock by conduction.

Heat transfer is by conduction and possibly by radiation in a *still fluid* (no bulk fluid motion) and by convection and radiation in a *flowing fluid*. In the absence of radiation, heat transfer through a fluid is either by conduction or convection, depending on the presence of any bulk fluid motion. Convection can be viewed as combined conduction and fluid motion, and conduction in a fluid can be viewed as a special case of convection in the absence of any fluid motion (Fig. 1–42).

Thus, when we deal with heat transfer through a *fluid*, we have either *conduction* or *convection*, but not both. Also, gases are practically transparent to radiation, except that some gases are known to absorb radiation strongly at certain wavelengths. Ozone, for example, strongly absorbs ultraviolet radiation. But in most cases, a gas between two solid surfaces does not interfere with radiation and acts effectively as a vacuum. Liquids, on the other hand, are usually strong absorbers of radiation.

Finally, heat transfer through a *vacuum* is by radiation only since conduction or convection requires the presence of a material medium.