Heat Transfer: A Practical Approach
Second Edition
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Chapter 1
INTRODUCTION AND BASIC CONCEPTS

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Objectives

- 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
- Solve various heat transfer problems encountered in practice

THERMODYNAMICS AND HEAT TRANSFER

- **Heat:** The form of energy that can be transferred from one system to another as a result of temperature difference.
- **Thermodynamics** is concerned with the *amount* of heat transfer as a system undergoes a process from one equilibrium state to another.
- **Heat Transfer** deals with the determination of the *rates* of such energy transfers as well as variation of temperature.
- The transfer of energy as heat is always from the higher-temperature medium to the lower-temperature one.
- Heat transfer stops when the two mediums reach the same temperature.
- Heat can be transferred in three different modes:

conduction*, *convection*, *radiation

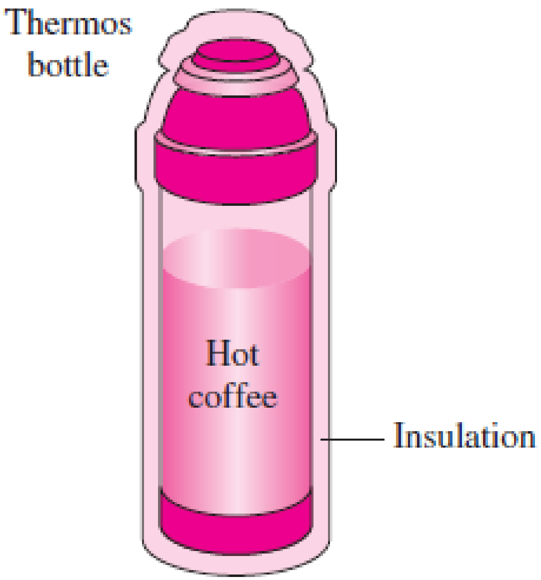

FIGURE 1–1
We are normally interested in how long it takes for the hot coffee in a thermos bottle to cool to a certain temperature, which cannot be determined from a thermodynamic analysis alone.

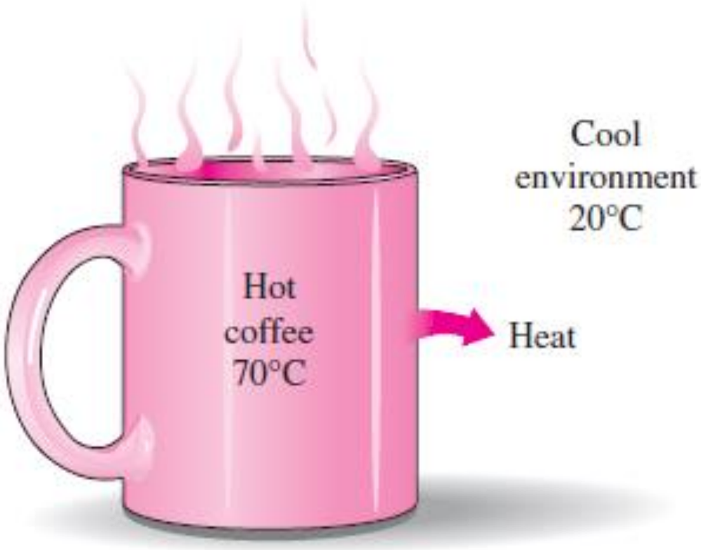

FIGURE 1–2
Heat flows in the direction of decreasing temperature.

Application Areas of Heat Transfer

The human body
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Air conditioning systems
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Heating systems
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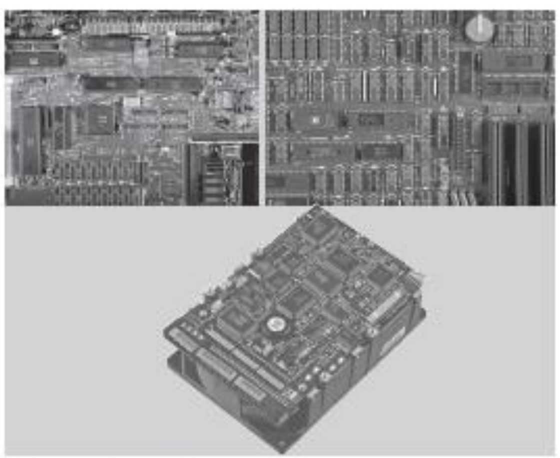


Electronic equipment

Power plants

Refrigeration systems

Historical Background

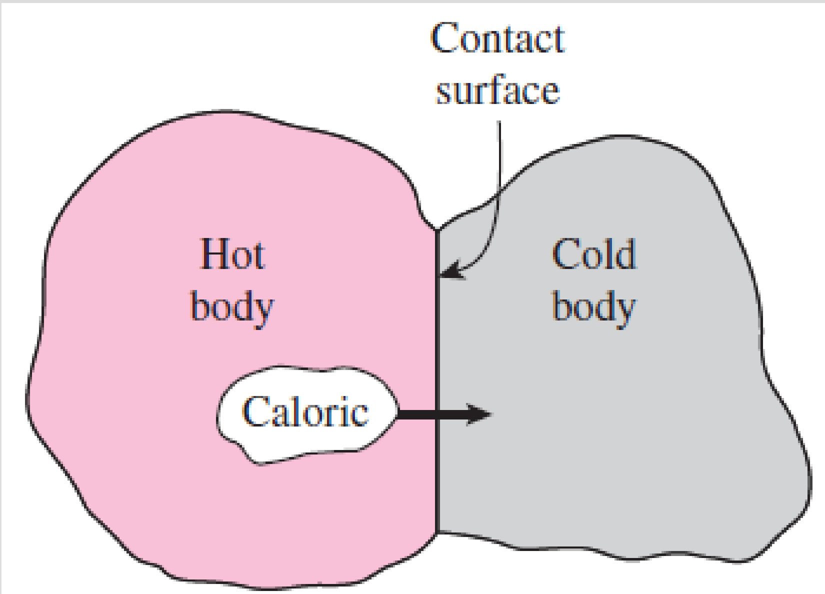


FIGURE 1–4
In the early nineteenth century, heat was thought to be an invisible fluid called the *caloric* that flowed from warmer bodies to the cooler ones.

Kinetic theory: Treats molecules as tiny balls that are in motion and thus possess kinetic energy.

Heat: The energy associated with the random motion of atoms and molecules.

Caloric theory: Heat is a fluidlike substance called the **caloric** that is a massless, colorless, odorless, and tasteless substance that can be poured from one body into another

It was only in the middle of the nineteenth century that we had a true physical understanding of the nature of heat.

Careful experiments of the Englishman James P. Joule published in 1843 convinced the skeptics that heat was not a substance after all, and thus put the caloric theory to rest.

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.

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.

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.

Modeling in Engineering

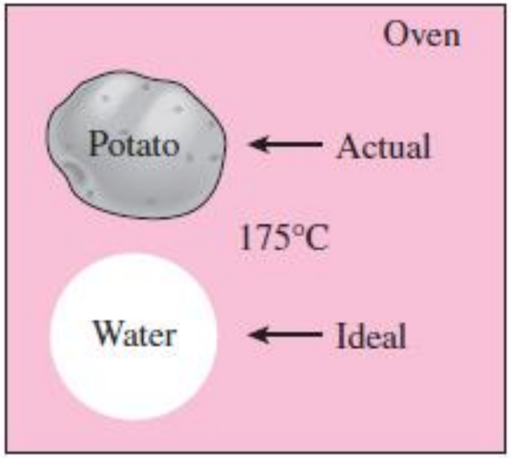


FIGURE 1–7
Modeling is a powerful engineering tool that provides great insight and simplicity at the expense of some accuracy.

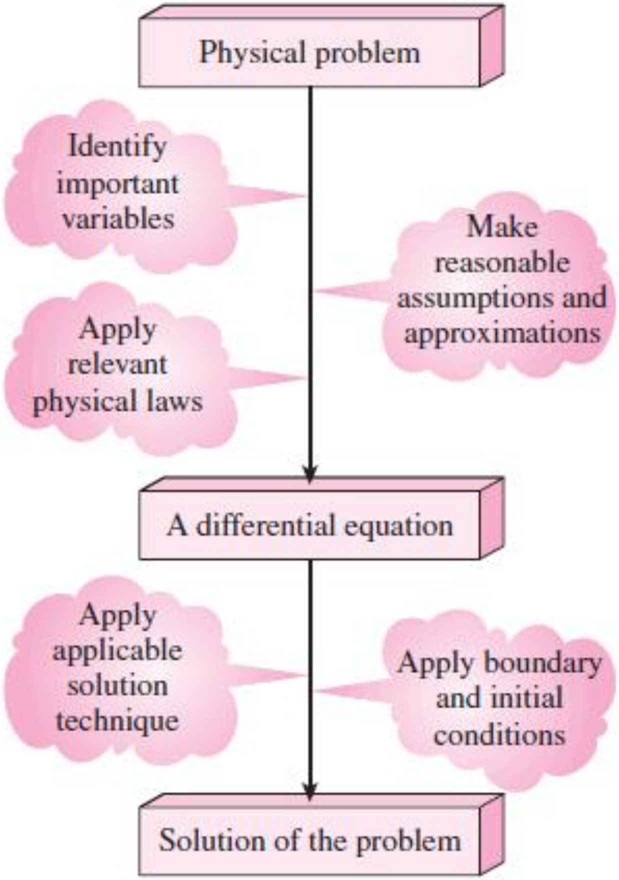


FIGURE 1–6
Mathematical modeling of physical problems.

HEAT AND OTHER FORMS OF ENERGY

- Energy can exist in numerous forms such as:
  - ✓ thermal,
  - ✓ mechanical,
  - ✓ kinetic,
  - ✓ potential,
  - ✓ electrical,
  - ✓ magnetic,
  - ✓ chemical,
  - ✓ nuclear.
- Their sum constitutes the **total energy** *E* (or *e* on a unit mass basis) of a system.
- The sum of all microscopic forms of energy is called the **internal energy** of a system.

- **Internal energy:** May be viewed as the sum of the kinetic and potential energies of the molecules.
- **Sensible heat:** The kinetic energy of the molecules.
- **Latent heat:** The internal energy associated with the phase of a system.
- **Chemical (bond) energy**: The internal energy associated with the atomic bonds in a molecule.
- **Nuclear energy:** The internal energy associated with the bonds within the nucleus of the atom itself.

What is thermal energy?

What is the difference between thermal energy and heat?

Internal Energy and Enthalpy

- In the analysis of systems that involve fluid flow, we frequently encounter the combination of properties *u* and *Pv*.
- The combination is defined as **enthalpy** ($h = u + Pv$).
- The term *Pv* represents the flow energy of the fluid (also called the flow work).

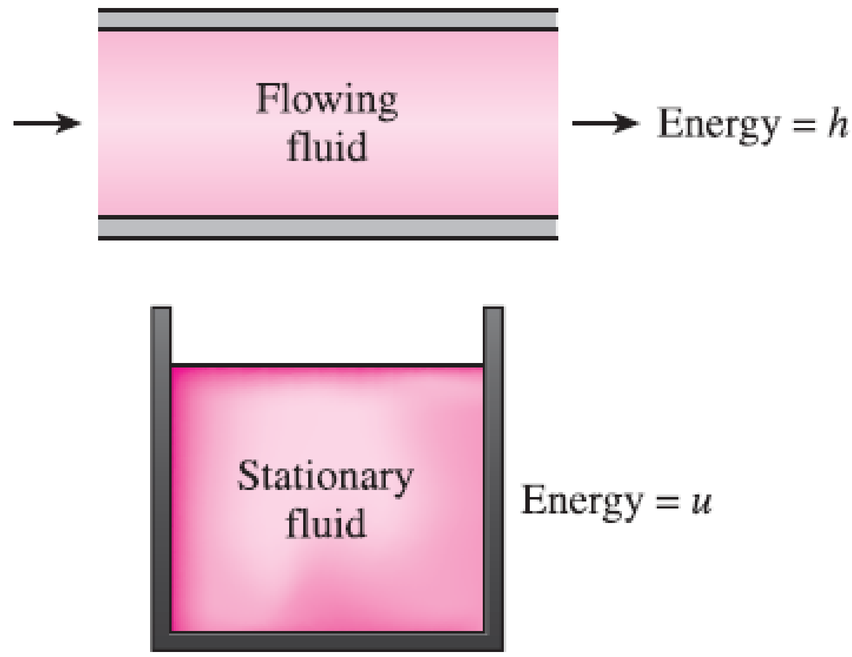


FIGURE 1–8
The *internal energy u* represents the microscopic energy of a nonflowing fluid, whereas *enthalpy h* represents the microscopic energy of a flowing fluid.

Specific Heats of Gases, Liquids, and Solids

- **Specific heat:** *The energy required to raise the temperature of a unit mass of a substance by one degree.*
- Two kinds of specific heats:
  - ✓ specific heat at constant volume c_v
  - ✓ specific heat at constant pressure c_p
- The specific heats of a substance, in general, depend on two independent properties such as temperature and pressure.
- At low pressures all real gases approach ideal gas behavior, and therefore their specific heats depend on temperature only.

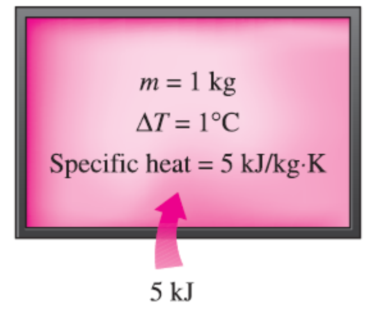


FIGURE 1–9
Specific heat is the energy required to raise the temperature of a unit mass of a substance by one degree in a specified way.

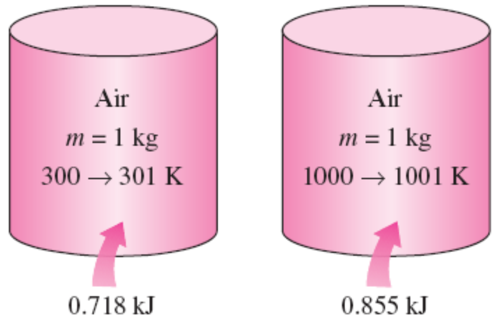


FIGURE 1–10
The specific heat of a substance changes with temperature.

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

$$du = c_v\,dT \qquad \text{and} \qquad dh = c_p\,dT$$

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

$$\Delta U = mc_{v,\,\text{avg}}\Delta T \qquad \text{and} \qquad \Delta H = mc_{p,\,\text{avg}}\Delta T \qquad (\text{J})$$

- **Incompressible substance:** A substance whose specific volume (or density) does not change with temperature or pressure.
- The constant-volume and constant-pressure specific heats are identical for incompressible substances.
- The specific heats of incompressible substances depend on temperature only.

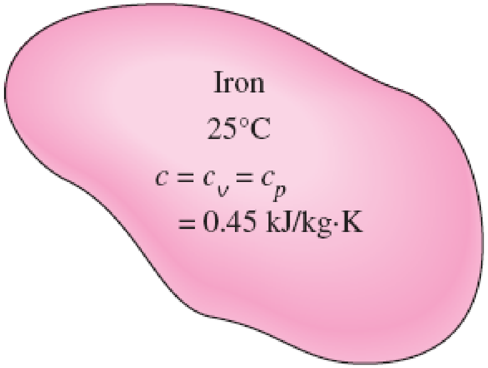


FIGURE 1–11
The c_v and c_p values of incompressible substances are identical and are denoted by c.

$$\Delta U = mc_{\text{avg}}\Delta T \qquad (\text{J})$$

Energy Transfer

Energy can be transferred to or from a given mass by two mechanisms:

heat transfer and **work**.

Heat transfer rate: The amount of heat transferred per unit time.

Heat flux: The rate of heat transfer per unit area normal to the direction of heat transfer.

Power: The work done *per unit time.*

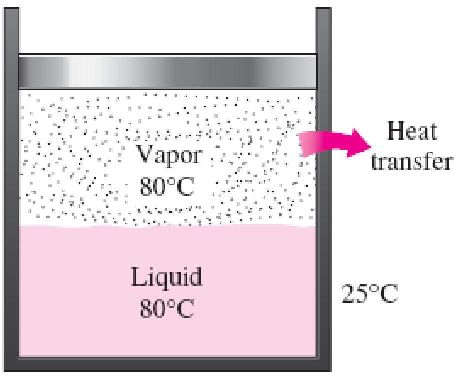


FIGURE 1–12
The sensible and latent forms of internal energy can be transferred as a result of a temperature difference, and they are referred to as *heat* or *thermal energy*.

$$Q = \int_0^{\Delta t} \dot{Q}\,dt \qquad \text{(J)}$$

when $\dot{Q}$ is constant:

$$Q = \dot{Q}\,\Delta t \qquad \text{(J)}$$

$$\dot{q} = \frac{\dot{Q}}{A} \qquad (\text{W/m}^2)$$

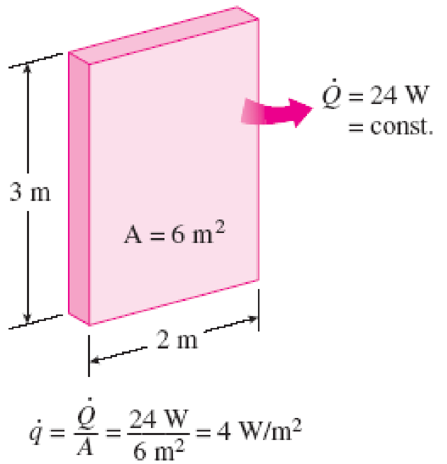


FIGURE 1–13
Heat flux is heat transfer *per unit time* and *per unit area*, and is equal to $\dot{q} = \dot{Q}/A$ when $\dot{Q}$ is uniform over the area A.

THE FIRST LAW OF THERMODYNAMICS

The **first law of thermodynamics (conservation of energy principle)** states that *energy can neither be created nor destroyed during a process; it can only change forms.*

$$\begin{pmatrix}\text{Total energy}\\ \text{entering the}\\ \text{system}\end{pmatrix} - \begin{pmatrix}\text{Total energy}\\ \text{leaving the}\\ \text{system}\end{pmatrix} = \begin{pmatrix}\text{Change in the}\\ \text{total energy of}\\ \text{the system}\end{pmatrix}$$

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.

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

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

The **energy balance** for any system undergoing any process in the rate form

Steady, rate form:

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

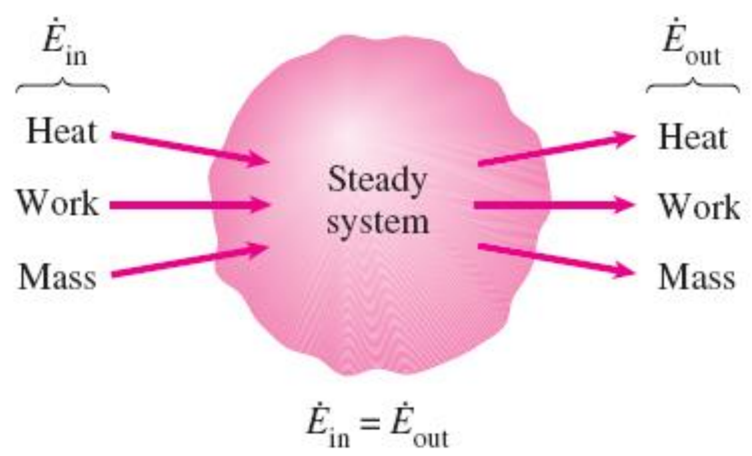


FIGURE 1–15
In steady operation, the rate of energy transfer to a system is equal to the rate of energy transfer from the system.

In heat transfer problems 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.***

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

Energy Balance for Closed Systems *(Fixed Mass)*

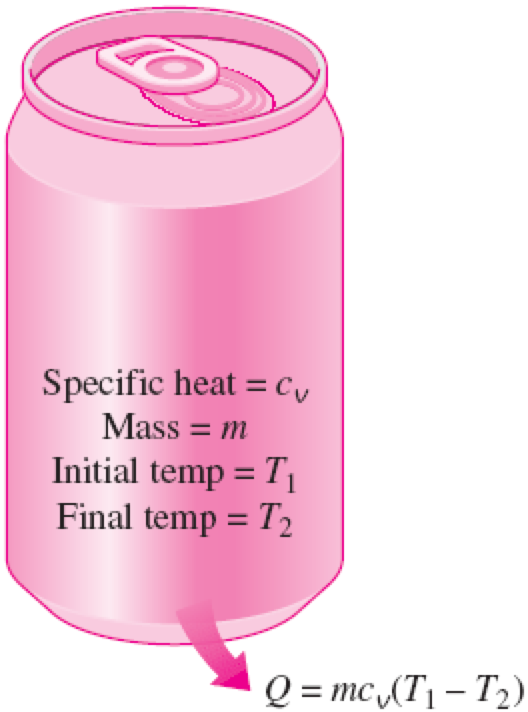


FIGURE 1–16
In the absence of any work interactions, the change in the energy content of a closed system is equal to the net heat transfer.

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.

Stationary closed system:

$$E_{in} - E_{out} = \Delta U = mc_v \Delta T \qquad \text{(J)}$$

Stationary closed system, no work:

$$Q = mc_v \Delta T \qquad \text{(J)}$$

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.

Mass flow rate: The amount of mass flowing through a cross section of a flow device per unit time.

Volume flow rate: The volume of a fluid flowing through a pipe or duct per unit time.

$$\dot{m} = \rho V A_c \qquad \text{(kg/s)}$$

$$\dot{V} = V A_c = \frac{\dot{m}}{\rho} \qquad (\text{m}^3/\text{s})$$

$$\dot{Q} = \dot{m}\Delta h = \dot{m} c_p \Delta T \qquad \text{(kJ/s)}$$

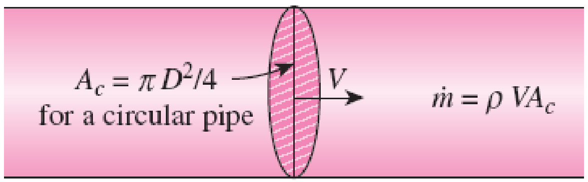


FIGURE 1–17
The mass flow rate of a fluid at a cross section is equal to the product of the fluid density, average fluid velocity, and the cross-sectional area.

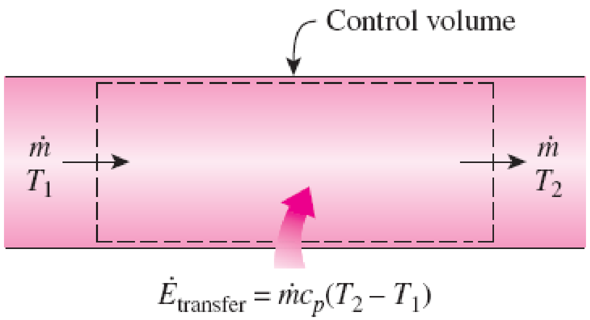


FIGURE 1–18
Under steady conditions, the net rate of energy transfer to a fluid in a control volume is equal to the rate of increase in the energy of the fluid stream flowing through the control volume.

Surface Energy Balance

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

Surface energy balance: $\dot{E}_{in} = \dot{E}_{out}$

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.

$$\dot{Q}_1 = \dot{Q}_2 + \dot{Q}_3$$

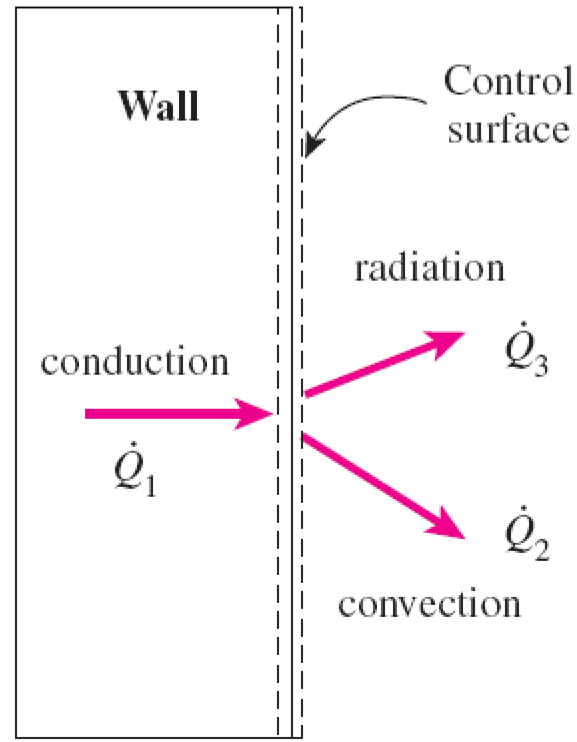


FIGURE 1–19
Energy interactions at the outer wall surface of a house.

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 $\sum \dot{E}_{in} = 0$. Note that the interactions in opposite direction will end up having negative values, and balance this equation.

HEAT TRANSFER MECHANISMS

- *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 basic modes:
  - ✓ conduction
  - ✓ convection
  - ✓ radiation
- All modes of heat transfer require the existence of a temperature difference.

CONDUCTION

Conduction: 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.

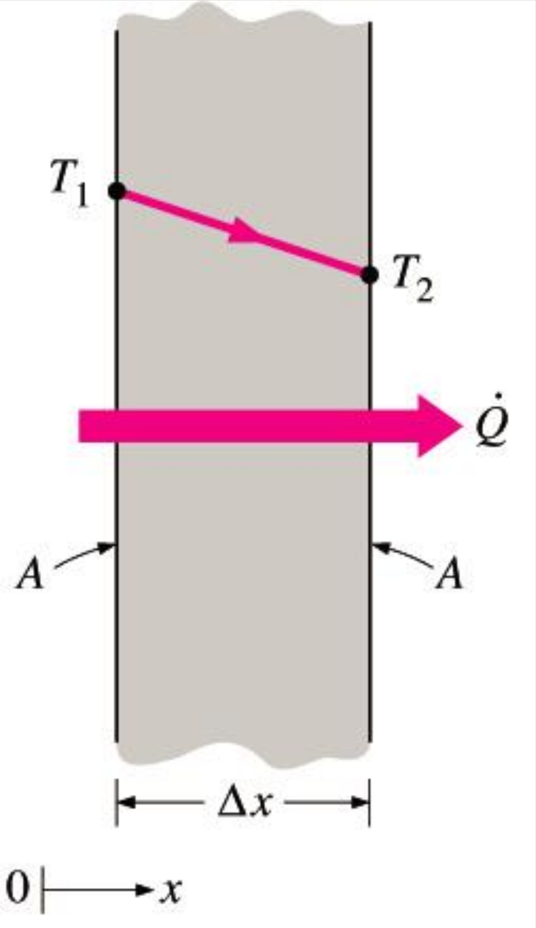
In gases and liquids, conduction is due to the *collisions* and *diffusion* of the molecules during their random motion.

In solids, it is due to the combination of *vibrations* of the molecules in a lattice and the energy transport by *free electrons.*

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.

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

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



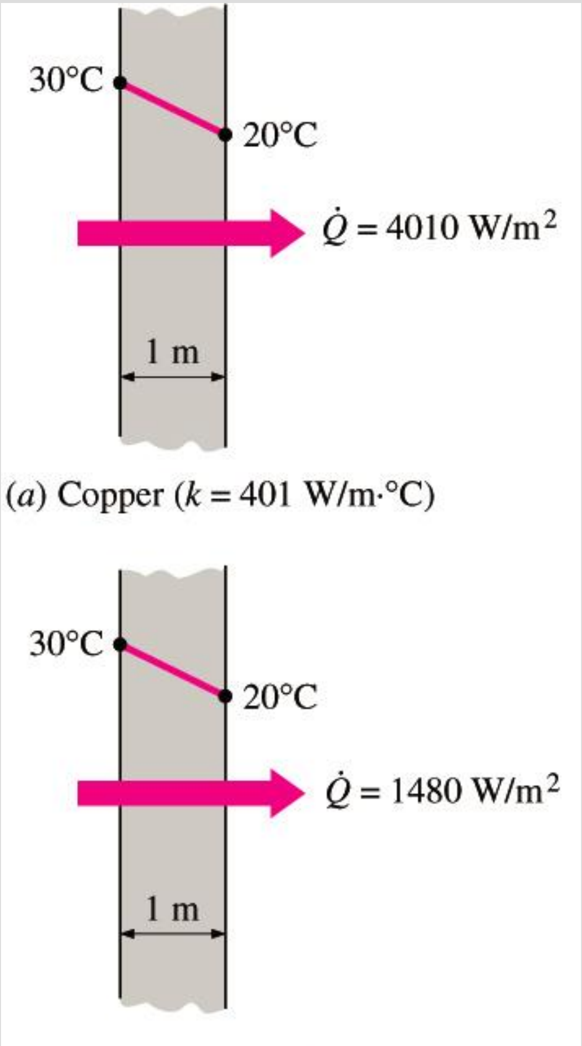
Heat conduction through a large plane wall of thickness Δx and area A.

When $x \to 0$ $$\dot{Q}_{\text{cond}} = -kA\frac{dT}{dx}$$ **Fourier's law of heat conduction**

Thermal conductivity, *k*: A measure of the ability of a material to conduct heat.

Temperature gradient *dT/dx*: The slope of the temperature curve on a *T*-*x* diagram.

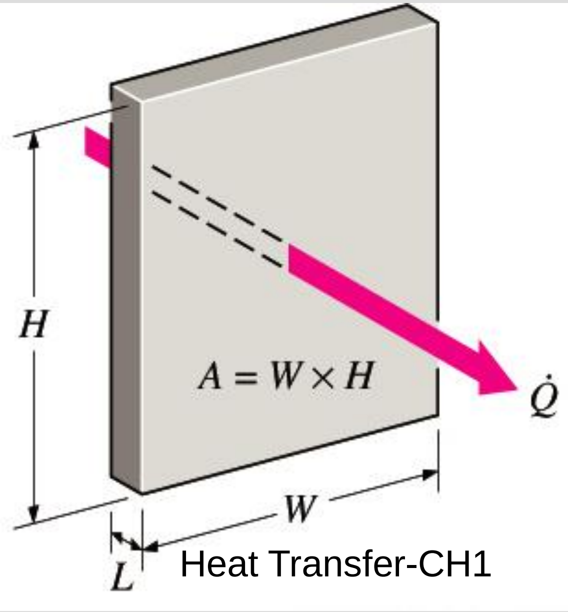
Heat is conducted in the direction of decreasing temperature, and the temperature gradient becomes negative when temperature decreases with increasing *x*. The *negative sign* in the equation ensures that heat transfer in the positive *x* direction is a positive quantity.



(*a*) Copper (k = 401 W/m·°C)

(*b*) Silicon (k = 148 W/m·°C)

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



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

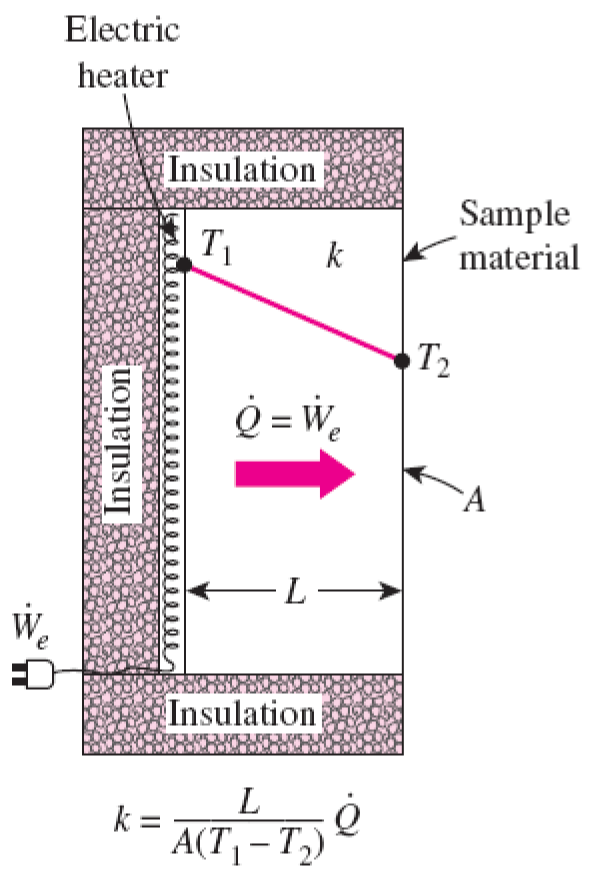
Jean Baptiste Joseph Fourier (1768–1830) was a French mathematician and physicist born in Auxerre, France. He is best known for his work on the infinite series of trigonometric functions that bear his name and for his development of the mathematical theory of heat conduction. Fourier established the 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.

Thermal Conductivity

Thermal conductivity: The rate of 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.

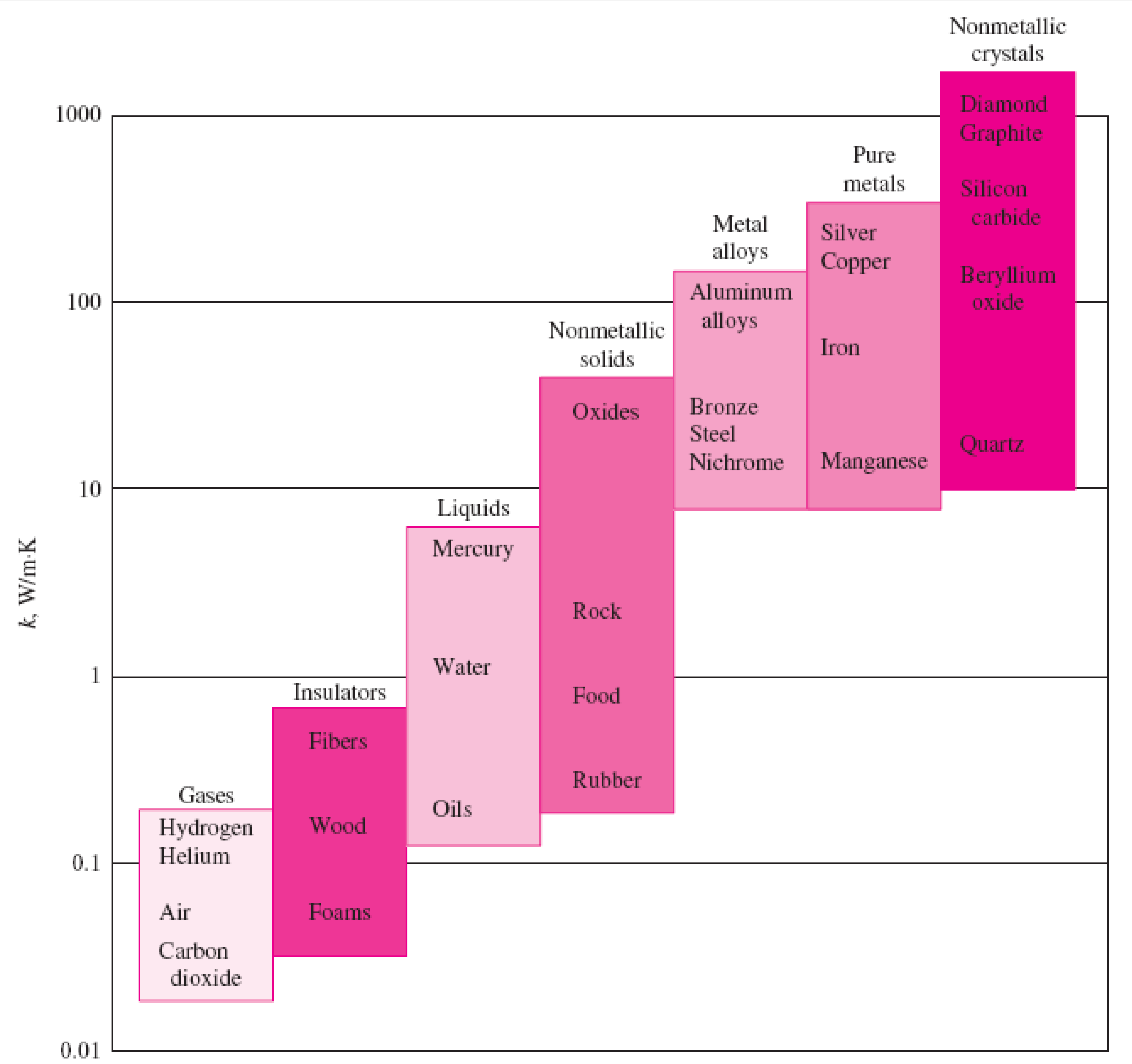
A high value for thermal conductivity indicates that the material is a good heat conductor, and a low value indicates that the material is a poor heat conductor or *insulator*.



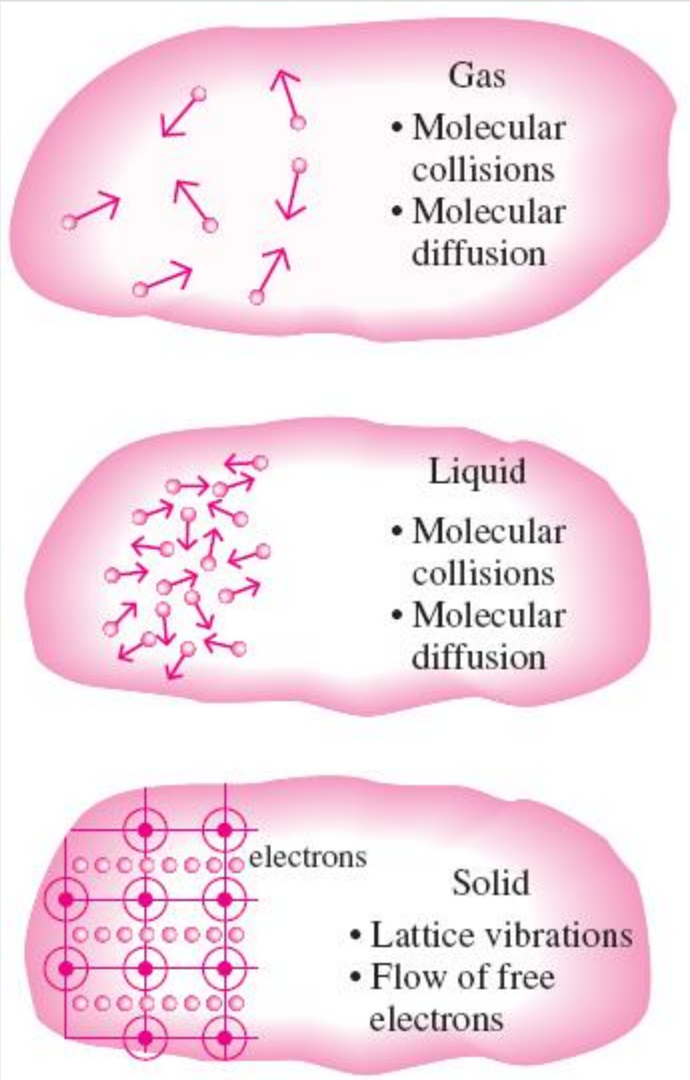
A simple experimental setup to determine the thermal conductivity of a material.

The thermal conductivities of some materials at room temperature

Material	k, W/m · °C*
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



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



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

The thermal conductivities of gases such as air vary by a factor of 10^4 from those of pure metals such as copper.

Pure crystals and metals have the highest thermal conductivities, and gases and insulating materials the lowest.

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

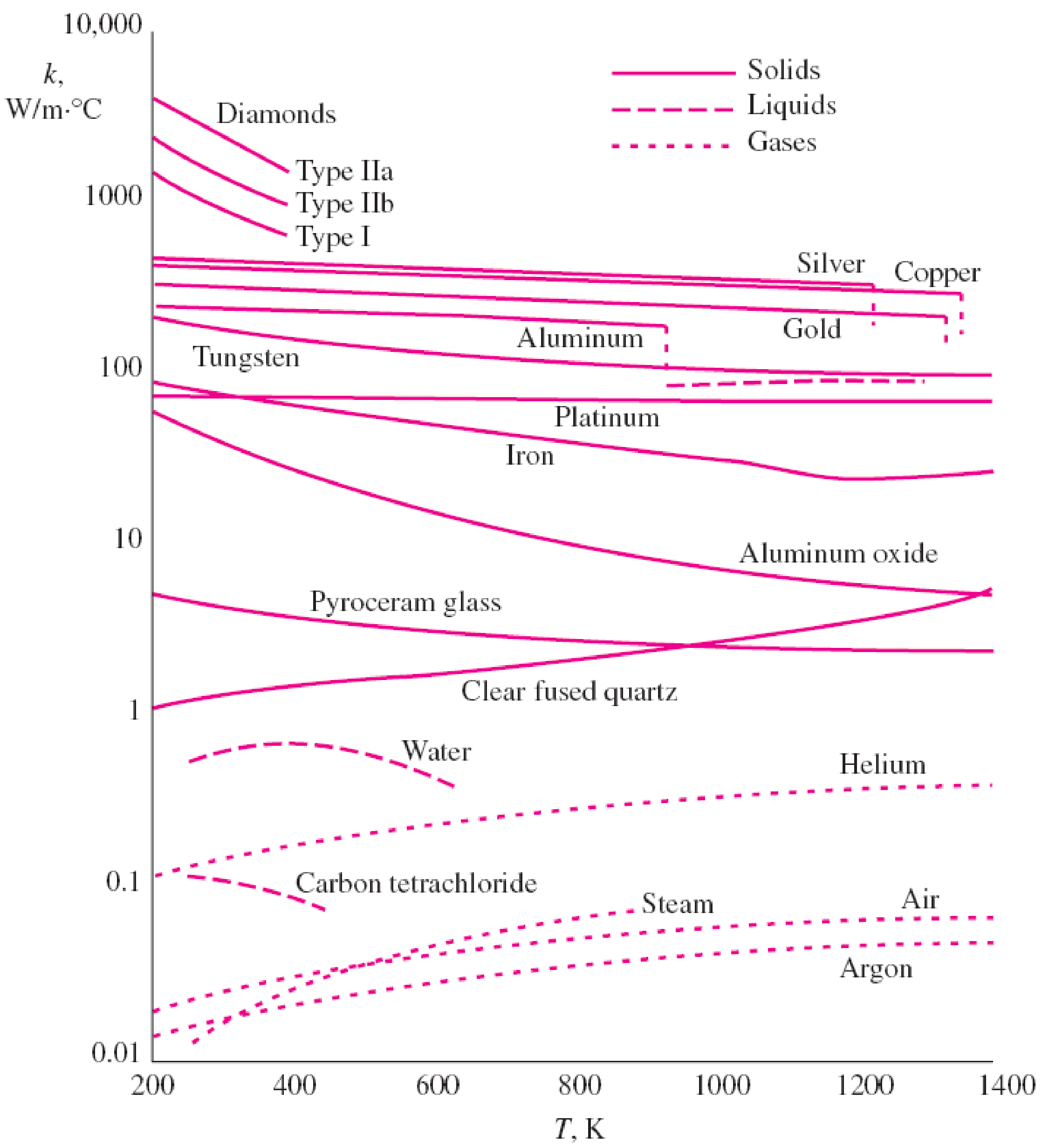


TABLE 1–3

Thermal conductivities of materials vary with temperature

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

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

Thermal Diffusivity

c_p **Specific heat, J/kg · °C:** Heat capacity per unit mass

ρc_p **Heat capacity, J/m³·°C:** Heat capacity per unit volume

α **Thermal diffusivity, m²/s:** Represents how fast heat diffuses through a material

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

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 materials at room temperature

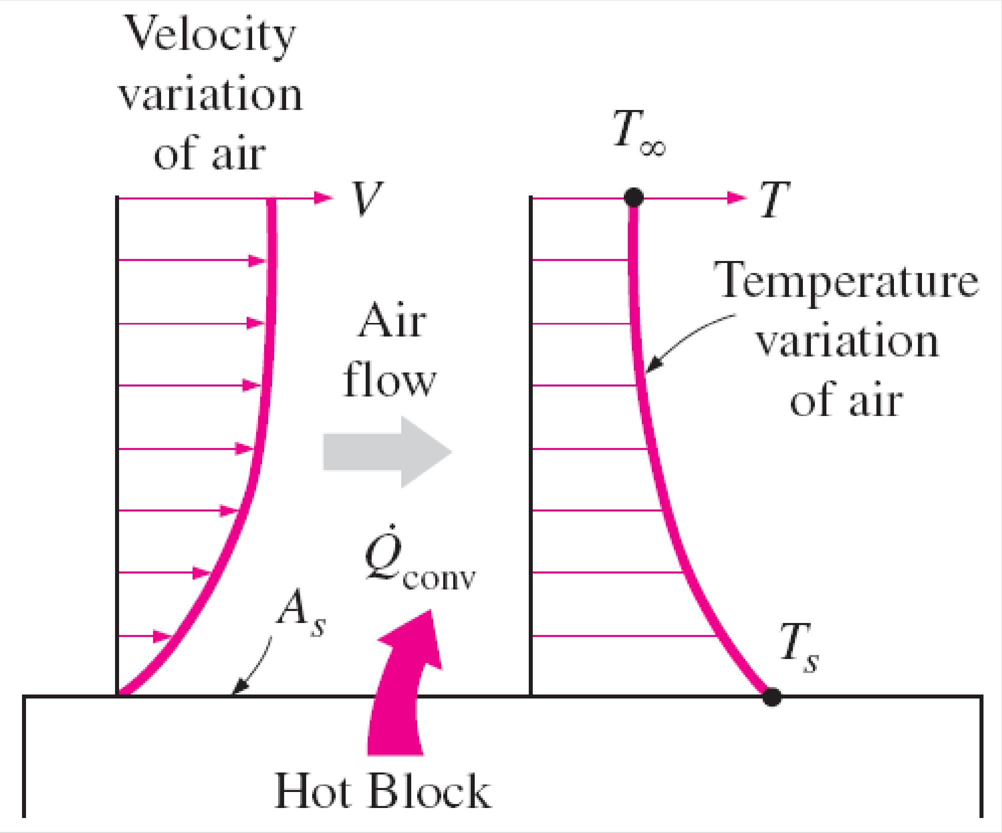
Material	α, m²/s*
Silver	149×10^{-6}
Gold	127×10^{-6}
Copper	113×10^{-6}
Aluminum	97.5×10^{-6}
Iron	22.8×10^{-6}
Mercury (l)	4.7×10^{-6}
Marble	1.2×10^{-6}
Ice	1.2×10^{-6}
Concrete	0.75×10^{-6}
Brick	0.52×10^{-6}
Heavy soil (dry)	0.52×10^{-6}
Glass	0.34×10^{-6}
Glass wool	0.23×10^{-6}
Water (l)	0.14×10^{-6}
Beef	0.14×10^{-6}
Wood (oak)	0.13×10^{-6}

CONVECTION

Convection: 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.

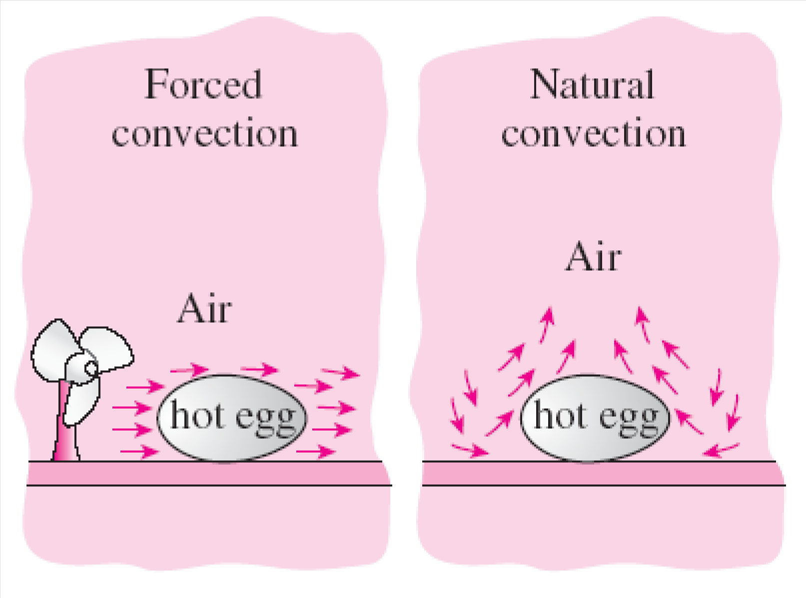
In the absence of any bulk fluid motion, heat transfer between a solid surface and the adjacent fluid is by pure conduction.



Heat transfer from a hot surface to air by convection.

Forced convection: If the fluid is forced to flow over the surface by external means such as a fan, pump, or the wind.

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.



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

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.

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

Newton's law of cooling

h	convection heat transfer coefficient, W/m^2 · °C
A_s	the surface area through which convection heat transfer takes place
T_s	the surface temperature
T_∞	the temperature of the fluid sufficiently far from the surface.

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
- the bulk fluid velocity

Typical values of convection heat transfer coefficient

Type of convection	*h*, W/m^2 · °C*
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

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 *Philosophiae 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.

RADIATION

- **Radiation:** 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.
- 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 usually considered to be a *surface phenomenon* for solids.

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

Stefan–Boltzmann law

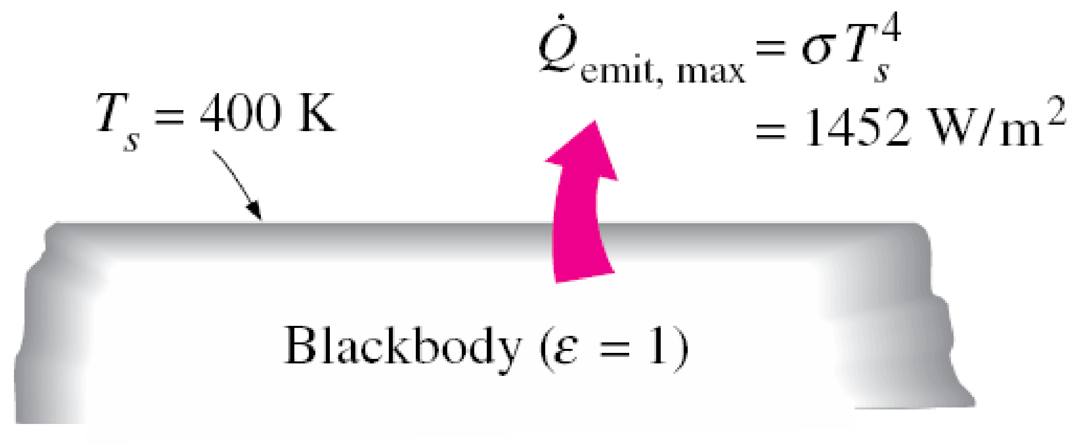
$\sigma = 5.670 \times 10^{-8}$ W/m$^2 \cdot$ K^4 *Stefan–Boltzmann constant*

Blackbody: The idealized surface that emits radiation at the maximum rate.

$$\dot{Q}_{\text{emit}} = \varepsilon \sigma A_s T_s^4 \quad \text{(W)}$$

Radiation emitted by real surfaces

Emissivity ε : A measure of how closely a surface approximates a blackbody for which $\varepsilon = 1$ of the surface. **$0 \le \varepsilon \le 1$**.



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

Emissivities of some materials at 300 K

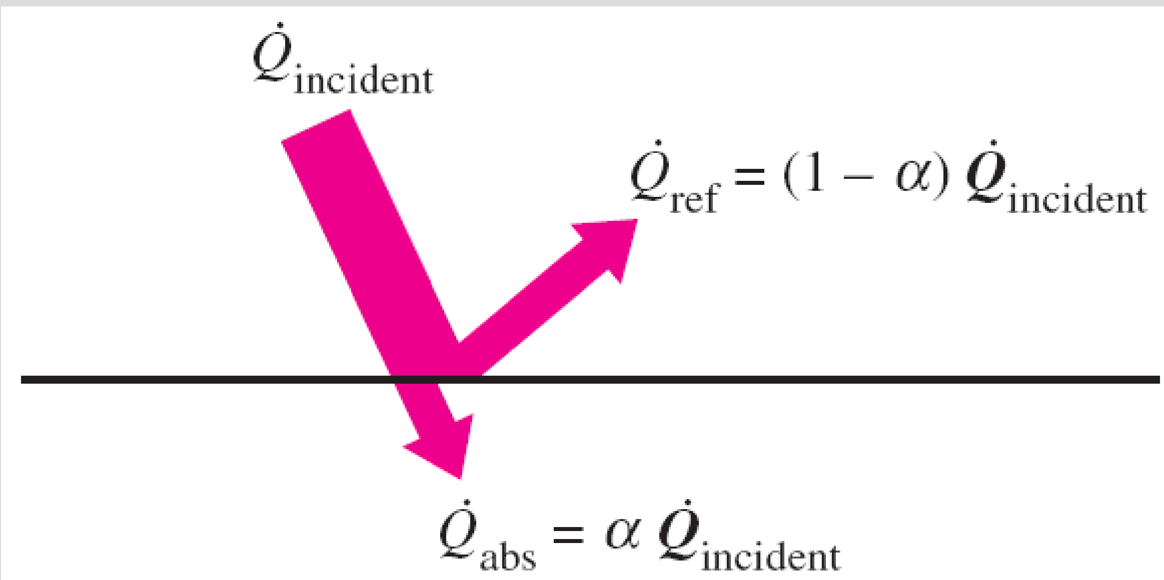
Material	Emissivity
Aluminum foil	0.07
Anodized aluminum	0.82
Polished copper	0.03
Polished gold	0.03
Polished silver	0.02
Polished stainless steel	0.17
Black paint	0.98
White paint	0.90
White paper	0.92–0.97
Asphalt pavement	0.85–0.93
Red brick	0.93–0.96
Human skin	0.95
Wood	0.82–0.92
Soil	0.93–0.96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

Absorptivity α: The fraction of the radiation energy incident on a surface that is absorbed by the surface. **$0 \leq \alpha \leq 1$**

A blackbody absorbs the entire radiation incident on it (**$\alpha = 1$**).

Kirchhoff's law: The emissivity and the absorptivity of a surface at a given temperature and wavelength are equal.

$$\dot{Q}_{\text{absorbed}} = \alpha \dot{Q}_{\text{incident}} \qquad \text{(W)}$$



The absorption of radiation incident on an opaque surface of absorptivity .

Net radiation heat transfer: The difference between the rates of radiation emitted by the surface and the radiation absorbed.

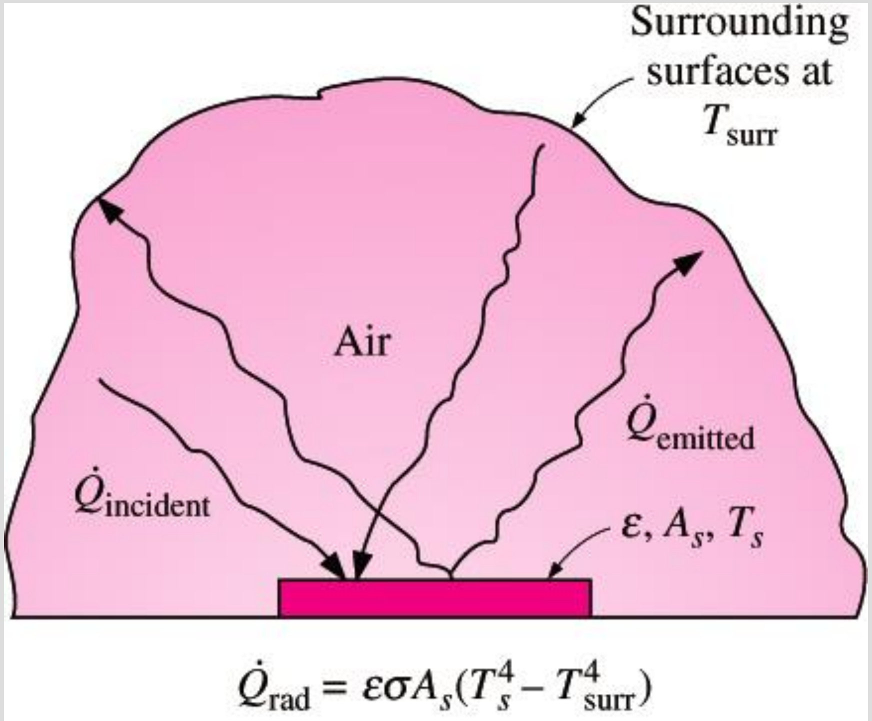
The determination of the net rate of heat transfer by radiation between two surfaces is a complicated matter since it depends on

- the properties of the surfaces
- their orientation relative to each other
- the interaction of the medium between the surfaces with radiation

Radiation is usually significant relative to conduction or natural convection, but negligible relative to forced convection.

When a surface is *completely enclosed* by a much larger (or black) surface at temperature T_{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

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



Radiation heat transfer between a surface and the surfaces surrounding it.

When radiation and convection occur simultaneously between a surface and a gas:

$$\dot{Q}_{\text{total}} = h_{\text{combined}} A_s (T_s - T_\infty) \qquad \text{(W)}$$

Combined heat transfer coefficient $h_{combined}$

Includes the effects of both convection and radiation

$$\dot{Q}_{\text{total}} = \dot{Q}_{\text{conv}} + \dot{Q}_{\text{rad}} = h_{\text{conv}} A_s (T_s - T_{\text{surr}}) + \varepsilon\sigma A_s (T_s^4 - T_{\text{surr}}^4)$$

$$\dot{Q}_{\text{total}} = h_{\text{combined}} A_s (T_s - T_\infty) \qquad \text{(W)}$$

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

SIMULTANEOUS HEAT TRANSFER MECHANISMS

Heat transfer is only by conduction in *opaque solids,* but by conduction and radiation in *semitransparent solids.*

A solid may involve conduction and radiation but not convection. A solid may involve convection and/or radiation on its surfaces exposed to a fluid or other surfaces.

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.*

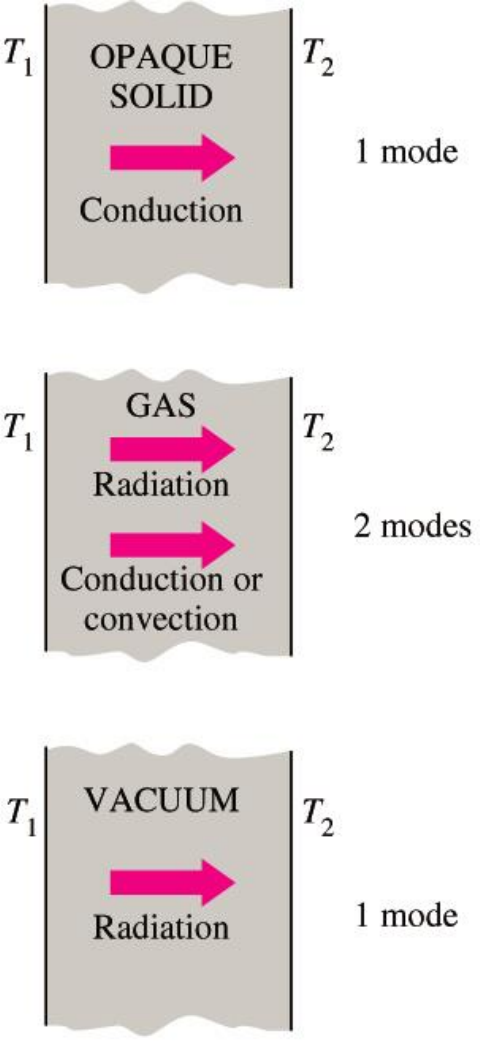
In the absence of radiation, heat transfer through a fluid is either by conduction or convection, depending on the presence of any bulk fluid motion.

Convection = Conduction + Fluid motion

Heat transfer through a *vacuum* is by radiation.

Most gases between two solid surfaces do not interfere with radiation.

Liquids are usually strong absorbers of radiation.



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

PROBLEM-SOLVING TECHNIQUE

- Step 1: Problem Statement
- Step 2: Schematic
- Step 3: Assumptions and Approximations
- Step 4: Physical Laws
- Step 5: Properties
- Step 6: Calculations
- Step 7: Reasoning, Verification, and Discussion

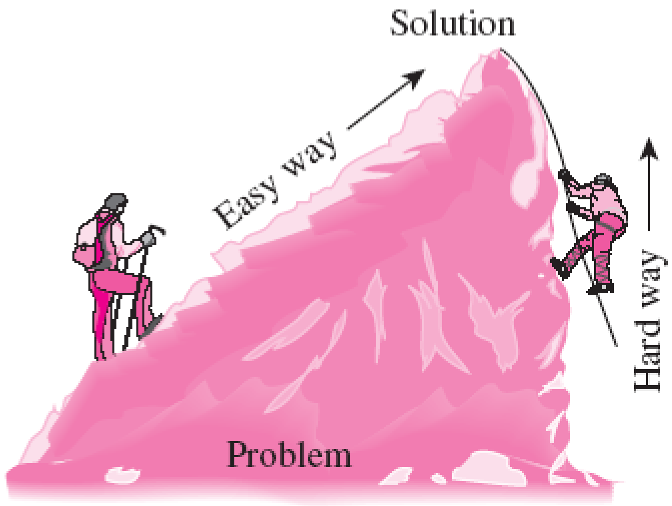


FIGURE 1–48
A step-by-step approach can greatly simplify problem solving.

Given: Air temperature in Denver

To be found: Density of air

Missing information: Atmospheric pressure

Assumption #1: Take $P = 1$ atm (Inappropriate. Ignores effect of altitude. Will cause more than 15% error.)

Assumption #2: Take $P = 0.83$ atm (Appropriate. Ignores only minor effects such as weather.)

FIGURE 1–49
The assumptions made while solving an engineering problem must be reasonable and justifiable.

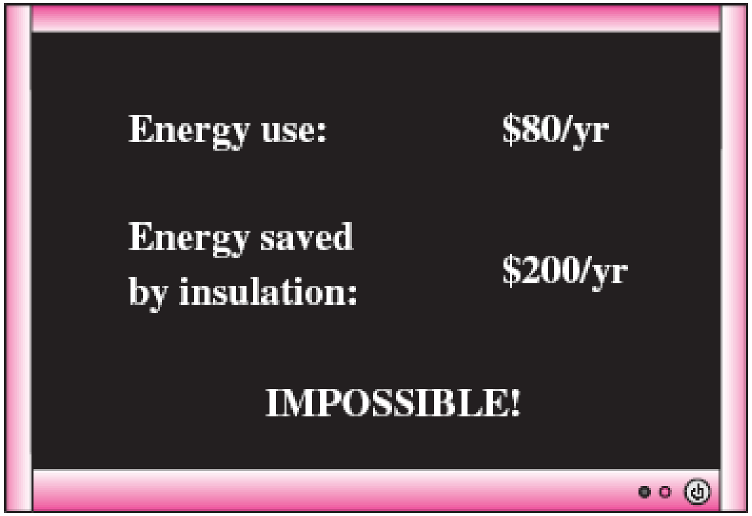


FIGURE 1–50
The results obtained from an engineering analysis must be checked for reasonableness.

FIGURE 1–51
Neatness and organization are highly valued by employers.

Engineering Software Packages

Thinking that a person who can use the engineering software packages without proper training on fundamentals can practice engineering is like thinking that a person who can use a wrench can work as a car mechanic.

EES (Engineering Equation Solver)

(Pronounced as ease): EES is a program that solves systems of linear or nonlinear algebraic or differential equations numerically. It has a large library of built-in thermodynamic property functions as well as mathematical functions. Unlike some software packages, EES does not solve engineering problems; it only solves the equations supplied by the user.

FIGURE 1–52
An excellent word-processing program does not make a person a good writer; it simply makes a good writer a better and more efficient writer.

A Remark on Significant Digits

In engineering calculations, the information given is not known to more than a certain number of significant digits, usually three digits.

Consequently, the results obtained cannot possibly be accurate to more significant digits.

Reporting results in more significant digits implies greater accuracy than exists, and it should be avoided.

Given: Volume: $V = 3.75$ L

Density: $\rho = 0.845$ kg/L

(3 significant digits)

Also, $3.75 \times 0.845 = 3.16875$

Find: Mass: $m = \rho V = 3.16875$ kg

Rounding to 3 significant digits:

$m = 3.17$ kg

A result with more significant digits than that of given data falsely implies more accuracy.

Summary

- Thermodynamics and Heat Transfer
  - ✓ Application areas of heat transfer
  - ✓ Historical background
- Engineering Heat Transfer
  - ✓ Modeling in engineering
- Heat and Other Forms of Energy
  - ✓ Specific heats of gases, liquids, and solids
  - ✓ Energy transfer
- The First Law of Thermodynamics
  - ✓ Energy balance for closed systems (Fixed Mass)
  - ✓ Energy balance for steady-flow systems
  - ✓ Surface energy balance

- Heat Transfer Mechanisms
- Conduction
  - ✓ Fourier's law of heat conduction
  - ✓ Thermal Conductivity
  - ✓ Thermal Diffusivity
- Convection
  - ✓ Newton's law of cooling
- Radiation
  - ✓ Stefan–Boltzmann law
- Simultaneous Heat Transfer Mechanisms
- Problem Solving Technique
  - ✓ Engineering software packages
  - ✓ Engineering Equation Solver (EES)
  - ✓ A remark on significant digits