Chapter 1: Introduction and Basic Concepts

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Objectives

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

- 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.

Heat And Energy

DEFINITION OF HEAT AND ENERGY

- Heat is the form of energy that can be transferred from one system to another as a result of temperature difference.
- Energy is the capacity of a physical system to perform work. The simplest definition of energy or work is that 1 Joule is the work done by a force of 1 Newton acting over a distance of 1 meter.

Units Of Energy And Heat

- 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.

TABLE 1

Units and Conversion Factors for Heat Measurements		
	SI Units	English Units
Thermal Energy (Q)	1 J	9.4787×10^{-4} Btu
Heat Transfer Rate ($\dot{Q}$)	1 J/s or 1 W	3.4123 Btu/h
Heat Flux (q)	1 W/m^2	0.3171 Btu/h ft^2

THERMODYNAMICS AND 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**.

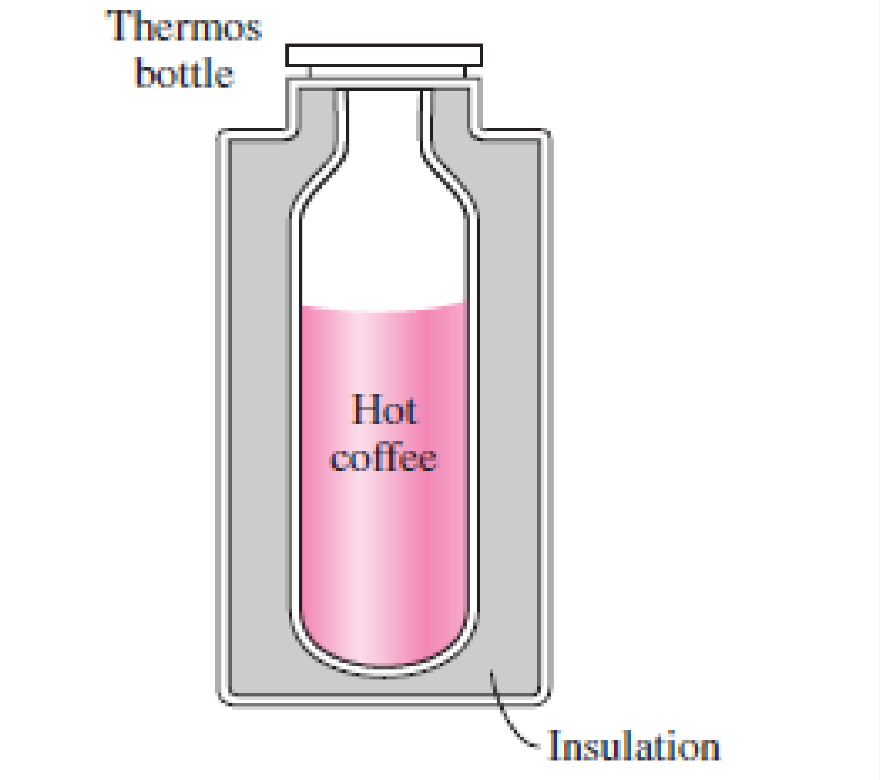
- A thermodynamic analysis simply tells us how much heat must be transferred to realize a specified change of state to satisfy the conservation of energy principle.

- 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°C to 80°C by a thermodynamic analysis alone.

- But a typical user or designer of a thermos is primarily interested in *how long* it will be before the hot coffee inside cools to 80°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 cooling or heating, as well as the variation of the temperature, is the subject of *heat transfer*



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

Application Areas Of Heat Transfer

- Heat transfer is commonly encountered in engineering systems and other aspects of life

- 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.

- **Household appliances** :
  - electric or gas range,
  - the heating
  - air-conditioning system,
  - the refrigerator and freezer,
  - the water heater, the iron,
  - and even the computer, the TV

- **Devices** : car radiators, solar collectors, various components of power plants, and even spacecraft

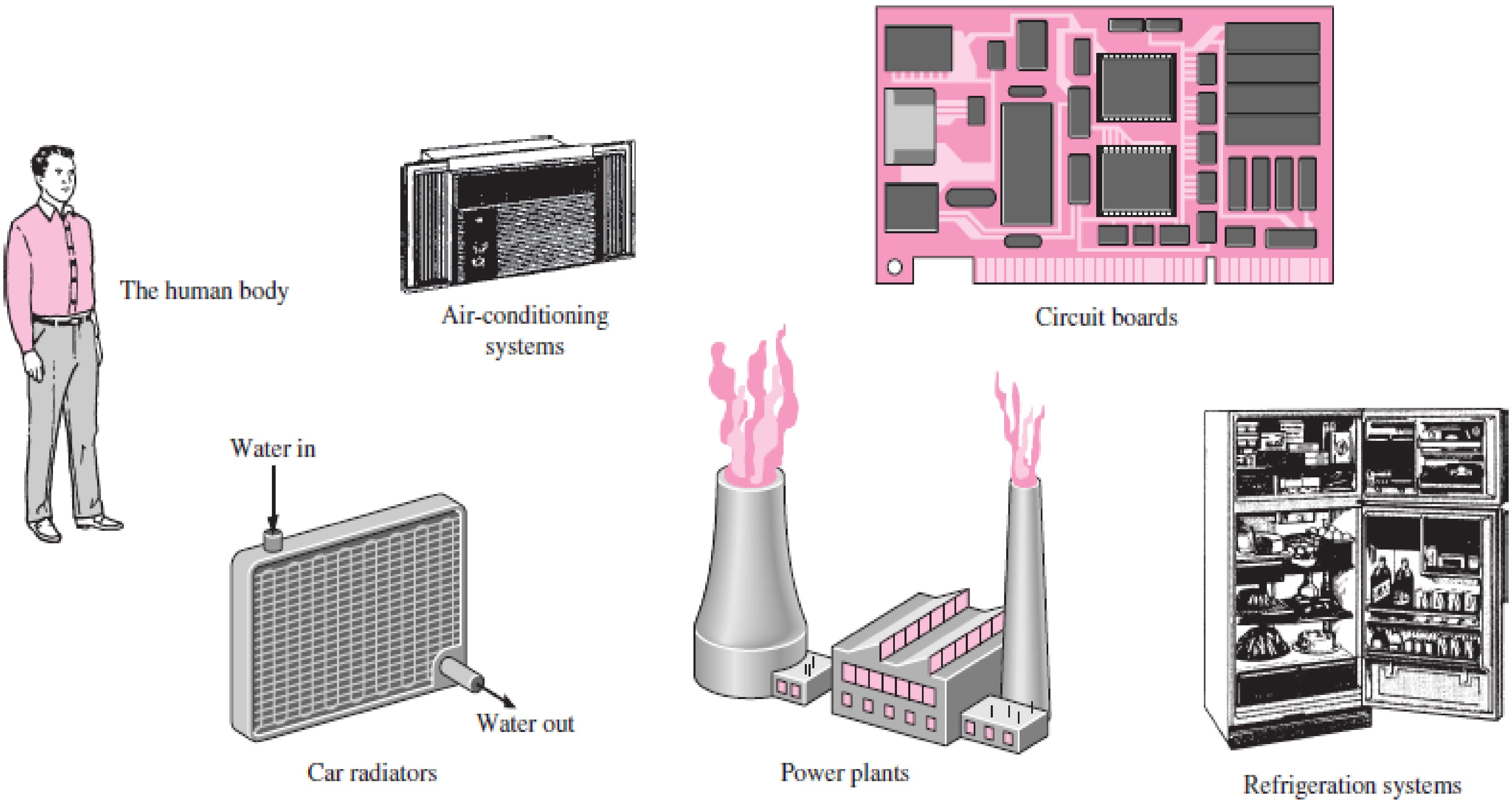


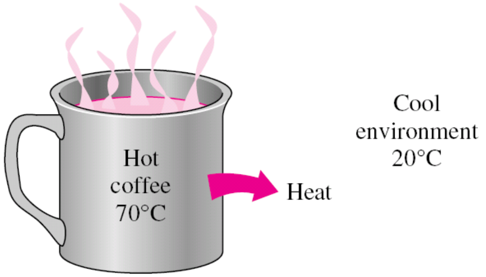
FIGURE 1–3

Some application areas of heat transfer.

Heat Transfer

- The basic requirement for heat transfer is the presence of a temperature difference.

- The second law requires that heat be transferred in the direction of decreasing temperature.



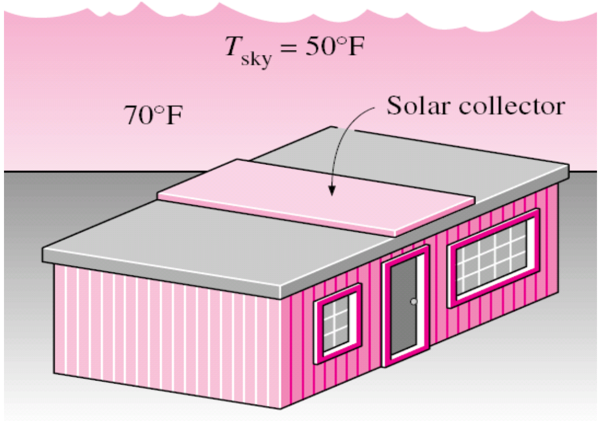
- The temperature difference is the driving force for heat transfer.

- The rate of heat transfer in a certain direction depends on the magnitude of the temperature gradient in that direction.

- The larger the temperature gradient, the higher the rate of heat transfer.

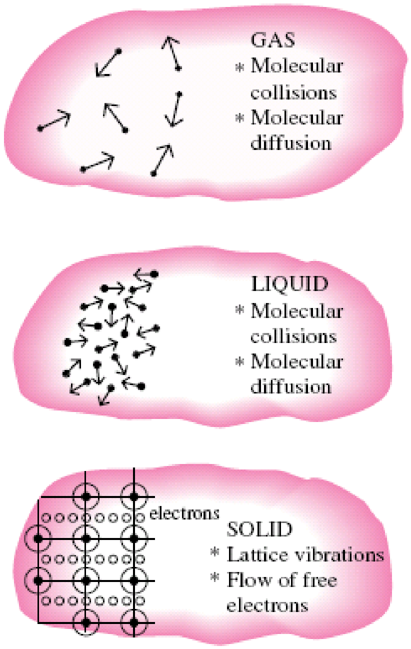
Heat Transfer Mechanisms

- Heat can be transferred in three basic modes:
  - conduction,
  - convection,
  - radiation.
- All modes of heat transfer require the existence of a temperature difference.
- All modes are from the high-temperature medium to a lower-temperature one.



Conduction

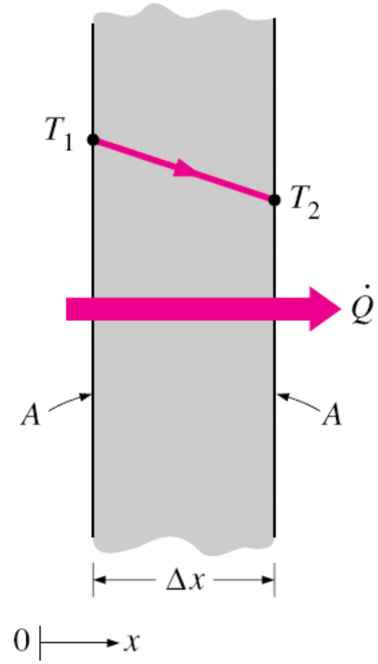
- Conduction is the transfer of energy from the more energetic particles of a substance to the adjacent less energetic ones as a result of interactions between the particles.
- Conduction can take place in solids, liquids, or gases
  - In gases and liquids conduction is due to the collisions and diffusion of the molecules during their random motion.
  - In **solids** conduction is due to the combination of vibrations of the molecules in a lattice and the energy transport by free electrons.



Conduction

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

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



where the constant of proportionality ***k*** is the **thermal conductivity** of the material.

In differential form

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

which is called **Fourier's law of heat conduction**.

Thermal Conductivity

- The thermal conductivity of a material is a measure of the ability of the material to conduct heat.
- High value for thermal conductivity

  → good heat conductor

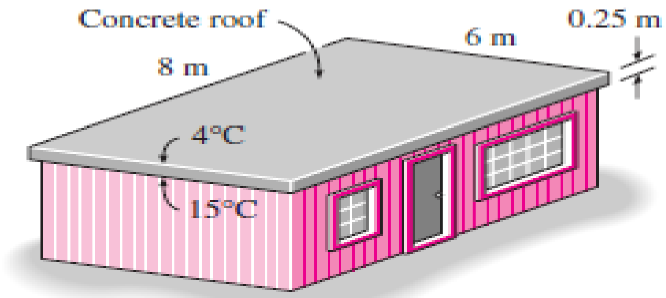
- Low value

  → poor heat conductor or *insulator*.

EXAMPLE : 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 W/m · °C. The temperatures of the inner and the outer surfaces of the roof one night are measured to be 15°C and 4°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/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 $k = 0.8\ W/m \cdot °C$

- Analysis

(a) Noting that heat transfer through the roof is by conduction and the area of the roof is A = 6 m x 8 m x 48 m^2, the steady rate of heat transfer through the roof is determined to be

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

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

$$Q = \dot{Q}\,\Delta t = (1.69\text{ kW})(10\text{ h}) = 16.9\text{ kWh}$$

$$\text{Cost} = (\text{Amount of energy})(\text{Unit cost of energy})$$

$$= (16.9\text{ kWh})(\$0.08/\text{kWh}) = \$1.35$$

Discussion

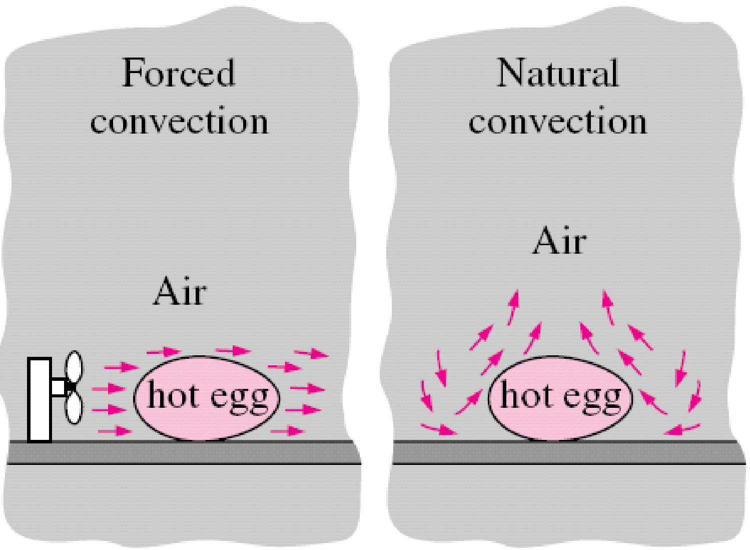
The cost to the home owner of the heat loss through the roof that night was $1.35. The total heating bill of the house will be much larger since the heat losses through the walls are not considered in these calculations.

Convection

Convection = **Conduction** + **Advection**

(fluid motion)

- Convection is the mode of energy transfer between a solid surface and the adjacent liquid or gas that is in motion.
- Convection is commonly classified into three sub-modes:
  - Forced convection,
  - Natural (or free) convection,
  - Change of phase (liquid/vap solid/liquid, etc.)



- The rate of *convection heat transfer* is expressed by **Newton's law of cooling** as *h* is the *convection heat transfer coefficient* in **W/m²°C**.

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

- *h* depends on variables such as the surface geometry, the nature of fluid motion, the properties of the fluid, and the bulk fluid velocity.

TABLE 1–5

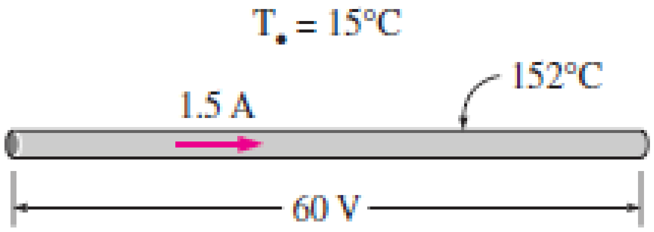
Typical values of convection heat transfer coefficient

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

*Multiply by 0.176 to convert to Btu/h · ft^2 · °F.

Example : Measuring Convection Heat Transfer Coefficient

- A 2-m-long, 0.3-cm-diameter electrical wire extends across a room at 15°C, as shown in Figure 2. Heat is generated in the wire as a result of resistance heating, and the surface temperature of the wire is measured to be 152°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 will equal the rate of heat generation in the wire as a result of resistance heating. That is,

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

The surface area of the wire is

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

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

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

- 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

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

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.
- Heat transfer by radiation does not require the presence of an intervening medium.
- In heat transfer studies we are interested in thermal radiation (radiation emitted by bodies because of their temperature).
- Radiation is a volumetric phenomenon. However, radiation is usually considered to be a surface phenomenon for solids that are opaque to thermal radiation.

Radiation - Emission

- 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

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

- *s* =5.670X10^{8} W/m^2·K^4 is the *Stefan–Boltzmann constant.*

- The idealized surface that emits radiation at this maximum rate is called a **blackbody.**

- The radiation emitted by all real surfaces is less than the radiation emitted by a blackbody at the same temperature, and is expressed as

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

$$0 \le \varepsilon \le 1$$

- *e* is the **emissivity** of the surface.

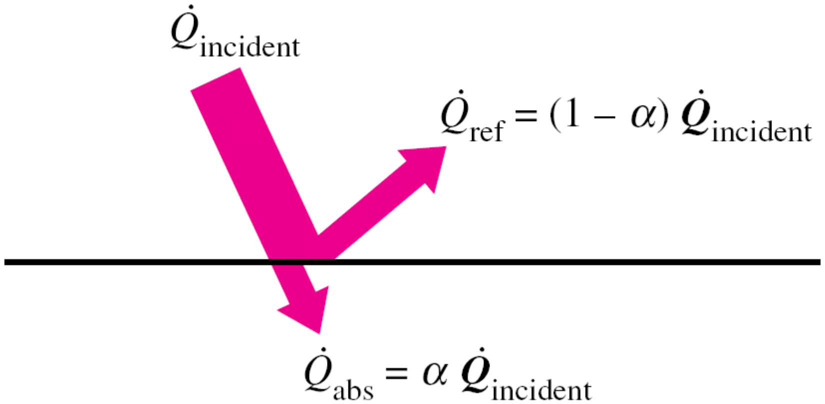
TABLE 1–6

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

Radiation - Absorption

- The fraction of the radiation energy incident on a surface that is absorbed by the surface is termed the **absorptivity** *a*.



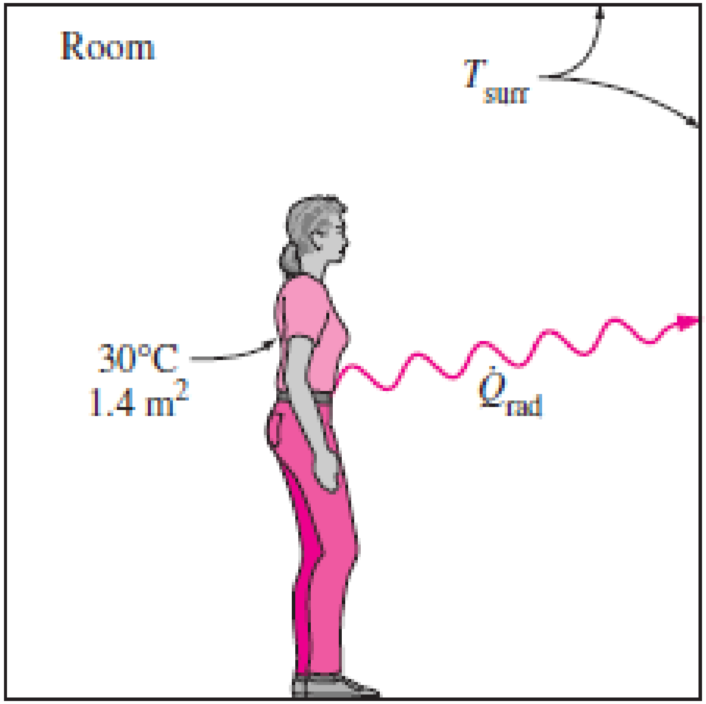
$$0 \le \alpha \le 1$$

- Both *e* and *a* of a surface depend on the temperature and the wavelength of the radiation.

Example : 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. 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 m2 and 30°C, respectively



- **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*** ε ***= 0.95 (table 1-6)***

Analysis

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

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

and

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