INTRODUCTION

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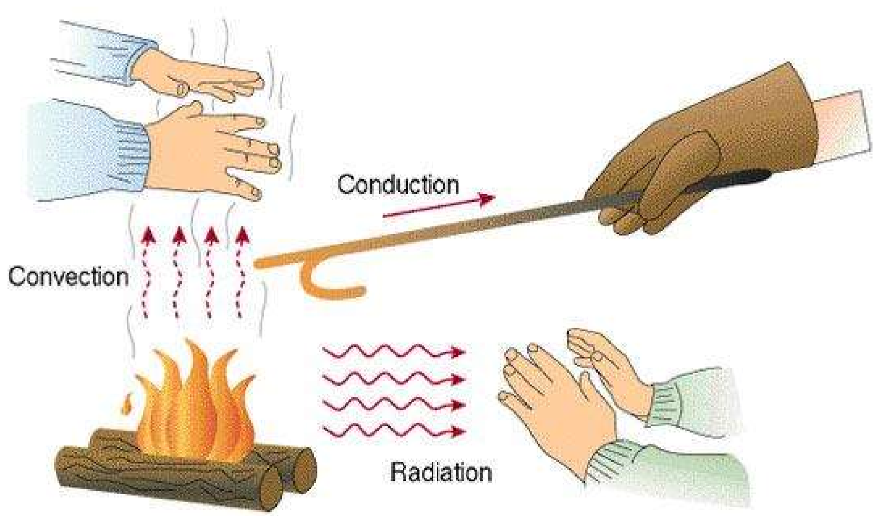

1.1 Introduction

- Heat is fundamentally transported, or "moved," by a temperature gradient; it flows or is transferred from a high temperature region to a low temperature one. An understanding of this process and its different mechanisms are required to connect principles of thermodynamics and fluid flow with those of heat transfer.

1.2 Thermodynamics and Heat Transfer

- 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 (Figure 1.1).

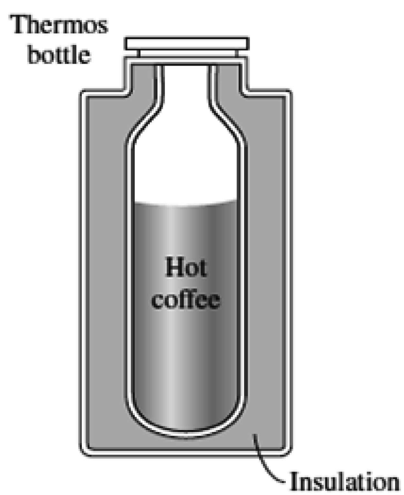

Fig. 1.1 Heat transfer from the thermos

- 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 (Figure 1.2).

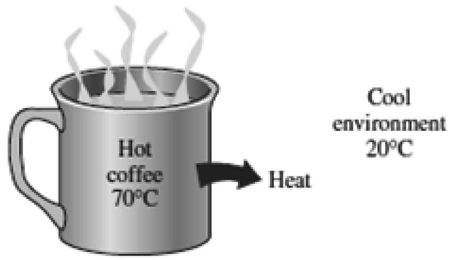

Fig. 1.2 Heat transfer from high temperature to low temperature

1.3 Application Areas of Heat Transfer

- Many ordinary household appliances are designed, in whole or in part, by using the principles of heat transfer. Some examples:
- Design of the heating and air-conditioning system, the refrigerator and freezer, the water heater, the iron, and even the computer, the TV, and the VCR
- 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.
- 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 (Figure 1.3)

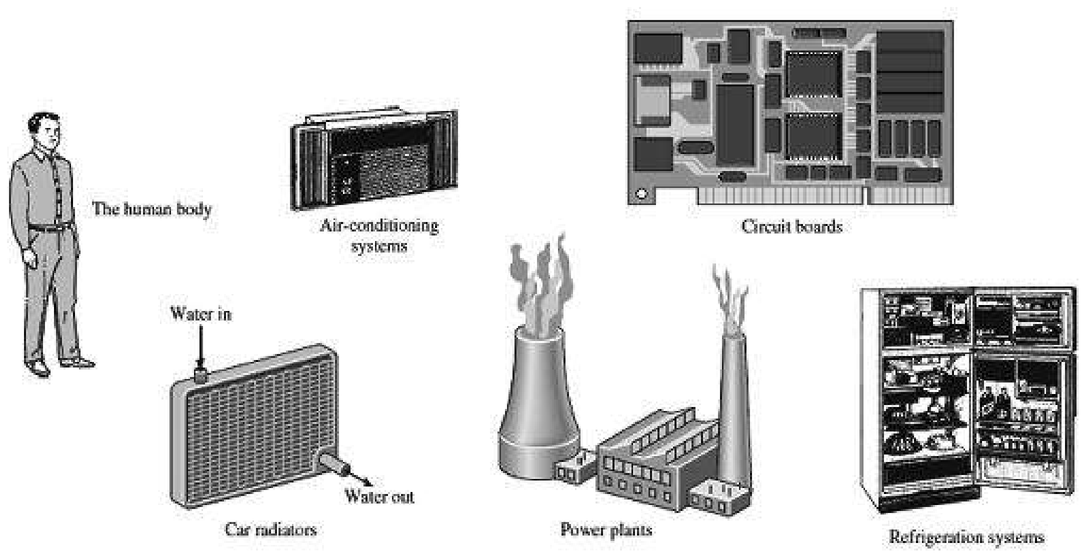

Fig. 1.3 Application of heat transfer

- **ENGINEERING HEAT TRANSFER**

- The heat transfer problems encountered in practice can be considered in two groups:
  i rating and
  ii 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.

1.4 Heat Transfer Mechanisms

- 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.

1.5 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, 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 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 will lose 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.

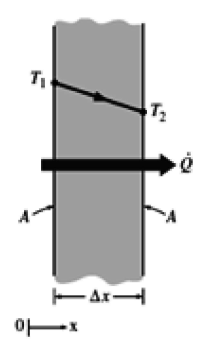

Fig. 1.4 Heat conduction through large plain wall

- Consider steady heat conduction through a large plane wall of thickness $\Delta x = L$ and area A, as shown in figure 1.4. 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 ΔT 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,

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

or

$$\dot{Q}_{cond} = kA\frac{T_1 - T_2}{\Delta x} = -kA\frac{\Delta T}{\Delta x}\ (W) - - - - - - - - (1.1)$$

- 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. In the limiting case of $\Delta x \rightarrow 0$, the equation above reduces to the differential form

$$\dot{Q}_{cond} = -kA\frac{dT}{dx}\ (W) - - - - - - - - (1.2)$$

- Which is called Fourier's law of heat conduction. 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 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. 1.2 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.

1.6 Thermal Conductivity

- The thermal conductivity of a material can be defined as 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.
- 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.

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.

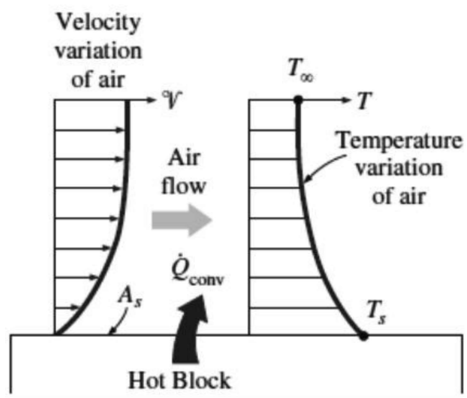

Fig. 1.5 Heat transfer by convection

- Consider the cooling of a hot block by blowing cool air over its top surface (Figure 1.5).
- Energy is first transferred to the air layer adjacent to the block by conduction.
- This energy 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.

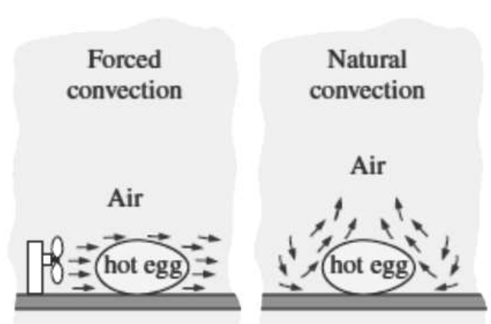

Fig. 1.6 Forced and Free (Natural) convection

- 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 (Figure 1.6).

- For example, in the absence of a fan, heat transfer from the surface of the hot block in figure 1.5 will be by natural convection since any motion in the air in this case will be 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 will be 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

$$\dot{Q}_{conv} = hA_s(T_s - T_\infty)\ (W) - - - - - - - (1.3)$$

- Where h is the convection heat transfer coefficient in $W/m^2{}^\circ C$, A_s is the surface area through which convection heat transfer takes place, T_s is the surface temperature, and T_∞ 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.

> - 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."

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 energy by radiation does not require the presence of an intervening medium. In fact, energy 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.

– The mechanism of the heat flow by radiation consists of three distinct phases:

i Conversion of thermal energy of the hot source into electromagnetic waves:

– All bodies above absolute zero temperature are capable of emitting radiant energy. Energy released by a radiating surface is not continuous but is in the form of successive and separate (discrete) packets or quanta of energy called photons. The photons are propagated through the space as rays; the movement of swarm of photons is described as the electromagnetic waves.

ii Passage of wave motion through intervening space:

– The photons, as carries of energy travel with unchanged frequency in straight paths with speed equal to that of light.

iii Transformation of waves into heat:

– When the photons approach the cold receiving surface, there occurs reconversion of wave motion into thermal energy which is partly absorbed, reflected or transmitted through the receiving surface.

– 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.

– The maximum rate of radiation that can be emitted from a surface at an absolute temperature T (in K) is given by the Stefan–Boltzmann law as

$$E_b = \sigma_b A T^4 \ (W) - - - - - - - - (1.4)$$

– Where, $\mathrm{E_b}$ is the energy radiated by black body, σ_b is the Stefan Boltzman constant.

$$\sigma_b = 5.67 \cdot 10^{-8} \, W/m^2K^4$$

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

$$E = \varepsilon \ \sigma_b A T^4 \ (W) - - - - - - - - (1.5)$$

– Where, ε is a radiative property of the surface and is called emissivity; its value depends upon surface characteristics and temperature. It indicates how effectively the surface emits radiations compared to an ideal or black body radiator.

– Normally a body radiating heat is simultaneously receiving heat from other bodies as radiation.

– Consider that surface 1 at temperature $\mathrm{T_1}$ is completely enclosed by another black surface 2 at temperature $\mathrm{T_2}$. The net radiant heat transfer is

$$Q = \ \sigma_b A_1 (T_1^4 - T_2^4) \ (W) - - - - - - - - (1.6)$$

– Likewise, the net rate of heat transfer between the real surface (called gray surface) at temperature $\mathrm{T_1}$ to a surrounding black surface at temperature $\mathrm{T_2}$ is