HEAT TRANSFER

CHAPTER1

BASIC CONCEPTS IN HEAT TRANSFER

INTRODUCTION

Heat 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 called heat transfer.

THERMODYNAMICS VS 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 idea about *how long* the process will take.

Heat transfer helps in 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.

- Thermodynamics deals with equilibrium states and changes from one equilibrium state to another and preclude the existence of temperature difference.
- Heat transfer deals with systems that lack thermal equilibrium, and thus it is a *non-equilibrium* phenomenon. For heat exchange, temperature gradient must exist.

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.

ESSENTIAL CONDITIONS FOR HEAT TRANSFER

The basic requirement for heat transfer is the presence of a *temperature difference.* There can be no net heat transfer between two mediums 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

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
R*ating* Problems The rating problems deal with the determination of the heat transfer rate for an existing system at a specified temperature difference
Sizing Problems. 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

HEAT TRANSFER MECHANISMS

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,*
- *Radiation.*

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.*

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*
- *The material of the medium*
- *The temperature difference* across the medium.

FOURIER'S LAW OF HEAT CONDUCTION

"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"

$$Rate\ of\ heat\ conduction \propto \frac{Temperature\ difference \times Area}{Thickness}$$

$$Q_{cond} = -kA\frac{dT}{dx}$$

Where

$$Q_{cond} = rate\ of\ heat\ transfer$$

$$A = area\ of\ heat\ transfer\ surface$$

The heat transfer area A is always *normal* to the direction of heat transfer

$$dT = temperature\ difference\ across\ the\ thickness\ dx$$

$$k = thermal\ conductivity\ of\ surface\ material$$

The *negative sign* ensures that heat transfer in the positive x direction is a positive quantity

dT/dx = 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.

CONCLUSIONS

1. The rate of heat conduction in a direction is proportional to the temperature gradient in that direction.
2. Heat is conducted in the direction of decreasing temperature, and the temperature gradient becomes negative when temperature decreases with increasing x.

$$Q_{cond} = -kA \times \frac{(T_2 - T_1)}{\delta}$$

$$Q_{cond} = kA \times \frac{(T_1 - T_2)}{\delta}$$

HEAT FLUX

Heat conducted per unit time and per unit area is defined as heat flux.

$$q = \frac{Q_{cond}}{A} = \frac{k(T_1 - T_2)}{\delta}$$

THERMAL CONDUCTIVITY

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.*

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.

- 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

Thermal conductivity of gases

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.

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 absolute temperature T,* and inversely proportional to the *square root of the molar mass M.*
- Therefore, the thermal conductivity of a gas increases with increasing temperature and decreasing molar mass.

The thermal conductivity of gases is *independent of pressure* in a wide range of pressures encountered in practice.

Thermal conductivity of liquids

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.
- 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.

Thermal conductivity of solids

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 . 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. Despite their higher price, diamond heat sinks are used in the cooling of sensitive electronic components because of the excellent thermal conductivity of diamond.

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 wide spread use in the electronics industry.

- Silicon oils and gaskets are commonly used in the packaging of electronic components because they provide both good thermal contact and good electrical insulation.

Thermal conductivity of alloys

The thermal conductivity of an alloy of two metals is usually much lower than that of either metal,

Even small amounts in a pure metal of "foreign" molecules that are good conductors themselves seriously disrupt the flow of heat in that metal.

Variation of thermal conductivity with the temperature

- The thermal conductivities of materials vary with temperature.
- The variation of thermal conductivity over certain temperature ranges is negligible for some materials, but significant for others.
- The thermal conductivities of certain solids exhibit dramatic increases at temperatures near absolute zero, when these solids become *superconductors*..

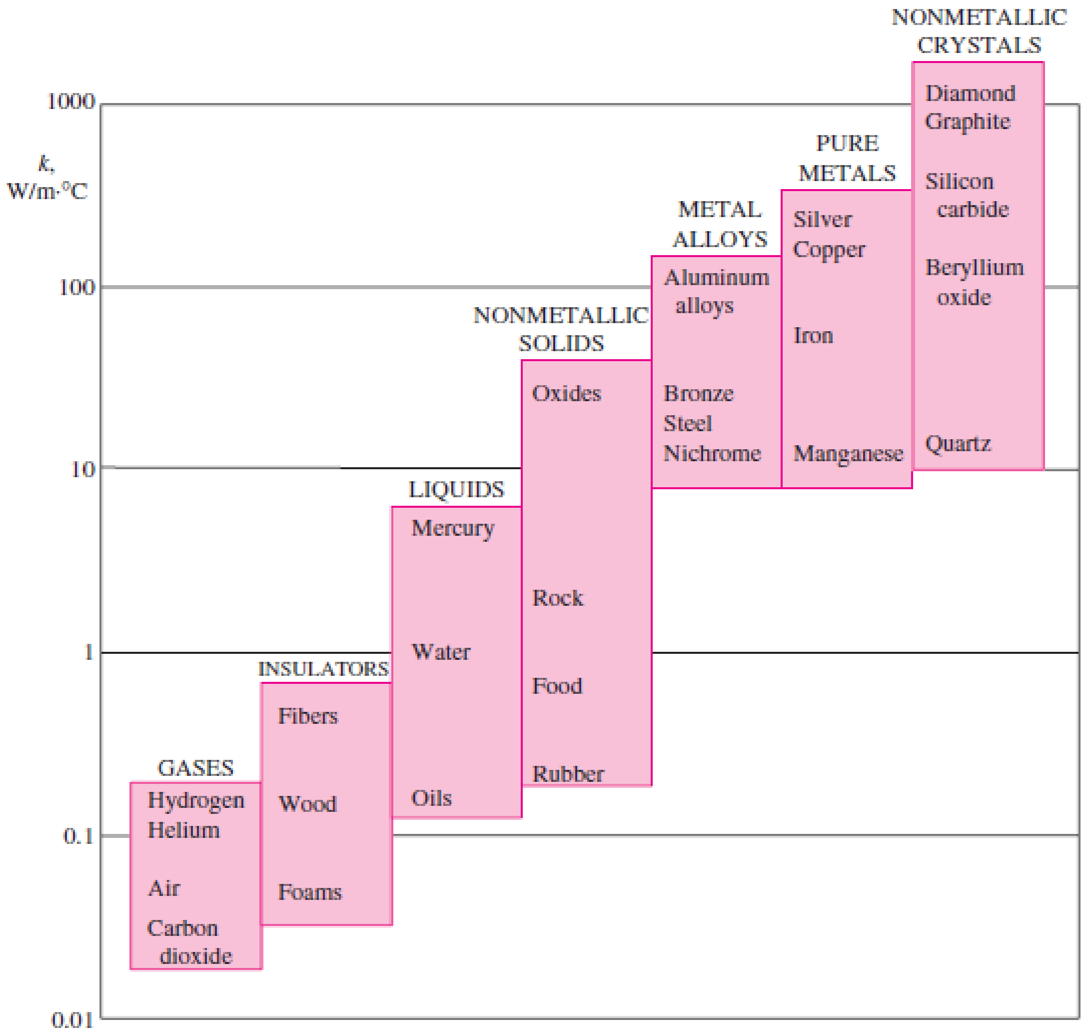
- The temperature dependence of thermal conductivity causes considerable complexity in conduction analysis. Therefore, it is common practice to evaluate the thermal conductivity k at the *average temperature* and treat it as a *constant* in calculations.

Thermal conductivity of isotropic materials

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



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 transfers. 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.

- 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.

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

$$Q_{conv} = hA\,(T_1 - T_2)$$

Where

h is the *convection heat transfer coefficient* in $W/m^2 \cdot {}^\circ C$

A is the surface area through which convection heat transfer takes place,

T_1 is the surface temperature, and

T_2 is the temperature of the fluid sufficiently far from the surface.

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.

The value of h depends upon

- *the surface geometry,*
- *the nature of fluid motion,*
- *the properties of the fluid, and*
- *the bulk fluid velocity*

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.

Thermal radiations are 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 *u*sually 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 an absolute temperature T_s(in K or R) is given by the Stefan–Boltzmann law as

$$E_b = \sigma_b A T^4$$

Where

$$E_b = \text{energy radiated per unit time}$$
$$\sigma_b = \text{Stefan– Boltzmann Constant} = 5.67 \times 10^{-8} W/m^2K^4$$
$$T = \text{absolute temperature of the body}$$

The idealized surface that emits radiation at this maximum rate is called a blackbody, and the radiation emitted by a black- body is called blackbody radiation.

Emissivity

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

  $$E = \in \sigma_b A T^4$$

  Where

  $\in$ is the emissivity of the surface.

  The property emissivity, whose value is in the range 0 to 1(black body)., is a measure of how closely a surface approximates a black body.

Absorptivity

Absorptivity 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 to1.

A blackbody absorbs the entire radiation incident on it. That is, a blackbody is a perfect absorber.

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.

COMBINED HEAT TRANSFER COEFFICIENT

For simplicity and convenience, this is often done by defining a combined heat transfer coefficient h 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

$$Q_{total} = h_{combined} A\,(T_1 - T_2)$$

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.