UPPSC-AE 2025

Uttar Pradesh Public Service Commission

Combined State Engineering Services Examination

Assistant Engineer

Mechanical Engineering

Heat Transfer

Well Illustrated **Theory** *with*
Solved Examples and **Practice Questions**

MADE EASY PUBLICATIONS

Heat Transfer

Contents

CHAPTER 1

Basic Concepts and Dimensionless Numbers

1.1 Introduction

- The transmission of energy from one region to another as a result of temperature gradient, is called as heat transfer.
- The heat transfer the driving potential is the temperature difference.
- The study of heat transfer is carried out for following purposes:
  1. To estimate the rate of flow of energy as heat through the boundary of a system under study (both under steady and transient conditions).
  2. To determine the temperature field under steady and transient conditions.
- The areas covered under discipline of heat transfer are:
  1. Design of thermal and nuclear power plants.
  2. Internal combustion engines
  3. Refrigeration and air-conditioning units.
  4. Thermal control and space vehicles.
  5. Heat treatment of metals
  6. Dispersion of atmospheric pollutants.

1.1.1 Difference between Thermodynamic and Heat Transfer

- Thermodynamics deals with the amount of heat transfer as a system undergoes a process, and makes no reference to how long the process will take. Whereas science of heat transfer deals with the rate of heat transfer, which is the main quantity of interest in the design and evaluation of heat transfer equipment.
- Heat transfer has direction as well as magnitude. The rate of heat conduction in a specified direction is proportional to the temperature gradient. Which is the change in temperature per unit length in that direction.
- $T = T(x, y, z, t)$, the temperature in a medium varies with position as well as time.
- Heat conduction in a medium is said to be steady when the temperature does not vary with time, and unsteady or transient when it does.
- Determining the rate of heat transfer to or from a system and thus the rate of cooling or heating as well as the variation of the temperature is the subject of heat transfer.
- The first law requires that the difference of rate of heat transfer into a system and from the system be equal to the rate of increase of energy of that system. The second law requires that heat be transferred in the direction of decreasing temperature.
- There can be no net heat transfer between two mediums that are at same temperature. The larger the temperature difference, the higher the rate of heat transfer.

- The rate of heat transfer per unit surface area is called heat flux.

$$q = \frac{Q}{A} \text{ W/m}^2$$

Heat flux may vary with time as well as position of the heat transfer surface.

1.2 Conduction

Conduction is the transfer of heat from one part of a substance to another part of the same substance, or from one substance to another in physical contact with it, without appreciable displacement of molecules forming the substance.

- In solids, heat is conducted by following two mechanisms:
  - (a) By lattice vibration (the faster moving molecules or atoms in the hottest part of a body transfer heat by impacts some of their energy to adjacent molecules).
  - (b) By transfer of free electrons (free electrons provide an energy flux in the direction of decreasing temperature-for metals, especially good electrical conductors, the electronic mechanism is responsible for the major portion of the heat flux except at low temperature).
- In case of gases, the mechanism of heat conduction is simple. The kinetic energy of a molecule is a function of temperature. These molecules are in a continuous random motion exchanging energy and momentum. When a molecules from the high temperature region collides with a molecule from the low temperature region, it losses energy by collisions.
- In liquids, the mechanism of heat is nearer to that of gases. However, the molecules are more closely spaced and intermolecular forces into play.

Effect of Temperature on Thermal Conductivity

1. In pure metals and alloys, as temperature increases both number of free electrons and lattice vibration increase. Thus thermal conductivity increases.

   However increased lattice vibrations obstruct the flow of free electrons. The combined effect of this phenomenon, in most cases, results in decrease in thermal conductivity with increase in temperature.

   e.g; for iron; as temperature increases, thermal conductivity first decreases and then increase for platinum, '*k*' value increases with temperature.
2. In gases, molecular collision increases with increase in temperature. Thus '*k*' value for gases increases with increase in temperature.

   $$k_{gas} \propto \sqrt{\frac{T}{M}};$$ where T is temperature (in kelvin)

   '*M*' is molecular weight of gas
3. In liquids, thermal conductivity depends on molecular diffusion mainly. As the temperature increases, randomness increases this obstructs the flow of heat through liquids.

   Thus, the value of '*k*' decreases with increase in temperature for liquids.

   exception $\rightarrow$ water

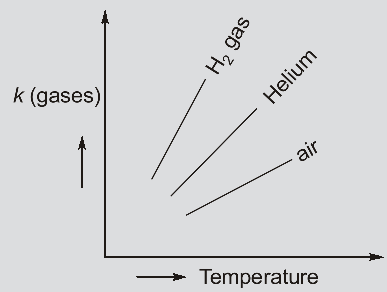
   In case of water, '*k*' first increases with increase in temperature and then starts decreases.

Values of Thermal Conductivity of Some Substances

1. Asbestos $\rightarrow k = 0.2$ W/mK
2. Glass wool $\rightarrow k = 0.075$ W/mK
3. Refractory bricks $\rightarrow k = 0.9$ W/mK
4. Glass $\rightarrow k = 1.2$ W/mK
5. Air $\rightarrow k = 0.026$ W/mK
6. Water $\rightarrow k = 0.063$ W/mK

NOTE

$[k_{ice} > k_{water} > k_{water\ vapour}]$



NOTE

1. Among liquids, mercury (H_g) has highest thermal conductivity (k_{H_g} = 8.34 W/mK).
2. Mercury (H_g) is used in thermometers due to good thermal conductivity, low vapour pressure and good expansion property.

- 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 temperature difference across the medium.

$$Q_{Cond} = kA\frac{\Delta T}{\Delta x}$$

where, k is the thermal conductivity; Q_{cond} is in watt; A = Area in m^2; ΔT = Temperature difference; Δx = Distance between two points between which heat is conducted.

- It is also called Fourier's law of heat conduction.
- The heat transfer surface area 'A' is always normal to the direction of heat transfer.

NOTE

- Thermal conductivity is a transport property of the medium through which heat is conducted.
- For an isotropic medium, the thermal conductivity (k) is scalar quantity which depends upon temperature only.

1.3 Convection

- The convection heat transfer refers to the heat transfer occurring due to random molecular motion (diffusion) and the bulk or macroscopic, motion of the fluid.
- The random molecular motion (diffusion) is conduction. Whereas the bulk or macroscopic motion is termed 'advection'.

  In free convection the flow is induced by buoyancy forces which are due to density difference caused by temperature variations in the fluid.

  When the flow is caused by external means, such as by fan, pump, or atmospheric winds it is called forced convection.
- Newton's law of cooling $\quad Q_{conv} = hA(T_s - T_\infty)$ watt

  h = Convection heat transfer coefficient (W/m^2°C), A = Surface area (m^2)

- Unlike thermal conductivity (k), convection heat transfer coefficient (h) is not a property of material but it depends upon some of the thermophysical properties of the fluid like density (ρ), specific heat (c_p), thermal conductivity (k), viscosity (μ) etc.

  In forced convection heat transfer;

  $$h = (\vec{v}, D, \mu, c_p, k, \rho)$$

  where $\vec{v}$ = velocity of fluid ; D = characteristic dimension of body

  In free convection heat transfer:

  $h = f(g, \beta, \Delta T, L_c, \mu, \rho, c_p, k)$; g = Acceleration due to gravity;

  β = Isobaric volumetric expansion coefficient of fluid; L_C = characteristic dimension.

1.4 Radiation

- Unlike conduction and convection, the transfer of energy by radiation does not require the presence of an intervening medium.
- Energy transfer by radiation is fastest and occurs most efficiently in vacuum.
- All bodies at a temperature above absolute zero emit thermal radiation according to Stefan-Boltzmann law.

  $$q_{max} = \sigma T^4$$

  where, $\sigma = 5.67 \times 10^{-8}$ W/m^{2}K^4 is called Stefan-Boltzmann constant and T is the absolute temperature of the surface in Kelvin.
- The radiation emitted by all real surfaces is less than the radiation emitted by a black body at the same temperature.

  $$q = \in \sigma T^4 \qquad \text{where, } \in \text{ is the emissivity of the surface}$$
- The property emissivity whose value is in the range of $0 \le \in \le 1$ is a measure of how closely a surface approximates a blackbody.
- Also the rate at which radiant energy is absorbed per unit surface area may be evaluated from knowledge of a surface radiative property termed the absorptivity 'α' where $0 \le \alpha \le 1$.
- If $\alpha = \in$ (a gray surface), then the net rate of radiation heat transfer from the surface, is expressed as:

  $$Q = \in \sigma A\left(T^4 - T_{Surr.}^4\right)$$
- Radiation heat transfer is dominant mostly at high temperature only.
- Black body is the body which absorbs all the thermal radiation incident or falling upon it.

NOTE

A black body absorbs all the thermal radiation incident or falling upon it may or may not appear black in colour to human eye.

e.g: Ice is a black body.

Black body →
- perfect absorber
- ideal emitter
- diffusive in nature

Example - 1.1 One face of a copper plate is maintained at 400°C, the other face is maintained at 200°C. How much heat is transferred through the plate per unit and for 1 m length. [Given K_{copper} = 370 W/mK]

Solution:

From Fourier's law: $\frac{q}{A} = -\frac{kdT}{dx} = (-k)\frac{\Delta T}{\Delta x} = \frac{(-370)(200-400)}{1} = \frac{(370)(200)}{1} = 74000 \text{ W/m}^2 = 74 \text{ kW/m}^2$

Example - 1.2 Air at 20°C blows over a hot plate (50 × 50) cm maintained at 270°C. The convection heat transfer coefficient is 25 W/m²K. Calculate heat transfer.

Solution:

From Newton's law of cooling. $q = hA(T_w - T_\infty) = (25)(0.5)(0.5)[270-20] = (25)(0.25)(250) = 1562.5 \text{ W}$

Example - 1.3 Two infinite black plates at 727°C and 227°C exchange heat by radiation. Calculate the heat transfer per unit area.

Solution:

Given: T_1 = 727°C = 1000 K, T_2 = 227°C = 500 K

$$\frac{q}{A} = \sigma\left(T_1^4 - T_2^4\right)$$

$$= (5.67 \times 10^{-8})[1000^4 - 500^4] = (5.67)(10^{-8})[10000-625](10^8)$$

$$= (5.67)(9375) = 53156.25 \text{ W/m}^2 = 53.156 \text{ kW/m}^2$$

Observation: In this question temperatures are high therefore radiation heat transfer is significant.

Example - 1.4 Suppose a person stated that heat cannot be transferred in a vacuum. How do you respond?

Solution:

We will say that the person is wrong as there is heat transfer between sun and the earth without any medium i.e., vacuum. This kind of heat transfer only occurs by radiation mode.

For Solids

- Thermal conductivity of an alloy of two metals is usually much lower than that of either metals.
- Thermal conductivity of pure metals decreases with increase in temperature.
- Thermal conductivity of alloys increases with increase in temperature.

For Liquids and Gases

- The thermal conductivity of gases is independent of pressure in a wide range of pressures encountered in practice.
- Because of large intermolecular spaces and hence a smaller number of molecular collisions, the thermal conductivities exhibited by gases are lower than those of the liquids.

1.5 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. The thermal conductivities of some common materials at room temperature are given in Table below.

1.7 Thermal Diffusivity

The ratio of thermal conductivity to the heat capacity appears to be an important property and is termed thermal diffusivity α. Therefore,

$$\alpha = \frac{\text{Heat conducted}}{\text{Heat stored}} = \frac{k}{\rho c}$$

Thermal conductivity k represents how well a material conducts heat, and the heat capacity ρc represents how much energy a material stores per unit volume.

The thermal diffusivity of a material is the measure of its ability to conduct thermal energy relative to its ability to store thermal energy. Materials having large values of α will respond quickly to a change in the thermal environment in establishing a steady-state temperature field within the material in transporting heat, while materials having small values of α will do it sluggishly.

Higher the conductivity of the material and lesser the heat capacity or storage ability of the material i.e., more value of its thermal diffusivity will be.

Generally:
$$\alpha_{\text{gases}} > \alpha_{\text{liquid}}$$
$$\alpha_{\text{air}} > \alpha_{\text{water}}$$

Student's Assignment

Q.1 The transfer of heat by radiation, conduction and convection simultaneously in
(a) Melting of ice
(b) Boiler furnaces
(c) Condensation of steam in condenser
(d) All of these

Q.2 The process of heat transfer from one particle of the body to another is called conduction, when the particle of the body:
(a) move actually
(b) does not move actually
(c) affect the intervening medium
(d) does not affect the intervening medium

Q.3 The rate of heat flow through a body is $Q = \frac{kA(T_1 - T_2)}{x}$. The term $\frac{x}{kA}$ is known as:
(a) Thermal coefficient
(b) Thermal resistance
(c) Thermal conductivity
(d) none of the above

Q.4 A high value of thermal diffusivity represents
(a) high storage, less conduction of heat.
(b) less storage, more conduction of heat.
(c) There is always equal amount of conduction and storage since it is a property.
(d) It has no relevance.

Q.5 Which substance has the minimum value of thermal conductivity?
(a) Air (b) Water
(c) Plastic (d) Rubber

Q.6 Cork is a gold thermal insulator because
(a) Its density is low.
(b) It is porous.
(c) It can be powdered.
(d) It is flexible.

Q.7 The temperature inside a furnace is generally measured by
(a) Mercury thermometer
(b) Alcohol thermometer
(c) Gas thermometer
(d) Optical pyrometer

Q.8 Two parallel plates are kept horizontally with small distance between them. The gap between them is filled with air. The upper plate is maintained at higher temperature than the lower plate. The mode of heat transfer between them will be
(a) Convection and radiation
(b) Convection only
(c) Conduction and radiation
(d) Radiation only

Q.9 Which equation is used to determine the heat flux for convection?
(a) $-kA\dfrac{dT}{dx}$ (b) $-k$ grad T
(c) $h(T_1 - T_2)$ (d) $\varepsilon\sigma T^4$

Q.10 Thermal diffusivity is a
(a) function of temperature
(b) physical property of a substance
(c) dimensionless parameter
(d) all of these

Q.11 Thermal conductivity of water __________ with rise in temperature.
(a) remains same (b) decrease
(c) increase
(d) may increase or decrease depending on temperature available

Q.12 The correct order of increasing resistivity among the following material is:
(a) Nickel, doped silicon, sodium silicate, pure silica
(b) Doped silicon, nickel, pure silica, sodium silicate
(c) Nickel, pure silica, sodium silicate, doped silicon
(d) Sodium silicate, nickel, pure silica, doped silicon

Q.13 Thermal conductivity with increasing molecular weight ________.
(a) increases
(b) decreases
(c) remains constant
(d) does not affect

Q.14 In $LMT\theta$ system (T being time and θ being temperature), what is the dimension of thermal conductivity?
(a) $ML^{-1}T^{-1}\theta^{3}$ (b) $MLT^{-1}\theta^{-1}$
(c) $ML\theta^{-1}T^{-3}$ (d) $ML\theta^{-1}T^{-2}$

Q.15 In which one of the following materials, is the heat energy propagation minimum due to conduction heat transfer?
(a) lead (b) copper
(c) water (d) air

Q.16 Heat transfer takes place according to
(a) zeroth law of thermodynamics
(b) 1st law of thermodynamics
(c) second law of thermodynamics
(d) third law of thermodynamics

Q.17 Heat pipe is widely used nowadays because:
(a) It acts as an insulator
(b) It acts as conductor and insulator
(c) It acts as superconductor
(d) It acts as fin

ANSWER KEY — STUDENT'S ASSIGNMENT

1. (b)	**2.** (b)	**3.** (b)	**4.** (b)	**5.** (a)
6. (b)	**7.** (d)	**8.** (c)	**9.** (c)	**10.** (b)
11. (d)	**12.** (a)	**13.** (b)	**14.** (c)	**15.** (d)
16. (b)	**17.** (c)			

HINTS & SOLUTIONS — STUDENT'S ASSIGNMENT

1. (b)

The heat is transferred to the stock by radiation from the flame, hot combustion products and the furnace walls and roof. Convection due to movement of hot gases over the stock surface. Conduction occurs through walls and roofs.

2. (b)

Conduction is the movement of heat through a substance by the collision of molecules. At the molecules of warmer object collide with the slower moving molecules of the cooler object.