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ENGINEERS ACADEMY

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Volume - 9

Heat and Mass Transfer

SIERRA
INNOVATIONS

1

INTRODUCTION

THEORY

1.1 INTRODUCTION

Heat is the form of energy that can be transferred from one system to another as result of temperature difference. Heat transfer deals with system that take thermal equilibrium and thus it is non-equilibrium phenomenon.

The energy can exist in numerous forms such as thermal, mechanical, electric, magnetic, chemical and nuclear and their sum constitute the total energy E of the system. The form of energy related to molecular structure of system and degree of molecular activity is referred to as internal energy. Internal energy can be viewed as sum of kinetic and potential energies of the molecules. The portion of internal energy associated with kinetic energy of molecules is called sensible energy or sensible heat. The internal energy associated with inter molecular forces between molecules of as system is called latent energy or latent heat.

1.2 ENERGY TRANSFER

Energy can be transferred to or from a given mass by two mechanism: heat transfer Q and work W. The sensible and latent form of internal energy are termed as thermal energy. The transfer of thermal energy is heat transfer.

Since, first law of thermodynamic says,

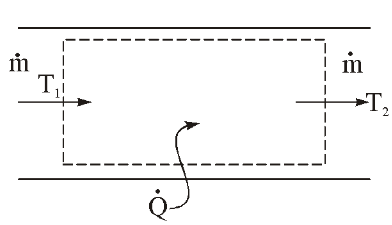
$$\underbrace{E_{in} - E_{out}}_{\substack{\text{Net energy transfer} \\ \text{by heat, work or mass}}} = \underbrace{\Delta E_{system}}_{\substack{\text{Rate of change in} \\ \text{Internal, kinetic, potential etc.}}}$$

In heat transfer analysis, we consider only that form of energy which can be transferred as a result of temperature difference i.e., thermal energy. The conversion of nuclear, chemical, mechanical and electrical energies into thermal energy is denoted by heat generation. i.e.,

$$\dot{Q}_{in} - \dot{Q}_{out} + \dot{Q}_{gen} = \frac{dE}{dt}$$

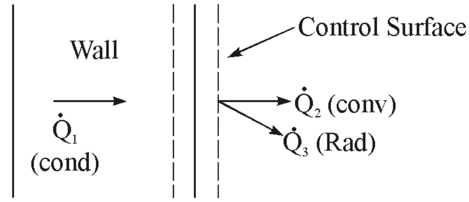
Thermal, system for steady flow system,

$$\dot{Q} = \dot{m}\Delta h = \dot{m}C_P\Delta T$$



1.3 Surface Energy Balance

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



$$\dot{E}_{in} = \dot{E}_{out} ; \ \dot{Q}_1 = \dot{Q}_2 + \dot{Q}_3$$

1.4 Heat Transfer Mechanisms

Heat can be transferred in three modes : conduction, convection and radiation. All modes of heat transfer require existence of temperature difference.

1.4.1 Conduction

Conduction is transfer of energy from more energetic particles of substance to adjacent less energetic ones as result of interaction between the particles. In gases and liquids, conduction is due to collision and diffusion of molecules during their random motion. In solids, it is due to combination of vibration of molecules in a **lattice** and energy transport by **free electrons.**

According to Fourier Law of heat conduction.

(a) Fourier's Law of conduction : The Law State that the rate of heat transfer by conduction along a given direction is directly proportional to the temperature gradient along the direction and is also directly proportional to the area of heat transfer lying perpendicular to the direction of heat transfer.

$$\dot{Q}_{cond} \propto A\frac{dT}{dx}$$

$$\dot{Q}_{cond} = -kA\frac{dT}{dx}$$

Where K = thermal conductivity of material and unit is given by W/m.K.

K is measure of material ability of conduct heat. The thermal conductivity is normally highest in solid phase and lowest in gas phase. The thermal conductivity of gas increase with increasing temperature and decreasing molar mass. The K of liquid decrease with increasing temperature with water being notable exception. Like gases, K of liquids decrease with increasing molar mass. **Liquid metals** such as Na, Hg have high **thermal conductivity** and are suitable for application where high transfer rate is desired, as in nuclear power plants.

The heat conduction in solid is due to lattice vibration effect and **flow of free electrons.** The high value of K are primarily due to electronic component. The lattice component depends on molecular arrangement. For example, diamond which is highly ordered crystalline solid has highest known thermal conductivity (K) at room temperature.

The metal alloy have thermal conductivity much lower than that of either metal.

The thermal conductivity of certain solid exhibit dramatic increase at temperature near absolute zero, when these solid become **super conductor.**

Thermal conductivity of some material

Diamond	2300 W/m.K
Silver	410 W/m.K
Gold	395 W/m.K
Copper	385 W/m.K
Aluminium	202 W/m.K

$$\alpha = \frac{\text{Heat conducted}}{\text{Heat stored}} = \frac{K}{\rho C_P} \ (m^2/s)$$

The product of ρC_P is called heat capacity, it is expressed as per unit volume and unit is J/m^3 K. Thermal diffusivity is defined as

Thermal diffusivity is viewed as ratio of heat conducted through the material to heat stored per unit volume. The larger the value of $\propto$ the faster the propagation of heat into the medium.

1.4.2 Convection

Convection is mode of energy transfer between solid surface and the adjacent liquid or gas that is in motion and it involve combined effect of **conduction** and **fluid motion.**

According to newton's law of cooling.

Newton's Law of Cooling : According to Newton's Law of Cooling the rate of heat transfer by convection between a solid and surrounding fluid is directly proportional to the temperature difference between them and is also directly proportional to area of contact between them.

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

Where h = convection heat transfer coefficient ($W/m^2.K$)

1.4.3 Radiation

The maximum rate of radiation that can be emitted from surface at absolute thermodynamic temperature T_S is given by Stefan-Boltzmann Law as

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

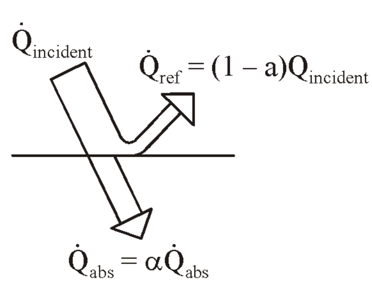
Where $\sigma = 5.67 \times 10^{-8}\ W/m^2.K^4$

Radiation emitted by real surface

$$\dot{Q}_{emit} = \varepsilon \sigma A_s T_s^4$$

Where ε = emissivity of surface

Absorptivity α is fraction of radiation energy incident on surface that is absorbed by the surface. The rate at which surface absorbs radiation is

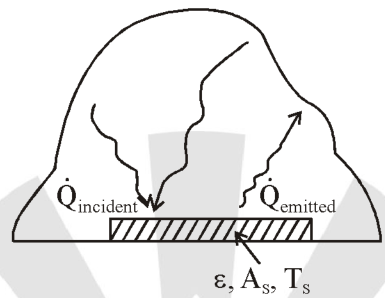


$$\dot{Q}_{absorbed} = \alpha \dot{Q}_{incident}$$

But, according to Kirchoff law the emissivity and absorptivity of surface at given temperature are equal.

$$\dot{Q}_{abs} = \varepsilon \dot{Q}_{incident}$$

When surface of emissivity ε and surface area A_s is completely enclosed by much larger (or black) surface at thermodynamic temperature $T_{surrounding}$ separated by gas that does not intervene with radiation, the net rate of radiation heat transfer between these two surfaces is



$$\dot{Q}_{rad} = \varepsilon A_s \sigma \left(T_s^4 - T_{surr}^4\right) (\because \alpha = \varepsilon)$$

There are three mechanisms of **heat transfer,** but not all three can exist simultaneously in a medium. **Heat transfer** is only by conduction in opaque solids, but by conduction and radiation in semitransparent solids. Thus, solid may involved **conduction** and **radiation** but not **convection.** How ever, a solid may involve heat transfer by convection and/or radiation at its surface exposed to fluid or other surfaces. For example, outer surface of solid piece of rock will warm up in warmer environment as result of heat gain by convection (from the air) and the radiation (from the sun and warmer surrounding surfaces). But inner part of rock will warm up as heat is transferred to inner region of rock by conduction.

Heat transfer is by conduction and by radiation in still fluid (no bulk fluid motion) and by convection and radiation in a flowing fluid.

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