Heat Transfer

CHE-S204

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Introduction

- In engineering practices, *heating* and *cooling* of materials is an indispensable part of processing, production, fabrication etc
- All such processes involve the *transfer of heat from one body to another*
- In our earlier study of thermodynamics (ESC-202), you have learned that energy can be transferred by interactions of a system with its surroundings. These interactions are called work and heat.
- The *first law of thermodynamics* states that energy cannot be created or destroyed in an isolated system – ‘when a system undergoes a cyclic process, the work done on the system is equal to the energy transferred as heat from the system to the surroundings’ – first law deals with the conservation of energy
- The *second law of thermodynamics* on the other hand states that the entropy of any isolated system always increases. Isolated systems spontaneously evolve towards thermal equilibrium—the state of maximum entropy of the system – it tells us about the direction of flow of energy
- It can, however, be observed that *thermodynamics does not refer to the rate at which the flow of energy takes place*
- It deals with the end states of the process during which an interaction occurs and provides no information concerning the nature of the interaction or the time rate at which it occurs
- This information is obtained from the *study of heat transfer*

- It is possible to understand the difference between thermodynamics and heat transfer by means of this example
- When a hot, steel bar placed in a pail of water (present at a lower temperature), thermodynamics (which deals with equilibrium) can be used to predict the final equilibrium temperature
- Thermodynamics will not tell us how long it would take to reach the equilibrium temperature or what temperature the bar will be after a certain length of time before equilibrium is reached
- Heat transfer can be used to determine the rate at which heat is transferred and the predict the temperature of both the steel bar and water as a function of time (under non-equilibrium conditions)

Heat transfer is the science which deals with the transport of energy from one point in a medium to another or from one medium to another, which are initially at different temperatures

Whenever there exists a temperature difference in a medium or between media, heat transfer must occur

The temperature difference between the two points in a medium or between two media is known as the '**driving force**' for heat transfer

The 'hot' and 'cold' bodies are called the '**source**' and '**receiver**', respectively

- *Heat transfer is a rate process* – the principles of heat transfer enables us to calculate the rate of transport of thermal energy
- When a kilogram (kg) of water is vaporized or condensed, the energy change in either process is identical - latent heat of vaporization of 2260kJ/kg is absorbed or latent heat of condensation equal to the same energy is released
- The rates of these processes that occur are , however, different. Vaporization is generally a much more rapid phenomenon that condensation
- The net flow of heat is always in the direction of decreasing temperature

Mechanism of heat transfer

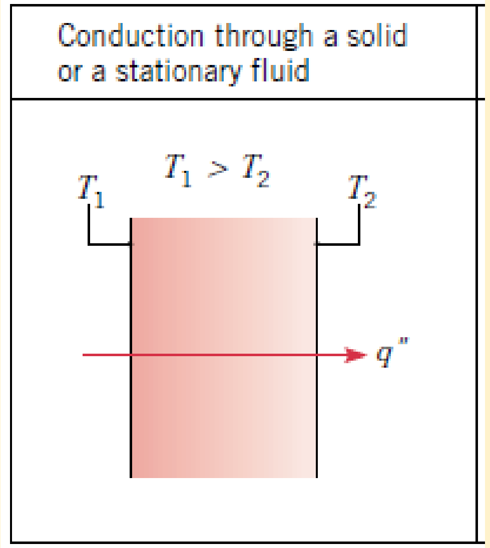
- There are *three distinct ways* in which heat may pass from a source to a receiver
- In most engineering applications, there is usually a combination of two or three of these modes
- The three modes of heat transfer are: **Conduction**

  Convection

  Radiation

Conduction

- When a temperature gradient exists in a stationary medium, which may be a solid or a fluid, we use the term *conduction* to refer to the heat transfer
- ***Conduction is the transfer of heat energy in a medium from a higher temperature to a lower temperature without any "macroscopic motion in the medium"***
- This type of heat transfer occurs in a solid, liquid or gaseous medium which are in physical contact with each other
- Conduction is the only mode of heat transfer in *solids*, where heat is transferred by *molecular vibrations*
- In *metals*, the *transfer of heat occurs more through the drift of free electrons* than molecular vibrations



Ref: Fundamentals of Heat and Mass Transfer, Incropera and Dewitt

- In case of some *solids and liquids which are bad conductors of electricity*, thermal conduction takes place by *transport of momentum of individual molecules*
- In *gases*, heat transfer occurs through *collisions of molecules having high thermal energy with molecules having lower thermal energy*
- Eg: heat flowing through the brick wall of a furnace or heat flowing through wall of a metal tube

The *basic law of conduction* is the *Fourier's law*

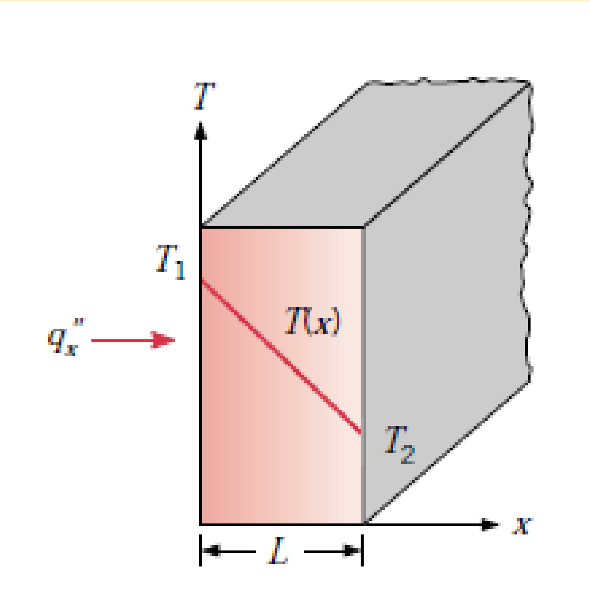
$$Q = -kA\frac{dT}{dx}$$

where Q = quantity of heat flow = rate of heat conduction, W (J/s)

$\frac{dT}{dx}$ = temperature gradient in the x-direction, °C/m

A = surface area, m^2

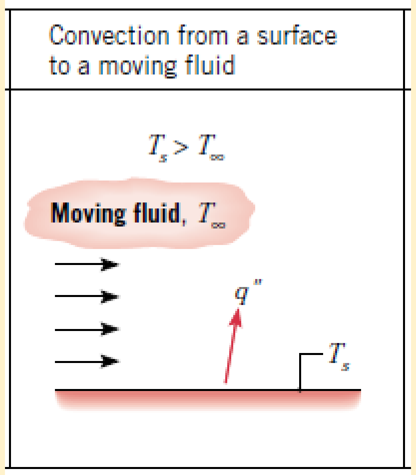
k= thermal conductivity, W/m°C



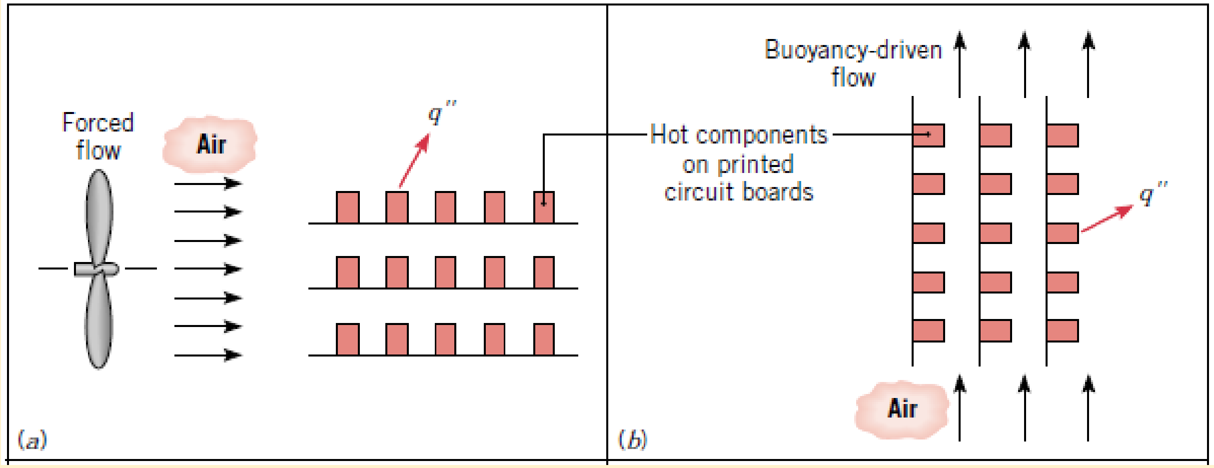
Convection

- The term *convection* refers to heat transfer that will occur between a surface and a moving fluid when they are at different temperatures
- ***Convection is the transport of heat energy by way of displacement of fluid elements from one point to another point which is at a different temperature***
- Depending on the nature of the forces which cause the material motion, convective heat transfer is classified as

(a) Forced convection (b) Natural or free convection



- ***Forced convection*** occurs when *motion in the medium is caused by an external mechanical agency* such as a pump, blower, agitator etc
- Eg., mixing a liquid with a stirrer placed over a hot flame
- ***Natural*** or ***free convection*** occurs when *motion in the medium is created by an adverse density gradient (buoyancy forces generated)* as a result of temperature difference This occurs when the temperature of a fluid at a lower level becomes higher than that of the fluid at a higher level



- In some cases, both types of forces may be active simultaneously and natural and forced convection may occur together
- Convection may be described by *Newton's law of cooling*

$$Q = hA\Delta T$$

where Q = rate of heat convection (or heat flow), W (J/s) A = surface area, m^2
ΔT = temperature gradient, ^oC h = heat transfer coefficient, $W/m^{2o}C$

- h is a function of *geometry of the system, physical variables of the system* (ρ, μ, σ) *and dynamic variables* (u)

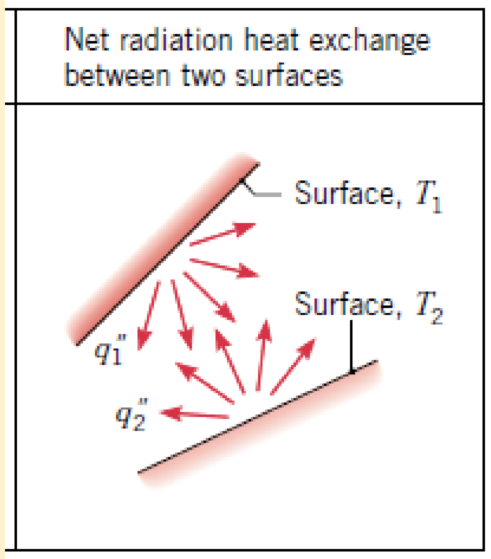
Radiation

- Radiation involves the *transfer of radiant energy from a source to a receiver*
- All surfaces of finite temperature emit energy in the form of electromagnetic waves
- In the absence of an intervening medium, there is net transfer of heat by radiation between two surfaces at different temperatures
- Radiation can be transmitted through regions where a perfect vacuum exists
- An ideal thermal radiator or blackbody will emit energy at a rate proportional to the fourth power of the absolute temperature of the body and directly proportional to its surface area

$$Q = \sigma A T^4$$

where σ is the Stefan-Boltzman constant = 5.669 x 10^{-8} W/m^2K^4

- This equation is called the *Stefan-Boltzman law*



- However, all bodies are not perfect emitters of radiation and are not blackbodies

- For real bodies the *rate of radiative heat transfer between two bodies at different temperatures* is given by

$$Q = \sigma \epsilon_1 F_{12} A_1 (T_1^4 - T_2^4)$$

where ϵ_1 = emissivity of body 1 (relates the radiation of a real grey body to that of an ideal black body)

A_1 = surface area of body 1

F_{12} = view factor of body 1 with respect to to body 2 (takes into account the fraction of the area of the body which is 'seen' by another body)

T_1 , T_2 = absolute temperature of body 1 and body 2

- In most practical situations, heat transfer occurs by a combination of two or all of the above modes
- For eg., in the case of heat loss from a furnace wall,
  - (i) the inner surface of the wall gains heat from the flame and the combustion gases by both radiation and convection
  - (ii) Heat transfer through the refractory and insulating brick layers of the furnace wall occurs by conduction
  - (iii) Finally, the transfer of heat from the outer surface of the furnace to the ambient occurs by convection and radiation

- In this course on Heat Transfer we will study,
  - Physical mechanism of transport of heat energy via different modes
  - Method of calculation of rates of transport of heat energy in various practical situations
  - Application of theoretical principles to design and sizing of heat transfer equipment

Syllabus

- **Introduction**: General Principles of heat transfer by conduction, convection, radiation.
- **Conduction:** Fourier’s law of heat conduction; steady state conduction in one dimension with and without heat source through plain wall, cylindrical & spherical surfaces; variable thermal conductivity, combined mechanism of heat transfer (conduction and convection), conduction through composite slab, cylinder and sphere; thermal contact resistance; thermal insulations, properties of insulating materials; critical radius of insulation; extended surfaces: heat transfer from a fin, effectiveness and efficiency
- **Convection:** Natural and forced convection; convective heat transfer coefficient; concept of thermal boundary layer; laminar & turbulent flow heat transfer inside and outside tubes; dimensional analysis, Buckingham pi theorem, dimensionless numbers in heat transfer and their significance; determination of individual & overall heat transfer coefficients and their temperature dependency
- **Forced convection:** correlation for heat transfer in laminar and turbulent flow in a circular tube and duct, Reynolds and Colburn analogies between momentum and heat transfer
- **Natural convection** – natural convection from vertical and horizontal surfaces, Grashof and Rayleigh numbers

- **Heat exchangers:** Types of heat exchangers like double pipe, shell & tube, plate type, extended surface, multi-pass exchangers; their detailed construction and operation; calculations on design of heat exchangers; effectiveness of a heat exchanger
- **Heat transfer with phase change:** condensation of pure and mixed vapours; film wise and drop wise condensation, calculations on condensers, heat transfer in boiling liquids, boiling curve, nucleate and film boiling; correlations for pool boiling
- **Evaporation:** elementary principles, boiling point elevation and Duhring's plot; types of evaporators – single, multiple (forward, backward, mixed feed), capacity and economy of evaporators simple calculation on single and multiple effect evaporators
- **Radiation:** Basic concepts of radiation from surface, black body and grey body concepts, Planks Law, Wein's displacement law, Stefan Boltzmann's law, Kirchoff's law, View factor, combined heat transfer coefficients by convection and radiation.
- **Introduction to unsteady state heat transfer:** lumped parameter model, unsteady state heat conduction in various geometries, Heisler charts

Recommended Books

- *Heat Transfer Principles and Applications*, B. K. Dutta, Prentice Hall India
- *Process Heat Transfer*, D.Q. Kern,, Mc Graw Hill
- *Heat Transfer*, J. P. Holman,, Mc Graw Hill
- *Fundamentals of Heat and Mass Transfer*, F.P. Incropera and D. P. Dewitt, John Wiley
- *Heat and Mass Transfer: Fundamentals & Applications,* Y. A, Cengel, A. J. Ghajar, McGraw Hill

Relevant NPTEL courses

- *Heat Transfer*, Prof. Ganesh Vishwanathan, IIT Bombay (https://nptel.ac.in/courses/103/101/103101137/)
- *Heat Transfer,* Prof. Sunando Dasgupta, IIT Kharagpur (https://nptel.ac.in/courses/103/105/103105140/)
- *Heat Transfer*, Dr. Anil Verma, IIT Guwahati (https://nptel.ac.in/courses/103/103/103103032/)
- *Heat Transfer*, Prof. A. K. Ghoshal, IIT Guwahati (https://nptel.ac.in/courses/103/103/103103031/)