MODULE I

BASICS OF HEAT TRANSFER

While teaching heat transfer, one of the first questions students commonly ask is the difference between *heat* and *temperature*. Another common question concerns the difference between the subjects of *heat transfer* and *thermodynamics*. Let me begin this chapter by trying to address these two questions.

1.1 Difference between heat and temperature

In heat transfer problems, we often interchangeably use the terms *heat* and *temperature*. Actually, there is a distinct difference between the two. *Temperature* is a measure of the amount of energy possessed by the molecules of a substance. It manifests itself as a degree of hotness, and can be used to predict the direction of heat transfer. The usual symbol for temperature is *T*. The scales for measuring temperature in SI units are the Celsius and Kelvin temperature scales. *Heat*, on the other hand, is energy in transit. Spontaneously, heat flows from a hotter body to a colder one. The usual symbol for heat is Q. In the SI system, common units for measuring heat are the Joule and calorie.

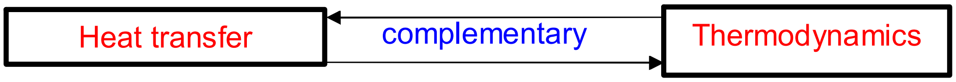
1.2 Difference between thermodynamics and heat transfer

Thermodynamics tells us:

- how much heat is transferred (δQ)
- how much work is done (δW)
- final state of the system

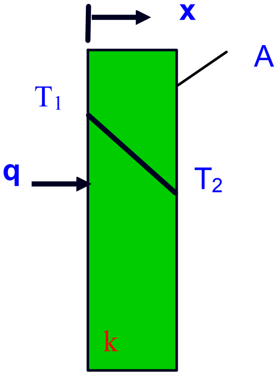
Heat transfer tells us:

- how (with what **modes**) δQ is transferred
- at what **rate** δQ is transferred
- temperature distribution inside the body



1.3 Modes of Heat Transfer

- **Conduction:** An energy transfer across a system boundary due to a temperature difference <u>by the mechanism of inter-molecular interactions</u>. Conduction needs matter and does not require any bulk motion of matter.



Conduction rate equation is described by the Fourier Law:

$$\vec{q} = -kA\nabla T$$

where: q = heat flow vector, (W)
k = thermal conductivity, a thermodynamic property of the material. (W/m K)
A = Cross sectional area in direction of heat flow. (m^2)
∇T = Gradient of temperature (K/m)
$= \partial T/\partial x \, \mathbf{i} + \partial T/\partial y \, \mathbf{j} + \partial T/\partial z \, \mathbf{k}$

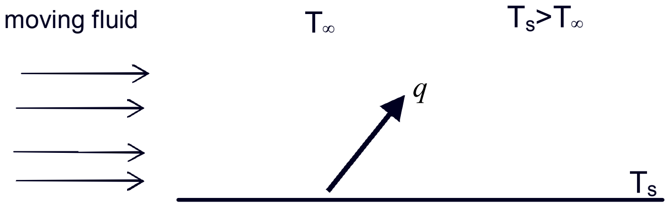
Note: Since this is a vector equation, it is often convenient to work with one component of the vector. For example, in the x direction:

$$q_x = - k \, A_x \, dT/dx$$

In circular coordinates it may convenient to work in the radial direction:

$$q_r = - k \, A_r \, dT/dr$$

- **Convection:** An energy transfer across a system boundary due to a temperature difference by the combined mechanisms of intermolecular interactions and bulk transport. Convection needs fluid matter.



Newton's Law of Cooling:

$$q = h \, A_s \, \Delta T$$

where: q = heat flow from surface, a scalar, (W)
h = heat transfer coefficient (which is not a thermodynamic property of the material, but may depend on geometry of surface, flow characteristics, thermodynamic properties of the fluid, etc. (W/m^2 K)
A_s = Surface area from which convection is occurring. (m^2)
$\Delta T = T_S - T_\infty$ = Temperature Difference between surface and coolant. (K)

Convection → Free or natural convection (induced by buoyancy forces)
Convection → Forced convection (induced by external means)

} May occur with phase change (boiling, condensation)

Table 1. Typical values of h (W/m^2K)

Free convection	gases: 2 - 25 liquid: 50 – 100
Forced convection	gases: 25 - 250 liquid: 50 - 20,000
Boiling/Condensation	2500 -100,000

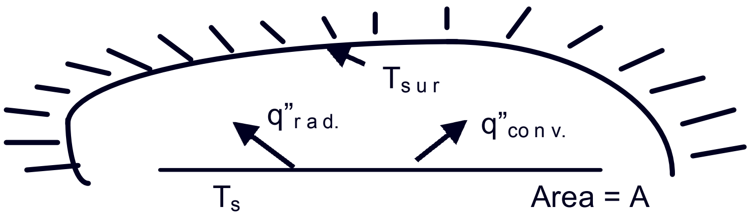
- **Radiation:** Radiation heat transfer involves the transfer of heat by electromagnetic radiation that arises due to the temperature of the body. Radiation does not need matter.

Emissive power of a surface:

$$E=\sigma\varepsilon T_s^4 \ (W/\ m^2)$$

where: ε = emissivity, which is a surface property ($\varepsilon = 1$ is black body)
σ = Steffan Boltzman constant = $5.67 \times 10^{-8}\ W/m^2\ K^4$.
T_s = Absolute temperature of the surface (K)

The above equation is derived from Stefan Boltzman law, which describes a gross heat emission rather than heat transfer. The expression for the actual radiation heat transfer rate between surfaces having arbitrary orientations can be quite complex, and will be dealt with in Module 9. However, the rate of radiation heat exchange between a small surface and a large surrounding is given by the following expression:



$$q = \varepsilon\cdot\sigma\cdot A\cdot(T_s^4 - T_{sur}^4)$$

where: ε = Surface Emissivity
A= Surface Area
T_s = Absolute temperature of surface. (K)
T_{sur} = Absolute temperature of surroundings.(K)

1.4 Thermal Conductivity, k

As noted previously, thermal conductivity is a thermodynamic property of a material. From the State Postulate given in thermodynamics, it may be recalled that thermodynamic properties of pure substances are functions of two independent thermodynamic intensive properties, say temperature and pressure. Thermal conductivity of real gases is largely independent of pressure and may be considered a function of temperature alone. For solids and liquids, properties are largely independent of pressure and depend on temperature alone.

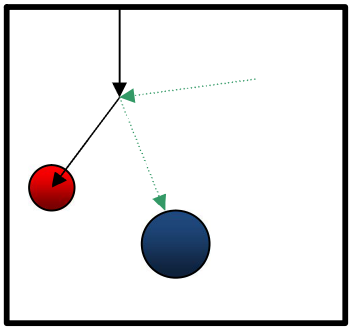
$$k = k\,(T)$$

Table 2 gives the values of thermal conductivity for a variety of materials.

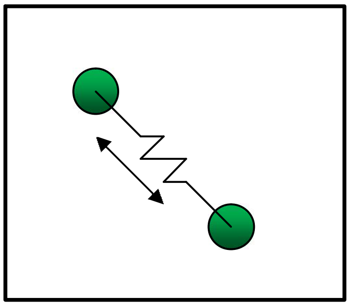
Table 2. Thermal Conductivities of Selected Materials at Room Temperature.

Material	Thermal Conductivity, W/m K
Copper	401
Silver	429
Gold	317
Aluminum	237
Steel	60.5
Limestone	2.15
Bakelite	1.4
Water	0.613
Air	0.0263

Let us try to gain an insight into the basic concept of thermal conductivity for various materials. The fundamental concept comes from the molecular or atomic scale activities. Molecules/atoms of various materials gain energy through different mechanisms. Gases, in which molecules are free to move with a mean free path sufficiently large compared to their diameters, possess energy in the form of kinetic energy of the molecules. Energy is gained or lost through collisions/interactions of gas molecules.



Kinetic energy transfer between gas molecules.



Lattice vibration may be transferred between molecules as nuclei attract/repel each other.

Solids, on the other hand, have atoms/molecules which are more closely packed which cannot move as freely as in gases. Hence, they cannot effectively transfer energy through these same mechanisms. Instead, solids may exhibit energy through vibration or rotation of the nucleus. Hence, the energy transfer is typically through lattice vibrations.

Another important mechanism in which materials maintain energy is by shifting electrons into higher orbital rings. In the case of electrical conductors the electrons are weakly bonded to the molecule and can drift from one molecule to another, transporting their energy in the process. Hence, flow of electrons, which is commonly observed in metals, is an effective transport mechanism, resulting in a correlation that materials which are excellent electrical conductors are usually excellent thermal conductors.