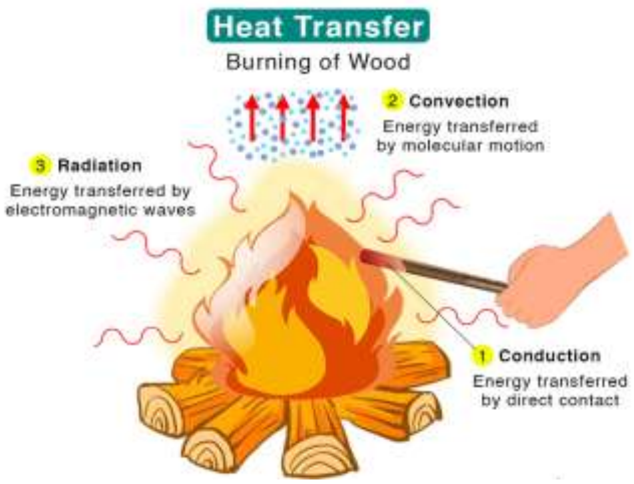
Chapter 1

Heat transfer: General



Heat Transfer: General

1.1. Introduction

Heat transfer, which should be called thermal transfer, is defined as thermal energy in transit because of a temperature difference. Two bodies having the same temperature are said to be in thermal equilibrium. If their temperatures are different, the warmer body transfers thermal energy to the colder body, we say that there is heat transfer.

Heat transfer occurs from the hot body to the cold body.

Heat transmission occurs through three basic mechanisms:

a) Conduction:

Thermal conduction, also called thermal diffusion, is a transfer of energy in a material medium without macroscopic movement, involving collisions of molecules (in fluids) or transfers of vibrations (in solids).

b) Convection:

Convection is a mode of heat transfer that involves the macroscopic movement of matter. This phenomenon occurs within flowing fluid media or between a solid wall and a moving fluid. There are two types of convection: natural and forced.

c) Radiation:

Every material body emits and absorbs energy in the form of electromagnetic radiation. The transfer of heat by radiation between two bodies separated by a vacuum or a semi-transparent medium occurs via electromagnetic waves, therefore without material support.

1.2. The importance of the heat transfer study

Heat transfer is energy in transit due to a difference in temperatures within a body or between different bodies. Whenever there is a difference in temperatures, energy is transferred from the higher temperature region to the lower temperature. According to the concepts of thermodynamics, the energy transferred as a result of a temperature difference is heat. The laws of thermodynamics concern the transfer of energy, but they only apply to systems in equilibrium (they can be used to predict the amount of energy needed to change a system from one equilibrium state to another), but they are not used to predict how quickly (time) these changes may take place. Heat transfer complements thermodynamic principles, providing analytical methods that predict this rate of heat transfer.

Example:

Heating a steel bar immersed in hot water: thermodynamic principles can be used to predict the final temperatures once the two systems have reached equilibrium and the amount of energy transferred between states of initial and final equilibrium, but this tells us nothing about the rate of heat transfer or the temperature of the bar after a certain time, or the time it takes to obtain a certain temperature at a certain position of the bar. Performing a heat transfer analysis allows you to predict the rate of heat transfer from the water to the bar and from this information you can calculate the bar temperature as well as the water temperature as a function of time.

To carry out a complete analysis of heat transfer, it is necessary to consider three different mechanisms: conduction, convection and radiation.

The design of heat exchange systems and energy conversion requires some familiarity with each of these mechanisms, as well as their interactions.

1.3. Fundamental concepts

1.3.1. Concept of heat

Heat is considered a special form of energy. According to the first law of thermodynamics, heat is equivalent to work; hence, they have the same unit: the Joule. It spreads naturally from the hottest environment to that with the lowest temperature, while keeping the volume constant. This constitutes the second law of thermodynamics.

a) Sensible heat:

When a body receives or releases heat, heats up or cools down without changing state, we then speak of sensible heat. The quantity of heat received by a body of mass m with heat capacity cp when it passes from an initial state at temperature T_1 to a final state at temperature T_2 is expressed by:

$$Q_{1\to 2} = m.c_p.(T_2 - T_1) \tag{1.1}$$

b) Latent heat:

We speak of latent heat when the body that receives or transfers heat uses it to change state, without its temperature changing. The quantity of heat that must be supplied to a material of mass m so that, at constant temperature, it changes state (solid -> liquid; liquid -> gas) is given by:

$$Q = m.\,L \tag{1.2}$$

Where L, is the Latent heat coefficient.

We then speak of "isothermal transformation" because the temperature of the system remains constant throughout the heat exchange process.

1.3.2. Temperature fields

We call temperature the physical quantity which measures the degree of heat of a medium, namely:

solids: it is the state of vibration of atoms inside a crystal lattice or movement of electrons for materials which have the ability to exchange electrons (metals for example);

fluids: this is the state of agitation of molecules. Temperature is expressed in degrees Kelvin (K), degrees Celsius (°C) or degrees Rankine (R).

$$
\begin{aligned}
T\left({}^{0}K\right) &= T\left({}^{0}C\right) + 273.15 \\
T\left({}^{0}F\right) &= 1.8 * T\left({}^{0}C\right) + 32 \\
T\left({}^{0}R\right) &= 1.8 * T\left({}^{0}C\right) + 491.67
\end{aligned}
\tag{1.3}
$$

The regime is permanent or stationary if the temperature field is independent of time $T = f\left(x, y, z, t\right)$. Otherwise, it is said to be variable or transient.

1.3.3. Isothermal surface

The locus of points having the same temperature at each instant is called isothermal surface. Two isothermal surfaces cannot intersect because we would then have two different temperatures at the same point, which is physically impossible.

In steady state: Isothermal surfaces are invariable.

In variable regime: They are mobile and deformable.

1.3.4. Temperature gradient

If we bring together all the points in space that have the same temperature, we obtain a surface called an isothermal surface. The temperature variation per unit length is maximum along the normal to the isothermal surface. This variation is characterized by the temperature gradient:

$$\overrightarrow{grad}(T) = \vec{n}.\frac{\partial T}{\partial n} \qquad (1.4)$$

$\vec{n}$: Unit vector of the normal. : $\frac{\partial T}{\partial n}$ Derivative of the temperature along the normal.

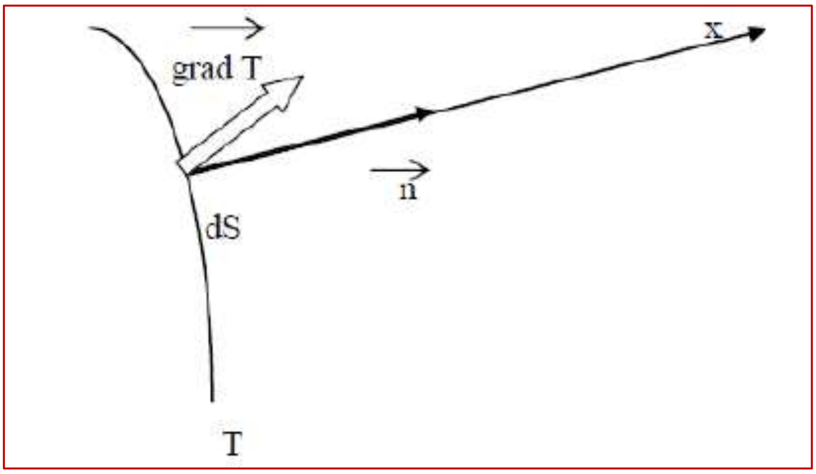


Figure 1. 1. Orthogonality of the gradient and the isotherm

1.3.5. Heat flux and density

The heat flow is the power exchanged per unit of time:

$$\Phi = \frac{dQ}{dt} \qquad [W] \qquad (1.5)$$

The heat flux density is the quantity of heat transmitted per unit of time and per unit of area of the isothermal surface:

$$\varphi = \frac{dQ}{S.dt} = \frac{\Phi}{S} \qquad \left[W/m^2\right] \qquad (1.6)$$

The heat source is defined by the thermal power it produces. In the case of a chemical reaction, it is expressed:

$$Q' = A_0 e^{\alpha t} \quad (1.7)$$

Where A0 and α se are constants.

1.4. The different modes of heat transfer

1.4.1. Heat transmission by conduction

This transfer of thermal energy, which does not require macroscopic movement of matter, is created by:

- molecular agitation (in gases and liquids)
- vibrations of crystal lattices (in non-conductive solids)
- the movement of free electrons (in conductive metals)

Jean-Baptiste Joseph Fourier (1768-1830) proposed in 1822 the law of conduction now known as Fourier's law. This relationship indicates that the heat flow is proportional to the temperature gradient and is in the direction of decreasing temperatures.

In the case of conduction, the flow is calculated by:

$$\Phi_S = -\lambda.S.\,gradT \quad (1.8)$$

For unidirectional conduction:

$$\overrightarrow{\Phi_S} = -\lambda.S.\frac{dT}{dx} \quad (1.9)$$

The (-) sign is a consequence of the second law of thermodynamics, according to which heat must flow towards the lowest temperature zone. The temperature gradient is negative if the temperature decreases for increasing values of x, therefore the heat transferred from the positive direction must be of positive magnitude, therefore a negative sign must be introduced in the right hand side of the equation former.

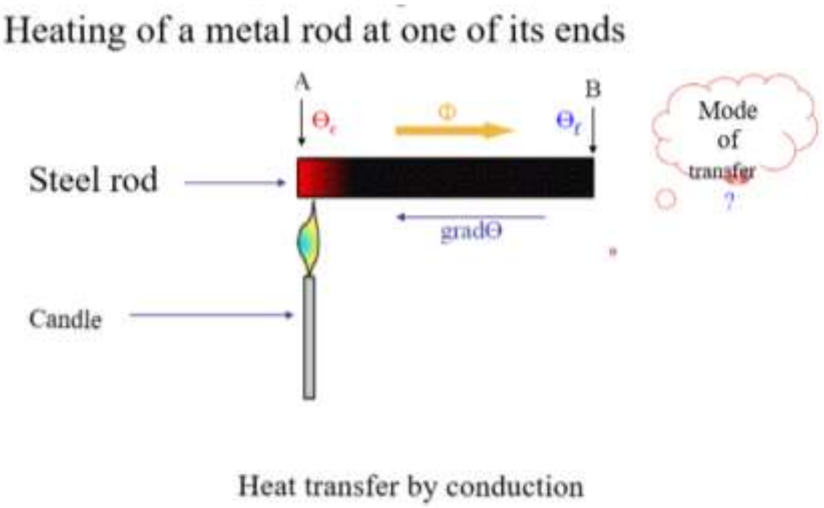


Figure 1. 2. Heating a metal bar at one of its ends

1.4.2. Heat transmission by convection

When a fluid at T_f comes into contact with a solid whose contact surface is at a temperature other than Ts, the process of thermal energy exchange is called convection. There are two types of convection.

a) Free or natural convection occurs when the driving force comes from the change in density in the fluid following contact with a surface at a different temperature, which gives rise to upward forces, with the fluid near the surface acquires a speed due only to this difference in density, without any external driving force.

b) Forced convection, occurs when an external driving force moves a fluid with

a speed (v), over a surface which is found at a temperature Ts higher or lower than that of the fluid T f, because the speed of the fluid in Forced convection is higher than natural convection, therefore, a greater quantity of heat is transferred for a given temperature.

Newton's law is used to calculate heat transfer by convection:

$$\Phi_S = h.S.(T_p - T_\infty) \qquad (1.10)$$

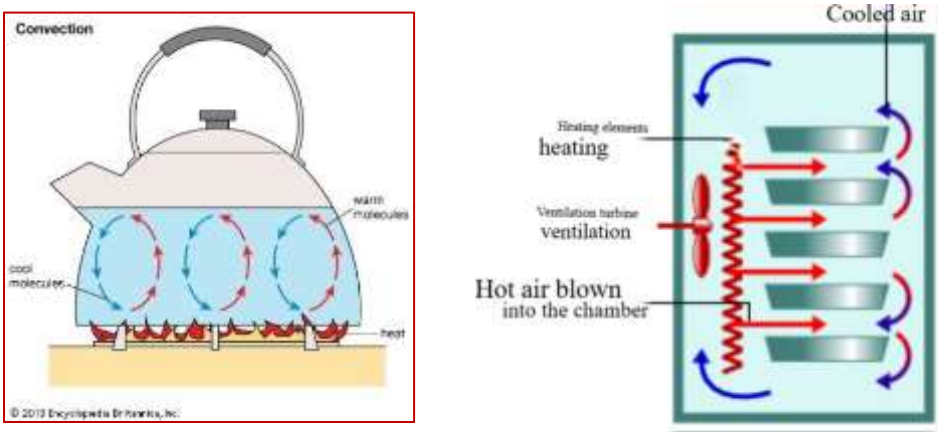


Figure 1. 3. Heat transfer by convection

1.4.3. Heat transmission by radiation

The maximum flux density emitted by a surface is given by the Stephan-Boltzmann law:

$$\Phi_{\max i} = \sigma.T_p^4 \qquad (1.11)$$

σ : Stephan's constant = $5{,}669.10^{-8}$ $W/m^2.K^4$.

The maximum flux is obtained for an ideal surface (black body). However, real surfaces (gray bodies) have a certain emissivity (ε) which reduces the flux emitted by the surface:

$$\Phi_{réel} = \varepsilon.\sigma.T_p^4 \qquad (1.12)$$

In the case where this surface is surrounded by another surface at a temperature T_∞, the net heat exchange is then:

$$\Phi_{net} = \sigma.\varepsilon_p S.(T_p^4 - T_\infty^4) \qquad (1.13)$$

Example: heating of a wall by solar radiation during the day, and heat emitted by the wall at night.

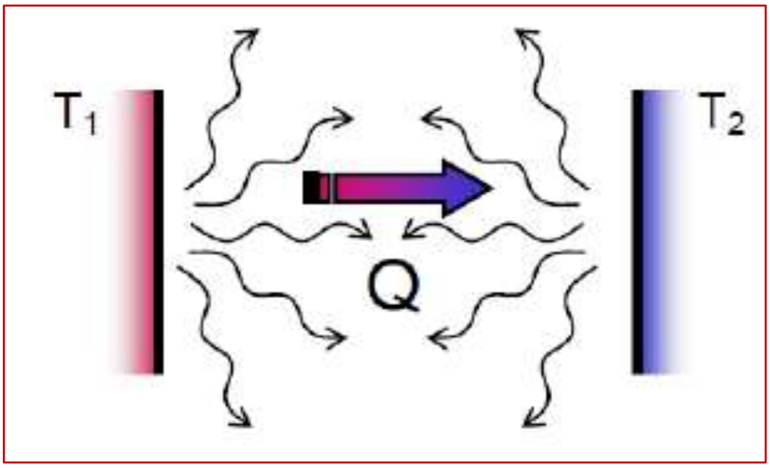


Figure 1. 4. Heat transfer by radiation

Noticed :

- ✓ In many thermal energy transformation problems, the three modes of heat transfer coexist but, generally, at least one of the three forms can be neglected, which will simplify the mathematical treatment of the transfer process;
- ✓ In the following figure, we can visualize the three modes of heat transfer at the same time.

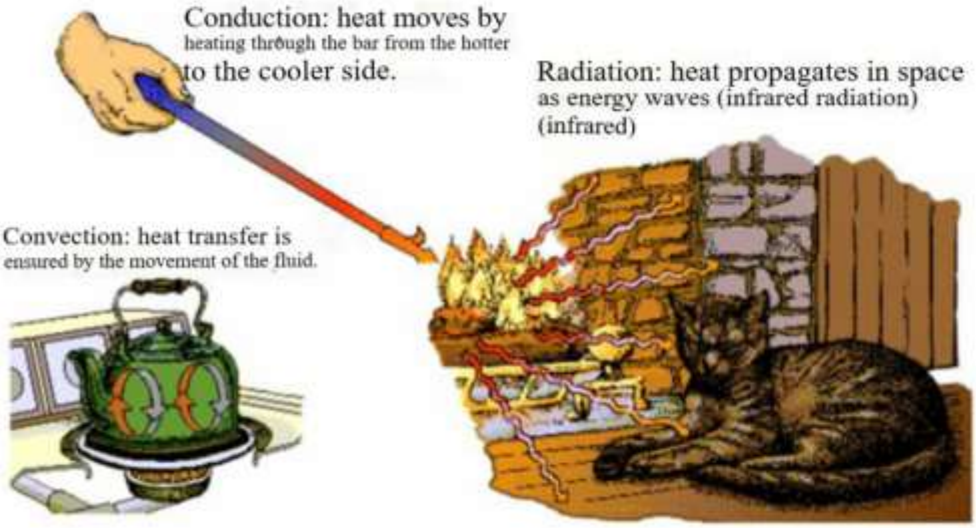


Figure 1. 5. Illustration of the three modes of heat transfer

1.5. Formulation of a heat transfer problem:

1.5.1. Energy balance:

Given a given control volume, at each instant, the energy conservation balance (mechanical energy + internal energy) on this volume is written:

(What goes in)- (What goes out)+ (What is generated)= (What stored)

$$E_e - E_s + E_g = E_{st} \quad (1.14)$$

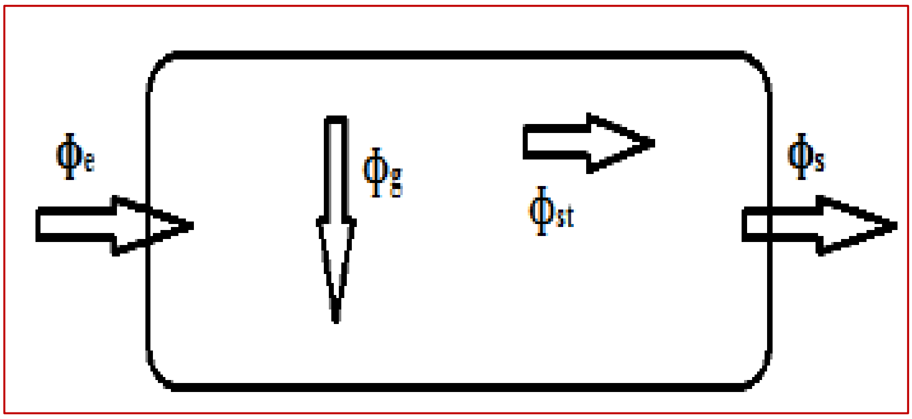


Figure 1. 6. Energy balance

The term "generated energy" should be considered in the broad sense: energy produced (in +) or consumed (in -). It is the same for the accumulation term (variation over time of the energy in the control volume). As part of the course, the energy balance will be limited to a thermal energy balance. The generation term, Eg, may appear in the following cases:

- exo or endothermic chemical reactions,
- nuclear reactions
- viscous dissipation
- Joule effect in an electrical resistance

Across a surface, the balance is simply reduced to:

$$\boxed{E_e - E_s = 0} \tag{1.15}$$