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CHAPTER 1

Basic Modes of Heat Transfer

1. INTRODUCTION

The radiation of the sun in which the planet is incessantly plunged, penetrates the air, the earth, and the waters; its elements are divided, change direction in every way, and, penetrating the mass of the globe, would raise its temperature more and more, if the heat acquired were not exactly balanced by that which escapes in rays from all points of the surface and expands through the sky.

The Analytical Theory of Heat, J. Fourier

Concepts and Analyses to be Learned

Heat is fundamentally transported, or "moved", by a temperature gradient; it *flows* or is *transferred* from a higher temperature region to a lower temperature one. An understanding of this process and its different mechanisms requires you to connect principles of thermodynamics and fluid flow with those of heat transfer. The latter has its own set of concepts and definitions, and the foundational principles among these are introduced in this chapter along with their mathematical descriptions and some typical engineering applications.

2. THE RELATION OF HEAT TRANSFER TO THERMODYNAMICS

Thermodynamics is concerned with the amount of heat transfer as a system undergoes a process from one equilibrium state to another, and it gives no indication about how long the process will take. A thermodynamic analysis simply tells us how much heat must be transferred to realize a specified change of state to satisfy the conservation of energy principle.

In practice we are more concerned about the rate of heat transfer (heat transfer per unit time) than we are with the amount of it. For example, we can determine the amount of heat transferred from a thermos bottle as the hot coffee inside cools from 90°C to 80°C by a thermodynamic analysis alone.

But a typical user or designer of a thermos is primarily interested in how long it will be before the hot coffee inside cools to 80°C, and a thermodynamic analysis cannot answer this question. Determining the rates of heat transfer to or from a system and thus the times of cooling or heating, as well as the variation of the temperature, is the subject of heat transfer (**Figure 2.1**).

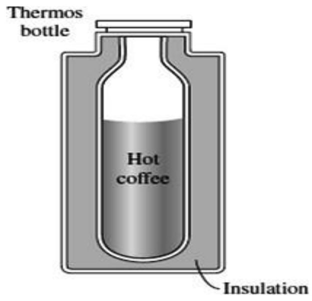


Figure 2.1 – *Heat transfer from the thermos*.

Thermodynamics deals with equilibrium states and changes, from one equilibrium state to another. On the other hand, heat transfer deals with systems that lack thermal equilibrium, and thus it is a non-equilibrium phenomenon. Therefore, the study of heat transfer cannot be based on the principles of thermodynamics alone.

However, the laws of thermodynamics lay the framework for the science of heat transfer. The first law requires that the rate of energy transfer into a system be equal to the rate of increase of the energy of that system. The second law requires that heat be transferred in the direction of decreasing temperature (**Figure 2.2**).

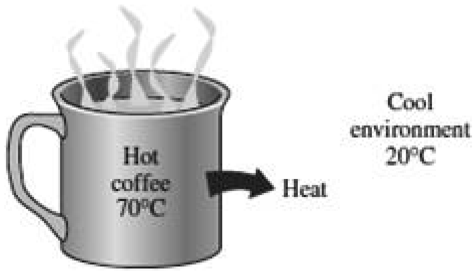


Figure 2.2 – *Heat transfer from high temperature to low temerature*.

3. MODES OF HEAT TRANSFER

Heat transfer is defined as the transfer of heat from one region to another by virtue of the temperature difference between them. The devices for transfer of heat are called heat exchangers. The concept of heat transfer is necessary for designing heat exchangers like boilers, evaporators, condensers, heaters and many other cooling and heating systems.

There are three modes of heat transfer as follow:

1. Conduction
2. Convection
3. Radiation.

3.1. Conduction Heat Transfer

At mention of the word conduction, we should immediately conjure up concepts of atomic and molecular activity because processes at these levels sustain this mode of heat transfer. Conduction may be viewed as "the *transfer of thermal energy from the more energetic to the less energetic particles of a substance due to interactions between the particles*".

Consider a gas in which a temperature gradient exists, and assume that there is no bulk, or macroscopic, motion. The gas may occupy the space between two surfaces that are maintained at different temperatures, as shown in (**Figure 3.1**). We associate the temperature at any point with the energy of gas molecules in proximity to the point. This energy is related to the random translational motion, as well as to the internal rotational and vibrational motions, of the molecules.

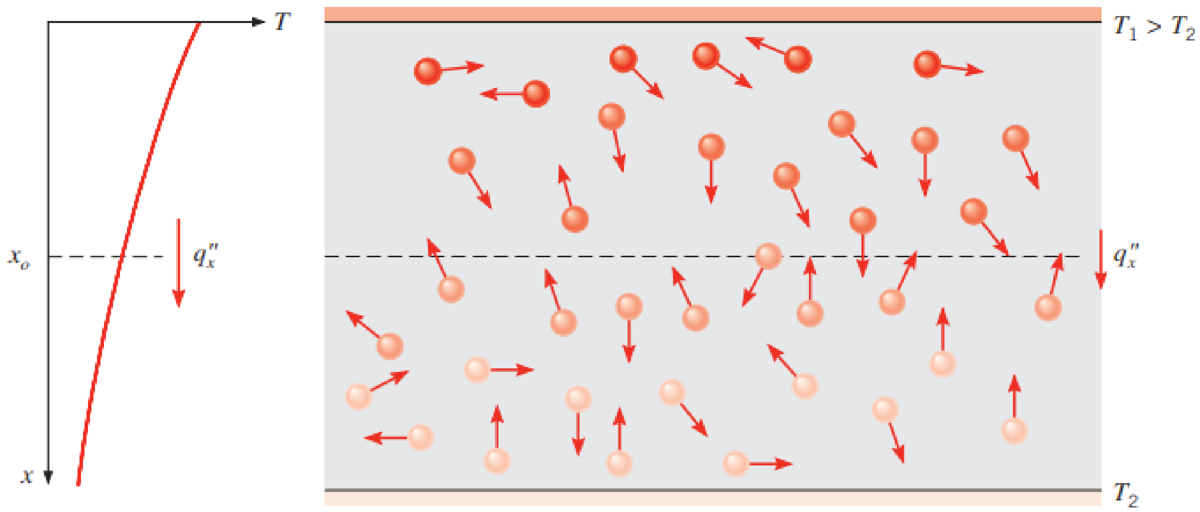


Figure 3.1 – *Association of conduction heat transfer with diffusion of energy due to molecular activity.*

Higher temperatures are associated with higher molecular energies. When neighboring molecules collide, as they are constantly doing, a transfer of energy from the more energetic to the less energetic molecules must occur. In the presence of a temperature gradient, energy transfer by conduction must then occur in the direction of decreasing temperature. This would be true even in the absence of collisions, as is evident from (**Figure 3.1**). The hypothetical plane at is constantly being crossed by molecules from above and below due to their random motion. However, molecules from above are associated with a higher temperature than those from below, in which case there must be a net transfer of energy in the positive x-direction. Collisions between molecules enhance this energy transfer. We may speak of the net transfer of energy by random molecular motion as a *diffusion* of energy.

The situation is much the same in liquids, although the molecules are more closely spaced and the molecular interactions are stronger and more frequent. Similarly, in a solid, conduction may be attributed to atomic activity in the form of lattice vibrations.

Examples of conduction heat transfer are legion. The exposed end of a metal spoon suddenly immersed in a cup of hot coffee is eventually warmed due to the conduction of energy through the spoon. On a winter day, there is significant energy loss from a heated room to the outside air. This loss is principally due to conduction heat transfer through the wall that separates the room air from the outside air.

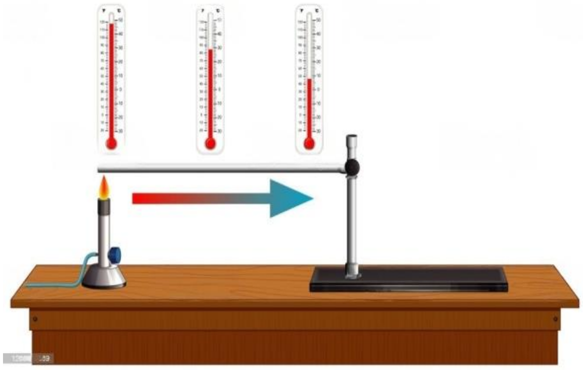


Figure 3.2 – *Heat conduction on a metal.*

When heat is transferred via conduction, the substance itself does not flow; rather, heat is transferred internally, by vibrations of atoms and molecules. Electrons can also carry heat, which is the reason metals are generally very good conductors of heat. Metals have many free electrons, which move around randomly; these can transfer heat from one part of the metal to another.

Heat transfer processes can be quantified in terms of appropriate *rate equations*. These equations may be used to compute the amount of energy being transferred per unit time. For heat conduction, *Joseph Fourier* published his remarkable book: "*Théorie analytique de la chaleur*" in 1822.

Fourier's Law of Heat Conduction

Fourier's Law states that for the one-dimensional plan wall, having a temperature distribution T(x) as shown in (**Figure 3.3**), the heat flux (q_x'' [W/m²]) resulting from thermal conduction is proportional to the magnitude of the temperature gradient and opposite to it in sign. If we call the constant of proportionality, k, then

$$\boldsymbol{q_x'' = -k\frac{dT}{dx}}$$

The parameter k is a *transport property* known as *the thermal conductivity* [W/m.K] and is a characteristic of the wall material. The minus sign is a consequence of the fact that heat is transferred in the direction of decreasing temperature.

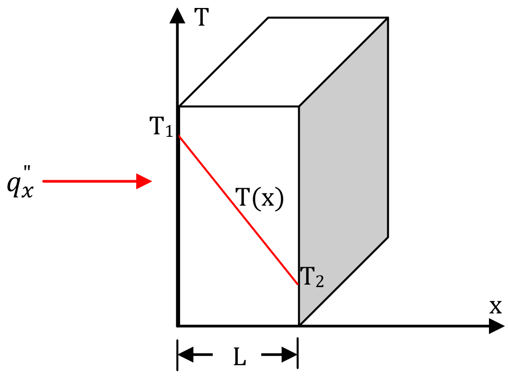


Figure 3.3 – One-dimensional heat transfer by conduction (diffusion of energy).

Under the steady-state conditions shown in (**Figure 3.3**), where the temperature distribution is linear; the temperature gradient may be expressed as

$$\frac{dT}{dx} = \frac{T_2 - T_1}{L}$$

and the heat flux is then

$$q_x'' = -k\frac{T_2 - T_1}{L}$$

Or

$$q_x'' = k\frac{T_1 - T_2}{L} = k\frac{\Delta T}{L}$$

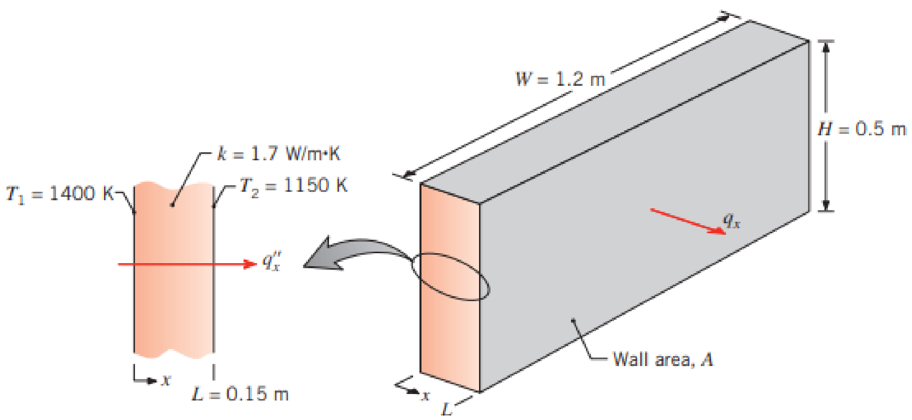
Note that this equation provides a *heat flux*, that is, the rate of heat transfer per *unit area*. The *heat rate* by conduction, (q_x [W]), through a plane wall of area A is then the product of the flux and the area

$$q_x = q_x''.A.$$

EXEMPLE 1

The wall of an industrial furnace is constructed from 0,15m thick fireclay brick having a thermal conductivity of 1,7W/mK. Measurements made during steady-state operation reveal temperatures of 1 400 and 1 150 K at the inner and outer surfaces, respectively. What is the rate of heat loss through a wall that is 0.5m x 1.2m on a side?

SOLUTION



Assumptions:

1. Steady-state conditions.
2. One-dimensional conduction through the wall.
3. Constant thermal conductivity.

Analysis:

Since heat transfer through the wall is by conduction, the heat flux may be determined from Fourier's law. Using previous Equation, we have

$$q_x^{"} = k\frac{\Delta T}{L} = 1{,}7.\frac{250}{0{,}15} = 2\,833\; W/m^2$$

The heat flux represents the rate of heat transfer through a section of unit area, and it is uniform (invariant) across the surface of the wall. The heat loss through the wall of area A = H x W is then

$$q_x = q_x^{"}.A = 2\,833\; x\;(0{,}5\; x\; 1{,}2) = 1\,700\; W.$$

EXEMPLE 2

The front of a slab of lead (k = 35 w/m.K) is kept at 110°C and the back is kept at 50 °C. If the area of the slab is 0,4m² and it is 0,03m thick, compute the heat flux and the heat transfer rate.

SOLUTION

The heat flux may be determined from Fourier's law. Using previous Equation, we have

$$q_x^{"} = k\frac{\Delta T}{L} = 35.\frac{(110-50)}{0{,}15} = 70\,000\;(\frac{W}{m^2}) = 70\;(\frac{kW}{m^2})$$

The heat transfer rate

$$q_x = q_x^{"}.A = 70\; x\;(0{,}4) = 28\; kW$$

Note that temperature units are in Celsius degree and thermal conductivity unit are in Kelvin degree.

RULE 1.

The conversion of Celsius to Kelvin

$$T(K) = T(°C) + 273{,}15$$

3.2. Convection Heat Transfer

Convection heat transfer is an exchange of heat between a surface and the surrounding fluid which are at different temperatures. Convection heat transfer is defined as a process of heat transfer by the combined action of *heat conduction* and *mixing motion*.

Consider a container fill of water. Heat is conducted through container wall.

1. First, heat is transferred from hot surface of wall to adjacent fluid purely by *conduction*.
2. Then, the hot fluid's density decreases by increase in temperature. This hot fluid particles move to top layer – low temperature region and mix with cold fluid and thus transfer heat by *mixing motion*.

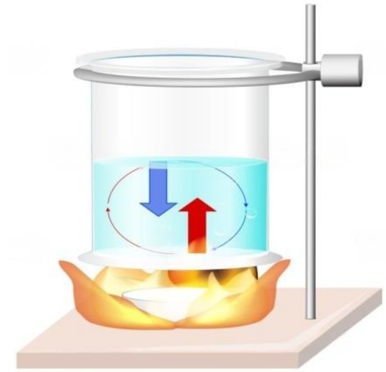


Figure 3.4 – Convection

If the mixing motion of fluid particles takes place due to density difference caused by temperature difference, then this convection heat transfer is called *free convection* or *natural convection*.

If the motion of fluid particles is due to *fan* or *pump* or *lower* or any external means, then this convection heat transfer is called *forced convection*.

(**Figure 3.5**) shows *velocity* and *temperature* profile for convection heat transfer from a heated plate with a fluid flow over its surface.

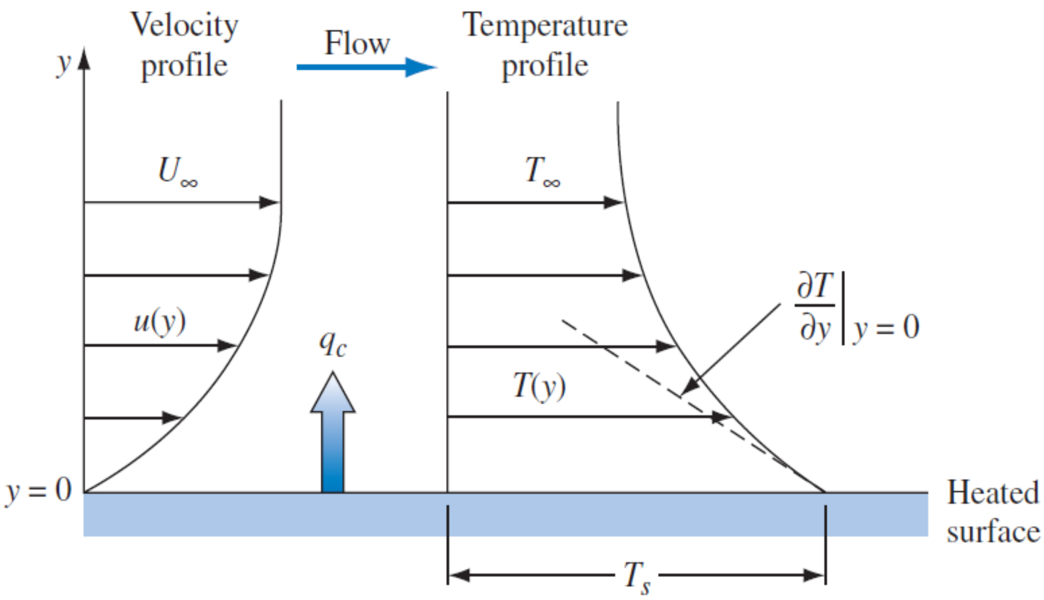


Figure 3.5 – Velocity and temperature profile for convection heat transfer from a heated plate with flow over its surface.

A consequence of the fluid–surface interaction is the development of a region in the fluid through which the velocity varies from zero at the surface to a finite value u_∞ associated with the flow. This region of the fluid is known as the *hydrodynamic*, or *velocity*, *boundary layer*. Moreover, if the surface and flow temperatures differ, there will be a region of the fluid through which the temperature varies from T_s at $y = 0$ to T_∞ in the outer flow. This region, called the *thermal boundary layer*, may be smaller, larger, or the same size as that through which the velocity varies. In any case, if $T_s > T_\infty$, convection heat transfer will occur from the surface to the outer flow.

Newton's law of cooling

For a fluid flowing at a mean temperature T_∞ over a surface at a temperature T_s, Newton proposed the following heat convection equation

$$q^{"} = h(T_s - T_\infty)$$

Where, $q^{"}$ is the convective heat flux [W/m²], is proportional to the difference between the surface and fluid temperatures, T_s and T_∞, respectively.

This expression is known as *Newton's law of cooling*, and the parameter h [W/m².K] is termed the *convection heat transfer coefficient*. This coefficient depends on conditions in the boundary layer, which are influenced by:

1. surface geometry
2. the nature of the fluid motion, and;
3. an assortment of fluid thermodynamic and transport properties.

TABLE 3.1 – Typical values of the convection heat transfer coefficient.

Process	h [W/m².K]
Free convection	
Gases	2–25
Liquids	50–1000
Forced convection	
Gases	25–250
Liquids	100–20,000
Convection with phase change	
Boiling or condensation	2500–100,000

EXEMPLE 3

A flat plate of length 1m and width 0,5m is placed in an air stream at 30°C blowing parallel to it. The convective heat transfer coefficient is 30 W/m².K. Calculate the heat transfer if the plate is maintained at a temperature of 300 °C.

SOLUTION

$$q_x = q_x^{"}.A = h.(T_s - T_\infty).A = 30.(300 - 30).(1.0,5) = 4,05\ kW$$

3.3. Radiation

Conduction and convection needs a medium for heat transfer, but radiation heat transfer takes place even in vacuum.

Radiation heat transfer occurs when the hot body and cold body are separated in space. The space may be filled up by a medium or vacuum.

Energy, emitted in the form of electromagnetic waves, by all bodies to their temperatures is called thermal radiation.

Thermal radiation is a form of heat transfer in which there's no need for a medium between the two bodies.

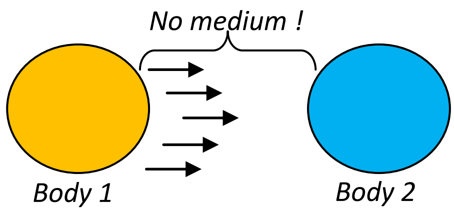


Figure 3.6 – Radiation between two bodies.

The energy is transferred in the form of electromagnetic waves that travel at the speed of light. A classical example for thermal radiation is transfer of solar energy from sun to earth and other planets. The sunlight travels through millions of miles of vacuum and yet delivers heat energy.

When thermal radiation is incident on a surface, depending on the properties of the surface, some energy is absorbed, some energy is reflected, and in case of transparent and translucent surfaces some energy is transmitted through it.

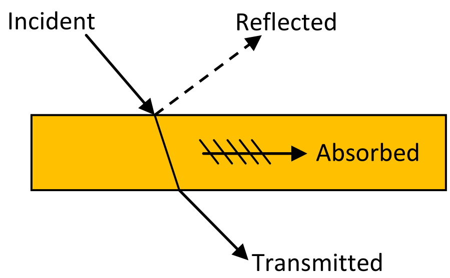


Figure 3.7 – Reflection, transmission and absorption of radiation.

In addition to this, any surface whose absolute temperature is more than 0 K emits thermal radiation. Depending on how much energy is entering and leaving the surface, it may be gaining or losing energy. The property of surface that defines how much energy is emitted by a surface is *emissivity*, which is defined as the ratio of the energy emitted by a surface to the energy emitted by a black body at the same temperature. Therefore, it has a value between 0 and 1.

$$\varepsilon = \frac{Energy\ emitted\ by\ a\ surface}{Energy\ emitted\ by\ a\ black\ body\ at\ same\ temperature}\ ;\ 0 \leq \varepsilon \leq 1$$

This property provides a measure of how efficiently a surface emits energy relative to a blackbody. It depends strongly on the surface material and finish.

From (**Figure 3.7**), we can model the radiation phenomenon as follow

$$q = q_A + q_R + q_T$$

Divided both sides of the equation by q, we get

$$\frac{q_A}{q} + \frac{q_R}{q} + \frac{q_T}{q} = 1$$

Where

$\frac{q_A}{q} = \alpha$: Absorptivity
$\frac{q_R}{q} = \rho$: Reflectivity
$\frac{q_T}{q} = \tau$: Transmissivity

Hence

$$\alpha + \rho + \tau = 1$$

The *reflectivity* is defined as the fraction of incident radiation reflected from the surface of the body.

The *transmissivity* is defined as the fraction of the incident radiation transmitted through the body.

The *absorptivity* is defined as the fraction of incident radiation absorbed by the body.

Bodies which do not transmit radiation are called *opaque*.

If the *transmissivity* of a body is equal to one, the *absorptivity* and *reflectivity* are equal to zero and whole of the *incident radiation* would pass through the body. Such a body is termed as *absolutely transparent* or *diathermanous*.

If the entire incident radiation is *absorbed* by the body, the absorptivity α = 1. Such a body is termed as a *blackbody*.

Stefan–Boltzmann law

Consider radiation transfer processes for the surface of (**Figure 3.8**). Radiation that is emitted by the surface originates from the thermal energy of matter bounded by the surface, and the rate at which energy is released per unit area [W/m^2] is termed the surface emissive power, E. There is an upper limit to the emissive power, which is prescribed by the *Stefan–Boltzmann law*.

$$E_b = \sigma . T_s^4$$

Where

T_s : the absolute temperature [K] of the surface

σ : the Stefan– Boltzmann constant .

Such a surface is called an *ideal radiator* or *blackbody*.

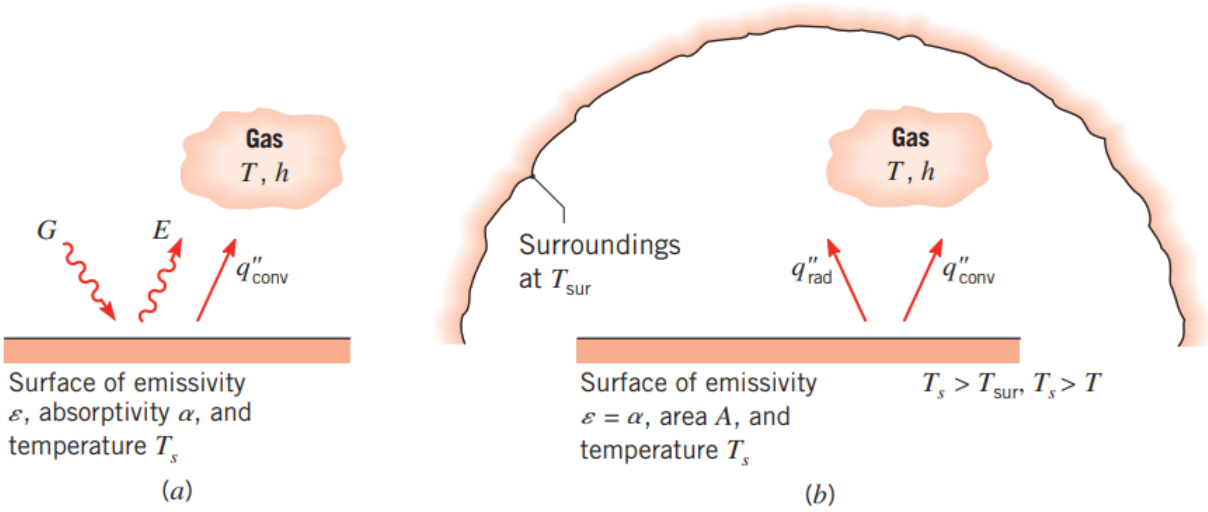


Figure 3.8 – Radiation exchange: (a) at a surface and (b) between a surface and large surroundings.

The heat flux emitted by a *real surface* is less than that of a *blackbody* at the same temperature and is given by

$$E_b = \varepsilon.\sigma\,.T_s^4$$

Where

ε : emissivity.

Radiation may also be incident on a surface from its surroundings. The radiation may originate from a special source, such as the sun, or from other surfaces to which the surface of interest is exposed. Irrespective of the source(s), we designate the rate at which all such radiation is incident on a unit area of the surface as the *irradiation* G (**Figure 3.8a**).

A portion, or all, of the irradiation may be *absorbed* by the surface, thereby increasing the thermal energy of the material. 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. That is,

$$G_{abs} = \alpha.G$$

However, whereas absorbed and emitted radiation increase and reduce, respectively, the thermal energy of matter, reflected and transmitted radiation have no effect on this energy. Note that the value of depends on the nature of the irradiation, as well as on the surface itself. For example, the absorptivity of a surface to solar radiation may differ from its absorptivity to radiation emitted by the walls of a furnace.

A special case that occurs frequently involves radiation exchange between a *small surface* at T_s and a *much larger*, isothermal surface that completely surrounds the smaller one (**Figure 3.8b**). The surroundings could, for example, be the walls of a room or a furnace whose temperature T_{surr} differs from that of an enclosed surface ($T_{surr} \neq T_s$). For such a condition, the irradiation may be approximated by emission from a blackbody at T_{surr} in wich case

$$G = \sigma . T_{surr}^4$$

If the surface is assumed to be one for which α = ε (a gray surface), the net rate of radiation heat transfer from the surface, expressed per unit area of the surface, is

$$q_{rad}^{"} = \frac{q}{A} = \varepsilon . E_b . T_s - \alpha . G = \varepsilon . \sigma . (T_s^4 - T_{surr}^4)$$

This expression provides the difference between thermal energy that is released due to radiation emission and that gained due to radiation absorption.

The surfaces of (**Figure 3.8**) may also simultaneously transfer heat by convection to an adjoining gas. For the conditions of **Figure 3.8b**, the total rate of heat transfer from the surface is then

$$q = q_{conv} + q_{rad} = h . A . (T_s - T_\infty) + \varepsilon . A . \sigma . (T_s^4 - T_{surr}^4)$$

EXEMPLE 4

A furnace inside temperature of 2250 K has a glass circular viewing of 6 cm diameter. If the transmissivity of glass is (τ = 0,08), make calculations for the heat loss from the glass window due to radiation.

SOLUTION

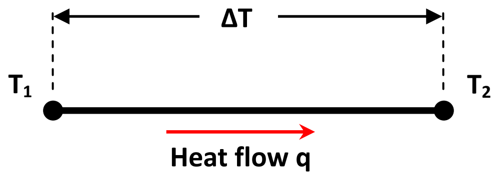
The radiation heat loss from window is given by:

$$q_x = \tau . \sigma . T_s^4 . A \qquad (\textit{Heat will transmits the glass})$$

$$q_x = 0{,}08 \,.\, 5{,}67 \,.\, 10^{-8} . 2250^4 . \frac{\pi}{4} . (0{,}06)^2 = 328{,}5\ W$$

3.4. The Thermal Resistance Concept

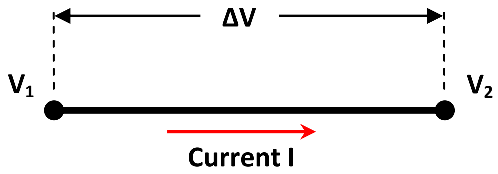
Thermal resistance is a quantification of how difficult it is for heat to be conducted. Thermal resistance is represented as the quotient of the temperature difference between two given points by the heat flow between the two points (amount of heat flow per unit time). This means that the higher the thermal resistance, the more difficult it is for heat to be conducted, and vice versa.



$$Thermal\ resistance = \frac{Temperature\ difference}{Heat\ flow} \quad \rightarrow \quad R = \frac{\Delta T}{q}$$

The unit of thermal resistance is K/W or °C/W (K represents kelvins).

Thermal Ohm's law – The thermal resistance can be considered in the same way as the electric resistance. The basic formulas of thermal calculation can be treated in the same way as Ohm's law. In the figure below, Ohm's law is represented with an illustration and equations. It can be seen that the respective parameters are replaceable by heat and electricity.



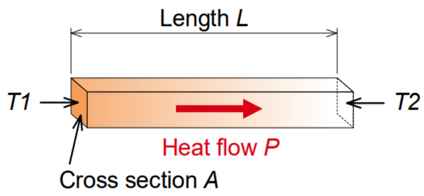
$$Electric\ resistance = \frac{Voltage\ difference}{Current} \quad \rightarrow \quad R = \frac{\Delta V}{I}$$

Therefore, as potential difference ΔV is calculated with R × I, temperature difference ΔT can be calculated with R × q.

Conductive thermal resistance

$$\text{Conductive thermal resistance} = \frac{Lenght}{Thermal\ conductivity\ .\ Cross\ section} \quad \rightarrow \quad \mathrm{R}_{cond} = \frac{\mathrm{L}}{\mathrm{k.A}}$$

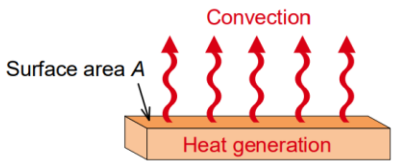
To decrease the thermal resistance:
- increase the cross section of the object,
- decrease the length of the object, or
- select material with a higher thermal conductivity



Convective thermal resistance

$$\text{Convective thermal resistance} = \frac{1}{Convective\ heat\ transfer\ coefficient\ .\ Surface\ area} \rightarrow \mathrm{R}_{conv} = \frac{1}{\mathrm{h.A}}$$

To decrease the thermal resistance:
- increase the surface area of the object,
- for the natural convection, consider the configuration so that the temperature difference is increased, or
- for the forced convection, increase the air velocity



Radiative thermal resistance

$$\text{Radiative thermal resistance} = \frac{1}{Radiative\ heat\ transfer\ coefficient\ .\ Surface\ area} \rightarrow \mathrm{R}_{rad} = \frac{1}{\mathrm{h}_{rad}.\mathrm{A}}$$

Where, $h_{rad} = \varepsilon\sigma(T_1^2 + \mathrm{T}_2^2)(T_1 + T_2)$

To decrease the thermal resistance:
- increase the surface area of the object, or
- Select material with a high emissivity.