Chapter One

Introduction to Heat Transfer

• Introduction

The science of ***Thermodynamics*** deals with the *amount of heat transfer* as a system undergoes a process from one equilibrium state to another, and makes no reference to *how long* the process will take. But in engineering, we are often interested in the *rate of heat transfer*, which is the topic of the science of *heat transfer*. We can defined ***Heat Transfer*** as the form of energy that can be transferred from one system to another as a result of temperature difference. The transfer of energy as heat is always from the higher-temperature medium to the lower-temperature one, and heat transfer stops when the two mediums reach the same temperature. There are many area of heat transfer applications such as, thermal power plants, refrigerators system, combustion plant, solar-thermic system…..etc. Heat can be transferred in three different modes: *conduction*, *convection*, and *radiation*. All modes of heat transfer require the existence of a temperature difference, and all modes are from the high-temperature medium to a lower-temperature one.

• Conduction

Conduction is the transfer of energy from the more energetic particles of a substance to the adjacent less energetic ones as a result of interactions between the particles.

The *rate* of heat conduction through a medium depends on the *geometry* of the medium, its *thickness*, and the *material* of the medium, as well as the *temperature difference* across the medium. Consider steady heat conduction through a large plane wall of thickness $\Delta x = L$ and area A, as shown in Figure 1-1. The temperature difference across the wall is ΔT = $T2$ - $T1$.

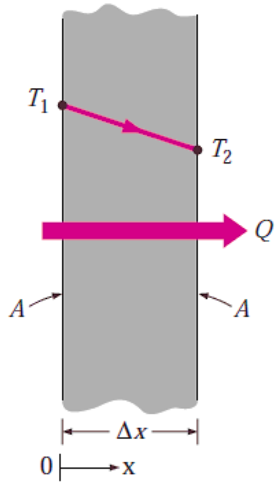


Figure 1-1 Heat conduction through a large plane wall of thickness Δx and area A.

$$Rate\ of\ heat\ conduction = \frac{(Area)(Temperature\ difference)}{Thicknes}$$

or,

$$Q_{cond} = kA\frac{(T_1 - T_2)}{\Delta x} = -kA\frac{\Delta T}{\Delta x} \qquad (W) \qquad 1\text{-}1$$

where the constant of proportionality k is the ***thermal conductivity*** of the material, which is a *measure of the ability of a material to conduct heat* (Figure 1–2)

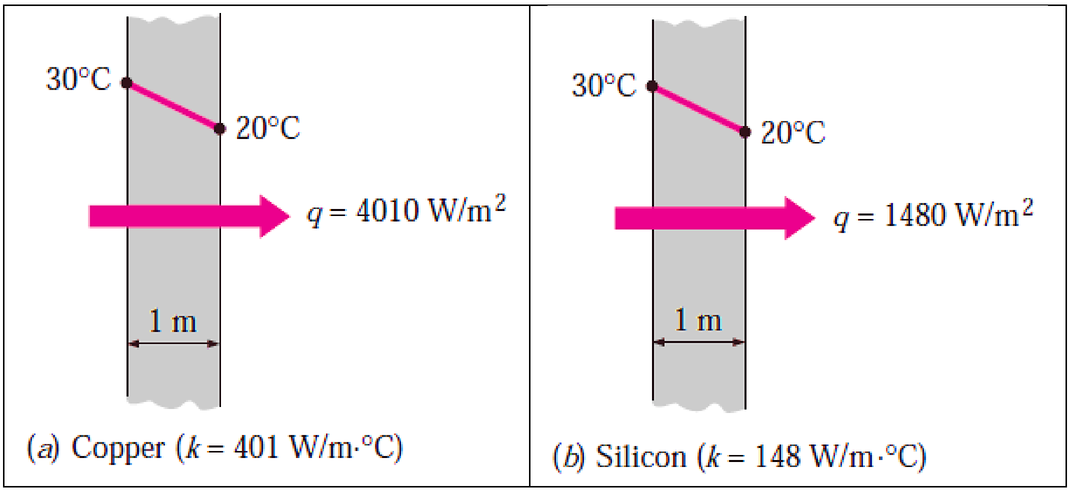


Figure 1-2 The rate of heat conduction through a solid is directly proportional to its thermal conductivity.

In the limiting case of $\Delta x \rightarrow 0$, reduces to the differential form

$$Q_{cond} = -kA\frac{dT}{dx} \qquad (W) \qquad 1\text{-}2$$

which is called ***Fourier's law of heat conduction.***

Q_{cond} is the ***heat transferred*** (W), k is ***thermal conductivity*** (W/m. ºC) A is ***cross-section area*** (m²) and *dT/dx* is the ***temperature gradient,*** which is the slope of the temperature curve on a *T-x* diagram (the rate of change of *T* with *x*), at location *x*. This relation indicates that the rate of heat conduction in a direction is proportional to the temperature gradient in that direction. Heat is conducted in the direction of decreasing temperature, and the temperature gradient becomes negative when temperature decreases with increasing *x*. The *negative sign* in Equation. 1–2 ensures that heat transfer in the positive *x* direction is a positive quantity.

Example 1/ The roof of an electrically heated home is 6 m long, 8 m wide, and 0.25 m thick, and is made of a flat layer of concrete whose thermal conductivity is *k* = 0.8 W/m.°C (Figure. 1-3). The temperatures of the inner and the outer surfaces of the roof one night are measured to be 15°C and 4°C, respectively, for a period of 10 hours. Determine the rate of heat loss through the roof at night.

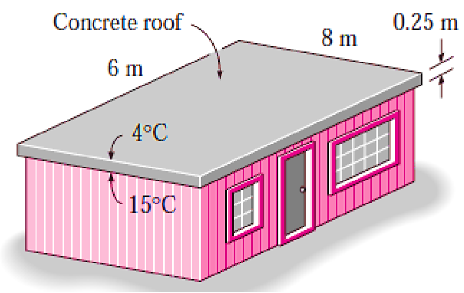


Figure 1-3 Schematic for Example 1

Solution:

A= 6 m x 8 m = 48 m^2, k = 0.8 W/m.°C, x=0.25m, T1=15° C and T2=4°C

$$Q_{cond} = kA\frac{(T_2 - T_1)}{x} = (0.8\ W/m\cdot°C)(48\ m^2)\frac{(15-4)°C}{0.25m} = 1690\ W = 1.69kW$$

Example 2/ An aluminum pan whose thermal conductivity is 237 W/m.°C has a flat bottom with diameter 20 cm and thickness 0.4 cm. Heat is transferred steadily to boiling water in the pan through its bottom at a rate of 800 W. If the inner surface of the bottom of the pan is at 105°C, determine the temperature of the outer surface of the bottom of the pan.

Solution:

$A = \pi r^2 = 3.14x(0.1)^2 = 0.0314m^2$, k=237W/m.°C, x=0.004m,

$\mathrm{Q_{cond}} = 800W$, T_1=105°C and T_2=?

$$\mathrm{Q_{cond}} = \mathrm{kA}\frac{(\mathrm{T_2} - \mathrm{T_1})}{\mathrm{x}}$$

$$800W = (237\mathrm{W/m.°C})(0.0314m^2)\frac{(\mathrm{T_2} - 105°\mathrm{C})}{0.004}$$

$$\mathrm{T_2} = 105.43°\mathrm{C}$$

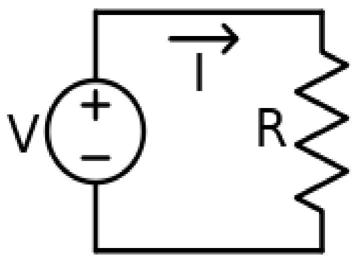
As well as, we can rewrite equation 1-2 as below

$$\mathrm{Q_{cond}} = \frac{(\mathrm{T_1} - \mathrm{T_2})}{\frac{\mathrm{x}}{\mathrm{kA}}}$$

$\frac{\mathrm{x}}{\mathrm{kA}}$ = Thermal resistance (R)

If an electric resistance (R) has a voltage difference (V) impressed across it, an electric current (I) will flow through the resistor. As shown below with Ohme´s Law :

$$I = \frac{V}{R}$$



- ## Thermal Conductivity

Thermal conductivity of a material can be defined as *the rate of heat transfer through a unit thickness of the material per unit area per unit temperature difference.* The thermal conductivity of a material is a measure of the ability of the material to conduct heat. A high value for thermal conductivity indicates that the material is a good heat conductor, and a low value indicates that the material is a poor heat conductor or insulator. The thermal conductivities of some common materials at room temperature are given in table 1–1.

Table 1-1 The thermal conductivities of some materials at room temperature

Material	k, W/m . °C
Diamond	2300
Silver	429
Copper	401
Gold	317
Aluminum	237
Iron	80.2
Mercury	8.54
Glass	0.78
Brick	0.72
Water	0.613
Human skin	0.37
Wood (oak)	0.17
Helium	0.152
Soft rubber	0.13
Glass fiber	0.043
Air (g)	0.026
Urethane, rigid foam	0.026

The thermal conductivities of materials vary with temperature show table 1–2. The variation of thermal conductivity over certain temperature ranges is negligible for some materials, but significant for others, as shown in Fig. 1–4. The thermal conductivities of certain solids exhibit dramatic increases at temperatures near absolute zero, when these solids become superconductors. For example, the conductivity of copper reaches a maximum value of about 20,000 W/m.°C at 20 K, which is about 50 times the conductivity at room temperature.

Table 1-2 Thermal conductivities of materials vary with temperature

T, K	Copper	Aluminum
100	482	302
200	413	237
300	401	237
400	393	240
600	379	231
800	366	218

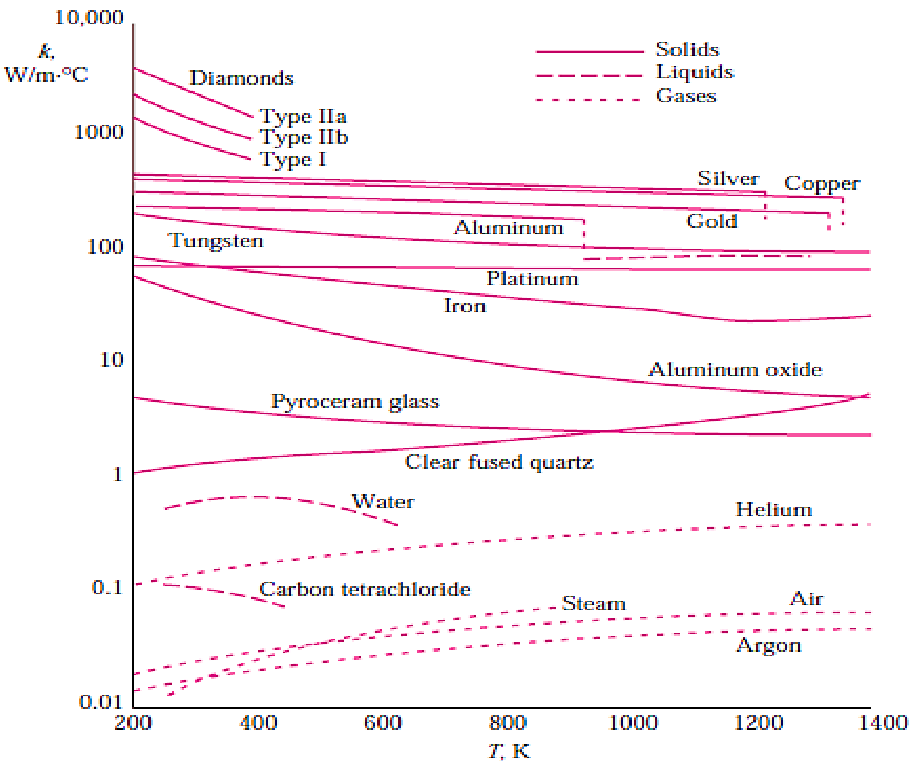


Figure 1-4 The variation of the thermal conductivity of various solids, liquids, and gases with temperature.

Note:- The temperature dependence of thermal conductivity causes considerable complexity in conduction analysis. Therefore, it is common practice to evaluate the thermal conductivity k at the average temperature and treat it as a ***constant in calculations***.

- **Convection**

Convection is the mode of energy transfer between a solid surface and the adjacent liquid or gas that is in motion, and it involves the combined effects of conduction and fluid motion.

Consider the cooling of a hot block by blowing cool air over its top surface as shown in figure 1–5. Energy is first transferred to the air layer adjacent to the block by conduction. This energy is then carried away from the surface by convection, that is, by the combined effects of conduction within the air that is due to random motion of air molecules and the bulk or macroscopic motion of the air that removes the heated air near the surface and replaces it by the cooler air.

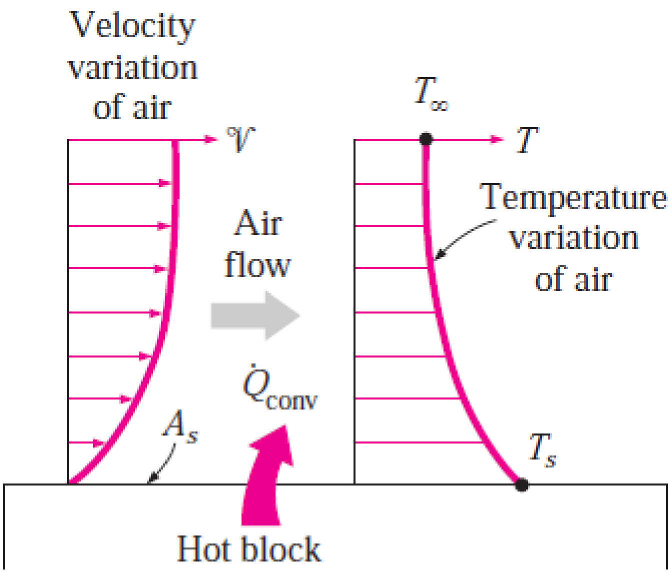


Figure 1-5 Heat transfer from a hot surface to air by convection

The faster the fluid motion, the greater the convection heat transfer. According this fact, the convection can be divided to two types namely:

1- Force Convection

If the fluid is forced to flow over the surface by external means such as a fan, pump, or the wind, see figure 1-6.

2- Natural (or free) Convection

If the fluid motion is caused by buoyancy forces that are induced by density differences due to the variation of temperature in the fluid, see figure 1-6.

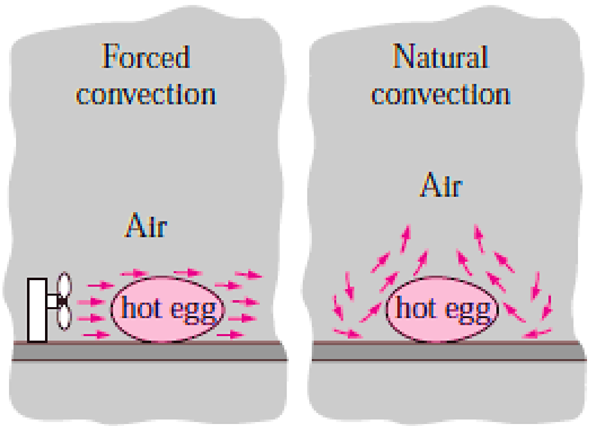


Figure 1-6 The cooling of a boiled egg by forced and natural convection.

Despite the complexity of convection, the rate of *convection heat transfer* is observed to be proportional to the temperature difference, and is conveniently expressed by ***Newton's law of cooling*** as

$$\mathrm{Q_{conv}} = \mathrm{h}A_s(T_s - T_\infty) \qquad \mathrm{(W)} \qquad 1\text{-}3$$

where $\mathrm{Q_{conv}}$ is the heat transferred by convection(W)

h is the convection heat transfer coefficient in W/m^2·°C.

As is the surface area through which heat transfer takes place (m^2).

Ts is the surface temperature (°C).

T_∞ is the temperature of the fluid sufficiently far from the surface (°C).

Note:- The convection heat transfer coefficient *h* is not a property of the fluid. It is an experimentally determined parameter whose value depends on all the variables influencing convection such as the surface geometry, the nature of fluid motion, the properties of the fluid, and the bulk fluid velocity. Typical values of *h* are given in table 1–3.

Table 1-3 Typical values of convection heat transfer coefficient

Type of convection	h, W/m² · °C*
Free convection of gases	2–25
Free convection of liquids	10–1000
Forced convection of gases	25–250
Forced convection of liquids	50–20,000
Boiling and condensation	2500–100,000

Example 3 / A 2-m-long, 0.3-cm-diameter electrical wire extends across a room at 15°C, as shown in Fig. 1–7. Heat is generated in the wire as a result of resistance heating, and the surface temperature of the wire is measured to be 152°C in steady operation. Also, the voltage drop and electric current through the wire are measured to be 60 V and 1.5 A, respectively. Disregarding any heat transfer by radiation, determine the convection heat transfer coefficient for heat transfer between the outer surface of the wire and the air in the room.

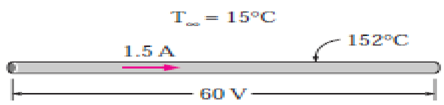


Figure 1-7 Schematic for example 4

Solution:

Heat generated = *VI* = (60 V)(1.5 A) = 90 W

The surface area of the wire is

$A_s = \pi DL = \pi\,(0.003\text{ m})(2\text{ m}) = 0.01885\text{ m}^2$

Newton's law of cooling for convection heat transfer is expressed as

$$Q_{conv} = hA_s(T_s - T_\infty)$$

Disregarding any heat transfer by radiation and thus assuming all the heat loss from the wire to occur by convection, the convection heat transfer coefficient is determined to be

$$h = \frac{Q_{conv}}{A_s(T_s - T_\infty)} = \frac{90}{(0.01885)(152-15)} = 34.9\text{ W/m}^2.°C$$

- **Radiation**

Radiation is the energy emitted by matter in the form of *electromagnetic waves* (or *photons*) as a result of the changes in the electronic configurations of the atoms or molecules.

Unlike conduction and convection, the transfer of energy by radiation does not require the presence of an intervening medium. In fact, energy transfer by radiation is fastest (at the speed of light) and it suffers no attenuation in a vacuum. This is how the energy of the sun reaches the earth. All bodies at a temperature above absolute zero emit thermal radiation.

The maximum rate of radiation that can be emitted from a surface at an absolute temperature *Ts* (in K) is given by the ***Stefan–Boltzmann law*** as

$$Q_{rad} = \sigma A_s T_s^4 \quad (W) \qquad 1\text{-}4$$

Where σ is Stefan–Boltzmann constant (5.67×10^{-8} W/m^2.K^4)

The idealized surface that emits radiation at this maximum rate is called a blackbody, and the radiation emitted by a blackbody is called blackbody radiation (Figure 1–8).

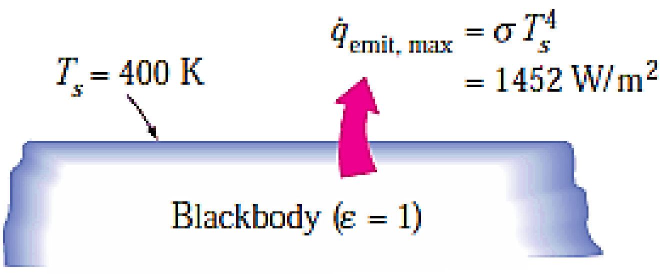


Figure 1-8 Blackbody radiation represents the maximum amount of radiation that can be emitted from a surface at a specified temperature.

The radiation emitted by all real surfaces is less than the radiation emitted by a blackbody at the same temperature, and is expressed as

$$Q_{rad} = \varepsilon \sigma A_s T_s^4 \quad (W) \qquad 1\text{-}5$$

Where ε is the emissivity of the surface. The property emissivity, whose value is in the range $0 \leq \varepsilon \geq 1$, is a measure of how closely a surface approximates a blackbody for which ε=1. The emissivities of some surfaces are given in table 1–4.

Table 1-4 Emissivities of some materials at 300 K

Material	Emissivity
Aluminum foil	0.07
Anodized aluminum	0.82
Polished copper	0.03
Polished gold	0.03
Polished silver	0.02
Polished stainless steel	0.17
Black paint	0.98
White paint	0.90
White paper	0.92–0.97
Asphalt pavement	0.85–0.93
Red brick	0.93–0.96
Human skin	0.95
Wood	0.82–0.92
Soil	0.93–0.96
Water	0.96
Vegetation	0.92–0.96

In general, the determination of the net rate of heat transfer by radiation between two surfaces is a complicated matter since it depends on the properties of the surfaces, their orientation relative to each other, and the interaction of the medium between the surfaces with radiation. The net rate of radiation heat transfer between these two surfaces is given by

$$Q_{rad} = \varepsilon \sigma A_s (T_s^4 - T_{surr}^4) \qquad (W) \qquad 1\text{-}6$$

Where T_{surr} is surrounding temperature (k)

Example 4 / Two infinite black plates at 800°C and 300°C exchange heat by radiation. Calculate the heat transfer per unit area.

Solution:

$$q/A = \sigma\left(T_1^4 - T_2^4\right)$$
$$= (5.669\times10^{-8})(1073^4 - 573^4)$$
$$= 69.03 \text{ kW/m}^2$$

Example 5 / A 5.0-cm-diameter cylinder is heated to a temperature of 200°C, and air at 30°C is forced across it at a velocity of 50 m/s. If the surface emissivity is 0.7, calculate the total heat loss per unit length if the walls of the enclosing room are at 10°C. Comment on this calculation. (h = 180 W/m².°C)

Solution:

The heat conducted through the plate must be equal to the sum of convection and radiation heat losses:

$$Q_{total} = Q_{conv} + Q_{rad}$$
$$= hA\,(Tw - T\infty) + \varepsilon_1 \sigma A_1\left(T_1^4 - T_2^4\right)$$

$$Q_{conv} = (180)\pi(0.05)(1)(200\text{-}30)$$
$$= 4807 \text{ W/m}$$

$$Q_{rad} = (5.669\times10^{-8})(0.7)\pi(0.05)(1)(473^4 - 283^4)$$
$$= 272 \text{ W/m}$$

$$Q_{total} = 4807 + 272 = 5079 \text{ W/m}$$

Most heat transfer is by convection

Table 2. Summary of heat transfer rate processes

Mode	Transfer Mechanism	Rate of heat transfer(W)	Thermal Resistance (K/W)
Conduction	Diffusion of energy due to random molecular motion	$q = -kA\frac{dT}{dx}$	$R_k = \frac{L}{kA}$
Convection	Diffusion of energy due to random molecular motion plus bulk motion	$q = hA(T_s - T_\infty)$	$R_c = \frac{1}{h\,A}$
Radiation	Energy transfer by electromagnetic Waves	$q = \sigma\varepsilon A(T_s^4 - T_{sur}^4)$	$R_r = \frac{T_s - T_{sur}}{\sigma\varepsilon A(T_s^4 - T_{sur}^4)}$