

# Brief Introduction to Heat Transfer

Revision 10/25/04

## Introduction

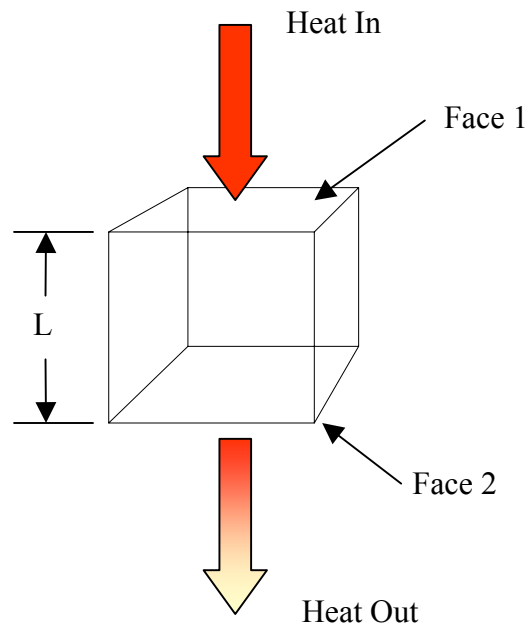
Heat transfer is a science that studies the energy transfer between two bodies due to temperature difference. There are three types or modes of heat transfer:

1. Conduction
2. Convection
3. Radiation

## 1. Conduction

Conduction is a mode of heat transfer that occurs when there is a temperature gradient across a body. In this case, the energy is transferred from a high temperature region to low temperature region due to random molecular motion – diffusion. Higher temperatures are associated with higher molecular energies and when they collide with less energetic molecules the transfer of energy occurs.

The simplest conduction heat transfer can be described as “one dimensional heat flow” depicted in Figure 1. In this situation, the heat flows into one face of the object and out the opposite face with no heat loss (flow) out the sides of the object. The surfaces 1 and 2 are held at constant temperature. Clearly, “in one dimensional heat flow,” the temperature of an object is a function of only one variable, namely the distance from either face of the object (face 1 or 2).



**Figure 1:** One-Dimensional Heat Flow

The heat transfer rate by conduction can be expressed as:

$$q = -kA \frac{\partial T}{\partial x} \quad (1)$$

where,

q – heat transfer rate (W)

$\frac{\partial T}{\partial x}$  - temperature gradient in the direction of the flow (K/m)

k – thermal conductivity of the material (W/mK)

A – cross-sectional area of heat path

Equation (1) is known as Fourier's law of heat conduction. Therefore, the heat transfer rate by conduction through the object in Figure 1 can be expressed:

$$q = \frac{kA}{L} \Delta T_{12} \quad (2)$$

where,

A – cross-sectional area of the object

L – wall thickness

$\Delta T_{12}$  – temperature difference between two surfaces ( $\Delta T_{12} = T_1 - T_2$ )

k – thermal conductivity of object's material (W/mK)

Analyzing Equations (1) and (2), the heat transfer rate can be considered as a flow, and the combination of thermal conductivity, thickness of material and area as a resistance to this flow. Considering the temperature as a potential or driving function of the heat flow, the Fourier law can be written as:

$$\text{Heat Flow} = \frac{\text{Thermal Potential Difference}}{\text{Thermal Resistance}} \quad (3)$$

In other words, defining resistance as the ratio of driving potential to the corresponding transfer rate, the thermal resistance for conduction can be expressed as:

$$R_{cond} = \frac{T_1 - T_2}{q} = \frac{L}{kA} \quad (4)$$

From the above equations it can be observed that decreasing the thickness or increasing the cross-sectional area or thermal conductivity of an object will decrease its thermal resistance and increase its heat transfer rate. Table 1 lists the thermal conductivities of various materials.

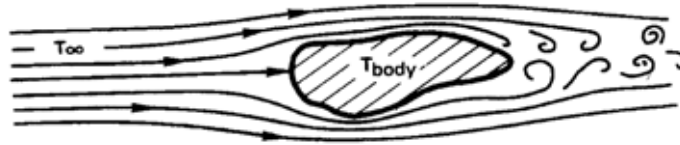
**Table 1:** Thermal Conductivity of Various Materials at 0°C

Material	Thermal Conductivity k	
	W/m °C	Btu/h ft °F
<b>Metals:</b>		
Silver (pure)	410	237
Copper (pure)	385	223
Aluminum (pure)	202	117
Nickel (pure)	93	54
Iron (pure)	73	42
Carbon Steel, 1% C	43	25
Lead (pure)	35	20.3
Chrome-nickel steel (18% Cr, 8% Ni)	16.3	9.4
<b>Nonmetallic Solids:</b>		
Quartz, parallel to axis	41.6	24
Magnesite	4.15	2.4
Marble	2.08-2.94	1.2-1.7
Sandstone	1.83	1.06
Glass, window	0.78	0.45
Maple or Oak	0.17	0.096
Sawdust	0.059	0.034
Glass wool	0.038	0.022
<b>Liquids:</b>		
Mercury	8.21	4.74
Water	0.556	0.327
Ammonia	0.054	0.312
Lubricating oil, SAE 50	0.147	0.085
Freon 12, CCl <sub>2</sub> F <sub>2</sub>	0.073	0.042
<b>Gases:</b>		
Hydrogen	0.175	0.101
Helium	0.141	0.081
Air	0.024	0.0139
Water vapor (saturated)	0.0206	0.0119
Carbon dioxide	0.0146	0.00844

Holman, J. P. (1990) Heat Transfer. 7<sup>th</sup> ed. McGraw-Hill

## 2. Convection

The convection heat transfer mode is comprised of two mechanisms: random molecular motion (diffusion), and energy transferred by bulk or macroscopic motion of the fluid. The convection heat transfer occurs when a cool fluid flows past the warm body as depicted in Figure 2. The fluid adjacent to the body forms a thin slowed down region called the boundary layer. The velocity of the fluid at the surface of the body is reduced to zero due to the viscous action. Therefore, at this point, the heat is transferred only by conduction. The moving fluid then carries the heat away. The temperature gradient at the surface of the body depends on the rate at which the fluid carries the heat away.



**Figure 2:** Convective Cooling of a Heated Body (Lienhard IV, John H. and Lienhard V, John H. (2002) Heat Transfer Textbook)

Newton's law of cooling expresses the overall effect of convection:

$$q = hA(T_w - T_\infty) \quad (5)$$

where,

A – surface area

$T_w$  – wall (surface) temperature

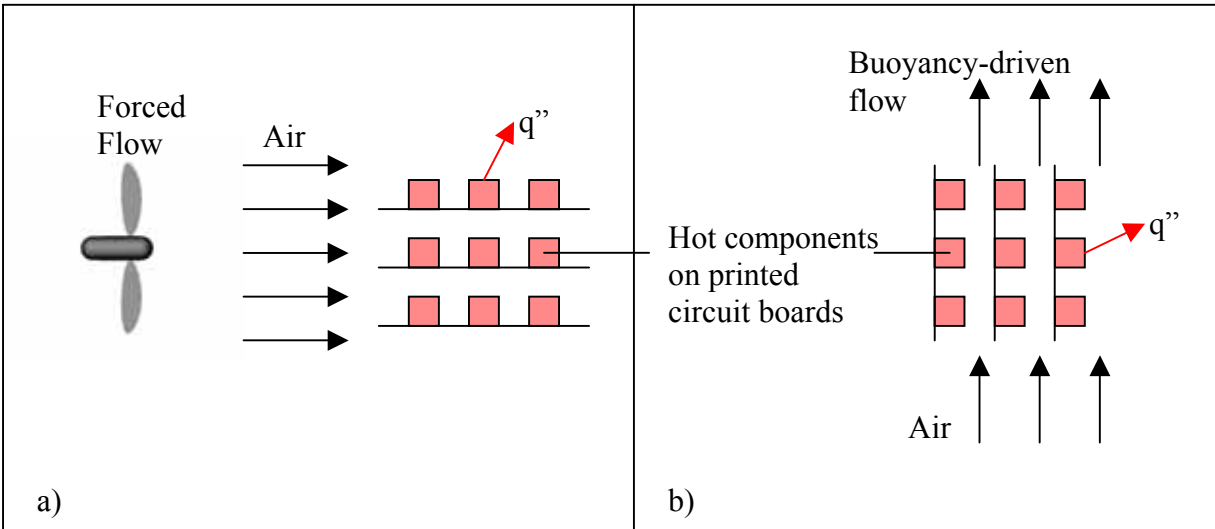
$T_\infty$  - fluid temperature

h- convection heat transfer coefficient ( $\text{W}/\text{m}^2\text{K}$ )

As in the case of conduction, thermal resistance is also associated with the convection heat transfer and can be expressed as:

$$R_{conv} = \frac{T_w - T_\infty}{q} = \frac{1}{hA} \quad (6)$$

The convection heat transfer may be classified according to the nature of fluid flow. Forced convection occurs when the flow is caused by external means, such as a fan, a pump and similar. An example is a fan which provides forced convection air cooling of hot electrical components on a printed circuit board as depicted in Figure 3 a).



**Figure 3:** Convection Heat Transfer Process: a) Forced Convection b) Natural Convection

In contrast, for the natural (or free) convection, the flow is induced by buoyancy forces, which arise from density differences caused by temperature variations in the fluid. An example is the free convection heat transfer that occurs from hot components on a vertical array of printed circuit boards in still air as depicted in Figure 3 b). In such situation, air that makes contact with the hot components experiences an increase in temperature and therefore reduction in density. Since the warm air is now lighter than surrounding air, buoyancy forces induce a vertical motion and the hot air rising from the boards is replaced by the inflow of air at room temperature. Boiling and condensation are also grouped under general subject of convection heat transfer. The approximate values of convection heat transfer coefficients are listed in Table 2.

**Table 2:** Approximate Values of Convection Heat-Transfer Coefficients

Mode	$h$ W/m <sup>2</sup> °C	Btu/h ft <sup>2</sup> °F
<b>Free convection, <math>\Delta T = 30^\circ\text{C}</math></b>		
Vertical plate 0.3 m (1ft) high in air	4.5	0.79
Horizontal cylinder, 5 cm diameter, in air	6.5	1.14
Horizontal cylinder, 2 cm diameter, in water	890	157
<b>Forced Convection</b>		
Airflow at 2 m/s over 0.2 m square plate	12	2.1
Airflow at 35 m/s over 0.75 m square plate	75	13.2
Air at 2 atm flowing in 2.5 cm diameter tube at 10 m/s	65	11.4
Water at 0.5 kg/s flowing in 2.5 cm diameter tube	3500	616
Airflow across 5 cm diameter cylinder with velocity of 50 m/s	180	32
<b>Boiling Water</b>		
In a pool or container	2,500-35,000	440-6,200
Flowing in a tube	5,000-100,000	880-17,600
<b>Condensation of water vapor, 1 atm</b>		
Vertical surfaces	4,000-11,300	700-2,000
Outside horizontal tube	9,500-25,000	1,700-4,400

Holman, J. P. (1990) Heat Transfer. 7<sup>th</sup> ed. McGraw-Hill

### 3. Radiation

All bodies emit energy by means of electromagnetic radiation. The electromagnetic radiation propagated as a result of a temperature difference is called thermal radiation. An ideal thermal radiator or a blackbody, will emit energy at a rate proportional to the forth power of its absolute temperature and its surface area. Thus,

$$q_{emitted} = \sigma A T^4 \quad (7)$$

where,

$\sigma$  - proportionality constant (Stefan – Boltzmann constant)  $\sigma = 5.669 \times 10^{-8} \text{ W/m}^2\text{K}^4$

Equation (7) is called the Stefan-Boltzmann law of thermal radiation and it applies only to the blackbodies. For surfaces not behaving as a blackbody a factor known as emissivity  $\epsilon$ , which relates the radiation of a surface to that of an ideal black surface, is introduced. In addition, it must be taken into account that not all radiation leaving one

surface will reach the other surface. Therefore, for two bodies at temperatures  $T_1$  and  $T_2$ , the radiation heat exchange can be expressed as:

$$q = F_{\varepsilon} F_G \sigma A (T_1^4 - T_2^4) \quad (8)$$

where,

$F_{\varepsilon}$  - emissivity function

$F_G$  – geometric “view factor” function

Due to the fact that thermal radiation can be extremely complex, we will examine a simple radiation problem where a radiation heat transfer occurs between a surface at temperature  $T_1$  completely enclosed by a much larger surface maintained at temperature  $T_2$ . For such case, the net radiant exchange can be calculated with:

$$q = \varepsilon_1 \sigma A_1 (T_1^4 - T_2^4) \quad (9)$$

where,

$\varepsilon_1$  – emissivity of surface at temperature  $T_1$

$A_1$  – surface area

With values ranging from  $0 \leq \varepsilon \leq 1$ , emissivity provides a measure of how efficiently a surface emits energy relative to a blackbody ( $\varepsilon = 1$ ). The emissivity depends strongly on the surface material and finish and representative values can be found in various heat transfer texts.

## References:

1. Holman, J. P. (1990) Heat Transfer. 7<sup>th</sup> ed. McGraw-Hill
2. Incropera, Frank P. and DeWitt, David P. (1996) Fundamentals of Heat and Mass Transfer. 4<sup>th</sup> ed. Willey
3. Lienhard IV, John H. and Lienhard V, John H. (2002) Heat Transfer Textbook. 3<sup>rd</sup> ed. Lienhard IV, John H. and Lienhard V, John H