Heat Transfer

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Introduction to Heat Transfer

In the thermodynamics, heat transfer is the transfer of thermal energy from a heated body to a colder body. When an object or fluid, is at a different temperature than its surroundings or another body, transfer of thermal energy is also known as heat transfer. Exchange of heat occurs till body and the surroundings reach at the same temperature. According to the second law of thermodynamics, 'Where there is a temperature difference between objects in proximity, heat transfer between them can never be stopped; it can only be slowed down. Energy flow due to temperature difference is called heat; and the study of heat transfer deals with the rate at which such energy is transferred. Heat is thus the energy in transit between systems which occurs by virtue of their temperature difference when they communicate.

Modes of Heat transfer

Heat transfer generally recognizes three distinct modes of heat transmission; conduction, convection and radiation. These three modes are similar in that a temperature differential must exist and the heat exchange is in the direction of decreasing temperature. Each method has its, different physical picture and different controlling laws.

- **CONDUCTION HEAT TRANSFER**

When a temperature gradient exists in a body, experience has shown that there is an energy transfer from the high-temperature region to the low-temperature region. We say that the energy is transferred by conduction and that the heat-transfer rate per unit area is proportional to the normal temperature gradient:

$$\frac{q_x}{A} \sim \frac{\partial T}{\partial x}$$

When the proportionality constant is inserted,

$$q_x = -kA\frac{\partial T}{\partial x} \qquad \textbf{[1-1]}$$

Where q_x is the ***heat-transfer rate*** and $\partial T/\partial x$ is the ***temperature gradient*** in the direction of the heat flow. The positive constant k is called the ***thermal conductivity*** of the material, and the minus sign is inserted so that the second principle of thermodynamics will be satisfied; i.e., heat must flow downhill on the temperature scale, as indicated in the coordinate system of Figure 1-1. Equation (1-1) is called Fourier's law of heat conduction.

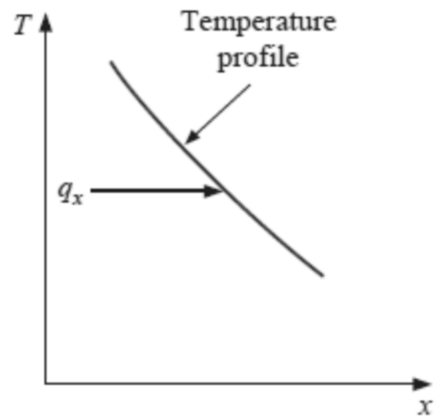


Figure 1-1 | Sketch showing direction of heat flow.

It is important to note that Equation (1-1) is the defining equation for the ***thermal conductivity*** and that ***k*** has the units of watts per meter per Celsius degree in a typical system of units in which the heat flow is expressed in watts.

THERMAL CONDUCTIVITY

We have seen that different materials store heat differently, and we have defined the property specific heat c_p as a measure of a material's ability to store thermal energy. For example, c_p = 4.18 kJ/kg·°C for water and c_p = 0.45 kJ/kg ·°C for iron at room temperature, which indicates that water can store almost 10 times the energy that iron can per unit mass. Likewise, the thermal conductivity k is a measure of a material's ability to conduct heat.

For example , k = 0.608 W/m · °C for water and k = 80.2 W/m ·°C for iron at room temperature, which indicates that iron conducts heat more than 100 times faster than water can. Thus we say that water is a poor heat conductor relative to iron, although water is an excellent medium to store thermal energy. 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. In general, the thermal conductivity is strongly temperature-dependent.

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 (l)	8.54
Glass	0.78
Brick	0.72
Water (l)	0.613
Human skin	0.37
Wood (oak)	0.17
Helium (g)	0.152
Soft rubber	0.13
Glass fiber	0.043
Air (g)	0.026
Urethane, rigid foam	0.026

Thermal Diffusivity

Another material property that appears in the transient heat conduction analysis is the **thermal diffusivity,** which represents how fast heat diffuses through a material and is defined as

$$\alpha = \frac{\text{Heat conducted}}{\text{Heat stored}} = \frac{k}{\rho C_p} \qquad (\text{m}^2/\text{s})$$

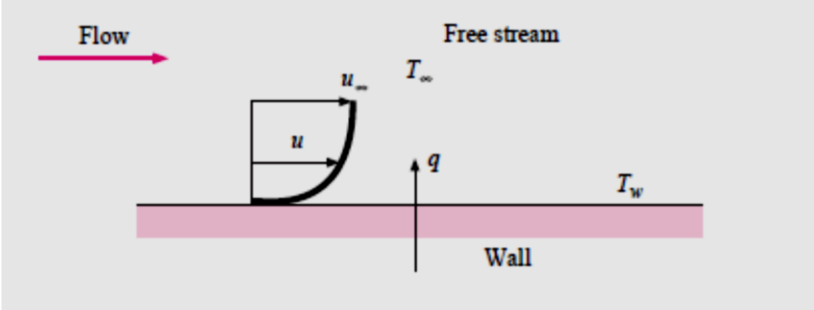
Note that the thermal conductivity k represents how well a material conducts heat, and the heat capacity ρc_p represents how much energy a material stores per unit volume. Therefore, the thermal diffusivity of a material can be viewed as the ratio of the *heat conducted* through the material to the *heat stored* per unit volume. A material that has a high thermal conductivity or a low heat capacity will obviously have a large thermal diffusivity. The larger the thermal diffusivity, the faster the propagation of heat into the medium. A small value of thermal diffusivity means that heat is mostly absorbed by the material and a small amount of heat will be conducted further.

- CONVECTION HEAT TRANSFER

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.* The faster the fluid motion, the greater the convection heat transfer. In the absence of any bulk fluid motion, heat transfer between a solid surface and the adjacent fluid is by pure conduction. The presence of bulk motion of the fluid enhances the heat transfer between the solid surface and the fluid, but it also complicates the determination of heat transfer rates.

Consider the heated plate shown in Figure 1-7. The temperature of the plate is *Tw*, and the temperature of the fluid is *T*∞. The velocity of the flow will appear as shown, being reduced to zero at the plate as a result of viscous action.

Figure 1-7 | Convection heat transfer from a plate.



To express the overall effect of convection, we use Newton's law of cooling:

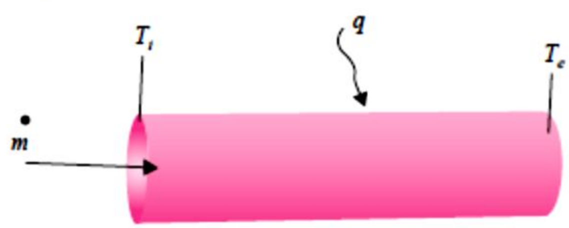
$$q = hA\,(T_w - T_\infty) \qquad \textbf{[1-8]}$$

Here the heat-transfer rate is related to the overall temperature difference between the wall and fluid and the surface area *A*. The quantity *h* is called the *convection heat-transfer* *coefficient*, and Equation (1-8) is the defining equation. An analytical calculation of *h* may be made for some systems. For complex situations it must be determined experimentally. The heat-transfer coefficient is sometimes called the *film conductance* because of its relation to the conduction process in the thin stationary layer of fluid at the wall surface. From Equation (1-8) we note that the units of *h* are in watts per square meter per Celsius degree when the heat flow is in watts.

Convection Energy Balance on a Flow Channel

The energy transfer expressed by Equation (1-8) is used for evaluating the convection loss for flow over an external surface. Of equal importance is the convection gain or loss resulting from a fluid flowing inside a channel or tube as shown in Figure 1-8. In this case, the heated wall at *Tw* loses heat to the cooler fluid, which consequently rises in temperature as it flows

Figure 1-8 | **Convection in a channel.**



from inlet conditions at T_i to exit conditions at T_e. Using the symbol *i* to designate enthalpy (to avoid confusion with *h*, the convection coefficient), the energy balance on the fluid is

$$q = \dot{m}(i_e - i_i)$$

Where $\dot{m}$ is the fluid mass flow rate. For many single-phase liquids and gases operating over reasonable temperature ranges $\Delta i = c_p \Delta T$ and we have

$$q = \dot{m} c_p (T_e - T_i)$$

Which may be equated to a convection relation like Equation (1-8)

$$q = \dot{m} c_p (T_e - T_i) = hA(T_{w,\,\text{avg}} - T_{\text{fluid, avg}}) \qquad \textbf{[1-8}a\textbf{]}$$

In this case, the fluid temperatures T_e, T_i, and *T* fluid are called *bulk* or *energy average* temperatures. *A* is the surface area of the flow channel in contact with the fluid.

We must be careful to distinguish between the surface area for convection that is employed in convection Equation (1-8) and the cross-sectional area that is used to calculate the flow rate from

$$\dot{m} = \rho u_{\text{mean}} A_c$$

where $A_c = \pi d^2/4$ for flow in a circular tube. The surface area for convection in this case would be πdL, where L is the tube length. The surface area for convection is always the area of the heated surface in contact with the fluid.

- RADIATION HEAT TRANSFER

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 heat transfer studies we are interested in *thermal radiation,* which is the form of radiation emitted by bodies because of their temperature. It differs from other forms of electromagnetic radiation such as x-rays, gamma rays, microwaves, radio waves, and television waves that are not related to temperature. All bodies at a temperature above absolute zero emit thermal radiation.

Thermodynamic considerations show∗ that an ideal thermal radiator, or blackbody, will emit energy at a rate proportional to the fourth power of the absolute temperature of the body and directly proportional to its surface area. Thus

$$q_{\text{emitted}} = \sigma A T^4 \qquad \textbf{[1-9]}$$

where σ is the proportionality constant and is called the Stefan-Boltzmann constant with the value of $\mathbf{5.669 \times 10^{-8}\ W/m^2 .K^4}$. Equation (1-9) is called the Stefan-Boltzmann law of thermal radiation, and it applies only to blackbodies. The net radiant *exchange* between two surfaces will be proportional to the difference in absolute temperatures to the fourth power; i.e.

$$\frac{q_{\text{net exchange}}}{A} \propto \sigma(T_1^4 - T_2^4) \qquad \textbf{[1-10]}$$

We have mentioned that a blackbody is a body that radiates energy according to the T^4 law. We call such a body *black* because black surfaces, such as a piece of metal covered with carbon black, approximate this type of behavior. Other types of surfaces, such as a glossy painted surface or a polished metal plate, do not radiate as much energy as the blackbody; however, the total radiation emitted by these bodies still generally follows the T^4 proportionality.

To take account of the "gray" nature of such surfaces we introduce another factor into Equation (1-9), called the *emissivity* ε, which relates the radiation of the "gray" surface to that of an ideal black surface. In addition, we must take into account the fact that not all the radiation leaving one surface will reach the other surface since electromagnetic radiation travels in straight lines and some will be lost to the surroundings. We therefore introduce two new factors in Equation (1-9) to take into account both situations, so that

$$q = F_\epsilon F_G \sigma A \,(T_1^4 - T_2^4) \qquad \textbf{[1-11]}$$

where F_ε is the emissivity function, and F_G is the geometric "view factor" function. A simple radiation problem is encountered when we have a heat-transfer surface at temperature T_1 completely enclosed by a much larger surface maintained at T_2. The net radiant exchange in this case can be calculated with

$$q = \epsilon_1 \sigma A_1 \,(T_1^4 - T_2^4) \qquad \textbf{[1-12]}$$

- ***Temperature conversions are performed with the familiar formulas***

$$
\begin{aligned}
^\circ\mathrm{F} &= \tfrac{9}{5}{}^\circ\mathrm{C} + 32 \\
^\circ\mathrm{R} &= {}^\circ\mathrm{F} + 459.69 \\
\mathrm{K} &= {}^\circ\mathrm{C} + 273.16 \\
^\circ\mathrm{R} &= \tfrac{9}{5}\mathrm{K}
\end{aligned}
$$

In SI system, the fundamental units are meter, newton, kilogram mass, second, and degree Celsius; a "thermal" energy unit is not used; i.e., the joule (newton-meter) becomes the energy unit used throughout. The watt (joules per second) is the unit of power in this system. In the SI system, the standard units for thermal conductivity would become ***k*** in **W/m·◦C** , and the convection heat-transfer coefficient would be expressed as ***h*** in **W/m².◦C**

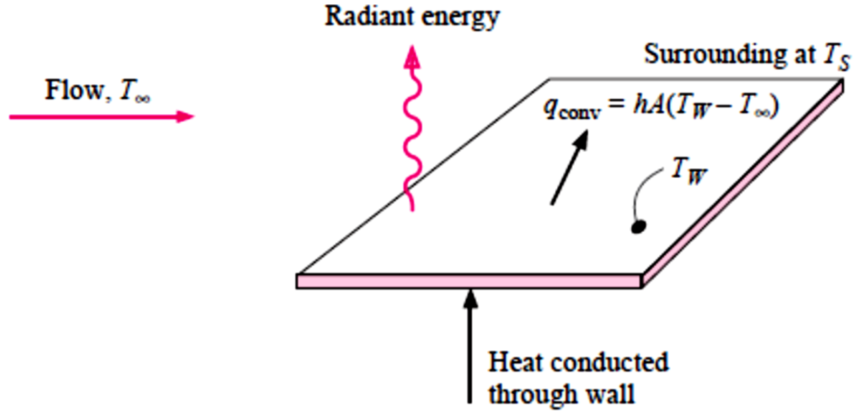
Table 1-4 | Multiplier factors for SI units.

Multiplier	Prefix	Abbreviation
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{2}	hecto	h
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-18}	atto	a

Table 1-5 | SI quantities used in heat transfer.

Quantity	Unit abbreviation
Force	N (newton)
Mass	kg (kilogram mass)
Time	s (second)
Length	m (meter)
Temperature	°C or K
Energy	J (joule)
Power	W (watt)
Thermal conductivity	W/m · °C
Heat-transfer coefficient	$W/m^2 \cdot °C$
Specific heat	J/kg · °C
Heat flux	W/m^2

Combination of conduction, convection, and radiation heat transfer.



$$-kA\left.\frac{dT}{dy}\right]_{\text{wall}} = hA\,(T_w - T_\infty) + F_\epsilon F_G \sigma A\,(T_w^4 - T_s^4)$$