

HEAT TRANSFER

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Summary

As the world energy crisis is currently being confronted, extensive efforts are being made for conserving energy and enhancing energy efficiency. In all energy generation and transformation technologies, energy is lost in terms of waste heat. Therefore, heat transfer is the key to combating the energy crisis.

This chapter deals with fundamentals and applications of heat transfer with regard to conductive, convective (single and two-phase), and radiative heat transfer. The state-of-the-art technologies that facilitate heat transfer management are also briefly reviewed.

1. Conductive Heat Transfer

Heat conduction is a fundamental phenomenon describing transfer of thermal energy due to a temperature gradient. The ability to conduct heat can be quantified in terms of thermal conductivity, where higher thermal conductivity implies more efficient heat conduction. This section deals with the origin of heat conduction from both macroscopic and microscopic viewpoints. Further, it briefly discusses some recent developments in altering thermal conductivity.

1.1. Fourier’s Law of Heat Conduction: A Macroscopic Viewpoint

Conduction of heat occurs through vibration or direct collision of nearby atoms and/or molecules under a temperature gradient without any form of mass transfer. This implies that conduction is the major mode of heat transfer in solids while it is nearly negligible in fluids, where the convection is dominant. Heat conduction can be simply expressed using Fourier’s law of heat conduction as follows;

$$q = -k\nabla T \quad (1.1)$$

where q is the heat flux, i.e., heat flow per unit area [W/m^2]; k , the thermal conductivity [$\text{W}/\text{m}\cdot\text{K}$]; and T , the temperature [K]. This equation implies that heat flow is directly proportional to the temperature gradient and thermal conductivity. Thermal conductivity is an intrinsic property that describes the amount of heat that is transferred through a medium under a certain temperature difference. The unit of thermal conductivity [$\text{W}/\text{m}\cdot\text{K}$] denotes the amount of heat conducted per unit length and per unit temperature gradient. From a macroscopic perspective, thermal conductivity is treated as an intrinsic property at a certain temperature where it has a constant value regardless of the feature size. However, with respect to micro/nanoscales, thermal conductivity can be significantly varied with size as it cannot be considered as an intrinsic value when the dimensions are very small. This will be discussed later on in detail.

Eq. (1.1) can be re-expressed by considering geometrical factors. By integrating Eq. (1.1) and multiplying by the area of interest, it is expressed as follows;

$$\dot{Q} = kA \frac{\Delta T}{L} = \frac{\Delta T}{L/kA} = \frac{\Delta T}{R_{th}} \quad (1.2)$$

where A is the cross-sectional area [m^2] and L , the length [m] of a feature where heat flows perpendicular to the surface A . Since this equation shows that the heat flow is proportional to the temperature difference, the equation can be analogously compared with Ohm’s law ($i = V / R$) where electron flow, i.e., current, i , is proportional to the electric potential difference. Accordingly, $R_{th} \equiv L / kA$ can be regarded as “thermal” resistance, analogous to electrical resistance. Moreover, heat conduction can be modeled as a thermal circuit where series/parallel heat flows can be considered. A series heat flow occurs when the heat is flowing through different media stacked perpendicular to the heat flow direction, while parallel heat flow occurs when the media are stacked

along the heat flow direction. This concept is illustrated in Figure 1. Effective thermal resistance can be calculated in exactly the same manner as that for calculating effective electrical resistance; the series resistance is calculated as a sum of individual resistances while the parallel resistance is calculated as an inverse of the sum of individual inverse resistances.

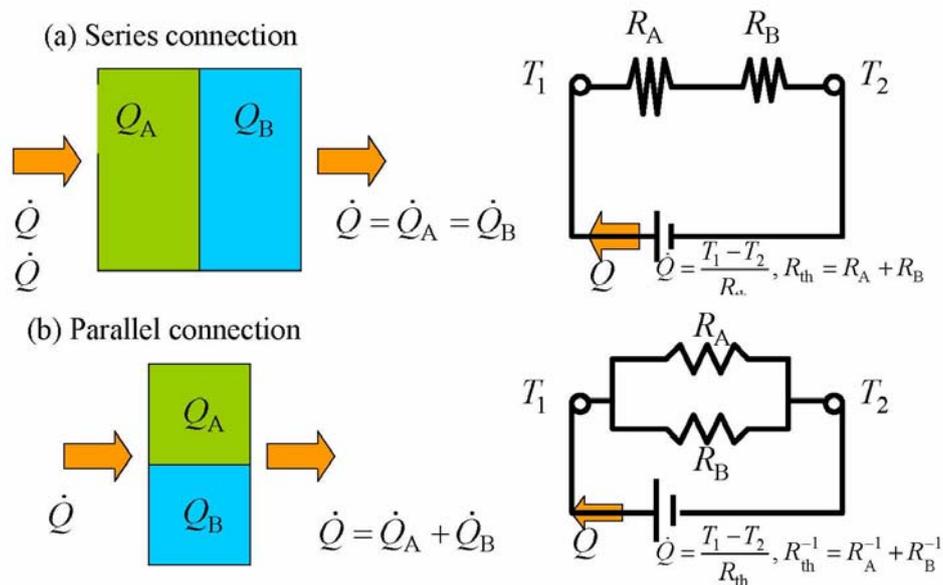


Figure 1. Schematic of thermal circuit concept. (a) Series connection; (b) parallel connection.

1.2. Microscopic Viewpoint of Heat Conduction

In the microscopic viewpoint, heat conduction originates from the individual atomic/molecular interactions, where the direct molecular collisions result in heat conduction of gases. In solids, heat is transported through the lattice vibrations, i.e., phonons and electrons.

Under the microscopic viewpoint, thermal conductivity is crucial in understanding the fundamental aspects of heat conduction. Next, we will briefly discuss the derivation of the thermal conductivity of gases using simple kinetic theory, in which gas molecules are considered as particles.

1.2.1. Thermal Conductivity of Gases

Before starting, certain assumptions should be made. First, the gas is sufficiently dilute so that the intermolecular interactions can be neglected. Second, intermolecular collisions are elastic and instantaneous.

Third, molecules are so widely far apart that the intermolecular distance is significantly larger than the radius of a molecule. Fourth, each molecule exhibits local thermodynamic equilibrium so that a temperature can be defined within a single molecule. Further, molecular motions are isotropic.

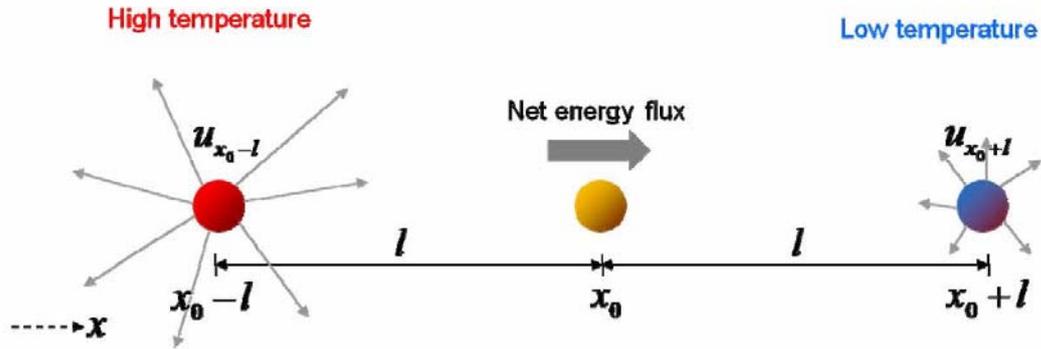


Figure 2. Heat conduction in gas molecules

Let us begin by assuming that there are three gas molecules that are apart by a distance of mean free path, l , which is the average distance traveled by a molecule between consecutive collisions (see Figure 2). The left molecule possesses higher internal energy—higher temperature—compared to the right one. Therefore, the middle molecule will exhibit a net energy flux directed toward the right. This net energy flux can be expressed as follows;

$$q = \frac{1}{2} \bar{v}_x [u(T)_{x_0-l} - u(T)_{x_0+l}] \quad (1.3)$$

where \bar{v}_x is the mean velocity of a molecule in the x direction [m/s] and $u(T)$, the internal energy density of a molecule at temperature T [J/m³]. The 1/2 factor originates from the isotropic molecular motion assumption that only half of the total energy possessed by a gas molecule is transferred to the nearby molecule. By Taylor-expanding the energy density terms and differentiating in temperature, Eq. (1.3) can be rewritten as follows;

$$q = \bar{v}_x l \left(\frac{du}{dT} \right) \left(-\frac{dT}{dx} \right) \quad (1.4)$$

From the isotropic motion assumption, \bar{v}_x is approximately $\frac{1}{3} \bar{v}$, and $\frac{du}{dT}$ is the specific heat. Therefore, Eq. (1.4) can be rearranged as follows;

$$q = \frac{1}{3} C_v \bar{v} l \left(-\frac{dT}{dx} \right) \quad (1.5)$$

This is Fourier's law of conduction, i.e., Eq. (1.1), where the thermal conductivity is

$$k = \frac{1}{3} C_v \bar{v} l \quad (1.6)$$

The above equation is the simple kinetic theory of heat conduction in gases where thermal conductivity is a product of specific heat, molecular speed, and mean free path. From this equation, the physical concept of heat conduction can be easily understood. A heat-conducting carrier can be considered suitable in the following three aspects. First, a heat carrier should carry a large amount of heat, i.e., a large specific heat. Second, a heat carrier should move fast, i.e., possess high molecular speed. Third, the number of molecular collisions that can hinder the heat transferring action should be minimal, i.e., the heat carrier should have a large mean free path.

These three features are keys to heat conduction, as thermal conductivity can be actively manipulated by altering the specific heat, molecular speed, and/or mean free path. These features are widely studied in solids, where the fundamental concept of heat conduction is very similar to that of a gas. This will be discussed later in detail.

1.2.2. Heat Conduction in Solids

Unlike gases, where heat is conducted through direct molecular collisions, solids conduct heat through two individual heat carriers—phonons and electrons. Phonons, quantized packets of lattice vibrations, are fundamental units for heat carrying atoms. Since atoms in a solid are strongly bonded, they cannot travel freely, as they can do in gases. Therefore, solids conduct heat through atomic vibrations. By treating the phonons as particles, we can also derive the thermal conductivity of solids using the Boltzmann transport equation. For the derivation of the complete equation, one may refer to other textbooks (Tien et al., 1998). The phonon thermal conductivity of solids is as follows;

$$k_{\text{ph}} = \frac{1}{3} \int_{\omega} C_v(\omega) \cdot v(\omega) \cdot l(\omega) d\omega \quad (1.7)$$

where C_v is the specific heat [$\text{J}/\text{m}^3 \cdot \text{K}$]; v , the phonon velocity [m/s]; and l , the phonon mean free path [m]. This equation is very similar to Eq. (1.6), where the thermal conductivities of gases and solids share the same concept.

However, since phonons are the sum of lattice vibrations, they are characterized by their vibration frequencies, or wavelengths. Each phonon has a unique wavelength, which is mostly determined by the strength of the atomic bond. The distribution of phonon wavelengths in the lattice space (to be exact, reciprocal lattice space) is called the phonon dispersion relation. This relationship shows how the phonons are dispersed in every lattice direction of a solid. Further, it directly shows the phonon velocity, given by the slope of the phonon dispersion relation. The phonon dispersion relation can be calculated by treating the lattice as a spring-mass system.

Like photons, phonons are also governed by Wien's displacement law. This law states that the wavelength of dominantly populated phonons is linearly proportional to the inverse of temperature. For instance, short-wavelength phonons are mostly populated when the temperature is increased. This leads to different phonon scattering mechanisms at varying temperatures.

Phonon scattering is a term describing reflection, refraction, and diffraction of phonons under certain circumstances. Since phonons are treated as particles, they can also be scattered under various circumstances. Phonon scattering may occur because of defects inside solids, such as vacancies, voids, and/or dopants. This is called defect scattering. Phonons may also be scattered at a physical interface or a boundary. This is referred to as boundary scattering. Further, a phonon may scatter another individual phonon, a phenomenon referred to as phonon–phonon (Umklapp) scattering. All these scattering processes occur when the phonon wavelength exhibits the same length scale as the feature size of the scattered object. For instance, at low temperatures, the significant phonon scattering mechanism is boundary scattering since dominant phonons have large wavelengths. By increasing the temperature, few nanometer-sized defects may be introduced as scatterers. At high temperature, since most phonons have short wavelengths, they tend not to be scattered by the large-sized defects or boundaries but by each other.

The abovementioned three scattering processes may occur simultaneously but with varying degrees. The effective magnitude of phonon scattering can be characterized by the effective phonon mean free path. The mean free path is governed by Matthiessen's rule, which states that the smallest one dominates the entire scattering process. The effective mean free path based on Matthiessen's rule can be expressed as follows;

$$l_{\text{eff}}^{-1} = l_{\text{boundary}}^{-1} + l_{\text{defect}}^{-1} + l_{\text{ph-ph}}^{-1} \quad (1.8)$$

where l_{boundary} is the feature size of a boundary; l_{defect} , the feature size of a defect; and $l_{\text{ph-ph}}$, the phonon mean free path. Therefore, with Eq. (1.8), one can identify the major phonon scattering process at a given condition. For instance, l_{boundary} may dominate the overall phonon scattering in typical nanoscale systems such as thin films or nanowires. Otherwise, the phonon thermal conductivity can be lowered by introducing a large artificial defect.

Free electrons, which carry electric charges, are also important heat carriers for heat conduction in solids. For insulators and degenerate semiconductors, phonons are the major heat carriers for heat conduction. However, for metals or heavily doped semiconductors, electrons are comparable, or even dominant, heat carriers.

Consequently, the thermal conductivity of a solid is comprised of phonon thermal conductivity and electron thermal conductivity. Generally, the electronic thermal conductivity is linearly related to the electrical conductivity (inverse of electrical resistivity). This fact, which is the so-called Wiedemann-Franz law, is valid for most metals and semiconductors when determining the electronic thermal conductivity. The Wiedemann-Franz law is as follows;

$$k_e = \frac{\pi^2}{3} \left(\frac{k_B}{q} \right)^2 \cdot \sigma \cdot T \quad (1.9)$$

where k_B is the Boltzmann constant [1.38×10^{-23} J/K]; q , the elementary charge [1.6×10^{-19} C]; and σ , the electrical conductivity [$1/\Omega \cdot m$]. From this equation, one may easily capture the origin of the high thermal conductivity of metals, which is mainly due to the large number of free electrons. The phonon and electron thermal conductivities of materials with respect to varying carrier concentration are depicted in Figure 3 where the phonon thermal conductivity is invariant to carrier concentration whereas the electron thermal conductivity increases with carrier concentration.

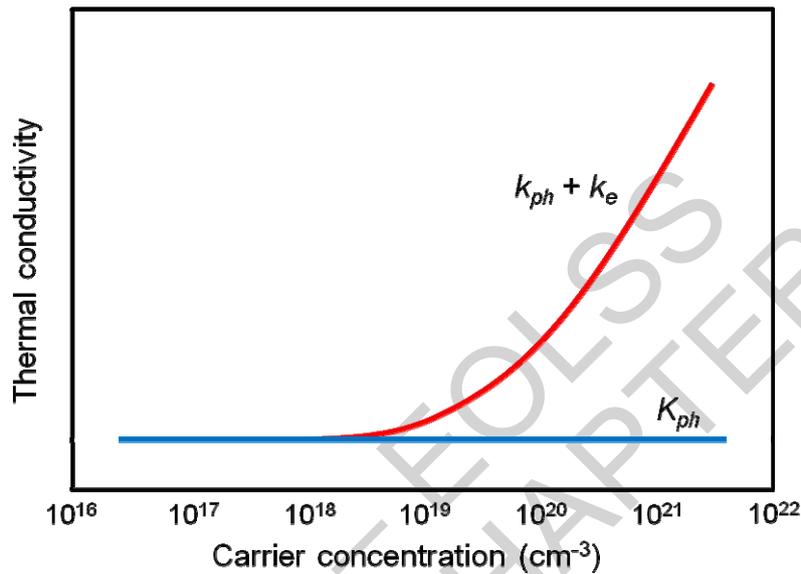


Figure 3. Thermal conductivity vs. carrier concentration. Blue line indicates phonon thermal conductivity while red curve indicates sum of electron thermal conductivity and phonon thermal conductivity.

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