3

Heat Transfer

Heat transfer is the science of study of heat transfer laws, mainly the law of heat transfer caused by temperature difference.

Heat transfer is formed as a discipline in the 19th century. Estimating the temperature of a mathematical expression in a red-hot iron bar, British scientist Newton presented Newton's law of cooling in terms of thermal convection in 1701. However, it did not reveal the mechanism of convective heat transfer.

Real development of convective heat transfer is in the late 19th century. In 1904, German physicist Prandtl presented the boundary layer theory. In 1915, Nusselt presented the dimensionless analysis. From the theoretical and experimental understanding correctly and quantitative research laid the foundation for convective heat transfer. In 1929, Schmidt pointed out the resemblance of mass transfer and heat transfer.

In terms of thermal conductivity, thermal conductivity of the flat wall that the French physicist Biot obtained in 1804 was the first expression of the law of heat conduction. Later, in France using mathematical Fourier method, more accurate to describe thermal conductivity, as a differential form became known as Fourier's Law.

Theoretical aspects of thermal radiation is more complex. In 1860, Kirchhoff by analog absolute blackbody through artificial cavities, demonstrated that at the same temperature blackbody radiation was the largest, and noted that the emissivity of the object with the same absorption rate of the object at a same temperature, being called Kirchhoff's laws.

In 1878, Stefan found the fact that the radiation rate is proportional to the absolute temperature of the fourth power. In 1884, Boltzmann demonstrated it in theory, known as the Stefan-Boltzmann law, commonly known as the fourth power of laws. In 1900, Planck studied the cavity blackbody radiation, and obtained the heat radiation law. This law not only describes the relationship between the temperature and the frequencies of blackbody radiation, but also demonstrates the displacement law of Wien about the blackbody energy distribution.

3.1 Heat Transfer Terminology

After briefly reviewing the history, we first introduce some terms frequently used in the field of heat transfer.

As long as there will be a temperature difference, there will be heat transfer. Heat transfers in three ways, namely, heat conduction, convection and radiation[42].

1. Heat Conduction

Need not occur relative movement between the parts of the object, or direct contact with different objects, the heat depending on the thermal motion of molecules, atoms and free electrons and other microscopic particles arising from the transfer is referred to thermal conductivity.

Conduction involves the transfer of heat by the interactions of atoms or molecules of a material through which the heat is being transferred.

2. Convection

Relative displacement occurs between the portions of the fluid. Heat transfer happens due to the mixing of hot and cold fluids and move on each other. Convection is a process that uniforms the temperature between hotter and cooler parts of liquid or gas, with the way of flow to make temperature uniform. Convection is a unique way of liquids and gases heat transfer. The convection of gas usually stronger than that of liquid significantly. Convection can be divided into natural convection and forced convection. Natural convection is naturally occurs due to the uneven temperature caused. Forced convection is due to a pump to drive fluid forced convection. Increase the flow velocity of the fluid can accelerate convective heat transfer.

Convection involves the transfer of heat by the mixing and motion of macroscopic portions of a fluid.

3. Thermal Radiation

Due to his or her own body temperature and having an emission energy outwardly ability, in this way is called thermal radiation heat transfer. Thermal radiation is a heat transfer way different with heat conduction and convection. It does not rely on a medium to transfer heat, but directly from one system to another system. Thermal radiation emitting electromagnetic radiation in the form of energy, the higher the temperature, the stronger the radiation. The wavelength distribution of the radiation also varies with temperature, as the temperature is low, mainly in the invisible infrared light radiation; while at a higher temperature 500℃, it will emit visible light or ultraviolet light. Thermal radiation is the main form of long-distance heat transfer, such as the sun's heat is in the form of heat radiation through space and then passed to the Earth.

Radiation, or radiant heat transfer, involves the transfer of heat by electromagnetic radiation that arises due to the temperature of a body.

There are some other terminologies should be introduced in heat transfer.

4. Heat Transfer Rate

The heat transferred per unit time is defined as heat transfer rate. A common unit for heat transfer rate is J/s or W. Because the power and the heat transfer rate have the same dimension, sometimes it is called heat power. Its physical symbol is P_Q.

5. Heat Flux

Sometimes it is important to determine the heat transfer rate per unit area, or heat flux. Units for heat flux are W/m^2. The heat flux can be determined by dividing the heat transfer rate by the area through which the heat is being transferred.

6. Thermal conductivity

The heat transfer characteristics of a solid material are measured by a property called the thermal conductivity (k) measured in W/(m·℃). It is a measure of a substance's ability to transfer heat through a solid by conduction. The thermal conductivity of most liquids and solids varies with temperature. For vapors, it depends upon pressure.

Thermal conductivity is a property of material. Different material has different thermal conductivity usually. It also depends on the structure, density, moisture, temperature, pressure, etc.

Thermal conductivity is generally referred to only the presence of thermally conductive heat transfer. When there are other forms of heat transfer, such as heat radiation transfer or convection, the conductivity is often referred to as the apparent thermal conductivity or effective thermal conductivity, in addition, the thermal conductivity for the purposes of homogeneous material. In engineering practice, there is also porous, multi-layer, multi-structure or anisotropic material, the thermal conductivity of these materials is actually an integrated thermal conductivity performance, also known as the average thermal conductivity.

Thermal conductivity is a property of the material itself, the thermal conductivity of different materials varies. The thermal conductivity of the material relates with its structure, density, humidity, temperature, pressure and other factors. Low moisture content of the same material, at lower temperatures, the thermal conductivity is small. In general, the thermal conductivity of solid is larger than that of liquid, and that of liquid larger than that of gas. This is largely due to the different forces between molecules of different state.

Usually low thermal conductivity material is called insulation material. According to the Chinese national standard, when the average temperature does not exceed 350℃, the material with the thermal conductivity of no more than 0.12W/(m·K) is called insulation material and the material with the thermal conductivity of 0.05W/(m·K) or less material called effective thermal insulation materials.

High thermal conductivity of the material has excellent thermal conductivity. In the same heat flux density and thickness, the temperature difference of the surface sidewall temperature between the cold and the hot decreases if the thermal conductivity increases. For example, when no furring, due to the high thermal conductivity of material of the boiler heat transfer tubes, the wall temperature difference is small. However, when the heat transfer surface furring due to scale, the thermal conductivity of scale is very small, the temperature difference increases with the thickness of scale, thereby the temperature of the wall is raised rapidly. When the thickness of the scale is quite large (about 1-3mm), the tube wall temperature will exceed the allowable value, resulting in tube overheating damage.

Typically, the thermal conductivity of a material can be obtained theoretically and experimentally in two ways. Now the thermal conductivity values of engineering calculations are measured out by specialized test. In theory, starting from the material microstructure, quantum mechanics and statistical mechanics, based on the material by heat conduction mechanism of the establishing thermal physical model, through a complex mathematical analysis and calculation of the thermal conductivity can be obtained. However, due to the applicability of the theoretical approach to certain restrictions, with the rapid increase in new materials, it is still yet to find a date and accurate enough for a wide range of theoretical equation, so the thermal conductivity experimental test method is still the main source of the data of the thermal conductivity of material.

In Chapter 8, materials science, we will detail the internal lattice structure of the solid. According to materials science and the solid by free electrons of atoms, atoms are bound in the crystal lattice of regularly arranged. Accordingly, the heat transfer is achieved by the two effects: the migration of free electrons and lattice vibrational waves. When regarded as quasi-particle phenomenon, lattice vibrations are called phonons. For pure metals, the electron contributes to the thermal conductivity of large; and for the non-conductor, the phonon contribution plays a major role. In all solids, the metal is the best conductor of heat. The thermal conductivity of pure metals generally decreases with increasing temperature. The effects of purity of the metal on the thermal conductivity is large, such as carbon-containing 1% of ordinary carbon steel with the thermal conductivity of 45W/(m·K), the thermal conductivity of stainless steel with trace elements added fall down to 16W/(m·K).

Liquid can be divided into two types of liquid: metal liquid and non-metallic liquid.

The former has high thermal conductivity and lower the latter. Among non-metallic liquids, water, has the maximum thermal conductivity. Besides of water and glycerin, the majority of the thermal conductivity of the liquid decreases slightly with increasing temperature. In general, the thermal conductivity of a solution is lower than the thermal conductivity of pure liquid.

The thermal conductivity of the gas increases with temperature. Within the normal range of pressure, the thermal conductivity change with pressure is small. Only when the pressure is greater than 200MPa, or a pressure less than about 3kPa, the thermal conductivity increases with pressure. Therefore, engineering calculations can often ignore the impact of the pressure on the gas thermal conductivity. The thermal conductivity of gas is very small, so the thermal detrimental but beneficial for insulation.

7. Log Mean Temperature Difference

In heat exchanger applications, the inlet and outlet temperatures are usually specified based on the fluid in the tubes. The temperature change that takes place across the heat exchanger from the entrance to the exit is not linear. A precise temperature change between two fluids across the heat exchanger is best represented by the log mean temperature difference (LMTD or $\Delta t_{\ln}$), defined in Equation (3-1).

$$\Delta t_{\ln} = \frac{\Delta t_2 - \Delta t_1}{\ln(\Delta t_2 / \Delta t_1)} \tag{3-1}$$

8. Convective Heat Transfer Coefficient

The convective heat transfer coefficient (h), defines, in part, the heat transfer due to convection. The convective heat transfer coefficient is sometimes referred to as a film coefficient. Convective heat transfer coefficient represents the thermal resistance of a relatively stagnant layer of fluid between a heat transfer surface and the fluid medium. Common units used to measure the convective heat transfer coefficient are W/(m^2 · ℃).

9. Overall Heat Transfer Coefficient

In the case of combined heat transfer, it is common practice to relate the total rate of heat transfer, the overall cross-sectional area for heat transfer, and the overall temperature difference using the overall heat transfer coefficient. The overall heat transfer coefficient combines the heat transfer coefficient of the two heat exchanger fluids and the thermal conductivity of the heat exchanger tubes. U_o is specific to the heat exchanger and the fluids that are used in the heat exchanger.

$$P_Q = U_o A_o \Delta t_o \tag{3-2}$$

where, U_o is the overall heat transfer coefficient, W/(m^2 · K); Δt_o is the overall temperature difference, K; A_o is the overall area for heat transfer, m^2.

10. Bulk Temperature

The fluid temperature (T_b), referred to as the bulk temperature, varies according to the details of the situation. For flow adjacent to a hot or cold surface, T_b is the temperature of the fluid that is "far" from the surface, for instance, the center of the flow channel. For boiling or condensation, T_b is equal to the saturation temperature.

3.2 Heat Conduction

Conduction involves the transfer of heat by the interaction between adjacent molecules of a material. Heat transfer by conduction is dependent upon the driving "force" of temperature difference and the resistance to heat transfer. The resistance to heat transfer is dependent upon the nature and dimensions of the heat transfer medium. All heat transfer problems involve the temperature difference, the geometry, and the physical properties of the object being studied.

In problems of conduction heat transfer, the object being studied is usually a solid. Convection problems involve a fluid medium. Problems of radiation heat transfer involve either solid or fluid surfaces, separated by a gas, vapor, or vacuum. There are several ways to correlate the geometry, physical properties, and temperature difference of an object with the rate of heat transfer through the object. In conduction heat transfer, the most common means of correlation is through Fourier's Law of Conduction.

Temperature difference within the system is a necessary condition for heat conduction. Alternatively, that as long as temperature difference exists, heat transfer can occur. However, the temperature difference is not a sufficient condition, because of the temperature difference between objects with vacuum division, there is no heat conduction. In addition to the temperature difference, but also the media is necessary for heat conduction.

The phenomenon that heat from a part of the system to another or from one part of the system spread to another is called heat transfer. Solid heat conduction is the main mode of heat transfer. In the boundary layer of liquid or gas, thermal conduction also exists in the flow and often occurs simultaneously with convection. Heat transfer rate is dependent on the distribution of temperature field inside an object.

In gas, the thermal conductivity is the result of gas molecules collide with each other at irregular thermal motion. The higher the gas temperature, the greater the kinetic energy of molecular motion results in molecules of different energy levels of collision of the heat transferred. In the conductive solid, a substantial number of free electrons in the lattice and heat are transmitted through the interaction of free electrons. In non-conductive solid, heat transfer through the vibration of the lattice structure, i.e. atoms, molecules near the equilibrium position of the vibration. As the mechanism of conduction in liquid is not yet available with unified understanding. A view similar to that of the gas molecules collide with each other, the liquid heat transfer happens. Because the small distance between liquid molecules, the impact force between the molecules is greater than gas molecules. Another view of point is that the reason the thermal fluid similar to non-conductive solid, relies mainly on the elastic wave.

Therefore, heat conduction in essence, is the energy transferring from the high temperature portion of an object to a low temperature portion by the diffusion of thermal motion of interacting molecules in a large number of substances, low temperature process or object passed by a hot object. In solids, the kinetic energy of the vibration of crystal particle is large in high temperature region. While in the low temperature region, the kinetic energy of particle vibration is less. Due to the vibration interaction between particles, the diffusion of heat happens inside a solid from high kinetic energy region to low kinetic energy region. Heat transfer process is a process of energy diffusion in the essence.

In a conductor, due to the presence of a large number of free electrons, constantly making random thermal motion, energy transfer by lattice vibration is relatively small. The free electrons in metal crystals on the heat conduction play a major role. Therefore, the general electrical conductor is also a good conductor of heat. In a liquid, heat transfers as follows: the thermal motion of liquid molecules in areas of high temperature is relatively strong than that of low temperature region. The thermal motion will be gradually transferred from high temperature region to low temperature region causing the heat transfer phenomenon. Due to the small thermal conductivity of fluid, the heat transfer rate is slow. Spacing between gas molecules is relatively large, so the macroscopic heat transfer rely on the random thermal motion diffusion is relatively small.

Reactor design must deal with the various components within the reactor core at steady state and transient heat conduction problem conditions, namely by solving the heat conduction equation to determine the temperature distribution within the various components, to meet the appropriate safety requirements.

Heat conduction inside a reactor core has the following main features:

(1) Heat source, such as the huge heat release rate in core and the uneven spatial distribution;

(2) Reactor thermal properties, such as thermal conductivity varies under conditions of nuclear radiation;

(3) The geometric complexity of reactor internals, the shape and boundary conditions.

Therefore, when addressing an issue within a thermal reactor, reasonable simplification is often proposed under specific circumstances using certain methods and analytical models.

3.2.1 Fourier's Law of Conduction

The law, in its equation form of one dimension, is expressed as:

$$q = k\frac{\mathrm{d}t}{\mathrm{d}x} \tag{3-3}$$

where, q is the heat flux, $\mathrm{W/m^2}$; k is the thermal conductivity, $\mathrm{W/(m \cdot ℃)}$.

3.2.2 Rectangular

The use of Fourier's law of conduction in determining the amount of heat transferred by conduction is demonstrated in the following example.

Example 3-1: 1000W is conducted through a section of insulating material shown in Figure 3-1 that measures $1\mathrm{m}^2$ in cross-sectional area. The thickness is 1cm. and the thermal conductivity is 0.12W/(m · ℃). Compute the temperature difference across the material.

Solution: using Equation (3-3),

$$P_Q = qA = k\frac{\Delta t}{\Delta x}A = 1000\mathrm{W}$$

Solving for $\Delta t = 1000/0.12 \times 0.01 = 83℃$.

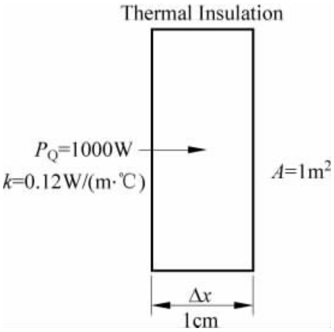

Figure 3-1 Thermal Insulation Problem

3.2.3 Equivalent Resistance

It is possible to compare heat transfer to current flow in electrical circuits. The heat transfer rate may be considered as a current flow and the combination of thermal conductivity, thickness of material, and area as a resistance to this flow. The temperature difference is the potential or driving function for the heat flow, resulting in the Fourier equation being written in a form similar to Ohm's Law of Electrical Circuit Theory. If the thermal resistance term $\Delta x/k$ is written as a resistance term where the resistance is the reciprocal of the thermal conductivity divided by the thickness of the material, the result is the conduction equation being analogous to electrical systems or networks.

Thermal resistance is a reflection of the amount of the comprehensive ability to prevent heat transfer. In heat transfer engineering applications, in order to meet the requirements of the production process, sometimes to enhance heat transfer by reducing the thermal resistance; and sometimes by increasing the resistance to inhibit heat transfer.

When the heat transfers inside a body, the thermal resistance is the resistance of conduction. For the heat flow through the same cross-sectional area of the plate, thermal resistance is $\Delta x/(kA)$. Where Δx is the thickness of plate, A is the cross-sectional area of the plate perpendicular to the direction of heat flow, k is the thermal conductivity of the plate material.

In the convective heat transfer process, the thermal resistance between the fluid and solid wall called convection thermal resistance, $1/(hA)$. Where h is the convective heat transfer coefficient, A is the heat transfer area.

Two objects with different temperature will radiation to each other. If two objects are black-body, and the heat absorbedby the gas between the two objects can be ignored, the radiation resistance is $1/(A_1F_{1\text{-}2})$ or $1/(A_2F_{2\text{-}1})$. Wherein A_1 and A_2 is the surface area of two objects mutually radiation, $F_{1\text{-}2}$ and $F_{2\text{-}1}$ are the radiation angle factors, it will be described in detail later.

As heat flows through the interface of two solid contact with each other, the interface itself will exhibit significant heat resistance. This resistance is called the thermal contact resistance. The main reason of contact resistance is that, the actual area of any good contact of two objects in direct contact is only part of the whole interface, and the rest are gaps. Heat rely on the thermal conduction of the gas within the gap and thermal radiation between the two faces. The heat transfer capability is far less than that of solid material. Because of this contact resistance, there will be a great temperature difference between the interface when heat flows through the interface. It is need to avoid in most engineering aplications. The methods to reduce the contact resistance are: ① Increase the pressure on the contact surface of the two objects, the protruding portion of the object boundary surface between each extrusion, thereby reducing the gap, increase the contact surface. ② Fill jelly grease into the interface between the two objects painted with higher thermal capacity-thermal grease. For example, between the computer's CPU and heat sink often you need to add a layer of thermal grease.

In summary, the thermal resistance of the heat transfer is encountered in the heat flow path, which reflects the size of the heat transfer capability of the medium or between media. Greater the resistance, the smaller the heat transfer capability. Thermal resistance indicates the size of the temperature rise caused by heat flow of 1W, unit ℃/W or K/W. Therefore, thermal power multiplied by the resistance, you can get the temperature difference of the heat transfer path. You can use a simple analogy to understand the significance of thermal resistance. It corresponds to the current strength of the heat transfer, the voltage corresponding to the temperature difference, the thermal resistance equivalent.

The electrical analogy may be used to solve complex problems involving both series and parallel thermal resistances. Figure 3-2 shows the equivalent resistance circuit.

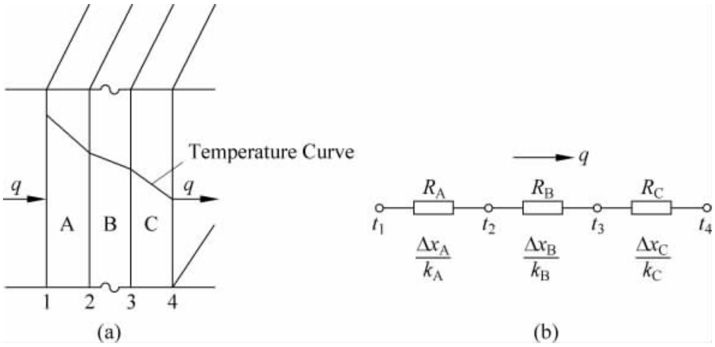

Figure 3-2 Equivalent Resistance

Example 3-2: A composite protective wall is formed of a 1cm copper plate, a 0.1cm layer of asbestos, and a 2 cm layer of fiberglass. The thermal conductivities of the materials are as follows: $k_{Cu} = 400$W/(m · ℃), $k_{asb} = 0.08$W/(m · ℃) and $k_{fib} = 0.04$W/(m · ℃). The overall temperature difference across the wall is 500℃. Calculate the heat transfer rate per unit area (heat flux) through the composite structure.

Solution:

$$q = \Delta t/(R_A + R_B + R_C) = 500/(0.01/400 + 0.001/0.08 + 0.02/0.04) = 976\text{W/m}^2$$

3.2.4 Cylindrical

Heat transfer across a rectangular solid is the most direct application of Fourier's law. Heat transfer across a pipe or heat exchanger tube wall is more complicated to evaluate. Across a cylindrical wall, the surface area of heat transfer is continually increasing or decreasing. Figure 3-3 is a cross-sectional view of a pipe constructed of a homogeneous material.

The surface area (A) for transferring heat through the pipe (neglecting the pipe ends) is directly proportional to the radius (r) of the pipe and the length (L) of the pipe. As the radius increases from the inner wall to the outer wall, the heat transfer area increases.

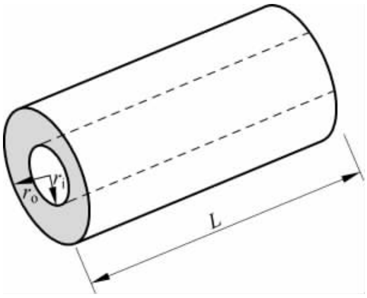

Figure 3-3 Cross-sectional Surface Area of a Cylindrical Pipe

From the discussion above, it is seen that no simple expression for area is accurate. Neither the area of the inner surface nor the area of the outer surface alone can be used in the equation. For a problem involving cylindrical geometry, it is necessary to define a log mean cross-sectional area: