1. Introduction

Energy is defined as the capacity of a substance to do work. It is a property of the substance and it can be transferred by interaction of a system and its surroundings. The student would have encountered these interactions during the study of Thermodynamics. However, Thermodynamics deals with the end states of the processes and provides no information on the physical mechanisms that caused the process to take place. Heat Transfer is an example of such a process. A convenient definition of heat transfer is energy in transition due to temperature differences. Heat transfer extends the Thermodynamic analysis by studying the fundamental processes and modes of heat transfer through the development of relations used to calculate its rate.

The aim of this chapter is to console existing understanding and to familiarise the student with the standard of notation and terminology used in this book. It will also introduce the necessary units.

1.1 Heat Transfer Modes

The different types of heat transfer are usually referred to as 'modes of heat transfer'. There are three of these: conduction, convection and radiation.

- Conduction: This occurs at molecular level when a temperature gradient exists in a medium, which can be solid or fluid. Heat is transferred along that temperature gradient by conduction.

- Convection: Happens in fluids in one of two mechanisms: random molecular motion which is termed diffusion or the bulk motion of a fluid carries energy from place to place. Convection can be either forced through for example pushing the flow along the surface or natural as that which happens due to buoyancy forces.

- Radiation: Occurs where heat energy is transferred by electromagnetic phenomenon, of which the sun is a particularly important source. It happens between surfaces at different temperatures even if there is no medium between them as long as they face each other.

In many practical problems, these three mechanisms combine to generate the total energy flow, but it is convenient to consider them separately at this introductory stage. We need to describe each process symbolically in an equation of reasonably simple form, which will provide the basis for subsequent calculations. We must also identify the properties of materials, and other system characteristics, that influence the transfer of heat.

1.2 System of Units

Before looking at the three distinct modes of transfer, it is appropriate to introduce some terms and units that apply to all of them. It is worth mentioning that we will be using the SI units throughout this book:

- The rate of heat flow will be denoted by the symbol Q. It is measured in Watts (W) and multiples such as (kW) and (MW).

- It is often convenient to specify the flow of energy as the heat flow per unit area which is also known as heat flux. This is denoted by q. Note that, $q = Q / A$ where A is the area through which the heat flows, and that the units of heat flux are (W/m2).

- Naturally, temperatures play a major part in the study of heat transfer. The symbol T will be used for temperature. In SI units, temperature is measured in Kelvin or Celsius: (K) and (°C). Sometimes the symbol t is used for temperature, but this is not appropriate in the context of transient heat transfer, where it is convenient to use that symbol for time. Temperature difference is denoted in Kelvin (K).

The following three subsections describe the above mentioned three modes of heat flow in more detail. Further details of conduction, convection and radiation will be presented in Chapters 2, 3 and 4 respectively. Chapter 5 gives a brief overview of Heat Exchangers theory and application which draws on the work from the previous Chapters.

1.3 Conduction

The conductive transfer is of immediate interest through solid materials. However, conduction within fluids is also important as it is one of the mechanisms by which heat reaches and leaves the surface of a solid. Moreover, the tiny voids within some solid materials contain gases that conduct heat, albeit not very effectively unless they are replaced by liquids, an event which is not uncommon. Provided that a fluid is still or very slowly moving, the following analysis for solids is also applicable to conductive heat flow through a fluid.

Figure 1.1 shows, in schematic form, a process of conductive heat transfer and identifies the key quantities to be considered:

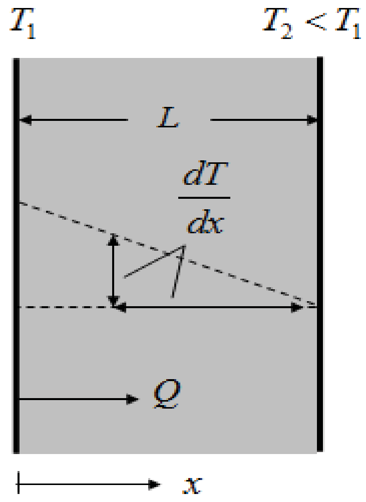


Figure 1-1: One dimensional conduction

Q : the heat flow by conduction in the x-direction (W)

A : the area through which the heat flows, normal to the x-direction (m2)

$\frac{dT}{dx}$: the temperature gradient in the x-direction (K/m)

These quantities are related by Fourier's Law, a model proposed as early as 1822:

$$Q = -k A \frac{dT}{dx} \quad \text{or} \quad q = -k \frac{dT}{dx} \quad (1.1)$$

1

A significant feature of this equation is the negative sign. This recognises that the natural direction for the flow of heat is from high temperature to low temperature, and hence down the temperature gradient.

The additional quantity that appears in this relationship is k, the thermal conductivity (W/m K) of the material through which the heat flows. This is a property of the particular heat-conducting substance and, like other properties, depends on the state of the material, which is usually specified by its temperature and pressure.

The dependence on temperature is of particular importance. Moreover, some materials such as those used in building construction are capable of absorbing water, either in finite pores or at the molecular level, and the moisture content also influences the thermal conductivity. The units of thermal conductivity have been determined from the requirement that Fourier's law must be dimensionally consistent.

Considering the finite slab of material shown in Figure 1.1, we see that for one-dimensional conduction the temperature gradient is:

$$\frac{dT}{dx} = \frac{T_2 - T_1}{L}$$

2

Hence for this situation the transfer law can also be written

$$Q = k A \frac{T_1 - T_2}{L} \quad \text{or} \quad q = k \frac{T_1 - T_2}{L} \quad (1.2)$$

3

$$\alpha = \frac{k}{\rho C} \quad (1.3)$$

4

Table 1.1 gives the values of thermal conductivity of some representative solid materials, for conditions of normal temperature and pressure. Also shown are values of another property characterising the flow of heat through materials, thermal diffusivity, which is related to the conductivity by:

Where ρ is the density in kg/m^3 of the material and C its specific heat capacity in $J/kg\,K$.

The thermal diffusivity indicates the ability of a material to transfer thermal energy relative to its ability to store it. The diffusivity plays an important role in unsteady conduction, which will be considered in Chapter 2.

As was noted above, the value of thermal conductivity varies significantly with temperature, even over the range of climatic conditions found around the world, let alone in the more extreme conditions of cold-storage plants, space flight and combustion. For solids, this is illustrated by the case of mineral wool, for which the thermal conductivity might change from 0.04 to 0.28 W/m K across the range 35 to - 35 °C.

Table 1-1 Thermal conductivity and diffusivity for typical solid materials at room temperature

Material	k W/m K	α mm2/s	Material	k W/m K	α mm2/s
Copper	350	115	Medium concrete block	0.5	0.35
Aluminium	236	85	Dense plaster	0.5	0.40
Mild steel	50	13	Stainless steel	14	4
Polyethylene	0.5	0.15	Nylon, Rubber	0.25	0.10
Face Brick	1.0	0.75	Aerated concrete	0.15	0.40
Glass	0.9	0.60	Wood, Plywood	0.15	0.2
Fireclay brick	1.7	0.7	Wood-wool slab	0.10	0.2
Dense concrete	1.4	0.8	Mineral wool expanded	0.04	1.2
Common brick	0.6	0.45	Expanded polystyrene	0.035	1.0

For gases the thermal conductivities can vary significantly with both pressure and temperature. For liquids, the conductivity is more or less insensitive to pressure. Table 1.2 shows the thermal conductivities for typical gases and liquids at some given conditions.

Table 1-2 Thermal conductivity for typical gases and liquids

Material	k [W/m K]
Gases	
Argon (at 300 K and 1 bar)	0.018
Air (at 300 K and 1 bar)	0.026
Air (at 400 K and 1 bar)	0.034
Hydrogen (at 300 K and 1 bar)	0.180
Freon 12 (at 300 K 1 bar)	0.070
Liquids	
Engine oil (at 20oC)	0.145
Engine oil (at 80oC)	0.138
Water (at 20oC)	0.603
Water (at 80oC)	0.670

Mercury(at 27oC)	8.540

Note the very wide range of conductivities encountered in the materials listed in Tables 1.1 and 1.2. Some part of the variability can be ascribed to the density of the materials, but this is not the whole story (Steel is more dense than aluminium, brick is more dense than water). Metals are excellent conductors of heat as well as electricity, as a consequence of the free electrons within their atomic lattices. Gases are poor conductors, although their conductivity rises with temperature (the molecules then move about more vigorously) and with pressure (there is then a higher density of energy-carrying molecules). Liquids, and notably water, have conductivities of intermediate magnitude, not very different from those for plastics. The low conductivity of many insulating materials can be attributed to the trapping of small pockets of a gas, often air, within a solid material which is itself a rather poor conductor.

Example 1.1

Calculate the heat conducted through a 0.2 m thick industrial furnace wall made of fireclay brick. Measurements made during steady-state operation showed that the wall temperatures inside and outside the furnace are 1500 and 1100 K respectively. The length of the wall is 1.2m and the height is 1m.

Solution

We first need to make an assumption that the heat conduction through the wall is one dimensional. Then we can use Equation 1.2:

$$Q = k\,A\,\frac{T_2 - T_1}{L}$$

The thermal conductivity for fireclay brick obtained from Table 1.1 is 1.7 W/m K

The area of the wall $A = 1.2 \times 1.0 = 1.2 \quad \text{m}^2$

Thus:

$$Q = 1.7\ \text{W/m K} \times 1.2\ \text{m}^2 \times \frac{1500\ \text{K} - 1100\ \text{K}}{0.2\ \text{m}} = 4080\ \text{W}$$

Comment: Note that the direction of heat flow is from the higher temperature inside to the lower temperature outside.

1.4 Convection

Convection heat transfer occurs both due to molecular motion and bulk fluid motion. Convective heat transfer may be categorised into two forms according to the nature of the flow: natural Convection and forced convection.

In natural of ‘free’ convection, the fluid motion is driven by density differences associated with temperature changes generated by heating or cooling. In other words, fluid flow is induced by buoyancy forces. Thus the heat transfer itself generates the flow which conveys energy away from the point at which the transfer occurs.

In forced convection, the fluid motion is driven by some external influence. Examples are the flows of air induced by a fan, by the wind, or by the motion of a vehicle, and the flows of water within heating, cooling, supply and drainage systems. In all of these processes the moving fluid conveys energy, whether by design or inadvertently.

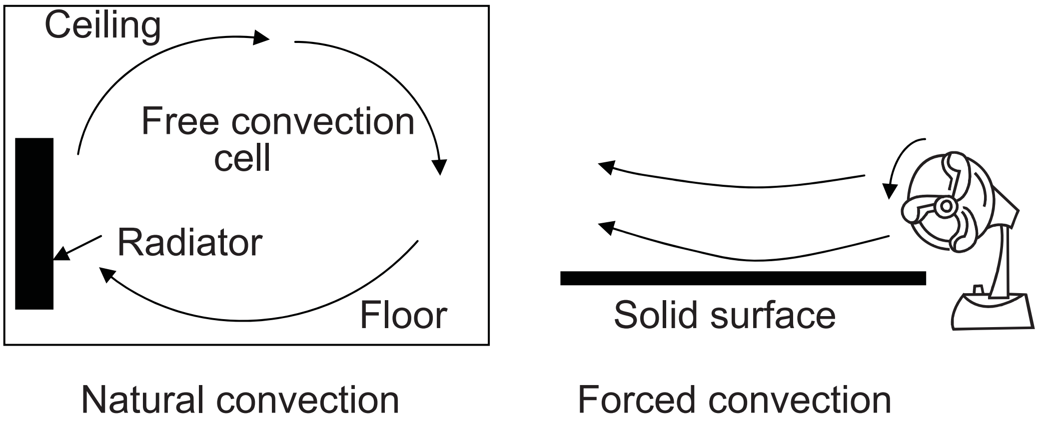


Figure 1-2: Illustration of the process of convective heat transfer

The left of Figure 1.2 illustrates the process of natural convective heat transfer. Heat flows from the 'radiator' to the adjacent air, which then rises, being lighter than the general body of air in the room. This air is replaced by cooler, somewhat denser air drawn along the floor towards the radiator. The rising air flows along the ceiling, to which it can transfer heat, and then back to the lower part of the room to be recirculated through the buoyancy-driven 'cell' of natural convection.

The word 'radiator' has been written above in that way because the heat transfer from such devices is not predominantly through radiation; convection is important as well. In fact, in a typical central heating radiator approximately half the heat transfer is by (free) convection.

The right part of Figure 1.2 illustrates a process of forced convection. Air is forced by a fan carrying with it heat from the wall if the wall temperature is lower or giving heat to the wall if the wall temperature is lower than the air temperature.

If T_1 is the temperature of the surface receiving or giving heat, and T_∞ is the average temperature of the stream of fluid adjacent to the surface, then the convective heat transfer Q is governed by Newton's law:

$$Q = h_c A(T_1 - T_2) \quad \text{or} \quad q = h_c\,(T_1 - T_2)\;5 \qquad (1.3)$$

Another empirical quantity has been introduced to characterise the convective transfer mechanism. This is hc, the convective heat transfer coefficient, which has units [W/m2 K].

This quantity is also known as the convective conductance and as the film coefficient. The term film coefficient arises from a simple, but not entirely unrealistic, picture of the process of convective heat transfer at a surface. Heat is imagined to be conducted through a thin stagnant film of fluid at the surface, and then to be convected away by the moving fluid beyond. Since the fluid right against the wall must actually be at rest, this is a fairly reasonable model, and it explains why convective coefficients often depend quite strongly on the conductivity of the fluid.

Table 1-3 Representative range of convective heat transfer coefficient

Nature of Flow	Fluid	hc [W/m2 K]
Surfaces in buildings	Air	1 - 5
Surfaces outside buildings	Air	5-150
Across tubes	Gas	10 - 60
	Liquid	60 - 600
In tubes	Gas	60 - 600
	Organic liquid	300 - 3000
	Water	600 - 6000
	Liquid metal	6000 - 30000
Natural convection	Gas	0.6 - 600
	Liquid	60 - 3000
Condensing	Liquid film	1000 - 30000
	Liquid drops	30000 - 300000
Boiling	Liquid/vapour	1000 - 10000

The film coefficient is not a property of the fluid, although it does depend on a number of fluid properties: thermal conductivity, density, specific heat and viscosity. This single quantity subsumes a variety of features of the flow, as well as characteristics of the convecting fluid. Obviously, the velocity of the flow past the wall is significant, as is the fundamental nature of the motion, that is to say, whether it is turbulent or laminar. Generally speaking, the convective coefficient increases as the velocity increases.

A great deal of work has been done in measuring and predicting convective heat transfer coefficients. Nevertheless, for all but the simplest situations we must rely upon empirical data, although numerical methods based on computational fluid dynamics (CFD) are becoming increasingly used to compute the heat transfer coefficient for complex situations.

Table 1.3 gives some typical values; the cases considered include many of the situations that arise within buildings and in equipment installed in buildings.

Example 1.2

A refrigerator stands in a room where the air temperature is 20oC. The surface temperature on the outside of the refrigerator is 16oC. The sides are 30 mm thick and have an equivalent thermal conductivity of 0.1 W/m K. The heat transfer coefficient on the outside 9 is 10 W/m2K. Assuming one dimensional conduction through the sides, calculate the net heat flow and the surface temperature on the inside.

Solution

Let $T_{s,i}$ and $T_{s,o}$ be the inside surface and outside surface temperatures, respectively and T_f the fluid temperature outside.

The rate of heat convection per unit area can be calculated from Equation 1.3:

$$q = h(T_{s,o} - T_f)$$

$$q = 10 \times (16 - 20) = -40 \text{ W/m}^2$$

This must equal the heat conducted through the sides. Thus we can use Equation 1.2 to calculate the surface temperature:

$$q = -k \frac{T_{s,o} - T_{s,i}}{L}$$

$$-40 = -0.1 \times \frac{16 - T_{s,i}}{0.03}$$

$$T_{s,i} = 4°C$$

Comment: This example demonstrates the combination of conduction and convection heat transfer relations to establish the desired quantities.

1.5 Radiation

While both conductive and convective transfers involve the flow of energy through a solid or fluid substance, no medium is required to achieve radiative heat transfer. Indeed, electromagnetic radiation travels most efficiently through a vacuum, though it is able to pass quite effectively through many gases, liquids and through some solids, in particular, relatively thin layers of glass and transparent plastics.

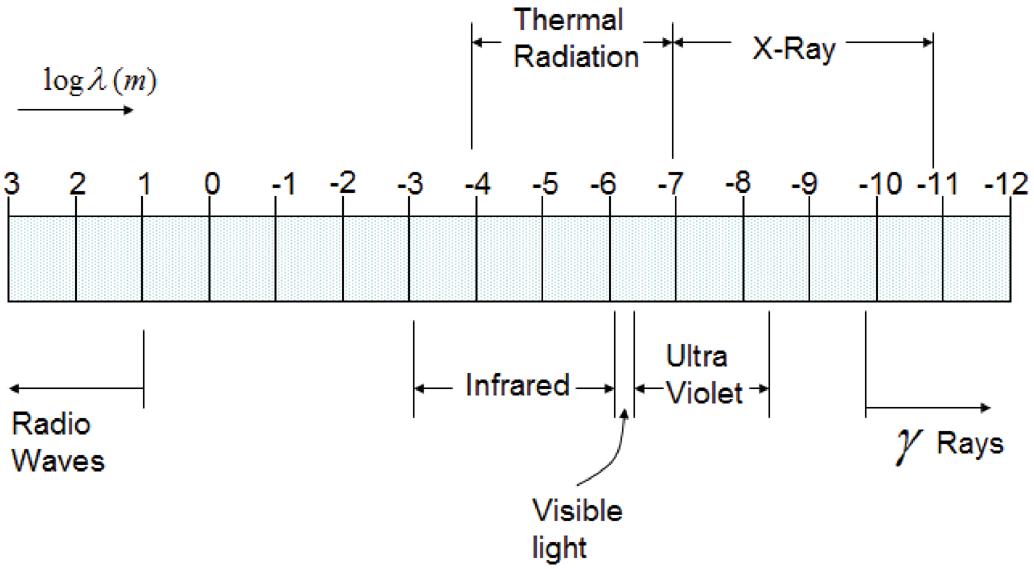


Figure 1-3: Illustration of electromagnetic spectrum

Figure 1.3 indicates the names applied to particular sections of the electromagnetic spectrum where the band of thermal radiation is also shown. This includes:

- the rather narrow band of visible light;
- the wider span of thermal radiation, extending well beyond the visible spectrum.

Our immediate interest is thermal radiation. It is of the same family as visible light and behaves in the same general fashion, being reflected, refracted and absorbed. These phenomena are of particular importance in the calculation of solar gains, the heat inputs to buildings from the sun and radiative heat transfer within combustion chambers.

It is vital to realise that every body, unless at the absolute zero of temperature, both emits and absorbs energy by radiation. In many circumstances the inwards and outwards transfers nearly cancel out, because the body is at about the same temperature as its surroundings. This is your situation as you sit reading these words, continually exchanging energy with the surfaces surrounding you.

In l884 Boltzmann put forward an expression for the net transfer from an idealised body (Black body) with surface area A1 at absolute temperature T1 to surroundings at uniform absolute temperature T2:

$$Q = \sigma A_1 (T_1^4 - T_2^4) \quad \text{or} \quad q = \sigma (T_1^4 - T_2^4)_6 \qquad (1.4)$$

with σ the Stefan-Boltzmann constant, which has the value 5.67 x 10-8 W/m2 K4 and T [K] = T [°C] + 273 is the absolute temperature.

The bodies considered above are idealised, in that they perfectly absorb and emit radiation of all wave-lengths. The situation is also idealised in that each of the bodies that exchange radiation has a uniform surface temperature. A development of Boltzmann's law which allows for deviations from this pattern is

$$Q = \varepsilon \sigma F_{12} A_1 (T_1^4 - T_2^4)_7 \quad (1.5)$$

With ε the emissivity, or emittance, of the surface A1, a dimensionless factor in the range 0 to 1,

F12 is the view factor, or angle factor, giving the fraction of the radiation from A1 that falls on the area A2 at temperature T2, and therefore also in the range 0 to 1.

Another property of the surface is implicit in this relationship: its absorbtivity. This has been taken to be equal to the emissivity. This is not always realistic. For example, a surface receiving short-wave-length radiation from the sun may reject some of that energy by re-radiation in a lower band of wave-lengths, for which the emissivity is different from the absorbtivity for the wave-lengths received.

The case of solar radiation provides an interesting application of this equation. The view factor for the Sun, as seen from the Earth, is very small; despite this, the very high solar temperature (raised to the power 4) ensures that the radiative transfer is substantial. Of course, if two surfaces do not 'see' one another (as, for instance, when the Sun is on the other side of the Earth), the view factor is zero. Table 1.4 shows values of the emissivity of a variety of materials. Once again we find that a wide range of characteristics are available to the designer who seeks to control heat transfers.

The values quoted in the table are averages over a range of radiation wave-lengths. For most materials, considerable variations occur across the spectrum. Indeed, the surfaces used in solar collectors are chosen because they possess this characteristic to a marked degree. The emissivity depends also on temperature, with the consequence that the radiative heat transfer is not exactly proportional to T3.

An ideal emitter and absorber is referred to as a 'black body', while a surface with an emissivity less than unity is referred to as 'grey'. These are somewhat misleading terms, for our interest here is in the infra-red spectrum rather than the visible part. The appearance of a surface to the eye may not tell us much about its heat-absorbing characteristics.

Table 1-4 Representative values of emissivity

Ideal 'black' body	1.00	Aluminium paint	0.5
White paint	0.97	Galvanised steel	0.3
Gloss paint	0.9	Stainless steel	0.15
Brick	0.9	Aluminium foil	0.12
Rusted steel	0.8	Polished copper	0.03
		Perfect mirror	0

Although it depends upon a difference in temperature, Boltzmann's Law (Equations 1.4, 1.5) does not have the precise form of the laws for conductive and convective transfers. Nevertheless, we can make the radiation law look like the others. We introduce a radiative heat transfer coefficient or radiative conductance through

$$Q = h_r A_1 (T_1 - T_2) \quad 8 \quad (1.6)$$

Comparison with the developed form of the Boltzmann Equation (1.5), plus a little algebra, gives

$$h_r = \frac{Q}{A_1 (T_1 - T_2)} = \varepsilon \sigma F_{12} (T_1 + T_2)(T_1^2 + T_2^2)$$

9

If the temperatures of the energy-exchanging bodies are not too different, this can be approximated by

$$h_r = 4 \varepsilon \sigma F_{12} T_{av}^3 \quad 10 \quad (1.7)$$

where Tav is the average of the two temperatures.

Obviously, this simplification is not applicable to the case of solar radiation. However, the temperatures of the walls, floor and ceiling of a room generally differ by only a few degrees. Hence the approximation given by Equation (1.7) is adequate when transfers between them are to be calculated.

Example 1.3

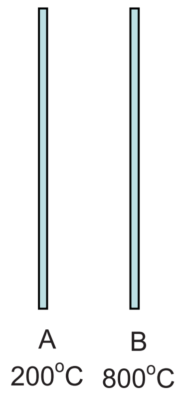
Surface A in the Figure is coated with white paint and is maintained at temperature of 200oC. It is located directly opposite to surface B which can be considered a black body and is maintained ate temperature of 800oC. Calculate the amount of heat that needs to be removed from surface A per unit area to maintain its constant temperature.

Solution

The two surfaces are assumed to be infinite and close to each other that they are only exchanging heat with each other. The view factor can then assumed to be 1.

The heat gained by surface A by radiation from surface B can be computed from Equation 1.5:

$$q = \varepsilon \sigma F_{AB} (T_B^4 - T_A^4)$$



The emissivity of white coated paint is 0.97 from Table 1.4

Thus

$$q = 0.97 \times 5.67 \times 10^{-8} \times 1 (1073^4 - 400^4) = 71469 \text{ W/m}^2$$

This amount of heat needs to be removed from surface A by other means such as conduction, convection or radiation to other surfaces to maintain its constant temperature.

1.6 Summary

This chapter introduced some of the basic concepts of heat transfer and indicates their significance in the context of engineering applications.

We have seen that heat transfer can occur by one of three modes, conduction, convection and radiation. These often act together. We have also described the heat transfer in the three forms using basic laws as follows:

Conduction: $Q = -kA\frac{dT}{dx}$ [W]

Where thermal conductivity k [W/m K] is a property of the material

Convection from a surface: $Q = hA(T_s - T_\infty)$ [W]

Where the convective coefficient h [W/m2 K] depends on the fluid properties and motion.

Radiation heat exchange between two surfaces of temperatures T_1 and T_2:

$$Q = \varepsilon \sigma F_{12} A_1 (T_1^4 - T_2^4)$$

Where ε is the Emissivity of surface 1 and F12 is the view factor.

Typical values of the relevant material properties and heat transfer coefficients have been indicated for common materials used in engineering applications.