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.

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:

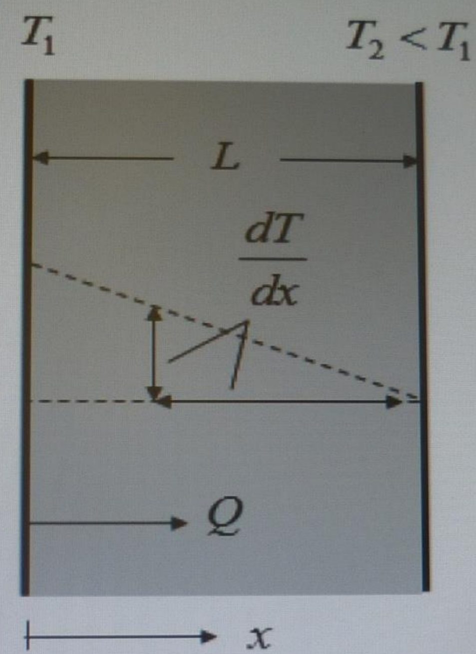

Figure 1-1: One dimensional conduction

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) 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 $A = 1.2 \times 1.0 = 1.2 \quad \mathrm{m}^2$

Thus:

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

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

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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.

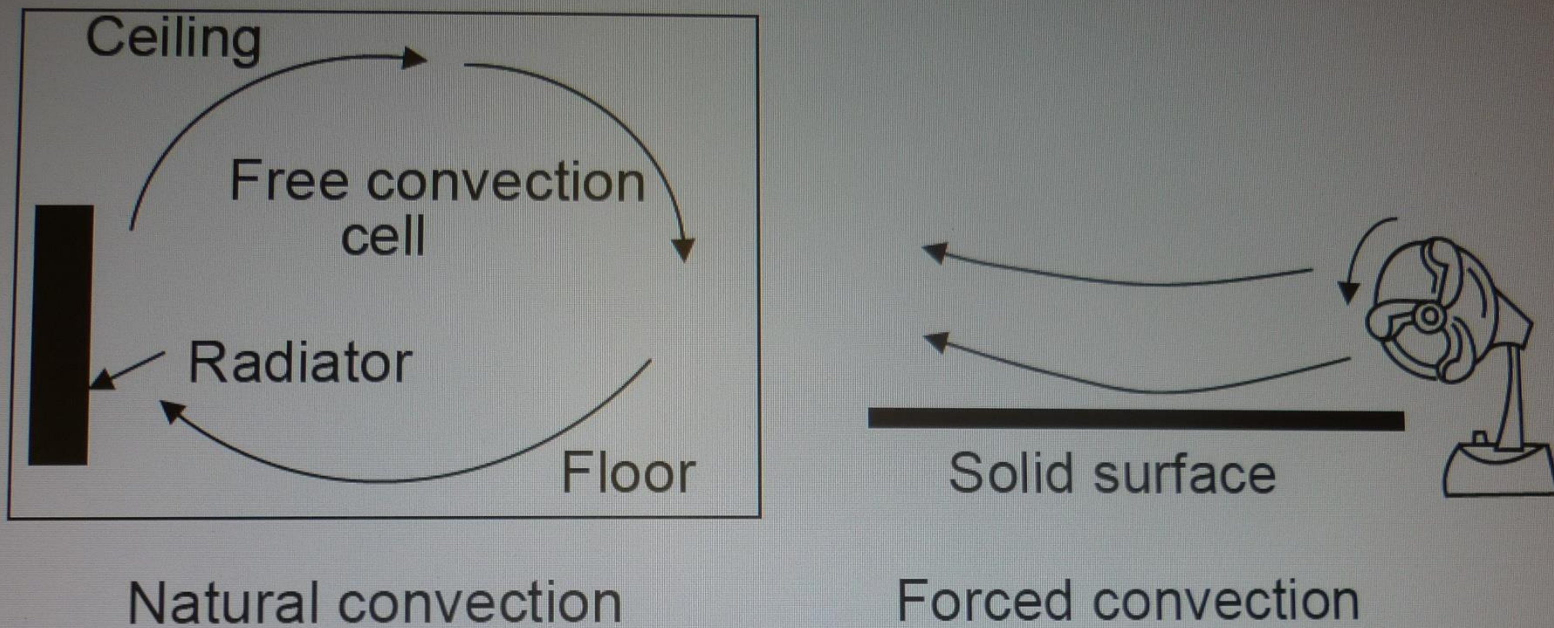

Figure 1-2: Illustration of the process of convective heat transfer

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.

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

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:

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

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

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

Solution

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

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

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,

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.

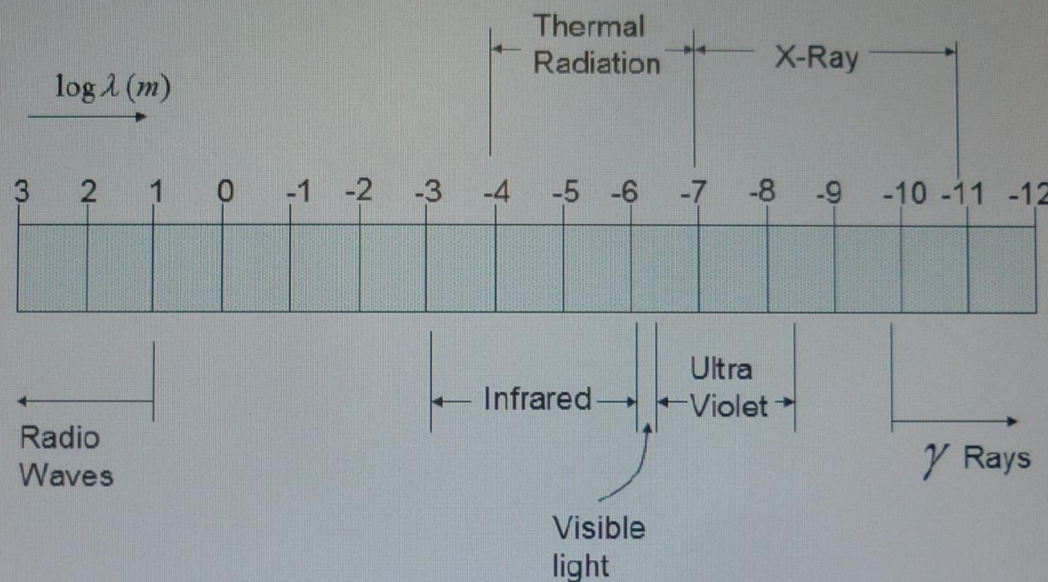

Figure 1-3: Illustration of electromagnetic spectrum

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.

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 1884 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.

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

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

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

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

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.

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Example 1.3

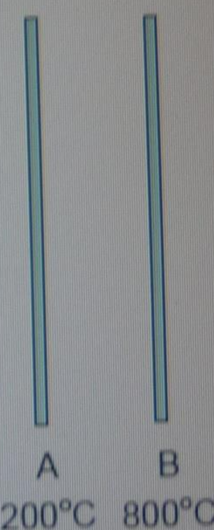
Surface A in the Figure is coated with white paint and is maintained at temperature of 200oC. It is located directly opposite to surface B which can be considered a black body and is maintained ate temperature of 800oC. Calculate the amount of heat that needs to be removed from surface A per unit area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

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



The emissivity of white coated paint is 0.97 from Table 1.4

Thus

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

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

2. Conduction

2.1 The General Conduction Equation

Conduction occurs in a stationary medium which is most likely to be a solid, but conduction can also occur in fluids. Heat is transferred by conduction due to motion of free electrons in metals or atoms in non-metals. Conduction is quantified by Fourier's law: the heat flux, q, is proportional to the temperature gradient in the direction of the outward normal. e.g. in the x-direction:

$$q_x \propto \frac{dT}{dx} \qquad (2.1)$$

$$q_x = -k\frac{dT}{dx} \qquad (W/m^2) \qquad (2.2)$$

The constant of proportionality, k is the thermal conductivity and over an area A, the rate of heat flow in the x-direction, Q_x is

$$Q_x = -k\,A\frac{dT}{dx} \qquad (W) \qquad (2.3)$$

Conduction may be treated as either steady state, where the temperature at a point is constant

$$Q_x = -k\,A\frac{dT}{dx} \qquad (W) \qquad (2.3)$$

Conduction may be treated as either steady state, where the temperature at a point is constant with time, or as time dependent (or transient) where temperature varies with time.

The general, time dependent and multi-dimensional, governing equation for conduction can be derived from an energy balance on an element of dimensions $\delta x, \delta y, \delta z$.

Consider the element shown in Figure 2.1. The statement of energy conservation applied to this element in a time period δt is that:

heat flow in + internal heat generation = heat flow out + rate of increase in internal energy

$$Q_x + Q_y + Q_z + Q_g = Q_{x+\delta x} + Q_{y+\delta y} + Q_{z+\delta z} + mC\frac{\partial T}{\partial t} \qquad (2.4)$$

or

$$Q_x - Q_{x+\delta x} + Q_y - Q_{y+\delta y} + Q_z - Q_{z+\delta z} + Q_g + mC\frac{\partial T}{\partial t} = 0 \qquad (2.5)$$

As noted above, the heat flow is related to temperature gradient through Fourier's Law, so:

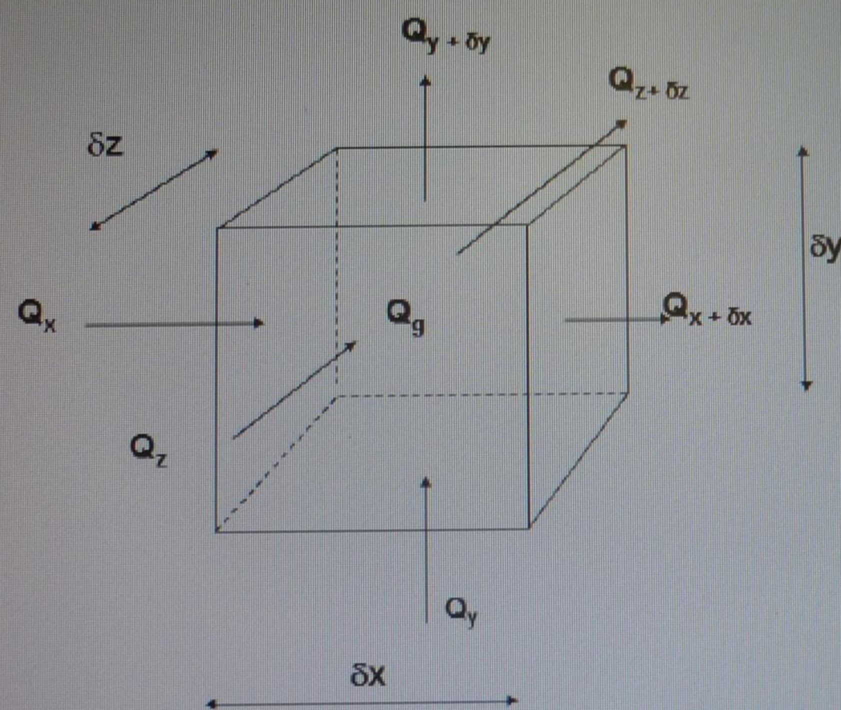


Figure 2-1 Heat Balance for conduction in an infinitismal element

For example, the heat flows through a boiler wall with convection on the outside and convection on the inside:

$$q = h_{inside}(T_{inside} - T_1)$$

$$q = (k/L)(T_1 - T_2)$$

$$q = h_{outside}(T_2 - T_{outside})$$

Rearrange, and add to eliminate T1 and T2 (wall temperatures)

$$q = \frac{T_{inside} - T_{otside}}{\left(\frac{1}{h_{inside}}\right) + \left(\frac{1}{k}\right) + \left(\frac{1}{h_{outside}}\right)} \qquad (2.16)$$

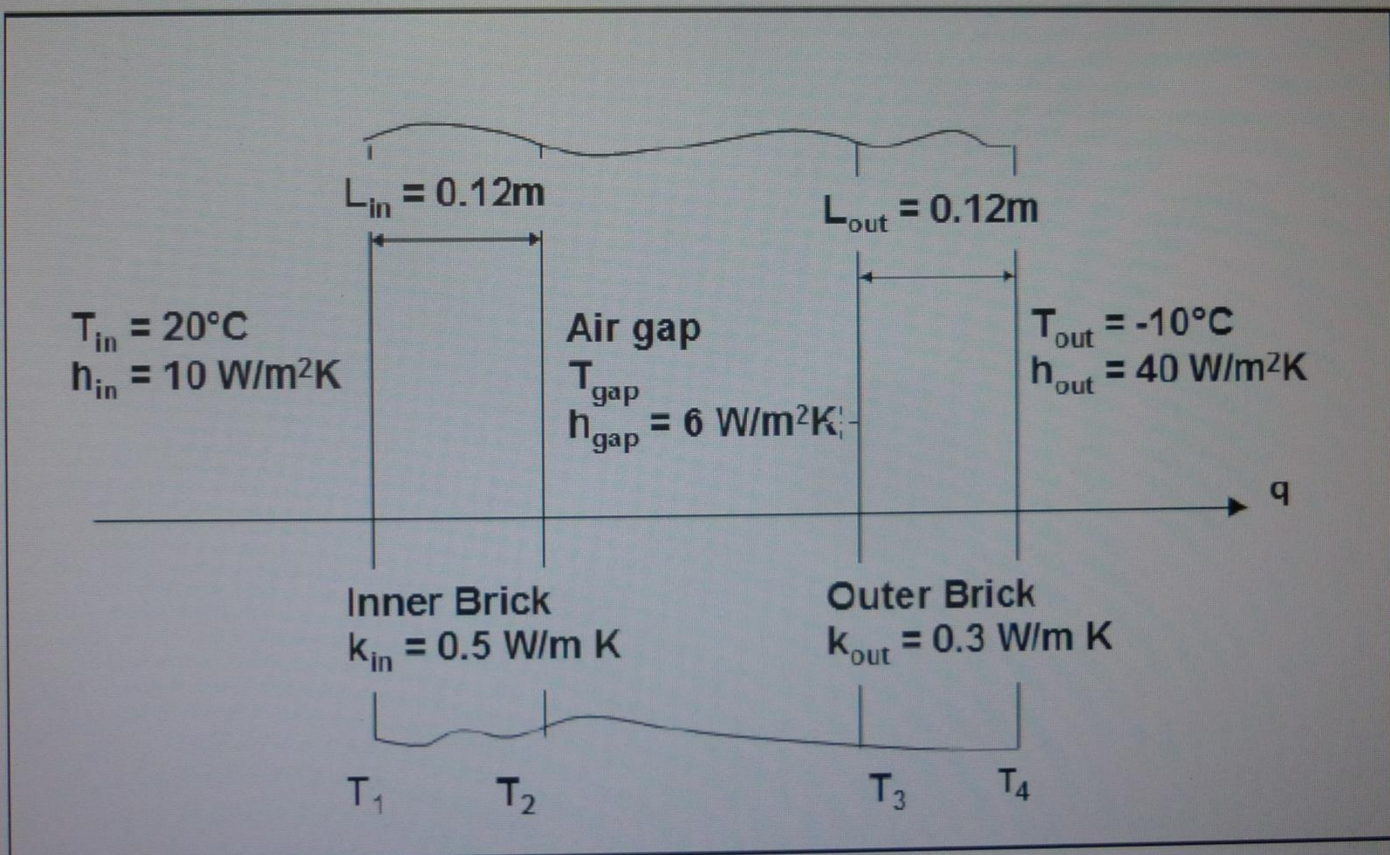
Note the similarity between the above equation with I = V / R (heat flux is the analogue of electrical current, temperature is of voltage and the denominator is the overall thermal resistance, comprising individual resistance terms from convection and conduction.

In building services it is common to quote a 'U' value for double glazing and building heat loss calculations. This is called the overall heat transfer coefficient and is the inverse of the overall thermal resistance.

$$U = \frac{1}{\left(\frac{1}{h_{inside}}\right) + \left(\frac{1}{k}\right) + \left(\frac{1}{h_{outside}}\right)} \qquad (2.17)$$

Example 2.1

The walls of the houses in a new estate are to be constructed using a 'cavity wall' design. This comprises an inner layer of brick (k = 0.5 W/m K and 120 mm thick), an air gap and an outer layer of brick (k = 0.3 W/m K and 120 mm thick). At the design condition the inside room temperature is 20°C, the outside air temperature is -10°C; the heat transfer coefficient on the inside is 10 W/m2 K, that on the outside 40 W/m2 K, and that in the air gap 6 W/m2 K. What is the heat flux through the wall?



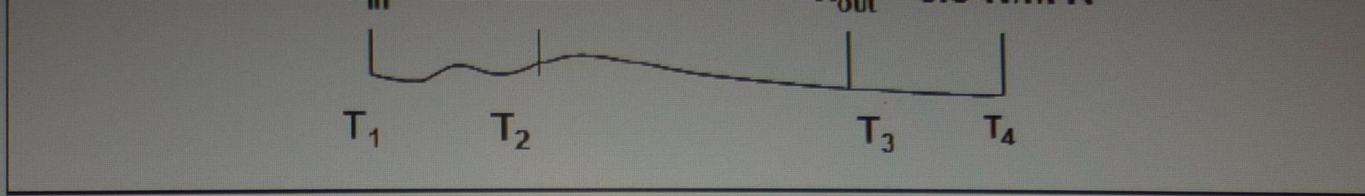


Figure 2-2: Conduction through a plane wall

Note the arrow showing the heat flux which is constant through the wall. This is a useful concept, because we can simply write down the equations for this heat flux.

Convection from inside air to the surface of the inner layer of brick

$$q = h_{in}(T_{in} - T_1)$$

Conduction through the inner layer of brick

$$q = k_{in} / L_{in}(T_1 - T_2)$$

Convection from the surface of the inner layer of brick to the air gap

$$q = h_{gap}(T_2 - T_{gap})$$

Convection from air gap to the surface of the outer layer of brick

$$q = h_{gap}(T_{gap} - T_3)$$

Conduction through the outer layer of brick

$$q = k_{out} / L_{out}(T_3 - T_4)$$

Convection from the surface of the outer layer of brick to the outside air

$$q = h_{out}(T_4 - T_{out})$$

The above provides six equations with six unknowns (the five temperatures T1, T2, T3, T4 and T_{gap} and the heat flux q). They can be solved simply by rearranging with the temperatures on the left hand side.

$$(T_{in} - T_1) = q / h_{in}$$