# Topic 2: Heat and Heat Transfer

## 2.1 Introduction

We said earlier that heat flows from a hotter body to a cooler body, but what is heat?

Heat is a form of energy. We have said that the temperature of a body is a measure of the average kinetic energy of its component atoms, so to increase the temperature of a body we must add to this kinetic energy. This is what we do when we supply heat, so heat must be another form of energy.

The science of thermodynamics, which we will study in this course, is largely the science of how heat, work and the internal energy of a material are converted into each other so as to drive engines, initiate chemical reactions, etc.

## 2.2 Heat transfer mechanisms

How is heat transferred? There are three possible mechanisms: **convection**, **conduction** and **radia­tion**.

### Convection

Convection is the transfer of heat by the net bulk motion of fluid (liquid or gas). Examples of heat transfer by convection include boiling water in a kettle, weather systems and cooling fans. We can divide convection systems into two categories: **natural** convection and **forced** convection.

Natural convection occurs when a heated fluid expands (thermal expansion). The expanded fluid is less dense than the surrounding, cooler, fluid. The less dense fluid rises and the cooler, denser fluid sinks. This results in a cyclical **convection current**. An everyday example of this is in central heating systems. The warm air rises above the radiator and the cold air (e.g. near a window) sinks, setting up a convection current cycle.

Fluid **viscosity,** i.e. the resistance of the fluid to deformation, slows the fluid flow near solid surfaces, resulting in a surface layer of more static fluid (e.g. air) that has an insulating effect. This is one reason why wind gives “wind chill”—it removes part or all of this static layer.

Forced convection occurs when the motion of hot or cold fluid is produced by external means, e.g. a pump or fan. Forced convection can be a very efficient method of transferring heat, and has many practical applications, e.g. fan oven, cooling fans in laptops, car engines, etc.

### Conduction

Conduction is the transfer of energy between atoms in a substance. Unlike convection, there is no bulk motion; instead, collisions at the atomic scale cause the transfer of heat. The atoms of the higher-temperature material have higher average kinetic energy, so collisions between them and the atoms of the lower-temperature material tend to transfer energy from hotter to cooler, increasing the velocity and kinetic energy of the cooler atoms and therefore their temperature.

Conductive heat flow is driven by temperature gradient: the greater the difference in average kinetic energy, the more energy will be transferred in each collision. This is described by the **heat flow equa­tion**,  
where *H* is the heat current, i.e. the derivative of heat *Q* with respect to time *t*, *A* is the cross-sectional area through which the heat flows and *k* is the **thermal conductivity** of the material. The negative sign indicates that the direction of heat flow is from hot to cold. Since heat is a form of energy, *H* (energy per unit time) is measured in watts; *k* is measured in W m−1 K−1.

Thermal conductivity is a property of the material, and depends on the efficiency with which its atoms can transfer kinetic energy to their neighbours. Metals generally have high thermal conductivity, because the free electrons that carry electrical current can also transfer kinetic energy. In non-metallic crystals, kinetic energy is transferred by vibrations in the crystal lattice, and this can also be very effi­cient (diamond, for example, has an extremely high thermal conductivity). In contrast, gases have low thermal conductivity, because collisions between gas atoms are uncommon.

### *Example 2.1*

Window glass has a thermal conductivity of 0.96 W m−1 K−1. If the inside temperature is 25° C and the outside temperature is 10° C, what is the rate of heat loss through a 1.00 m2 window made of 2.5 mm thick glass? How is this modified if the window is made of a double-glazed unit consisting of two panes of 2.5 mm thick glass separated by a 5 mm air gap (the thermal conductivity of air is 0.026 W m−1 K−1)?

### *Answer*

The first part is straightforward. We assume that the temperature decreases linearly through the glass, so K m−1. Therefore = 5800 W (rounding to two significant figures to match the precision of the input variables).

For the second part, we have three distinct regions of heat flow: the inner pane, the outer pane and the air gap. We know the temperature of the inner face of the inner pane and the outer face of the outer pane, but we do not know the other two temperatures. If we call the four temperatures *T*1, *T*2, *T*3 and *T*4 (working from the inside out, so that *T*1 = 25° C and *T*4 = 10° C), we have   
where are the conductivity and thickness of the glass, and of the air.

If the system has reached a steady state, we must have , otherwise the air in the gap is either heating up or cooling down. Therefore

From the first and last terms of this, it is obvious that . From the first two terms,

Therefore . It follows that K. We put this in our equation for heat flow to get

Double glazing is a very effective means of reducing heat loss!

### Radiation

Any object at a temperature above absolute zero will emit electromagnetic radiation. This can come from many sources: charged particles emit electromagnetic radiation when they are accelerated (and if two atoms collide and change their velocities, they have undergone acceleration), electrons move to lower energy states, molecules move to lower rotational or vibrational states, etc. If the material is dense enough, the photons produced by these various processes will randomise their energies by collisions until they reach a state where the photon energy distribution is independent of the material composition and is determined purely by the temperature of the body. In the ideal case, this is known as **blackbody radiation** or **thermal radiation** and the power emitted is   
where *A* is the surface area of the emitting body and *σ* is a constant known as **Stefan’s constant** (or the Stefan-Boltzmann constant); in SI units *σ* = 5.670×10−8 W m−2 K−4.

Real bodies are less efficient emitters of electromagnetic radiation than the ideal blackbody (which is defined as an object that is 100% efficient at emitting or absorbing radiation). This is described by the **emissivity** *ε*, which is a number between 0 and 1: a body with emissivity *ε* will radiate power

The emissivity is a property of the material and of the nature of the surface: for example[[1]](#footnote-1), highly polished stainless steel has an emissivity of 0.075, but rough, weathered stainless steel has an emissivity of 0.85. Generally, shiny, polished surfaces have very low emissivity and rough, dark surfaces have high emissivity.

Since electromagnetic radiation can propagate in a vacuum, radiative heat transfer differs from con­vective and conductive heat transfer in not requiring the two bodies to be in physical contact—for example, the Sun can heat the Earth by radiative heat transfer.

Thermal radiation has a continuous spectrum extending over the whole wavelength range, but the wavelength of peak emission depends on the temperature according to **Wien’s law**,   
At temperatures near room temperature, ~300 K, emission peaks around 10 µm, in the infrared part of the spectrum. This is why cameras operating at infrared wavelengths are known as **thermal cam­eras** and can be used to measure temperature. It is worth noting that thermal cameras translate to temperature using equation 2.2, and therefore will not give accurate readings when pointed at shiny surfaces with low emissivities.

## 2.3 Heat capacity

Supplying heat to an object will, in general, raise its temperature. But what is the relationship between the amount of heat supplied and the change in temperature? This is quantified by the **heat capacity** of the object, *C*:   
where *Q* is the heat supplied, is the resulting temperature change, 𝑚 is the mass of the object and *c* is the **specific heat capacity**. The SI units of *C* are J K−1, and of *c*, J K−1 kg−1. When dealing with gases, it is often useful to define the **molar heat capacity**, measured in J K−1 mol−1; confusingly, this is also usually denoted *c*, so if you have a problem involving the heat capacity of a gas, make sure that you know whether you are dealing with specific heat capacity or molar heat capacity.

The heat capacity at constant pressure, *Cp*, differs from the heat capacity at constant volume, *CV.* This difference is not generally important for solids and liquids, but is very significant for gases. The specific heat capa­city of a given material is also usually dependent on temperature; we will explore this later in the course.

## 2.4 Latent heat

Supplying heat to an object does not *always* raise its temperature. Sometimes the energy will cause the material to undergo a **phase transition**, such as melting, vaporisation, or ionisation. For example, supplying heat to a mixture of ice and water at 0° C will not, initially, increase the temperature: instead, it will cause the ice to melt. Only when all the ice has melted will the temperature of the water start to increase (this is why we add ice to drinks to keep them cool). The heat required to cause a phase transition is called the **latent heat**, is measured in J kg−1, and is given by   
where *L* is the (specific) latent heat and 𝑚 is the mass of material. The latent heat required to melt a solid is called the **latent heat of fusion**; that required to vaporise a liquid is the **latent heat of vaporisa­tion**. When a vapour condenses into a liquid, or a liquid freezes into a solid, the latent heat is released back into the environment. This feature is commonly used in refrigeration systems, where the refrige­rant enters the area to be cooled as a liquid, absorbs heat by evaporating into a vapour, and is subse­quently condensed back into a liquid to release the waste heat.

Like specific heat capacity, latent heat is temperature-dependent. In particular, latent heat of vapor­isa­tion decreases with increasing temperature and will reach zero at the **critical point** of the material, at which point the difference between the liquid and gas phases essentially disappears.

### *Example 2.2*

The half-litre bottle of water you carelessly left standing in the sunshine has reached a temperature of 35° C. You decide to cool it to a more refreshing 10° C by adding ice cubes from your freezer. If each ice cube has a mass of 20 g and your freezer has a temperature of −18° C, how many ice cubes do you need to add?

(The specific heat capacity of liquid water is 4.2 kJ K−1 kg−1, the specific heat capacity of ice is 2.1 kJ K−1 kg−1, and the latent heat of fusion of ice is 334 kJ kg−1. The density of water is 1000 kg m−3.)

### *Answer*

The heat lost by the water is kJ.

This is supplied to a mass *M* of ice. The ice has to warm from −18° C to 0° C, then melt, then warm as liquid water to 10° C. The total heat required is therefore kJ. If we equate this to the heat supplied by the water, we find kg.

Six ice cubes won’t quite do it, so you need to add seven.

1. Values from the Engineering Toolbox, <https://www.engineeringtoolbox.com/emissivity-coefficients-d_447.html> [↑](#footnote-ref-1)