

4

Thermal physics

PRIOR KNOWLEDGE

Before you start, make sure that you are confident in your knowledge and understanding of the following points:

- The kinetic theory model of solids, liquids and gases assumes that particles are incompressible spheres.
- Solids have a close-packed, regular particle structure – the particles vibrate about fixed points.
- Liquids have a close-packed, random, irregular particle structure – the particles are free to move.
- Gases have a widely spaced, irregular particle structure – the particles move at high speed in random directions.
- Thermal energy can be transferred from somewhere hot (at a high temperature) to somewhere cooler (at lower temperature) by the processes of conduction, convection, radiation and evaporation.

TEST YOURSELF ON PRIOR KNOWLEDGE

- 1 Draw simple diagrams showing the arrangements of particles inside a solid, a liquid and a gas.
- 2 Explain the difference between the transfer of thermal energy, from a hot body to a cold body, through conduction and through convection.
- 3 Explain how evaporation transfers thermal energy away from a hot cup of tea.

Thermodynamics

During the late 18th and early 19th centuries scientists, inventors and engineers began to develop steam engine technology, such as the giant steam-powered beam-engine pumps used to pump water out of deep Cornish tin mines.

Development of the engines required a systematic and fundamental understanding of the nature of heat energy; its relationship to the behaviour of steam and the other materials making up the engines; and the work done by the engine. This study became known as thermodynamics and Britain led the world, not only in the development of the new engines, but also in the fundamental physics of thermodynamics.

Thermodynamics deals with the macroscopic (large-scale) behaviour of a system, but it is complemented by the kinetic theory of matter, which deals with the microscopic, particle-scale behaviour of matter. Some

aspects of thermal physics are best explained in terms of macroscopic thermodynamics, such as the behaviour of engines, but other aspects are best explained using microscopic kinetic theory, such as Brownian motion (the tiny random motion of pollen or smoke particles seen under a microscope).

Internal energy

One of the most fundamental properties of thermodynamics is the concept of **internal energy**, U , which is the sum (sometimes called an *ensemble* in thermodynamics) of the randomly distributed kinetic energies and potential energies of the particles in a body:

$$U = \Sigma(\text{kinetic energies}) + \Sigma(\text{potential energies})$$

Consider a glass of water (Figure 4.1). The water particles have two types of energy – kinetic energy associated with their movement (the faster they move, or vibrate or rotate, the higher their kinetic energy) and potential energy associated with any forces or interactions between the particles (such as any electrostatic attraction or repulsion).

The kinetic energies of the particles depend on their temperature, and the potential energies depend on any intermolecular forces between the particles. For ideal gases, in which there are no intermolecular forces, the internal energy is dependent on only the kinetic energies.

The first law of thermodynamics

The physicists working on the theories of how engines worked quickly realised that there was an interplay between the changes in heat energy and the work being done on or by the **fluids** in the engines. This was formalised by the first law of thermodynamics, written by Rudolf Clausius in 1850. A modern version of his law can be stated as follows:

The increase in internal energy of a system is equal to the heat added to the system minus the work done by the system.

In terms of symbols, this can be written:

$$\Delta U = \Delta Q - \Delta W$$

where ΔU is the increase in internal energy of the system (usually a gas), ΔQ is the thermal energy added to the system and ΔW is the work done by the system.

Work done by an expanding gas

When a gas expands, it exerts a force on the surroundings, causing them to move – the gas does *work* on the surroundings. We can use the first law of thermodynamics to determine the work done, ΔW , by an expanding gas at constant temperature (called an *isothermal* change). Consider a gas enclosed in a cylinder by a frictionless piston, as shown in Figure 4.2.

The gas of volume V exerts a pressure p on the walls of the cylinder. This in turn exerts a force F on the frictionless piston of area A , where

$$F = pA$$

This causes an increase in the volume, ΔV . We assume that ΔV is very small and that the force moves the piston at a slow but steady rate such that the

Internal energy The sum of the randomly distributed kinetic and potential energies of the particles in a body.

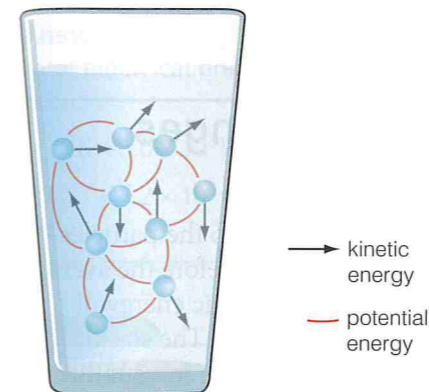


Figure 4.1 Glass of water, showing internal energy.

Fluid A substance that can flow – i.e. a gas or a liquid.

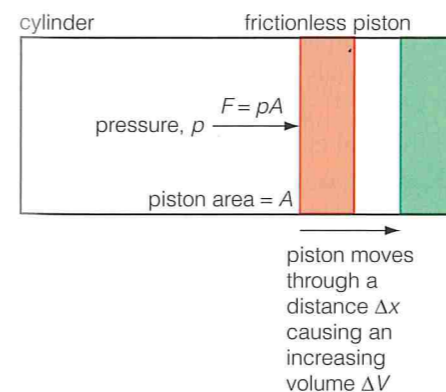


Figure 4.2 A gas expanding in a cylinder.

TEST YOURSELF

- 1 What is thermodynamics?
- 2 State two ways in which the internal energy of a gas inside a bicycle tyre pump can be increased.
- 3 Calculate the work done on a gas when its internal energy increases by 1864 kJ as it is heated, causing its thermal energy to increase by 1247 kJ.

external force exerted on the piston is equal to the force exerted by the pressure p of the gas in the cylinder. This effectively makes the pressure exerted by the gas constant during the expansion. The gas does work, and so ΔW is positive. The force on the piston moves it through a distance, Δx , such that:

$$\Delta W = -F\Delta x$$

substituting for $F = pA$ gives

$$\Delta W = pA\Delta x$$

But $A\Delta x = \Delta V$, the change in volume of the gas, so

$$\Delta W = p\Delta V$$

Heating up substances and changes of state

When substances are heated, thermal energy is supplied to the particles of the substance, increasing their internal energy U , and therefore the average kinetic energy of the particles. Increasing the average kinetic energy of the particles causes the temperature of the particles to rise. The size of temperature change, $\Delta\theta$, is dictated by several macroscopic, measurable factors: the amount of thermal heat energy supplied, Q ; the mass of the substance, m ; and a quantity called the specific heat capacity of the substance, c , which is unique to each substance; and its state. These factors are related to each other by the equation:

$$Q = mc\Delta\theta$$

The thermal energy Q is measured in joules (J), the mass m is measured in kilograms (kg), and the temperature change $\Delta\theta$ is measured in kelvin (K), so the units of specific heat capacity, c , are $\text{J kg}^{-1} \text{K}^{-1}$.

The specific heat capacity of a material is a fundamental property of the material and is particularly important to engineers and scientists designing engines and insulation systems. A specific heat capacity dictates how easy it is for a material to change its temperature. Materials with very high specific heat capacities, such as water, $c_w = 4186 \text{ J kg}^{-1} \text{K}^{-1}$ (usually rounded up to $4200 \text{ J kg}^{-1} \text{K}^{-1}$), require a great deal of thermal energy to increase the temperature of 1 kg of the material by 1 K, whereas materials such as gold with quite low specific heat capacities, $c_{\text{Au}} = 126 \text{ J kg}^{-1} \text{K}^{-1}$, require only a small quantity of thermal energy to increase the temperature of 1 kg of the material by 1 K.

Water has a particularly high specific heat capacity. Other common materials on Earth have substantially lower values: granite rock, for example, has a specific heat capacity of $790 \text{ J kg}^{-1} \text{K}^{-1}$, less than one fifth that of water. Without this property, life may not have been possible on Earth, because water would almost always be in the gaseous state.

The specific heat capacity of a material enables us to measure the change in temperature of a material following a change in thermal energy.

EXAMPLE

Warming water

An aluminium saucepan is used to warm 1.50 kg of tap water (at 18°C) for a hot-water bottle by heating it on a 3.0 kW electric hob for 4.0 minutes. Assuming that 60% of the electrical energy is absorbed by the water, and that there are no subsequent heat losses, calculate the final temperature of the warm water. The specific heat capacity of water is $c_w = 4186 \text{ J kg}^{-1} \text{K}^{-1}$.

Answer

Total electrical energy produced by the electric hob is

$$\begin{aligned} E &= 3.0 \times 10^3 \text{ W} \times 4.0 \times 60 \text{ s} \\ &= 7.2 \times 10^5 \text{ J} \end{aligned}$$

Thermal energy supplied to the water is

$$\begin{aligned} Q &= \frac{60}{100} \times 7.2 \times 10^5 \text{ J} \\ &= 4.32 \times 10^5 \text{ J} \end{aligned}$$

But $Q = mc\Delta\theta$ so

$$\begin{aligned} \Delta\theta &= \frac{Q}{mc} \\ &= \frac{4.32 \times 10^5 \text{ J}}{1.50 \text{ kg} \times 4186 \text{ J kg}^{-1} \text{K}^{-1}} \\ &= 68.8 \text{ K} = 69 \text{ K (2 s.f.)} \end{aligned}$$

Because a temperature change of 1 K is equal to a temperature change of 1°C , the final temperature of the water in the saucepan is $18^\circ\text{C} + 69^\circ\text{C} = 87^\circ\text{C}$.

EXAMPLE

Falling lead shot

The specific heat capacity of lead can be determined by letting lead shot fall inside a long tube. The lead shot heats up as gravitational potential energy is transferred to thermal energy of the shot. The experiment is shown in Figure 4.3.

A student tipped some lead shot up and down in the tube and found that after 20 turns the temperature of the lead had risen by 1.5°C . Estimate the specific heat capacity of lead. You may assume that the tube itself does not warm up.

Note: If you are handling lead shot, make sure to wash your hands afterwards.

Answer

The gravitational potential energy of the falling lead is transferred to heat in the lead. So $mgh = mc\Delta\theta$ and (because a temperature change of 1°C is equal to a temperature change of 1 K) we obtain

$$\begin{aligned} c &= \frac{gh}{\Delta\theta} \\ &= \frac{9.8 \text{ N kg}^{-1} \times 20 \text{ m}}{1.5 \text{ K}} \\ &= 130 \text{ J kg}^{-1} \text{K}^{-1} \end{aligned}$$

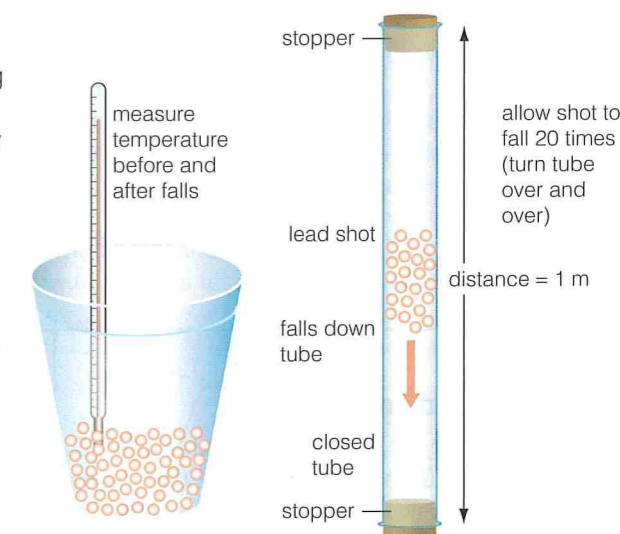


Figure 4.3 Lead shot experiment.

Mixing hot with cold

If a hot liquid or a solid is placed into a cold liquid, the internal energy transferred from the hot object when it cools down is equal to the thermal energy gained by the cold liquid and its container, plus the thermal energy lost to its surroundings. In the example shown in Figure 4.4, the thermal energy lost to the surroundings is assumed to be negligible.

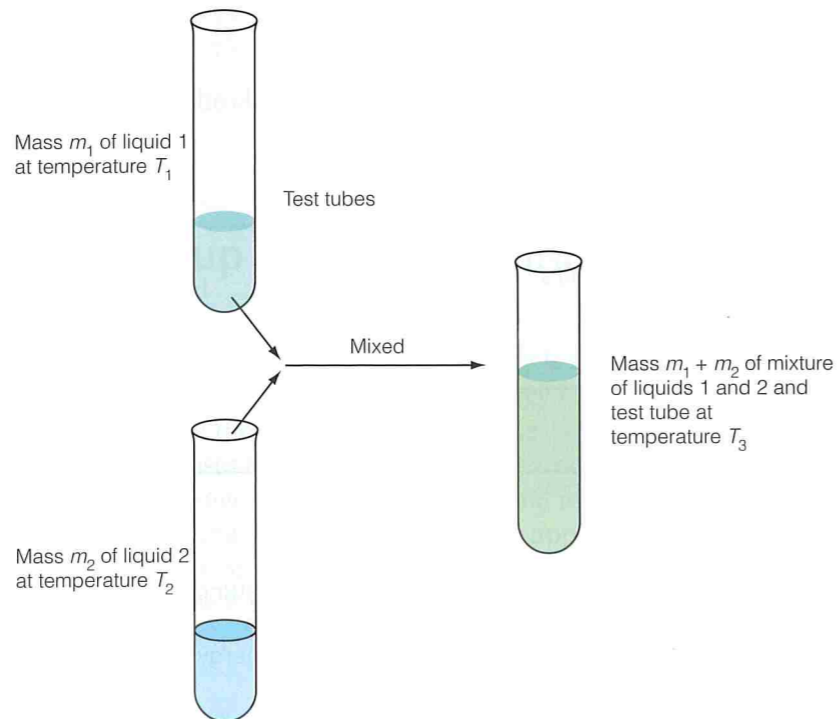


Figure 4.4 Specific heat capacity and mixtures.

EXAMPLE

Mixing hot and cold liquids

In an experiment, 20.0 g of hot seawater at 65°C is mixed with 80.0 g of tap water at 12.0°C inside a copper calorimeter of mass 75.0 g also at 12°C. If the thermal energy lost to the surroundings is negligible, calculate the new temperature of the mixture and the calorimeter. The specific heat capacities of seawater, tap water and copper are 3990 J kg⁻¹ K⁻¹, 4200 J kg⁻¹ K⁻¹ and 386 J kg⁻¹ K⁻¹, respectively.

Answer

The new (unknown) final temperature of the water mixture and the calorimeter we will call T (°C). So (because a temperature change in °C is equal to a temperature change in K) the thermal energy Q lost by the hot seawater is:

$$\begin{aligned} Q &= m_{\text{seawater}} \times c_{\text{seawater}} \times \Delta\theta_{\text{seawater}} \\ &= 20.0 \times 10^{-3} \text{ kg} \times 3990 \text{ J kg}^{-1} \text{ K}^{-1} \times (65 - T) \text{ K} \\ &= [5187 - 79.8T] \text{ J} \end{aligned}$$

This is equal to the thermal energy Q gained by the tap water and the copper calorimeter:

$$\begin{aligned} Q &= [80.0 \times 10^{-3} \text{ kg} \times 4200 \text{ J kg}^{-1} \text{ K}^{-1} \times (T - 12) \text{ K}] \text{ J} \\ &\quad + [75.0 \times 10^{-3} \text{ kg} \times 386 \text{ J kg}^{-1} \text{ K}^{-1} \times (T - 12) \text{ K}] \text{ J} \\ &= [336T - 4032] \text{ J} + [28.95T - 347.4] \text{ J} \\ &= [364.95T - 4379.4] \text{ J} \end{aligned}$$

Equating these two values and rearranging gives

$$\begin{aligned} 5187 - 79.8T &= 364.95T - 4379.4 \\ 444.75T &= 9566.4 \\ T &= 21.5^\circ\text{C} \end{aligned}$$

ACTIVITY

Measuring the specific heat capacity of a metal block

The specific heat capacity of a solid material can be measured (with reasonable certainty in the laboratory) by heating a known mass of the material with a known quantity of thermal energy, usually supplied via an electrical heater. One such experiment involving a copper block is shown in Figure 4.5.

In this experiment, the mass of the copper block was measured with an electronic balance and was found to be 0.814 kg. The block is heated using a stabilised 12.0 V dc power supply delivering 4.0 A of current to the electric heater in the block. The temperature of the block was measured every 20 s for 2 minutes while all the apparatus came to thermal equilibrium. After 2 minutes the heater was switched on and the temperature recorded every 20 s again for a further 3 minutes, before it was switched off. The temperature of the block continued to be measured every 20 s for a further 2 minutes, during which time the block started to cool down.

The results of the experiment are shown in Table 4.1.

Table 4.1

| Time, t/s | Temperature, T/°C |
|-----------|-------------------|
| 0 | 16.4 |
| 20 | 16.5 |
| 40 | 16.4 |
| 60 | 16.4 |
| 80 | 16.3 |
| 100 | 16.4 |
| 120 | 16.4 |
| 140 | 19.1 |
| 160 | 21.9 |
| 180 | 24.6 |
| 200 | 27.4 |
| 220 | 30.1 |
| 240 | 32.9 |
| 260 | 35.6 |
| 280 | 38.4 |
| 300 | 41.1 |
| 320 | 40.8 |
| 340 | 40.5 |
| 360 | 40.2 |
| 380 | 39.9 |
| 400 | 39.6 |
| 420 | 39.3 |

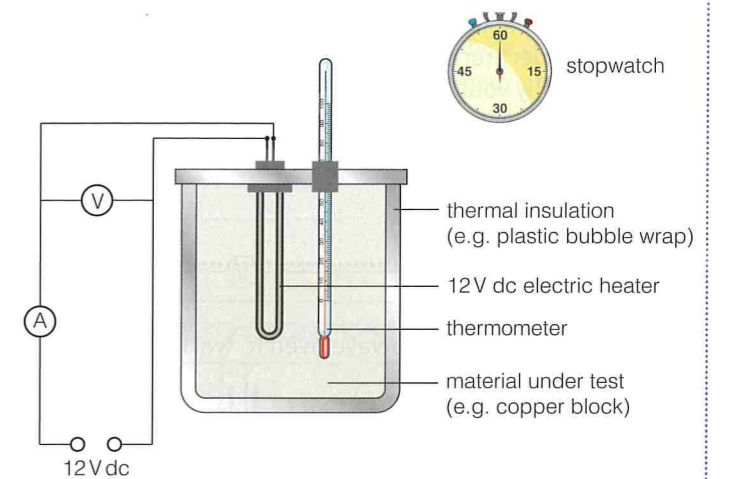


Figure 4.5 Experiment to measure the specific heat capacity of a metal block.

- 1 Plot a graph of the results and draw a smooth best-fitting line through the points.
- 2 A calorimetric technique is used to determine the temperature change of the block. The cooling part of the graph is used to take into account the heat still present in the electric heater when it was turned off but had not transferred into the block. A sketch of how to use this technique is shown in Figure 4.6.

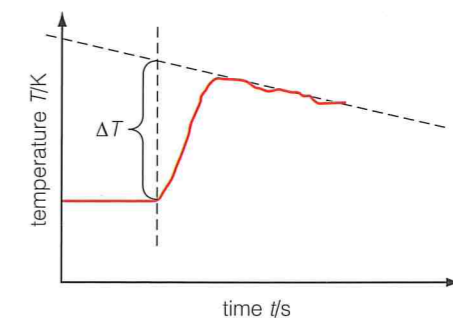


Figure 4.6 Graph showing how to calculate the temperature change.

The change in temperature of the block, ΔT , will always be slightly higher than the highest temperature reached minus the starting temperature – this accounts for the extra thermal energy left in the heater when it is switched off. In other words, ΔT gives the temperature the block would have reached if all the energy could be transferred instantly to the block, without any heat being lost. Use this graphical calorimetric



- technique to determine the temperature change of the copper block in this experiment.
- Use the rest of the data to calculate the specific heat capacity of the copper in the block.
 - The given specific heat capacity of copper at room temperature is about $386 \text{ J kg}^{-1} \text{ K}^{-1}$. Suggest reasons why your calculated value may be different from the given value.

- Explain how repeating the experiment would lead to determining the uncertainty in the measurement of the specific heat capacity of copper using this technique.
- This experiment suffers from a collection of random and systematic errors. Identify these errors, state whether they are random or systematic in nature, and suggest ways in which they could be minimised.

TEST YOURSELF

- A student uses a microwave oven to warm up a cup of cold tea.
 - Thermal energy is supplied to the tea at a rate of 750 W . The tea has a mass of 0.42 kg and an initial temperature of 17°C . Calculate the final temperature of the tea. Assume that the specific heat capacity of the tea is $4200 \text{ J kg}^{-1} \text{ K}^{-1}$.
 - In reality, some of the thermal energy goes into the cup and some is used by [water] particles to evaporate. What is the effect of this evaporation on the final temperature of the tea?
 - Following re-heating the tea, the student decides that the tea is too strong and adds milk from the fridge at a temperature of 5.5°C , and the temperature of the tea drops to 71.0°C . During this time the student assumes that no thermal energy is lost to the surroundings. Calculate the decrease in thermal energy of the tea.
 - If all the thermal energy transferred by the tea is used to heat up the milk, calculate the mass of the milk added by the student to the tea. Take the specific heat capacity of milk to be $4000 \text{ J kg}^{-1} \text{ K}^{-1}$.
- A college sports dome has an internal air volume of 24000 m^3 .
 - If the air inside the dome has a density of 1.2 kg m^{-3} , calculate the mass of air inside the dome.
 - During winter, the dome is kept inflated with air pumped in from outside with a temperature of 5.0°C . Overnight, the heater in the dome is turned off, and the average temperature of the air in the dome falls to 5.0°C . Calculate the thermal energy required to heat the air in the dome to a more pleasant 16°C in the morning. The specific heat capacity of air is $1000 \text{ J kg}^{-1} \text{ K}^{-1}$.
 - The dome contains four industrial space heaters rated at 14.7 kW . If the space heaters are 100%

efficient, how long will it take for the heaters to warm the air up in the dome to 16°C ?

- Explain why the actual energy value required to heat up the dome will be larger than that calculated in (b).
- A large tropical fish tank has dimensions of $240 \text{ cm} \times 60 \text{ cm} \times 60 \text{ cm}$.
 - If the density of water is 1.0 g cm^{-3} , calculate the mass of water in the tank (in kg).
 - The tank is set up using water from an outside water butt with a temperature of 9.5°C . The thermostat on the heater is set to 25.5°C . Calculate the thermal energy needed to warm up the water in the tank to the desired temperature. The specific heat capacity of water is $4200 \text{ J kg}^{-1} \text{ K}^{-1}$.
 - The tank is kept at its optimum temperature of 25.5°C by a 100 W heater and thermostat. If the heater should develop a fault and fail, show that the initial rate of fall of temperature in the tank will be about 0.1°C per hour.
 - The rate of fall of temperature of the water in the fish tank, $\Delta\theta/\Delta t$, can be described using Newton's law of cooling:

$$\frac{\Delta\theta}{\Delta t} = -k(\theta_w - \theta_s)$$

where θ_w is the temperature of the water in the tank and θ_s is the temperature of the surroundings. If the temperature of the water when the heater failed was 25.5°C and the temperature of the room it was in was 15.0°C , use your answer to (c) to determine the value of the constant k .

- Use your value of k to determine the rate of cooling of the water in the fish tank if the temperature of the room was to fall to 8°C .

EXAMPLE

Continuous flow method

Work out the specific heat capacity of water using the following data measured during one such experiment involving water in a continuous flow method:

- time of each experiment, $t = 60 \text{ s}$
- temperature difference in both experiments, $\Delta\theta = 10.0^\circ\text{C}$
- p.d. across the heater, $V_1 = V_2 = 12.0 \text{ V}$
- current through heater in experiment 1, $I_1 = 6.0 \text{ A}$
- current through heater in experiment 2, $I_2 = 2.0 \text{ A}$
- mass of water flowing in experiment 1 for 60 s, $m_1 = 126.0 \text{ g}$
- mass of water flowing in experiment 2 for 60 s, $m_2 = 56.0 \text{ g}$

Answer

The specific heat capacity is worked out by substituting values in the equation:

$$\begin{aligned} c &= \frac{(I_1 V_1 - I_2 V_2)t}{(m_1 - m_2)\Delta\theta} \\ &= \frac{[(6 \text{ A} \times 12 \text{ V}) - (2 \text{ A} \times 12 \text{ V})] \times 60 \text{ s}}{(0.126 \text{ kg} - 0.056 \text{ kg}) \times 10 \text{ K}} \\ &= 4114 \text{ J kg}^{-1} \text{ K}^{-1} \end{aligned}$$

Measuring the specific heat capacity of water using a continuous flow method

The specific heat capacity of a fluid can be measured using a continuous flow method (Figure 4.7), where the fluid moves over an electric heater at a constant rate. It is assumed that the thermal energy transferred from the apparatus to the surroundings is constant. The experiment is carried out and then the flow rate of the fluid is changed, and a second set of readings is taken. The heat loss can then be eliminated from the calculations.

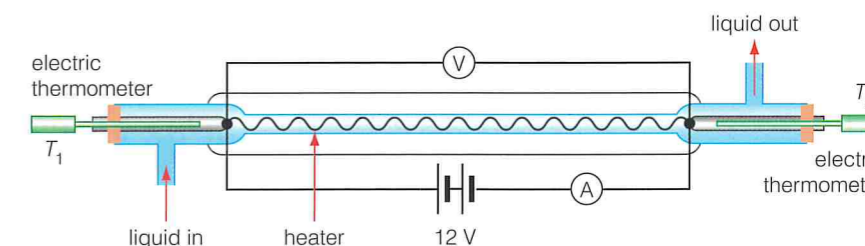


Figure 4.7 Measurement of specific heat capacity by the continuous flow method.

A fluid flows through an insulated tube containing an electric heating wire, as shown in Figure 4.8. The rise in temperature of the fluid is measured by the two electronic thermometers and calculated by $\Delta\theta = T_2 - T_1$. The mass of the fluid that flows through the apparatus in a time t_1 is m_1 , and is measured using a beaker on a balance and a stopwatch. The flow rate of the fluid is then altered to give another value, m_2 , and the heater controls are changed to give the same temperature difference $\Delta\theta$. The specific heat capacity of the fluid can then be determined by assuming that the thermal losses to the surroundings are constant for both flow rates.

For the first flow rate, the electrical energy supplied to the fluid in time t_1 is given by

$$I_1 V_1 t_1 = m_1 c \Delta\theta + E_{\text{lost}} \quad (\text{i})$$

where I_1 and V_1 are the initial current and p.d. of the heater and E_{lost} is the thermal energy lost to the surroundings. For the second flow rate:

$$I_2 V_2 t_2 = m_2 c \Delta\theta + E_{\text{lost}} \quad (\text{ii})$$

E_{lost} can be assumed to be the same in each experiment, so subtracting equation (ii) from equation (i) gives

$$\begin{aligned} I_1 V_1 t_1 - I_2 V_2 t_2 &= m_1 c \Delta\theta - m_2 c \Delta\theta \\ &= c \Delta\theta (m_1 - m_2) \end{aligned}$$

If the experiments are both run for the same time t , then

$$c = \frac{(I_1 V_1 - I_2 V_2)t}{(m_1 - m_2)\Delta\theta}$$

Specific latent heat The specific latent heat of a material is the amount of thermal energy required to change the state of 1 kg of material, without a change in temperature, at a specified ambient pressure (normally atmospheric pressure, $p = 1 \text{ atm}$).

Changing state

When liquids are heated up to their boiling point, the thermal energy is used to increase the internal energy of the molecules of the liquid. We measure this as a temperature change. However, at the boiling point, the temperature change stops and all the thermal energy input is used to overcome the intermolecular forces between the particles of the liquid, converting it into a gas.

The amount of thermal energy required to change the state of a substance, without a change in temperature, Q (in J), is given by

$$Q = ml$$

where m is the mass of the substance (in kg) and l is the **specific latent heat** ('latent' means 'hidden') of the substance (in J kg^{-1}). This equation applies to all the phase changes involved with changes of state. So water, for example, has a specific latent heat of vaporisation, l_v , which deals with the phase change from liquid to gas (and vice versa), and a specific latent heat of fusion, l_f , which deals with the phase change from solid to liquid (and vice versa).

The relationship between the kinetic theory models of solids, liquids and gases and the concept of latent heat is illustrated by Figure 4.8. Thermal energy supplied to a substance that is changing state is

used to loosen the intermolecular bonds holding the particles together (completely in the case of a liquid turning into a gas). The thermal energy is called a *latent heat* because during the change of state the temperature does not change, despite thermal energy being supplied to the substance.

The values of l_v and l_f for a few selected materials are shown in Table 4.2. Once again, the high values for water mean that a high proportion of the water on planet Earth is in the liquid state, and our ambient temperature is kept within a relatively small range.

Table 4.2.

| Material | Specific latent heat of vaporisation, $l_v/\text{kJ kg}^{-1}$ | Specific latent heat of fusion, $l_f/\text{kJ kg}^{-1}$ |
|----------------|---|---|
| Water | 2260 | 334 |
| Carbon dioxide | 574 | 184 |
| Nitrogen | 200 | 26 |
| Oxygen | 213 | 14 |
| Lead | 871 | 23 |

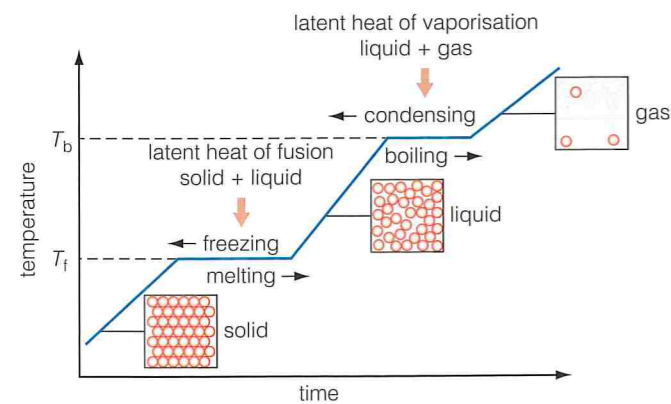


Figure 4.8 Kinetic theory graph.

EXAMPLE

Evaporating water

A Bunsen burner delivers heat energy at a rate of 900 W to water inside a glass beaker. The water is at its boiling point, and the 900 W of thermal energy is used to turn 0.50 kg of water into steam. Calculate how long it will take for the water to turn to steam. The specific latent heat of vaporisation of water is 2260 kJ kg^{-1} .

Answer

Using the equation from the main text

$$Q = ml_v = 0.50 \text{ kg} \times 2260 \times 10^3 \text{ J kg}^{-1} = 1.13 \times 10^6 \text{ J}$$

If the power supplied as thermal heat to the water is 900 W, the time required to boil the water is:

$$t = \frac{Q}{P} = \frac{1.13 \times 10^6 \text{ J}}{900 \text{ W}} = 1256 \text{ s} \approx 21 \text{ minutes}$$

TEST YOURSELF

- A 12.5 g ice cube melts in the sunshine. Calculate the thermal energy from the Sun absorbed by the ice during melting. The specific latent heat of fusion of water is 334 kJ kg^{-1} .
- Lead is a major component of the solder used to construct integrated circuits. A soldering iron delivers 18 W of thermal energy to a small 4.2 g block of lead. Calculate the time taken for all the lead to melt. The specific latent heat of fusion of lead is 23 kJ kg^{-1} .
- A range oven rated at 3 kW actually delivers 2.7 kW of thermal power to 1.5 kg of water inside a whistling kettle. The specific heat capacity of water, c , is $4200 \text{ J kg}^{-1} \text{ K}^{-1}$, and the specific latent heat of vaporisation of water, l_v , is 2260 J kg^{-1} .
 - How much thermal energy is required to heat the water from 8°C to 100°C ?
 - How long does it take the kettle to heat the water from 8°C to 100°C ?
 - The water starts to boil and the whistle on the kettle starts to blow and keeps blowing for 25 s until the kettle is removed from the heat. What mass of water is converted into steam during the 25 s of boiling?
- The specific latent heat of vaporisation of a liquid (such as water) can be measured using the apparatus shown in Figure 4.9.

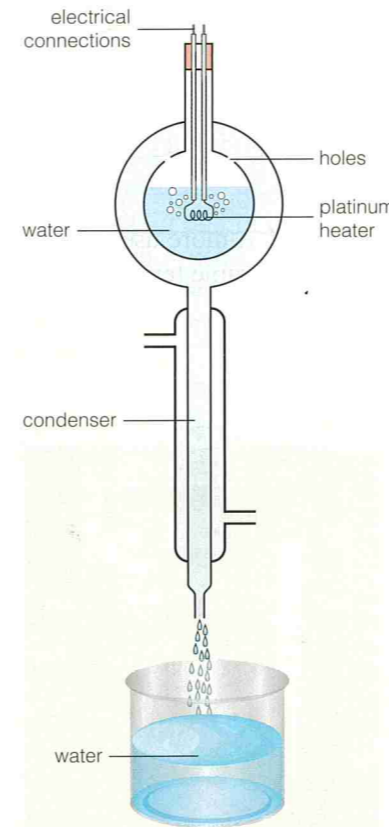


Figure 4.9 Apparatus for measuring the specific latent heat of vaporisation of water.

The heat supplied to the water is given by

$$V_1 I_1 t = m_1 l_v + E$$

where V_1 is the p.d. across the heater, I_1 is the current supplied to the heater, t is the time that the experiment is left to run, boiling a mass of water m_1 in the time t , l_v is the specific latent heat of vaporisation of water and E is the thermal energy lost to the surroundings. The experiment is then repeated with a different p.d., V_2 , across the heater and a different current, I_2 , flowing through it, boiling a different mass of water, m_2 , in the same time t . In this case:

$$V_2 I_2 t = m_2 l_v + E$$

(The thermal energy lost in each experiment, E , will be the same.)

- Use both equations to derive an expression for the specific latent heat of vaporisation of water.
- In one such experiment, the following data was obtained in $t = 600 \text{ s}$.

| Quantity | Value | Quantity | Value |
|----------|--------|----------|---------|
| V_1 | 8.00 V | V_2 | 12.00 V |
| I_1 | 2.41 A | I_2 | 3.00 V |
| m_1 | 5.8 g | m_2 | 10.3 g |

Use this data and your answer to (a) to calculate a value for the specific heat capacity of water.

- Stearic acid, a common chemical found in soaps, is frequently used to show the phase change of a material. A student set up an experiment using a test tube with 4 g of initially liquid stearic acid contained in a small water bath containing 25 g of water set at 95°C . She puts thermometer probes connected to a data logger into the stearic acid and the water in the water bath and then she turns off the temperature control. The data logger measures and records the temperatures over the course of ten minutes as the water and the stearic acid cool down. Her results are shown in Figure 4.10.

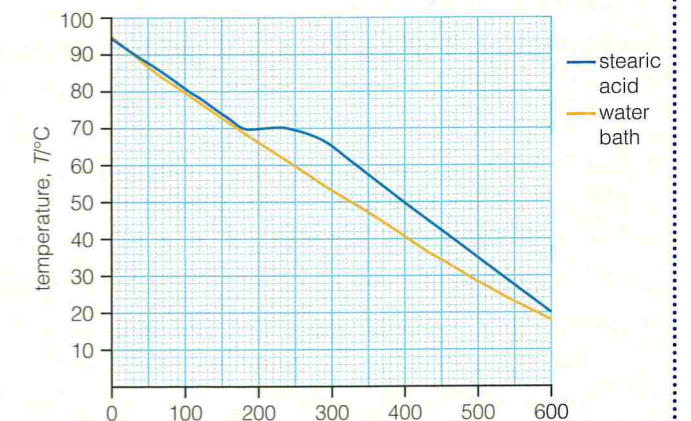


Figure 4.10



- a) Draw a diagram of the experimental set-up.
- b) The specific heat capacity of water is $4200 \text{ J kg}^{-1} \text{ K}^{-1}$. Neglecting the effect of the glass test tube, estimate the rate of thermal energy transfer from the water (and the stearic acid).
- c) Use the graph and the rate of thermal heat transfer to estimate:
- the specific heat capacity of solid stearic acid
 - the specific latent heat of fusion of stearic acid.

The gas laws

Between 1662 and 1802 three laws were discovered by a collection of European physicists that seemed to describe the behaviour of gases in response to changes in their pressure, volume and temperature. The laws themselves are all empirical, which means that they describe the mathematical relationships between the three variables purely based on experiments.

Boyle's law

The first gas law to be discovered was Boyle's law, the relationship between the pressure and volume of a gas. The experiments were carried out by Robert Boyle and his research student Robert Hooke in 1662, involving J-shaped tubes of sealed glass and mercury. Boyle quickly realised that there was a relationship between the volume of the air trapped behind the mercury and the weight of the mercury acting across the cross-sectional area of the tube causing increased pressure.

Boyle realised that the pressure acting on the gas and the volume occupied by the gas were inversely proportional to each other. Boyle would have obtained results similar to those shown in Figure 4.11. A modern version of his law states:

For a fixed mass of an ideal gas at constant temperature, the pressure of the gas is inversely proportional to its volume.

Writing this mathematically:

$$p \propto \frac{1}{V} \text{ or } p \times V = \text{constant}$$

where p is the pressure acting on a gas of volume V . A more useful version of this equation involves the same mass of gas at the same temperature, but different pressures and volumes, where

$$p_1 V_1 = p_2 V_2$$

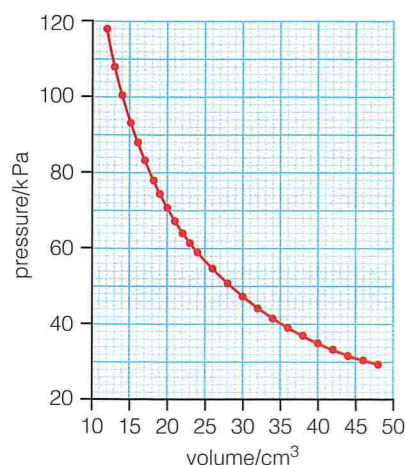


Figure 4.11 Boyle's law graph.

REQUIRED PRACTICAL 8

Investigating Boyle's (constant temperature) law

Note: This is just one example of how you might tackle this required practical.

A student uses the standard Boyle's law apparatus shown in Figure 4.12 to determine the value of the constant involved in the equation

$$pV = \text{constant}$$

In the experiment, performed at 17°C , the foot pump is used to pressurise the oil inside the cylinder, which compresses the air column above it, reducing its volume. The pump valve is closed when the pressure is at a maximum and the air column volume is at a minimum.

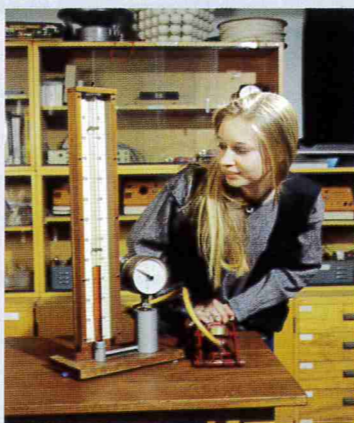


Figure 4.12 Apparatus used to investigate Boyle's law.



The apparatus is then left to come to (thermal) equilibrium as the oil drains back down the sides of the column. The pressure and the volume of the air column then measured and recorded. The student then opens the pump valve very slightly and the pressure is reduced slightly, expanding the air in the column. The valve is shut, the apparatus is allowed to come to thermal equilibrium again and the pressure and volume are measured and recorded. This process is repeated until the pressure returns fully to its atmospheric value. The student's results are shown in Table 4.3.

Table 4.3

| Pressure, $p/10^5 \text{ Pa}$ ($\pm 0.01 \times 10^5 \text{ Pa}$) | Volume, V/cm^3 ($\pm 0.5 \text{ cm}^3$) |
|--|--|
| 3.5 | 9.0 |
| 3.0 | 10.0 |
| 2.5 | 12.0 |
| 2.0 | 15.5 |
| 1.5 | 20.0 |
| 1.0 | 30.5 |

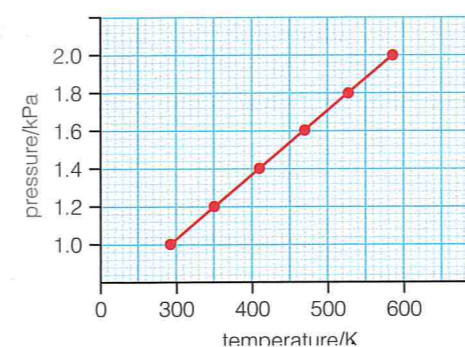


Figure 4.13 Amontons's law (pressure-temperature law).

The pressure-temperature law (Amontons's law) and absolute zero temperature

In 1702 Guillaume Amontons discovered the empirical relationship between the pressure and temperature of a gas as a result of his efforts to design and build air thermometers. Amontons realised empirically that there was a linear relationship between the two variables, provided that the mass and the volume of the gas were kept constant. Amontons struggled to build accurate thermometers and, although his ideas were published, they lacked basic quantitative data. A modern version of his graph is shown in Figure 4.13.

A modern version of Amontons's law can be written more formally as:

The pressure of a fixed mass and fixed volume of gas is directly proportional to the absolute temperature of the gas.

Writing this mathematically:

$$p \propto T$$

or

$$\frac{p}{T} = \text{constant}$$

This relationship has a third, more useful, form that is used to compare the same gas under different pressures and temperatures. This can be written as:

$$\frac{p_1}{T_1} = \frac{p_2}{T_2}$$

Amontons realised at the time of his experiments that if he extrapolated his data back through lower and lower temperatures there would be a temperature where the pressure of a gas dropped to zero. At this