National 5 Physics

Thermodynamics

HEAT AND TEMPERATURE

Heat and temperature are not the same thing!

Heat

Heat is a type of **energy**. Like all types of energy it is measured in joules (J). The heat energy depends on the mass of the object, the material of the object and the temperature of the object.

Temperature

Temperature is a measure of how fast the particles in a substance are vibrating (moving around). The faster the particles are vibrating the higher the temperature. In physics temperature is either measured in degrees celsius (or centigrade) or in kelvin. The coldest temperature possible is when the particles in a substance are not moving at all, this is known as **absolute zero**, this occurs at –273 °C or 0 K. You can convert temperatures from celsius to kelvin by **adding** 273. You can convert temperatures from kelvin to celsius by **subtracting** 273.

Try these questions on converting between celsius and kelvin:

1. Convert the following temperatures from celsius to kelvin:

   a) 0 °C

   b) 100 °C

   c) –273 °C

   d) 22 °C

   e) 500 °C

2. Convert the following temperatures from kelvin to celsius:

   a) 300 K

   b) 5000 K

   c) 267 K

   d) 4 K

   e) 423 K

Specific Heat Capacity

Temperature and Heat

The temperature of an object is a measure of how hot or cold an object is. The hotter an object is the faster the particles inside the object move about. In other words temperature is a measure of the **mean kinetic energy** of the particles in an object. In Physics temperature is measured in Celsius or Kelvin, **never** Fahrenheit. Heat is how much heat **energy** a substance contains. It is linked to temperature but is **not the same**.

Specific Heat Capacity

Different substances require different amounts of energy to heat them up. We measure this by working out the amount of energy required to heat 1 kg of a substance by 1 °C. This is called the specific heat capacity and is measured in joules per kilogram per degree celsius or $\mathrm{J\,kg^{-1}\,°C^{-1}}$. For instance the specific heat capacity of water is 4180 $\mathrm{J\,kg^{-1}\,°C^{-1}}$, water requires 4180 J of energy to raise the temperature of 1 kg of water by 1 °C. Substances with a **lower** heat capacity are **easier** to heat up. Substances with a **higher** specific heat capacity are **harder** to heat up.

Specific Heat Capacity Formula

We can calculate the amount of heat energy in, added to or lost by an object by multiplying the specific heat capacity of an object by the objects mass and the objects **change** in temperature (in Celsius or Kelvin). The formula appears on the formula sheet and is given below:

Mass measured in kilograms (kg)

$$E_h = cm\Delta T$$

Heat energy measured in joules (J)

Specific heat capacity measured in joules per kilogram per Celsius ($\mathrm{J\,kg^{-1}\,°C^{-1}}$)

Change in temperature measured in Celsius or Kelvin

Example Question

How much heat energy is required to bring 0.2 kg of water to boiling point from 15 °C? You may assume that the specific heat capacity of the water is 4180 $J\,kg^{-1}\,°C^{-1}$.

Practice Problems

1. How much energy is required to heat up 1 kg of sea water (of specific heat capacity 3,900 $J kg^{-1} °C^{-1}$) by 1 °C?

2. A 4 kg bar of aluminium (of specific heat capacity 900 $J kg^{-1} °C^{-1}$) is supplied with 1800 J of heat energy. What temperature increase would be measured?

3. A cup of boiling water (of specific heat capacity 4,200 $J kg^{-1} °C^{-1}$) cools down from 95 °C to 80 °C. If the mass of water in the cup is 0.1 kg, how much heat energy is lost?

4. An immersion heater is used to heat 30 kg of water at 12 °C. The immersion heater supplies 8.6 MJ of heat. Ignoring heat losses to the surroundings calculate the final temperature of the water.

5. A 250 g block of copper is allowed to cool down from 80 °C to 42 °C. How much heat energy will it give out?

6. During an experiment, a girl supplies 12,000 J of energy to 0.25 kg of water in a glass container.

    a) What should the temperature increase be?

    b) She finds the temperature increase is less than expected. Explain why this might have happened.

    c) How could she reduce this heat loss?

7. Which of the following would give out more heat energy?

    A — a 2 kg block of aluminium as it cools from 5 °C to 20 °C?

    B — or a 4 kg block of copper as it cools from 83 °C to 40 °C?

More Practice Problems

1. Fire clay blocks of specific heat capacity 800 $J kg^{-1} °C^{-1}$ are used in a night storage heater.

    a) If 60 kg of blocks are heated by 100 °C, how much heat energy is supplied to the blocks?

    b) If the heater has an output power rating of 1 kW, how long will it take to heat the blocks?

    c) In practice it takes longer to heat the blocks. Suggest a reason for this.

2. Oil filled radiators are a useful means of providing heating in a room. An electrical element heats up the oil inside the radiator which contains 2 kg of oil of specific heat capacity 2,500 $J kg^{-1} °C^{-1}$.

    a) If the temperature of the oil is raised from 15 °C to 40 °C, how much heat energy is supplied to the oil?

    b) The heater takes 8 minutes to heat the oil through the above temperature change. What is the output power of the heating element?

    c) The element works at 230 V. What is the current in the element while it is heating the oil? Assume the heating element is 100% efficient.

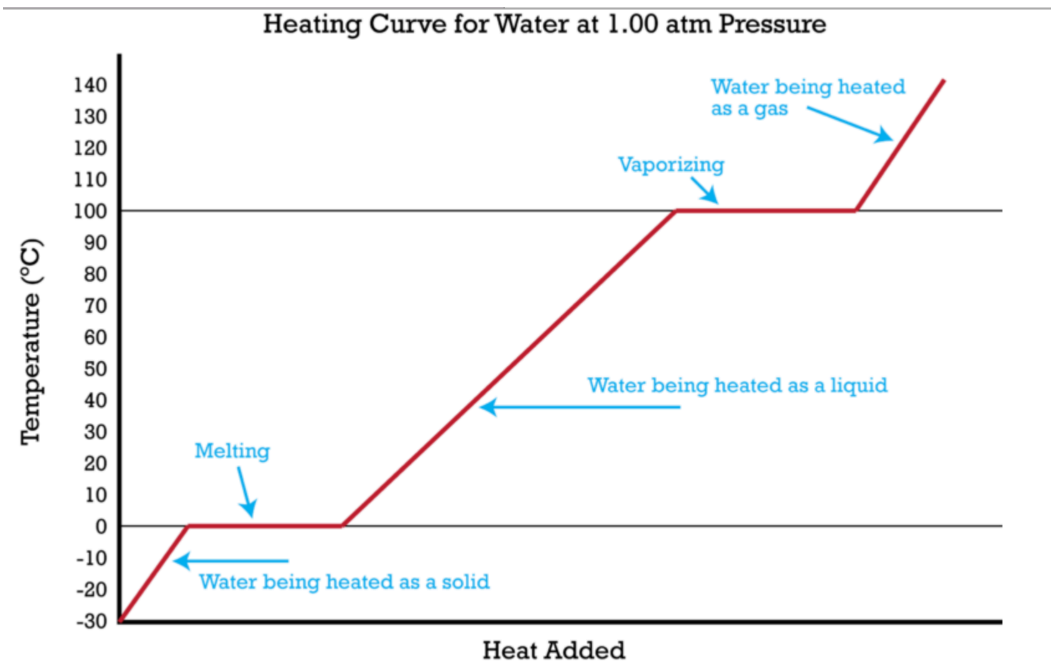
4. An electric cooker has a 500 W heating element. It takes the heating element 5 minutes to raise a 1 kg pan of water from 20 °C to 60 °C.

5. What value does this information give for the specific heat capacity of water?

6. Why is this value lower than it should be?

Latent Heat

When a substance changes state from a solid to a liquid or liquid to a gas it **requires** energy. When a substance changes state from a gas to a liquid or liquid to a solid it **releases** energy. This effect is called **latent heat**. Whilst an object is changing state the heat energy is is absorbing or releasing is restructuring the material, not changing its temperature. Therefore an object undergoing a phase change will do so **at a constant temperature**.



Latent heat formula

The energy required to change the state of a substance is given by multiplying the mass of an object by its latent heat. There are two latent heats for every material. The *latent heat of fusion* is used when going between **solid** and **liquid**. The *latent heat of vaporisation* is used when going between **liquid** and **gas**. The formula appears in the formula book and looks like this:

Mass measured in kilograms (kg)

$$E_h = ml$$

Heat energy measured in joules (J)

Latent heat of fusion or vaporisation measured in joules per kilogram ($\text{J}\,\text{kg}^{-1}$)

Example:

How much heat energy is required to turn 5 kg of water at 100 °C to 5 kg of steam at 100 °C? (l_v water = 2.26×10^6 J kg^{-1})

Solution:

$E_h = m \times l_v$

$E_h = 5 \times 2.26 \times 10^6$

$E_h = 1.13 \times 10^7$ J

Note that if 5 kg of steam condenses then it would *release* the same amount of energy. This is why a steam burn is much worse than a hot water burn.

Practice problems

1. Which of the following liquids has the larger latent heat of vaporisation? Vinegar which requires 195 kJ to vaporise 500 g or benzene which requires 320 kJ to vaporise 800 g.

2. At 357 °C Mercury boils into a vapour. If 20 g of Mercury can be vaporised with 5880 J of energy, what is the specific latent heat of vaporisation of Mercury?

Pressure

In Physics pressure is defined as the amount of force per unit area. More simply pressure is equal to the force divided by the area it is acting on. Pressure is measured (in Physics) in either newtons per square metre or pascals. We do not use units such as bars, atmospheres, pounds per square inch or millimetres (or inches) of mercury in National 5. There is a formula for pressure that appears on the formula sheet and it is given below:

Force measured in newtons (N)

$$p = \frac{F}{A}$$

Pressure measured in newtons per square metre ($N\,m^{-2}$) or pascals (Pa).

Area measured in square metres (m^2)

Note that a P is used for both pressure and power on the formula sheet. Do not confuse the two!

Practice Problems

1. A cube of side 3 m is sitting on a bench. If the mass of the cube is 27 kg, what is the pressure on the bench?

2. A man of mass 70 kg is standing still on both feet. The average area of each foot is 0.025 m^2.

    a) Calculate the force the man exerts on the ground (his weight in N).

    b) Calculate the pressure exerted by the man on the ground.

    c) If the man now stands on only one foot, calculate the pressure this time.

4. A man of mass 60 kg is standing on a block of wood measuring 0.28 m × 0.08 m. Calculate the pressure on the ground.

5. A woman of mass 60 kg stands on one high heeled shoe. The area of sole in contact with the ground is 1.2×10^{-3} m^2. The area of the heel in contact with the ground is 2.5×10^{-5} m^2. Calculate the pressure on the ground.

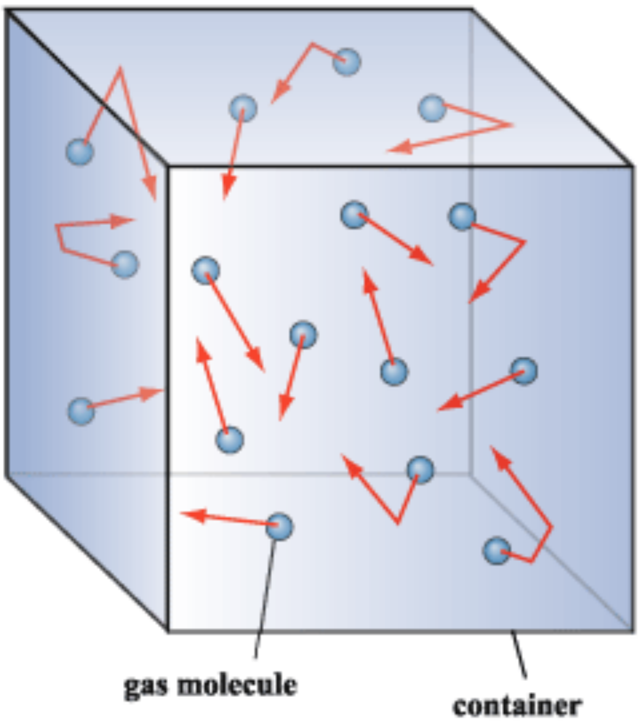
6. Although the man in question 4 and the woman in question 5 had the same mass, they did not have the same pressure. Explain why this is the case.

7. Why is it necessary to wear snow shoes to walk over soft snow?

Kinetic Model of a Gas

In Physics we assume that in gases, small particles are far apart and move in random directions at high speed. On average they are 10 molecular diameters apart and move at speeds of around 500 $m\,s^{-1}$. They can collide with the walls of the container and with each other. Increasing the temperature of a gas increases the average speed of the particles. You know from S1/2 that the volume and shape of a gas is determined by the volume and shape of its container.

This model, which can be used to explain a number of properties of a gas, is called the kinetic theory model.



Practice Problems

1. What two things can you say about the movement of the particles in a gas (i.e. speed, direction of movement)?

2. How does raising the temperature of the gas affect the particles in the gas?

3. What determines the “shape” of a gas?

4. If a jar of gas was opened in the middle of your classroom what would the gas do and what would determine the new volume of the gas?

Pressure of a Gas

The particles in a gas often collide with the walls of their container. Billions of them do this every second. Each particle exerts a tiny force on the wall of the container as it collides with it. The addition of the forces from these many collisions can become very large. The average size of this overall force divided by the area of the container gives the pressure of the gas.

Practice Problems

1. Air molecules exert an average force of 6×10^5 N on a wall. The wall measures 2 m $\times$ 3 m. What is the air pressure in the room?

2. Hydrogen molecules at low pressure exert an average force of 3×10^4 N on one wall of a cubic container. One edge of the cube measures 2m. Calculate the pressure of the hydrogen.

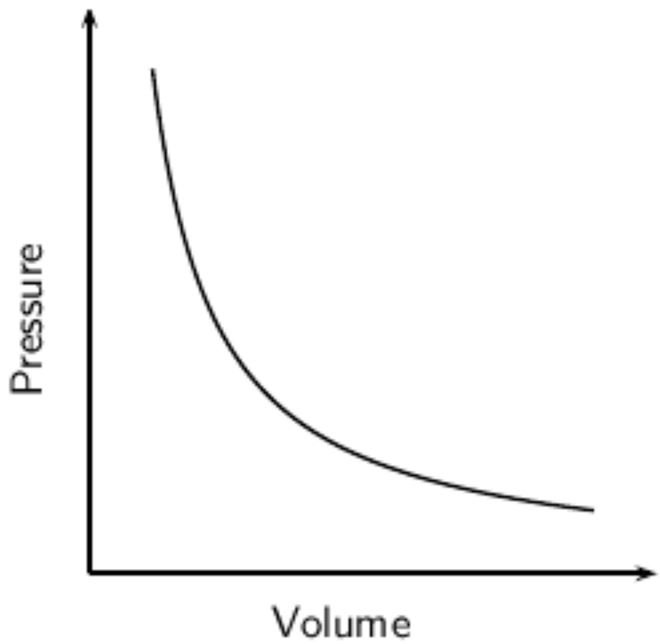
3. The pressure of air at sea level is approximately 1×10^5 Pa. What is the average force that air molecules exert on a wall at sea level measuring 3 m $\times$ 5 m?

4. Comment on the force exerted on an identical wall 10,000 m above sea level.

Gas Laws

Boyle's Law (Pressure and Volume in a Gas)

If a gas is compressed, its volume is **decreased**, then the particles within the gas will become closer together. This means that they will hit the walls of their container more often. In turn this will **increase** the pressure of the gas. Conversely if a gas is expanded, its volume is **increased**, then the pressure will **decrease**.

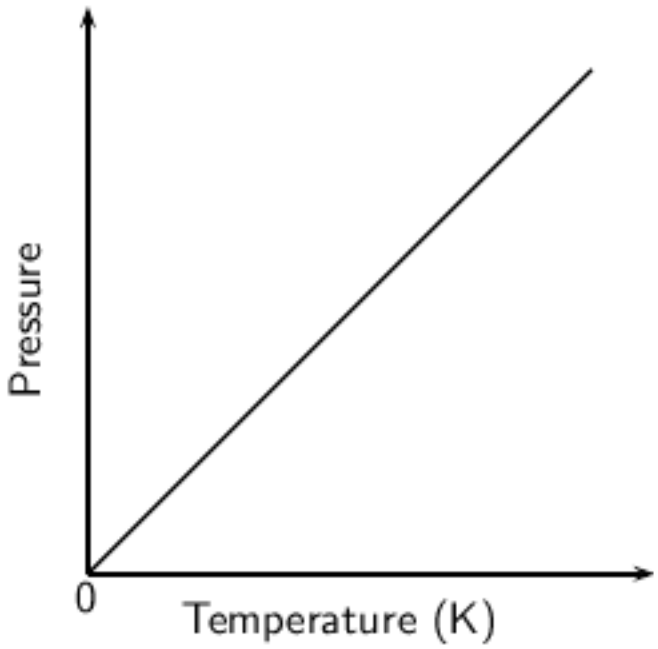


Amontons' Law (Pressure and Temperature in a Gas)

If a gas is heated and its temperature **increases** the particles in the gas will start to move faster. This means that they impact on the walls of the container with more force which causes the pressure of the gas to **increase**. Conversely if a gas has its temperature **decreased** then its pressure will also **decrease.** This is why deodorant sprays feel cold!

Amontons' Law only works when the temperature is measured in **Kelvin**.

When dealing with gasses **always use Kelvin**.

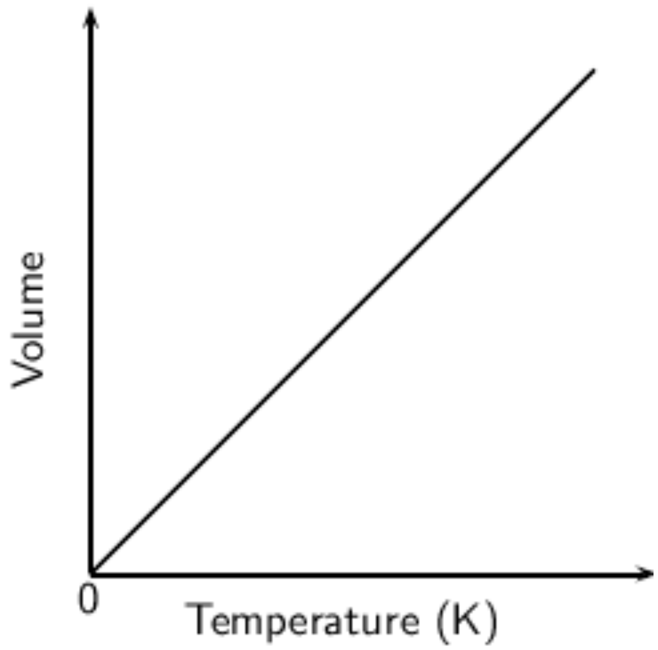


Charles’ Law (Volume and Temperature in a Gas)

If you **decrease** the temperature of a gas then the particles in the gas will start to slow down. They will push less hard on their container and if it is able to do so the container will shirk, **decreasing** its volume. Likewise if you **increase** the temperature of a gas then the particles will move faster and push harder on their container, making it expand and **increasing** its volume.

Charles’ Law only works when the temperature is measured in **Kelvin**.

When dealing with gasses **always use Kelvin**.



The Combined Gas Law

Boyle's Law, Amonton's Law and Charles' Law can all be combined into a single relationship that links the pressure, volume and temperature of a fixed mass of gas. It states that the pressure of a gas multiplied by its volume and then divided by its temperature in **kelvin** is equal to a constant. This formula appears on the formula sheet and is given below:

Pressure measured in pascals (Pa)

Volume measured in metres cubed (m^3)

$$\frac{pV}{T} = k$$

Temperature measured in kelvin (K)

A constant number

The value of the constant never changes for a certain fixed mass of a particular gas. This formula does not work if the mass of the gas changes. However it is common to deal with situations where one of the variables is fixed. This makes things much simpler!

Boyle’s Law Formula

When the temperature of a gas is fixed we can use a simplified version of the combined gas law formula. If we only look at situations where we have an initial and a final state of a gas then things become simpler still and we are left with the following formula:

$$p_1V_1 = p_2V_2$$

Essentially this states that the pressure multiplied by the volume before something happens to the gas is the same as the pressure multiplied by the volume after something happens to the gas.

As long as you use the **same** units for volume for both V_1 and V_2 you can use any unit of volume you wish — saving you the hassle of converting cm^3 into m^3 or a similar tricky conversion.

Example

100 cm^3 of air is contained in a syringe at atmospheric pressure (1×10^5 Pa). If the volume is reduced to 50 cm^3, without a change in temperature, what will be the new pressure?

Practice Problems

1. 100 cm^3 of air is contained in a syringe at atmospheric pressure (1×10^5 Pa). If the volume is reduced to 20 cm^3, without a change in temperature, what will be the new pressure?

2. If the piston in a syringe containing 300 cm^3 of gas at a pressure of 1×10^5 Pa is moved outwards so that the pressure of the gas falls to 8×10^4 Pa, find the new volume of the gas.

3. A weather balloon contains 80 m^3 of helium at normal atmospheric pressure of 1×10^5 Pa. What will be the volume of the balloon at an altitude where the air pressure is 8×10^4 Pa?

4. A swimmer underwater uses a cylinder of compressed air which holds 15 litres of air at a pressure of 12000 kPa. Calculate the volume this air would occupy at a depth where the pressure is 200 kPa.

Amontons' Law Formula

When the volume of a gas is fixed we can use a simplified version of the combined gas law formula. If we only look at situations where we have an initial and a final state of a gas then things become simpler still and we are left with the following formula:

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

Remember that all of the temperatures must be measured in **kelvin**.

Practice Problems

1. A cylinder of oxygen at 27 °C has a pressure of 3×10^6 Pa. What will be the new pressure if the gas is cooled to 0 °C?

2. An electric light bulb is designed so that the pressure of the inert gas inside it is 100 kPa (normal air pressure) when the temperature of the bulb is 350 °C. At what pressure must the bulb be filled if this is done at 15 °C?

3. The pressure in a car tyre is 2.5×10^5 Pa at 27 °C. After a long journey the pressure has risen to 3.0×10^5 Pa. Assuming the volume has not changed, what is the new temperature of the tyre?

Charles' Law Formula

When the pressure of a gas is fixed we can use a simplified version of the combined gas law formula. If we only look at situations where we have an initial and a final state of a gas then things become simpler still and we are left with the following formula:

$$\frac{V_1}{T_1} = \frac{V_2}{T_2}$$

As long as you use the **same** units for volume for both V_1 and V_2 you can use any unit of volume you wish — saving you the hassle of converting cm^3 into m^3 or a similar tricky conversion. However, remember that all of the temperatures must be measured in **kelvin**.

Practice Problems

1. 100 cm^3 of a fixed mass of air is at a temperature of 0 °C. At what temperature will the volume be 110 cm^3 if its pressure remains constant?

2. Air is trapped in a glass capillary tube by a bead of mercury. The volume of air is found to be 0.1 cm^3 at a temperature of 27 °C. Calculate the volume of air at a temperature of 87 °C.

3. The volume of a fixed mass of gas at constant temperature is found to be 50 cm^3. The pressure remains constant and the temperature doubles from 20 °C to 40 °C. Explain why the new volume of gas is not 100 cm^3.

4. A fixed mass of gas is cooled from 100 °C to 20 °C. The pressure is kept at atmospheric pressure throughout. If the initial volume is 6 cm^3, calculate the final volume.

Combined Law Problems

Example: A balloon contains 1.3 m^3 of helium at a pressure of 100 kPa at a temperature of 27 °C. If the pressure is increased to 250 kPa at a temperature of 127 °C, calculate the new volume of the balloon.

Practice Problems

1. A sealed syringe contains 100 cm^3 of air at atmospheric pressure 1×10^5 Pa and a temperature of 27 °C. When the piston is depressed, the volume of air is reduced to 20 cm^3 and this produces a temperature rise of 4 °C. Calculate the new pressure of the gas.

2. 200 cm^3 of carbon dioxide at 27 °C is heated to 127 °C. If the initial pressure is 6×10^5 Pa and the final pressure is 1×10^6 Pa, what is the volume after heating?

3. Hydrogen in a sealed container was heated from 77 °C to 400 K. If the gas was allowed to expand during heating from 50 cm^3 to 120 cm^3 and the pressure after expansion was 2×10^5 Pa, what was the pressure before the container was heated?

4. The pressure of a fixed mass of nitrogen is increased from 1.3×10^5 Pa to 2.5×10^5 Pa. At the same time, the container is compressed from 125 cm^3 to 100 cm^3. If the initial temperature of the gas was 30 °C, find the final temperature of the gas.

5. Oxygen at atmospheric pressure (1×10^5 Pa) is heated from 400 K to 500 K in a sealed container. If the volume increases during heating from 80 cm^3 to 100 cm^3, find the final pressure of the oxygen.

More Practice Problems

1. A 1 kg sample of air is contained in a gas tight cylinder. The cylinder has a moveable piston. The sample of air is at a temperature of 0 °C and under a pressure of 101 kPa. The density of air at 0 °C and a pressure of 100 kPa is 1.28 $kg\,m^{-3}$.

2. Calculate the volume of air in the cylinder.

3. The air in the cylinder is now heated to a temperature of 70 °C. The pressure of the air is kept constant at 101 kPa. Calculate the new volume of the air in the cylinder.

4. What is the density of the air in the cylinder when the temperature of the air is 70 °C and pressure of the air is 101 kPa?

THERMODYNAMICS

You need to know:

	✓ ? ✘
What latent heat is and how to use the Eh=ml formula	
That temperature is a measure of the mean kinetic energy of the particles in a substance	
The difference between temperature and heat	
That different materials require different amounts of heat energy to raise the temperature of the same amount of mass	
How to use the $E_h = cm\Delta T$ formula	
That pressure is the force per unit area	
How the kinetic model of a gas explains the pressure of a gas	
How the kinetic model of a gas explains the relationship between pressure, temperature and volume	
How to convert temperatures between celsius and kelvin	
How to use the PV/T = constant formula	