2 **(a)** The equation of state for an ideal gas may be expressed as

$$pV = NkT.$$

(i) State the meaning of each of the symbols in this equation.

p: ....

V: ....

N: ....

k: ....

T: ....

[3]

(ii) Using the equation of state, derive an expression for the average translational kinetic energy E_K of a particle in the gas in terms of some or all of N, k and T.

E_K = ... [2]

(b) A molecule of hydrogen gas consists of two hydrogen atoms, each of nucleon number 1.
A molecule of oxygen gas consists of two oxygen atoms, each of nucleon number 16.

Assume that hydrogen and oxygen both behave as ideal gases.

A sample of hydrogen gas is at the same temperature as a sample of oxygen gas.

For the two samples, determine the ratio

$$\frac{\text{root-mean-square (r.m.s.) speed of hydrogen molecules}}{\text{root-mean-square (r.m.s.) speed of oxygen molecules}}.$$

ratio = ... [2]

3 **(a)** With reference to molecular kinetic energy and molecular potential energy, explain what is meant by the internal energy of an ideal gas.

....

....

.... [2]

(b) A sample of an ideal gas is initially in state A, at a pressure of 2.0×10^5 Pa and with a volume of $0.016\,m^3$, as shown in Fig. 3.1.

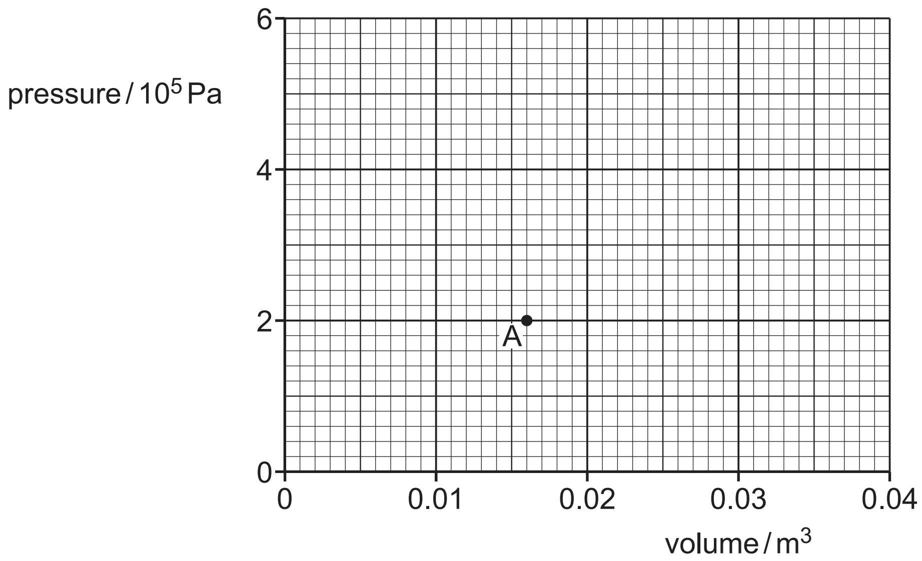

Fig. 3.1

In state A, the temperature of the gas is 400 K.

The gas undergoes two successive changes X and Y.

In change X, it is heated at constant volume to a pressure of 4.0×10^5 Pa. At the end of change X, the gas is in state B.

In change Y, it is then allowed to expand at constant temperature back to its original pressure. At the end of change Y, the gas is in state C.

(i) Determine the internal energy of the gas in state A.

internal energy = ... J [2]

(ii) Determine the temperature of the gas in state B.

temperature = ... K [1]

(iii) Determine the volume of the gas in state C.

volume = ... m^3 [1]

(iv) On Fig. 3.1, draw two lines, one to represent change X and one to represent change Y. Label your lines X and Y respectively. [3]

2 **(a)** State Newton's law of gravitation.

....

....

.... [2]

(b) One of the basic assumptions of the kinetic theory of gases is that there are no forces exerted between the molecules of the gas except during collisions.

State **two** other basic assumptions of the kinetic theory of gases.

1 ....

....

2 ....

....
[2]

(c) Hydrogen gas consists of molecules that each have a mass of 3.34×10^{-27} kg. Hydrogen may be considered to be an ideal gas.

A spherical balloon contains 0.0160 mol of hydrogen gas at a temperature of 282 K. At this temperature, the volume of gas in the balloon is $1.87 \times 10^{-4}\,\text{m}^3$.

(i) Determine the pressure of the gas.

pressure = ... Pa [2]

(ii) Estimate the average separation of the hydrogen molecules in the gas.

average separation = ... m [2]

(d) **(i)** Use your answer in **(c)(ii)** to calculate the average gravitational force between adjacent molecules in hydrogen gas.

average force = ... N [2]

(ii) By considering the weight of a molecule, suggest with a reason whether your answer in **(d)(i)** is consistent with the assumption of the kinetic theory of gases that there are no forces exerted between molecules.

....

....

.... [1]

4 **(a)** State the value of absolute zero on:

(i) the Celsius temperature scale

temperature = ... °C [1]

(ii) the thermodynamic temperature scale. Give a unit with your answer.

temperature = ... unit .... [1]

(b) A sample contains a fixed amount of gas. The gas has pressure p, volume V and thermodynamic temperature T.

Fig. 4.1 shows the variation of pV with kT for the sample, where k is the Boltzmann constant.

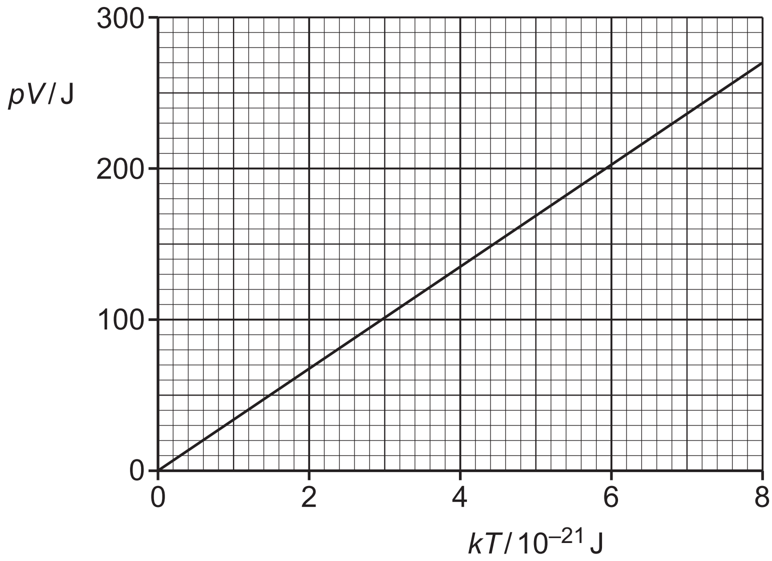

Fig. 4.1

(i) State what is indicated about the nature of the gas from the variation shown in Fig. 4.1.

.... [1]

(ii) Determine the number N of molecules of the gas in the sample.

N = ... [2]

(iii) Use your answer in **(b)(ii)** to determine the amount n of gas in the sample.

n = ... mol [1]

(c) The root-mean-square (r.m.s.) speed of the molecules of the gas is $1900\,m\,s^{-1}$ when pV is equal to 270 J.

Determine the mass, in u, of one molecule of the gas, where u is the unified atomic mass unit.

mass = ... u [4]

3 **(a)** State what is meant by an ideal gas.

....

....

.... [2]

(b) An ideal gas at a pressure of 1.6×10^5 Pa has a density of $1.9\,\mathrm{kg\,m^{-3}}$.

(i) Show that the root-mean-square (r.m.s.) speed of molecules of this gas is approximately $500\,\mathrm{m\,s^{-1}}$.

[3]

(ii) One molecule of the gas has a mass of 4.7×10^{-26} kg.

Determine the thermodynamic temperature of the gas.

temperature = ... K [2]

(c) Calculate the internal energy U of 6.0 mol of the gas in **(b)**. Explain your reasoning.

U = ... J [3]

4 **(a)** The equation of state for an ideal gas may be written as

$$pVA = NBT$$

where p is the pressure of the gas, V is the volume of the gas, A is the Avogadro constant, B is another constant and N is the number of molecules of the gas.

(i) State the meaning, in the equation, of the symbol T.

.... [1]

(ii) Identify the constant B.

.... [1]

(b) The product pV for an ideal gas is also given by

$$pV = \tfrac{1}{3} Nm \langle c^2 \rangle.$$

(i) State the meanings, in this equation, of the symbols m and $\langle c^2 \rangle$.

m: ....

$\langle c^2 \rangle$: ....

[2]

(ii) Use the equations in **(a)** and **(b)** to derive an expression, in terms of A, B and T, for the mean kinetic energy E_K of a molecule of the gas.

E_K = ... [2]

(c) On Fig. 4.1, sketch the variation with T of the root-mean-square (r.m.s.) speed of the molecules of an ideal gas.

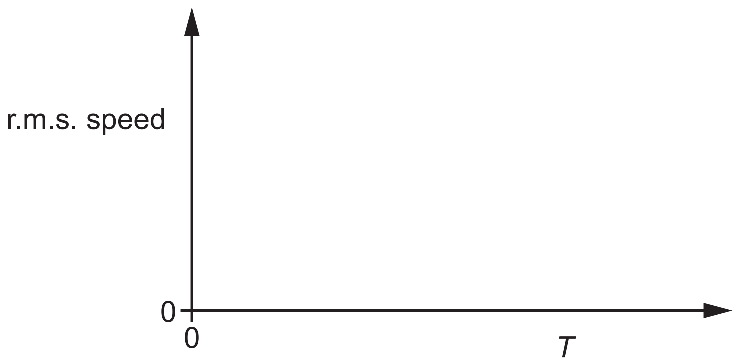

Fig. 4.1

[2]

3 **(a)** Two metal cuboids P and Q are in thermal contact with each other.

(i) P and Q are in thermal equilibrium.

State what is meant by the term thermal equilibrium.

....

....

.... [2]

(ii) Data for P and Q are given in Table 3.1.

Table 3.1

	P	Q
specific heat capacity / $J\,kg^{-1}\,K^{-1}$	390	910
mass / kg	0.54	0.37

P and Q are initially both at the same temperature.

P is supplied with 24 kJ of thermal energy. After some time, P and Q are once again both at the same temperature as each other.

P and Q are perfectly insulated from the surroundings.

Determine the change in temperature ΔT of Q.

ΔT = ... K [3]

(b) Nitrogen may be assumed to be an ideal gas. A fixed amount of nitrogen gas is contained at a constant pressure of 1.6×10^5 Pa.

The variation of the volume V of the gas with the temperature θ of the gas is shown in Fig. 3.1.

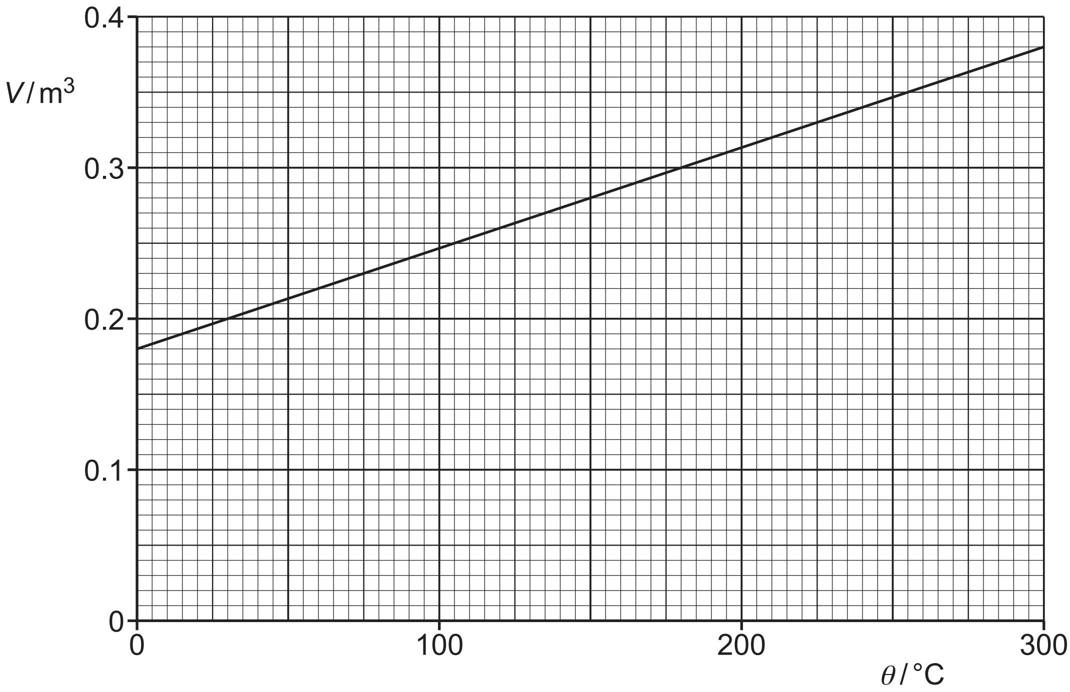

Fig. 3.1

(i) The temperature of the nitrogen gas is increased from 0 °C to 210 °C.
Determine the work done on the gas.

work done = ... J [3]

(ii) Determine the number N of molecules of nitrogen gas.

N = ... [2]

(iii) The mass of a nitrogen molecule is 4.7×10^{-26} kg.

Calculate the root-mean-square (r.m.s.) speed of a nitrogen molecule at 210 °C.

r.m.s. speed = ... $m s^{-1}$ [2]

4 **(a)** State **three** of the basic assumptions of the kinetic theory of gases.

1 ....

....

2 ....

....

3 ....

.... [3]

(b) Explain how molecular movement causes the pressure exerted by a gas.

....

....

....

....

.... [3]

(c) Fig. 4.1 shows the variation with thermodynamic temperature T of the mean-square speeds $\langle c^2 \rangle$ for two gases X and Y.

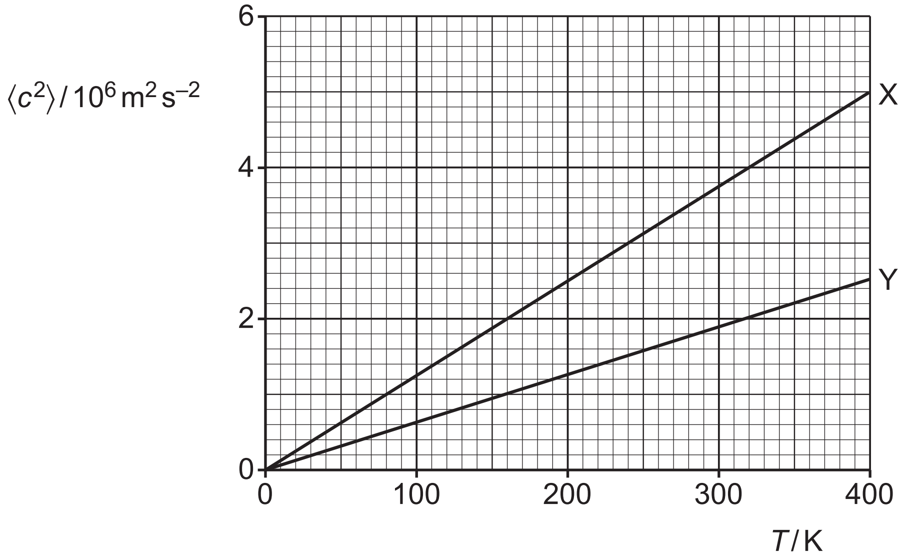

Fig. 4.1

Fig. 4.2 shows the variation with T of the product pV for samples of the two gases, where p is the pressure of the gas and V is the volume of the gas.

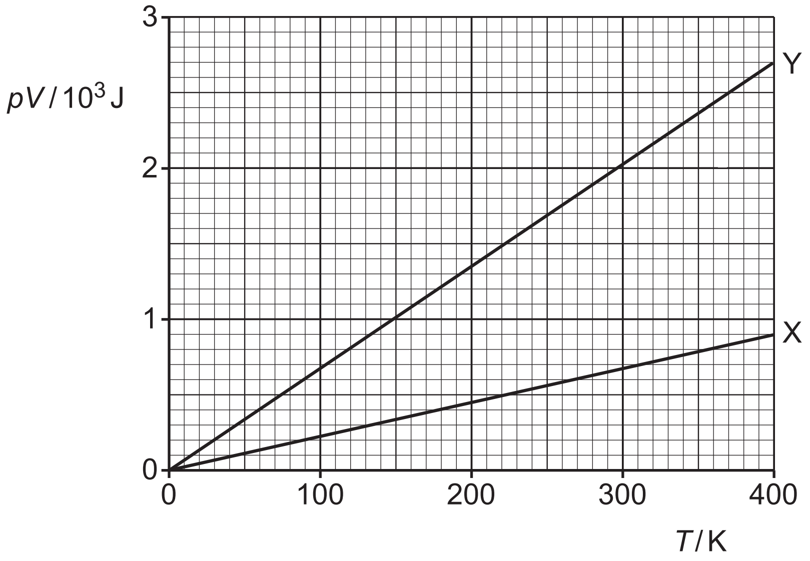

Fig. 4.2

State **three** conclusions about the gases and their samples that may be drawn from Fig. 4.1 and Fig. 4.2. The conclusions may be qualitative or quantitative. Use the space below for any working that you need.

1 ....

....

2 ....

....

3 ....

....

[3]

3 **(a)** **(i)** State what is meant by the Avogadro constant.

....

....

.... [1]

(ii) State the relationship between the Avogadro constant N_A, the molar gas constant R and the Boltzmann constant k.

[1]

(b) Two samples X and Y of ideal gases are both at thermodynamic temperature T.

Sample X has volume V and consists of N molecules, each of mass m.
Sample Y has volume $2V$ and consists of $2N$ molecules, each of mass $2m$.

(i) Complete Table 3.1 by giving expressions, in terms of some or all of N, m, T, V and the constants in **(a)(ii)**, for the quantities indicated.

Table 3.1

	sample X	sample Y
pressure		
amount of substance		
mean-square speed of molecules		
internal energy		

[4]

(ii) The temperature of sample X is now varied.

On Fig. 3.1, sketch the variation with thermodynamic temperature of the root-mean-square (r.m.s.) speed of the molecules of the gas.

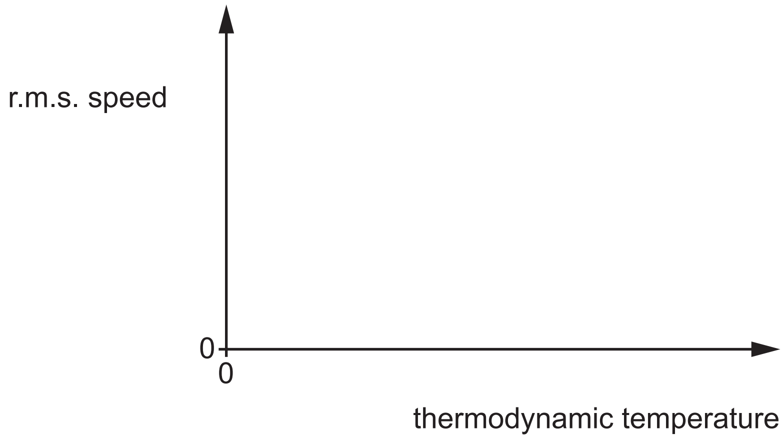

Fig. 3.1

[2]

2 **(a)** With reference to thermal energy, state what is meant by two objects being in thermal equilibrium.

....

....

.... [1]

(b) Two cylinders X and Y each contain a sample of an ideal gas. The samples are in thermal equilibrium with each other.

X has a volume of $0.0260\,m^3$ and contains 0.740 mol of gas at a pressure of $1.20 \times 10^5\,Pa$. Y has a volume of $0.0430\,m^3$ and contains gas at a pressure of $2.90 \times 10^5\,Pa$. Data for the two cylinders are shown in Fig. 2.1.

X	Y
0.740 mol	
$1.20 \times 10^5\,Pa$	$2.90 \times 10^5\,Pa$
$0.0260\,m^3$	$0.0430\,m^3$

Fig. 2.1

(i) Show that the temperature of the gas in X is 234 °C.

[3]

(ii) Determine the number *N* of molecules of the gas in Y. Explain your reasoning.

N = ... [3]

(iii) The gas in X consists of molecules that each have a mass that is four times the mass of a molecule of the gas in Y.

Explain how the root-mean-square (r.m.s.) speed of the molecules in X compares with the r.m.s. speed of the molecules in Y.

....

....

....

....

.... [3]

3 **(a)** **(i)** State what is meant by an ideal gas.

....

....

.... [2]

(ii) Use one of the basic assumptions of the kinetic theory to explain what can be deduced about the potential energy associated with the random motion of molecules in an ideal gas.

....

....

.... [2]

(b) A sample of $0.26\,m^3$ of an ideal gas is at pressure $2.0 \times 10^5\,Pa$ and temperature 290 K.

Determine:

(i) the number N of molecules of the gas

N = ... [2]

(ii) the average translational kinetic energy E_K of one molecule of the gas

E_K = ... J [2]

(iii) the internal energy of the gas. Explain your reasoning.

internal energy = ... J [2]

(c) The volume V of the gas in **(b)** is now varied, keeping its pressure constant.

On Fig. 3.1, sketch the variation with V of the internal energy U of the gas.

Fig. 3.1

[2]

2 **(a)** By referring to both kinetic energy and potential energy, explain what is meant by the internal energy of an ideal gas.

....

....

....

.... [2]

(b) A fixed mass of an ideal gas at a temperature of 20 °C is sealed in a cylinder by a piston, as shown in Fig. 2.1.

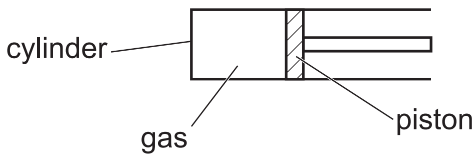

Fig. 2.1

The initial volume of the gas is $1.24 \times 10^{-4}\,\text{m}^3$.
Thermal energy is supplied to the gas and its volume increases by $5.20 \times 10^{-5}\,\text{m}^3$.

(i) The piston is freely moving so that the gas is always at atmospheric pressure.

Atmospheric pressure is $1.01 \times 10^5\,\text{Pa}$.

Calculate the work done by the gas.

work done by gas = ... J [2]

(ii) Calculate the final thermodynamic temperature T of the gas.

T = ... K [2]

(iii) The mass of the gas is 16 g. For this expansion, there is a net transfer of 960 J of thermal energy to the gas.

Calculate the specific heat capacity c of the gas at this pressure.

c = ... $J\,kg^{-1}\,K^{-1}$ [2]

(c) The gas in **(b)** is allowed to return to its starting temperature. The piston is now fixed in position.

Thermal energy is supplied to increase the temperature to the same final temperature as in **(b)**.

Use the first law of thermodynamics to suggest and explain how the specific heat capacity of the gas for this situation compares with the value in **(b)(iii)**.

....

....

....

.... [3]

2 **(a)** **(i)** Define gravitational potential at a point.

....

....

.... [2]

(ii) The Moon may be considered to be an isolated uniform sphere of mass 7.3×10^{22} kg and radius 1.7×10^{6} m.

Calculate the gravitational potential at the surface of the Moon. Give a unit with your answer.

gravitational potential = ... unit .... [2]

(b) An isolated uniform spherical planet has gravitational potential ϕ at its surface.

A particle of mass m is projected vertically upwards from the surface. The particle is given just enough kinetic energy to travel to an infinite distance away from the planet, escaping from the gravitational pull of the planet, without any additional work being done on it.

(i) Determine an expression, in terms of m and ϕ, for the gravitational potential energy E_P of the particle at the surface of the planet.

E_P = ... [1]

(ii) Show that the speed v at which the particle is projected upwards from the surface of the planet is given by

$$v = \sqrt{-2\phi}.$$

[2]

(c) A particle is moving upwards at the surface of the Moon.

Use your answer in **(a)(ii)** and the expression in **(b)(ii)** to determine the minimum speed of this particle that will result in it escaping from the gravitational pull of the Moon.

speed = ... $m\,s^{-1}$ [1]

(d) Hydrogen may be assumed to be an ideal gas.
The mass of a hydrogen molecule is 3.34×10^{-27} kg.

Calculate the root-mean-square (r.m.s.) speed of a hydrogen molecule in hydrogen gas that is at a temperature of 400 K.

r.m.s. speed = ... $m\,s^{-1}$ [3]

(e) The surface of the Moon reaches temperatures of approximately 400 K when in direct sunlight.

Use your answers in **(c)** and **(d)** to suggest a reason why the Moon does not have an atmosphere consisting of hydrogen.

....

.... [1]

3 **(a)** The product pV for an ideal gas is given by

$$pV = \frac{1}{3}Nm\langle c^2\rangle$$

where p is the pressure of the gas and V is the volume of the gas.

(i) State the meaning of the symbols N, m and $\langle c^2\rangle$ in this equation.

N: ....

m: ....

$\langle c^2\rangle$: ....
[3]

(ii) Use the equation of state for an ideal gas to show that the average translational kinetic energy E_K of a molecule of the gas at thermodynamic temperature T is given by

$$E_K = \frac{3}{2}kT.$$

[2]

(b) The surface of a star consists mainly of a gas that may be assumed to be ideal. The molecules of the gas have a root-mean-square (r.m.s.) speed of $9300\,\mathrm{m\,s^{-1}}$.

The mass of a molecule of the gas is 3.34×10^{-27} kg.

Determine, to three significant figures, the temperature of the surface of the star.

temperature = ... K [2]

(c) The radiant flux intensity of the radiation from the star in **(b)** is $2.52 \times 10^{-8}\,\mathrm{W\,m^{-2}}$ when observed at a distance of $4.16 \times 10^{16}\,\mathrm{m}$ from the star.

(i) Calculate the luminosity of the star. Give a unit with your answer.

luminosity = ... unit .... [2]

(ii) Determine the radius of the star.

radius = ... m [2]

(d) The gas at the surface of a star has a very high pressure.

Use the basic assumptions of the kinetic theory to suggest why, in practice, a gas at the surface of a star is unlikely to behave as an ideal gas.

....

....

....

.... [2]

2 **(a)** **(i)** State what is meant by an ideal gas.

....

....

.... [2]

(ii) State the temperature, in degrees Celsius, of absolute zero.

temperature = ... °C [1]

(b) A sealed vessel contains a mass of 0.0424 kg of an ideal gas at 227 °C.
The pressure of the gas is 1.37×10^5 Pa and the volume of the gas is $0.640\,m^3$.

Calculate:

(i) the number of molecules of the gas in the vessel

number of molecules = ... [3]

(ii) the mass of one molecule of the gas

mass = ... kg [1]

(iii) the root-mean-square (r.m.s.) speed *v* of the molecules of the gas.

v = ... $m\,s^{-1}$ [3]

(c) The gas in **(b)** is now cooled gradually to absolute zero.

On Fig. 2.1, sketch the variation with thermodynamic temperature T of the r.m.s. speed of the molecules of the gas.

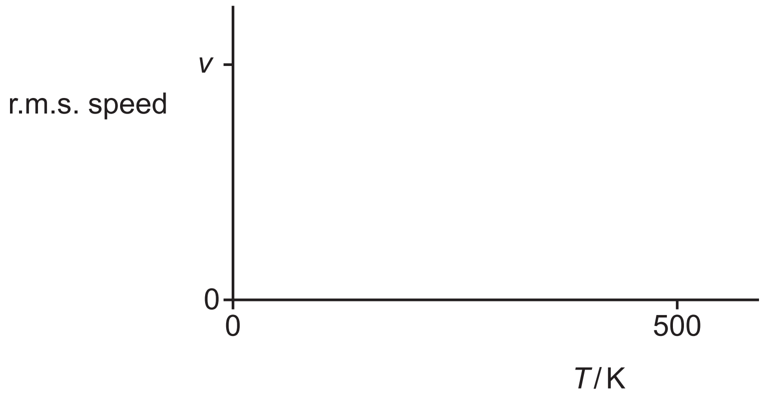

Fig. 2.1

[2]

4 **(a)** State **two** of the basic assumptions of the kinetic theory of gases.

1 ....

....

2 ....

....
[2]

(b) An ideal gas has amount of substance n.
The gas is initially in state X, with pressure $2p$ and volume V.
The gas is cooled at constant volume to state Y, with pressure p.
The gas is then heated at constant pressure to state Z, with volume $2V$.
Finally, the gas returns at constant temperature to state X.

(i) Determine an expression for the temperature T of the gas in state X, in terms of n, p and V.
Identify any other symbols that you use.

[2]

(ii) On Fig. 4.1, sketch the variation with volume of pressure for the gas as the gas undergoes the three changes. The state X is labelled. Label states Y and Z.

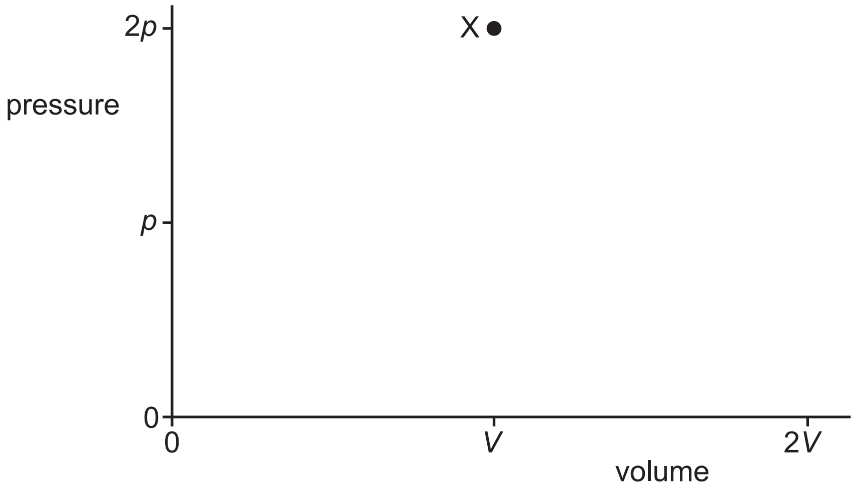

Fig. 4.1

[3]

(iii) During the change of state from Y to Z, the increase in internal energy of the gas is *U*. During the change of state from Z to X, the work done on the gas is *W*.

Complete Table 4.1 to indicate, for each of the three changes of state, the increase in internal energy of the gas, the thermal energy transferred to the gas and the work done on the gas, in terms of *p*, *V*, *U* and *W*.

Table 4.1

change	increase in internal energy of gas	thermal energy transferred to gas	work done on gas
X to Y			
Y to Z	+*U*		
Z to X			+*W*

[5]

2 **(a)** State what is meant by an ideal gas.

....

....

.... [2]

(b) A fixed amount of helium gas is sealed in a container. The helium gas has a pressure of 1.10×10^5 Pa, and a volume of $540\,cm^3$ at a temperature of $27\,°C$.

The volume of the container is rapidly decreased to $30.0\,cm^3$. The pressure of the helium gas increases to 6.70×10^6 Pa and its temperature increases to $742\,°C$, as illustrated in Fig. 2.1.

initial state	final state
1.10×10^5 Pa	6.70×10^6 Pa
$540\,cm^3$	$30.0\,cm^3$
$27\,°C$	$742\,°C$

Fig. 2.1

No thermal energy enters or leaves the helium gas during this process.

(i) Show that the helium gas behaves as an ideal gas.

[2]

(ii) The first law of thermodynamics may be expressed as

$$\Delta U = q + W.$$

Use the first law of thermodynamics to explain why the temperature of the helium gas increases.

....

....

....

....

.... [2]

(iii) The average translational kinetic energy E_K of a molecule of an ideal gas is given by

$$E_K = \frac{3}{2}kT$$

where k is the Boltzmann constant and T is the thermodynamic temperature.

Calculate the change in the total kinetic energy of the molecules of the helium gas.

change in kinetic energy = ... J [3]

(c) The mass of nitrogen gas in another container is 24.0 g at a temperature of 27 °C. The gas is cooled to its boiling point of –196 °C. Assume all the gas condenses to a liquid.

For this change the specific heat capacity of nitrogen gas is 1.04 $kJ\,kg^{-1}\,K^{-1}$.

The specific latent heat of vaporisation of nitrogen is 199 $kJ\,kg^{-1}$.

Determine the thermal energy, in kJ, removed from the nitrogen gas.

energy = ... kJ [3]

3 **(a)** The equation of state for an ideal gas can be written as

$$pV = NkT.$$

State the meaning of each of the symbols in this equation.

p: ....

V: ....

N: ....

k: ....

T: ....
[3]

(b) Use the equation in **(a)** to show that the average translational kinetic energy E_K of a molecule of an ideal gas is given by

$$E_K = \frac{3}{2}kT.$$

[2]

(c) The mass of an oxygen molecule is 5.31×10^{-26} kg. Assume that oxygen behaves as an ideal gas.

(i) Use the equation in **(b)** to determine the root-mean-square (r.m.s.) speed u of an oxygen molecule at 23 °C.

u = ... $\mathrm{m\,s^{-1}}$ [3]

(ii) A fixed mass of oxygen gas at initial pressure P is sealed in a cylindrical container by a movable piston at one end, as shown in Fig. 3.1.

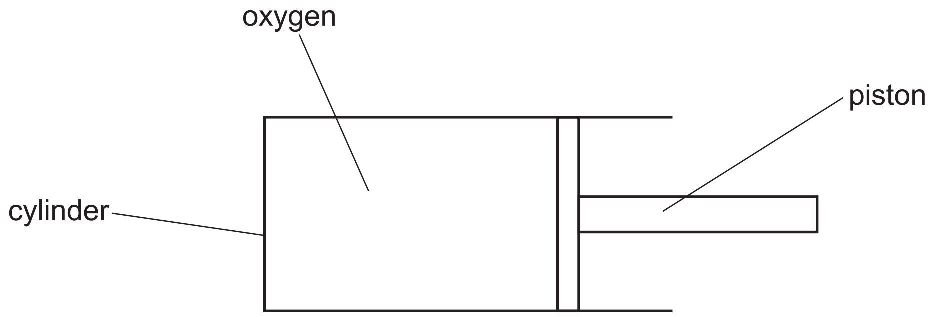

Fig. 3.1

The temperature of the gas is 23 °C.

The piston is slowly moved into the cylinder so that the oxygen gas is compressed. At all times, the gas and the container remain in thermal equilibrium with the surroundings.

On Fig. 3.2, sketch the variation with pressure of the r.m.s. speed of the oxygen molecules as the pressure increases.

Fig. 3.2

[2]