

A-level PHYSICS (7408/3BC)

Paper 3 – Section B (Engineering Physics)

Specimen 2014

Morning

Time allowed: 2 hours

Materials

For this paper you must have:

- a pencil
- a ruler
- a calculator
- a data and formulae booklet
- a question paper / answer book for Section A.

Instructions

- Answer **all** questions.
- Show **all** your working.
- The total time for both sections of this paper is 2 hours.

Information

- The maximum mark for this section is 35.

Please write clearly, in block capitals, to allow character computer recognition.

Centre number

Candidate number

Surname

Forename(s)

Candidate signature _____

Section B

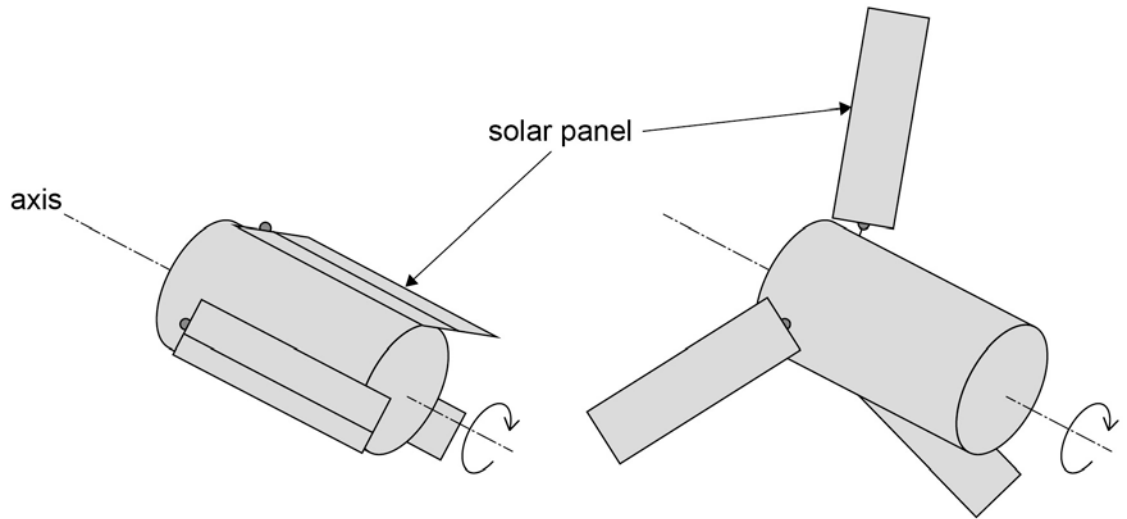
Answer **all** questions in this section.

0 1

Figure 1 shows a satellite with three solar panels folded in close to the satellite's axis for the journey into space in the hold of a cargo space craft.

Figure 1

Figure 2



Just before it is released into space, the satellite is spun to rotate at 5.2 rad s^{-1} . Once released, the solar panels are extended as shown in **Figure 2**.

moment of inertia of the satellite about its axis with panels folded = 110 kg m^2

moment of inertia of the satellite about its axis with panels extended = 230 kg m^2

0 1

. 1 State the law of conservation of angular momentum.

[1 mark]

The total angular momentum of a system remains constant, provided

no external torque acts on the system.

- 0 1 . 2** The total mass of the satellite is 390 kg and the solar panels each have a mass of 16 kg.

State what is meant by moment of inertia and explain why extending the solar panels changes the moment of inertia of the satellite by a large factor.

[3 marks]

Moment of inertia $I = \sum mr^2$; the sum of the mr^2 products for all the point masses m in the satellite, at radius r from the axis.

Extending the panels puts more of the mass at a greater radius.

The panels' m is small, but $I \propto r^2$, so a small change in r gives a large change in I .

- 0 1 . 3** Calculate the angular momentum of the satellite when it is rotating at 5.2 rad s^{-1} with the solar panels folded. State an appropriate unit for your answer.

[2 marks]

angular momentum $L = I\omega$

$$L = 110 \times 5.2 = 572$$

angular momentum = 572 unit N m s

- 0 1 . 4** Calculate the angular speed of the satellite after the solar panels have been fully extended.

[2 marks]

conservation of angular momentum: $I_1\omega_1 = I_2\omega_2$

$$572 = 230 \times \omega_2$$

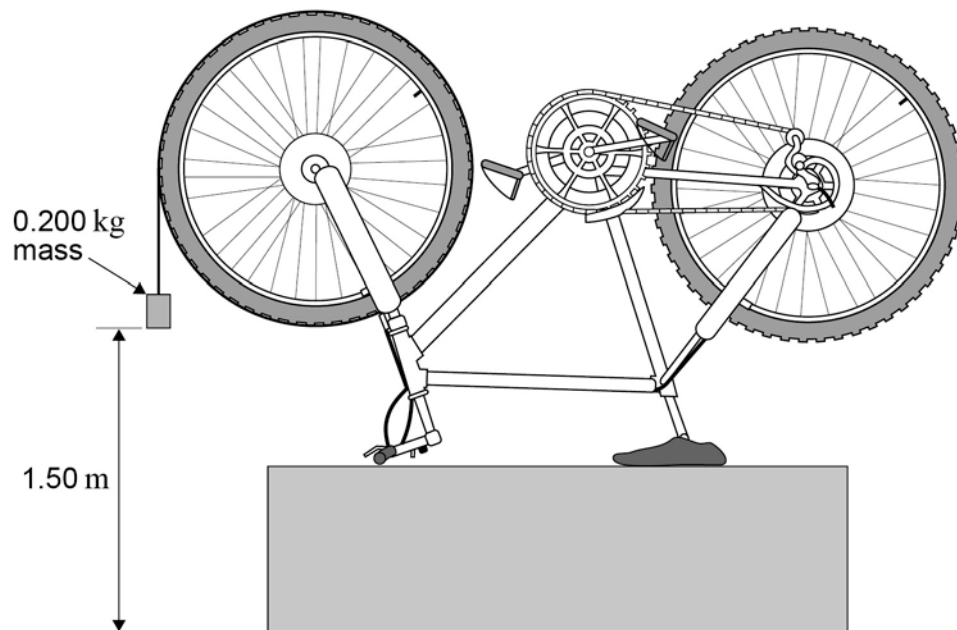
$$\omega_2 = 572 \div 230 = 2.49 \text{ rad s}^{-1}$$

angular speed = 2.49 rad s^{-1}

0 2

Figure 3 shows an experiment to determine the moment of inertia of a bicycle wheel. One end of a length of strong thread is attached to the tyre. The thread is wrapped around the wheel and a 0.200 kg mass is attached to the free end. The wheel is held so that the mass is at a height of 1.50 m above the floor. The wheel is released and the time taken for the mass to reach the floor is measured.

Figure 3



0 2

. 1

State the energy transfers that take place from the moment the wheel is released until the mass hits the floor.

[2 marks]

The gravitational potential energy of the falling mass is converted into translational (linear) kinetic energy of the mass and rotational kinetic energy of the wheel.

Some energy is also transferred to internal energy (heating) in the bearings and the air around the wheel, due to friction.

0 2 . 2 Calculations based on the measurements made show that at the instant the mass hits the floor:

- the speed of the mass is 2.22 m s^{-1}
- the wheel is rotating at 6.73 rad s^{-1}
- the wheel has turned through an angle of 4.55 rad from the point of release.

A separate experiment shows that a constant frictional torque of $7.50 \times 10^{-3} \text{ N m}$ acts on the wheel when it is rotating.

By considering the energy changes in the system, show that the moment of inertia of the wheel about its axis is approximately 0.1 kg m^2 .

[3 marks]

loss of $E_p = \text{gain in } \frac{1}{2}mv^2 + \text{gain in } \frac{1}{2}I\omega^2 + \text{work against friction } T\theta$

$$mgh = \frac{1}{2}mv^2 + \frac{1}{2}I\omega^2 + T\theta$$

$$0.200 \times 9.81 \times 1.50 = (0.5 \times 0.200 \times 2.22^2) + (0.5 \times I \times 6.73^2) + (7.50 \times 10^{-3} \times 4.55)$$

$$2.94 \text{ J} = 0.493 \text{ J} + 22.6 \text{ J} + 0.0341 \text{ J}$$

$$I = (2.94 - 0.493 - 0.034) \div 22.6 = 2.41 \div 22.6 = 0.107 \text{ kg m}^2 \approx 0.1 \text{ kg m}^2$$

0 2 . 3 When the mass hits the floor the thread is released from the wheel.

Calculate the angle turned through by the wheel before it comes to rest after the thread is released.

[2 marks]

$$\alpha = T / I = 7.50 \times 10^{-3} \div 0.107 = 0.0701 \text{ rad s}^{-2} \text{ (deceleration)}$$

$$\omega_2^2 = \omega_1^2 - 2\alpha\theta \text{ with } \omega_2 = 0, \omega_1 = 6.73 \text{ rad s}^{-1}$$

$$0 = 6.73^2 - 2 \times 0.0701 \times \theta$$

$$\theta = 45.3 \div 0.140 = 323 \text{ rad}$$

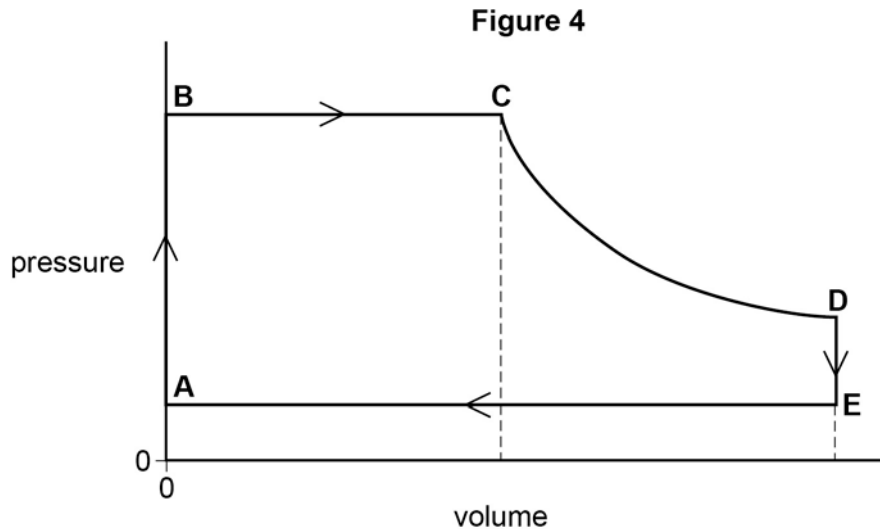
angle = 323 rad

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0 3

A single-cylinder air motor running on compressed air has the theoretical indicator diagram shown in **Figure 4**.



- From **B** to **C** the high-pressure air pushes a piston down a cylinder, doing work.
- At **C**, a valve cuts off the supply of air and the air in the motor expands adiabatically to **D**, pushing the piston further down the cylinder.
- At **D** an exhaust valve opens and from **D** to **E** to **A** the air is exhausted to the surrounding atmosphere as the piston moves up the cylinder.
- At **A** the exhaust valve closes and the inlet valve opens connecting the cylinder to the supply of compressed air.

0 3

. 1

Use the first law of thermodynamics to explain why the temperature falls during the adiabatic change between **C** and **D**.

[3 marks]

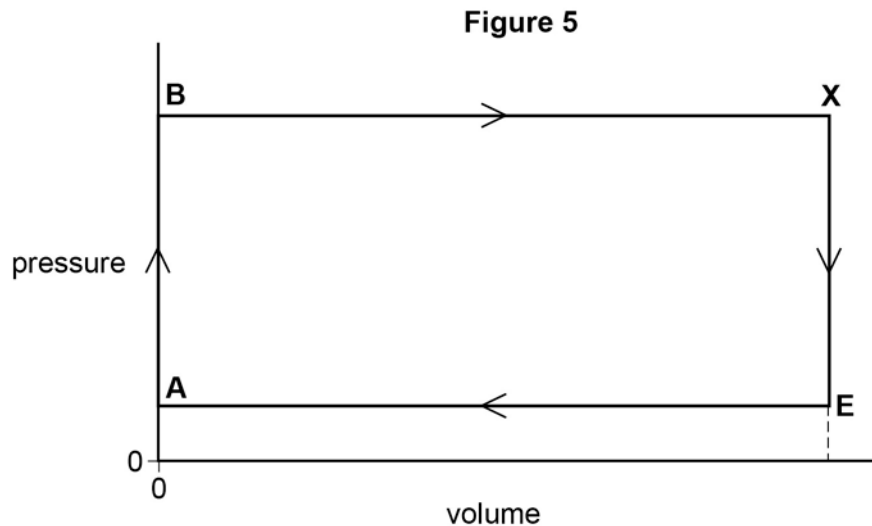
First law: $Q = \Delta U + W$, where W is the work done by the gas. For an adiabatic change $Q = 0$, so $W = -\Delta U$.

From C to D the air expands and does work on the piston, so W is positive and ΔU is negative: the internal energy decreases.

Internal energy depends on temperature (molecular k.e.), so T falls.

0 3 . 2

In practice the cut-off point **C** can be altered without changing points **A**, **B** and **E**. **Figure 5** shows the theoretical indicator diagram of the motor when the air is admitted for the complete stroke, so that the inlet valve opens at **A** and closes at **X**. The exhaust valve opens at **X** and closes at **A**.



Compare **Figures 4** and **5** and discuss the effect this change has on the operation of the motor, assuming that it continues to run at about the same speed and with air at the same pressure.

You should include in your answer how the change affects:

- the rate of consumption of air
- the output torque and power
- the overall efficiency.

[6 marks]

Rate of consumption of air: in Figure 4 air enters the cylinder only from A to B to C, but in Figure 5 the inlet valve stays open for the whole stroke, from A to B to X. The volume of compressed air admitted per cycle increases from the volume at C (about half of the swept volume) to the full volume at X, so the air consumption per cycle is roughly doubled. At the same speed the rate of consumption of air, and hence the input power, is roughly doubled.

Output torque and power: the work done per cycle is the area enclosed by the indicator diagram. The area of Figure 5 is greater than the area of Figure 4, because the region under the adiabatic curve C to D is replaced by the full rectangle up to X. So the output power is increased, but not as much as doubled: comparing the areas, the work per cycle,

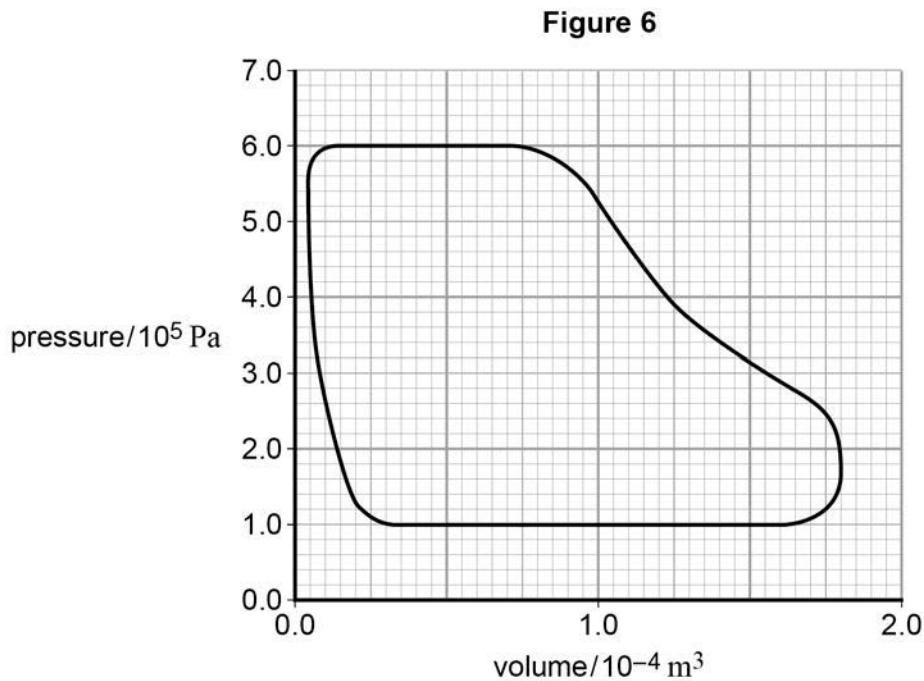
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and so the output power, increases by only about 25%.

The average pressure on the piston during the stroke is greater, so the average force and therefore the output torque are greater. Since $P = T\omega$ and the angular speed ω is about the same (the motor runs at the same speed), the greater output power means a greater torque; this comparison is only valid if the speed stays the same as before.

Overall efficiency: efficiency = useful output power $\div$ input power. The input power (rate of supply of compressed air) is roughly doubled but the output power increases by only about 25%. In Figure 5 the air is exhausted at X while still at high pressure, so energy that could have been used during the adiabatic expansion is wasted. Hence the overall efficiency of the motor decreases.

Figure 6 shows the actual indicator diagram for the air motor.



- 0 3 . 3** The motor was running at 20 cycles per second when the indicator diagram was recorded.

Determine the indicated power of the motor.

[4 marks]

work done per cycle = area enclosed by the indicator diagram

1 small square = $0.05 \times 10^{-4} \text{ m}^3 \times 0.2 \times 10^5 \text{ Pa} = 0.1 \text{ J}$ (1 large square = 2.5 J)

counting squares: about 641 small squares enclosed (≈ 27 large squares)

work per cycle = $641 \times 0.1 = 64 \text{ J}$

$P = 64 \times 20 = 1280 \text{ W}$

1280
power = _____ W

- 0 3 . 4** Explain why the indicated power for the air motor is different from the output power.

[1 mark]

The indicated power is the power developed by the air in the cylinder; it does not take into account the frictional losses at the bearings, between the cylinder and piston, and in opening the valves, so the output power is less.

Turn over ►

0 4

A company claims to be able to provide a combined heat and power plant for a market garden that requires both electrical power and space heating for greenhouses. The engine-driven generator will operate between temperatures of 1450 K and 310 K.

0 4

. 1

Show that the maximum theoretical efficiency of any heat engine operating between temperatures of 1450 K and 310 K is about 80%.

[1 mark]

$$\text{maximum efficiency } \eta = (T_H - T_C) / T_H$$

$$\eta = (1450 - 310) / 1450 = 1140 / 1450$$

$$\eta = 0.79 = 79\%, \text{ which is about } 80\%$$

0 4 . 2

The company makes the following two claims about the performance of the plant:

- **Claim 1** When consuming biogas of calorific value 55.5 MJ m^{-3} at the rate of $5.00 \times 10^{-3} \text{ m}^3 \text{ s}^{-1}$, the electrical power output will be 210 kW.
- **Claim 2** At the same time the engine will provide heating for greenhouses at the rate of at least 55.0 kW.

Discuss the extent to which the company's claims are justified.

[5 marks]

Claim 1: input power = calorific value $\times$ rate of consumption = $55.5 \times$

$10^6 \times 5.00 \times 10^{-3} = 2.78 \times 10^5 \text{ W} = 278 \text{ kW}.$

Actual claimed efficiency = $210 \div 278 = 0.76$ (76%).

This is too close to the maximum theoretical efficiency of 79%. No real engine can get this close, because of friction and other energy losses, so claim 1 is not justified. (Even running at the maximum efficiency the electrical power would only be $0.79 \times 278 = 218 \text{ kW}.$)

Claim 2: if 210 kW is output as electrical power, the heat rejected = $278 \text{ kW} - 210 \text{ kW} = 68 \text{ kW}.$

Claim 2 is justified because $55 \text{ kW} < 68 \text{ kW}$, which allows for some unwanted energy loss to the surroundings. Also, any real efficiency lower than 79% will give more than 68 kW of heating, so claim 2 is justified.

END OF QUESTIONS

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