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Centre number

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Candidate number

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Surname

StemUp Model Solution

Forename(s)

Candidate signature

I declare this is my own work.

A-level PHYSICS

Paper 3

Section B Engineering physics

Materials

For this paper you must have:

- a pencil and a ruler
- a scientific calculator
- a Data and Formulae Booklet
- a protractor.

Instructions

- Use black ink or black ball-point pen.
- Fill in the boxes at the top of this page.
- Answer **all** questions.
- You must answer the questions in the spaces provided. Do not write outside the box around each page or on blank pages.
- If you need extra space for your answer(s), use the lined pages at the end of this book. Write the question number against your answer(s).
- Do **all** rough work in this book. Cross through any work you do not want to be marked.
- Show **all** your working.

Information

- The marks for questions are shown in brackets.
- The maximum mark for this paper is 35.
- You are expected to use a scientific calculator where appropriate.
- A Data and Formulae Booklet is provided as a loose insert.

Time allowed: The total time for both sections of this paper is 2 hours. You are advised to spend approximately 50 minutes on this section.

For Examiner's Use

Question	Mark
1	
2	
3	
4	
5	
TOTAL	



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Section B

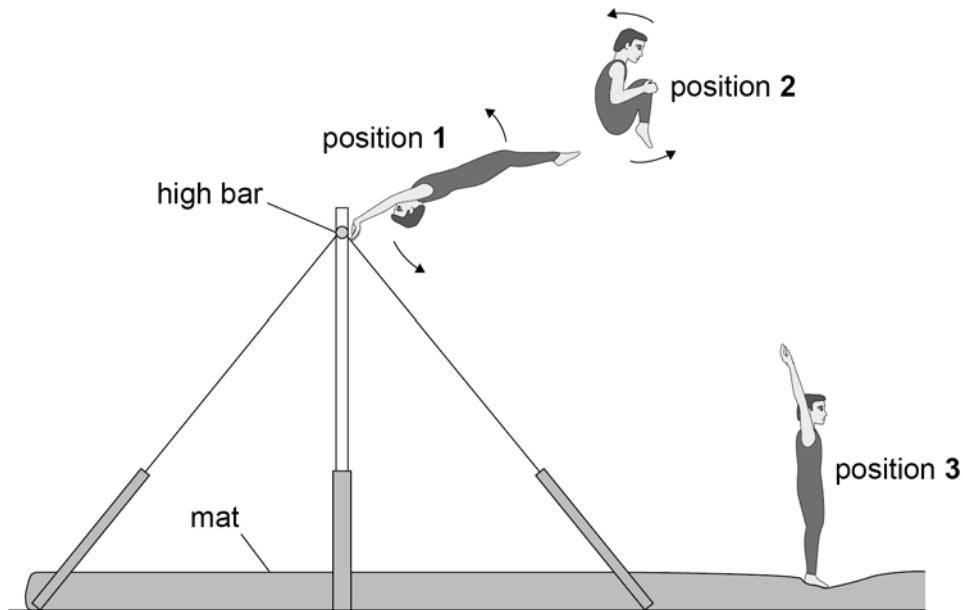
Answer **all** questions in this section.

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A gymnast dismounts from an exercise in which he swings on a high bar. The gymnast rotates in the air before landing.

Figure 1 shows the gymnast in three positions during the dismount.

Figure 1



The arrows show the direction of rotation of the gymnast.

In **position 1** the gymnast has just let go of the bar. His body is **fully** extended.

Position 2 shows the rotating gymnast a short time later. His knees have been brought close to his chest into a 'tuck'.

Position 3 is at the end of the dismount as the gymnast lands on the mat. His body is once again **fully** extended.



0 1 . 1

Explain why the moment of inertia about the axis of rotation decreases when his knees are moved towards his chest.

Go on to explain the effect this has on his angular speed.

[3 marks]

When his knees are moved towards his chest, more of his mass is closer to the axis of rotation (the mass is distributed nearer the axis), so the moment of inertia $I = \sum mr^2$ decreases.

There is no external torque acting on him in the air, so his angular momentum $I\omega$ is conserved (constant).

Since I decreases, his angular speed ω must increase.

Table 1 gives some data about the gymnast in position 1 and in position 2.

Table 1

Position	Moment of inertia / kg m ²	Angular speed / rad s ⁻¹
1	13.5	ω
2	4.1	14.2

0 1 . 2

Calculate the angular speed ω of the gymnast in position 1.

[1 mark]

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

$$13.5 \times \omega = 4.1 \times 14.2$$

$$\omega = (4.1 \times 14.2) \div 13.5 = 4.3 \text{ rad s}^{-1}$$

$$\omega = \underline{4.3} \text{ rad s}^{-1}$$

Question 1 continues on the next page

Turn over ►



0 1 . 3

The gymnast stays in the tuck for 1.2 s.

Determine the number of **complete** rotations performed by the gymnast when in the tuck during the dismount.

[2 marks]

$$\text{Angle turned in 1.2 s: } \theta = \omega t = 14.2 \times 1.2 = 17.04 \text{ rad}$$

$$\text{Number of rotations} = 17.04 \div 2\pi = 2.7 \text{ rotations}$$

$$(\text{time for one rotation} = 2\pi \div 14.2 = 0.442 \text{ s}, 1.2 \div 0.442 = 2.7)$$

so 2 complete rotations (not rounded up)

number of complete rotations = 2

0 1 . 4

The gymnast repeats the exercise. The height of the bar remains unchanged.

State and explain **two** actions the gymnast can take to complete more rotations during the dismount.

[4 marks]

1 Build up a greater initial angular speed around the bar before letting
go, so he leaves the bar faster and reaches a greater height, giving
more time in the air, and he also rotates faster in the tuck.

2 Get into the tuck position earlier and get out of it later, so he spends
more time turning at the high angular speed. Also get into a tighter
tuck, which reduces I_2 and so increases ω_2 .

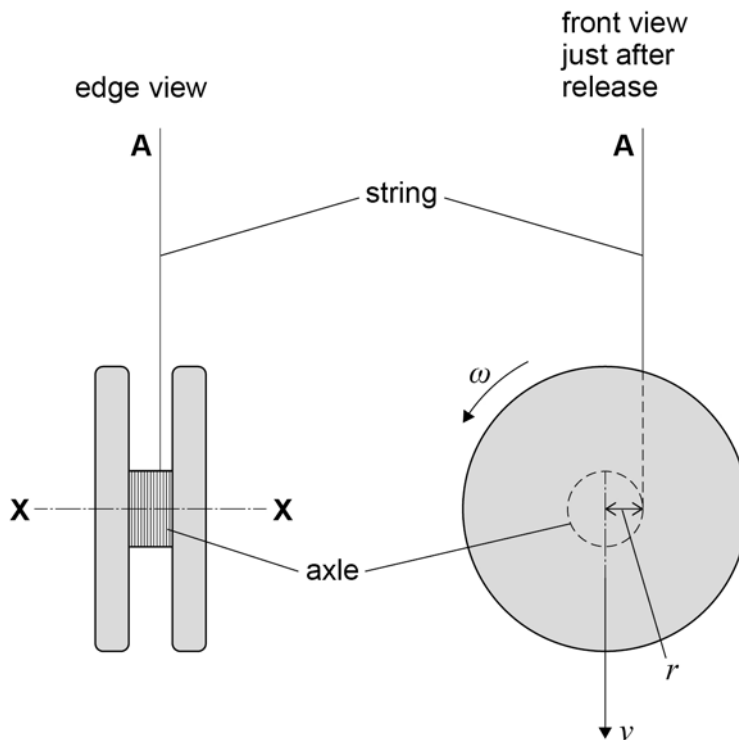


0 2

Figure 2 shows a yo-yo made of two discs separated by a cylindrical axle. Thin string is wrapped tightly around the axle.

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Figure 2



Initially both the free end **A** of the string and the yo-yo are held stationary.

With **A** remaining stationary, the yo-yo is now released so that it falls vertically. As the yo-yo falls, the string unwinds from the axle so that the yo-yo spins about its centre of mass.

The linear velocity v of the centre of mass of the falling yo-yo is related to the angular velocity ω by $v = r\omega$ where r is the radius of the axle.

Question 2 continues on the next page

Turn over ►



0 2 . 1

The yo-yo accelerates uniformly as it falls from rest. The string remains taut and has negligible thickness.

$$\text{mass of yo-yo} = 9.2 \times 10^{-2} \text{ kg}$$

$$\text{radius of axle} = 5.0 \times 10^{-3} \text{ m}$$

$$\text{moment of inertia of yo-yo about axis X-X} = 8.6 \times 10^{-5} \text{ kg m}^2$$

When the yo-yo has fallen a distance of 0.50 m, its linear velocity is V .

Calculate V by considering the energy transfers that occur during the fall.

[3 marks]

$$\text{Loss of } E_p = \text{gain in linear } E_k + \text{gain in rotational } E_k$$

$$mgh = \frac{1}{2}mV^2 + \frac{1}{2}I\omega^2, \text{ with } \omega = V \div r$$

$$9.2 \times 10^{-2} \times 9.81 \times 0.50 = (\frac{1}{2} \times 9.2 \times 10^{-2} \times V^2) + (\frac{1}{2} \times 8.6 \times 10^{-5} \times V^2 \div 0.005^2)$$

$$0.451 = 0.046V^2 + 1.72V^2 = 1.766V^2$$

$$V^2 = 0.451 \div 1.766 = 0.256$$

$$V = 0.51 \text{ m s}^{-1}$$

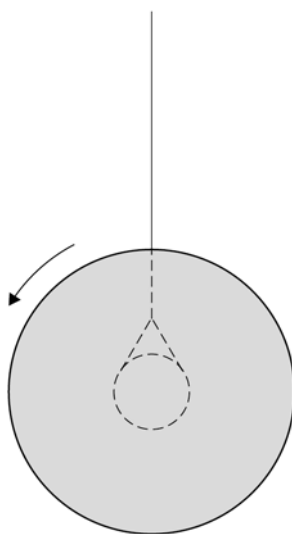
$$V = \underline{\quad 0.51 \quad} \text{ m s}^{-1}$$



0 2 . 2

The yo-yo falls further until **all** the string is unwound. The yo-yo then 'sleeps'. This means the yo-yo continues to rotate in a loose loop of string as shown in **Figure 3**.

Figure 3



The string applies a constant frictional torque of $8.3 \times 10^{-4} \text{ N m}$ to the axle. The angular velocity of the yo-yo at the start of the sleep is 145 rad s^{-1} .

Determine, in rad, the **total angle** turned through by the yo-yo during the first 10 s of sleeping.

[3 marks]

$$\text{Angular deceleration } \alpha = T \div I = 8.3 \times 10^{-4} \div 8.6 \times 10^{-5}$$

$$\alpha = 9.65 \text{ rad s}^{-2}$$

$$(\omega \text{ reaches zero after } 145 \div 9.65 = 15 \text{ s, so it is still turning at } 10 \text{ s})$$

$$\theta = \omega t + \frac{1}{2} \alpha t^2 = (145 \times 10) - (\frac{1}{2} \times 9.65 \times 10^2)$$

$$\theta = 1450 - 483 = 967 \text{ rad}$$

angle = 967 rad

6

Turn over ►



0 3

Figure 4 shows the results of a test on an internal combustion engine which uses purified biogas.

Figure 4

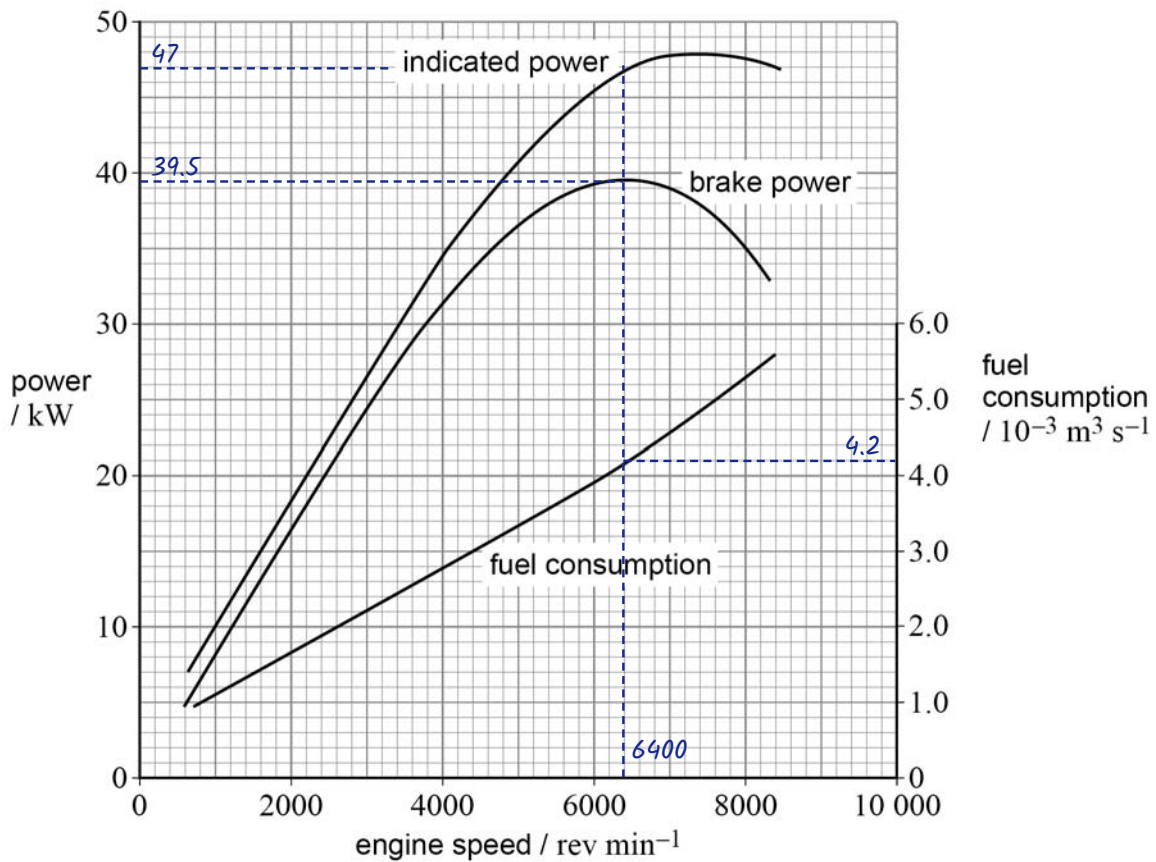


Figure 4 shows how the indicated power, brake (or output) power and fuel consumption of the engine vary with the engine speed. The scale on the left-hand axis is power and the scale on the right-hand axis is fuel consumption.



0 3 1

Figure 4 can be used to analyse the performance of the engine.

Determine, for the speed at which the engine develops its maximum brake power:

- the overall efficiency
- the thermal efficiency
- the mechanical efficiency.

Go on to explain how knowledge of these efficiencies can be useful to an engineer.

calorific value of biogas used in the test = $32.3 \times 10^6 \text{ J m}^{-3}$

[6 marks]

Maximum brake power = 39.5 kW at about 6400 rev min⁻¹

At 6400 rev min⁻¹: indicated power = 47 kW, fuel consumption = $4.2 \times 10^{-3} \text{ m}^3 \text{ s}^{-1}$

Input power = fuel flow $\times$ calorific value = $4.2 \times 10^{-3} \times 32.3 \times 10^6 = 136 \text{ kW}$

Overall efficiency = brake power $\div$ input power = $39.5 \div 136 = 0.29$

Thermal efficiency = indicated power $\div$ input power = $47 \div 136 = 0.35$

Mechanical efficiency = brake power $\div$ indicated power = $39.5 \div 47 = 0.84$

(check: $0.35 \times 0.84 = 0.29$)

Friction power = indicated – brake = $47 - 39.5 = 7.5 \text{ kW}$

Usefulness of these efficiencies to an engineer:

The thermal efficiency (0.35) shows how well the energy from the calorific value of the fuel is converted into work (indicated power) done on the pistons inside the engine. A low value tells the engineer to improve the combustion or thermodynamic cycle, e.g. compression ratio, ignition timing or reducing heat losses.

The mechanical efficiency (0.84) shows how much of the indicated power is lost in overcoming friction and viscous forces inside the engine, and in work done to operate the valves, water and oil pumps etc. (7.5

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kW here). A low value tells the engineer to improve lubrication, bearings or reduce moving parts.

The overall efficiency (0.29) gives an idea of how well the energy in the fuel is converted into useful work output at the shaft, so it can be used to compare engines and running costs. Knowing the separate efficiencies shows where the losses are, so the engineer knows which part of the engine to improve.



0 3 . 2

Explain why it is **not** advisable to run this engine at speeds above $7000 \text{ rev min}^{-1}$. Refer to **Figure 4** in your answer.

[2 marks]

Above $7000 \text{ rev min}^{-1}$ the brake power drops, while the input power continues to increase, as shown by the fuel consumption curve, which keeps rising. Also the indicated power flattens off while fuel consumption increases.

So the overall (and thermal and mechanical) efficiency decreases: more fuel is used for less useful output. This is because the friction power increases at high engine speeds (more work is done against friction and viscosity, and lubrication may break down).

8

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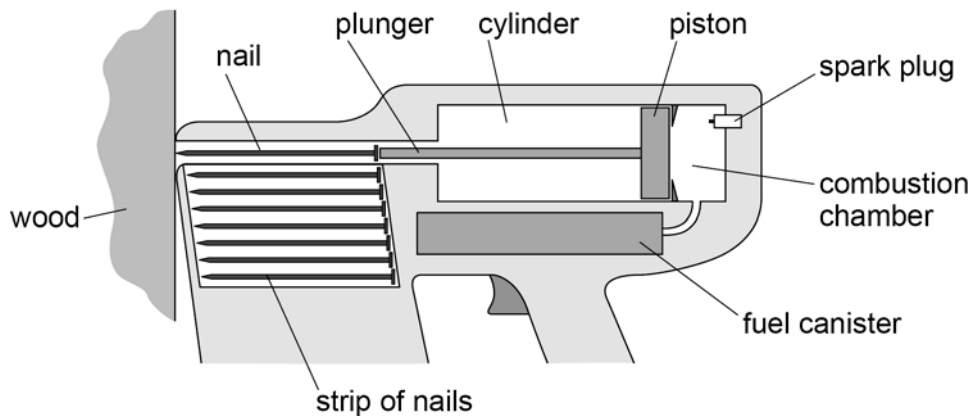
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0 4

Figure 5 shows a tool for driving nails into wood. Only part of the tool is shown.

Figure 5



Fuel is mixed with air in the combustion chamber and is ignited by a spark. The gas expands rapidly and drives the piston along the cylinder. The plunger attached to the piston drives the nail into the wood.

Table 2 shows the average force needed to drive nails of various lengths completely into a particular type of wood.

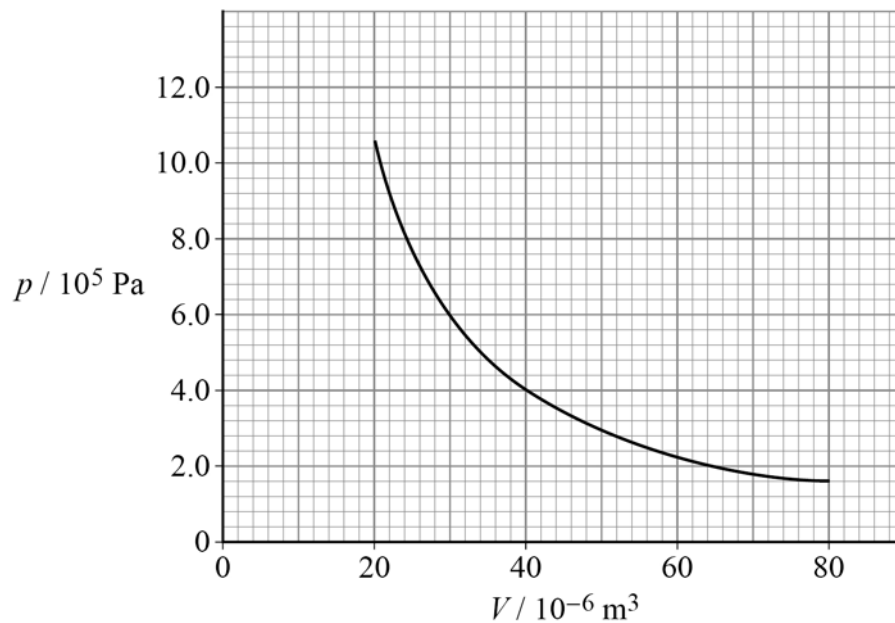
Table 2

Nail	Length / mm	Average force / N
A	32	250
B	38	320
C	45	370
D	50	420
E	63	560



0 4 . 1

Figure 6 shows the variation of pressure p with volume V as the gas expands on the right-hand side of the piston when the correct nail is used.

Figure 6

The combustion chamber has a volume of $20 \times 10^{-6} \text{ m}^3$ and the piston moves through a volume of $60 \times 10^{-6} \text{ m}^3$.

The work done by the expanding gas is just enough to drive the correct nail completely into the wood.

Deduce which nail in **Table 2** is the correct one to use in the tool.

[5 marks]

Work done by gas = area under p - V graph from $V = 20$ to $80 \times 10^{-6} \text{ m}^3$

1 large square = $2.0 \times 10^5 \text{ Pa} \times 10 \times 10^{-6} \text{ m}^3 = 2.0 \text{ J}$

9 large squares = 18 J, 67 small squares = $67 \times 2 \div 25 = 5.4 \text{ J}$, total $\approx 23 \text{ J}$

Work to drive nail = $F \times s$:

C: $370 \times 0.045 = 16.7 \text{ J}$, D: $420 \times 0.050 = 21.0 \text{ J}$, E: $560 \times 0.063 = 35.3 \text{ J}$

Nail D needs 21 J of work, just under the 23 J done by the gas, while nail E needs much more (35 J), so the expansion roughly matches the energy needed: nail D is the correct nail.

Question 4 continues on the next page

Turn over ►



0 4 . 2

After a nail has been used, another nail takes its place automatically. The tool can drive up to 180 nails per minute.

Discuss why the expansion **cannot** be isothermal.

[3 marks]

An isothermal expansion requires a relatively long time for the expansion to take place: the process must occur slowly.

This is because the gas does work as it expands, so to keep its temperature (internal energy) constant, energy must be transferred into the gas by heating (Q) from the surroundings, which takes time.

At 180 nails per minute each nail is fired in less than $1/3$ second, so the expansion is very fast and there is not enough time for this energy transfer. The process is close to adiabatic, so it cannot be isothermal.

8



0 5 . 1

Which is a correct statement about an ideal heat engine?

Tick (✓) **one** box.

[1 mark]

The efficiency is increased when the kelvin temperatures of the hot source and the cold sink are increased by equal amounts.

☐

The maximum efficiency depends on the p – V cycle.

☐

The efficiency is 50% when the kelvin temperature of the hot source is twice the kelvin temperature of the cold sink.

☒

0 5 . 2

An ideal heat engine has an efficiency of 0.33

The same engine works in reverse as an ideal refrigerator between the same hot and cold spaces.

Determine the coefficient of performance COP_{ref} of the refrigerator.

[2 marks]

$$\text{Efficiency} = W \div Q_H = 0.33, \text{ so } Q_H = 3W$$

$$Q_C = Q_H - W = 3W - W = 2W$$

$$\text{In reverse, as a refrigerator: } COP_{ref} = Q_C \div W$$

$$COP_{ref} = 2W \div W = 2$$

$$COP_{ref} = \underline{\hspace{2cm} 2 \hspace{2cm}}$$

3

END OF QUESTIONS



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