Q1. In an ideal 'hot air' engine, a fixed mass of air is continuously taken through the following four processes:

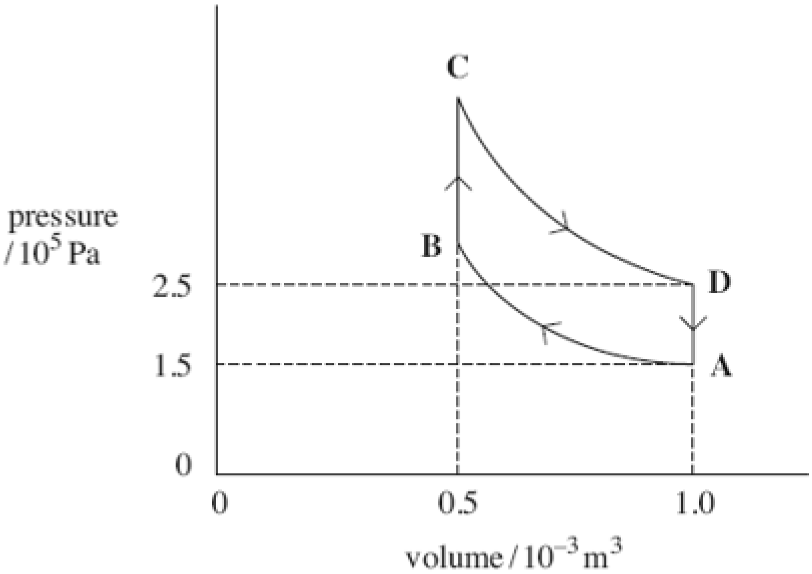
A → B isothermal compression at a temperature of 300 K. The work done on the air is 104 J.

B → C heating at constant volume.

C → D isothermal expansion. The work done by the expanding air is 173 J.

D → A cooling at constant volume.

The cycle is shown in the figure below.



(a) (i) Show that the temperature of the air at point D is 500 K.

(2)

(ii) Apply the first law of thermodynamics to calculate the energy supplied by heat transfer in process C → D.

answer = ... J

(2)

(b) The engine contains a device called a regenerator which stores **all** the energy rejected by cooling in process D → A and gives up **all** this energy to the air again in process B → C. This means that energy must be supplied to the air by heat transfer from an external source **only** in process C → D.

(i) Calculate the net work done during the cycle.

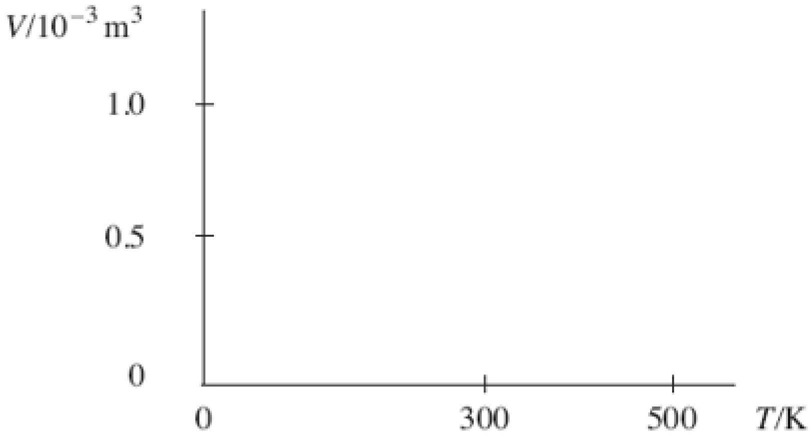
answer = ... J

(1)

(ii) Show that the efficiency of the cycle is the same as the maximum possible efficiency of any heat engine operating between the same highest and lowest temperatures in the cycle.

(2)

(c) On the axes below, sketch the cycle on a graph of volume *V* against temperature *T*. Label the points A, B, C and D.



(2)

(d) Several inventors have tried to build an engine that works on this cycle. Give **two** reasons why they have been unsuccessful.

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(2)
(Total 11 marks)

Q2. An inventor has designed a gas engine for a small combined heat and power plant which will operate between temperatures of 1400 K and 360 K. The inventor makes two claims about the performance of the engine:

claim 1 When the engine consumes gas of calorific value 36 MJ kg^{-1} at a rate of 9.6 kg h^{-1}, it will deliver a useful mechanical output power of 80 kW.

claim 2 At the same time, the engine will also provide energy at the rate of at least 20 kW for heating purposes.

(a) Show that the input power to the engine is approximately 100 kW.

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(2)

(b) Calculate the maximum possible efficiency of any heat engine which operates between temperatures of 1400 K and 360 K.

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(1)

(c) Using the result of your calculation in part (b) and any other necessary calculations, explain whether either or both of the inventor's claims are justified. You may be awarded marks for the quality of written communication in your answer.

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(4)
(Total 7 marks)

Q3. A spray can contains liquid paint with compressed gas in the space above it, as shown in **Figure 1**. Pressing down the cap opens a valve which allows the gas to expand, forcing paint through the nozzle. The cap is pressed until all the paint is expelled, leaving the can filled with gas at a pressure which is still greater than atmospheric.

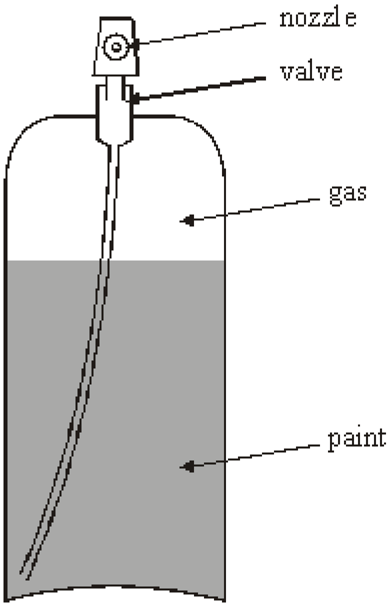

Figure 1

(a) The can has an internal volume of $6.6 \times 10^{-4} m^3$ and initially contains $5.0 \times 10^{-4} m^3$ of paint. The gas in the can is at an initial pressure of 7.8×10^5 Pa. The pressure of the gas left in the can when all the paint has just been expelled is 1.9×10^5 Pa. Show that the expansion of the gas was an approximately isothermal process.

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(2)

(b) The cap is now pressed again to open the valve and is held down to allow the gas to expand rapidly into the air around the can. The atmospheric pressure is 9.8×10^4 Pa and the temperature of the gas at the start of the expansion is 22 °C.

(i) Explain why this expansion can be considered to be approximately adiabatic.

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(ii) Calculate the total volume that the gas would occupy if it were collected at atmospheric pressure immediately after the expansion.

γ for the gas = 1.4

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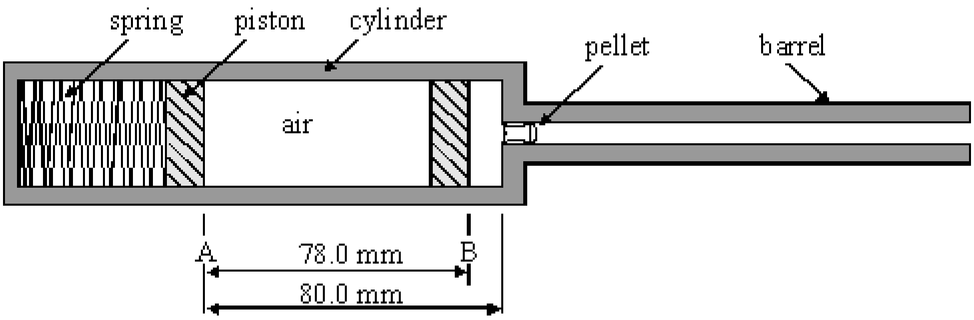
(3)
(Total 5 marks)

Q4. The diagram shows the mechanism of an air gun. The energy needed to propel the pellet is stored in a spring which is held in compression by a trigger. Pulling the trigger releases the spring, which pushes the piston rapidly along the cylinder from A to B. This compresses the air behind the pellet, exerting a force on it and causing it to accelerate along the barrel.



When the piston is at A, the air in the cylinder is at a pressure of 103 kPa and a temperature of 291 K. After the spring is released, the pellet remains in place until the piston reaches B.

(a) (i) The internal cross-sectional area of the cylinder is 1.77×10^{-4} m^2. Calculate the quantity of air, in moles, contained in the cylinder.

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(ii) Estimate the pressure of the air in the cylinder when the piston has just reached B.

γ for air = 1.4

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(iii) Estimate the temperature of the air in the cylinder when the piston has just reached B.

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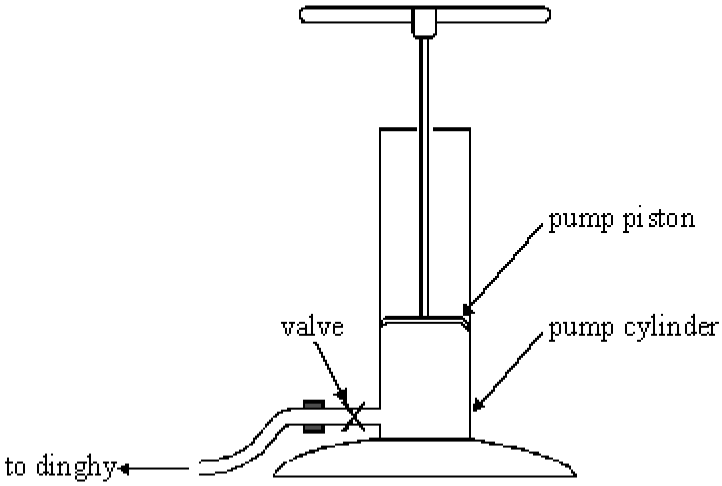
(Total 6 marks)

Q5. The diagram below shows a pump used to inflate a rubber dinghy. When the piston is pushed down, the pressure of air in the cylinder increases until it reaches the pressure of the air in the dinghy. At this pressure the valve opens and air flows at almost constant pressure into the dinghy.



(a) The pump is operated quickly so the compression of the air in the cylinder before the valve opens can be considered adiabatic.
At the start of a pump stroke, the pump cylinder contains 4.25×10^{-4} m^3 of air at a pressure of 1.01×10^5 Pa and a temperature of 23 °C. The pressure of air in the dinghy is 1.70×10^5 Pa.

Show that, when the valve is about to open, the volume of air in the pump is 2.93×10^{-4} m^3.

γ for air = 1.4

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(2)

(b) Calculate the temperature of the air in the pump when the valve is about to open.

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(3)

(c) State, explaining your reasons, whether the volume of air in the cylinder at the point when the valve opens would be less than, equal to or greater than 2.93×10^{-4} m^3 if the compression of the air had been carried out very slowly. You may find it helpful to sketch a *pV* diagram of the compression.

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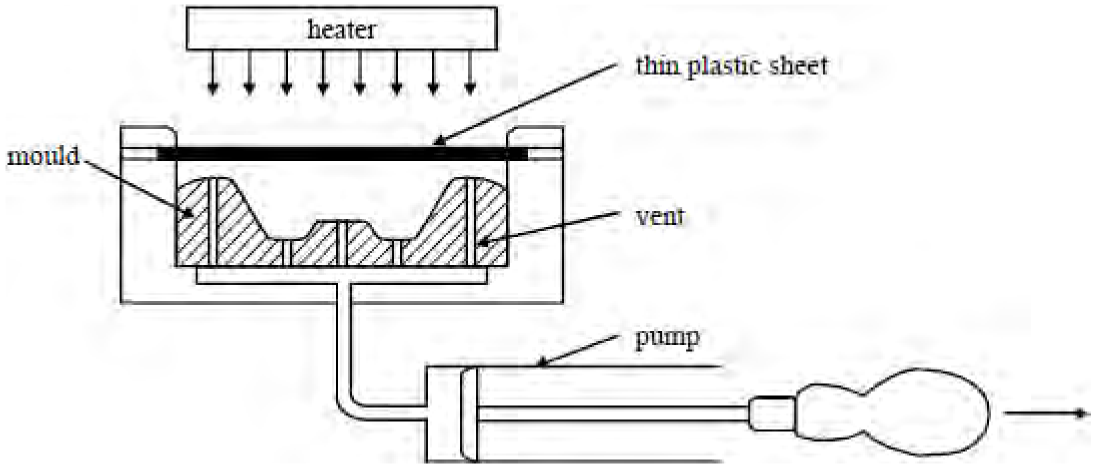
(3)
(Total 8 marks)

Q6. The diagram shows a section through a simple vacuum-forming machine for shaping a thin sheet of a thermoplastic material. The material is first softened by radiant heat from a heater mounted above it, and then forced into the cavity below, where it takes the shape of a wooden mould.

The force is applied by pulling back the pump handle quickly, causing a rapid expansion of the enclosed air which results in a sharp drop in pressure. The force arises from the difference in pressure between the atmosphere and the air in the cavity.



(a) To avoid the possibility of blistering the plastic sheet, the heater is left at low power until the plastic is soft enough to form. After the forming operation, the plastic is found to have developed cracks in its lower surface, which suggests that this surface was cooled during the operation.

Use the first law of thermodynamics, in the form $\Delta Q = \Delta U + \Delta W$, to explain why the rapid expansion of the air should cause it to cool.

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(3)

(b) The air in the cavity is initially at a pressure of 100 kPa and a temperature of 313K. When the pump is operated it expands adiabatically to 1.7 times its original volume before the plastic begins to move.

γ for air = 1.4

(i) Calculate the pressure of the air in the cavity just before the sheet begins to move.

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(ii) Calculate the temperature of the air at this stage.

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(5)

(c) State, with reasons, whether the air pressure in the cavity at the end of the pumping stroke would be higher or lower than that calculated in part (b) if the pump were operated slowly. Further calculation is not required, but a p–V sketch graph may be helpful.

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(2)
(Total 10 marks)