TVET CURRICULUM DEVELOPMENT, ASSESSMENT AND CERTIFICATION COUNCIL (TVET CDACC)

Qualification Code : 071606T4MCT

Qualification : Mechatronics Technician Level 6

Unit Code : ENG/OS/MC/CC/06/6/A

Unit of Competency : Apply Thermodynamics Principles

WRITTEN ASSESSMENT ASSESSOR'S GUIDE

INSTRUCTIONS TO ASSESSOR:

1. The candidate has **THREE HOURS** to attempt all the questions.
2. Marks for each section are indicated in the brackets
3. The paper consists of **TWO** sections: **A** and **B.**
4. The candidate is required to attempt **ALL** questions from section **A** and **ANY THREE** questions from section **B.**
5. The candidate is provided with a separate answer booklet for their responses.

NB: ***These only serves as a guide to expected responses.***

SECTION A: (40 MARKS)

1. Define the following terms as used in thermodynamics (4 marks)
   - *i.* Thermodynamics- ***it is that branch of science that deals with the interaction between heat and work in a system***
   - ii. Heat- ***Heat is defined as the energy crossing a system's boundary because of a temperature gradient between the system and its surroundings***
   - iii. Work- ***the work done on or by a system, W, may be expressed as the product of force and the distance moved in the direction of force.***
   - iv. System- ***it is a region of finite quantity of matter, or a space of fixed identity***

   (Award 1 mark for each correct definition)

2. Distinguish between a property and a process as used in thermodynamics. Give ONE example in each case. (4 marks)
   - **i. Property-** ***is an observable or calculable characteristic of a system e.g. density, pressure, temperature.***
   - ***ii.*** **Process-** ***it is the transformation of a system from one state to another e.g. isobaric, isochoric, isothermal and adiabatic.***

   (Award 1 mark for each correct definition and 1 mark for each correct example)

3. State any FOUR methods used to measure torque of an engine (4 marks)
   - ***Rope brake***
   - ***Prony brake***
   - ***Hydraulic brake***
   - ***Electric brake***

   (Award 1 mark for each correct method stated)

4. Identify any TWO types of steam turbines (2 marks)
   - ***Impulse turbine***
   - ***Reaction turbine***

   (Award 1 mark for each correct type)

5. List FOUR characteristics of a good refrigerant (4 marks)
   - ***Low boiling point***
   - ***High critical temperature***
   - ***High latent heat of vaporization***
   - ***Low specific heat of liquid***
   - ***Low specific volume of vapour***
   - ***Non corrosive to metal***
   - ***Non flammable***

- ***Non explosive***

(Award 1 mark for each for any 4 correct characteristic)

6. Define the term cogeneration as used in steam turbines (2 marks)

   Cogeneration is defined as the production of more than one useful form of energy from the same energy source, e.g., electric power and process heat obtained from steam.

   (Award 2 marks for the correct definition)

7. Give the meaning of Rankine cycle. (2 marks)

   It is a model used to predict the performance of a steam turbine system. It is an idealized thermodynamic cycle of a heat engine that converts heat into mechanical work while undergoing phase change

   (Award 2 marks for the correct definition)

8. Outline the FOUR processes of a Carnot cycle (4 marks)

   i. Isothermal heat supply
   ii. Isentropic expansion
   iii. Isothermal heat rejection
   iv. Isentropic compression

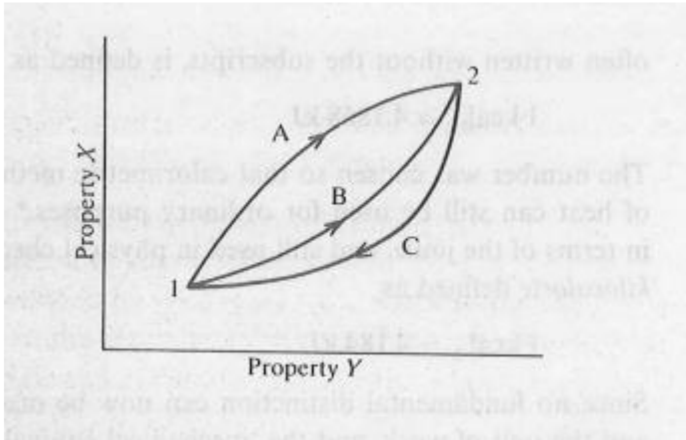
   (Award 1 mark for each for any 4 correct characteristic)

9. Differentiate between positive work done and negative work done in a system in thermodynamics (2 marks)

   Work done by the surroundings on the system and heat flowing from the surroundings into the system are taken as positive while Work done by the system on the surroundings and heat flowing from the system into the surroundings are taken as negative.

   (Award 2 marks for the correct definition of terms)

10. Using a well labelled graph, show proof of existence of the property 'internal energy' (4 marks)



(Award 1 mark for the labelling of axes, 3 marks for the correct graph labelling and arrows)

11. Define the following terms as used in thermodynamics (3 marks)
    a) Thermal equilibrium- ***The system and its surroundings are at the same temperature and there is no heat transfer across the boundary***
    b) Mechanical equilibrium- ***There is uniform pressure or balance of forces between the system and its surroundings***
    c) Chemical equilibrium- ***There is uniform chemical composition between the system and its surroundings.***

    (Award 1 mark for each correct definition)

12. Name THREE types of heat exchangers (3 marks)
    i. Recuperator
    ii. Regenerator
    iii. Evaporative type

    (Award 1 mark for each correct type)

13. Outline TWO types of recuperative heat exchangers (2 marks)
    i. Parallel flow
    ii. Counter flow

    (Award 1 mark for each correct type)

SECTION B: (60 MARKS)

14.

a) In the turbine of a gas turbine unit, the gases flow through the turbine at 17 kg/s and the power developed by the turbine is 14000 kW. The enthalpies of the gases at inlet and outlet are 1200 kJ/kg and 360 kJ/kg respectively, and the velocities of the gases at inlet and outlet are 60 m/s and 150 m/s respectively. Calculate the rate at which heat is rejected from the turbine. Find also the area of the inlet pipe given that the specific volume of the gases at inlet is 0.5 m^3/kg
(10 marks)

$$m = 17kg/s;$$

$$P = 14000kW;$$

$$W = 14000/17 = 823.5kJ/kg;$$

$$h_1 = 1200kJ/kg;$$

$$h_2 = 360kJ/kg;$$

$$C_1 = 60m/s;$$

$$C_2 = 150m/s;$$

$$v_1 = 0.5m^3/kg;$$

$$h_1 + \frac{C_1^2}{2} + Q = h_2 + \frac{C_2^2}{2} + W;$$

$$\frac{C_1^2}{2} = \frac{3600}{2} = 1800m^2/s^2 = 1.800kJ/kg;$$

$$\frac{C_2^2}{2} = \frac{22500}{2} = 11250m^2/s^2 = 11.250kJ/kg;$$

$$1200 + 1.8 + Q = 360 + 11.250 + 823.5;$$

$$Q = -7.05kJ/kg;$$

Heat rejected$= 7.05kJ/kg \cdot 17kg/s = 120kW;$

$$m = \frac{C_1 A_1}{v_1};$$

$$A_1 = \frac{mv_1}{C_1};$$

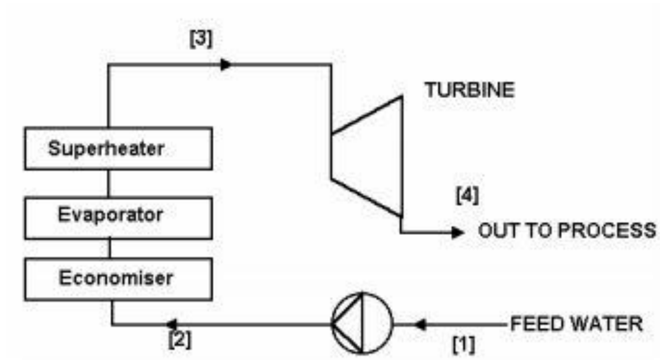
$$A_1 = \frac{17 \cdot 0.5}{60} = 0.14m^2;$$

Answer: $Q = 120kW;$

$A_1 = 0.14m^2.$

(Award 10 marks for the correct workings, correct steps, correct units and the correct answer)

b) A back pressure steam cycle works as follows. The boiler produces 8 kg/s of steam at 40 bar and 500°C. This is expanded to 2 bar with an isentropic efficiency of 0.88. The pump is supplied with feed water at 0.5 bar and 30oC and delivers it to the boiler at 31oC and 40 bar. Calculate the net power output of the cycle. (10 marks)



From tables h_3= 3445 kJ/kg s_3 = 7.089 kJ/kg K

For an ideal expansion

$S_3 = s_4 = 7.089 = 1.53 + x'_{sfg}$ at 3 bar

$6.646 = 1.672 + x_4'(5.597)$ at 2 bar

$x_4' = 0.993$

$h_4' = h_f + x'_{hfg}$ at 2 bar

$h_4' = 505 + 0.993(2202) = 2693$ kJ/kg

Ideal Power Out = 8(3445 –2693) = 6.024 MW

Actual Power = 0.88(6.024 = 5.3 MW

Next we examine the enthalpy change at the pump.

$h_1 = 125.7$ kJ/kg h_f at 30°C

$h_2 = mc\theta + pv = 1 \times 4186 \times 31 + 40 \times 10^5 \times 0.001 = 133.7$ kJ/kg

The power input to the pump is 8(133.7 – 125.7) = 64 kW

Net Power output of the cycle = 5300 – 64 = 5236 kW

(Award 3 marks for the correct workings and 7 marks for correct steps, correct units and the correct answer)

15. A single-acting two-stage compressor with complete intercooling delivers 6 kg/min of air at 16 bars. Assuming an intake state of 1 bar and 15°C, and that the compression and expansion processes are reversible and polytropic with n = 1.3, calculate the power required, the isothermal efficiency and the free air delivery. Also calculate the net heat transferred in each cylinder and in the intercooler. If the clearance ratios for the low- and high-pressure cylinders are 0.04 and 0.06 respectively, calculate the swept and clearance volumes for each cylinder. The speed is 420 rev/min (20 marks)

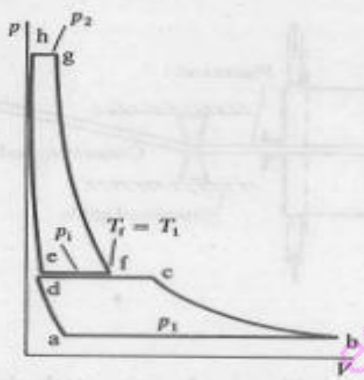
The pressure ratio per stage is

$$r_p = \frac{p_i}{p_1} = \frac{p_2}{p_i} = \sqrt{\left(\frac{16}{1}\right)} = 4$$

The work done in the two stages is

$$\dot{W} = \dot{W}_1 + \dot{W}_2 = 2\dot{m}\frac{n}{n-1}RT_1\{r_p^{(n-1)/n} - 1\}$$

$$= 2 \times \frac{6}{60} \times \frac{1.3}{0.3} \times 0.287 \times 288(4^{0.3/1.3} - 1) = 2 \times 13.50 = 27.00\,\text{kW}$$



The isothermal work is

$$\dot{W}_{iso} = \dot{m}RT_1 \ln\frac{p_2}{p_1} = \frac{6}{60} \times 0.287 \times 288 \ln\frac{16}{1} = 22.92\,\text{kW}$$

and the isothermal efficiency is

$$\eta_{iso} = \frac{\dot{W}_{iso}}{\dot{W}} = \frac{22.92}{27.00} = 84.9 \text{ per cent}$$

The free air delivery is

$$\dot{V} = \dot{m}\frac{RT_1}{p_1} = 6 \times \frac{0.287 \times 288}{100 \times 1} = 4.96\,\text{m}^3/\text{min}$$

The temperature at the exit of each stage is

$$T_c = T_g = T_1 r_p^{(n-1)/n} = 288 \times 4^{0.3/1.3} = 397\,\text{K}$$

Hence the net heat rejected from each cylinder is found from the energy equation

$$\dot{Q} = \dot{m}c_p(T_c - T_1) - \dot{W}_1 = \dot{m}c_p(T_g - T_1) - \dot{W}_2$$

$$= \frac{6}{60} \times 1.005(397 - 288) - 13.50 = -2.55\,\text{kW}$$

and from the intercooler

$$\dot{Q} = \dot{m}c_p(T_1 - T_c) = \frac{6}{60} \times 1.005(288 - 397) = -10.95\,\text{kW}$$

The volumetric efficiency for each stage is found from (16.16) as

$$\eta_{vol,1} = 1 - 0.04(4^{1/1.3} - 1) = 0.924$$

$$\eta_{vol,2} = 1 - 0.06(4^{1/1.3} - 1) = 0.887$$

Hence for the first stage the swept volume is

$$V_b - V_a = \frac{\text{free air delivery}}{\text{speed} \times \eta_{vol,1}} = \frac{4.96}{420 \times 0.924} = 0.012\,78\,\text{m}^3$$

and the clearance volume is

$$V_a = 0.04(V_b - V_a) = 0.000\,51\,\text{m}^3$$

For the second stage the swept volume is

$$V_f - V_h = \frac{1}{r_p}\frac{\text{free air delivery}}{\text{speed} \times \eta_{vol,2}} = \frac{1}{4} \times \frac{4.96}{420 \times 0.887} = 0.003\,33\,\text{m}^3$$

and the clearance volume is

$$V_h = 0.06(V_f - V_h) = 0.000\,20\,\text{m}^3$$

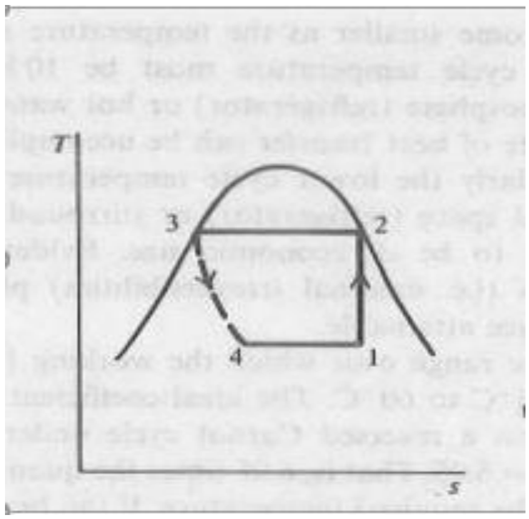
It must be noted that points d and e need not coincide on the indicator diagram because they represent different states and different clearance masses Δm_{c1} and Δm_{c2}. In this particular case

$$V_e = V_h r_p^{1/n} = 0.000\,20 \times 4^{1/1.3} = 0.000\,58\,\text{m}^3$$

(Award 20 marks for the correct workings, correct steps, correct units and the correct answer)

16.

a) Calculate the refrigeration effect and coefficient of performance for the refrigeration cycle shown in the figure below, when the fluid is ammonia and the upper and lower temperatures are 30 °C and —15 °C respectively. Find also the corresponding values for a reversed Carnot cycle operating between the same temperatures. (8 marks)



From the ammonia tables we have

$$h_4 = h_3 = h_f = 323.1\ \text{kJ/kg}, \quad h_2 = h_g = 1468.9\ \text{kJ/kg},$$

$$s_2 = 4.984\ \text{kJ/kg K}$$

From $s_1 = s_2$ we have $x_1 = 0.889$, and hence

$$h_1 = h_f + x_1 h_{fg} = 1280.7\ \text{kJ/kg}$$

The refrigeration effect is

$$Q_{41} = (h_1 - h_4) = 957.6\ \text{kJ/kg}$$

and the net work expended is

$$W = W_{12} = (h_2 - h_1) = 188.2\ \text{kJ/kg}$$

As a refrigerator the coefficient of performance is

$$CP_{ref} = \frac{957.6}{188.2} = 5.09$$

For the reversed Carnot cycle,

$$CP_{ref} = \frac{(273 - 15)}{30 - (-15)} = 5.73$$

$s_3 = 1.204$ kJ/kg K, and from $s_4 = s_3$ we have $x_4 = 0.147$, and hence $h_4 = 305.6$ kJ/kg. The refrigeration effect is therefore

$$Q_{41} = (h_1 - h_4) = 975.1\ \text{kJ/kg}$$

(Award 2 marks for the graphs and 6 marks correct workings, steps, units and the answer)

b) The cycle in (a) is modified so that the refrigerant enters the compressor as a saturated vapour, and is subcooled to 18°C before entering the throttle valve. Find the refrigeration effect and CP_{ref}. What would the result be if R134a were the refrigerant instead of ammonia? (7 marks)

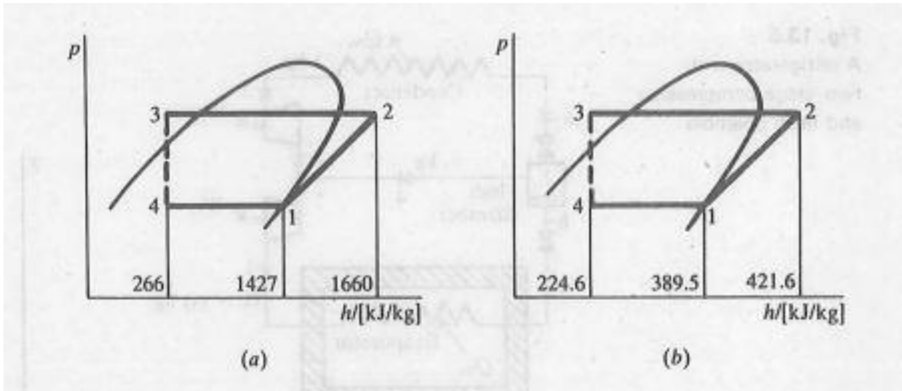


Figure (a) shows the cycle located on the p—h chart for ammonia, from which the following values are obtained:

$$h_1 = 1427\ \text{kJ/kg}, \qquad h_2 = 1660\ \text{kJ/kg},$$

$$h_3 = h_4 = 266\ \text{kJ/kg}$$

The refrigeration effect is

$$Q_{41} = (h_1 - h_4) = 1161\ \text{kJ/kg}$$

The net work required is

$$W = (h_2 - h_1) = 233\ \text{kJ/kg}$$

and the coefficient of performance is

$$CP_{ref} = \frac{Q_{41}}{W} = \frac{1161}{233} = 4.98$$

Similarly, Figure (b) shows the cycle on a p—h chart for R134a, from which we obtain the refrigeration effect

$$Q_{41} = 389.5 - 224.6 = 164.9\ \text{kJ/kg}$$

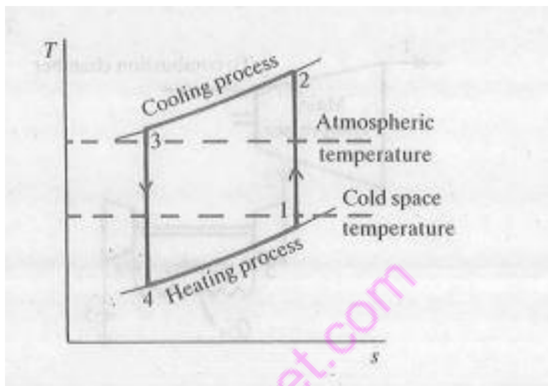
and the coefficient of performance

$$CP_{ref} = \frac{164.9}{32.1} = 5.14$$

(Award 2 marks for the graphs and 5 marks correct workings, steps, units and the answer)

c) Describe the process of a simple refrigeration of air (5 marks)

When a gas is used as a refrigerating fluid it is essential to employ an expander because the temperature remains substantially unchanged by throttling. The processes in the cooler and heater, which replace the condenser and evaporator of a vapour compression machine, are usually constant pressure, but not constant temperature, processes. For a refrigerator, the temperature at state 3 must be somewhat above atmospheric temperature, and at state 1 somewhat below the cold space temperature. Consequently a refrigerator using a gas as a working fluid is less efficient than one using a vapour, because its operating temperature range is very much wider, i.e. from T_4 to T_2 instead of from T_1 to T_3. It is also much bulkier than a vapour plant of the same duty, because a gas requires relatively larger surface areas for a given heat transfer.



(Award 3 marks for the correct description and 2 marks for the correct graph)

17.

a) Determine the throat area, exit area and exit velocity for a steam nozzle to pass a mass flow of 0.2 kg /s when the inlet conditions are 10 bar and 250 °C and the final pressure is 2 bars. Assume that the expansion is isentropic and that the inlet velocity is negligible. (16 marks)

Using n = 1.3 when finding the critical pressure ratio,

$$\frac{p_t}{p_1} = \left(\frac{2}{1.3 + 1}\right)^{1.3/0.3} = 0.546$$

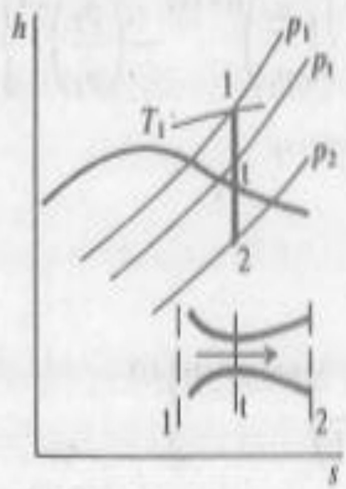
and hence

$$p_t = 0.546 \times 10 = 5.46 \text{ bar}$$

Since the expansion is isentropic,

$$s_t = s_1 = 6.926 \text{ kJ/kg K}$$

The steam is still superheated at the throat because s_t is greater than the saturation value 6.794 kJ/kg K at the throat pressure of 5.46 bar. By a double interpolation in the superheat table, of which only the second step is



given here, the enthalpy and specific volume at the throat are found to be

$$h_t = 2753 + (2854 - 2753)\frac{6.926 - 6.794}{7.018 - 6.794} \quad \text{(at 5.46 bar)}$$
$$= 2813\ \text{kJ/kg}$$

$$v_t = 0.3476 + (0.3916 - 0.3476)\frac{6.926 - 6.794}{7.018 - 6.794} \quad \text{(at 5.46 bar)}$$
$$= 0.3735\ \text{m}^3/\text{kg}$$

Now from the energy equation with $C_1 = 0$,

$$C_t = \{2(h_1 - h_t)\}^{1/2}$$
$$= \{2 \times 10^3(2944 - 2813)\}^{1/2} = 511.9\ \text{m/s}$$

From the continuity equation, the required throat area is

$$A_t = \frac{\dot{m}v_t}{C_t} = \frac{0.2 \times 0.3735}{511.9}[\text{m}^2] = 1.46\ \text{cm}^2$$

The dryness fraction at exit may be found from

$$s_2 = s_1 = s_{f2} + x_2 s_{fg2}$$
$$x_2 = \frac{6.926 - 1.530}{5.597} = 0.964$$

Therefore

$$h_2 = 505 + (0.964 \times 2202) = 2628\ \text{kJ/kg}$$
$$v_2 = 0.964 \times 0.8856 = 0.8537\ \text{m}^3/\text{kg}$$

The exit velocity is therefore

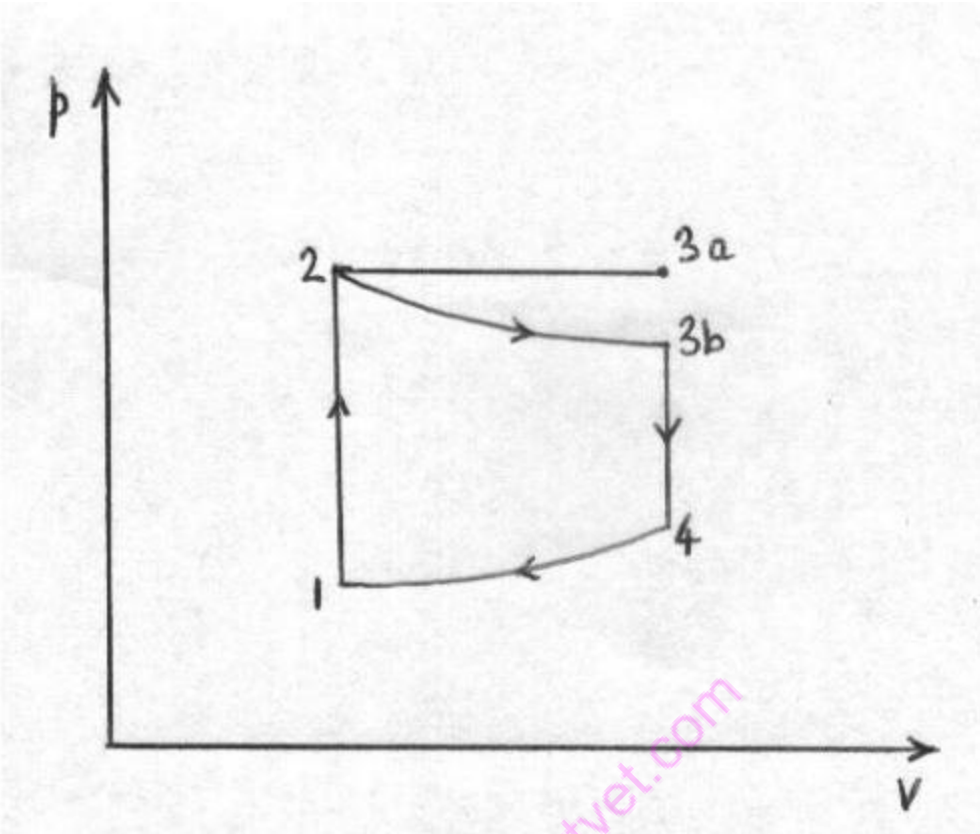
$$C_2 = \{2 \times 10^3(2944 - 2628)\}^{1/2} = 795.0\ \text{m/s}$$

and the exit area required is

$$A_2 = \frac{0.2 \times 0.8537}{795.0}[\text{m}^2] = 2.15\ \text{cm}^2$$

(Award 16 marks for the correct workings, correct steps, correct units and the correct answer)

b) Sketch a pressure-volume diagram for the heat engine (4 marks)



(Award 1 mark for the labelling of axes, 3 marks for the correct graph labelling)