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 response***

SECTION A: (40 MARKS)

1.

a) Name **two** types of systems in thermodynamics (2 marks)

i. ***Open system***

ii. ***Closed system***

(Award 1 mark for each correct type)

b) Identify the difference in the statement of the first law of thermodynamics between the systems named in (a) above (2 marks)

i. ***For a closed system: Energy can neither be created nor destroyed during a process, but it can change form.***

ii. ***For an open system: Energy entering a system must equal the energy leaving the system plus any accumulation of energy within the system.***

(Award 1 mark for each correct statement)

c) Give the general equation for each of the systems named in (a) above. (2 marks)

i. ***Closed system***

$$Q - W = \Delta E = \Delta(U + mgz + \frac{1}{2}mC^2),$$

(Award 1 mark for the correct equation)

ii. ***Open system***

$$\dot{Q} - \dot{W} = \dot{m}\left[(h_2 - h_1) + \frac{1}{2}(C_2^2 - C_1^2) + g(z_2 - z_1)\right]$$

(Award 1 mark for the correct equation)

2. Define the following cycles: (4 marks)

i. Rankine cycle- ***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.***

ii. Carnot cycle- ***an ideal reversible closed thermodynamic cycle in which the working substance goes through the four successive operations of isothermal expansion to a***

desired point, adiabatic expansion to a desired point, isothermal compression, and adiabatic compression back to its initial state.

(Award 2 marks for each correct definition)

3. List **three** types of compressors (3 marks)
    - ***Reciprocating compressor***
    - ***Rotary compressors***
    - ***Centrifugal compressors***

(Award 1 mark for each correct type)

4. Distinguish between a substance and a property of a system (2 marks)

A substance- ***it is the matter contained within the boundaries of a system.***

Property- ***is an observable or calculable characteristic of a system e.g. density, pressure, temperature.***

(Award 1 mark for each correct definition)

5. State any **three** commonly used refrigerants. (3 marks)
- ***R134A***
- ***R22***
- ***Ammonia***

(Award 1 mark for each correct item provided)

6. Outline **four** advantages of reciprocating engine cycles (4 marks)
    i. ***No heat exchanger required in reciprocating internal combustion engines, which results in mechanical simplicity and improved power plant efficiency.***
    ii. ***The average working temperatures of reciprocating internal combustion engines is very low. The reason is that the peak temperature exists for a very less time (in a cycle). This results in the application of high temperatures resulting in high thermal efficiency of reciprocating internal combustion engines.***
    iii. ***It is also possible with reciprocating internal combustion engines to generate very small power output (even a fraction of kilowatt) with reasonable thermal efficiency and cost.***
    iv. ***In reciprocating internal combustion engines high thermal efficiency can be obtained by the application of moderate maximum working pressure of the fluid. This results in less weight to power ratio in reciprocating internal combustion engines. Hence for the same power reciprocating internal combustion engines have less weight compared a steam power plant.***

(Award 1 mark for each correct statement)

7. Identify the **three** forms of equilibrium in thermodynamics. (3 marks)
    i. ***Thermal equilibrium***
    ii. ***Mechanical equilibrium***
    iii. ***Chemical equilibrium***

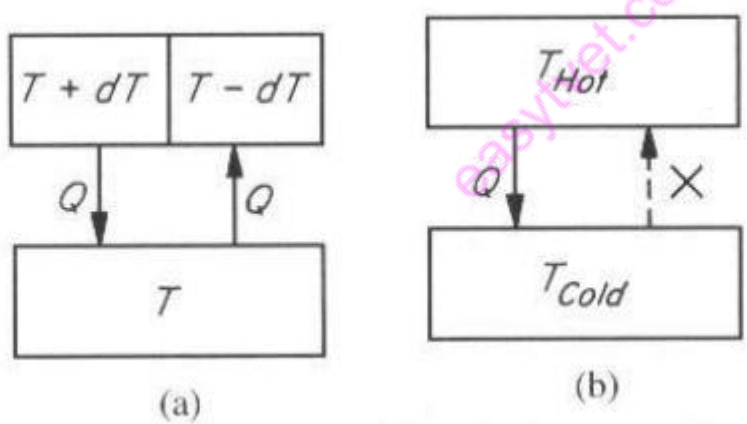
(Award 1 mark for each correct identification)

8. Define saturation state of a substance. (2 marks)

Saturation state is a state at which a change of phase may occur without change of pressure or temperature.

(Award 2 marks for the correct definition)

9. Using neat and well labelled diagrams, differentiate between reversible and irreversible heat transfer of substances. (4 marks)



a) Reversible heat transfer
b) Irreversible heat transfer

(Award 2 marks for each correct diagram)

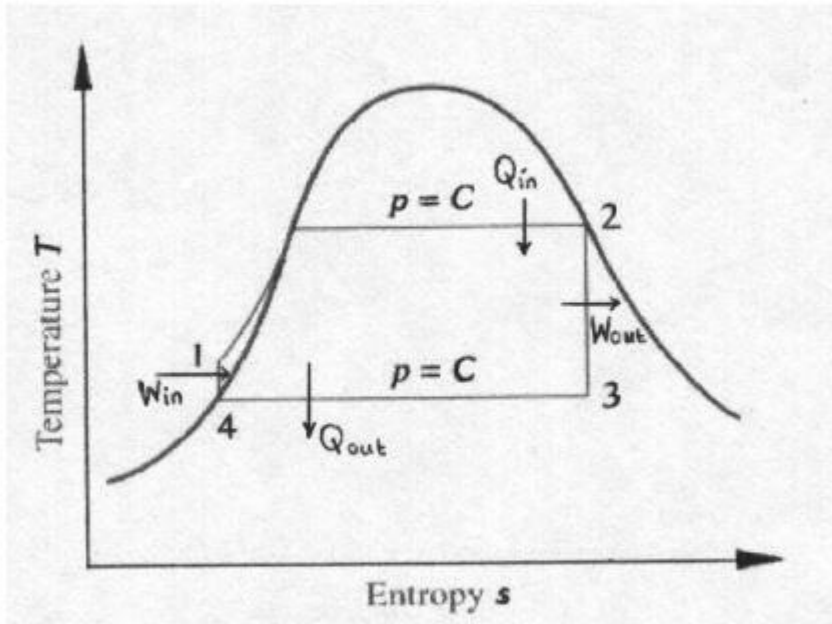
10. State Newton's second law of motion and write its expression. (2 marks)

Force is directly proportional to the product of mass (m) and acceleration of a body of constant mass.

F=ma

(Award 1 mark for the correct statement and 1 mark for the correct expression)

11. Draw a well labelled graph to show the Rankine cycle. (4 marks)



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

12. State the **three** modes of heat transfer. (3 marks)

   i. ***Conduction***
   ii. ***Convection***
   iii. ***Radiation***

(Award 1 mark for each correct mode)

SECTION A: (60 MARKS)

13. A steam engine cylinder has a swept volume of 0.03 m^3 and a clearance volume of 0.001 m^3. Cut-off is at 0.4 of the stroke. Saturated steam is admitted at 7 bar and expands isentropically to the blow-down. The mass which expands inside the cylinder during the blow-down may be assumed to do so isentropically. Cushioning is timed so that isentropic compression brings the clearance steam to the admission state. Calculate the work done per machine cycle and the isentropic efficiency when the engine exhausts at atmospheric pressure. (20 marks)

$$V_1 = 0.001\ \text{m}^3, \quad V_3 = V_4 = 0.031\ \text{m}^3,$$
$$V_2 = V_1 + 0.4(V_3 - V_1) = 0.013\ \text{m}^3$$

During the admission 1–2 the state is

$$p_1 = p_2 = 7\ \text{bar}, \quad v_1 = v_2 = 0.2728\ \text{m}^3/\text{kg}$$
$$u_1 = u_2 = 2573\ \text{kJ/kg}, \quad h_1 = h_2 = 2764\ \text{kJ/kg},$$
$$s_1 = s_2 = 6.709\ \text{kJ/kg K}$$

During exhaust 4–5 the pressure is 1.013 bar, and the dryness fraction is found from $s_1 = s_5 = s_4$ to be 0.893. Then

$$v_4 = v_5 = 1.494\ \text{m}^3/\text{kg}, \quad u_4 = u_5 = 2283\ \text{kJ/kg},$$
$$h_4 = h_5 = 2434\ \text{kJ/kg}$$

At the beginning of the blow-down, state 3, the specific volume is

$$v_3 = v_2\left(\frac{V_3}{V_2}\right) = 0.2728 \times \frac{0.031}{0.013} = 0.6505\ \text{m}^3/\text{kg}$$

By trial and error from tables, or more quickly from the h–s chart, we find that in state 3, defined by $v_3 = 0.6505\ \text{m}^3/\text{kg}$ and $s_3 = s_2 = 6.709\ \text{kJ/kg K}$, $p_3 = 2.6$ bar and $x_3 = 0.939$. Hence $u_3 = 2417\ \text{kJ/kg}$.

The masses of steam in the cylinder at the points 1 to 5 are

$$m_1 = m_5 = V_1/v_1 = 0.0037\ \text{kg}$$
$$m_2 = m_3 = V_2/v_2 = V_3/v_3 = 0.0477\ \text{kg},$$
$$m_4 = V_4/v_4 = 0.0207\ \text{kg}$$

Cushioning must begin when

$$V_5 = m_5 v_5 = 0.0055\ \text{m}^3$$

The total work done per machine cycle can now be found from five non-flow processes:

$$W_{12} = -p_1(V_2 - V_1) = -100 \times 7 \times 0.012 = \quad -8.40\text{ kJ}$$
$$W_{23} = m_2(u_3 - u_2) = -0.0477 \times 156 = \quad -7.44\text{ kJ}$$
$$W_{34} = \quad 0\text{ kJ}$$
$$W_{45} = -p_4(V_5 - V_4) = 100 \times 1.013 \times 0.0255 = \quad +2.58\text{ kJ}$$
$$W_{51} = m_5(u_1 - u_5) = 0.0037 \times 290 = \quad +1.07\text{ kJ}$$
$$W = \quad -12.19\text{ kJ}$$

The isentropic work can be found in two ways. Assuming that full expansion is achieved by lengthening the stroke to 3′, corresponding to the exhaust state 4,5,

$$V'_3 = m_3 v_4 = 0.0713\text{ m}^3$$

Hence the total work is

$$W_{12} = \quad -8.40\text{ kJ}$$
$$W_{23'} = m_2(u'_3 - u_2) = -0.0477 \times 290 = \quad -13.83\text{ kJ}$$
$$W_{3'5} = -p'_3(V_5 - V'_3) = 100 \times 1.013 \times 0.0658 = \quad +6.67\text{ kJ}$$
$$W_{51} = \quad +1.07\text{ kJ}$$
$$W_{isen} = \quad -14.49\text{ kJ}$$

We arrive at the same answer more easily using the steady-flow analysis. The flow steam per machine cycle is

$$\Delta m_f = m_2 - m_1 = 0.0477 - 0.0037 = 0.0440\text{ kg}$$

and, because from the h–s chart $(h'_3 - h_1) = -330\text{ kJ/kg}$,

$$W_{isen} = \Delta m_f(h'_3 - h_1) = -0.0440 \times 330 = -14.52\text{ kJ}$$

The isentropic efficiency is

$$\eta_{isen} = \frac{W}{W_{isen}} = \frac{-12.19}{-14.52} = 0.84$$

Note that the mean effective pressure for the complete reversible expansion is

$$(p_m)_{isen} = \frac{|W|_{isen}}{V'_3 - V_1} = \frac{14.52}{100 \times 0.0703} = 2.07\text{ bar}$$

and for the irreversible expansion is

$$p_m = \frac{|W|}{V_4 - V_1} = \frac{12.19}{100 \times 0.030} = 4.06\text{ bar}$$

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

14.

a) Describe the main events occurring in a four-stroke petrol CI engine (8 marks)

i. ***Induction stroke- A mixture of air and petrol vapour is drawn into the cylinder, the pressure of the mixture being a little below atmospheric owing to friction in the induction pipe. The inlet valve closes just after the end of the stroke.***
ii. ***Compression stroke- With both inlet and exhaust valves closed, the air—fuel mixture is compressed. Just before the piston reaches outer dead centre, ignition is effected by an electric spark. Combustion is not instantaneous, but occupies a finite period. Nevertheless, much of it occurs at nearly constant volume because the piston is moving relatively slowly near dead centre.***
iii. ***Expansion or working stroke- Combustion is nominally completed at the beginning of the expansion stroke, and the products expand until the exhaust valve opens just before the end of the stroke. As the valve opens, the gases blow down the exhaust duct until the pressure in the cylinder has fallen to approximately atmospheric pressure.***
iv. ***Exhaust stroke- The products which have not escaped from the cylinder during the blow-down are displaced by the piston. To provide the pressure difference necessary to overcome friction in the exhaust duct, the pressure in the cylinder is slightly above atmospheric. At the end of the stroke there will be some residual gases in the clearance volume, which will dilute the next charge drawn into the cylinder.***

(Award 2 marks for each correct event described)

b) Demonstrate how the events in a four-stroke CI engine described in (a) differ from those in an SI engine (4 marks)

i. ***During the induction stroke air alone is admitted to the cylinder.***
ii. ***During the compression stroke the air is compressed, and towards the end of the stroke liquid fuel is sprayed into the cylinder. The temperature of the air at the end of compression is sufficiently high for the droplets of fuel to vaporise and ignite as they enter the cylinder.***
iii. ***Expansion or working stroke- Since the fuel is sprayed into the cylinder at a controlled rate, the pressure may remain fairly constant during combustion. In modern high-speed engines, however, there is often a rise in pressure during the initial stages of combustion. At some point in the expansion stroke the combustion is nominally complete and the pressure then falls steadily until the exhaust valve is opened and blow-down occurs.***

(Award 4 marks for each correct events)

c) Explain how the operation of a two-stroke engine differs from a four-stroke engine. (8 marks)

i. ***The two-stroke engine does not require any mechanically operated valves. This implies not only considerable mechanical simplification, but also that the engine can be run in either direction. The two-stroke CI engine has established itself in marine practice primarily because it eliminates the need for a reversing gear.***

ii. ***For the same rotational speed, the two-stroke engine has twice the number of working strokes. The power output from an engine of given bulk and weight is therefore greater for a two-stroke engine, although for a number of reasons it is not twice as great. The greater frequency of working strokes in the two-stroke engine also implies a more uniform torque and a smaller flywheel.***

iii. ***The two-stroke engine tends to have a higher fuel consumption than the four-stroke engine. Little time is available for induction and exhaust in the two-stroke engine, so that the process of clearing the combustion products from the cylinder and recharging it is less complete.***

iv. ***Less time is available for the fresh charge of air to cool the cylinder, and overheating may be a more serious problem. In two-stroke SI engines some fuel may pass through the cylinder without combustion because of the necessary overlap of the periods when the inlet and exhaust ports are open.***

(Award 2 marks for each correct event operation)

15.

a. Briefly describe a steam engine (4 marks)

The reciprocating steam engine is a particular type of compressor designed to produce work from steam expanding from a high to a low pressure. It is used as an alternative to a turbine in small steam plant (up to a few hundred kilowatts) where a turbine would be very inefficient, and where the inherent intermittent working of a reciprocating machine, which allows only moderate rates of flow and rotational speeds, is no disadvantage. The range of expansion for the engine is governed by considerations of the thermodynamic cycle. This requirement leads to multistage expansion in successive cylinders.

(Award 4 marks for the correct description)

b. Discuss the two peculiar features of a steam engine. (4 marks)

i. ***The first lies in the fact that the temperature of the working fluid is always much greater than the surroundings. Thus, although the work done increases as the index of expansion decreases, the best that can be hoped for in practice***

is that the expansion shall be isentropic. An index of expansion less than the isentropic index would imply heat reception from the surroundings.

ii. ***The second peculiarity arises because with steam at low pressures there is a very rapid increase of specific volume as the pressure is decreased isentropically, i.e. — (dv/dp), is very large. With the pressure ranges employed in practice, this implies that a very long stroke would be required if the steam were to be expanded reversibly down to condenser pressure inside the engine cylinder.***

(Award 2 marks for each well explained feature)

c. A four cylinder-engine has a bore of 57mm and a stroke of 90mm. its rated speed is 2800rev/min and it is tested at this speed against a brake which has a torque arm of 0.356m. The net brake load is 155N and the fuel consumption is 6.74l/h. the specific gravity of the petrol is 0.735 and it has a lower calorific value, $Q_{net.c}$ of 44200kJ/kg. A morse test is carried out and the cylinders are cut out in order 1, 2, 3, 4 with corresponding brake loads of 111, 106.5, 104.2 and 111 N respectively. Calculate for this speed, the engine torque, the bmep, the brake thermal efficiency, the specific fuel consumption, the mechanical efficiency and the iemp. (12 marks)

$$\text{Torque, } T = WR = 155 \times 0.356 = 55.2 \text{ N m}$$

Using equation (13.5),

$$\text{bp} = 2\pi NT = \frac{2\pi \times 2800 \times 55.2}{60 \times 10^3} \text{ kN m/s} = 16.2 \text{ kW}$$

From equation (13.10),

$$\text{bmep} = \frac{\text{bp} \times 2}{ALNn} = \frac{16.2 \times 2 \times 4 \times 60 \times 10^3}{\pi \times 0.057^2 \times 0.09 \times 2800 \times 4 \times 10^5}$$

$$= 7.55 \text{ bar}$$

Using equation (13.11)

$$\eta_{BT} = \frac{\text{bp}}{\dot{m}_f \times Q_{net,v}} = \frac{16.2}{0.001\,376 \times 44\,200} = 0.266 \text{ or } 26.6\%$$

where $\dot{m}_f = (6.74/3600) \times 1 \times 0.735 = 0.001\,376$ kg/s.

Using equation (13.12),

$$\text{sfc} = \frac{\dot{m}_f}{\text{bp}} = \frac{0.001\,376}{16.2} = 0.000\,085 \text{ kg/kJ}$$

It is more convenient to express sfc in terms of fuel consumption rate per unit power and to express the fuel consumption rate in kilograms per hour rather than kg/s,

i.e. $\text{sfc} = 0.000\,085 \times 3600 = 0.306 \text{ kg/kW h}$

Using equation (13.8) for each cylinder in turn, and substituting brake loads

The condition of the exhaust implies a stoichiometric air–fuel ratio which for petrols can be taken to be 14.5/1.

From Example 13.1

$$\dot{m}_f = 0.001\,376 \text{ kg/s}$$

therefore

$$\text{Air mass flow rate} = 14.5 \times 0.001\,376 = 0.019\,95 \text{ kg/s}$$

therefore

$$\text{Volume drawn in per unit time, } \dot{V} = \frac{0.019\,95 \times 287 \times 288}{10^5 \times 1.013}$$

$$= 0.0163 \text{ m}^3/\text{s}$$

Now

$$\text{Swept volume of engine} = ALn \text{ m}^3/\text{cycle} = \frac{ALnN}{2} \text{ m}^3/\text{min}$$

i.e.

$$\dot{V}_s = \frac{\pi \times 0.057^2 \times 0.09 \times 4 \times 2800}{4 \times 2 \times 60} = 0.0214 \text{ m}^3/\text{s}$$

Then using equation (13.15)

$$\eta_v = \frac{\dot{V}}{\dot{V}_s} = \frac{0.0163}{0.0214} = 0.76 \text{ or } 76\%$$

(Award 12 marks for the correct workings, correct steps, correct units and the correct answer)

16.

a) Dry saturated steam at 2.8 bar is expanded in a simple convergent nozzle to a pressure of 1.7 bar. The throat area is 3 cm^2 and the inlet velocity is negligible. Estimate the exit velocity and mass flow:

i. If phase equilibrium is assumed throughout the expansion (7 marks)

(a) Assuming isentropic expansion, the dryness fraction at the exit is given by

$$s_1 = s_2 = s_{f2} + x_2 s_{fg2}$$

$$7.015 = 1.475 + x_2 5.707 \quad \text{and hence} \quad x_2 = 0.971$$

Hence

$$h_1 - h_2 = 2722 - \{483 + (0.971 \times 2216)\} = 87 \text{ kJ/kg}$$

$$C_2 = \{2(h_1 - h_2)\}^{1/2} = (2 \times 10^3 \times 87)^{1/2} = 417 \text{ m/s}$$

$$v_2 = x_2 v_{g2} = 0.971 \times 1.031 = 1.001 \text{ m}^3/\text{kg}$$

$$\dot{m} = \frac{A_2 C_2}{v_2} = \frac{3 \times 417}{10^4 \times 1.001} = 0.125 \text{ kg/s}$$

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

ii. Assuming the supersaturated expansion to conform to $pv^{1.3}$ = constant (7 marks)

$$C_2 = \left[\frac{2n}{1-n} p_1 v_1 \left\{\left(\frac{p_2}{p_1}\right)^{(n-1)/n} - 1\right\}\right]^{1/2}$$

v_1 is 0.6462 m^3/kg from tables, so that

$$C_2 = \left[\frac{2 \times 1.3}{0.3} 10^5 \times 2.8 \times 0.6462 \left\{1 - \left(\frac{1.7}{2.8}\right)^{0.3/1.3}\right\}\right]^{1/2} = 413 \text{ m/s}$$

$$v_2 = v_1 \left(\frac{p_1}{p_2}\right)^{1/n} = 0.6462 \left(\frac{2.8}{1.7}\right)^{1/1.3} = 0.949 \text{ m}^3/\text{kg}$$

$$\dot{m} = \frac{3 \times 413}{10^4 \times 0.949} = 0.131 \text{ kg/s}$$

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

b) Outline **three** conditions that need to be satisfied in order to achieve a steady flow in engineering processes (3 marks)

i. ***The mass rates of flow into and out of the system are equal and do not vary with time***

ii. ***The energy of the fluid both at the entrance and exit does not change with time***

iii. ***The rates of heat and/or work transfer across the system boundary do not vary with time***

(Award 1 mark for each correct condition)

c) A gas turbine expands 6 kg/s of air from 8 bar and 700oC to 1 bar isentropically. Calculate the exhaust temperature and the power output. γ= 1.4 c_p= 1005 J/kg K (3 marks)

$T_2 = T_1 (1/12)^{1-1/1.4} = 973 (1/8)^{0.2958} = 537.1$ K

$P = \Delta H/s = m\, c_p\, \Delta T = 6 \times 1005 \times (537.1 - 973)$

$P = - 2.628 \times 10^6$ W (Leaving the system) **P(out) = 2.628 MW**

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