Civil Services (Main) Examination, 2014

MECHANICAL ENGINEERING

(Paper II)

Time Allowed : Three Hours	Maximum Marks : 250

QUESTION PAPER SPECIFIC INSTRUCTIONS

(Please read each of the following instructions carefully before attempting questions)

There are EIGHT questions divided in two Sections.

Candidate has to attempt FIVE questions in all.

Question Nos. 1 and 5 are compulsory and out of the remaining, any THREE are to be attempted choosing at least ONE question from each Section.

The number of marks carried by a question/part is indicated against it.

Wherever any assumptions are made for answering a question, they must be clearly indicated.

Word limit in questions, wherever specified, should be adhered to.

Attempts of questions shall be counted in sequential order. Unless struck off, attempt of a question shall be counted even if attempted partly. Any page or portion of the page left blank in the Question-cum-Answer Booklet must be clearly struck off.

SECTION 'A'

1. **(a)** In a Carnot cycle, heat is received at 480 °C and rejected at 40 °C. The entropy of the sink increases by 0.0785 kJ/kg K per cycle. Determine the work done per cycle. **10**

(b) An open-cycle gas turbine plant with turbine efficiency η_t has a compressor of efficiency η_c. The minimum gas temperature is T_{min} and after heating in the combustion chamber, its temperature is T_{max}. If the pressure ratio for compression and expansion is r_p, what should be the limit for the product $\eta_c \cdot \eta_t \cdot \frac{T_{max}}{T_{min}}$? Neglect pressure losses and assume that working substance is a perfect gas. **10**

(c) Derive the following expression for normal shock in an ideal gas:

$$\frac{p_y}{p_x} = \frac{2\gamma}{\gamma+1} M_x^2 - \frac{\gamma-1}{\gamma+1}$$

where x and y are conditions before and after the shock, γ is ratio of specific heats and M is Mach number. **10**

(d) A thin radiation shield having equal emissivities on both sides is introduced parallel to and in between two large planes with emissivities 0.8 and 0.5 respectively. Determine the emissivity of the radiation shield to reduce the heat transfer rate by 92% of the original. **10**

(e) The outer and inner surfaces of a thick hollow cylinder have areas $1.25\,m^2$ and $0.25\,m^2$ respectively. The thickness of the cylinder is 10 cm and the thermal conductivity of the cylinder material is 50 W/m K. Find the radial heat transfer through the cylinder for 100 °C temperature difference at the surfaces. Derive the formula used. **10**

2. **(a)** A reciprocating air compressor is used to fill rapidly a $3\,m^3$ tank at 30 °C and 1 bar. The filling process is governed by $pv^{1.4} = \text{const.}$ The effects of kinetic energy are negligible. The ratio of the final to initial mass of air in the tank is 4. Work out the following: (i) Draw the system and show the control volume. (ii) List the assumptions made. (iii) What would be the work input to the compressor, if mechanical efficiency is 90%? **20**

(b) A centrifugal compressor running at 1200 r.p.m. delivers $800\,m^3/min$ of free air. The air is compressed from 1 bar, 30 °C to 4.8 bar with isentropic efficiency of 0.84. The impeller blades are

radial at outlet and the flow velocity of 80 m/s may be assumed constant throughout. The outer radius of the impeller is twice the inner. The slip factor may be assumed as 0.9. The blade area coefficient is equal to 0.9 at inlet. (i) Draw inlet and outlet velocity triangles for the impeller, and show the process on a T-s diagram. (ii) Calculate the input power needed, if mechanical efficiency is 95%. (iii) Calculate the impeller diameters at inlet and outlet. (iv) Calculate the impeller and diffuser blade angles at inlet. **20**

(c) The vapour, at the saturation temperature of an oil flowing at the rate of 500 kg/min, enters a heat exchanger tube, at 355 K and condenses while it is cooled by water flowing at the rate of 3600 kg/min entering the concentric tube of a parallel-flow heat exchanger at 286 K. Assuming overall heat transfer coefficient of $475\,W/m^2K$, latent heat of oil as 600 kJ/kg K, calculate the number of tubes required of 25 mm outer diameter and 2 mm thick with a length of 4.87 m. What will be the number of tube passes, if cooling water velocity should not exceed 2 m/s? Take C_p for water as 4.18 kJ/kg K and density of water as $1000\,kg/m^3$. **10**

3. (a) Using Buckingham's π theorem method, derive a relation for the efficiency η of a fan which depends on the following parameters: Mass density ρ, Dynamic viscosity μ, Angular velocity ω, Diameter of the rotor D, Discharge Q **20**

(b) Two long slender rods A and B, made of different materials having same diameter of 12 mm and length 1 m, are attached to a surface maintained at a temperature of 100 °C. The surfaces of the rods are exposed to ambient still air at 20 °C. By traversing along the length of the rods with a temperature sensor, it is found that the surface temperatures of rods A and B are equal at positions 15 cm and 7.5 cm respectively away from the base surface. If material of A is carbon steel with thermal conductivity 60 W/m K, what is the thermal conductivity of rod B? List the assumptions made. Assume that the average convection coefficient for air is $5\,W/m^2K$. Find the ratio of rate of heat transfer for rods A and B. **20**

(c) A certain amount of gas is filled in a tank X until its pressure is 100 kPa and temperature is 330 K. In another tank Y, 5 times the weight of gas in X is filled raising the pressure to 500 kPa and temperature 900 K. Both the tanks X and Y are now connected through a tube having a valve which is closed. Assuming the gas is ideal and if the valve is opened till equilibrium state is achieved, find the ratio of the volumes of both tanks, equilibrium temperature and pressure. The tanks are insulated. For the gas, take $R = 0.296\,kJ/kgK$ and $C_v = 0.75\,kJ/kgK$. **10**

4. (a) Liquid N_2 enters a thin-walled 20 mm diameter tube at 77 K and flows steadily. The outer surface of the tube has an emissivity of 0.02. This tube is placed concentrically in another tube of 50 mm inner diameter, whose inner surface emissivity is 0.05. The inner surface of the outer tube is maintained at 300 K and the space in between the tubes is evacuated. Determine the heat gained by the liquid N_2 per unit length of the tube. If a thin-walled radiation shield with emissivity 0.02 on both sides is inserted midway concentrically between inner and outer tubes, calculate the % change in heat gained by liquid N_2 per unit length of the tube. **20**

(b) A fluid flowing in a tube at the rate of 0.5 kg/s is heated from 30 °C to 60 °C by hot gases entering at a temperature of 180 °C and leaving at 80 °C. The specific heats of the fluid and gases are 4.186 kJ/kg K and 1.08 kJ/kg K. Calculate the change in entropy and increase in unavailable energy for ambient temperature of surrounding of 20 °C. **20**

(c) In a simple open-cycle gas turbine plant, air enters at 1 bar, 288 K and is compressed to 2 bar. It is then heated in the regenerator before entering the combustion chamber where it is heated to a temperature of 1700 K and then enters a turbine and expands to atmospheric pressure. The isentropic efficiencies of compressor and turbine are 87% and 88% respectively. The combustor and heat exchanger efficiencies are 0.97 each. Pressure loss in the combustor is 0.4 bar. Power

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developed by the turbine is 350 MW. Calorific value of fuel is 42 MJ/kg. Assume $C_{p_{air}} = C_{p_{gas}} = 1.005\,kJ/kg\,K$ and $\gamma = 1.4$. (i) Draw the system flow diagram and show the processes on a T-s diagram. (ii) Find out the mass flow rate of air and fuel. (iii) Find out the work ratio. (iv) Find out the thermal efficiency. (v) Find out the specific fuel consumption. **10**

SECTION 'B'

5. **(a)** The products of combustion of an unknown fuel $C_x H_y$ have the following composition as measured by an Orsat apparatus:

$$CO_2 = 8.0\%, CO = 0.9\%, O_2 = 8.8\%, N_2 = 82.3\%$$

Determine the values of x and y, the air-fuel ratio and % of excess air used. **10**

(b) Determine the expression for the ratio of chimney gas temperature to outside air temperature in terms of mass flow rate. **10**

(c) At a stage in a reaction turbine, the pressure of steam is 34 kPa ($v_g = 4.65\,m^3/kg$) and dryness fraction is 0.95. For a flow rate of 36000 kg/hr, the stage develops 950 kW. The turbine runs at 3600 r.p.m. and velocity of flow is 0.72 times the blade velocity. The outlet angles of both stator and rotor blades are 20°. Determine at this stage the mean rotor diameter and height of blades. **10**

(d) Mechanical air-conditioning can be used in all geographical locations, whereas desert air-coolers can be used only in some geographical locations. Explain why. Show the processes involved in both these equipments. **10**

(e) It is thermodynamically advantageous to employ a heat pump rather than employing a direct electrical resistance heater for a room air heating application. Explain why. **10**

6. **(a)** A 2-stroke oil engine was subjected to a test at room temperature of 20 °C with fuel oil of calorific value 44000 kJ/kg. Calculate the indicated and brake power, mechanical and brake thermal efficiency, and draw the heat balance sheet using the following data: Cylinder bore = 20 cm; Stroke-bore ratio = 1.3 : 1; Speed = 500 r.p.m.; Brake drum diameter = 120 cm; Rope diameter = 3 cm; Net brake load = 460 N; Indicated MEP = 2.8 bar; Oil consumption = 3.7 kg/hr; Jacket cooling water rate = 456 kg/hr with a rise in temperature of 27 °C; Exhaust gas temperature entering calorimeter is 320 °C and leaving 220 °C; Temperature rise in calorimeter water is 8 °C with a rate of flow 8 kg/min **20**

(b) In a combined gas turbine (GT)-steam turbine (ST) plant, the exhaust from GT is used to heat steam in boiler at which a further supply of fuel is burned in the gas. Pressure ratio of GT is 8, inlet air temperature is 15 °C, maximum cycle temperature is 800 °C. Combustion in boiler increases the gas temperature to 800 °C and gas leaves the boiler at 100 °C. The steam inlet in ST is at 60 bar and 600 °C ($h = 3656.2\,kJ/kg$, $s = 7.166\,kJ/kg\,K$) and condenser pressure is 0.05 bar ($h_f = 137.8\,kJ/kg$, $h_{fg} = 2423.8\,kJ/kg$, $s_f = 0.476\,kJ/kg\,K$, $s_{fg} = 7.92\,kJ/kg\,K$). Calculate flow rate of air and steam required for a total power output of 190 MW and the overall η of the combined plant. Assume that all processes are ideal. What is overall air-fuel ratio? Assume $C_{p_{gas}} = 1.11\,kJ/kg\,K$ and $C_{p_{air}} = 1.05\,kJ/kg\,K$, and γ for gas and air as 1.33 and 1.4 respectively. Neglect mass flow rate of fuel on the airflow. Calorific value of fuel is 43.3 MJ/kg. **20**

(c) Show that the enthalpy of humid air per kg of dry air is given by

$$h = C_{p_m} \times DBT + 2500\,w$$

where C_{p_m} = humid air specific heat = $(1.005 + 1.88\,w)$, w = specific humidity kg/kg of dry air, $h_{fg} = 2500\,kJ/kg$ at 0 °C for water and DBT = dry-bulb temperature. **10**

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7. **(a)(i)** Derive an expression for critical pressure ratio of a nozzle. Explain the phenomenon of choking in the nozzle. **10**

(a)(ii) A steam power station uses the following cycle: Steam boiler outlet 150 bar, 550 °C ($h = 3450.4\,kJ/kg$, $s = 6.523\,kJ/kg\,K$); Reheat at 40 bar to 550 °C ($h = 3560.34\,kJ/kg$, $s = 7.235\,kJ/kg\,K$); Condenser at 0.1 bar ($h_f = 191.8\,kJ/kg$, $h_{fg} = 2392.05\,kJ/kg$, $s_f = 0.649\,kJ/kg\,K$, $s_{fg} = 7.5\,kJ/kg\,K$) Assuming ideal processes, find quality of steam at turbine exhaust, cycle efficiency and steam flow rate per kWh. **10**

(b) The air handling unit in an AC plant supplies a total of 4500 cmm of dry air which comprises by weight 20% fresh air at 40 °C DBT, 27 °C WBT and 80% recirculated air at 25 °C DBT and 50% RH. Air leaves the cooling coil at 13 °C saturated. Calculate total cooling load and room heat gain: **20**

Condition	DBT (°C)	WBT (°C)	RH (%)	Sp. humidity (kg/kg of dry air)	Enthalpy (kJ/kg of dry air)
Outside air	40	27		17.2	85
Room air	25		50	10.0	50.8
ADP	13		100	9.4	37.0

(c) The following data refer to a 4-stroke, 4-cylinder diesel engine: Cylinder diameter = 36 cm; Stroke = 40 cm; Speed = 315 r.p.m.; Indicated MEP = 7 bar; Brake power = 250 kW; Fuel consumption = 80 kg/hr; Calorific value = 44 MJ/kg; Air consumption = 30 kg/min; Cooling water circulated = 90 kg/min with rise in temperature 38 °C; Exhaust gas temperature = 324 °C and Room temperature = 45 °C kJ/kg K; $C_{p_{air}} = 1.005\,kJ/kg\,K$, $C_{p_{gas}} = 1.05\,kJ/kg\,K$, $C_{p_{steam}} = 2.093\,kJ/kg\,K$. In exhaust gases, partial pressure of steam is 0.03 bar and fuel contains 13% H_2. Find mechanical efficiency, indicated thermal η, brake specific fuel consumption: Draw heat balance sheet for the engine in hourly basis. **10**

8. **(a)(i)** An R_{12} simple saturation cycle operates at temperatures of 35 °C and −15 °C. Determine the COP and HP per ton of refrigeration of the system: **10**

t (°C)	h_f (kJ/kg)	h_g (kJ/kg)	s_g (kJ/kg K)	Superheated 20 K: h (kJ/kg)	Superheated 20 K: s (kJ/kg K)	Superheated 40 K: h (kJ/kg)	Superheated 40 K: s (kJ/kg K)
35	69.5	201.5	0.6839	216.4	0.731	231.0	0.7741
−15		181.0	0.7052	193.2	0.751	205.7	0.7942

(a)(ii) Differentiate between summer and winter air-conditioning processes. **10**

(b) Even though velocity-compounded impulse turbines are less efficient, in the initial stages of high pressure turbines are normally velocity-compounded. Why? Plot the variation of pressure and velocities in velocity-compounded and pressure-compounded impulse turbines. **10**

(c) A steam power plant operates on ideal regenerative Rankine cycle. Steam enters the turbine at 6 MPa, 450 °C ($h = 3301.8\,kJ/kg$, $s = 6.7193\,kJ/kg\,K$) and is condensed in the condenser at 20 kPa ($h_f = 251.4\,kJ/kg$, $h_{fg} = 2358.3\,kJ/kg$, $v_f = 0.001\,m^3/kg$, $s_f = 0.832\,kJ/kg\,K$, $s_{fg} = 7.0766\,kJ/kg\,K$). Steam is extracted from the turbine at 0.4 MPa ($h_f = 604.74\,kJ/kg$, $v_f = 0.001\,m^3/kg$, $h_{fg} = 2133.8\,kJ/kg$, $s_f = 1.7766\,kJ/kg\,K$, $s_{fg} = 5.1193\,kJ/kg\,K$) to heat feedwater heater. Water leaves feedwater heater as saturated liquid. Show the cycle on T-s diagram and find net work output/kg of steam, the boiler and thermal efficiencies of the cycle. **20**

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