

CSM – 55/21
Mechanical Engineering
Paper – II

Time : 3 hours

Full Marks : 300

The figures in the right-hand margin indicate marks.

*Candidates should attempt Q. No. 1 from Section – A and Q. No. 5 from Section – B which are compulsory and any **three** of the remaining questions, selecting at least **one** from each Section.*

SECTION – A

1. Answer any **three** questions of the following :
- (a) (i) Define : Air-fuel ratio, Equivalence ratio, and Air index.
- (ii) Compare knocking phenomena in SI and CI engines.
- (iii) With a sketch describe the construction and working of a three-way catalytic converter.

6+6+8 = 20

- (b) Describe the detailed procedure for estimating the total cooling load for a room to be conditioned during summer. Consider various sources which contribute to the cooling load of the room. 20
- (c) In an oil-fired boiler the fuel had an analysis by mass : carbon 84%, hydrogen 10%, sulphur 3.2%, oxygen 1.6%, and the remainder is incombustible. The analysis of dry flue gas by volume gave : combined $\text{CO}_2 + \text{SO}_2$: 15.72%, O_2 : 1% there being no CO or SO_3 . Calculate per kg of fuel (i) mass of air supplied, (ii) percentage excess air supplied, (iii) mass of dry flue gas formed, and (iv) mass of water vapour formed. 20
- (d) An ideal gas undergoes a thermodynamic cycle consisting of the following processes :
 (i) Process 1-2 : Constant pressure $p = 1.4$ bar, $V_1 = 0.028 \text{ m}^3$, $T_1 = 300 \text{ K}$, Specific work, $w_{12} = 250 \text{ kJ/kg}$, (ii) Process 2-3 : 8.

Compression with $pV = \text{constant}$,
 (iii) Process 3-1 : Constant volume, Change
 in specific internal energy, $u_1 - u_3 = -580 \text{ kJ/kg}$.
 (i) Sketch the cycle on a p - V diagram.
 (ii) Calculate the net work for the cycle in kJ .
 (iii) Calculate the heat transfer for process
 1-2 (iv) Show that during the cycle $\sum Q = \sum W$.
 Take R of air $= 0.287 \text{ kJ/kg K}$. 20

2. (a) Saturated air at 2°C is to be supplied to a room where the temperature must be held at 20°C with a relative humidity of 50%. The air is first heated in a heater, and then water, at 10°C , is sprayed into it to give the required condition. The inlet flow rate of air is $80 \text{ m}^3/\text{min}$. **Without using the psychrometric chart**, Determine : (i) the temperature to which the air must be heated, (ii) the volume flow rate of air to the room (iii) the heating coil capacity, and (iv) the mass rate of spray water required. Assume

that the total pressure is constant at 1.013 bar and neglect the fan power. Take : Saturation pressure of water, $P_s = 0.7156$ kPa bar at 2°C and $P_s = 2.339$ kPa at 20°C . Specific enthalpy of water at 10° may be taken as 42 kJ/kg. For air, $c_p = 1.005$ kJ/kg-K, $R = 287$ J/Kg-K and $\gamma = 1.4$. 30

- (b) The power output of a six-cylinder four-stroke engine is absorbed by a hydraulic dynamometer for which the brake power relation is : $\text{BP (in kW)} = (W.N) / 20,000$, where the brake load W is in Newton, and the speed N is in RPM. The air consumption is measured by an air-box with a sharp-edged Orifice system. The following observations are made : Orifice diameter = 30 mm. Coefficient of discharge = 0.6, Pressure drop across the Orifice = 14 cm of Hg, Bore = 100 mm, Stroke = 110 mm, Brake load = 540 N, Engine speed = 2500 rpm, Calorific value of fuel = 44,000 kJ/kg, Ambient

pressure = 1 bar, Ambient temperature = 27°C , Time taken for 100 cm^3 of fuel consumption = 18 s, Fuel density = 780 kg/m^3 . Calculate (i) The volumetric efficiency, (ii) the brake thermal efficiency, (iii) the BMEP, (iv) the brake power, (v) the torque, and (vi) the BSFC. Take the specific gravity of Hg = 13.6. 30

3. (a) In a simple air refrigeration system for an aircraft, air enters the compressor at 1.1 bar and 280 K and leaves at 4.4 bar. The air is then passed through a heat exchanger, where there is a pressure drop of 0.2 bar. Ambient air at 280 K is used as a coolant in the heat exchanger, the effectiveness of which is 0.8. The air from the heat exchanger is then expanded in a turbine and supplied to the cabin, which is maintained at 1.01 bar and 26°C . The isentropic efficiencies of the compressor and the turbine are 80% and 85%, respectively, and the turbine work is fed

to drive the compressor. If air flows in the cabin at a rate of 0.4 kg/s, determine :
 (i) power consumption, (ii) COP, and
 (iii) tonnage of the refrigeration system. Take,
 for air, $c_p = 1.005 \text{ kJ/kg-K}$ $R = 287 \text{ J/Kg-K}$
 and $\gamma = 1.4$. 30

- (b) A closed adiabatic cylinder of volume 1 m^3 is divided by a partition into two compartments 1 and 2. Compartment 1 has a volume of 0.6 m^3 and contains methane at 0.4 MPa, 40°C , while compartment 2 has a volume of 0.4 m^3 and contains propane at 0.4 MPa, 40°C . The partition is removed, and the gases are allowed to mix. When the equilibrium state is reached, (i) find the entropy change of the universe. (ii) What are the molecular weight and the specific heat ratio of the mixture ? The mixture is now compressed reversibly and adiabatically to 1.2 MPa. Compute (iii) the final temperature

of the mixture, (iv) the work required per unit mass, and (v) the specific entropy change for each gas. Consider both methane and propane as ideal gases and take specific heat at constant pressure of methane and propane as 35.72 and 74.56 kJ/kmol-K, respectively. Molecular masses of methane and propane are 16 and 44 kg/kmol, respectively.

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4. (a) A gas turbine plant draws in air at 1.013 bar, 10°C and has a pressure ratio of 5.5. The maximum temperature in the cycle is limited to 750°C . Compression is conducted in an uncooled rotary compressor having an isentropic efficiency of 82%, and expansion takes place in a turbine with an isentropic efficiency of 85%. A heat exchanger with an effectiveness of 0.7 heats the compressed air before the combustion chamber. Neglect the effect of the mass flow rate of fuel on the

airflow and take $c_p = 1.11 \text{ kJ/kg K}$ and $\gamma = 1.33$ for combustion gases and $c_p = 1.005 \text{ kJ/kg K}$ and $\gamma = 1.4$ for air. For an airflow of 40 kg/s , find (i) the overall cycle efficiency, (ii) the turbine output, and (iii) the air-fuel ratio if the calorific value of the fuel used is 45.22 MJ/kg . 30

- (b) A mass of 6.98 kg of air is in a vessel at 200 kPa , 27°C . Heat is transferred to the air from a reservoir at 727°C until the temperature of the air rises to 327°C . The environment is at 100 kPa , 17°C . (i) Determine the initial and final availability of air, (ii) Make an exergy balance and determine the irreversibility associated associated with the process, (iii) Calculate entropy generation during the process and hence verify : $I = T_0 S_{\text{gen}}$. Assume air to be an ideal gas with $c_v = 0.718 \text{ kJ/kg. K}$ and $c_p = 1.005 \text{ kJ/kg.K}$. 30

SECTION – B

5. Answer any **three** questions of the following :

(a) (i) Describe the merits and demerits of alcohols as alternative fuels for internal combustion engines.

(ii) Describe the basic combustion phenomenon in SI engines with the help of a P- θ diagram. 10+10 = 20

(b) A reversible engine works between three thermal reservoirs A, B and C. The engine absorbs an equal amount of heat from the thermal reservoirs A and B, which are kept at temperatures T_A and T_B respectively, and rejects heat to the thermal reservoir C kept at temperature T_C . The efficiency of the engine is 'a' times the efficiency of the reversible engine, which works between the two reservoirs A and C. Prove that : 20

$$\frac{T_A}{T_B} = (2a - 1) + 2(1 - a) \frac{T_A}{T_C}$$

- (c) A thermal power plant consists of three units :
 one 60 MW unit, which runs for 8000 hours per year ; one 50 MW unit which runs for 7500 hours per year and one 30 MW unit which runs for 6000 hours per year. The energy produced by the plant is 736×10^6 k Wh per year. The plant load factor is 0.7. The following data pertain to the power plant : Capital cost = Rs. 50,000 per kW installed capacity ; Annual cost of fuel, taxes and salaries = Rs. 800×10^6 ; Rate of interest = 8% of the capital ; Rate of depreciation = 6% of the capital ; Energy used in running plant auxiliaries = 5% of the total units generated. Determine : (i) the capacity factor, use factor and reserve factor of the plant and (ii) the cost of generation of energy per kWh. 20
- (d) A composite wall separated combustion gases at 2600°C from a liquid coolant at 100°C , with gas and liquid-side convection coefficients of 50 and $1000 \text{ W/m}^2\text{-K}$. The wall

is composed of a 10-mm-thick layer of beryllium oxide on the gas side and a 20-mm-thick slab of stainless steel (AISI 304) on the liquid side. The contact resistance between the oxide and the steel is $0.05 \text{ m}^2\text{-K/W}$.

(i) What is the heat loss per unit surface area of the composite ? (ii) Sketch the temperature distribution from the gas to the liquid with values of temperatures at all surfaces. Thermal conductivities of beryllium oxide and stainless steel may be taken as 21 : 5 W/m.K and 25.4 W/m.K. respectively. 20

6. (a) An ammonia refrigeration plant operates at temperature limits of -10°C and 40°C and rejects 100 kW of heat to the condenser. The saturated vapour refrigerant from the evaporator is superheated in a heat exchanger by the saturated liquid refrigerant from the condenser and the liquid, in turn, is subcooled. The degree of superheat is 10°C . The isentropic efficiency of the compressor

is 80%. Determine (i) The refrigerant flow rate, (ii) the compressor power, (iii) the refrigeration capacity of the system, (iv) COP, and (v) the discharge temperature of the refrigerant from the compressor. 30

Properties of saturated NH_3

Temp. (°C)	Press. (MPa)	v_g (m ³ /kg)	h_f (kJ/kg)	h_g (kJ/kg)	s_g (kJ/kg-K)	$C_{p,\text{vap}}$ (kJ/kg-K)
-10	0.2916	0.417	154.2	1450.2	5.7550	2.4
40	1.56	0.083	390.6	1490.4	5.1558	2.8

- (b) Consider a circular furnace that is 0.3 m long and 0.3m in diameter. The two ends have diffuse, gray surfaces (A_1 and A_2) that are maintained at 400 and 500 K with emissivities of 0.4 and 0.5, respectively. The lateral curved surface (A_3) is also diffuse and gray with an emissivity of 0.8 and a temperature of 800 K. Determine the net radiative heat transfer from each of the surfaces. The view factor between the two end surfaces A_1 and A_2 may be taken as 0.17.

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7. (a) Circular copper rods of diameter $D = 1$ mm and length $L = 25$ mm are used to enhance heat transfer from a surface that is maintained at $T_{s,1} = 100^\circ\text{C}$. One end of the rod is attached to this surface at $(x = 0)$, while the other end $(x = 25 \text{ mm})$ is joined to a second surface, which is maintained at $T_{s,2} = 0^\circ\text{C}$. Air flowing between the surfaces (and over the rods) is also at a temperature of $T_\infty = 0^\circ\text{C}$, and a convection coefficient of $h = 100 \text{ W/m}^2\text{-K}$ is maintained. Starting from the general solution for temperature distribution given as :

$$\theta(x) = T(x) - T_\infty = C_1 e^{mx} + C_2 e^{-mx} ; \text{ where,}$$

$$m = \sqrt{\frac{hp}{kA_c}}.$$

- (i) Derive an expression to determine the rate of heat transfer by conduction as a function of x . Also, determine : (ii) The rate of heat transfer by conduction at $x = 0$, (iii) The rate of heat transfer by conduction at $x = 25$, and

- (iv) The rate of heat transfer by convection from the copper rod to the air. Take, the thermal conductivity of copper, $k = 400 \text{ W/m-K}$. 30
- (b) A single-stage double-acting reciprocating air compressor delivers air at 7 bar. The pressure and temperature at the end of the suction stroke are 1 bar and 27°C . It delivers 2m^3 of free air per minute when the compressor runs at 300 RPM. The clearance volume is 5% of the stroke volume. The pressure and temperature of the ambient are 1.03 bar and 20°C . The index of compression is 1.3, and the index of re-expansion is 1.35. Determine : (i) the volumetric efficiency of the compressor (ii) the indicated power required to run the compressor, (iii) the brake power required to run the compressor if the mechanical efficiency is 80%, (iv) the diameter and stroke length of the cylinder if $L/D = 1$. Take, for air, $c_p = 1.005 \text{ kJ/kg-K}$, $R = 287 \text{ J/kg-K}$ and $\gamma = 1.4$. 30

- (a) A shell-and-tube heat exchanger must be designed to heat 2.5 kg/s of water from 15 to 85°C. The heating is to be accomplished by passing hot engine oil, which is available at 160°C, through the shell side of the exchanger. The oil is known to provide an average convection coefficient of $h_o = 400 \text{ W/m}^2\text{-K}$ on the outside of the tubes. Ten tubes pass the water through the shell. Each tube is thin-walled, of diameter $D = 25 \text{ mm}$, and makes eight passes through the shell. If the oil leaves the exchanger at 100°C, determine (i) the flow rate of oil, (ii) the length of the tubes, and (iii) the length of the shell. For oil : Specific heat at constant pressure, $c_p = 2350 \text{ J/kg-K}$, For water : Specific heat at constant pressure, $c_p = 4181 \text{ J/kg-K}$, Thermal conductivity, $k = 0.643 \text{ W/m-K}$, Dynamic viscosity, $\mu = 548 \times 10^{-6} \text{ N.s/m}^2$, Prandtl number, $Pr = 3.56$. The correlation for estimating the Nusselt number for internal flow:

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$$Nu_D = \frac{hD}{k} = 0.023 Re_D^{0.8} Pr^{0.4}$$

- (b) A centrifugal compressor deliver $10 \text{ m}^3/\text{s}$ of free air when running at 10,000 RPM. The air is drawn at 1 bar and 300 K and delivered at 4 bar. The isentropic efficiency of compression is 80%. Blades are radial at the outlet, and the constant flow velocity is 64 m/s. The outer diameter of the impeller is twice the inner diameter, and the slip factor may be taken as 0.9. The blade area coefficient at the inlet is 0.8, and the power input factor is 1.04 determine : (i) the temperature of the air at the outlet, (ii) the power required to drive the compressor, (iii) impeller diameters at the inlet and outlet, (iv) the width of the impeller at the inlet, (v) impeller blade angle at the inlet, and (vi) diffuser blade angle at the inlet. Take for air, $c_p = 1.005 \text{ kJ/kg-K}$, $R = 287 \text{ J/kg-K}$ and $\gamma = 1.4$.

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