MECHANICAL ENGINEERING

PAPER - I

Time Allowed: Three Hours	Maximum Marks : 300

QUESTION PAPER SPECIFIC INSTRUCTIONS

Please read each of the following instructions carefully Before attempting questions

There are EIGHT full questions in this question paper with subsections in each question.

Candidates has to attempt FIVE full questions.

Question Nos. 1 and 2 are compulsory and out of the remaining six, any THREE are to be attempted in full. The first THREE optional questions in the order of their appearance in the answer book will only be evaluated.

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

All parts of a Question must be answered at one place.

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

Unless otherwise mentioned, symbols and notations have their usual standard meanings.

Answers must be written in ENGLISH only.

Candidate should write the examination on the assumption that all questions are correct. If the candidate still doubts the accuracy of any numeric constant, (s)he should assume its value and specify it clearly in the answer of the concerned question.

1 (a) A pressure cooker 6 litres in volume contains 5 kg of water, where the liquid is in equilibrium with the vapour above it, at 30°C. The cooker with its lid closed and weight on, is heated until the vapour produced results in an increase in pressure, and the weight just lifts up at 2 bar. **20**

i. Calculate the heat transferred in the process.

ii. If the flame heating the cooker is at 400°C, calculate the entropy generation due to the external irreversibility.

Assume that the heating of water is reversible; neglect heating of the cooker body; assume heat transfer to water takes place at its average temperature for the above process. Use property data given below.

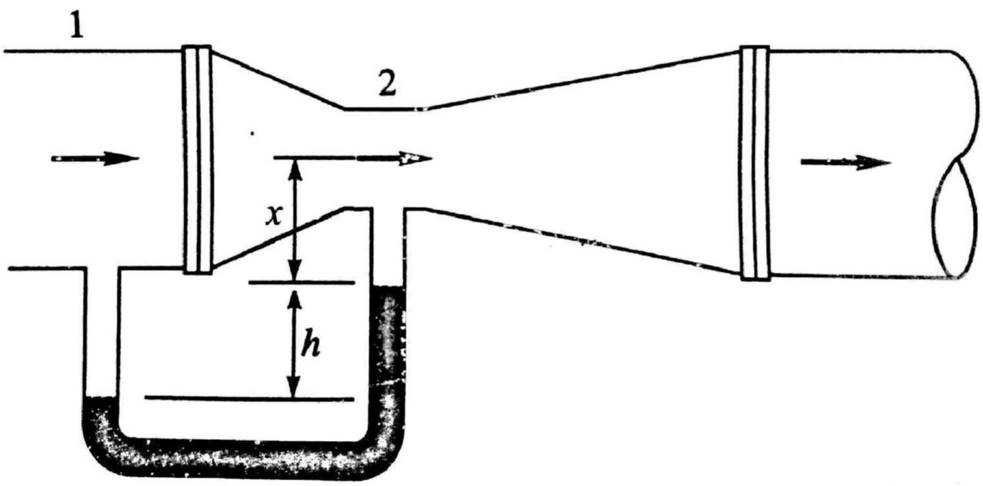
T °C	P kPa	v_f (m³/kg)	v_{fg} (m³/kg)	u_f (kJ/kg)	u_{fg} (kJ/kg)
30	4.246	0.001004	32.8922	125.77	2290.81
120.23	200	0.001061	0.884467	504.47	2025.02

T °C	P kPa	h_f (kJ/kg)	h_{fg} (kJ/kg)	s_f (kJ/kg-K)	s_{fg} (kJ/kg-K)
30	4.246	125.77	2430.48	0.4369	8.0164
120.23	200	504.68	2201.96	1.5300	5.5970

1 (b) A venturi-meter as shown in figure below is a constriction whose pressure difference is a measure of the flow rate in the pipe. Using Bernoulli's equation for steady incompressible flow with no losses, show that the flow rate Q is related to the manometer reading h by **20**

$$Q = \frac{A_2}{\sqrt{1-\left(D_2/D_1\right)^4}}\sqrt{\frac{2gh(\rho_m - \rho)}{\rho}}$$

where ρ_m is the density of the manometer fluid, ρ is the density of the fluid flowing through pipe of diameter D_1, D_2 is the diameter the throat, and A_2 is the cross-sectional area at the throat.



1 (c) A cubical block of copper (k=400 W/mK; ρ=8000 kg/m³ and C_p=400 J/kgK) of side 3 cm, initially at 400°C, is dropped into a large bath of oil kept at 90°C. The heat transfer coefficient on the block surface is 100 W/m²K. Calculate the temperature of the block after 5 minutes. State the simplifications made along with justifications. **20**

[P.T.O.

2 (a) Consider the steady fully developed laminar flow through the annular space formed by two coaxial tubes. The flow is along the axis of the tubes and is maintained by a pressure gradient dp/dx where x-direction is taken along the axis of the tubes. **20**

i. Show that the velocity at any radius is

$$u(r) = \frac{1}{4\mu}\frac{dp}{dx}\left[r^2 - a^2 - \frac{(b^2 - a^2)}{\ln(b/a)}\ln\left(\frac{r}{a}\right)\right]$$

where a is the radius of the inner tube and b is the radius of the outer tube.

ii. Find the radius at which the maximum velocity is reached.

iii. Find the stress distribution.

2 (b) Compressed natural gas, which can be modelled as methane, (CH_4, Molecular weight=16, C_p=2254 J/kgK; C_v=1738 J/kgK) is filled into a rigid 100 litre tank of a vehicle. The initial state of gas in the tank is 1 bar, 27°C, and the final pressure is 150 bar. The filling is done from a large reservoir at 300 bar, 27°C. Heat loss during filling can be neglected, and the gas can be treated as ideal. Compute the final mass and temperature of the gas in the tank. **20**

2 (c) A pre-calibrated thermocouple having a bead of 2 mm diameter is placed in a flame which exhibits a convective heat transfer coefficient of 200 W/m^2K on the bead surface. The bead is losing heat by radiation to the room whose walls are at 300 K. Take the surface emissivity of the bead to be 0.8. Stefan-Boltzmann constant is $\sigma = 5.67\times10^{-8}$ $W/m^2\text{-}K^4$ **20**

i. Derive the expression for radiative heat loss from the thermocouple bead.

ii. If the thermocouple reads 800 K, estimate the correct temperature of the flame.

3 (a) In an air-standard diesel cycle, the pressure and temperature at the beginning of compression stroke are 1.03 bar and 300 K. The maximum pressure of the cycle is 47 bar and the heat supplied is 545 kJ/kg. Calculate the compression ratio, maximum temperature of the cycle and thermal efficiency of the cycle. Take C_p=1.005 kJ/kgK and γ=1.4. **20**

3 (b) A horizontal tube in a condenser is maintained at constant surface temperature by the vapours condensing on its surface. Consider one such tube through which cooling water flows. If $T_{m,0}$ is the mean temperature of the water at the inlet and $T_{m,L}$ is the mean water temperature at the outlet of the tube of length L, show that the heat transfer to the water in the tube can be written as **20**

$$\dot{Q}_{conv} = -\bar{h}A_s\Delta T_{lm} = \dot{m}C_p(T_{m,L} - T_{m,0}),$$

where

$$\Delta T_{lm} = \frac{(T_{m,L} - T_w) - (T_{m,0} - T_w)}{\ln\left(\frac{T_{m,L} - T_w}{T_{m,0} - T_w}\right)}$$

is the log mean temperature difference between the fluid and the tube wall over the length of the tube.

3 (c) A four-cylinder 4-stroke gasoline engine develops a brake power of 20.9 kW at 3000 rpm. Using Morse test, at the same speed, one cylinder at a time is cut off by turns and the brake power is measured to be 14.9, 14.3, 14.8 and 14.5 kW respectively. Compute the indicated power of the cycle and its mechanical efficiency. **10**

3 (d) At the intake of a compressor, air is at 100 kPa, 28°C and 50% relative humidity. This air is compressed to 400 kPa and then sent to an intercooler. What is the minimum temperature to which it can be cooled in the intercooler, if condensation is to be avoided? Use data given below as needed. **10**

T °C	20	25	30	35	40	45	50
P_{sat} (kPa)	2.339	3.169	4.246	5.628	7.384	9.593	12.350

4 (a) An inward flow reaction turbine develops 70 kW at 370 rpm. The inner and outer diameters of the rotor are 0.4 m and 0.8 m respectively. The velocity of water at the exit is 2.8 m/s. The turbine discharges 545 litres/s under a head of 14 m. Assume that the discharge is radial and the width of the rotor is constant. Find **20**

i. The actual and the theoretical hydraulic efficiency of the turbine,
ii. Inlet angle of guide vanes
iii. Inlet angle of rotor vanes.

Take g = 9.81 m/s^2 and density of water as 1000 kg/m^3.

4 (b) A natural gas has a molar composition of 93% CH_4, 3%C_2H_6, 3%N_2 and 1% CO. It is burned in air (79% N_2, 21% O_2 molar composition) which is 30 times the volume of the fuel. **20**

i. Determine the empirical formula of the natural gas.
ii. Chemically balance the combustion equation.
iii. Assuming complete combustion, compute the product composition on dry basis.

4 (c) A centrifugal pump impeller runs at 1500 rpm and has the internal and the external diameter of 0.2 m and 0.4 m respectively. Assume constant radial velocity of 2.8 m/s. The vanes at the exit are set back (backswept) by an angle of 30°. Calculate **10**

i. the angle which the absolute velocity of water at the exit makes with the tangent
ii. inlet vane angle
iii. work done per kg of water.

Take g = 9.81 m/s^2 and density of water as 1000 kg/m^3.

4 (d) **10**

i. "Steam power plants exhibit a better thermal efficiency in winter due to lower cooling water temperatures in the condenser". True or false? Sketch a Rankine cycle to justify your answer.
ii. "Impulse stages are preferred at the high pressure end of a steam turbine". True or False? Give reasons.
iii. In an axial flow gas turbine in a power plant, the compressor has fewer stages than the turbine. True or false? Give reasons.
iv. Electrostatic precipitators are used in __________ (**coal** / **gas**) based power stations. Their function is ______________.

5 (a) The impeller of a double sided centrifugal compressor rotates at 15,500 rpm. Inlet stagnation temperature is 288 K and inlet stagnation pressure is 101 kPa. Impeller eye root and tip diameters are 18 cm and 31.75 cm respectively. Mass flow rate is 18.5 kg/s. Axial velocity at inlet is 150 m/s. The air is given 20° of pre-whirl at all the radii. **20**

i. Find values for the impeller vane angles at the root and tip of the eye.
ii. Find the maximum Mach number at the eye.

Take C_p=1.005 kJ/kgK, R = 0.287 kJ/kgK and γ=1.4

[P.T.O.

5 (b) Let θ be the angle between the incident solar beam and normal to a plane surface that is inclined at an angle β from the horizontal plane. The angle relationship is given by the following equation: **20**

$$\cos\theta = \sin\phi(\sin\delta\cos\beta + \cos\delta\cos\gamma\cos\omega\sin\beta) + \cos\phi(\cos\delta\cos\omega\cos\beta - \sin\delta\cos\gamma\sin\beta) + \cos\delta\sin\gamma\sin\omega\sin\beta$$

where ϕ is the latitude, γ is the surface azimuth angle, ω is the hour angle (which is assumed to be zero at solar noon) and δ is the declination angle (in degree) given by

$$\delta = 23.45\sin\left[\frac{360}{365}(284+n)\right]$$

where n is the day of the year.

i. Using the angle relationship given above, derive the angle relation for an inclined surface facing due south. Also, find an expression for the zenith angle θ_z and show that

$$\theta_{noon} = |\phi - \beta - \delta|, \theta_{z,noon} = |\phi - \delta|$$

ii. Find the days of the year, if any, on which the sun is directly overhead at noon in New Delhi $(28^\circ\ 35'N)$

iii. Derive the expression for hour angle at sunrise. Further, compute the hour angle at sunrise and day length (in hours) in New Delhi on 21st June.

5 (c) A stand-alone photo voltaic (PV) system for operating a street light consists of a PV array, storage battery, controller and DC-AC inverter to which an LED bulb of 20 Watts is connected. The PV array consists of 2 modules each containing 36 single crystal Si cells, each of 10 cm diameter. Conversion efficiency of the PV cells is 11%. The battery has an efficiency of 0.82 both while charging and discharging. DC-AC inverter has an efficiency of 0.85 while discharging the energy. The PV array receives solar radiation of approximately 22,600 $\mathrm{kJ/m^2}$ per day. **10**

i. Calculate the energy stored in the battery on this day.

ii. If the controller switches on the street light at 18:00 hrs, find the time when the street light would be switched off because of complete battery discharge.

5 (d) A Pelton wheel develops 12.9 MW at 425 rpm under a head of 505 m. The efficiency of the turbine is 84%. Assume C_v=0.98, and ratio of bucket speed to jet speed as 0.46. Find **10**

i. discharge of the turbine

ii. diameter of the wheel

iii. diameter of the nozzle.

Take g = 9.81 m/s^2 and density of water as 1000 kg/m^3.

6 (a) A single cylinder 4-stroke engine whose bore and stroke are both 80 mm runs at 2000 rpm. The volumetric efficiency is 0.8, and fuel flow rate is measured to be 38.5 ml/min. The density of the fuel is 800 kg/m^3, and that of air is 1.15 kg/m^3. The calorific value of the fuel is 44 MJ/kg. The dynamometer is balanced using a mass of 10 kg hanging from an arm of radial length 33 cm. Compute the following: **20**

i. Brake power in kW

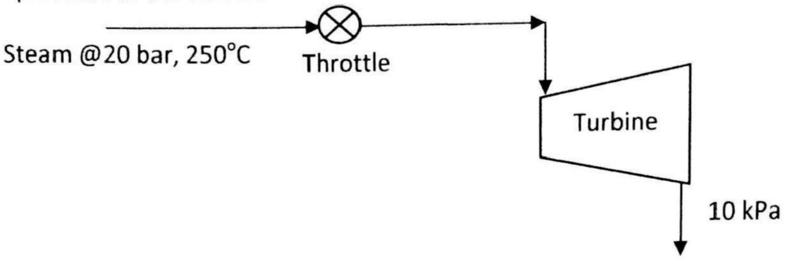
ii. Brake mean effective pressure (BMEP) in bar

iii. Brake specific fuel consumption (BSFC) in kg/kWh

iv. Air-fuel ratio

v. Brake thermal efficiency.

6 (b) Throttling 10 kg/s of steam at 20 bar, 250°C reduces the power output of the turbine (as shown in the figure) by 20%. The turbine has an isentropic efficiency of 0.8 and the exit pressure of the turbine is 10 kPa. **20**



i. Compute the power output when the steam is not throttled.
ii. Compute the quality and enthalpy at the exit of the turbine in the throttled operation.
iii. Compute the rate of irreversibility in the throttle, taking the ambient temperature to be 300 K.

T °C	P bar	v (m^3/kg)	u (kJ/kg)	h (kJ/kg)	s (kJ/kgK)
250	20	0.11144	2679.58	2902.46	6.5452

P kPa	T °C	h_f (kJ/kg)	h_{fg} (kJ/kg)	s_f (kJ/kg-K)	s_{fg} (kJ/kg-K)
10	45.81	191.81	2392.82	0.6492	7.5010

6 (c) A Carnot heat engine is operating between a source temperature of T_H and a sink temperature of T_L. If it is desired to double the thermal efficiency, what should be the new source temperature? **10**

6 (d) **10**

i. "Diesel fuel cannot be used as SI engine fuel". True or False? What role does autoignition temperature of diesel in air play in your answer?
ii. What is the connection between knock and ignition delay in CI engines?
iii. Sketch the p-V diagram of a 4-stroke SI engine at part-throttle operation and label the power and pumping loops.
iv. The X- and Y- axes in Willan's line plots are __________ and __________. Extrapolation of Willan's line is used to determine __________.

7 (a) Assume that the temperature of air in the atmosphere varies with height as **20**

$$T(z) = T_0 + kz$$

where k is a constant. Show that the pressure varies with height as

$$p(z) = P_0 \left[\frac{T_0}{T_0 + kz}\right]^{\frac{g}{kR}}$$

where R is gas constant.

7 (b) A vapour compression refrigeration cycle uses R134a as refrigerant. The state of the refrigerant at the exit of condenser is saturated liquid at 55°C and that at the exit of the evaporator is saturated vapour at -25°C. When it uses a throttling device for expansion, its refrigeration capacity is 500W. **20**

i. Sketch the cycle on a *p-h* diagram.
ii. If the throttle is replaced with an isentropic turbine, calculate
   a. the power output of the turbine and
   b. the new refrigerating effect,

if the other conditions of the cycle remain the same. Use the data given below.

T °C	P kPa	v_f (m^3/kg)	v_{fg} (m^3/kg)	u_f (kJ/kg)	u_{fg} (kJ/kg)
-25	107.2	0.000730	0.17957	167.3	196.31
55	1491.6	0.000928	0.01224	278.33	127.68
T °C	**P kPa**	**h_f (kJ/kg)**	**h_{fg} (kJ/kg)**	**s_f (kJ/kg-K)**	**s_{fg} (kJ/kg-K)**
-25	107.2	167.38	215.57	0.8754	0.8687
55	1491.6	279.72	145.93	1.2619	0.4447

7 (c) Consider a plane Couette flow of a viscous fluid confined between two flat plates at a distance *b* apart. At steady state, the velocity distribution is **10**

$$u = \frac{Uy}{b}, v = w = 0$$

where the upper plate at *y=b* is moving parallel to itself at a speed U and the lower plate is held stationery. Find:

i. the rates of linear strains
ii. rate of shear strain
iii. vorticity
iv. stream function.

7 (d) **10**

i. At constant specific humidity, when the temperature decreases, relative humidity ______; WBT ___________; Enthalpy ________; specific volume _________. (fill the blanks with either **increases** or **decreases**)
ii. If latent heat of vaporization of a refrigerant is low, the size of the evaporator, for a given refrigeration capacity, is _________(**high / low**). This is because __________ (reason).
iii. Joule Thompson coefficient of a refrigerant should be _________ (**positive / negative / zero**). This is because __________ (reason).
iv. Hydrocarbon refrigerants have a ___________ (**high / low / zero**) Ozone Depletion Potential and a __________ (**high / low / zero**) Global Warming Potential. This is because _________ (reasons).

8 (a) It is decided to electrically insulate a conducting wire of outer diameter 2 cm with a material whose thermal conductivity is 1 W/mK. The surrounding air at 20°C causes a heat transfer coefficient of 25 W/m^{2}K at the outer surface of the insulation. The maximum temperature of the insulation cannot exceed 50°C. Compute the maximum steady state heat generation pemissible per unit length of the conductor under this constraint. **20**

8 (b) Consider an air-standard Brayton Cycle, with a compressor whose isentropic efficiency is 0.8, and a turbine whose isentropic efficiency is 0.9. All the other processes are ideal. The compressor inlet air is at 1 bar, 300K, pressure ratio is 30 and the maximum cycle temperature is 1500 K. Compute the pressures and temperatures of the states of the cycle and its thermal efficiency. Take C_p=1.005 kJ/kgK and γ=1.4. **20**

8 (c) For the steady flow through a conical nozzle, the axial velocity is approximately given by **10**

$$u = \frac{U_0}{\left(1 - \frac{x}{L}\right)^2}$$

where U_o is the entry velocity, and L is the distance from the inlet plane to the apparent vortex of the cone.

i. Derive the general expression for the axial acceleration.
ii. Determine the acceleration at x=0 and x = 1.0m if U_0 = 5 m/s and L=2m

8 (d) i. "A fin with high effectiveness will also have a high fin efficiency" True or false? Justify your answer. **10**

ii. Entry lengths for development of velocity profile and temperature profiles are equal when________=1.0. When this parameter is >1.0, ________(**hydrodynamic / thermal**) entry length is higher.

iii. In mixed convection, the parameter when __________ <1.0, __________ (**natural / forced**) convection dominates over the other.

iv. In heat exchanger design, "number of transfer units" (NTU) is defined as __________. When this is large, the size of the heat exchanger is __________ (**large / small**).