Machakos University

(University Examinations 2021/2022)

SCHOOL OF ENGINEERING

DEPARTMENT OF MECHANICAL AND MANUFACTURING ENGINEERING

EMM 404: THERMODYNAMICS III

Time: 2 Hours

Instructions:

- This paper consists of FIVE questions
- Attempt **Question 1** and any other **TWO** questions
- Maximum marks for each part of a question are as indicated.

Provided

- Molar (Universal) gas constant R_O = 8314.5 J/kmolK
- Thermodynamic and Transport Properties of Fluids, SI Units - by Rogers G.F.C and Mayhew Y.R

Question 1(30 marks)

a) When two phases of a substance co-exist inequilibrium at constant temperature and pressure, their specific Gibbs free energies are equal. Using this fact, obtain the Clausius-Clapeyron equation. *[5 marks]*

b) Show that the volumetric efficiency of a compressor with clearance volume V_c and stroke volume V_s, is given by the expression:

$$\eta_v = 1 - \frac{V_c}{V_s}\left\{\left(\frac{P_2}{P_1}\right)^{\frac{1}{n}} - 1\right\}$$

Where P_1 and P_2 are the induction and delivery pressures respectively, while n is the polytropic index of compression/expansion. *[5 marks]*

c) Outline five advantages of multi-stage compression over single stage compression. *[5 marks]*

d) Explain the following methods of reduction of steam turbine rotor speed to optimum value.

i. Velocity compounding
ii. Pressure compounding *[5 marks]*

e) Show that the critical velocity C_c at the throat of a nozzle for a perfect gas can be found from the equation:

$$C_c = \sqrt{(\gamma R T_c)}$$

Where R is the gas constant and T_c is the temperature at the critical velocity. *[5 marks]*

f) Air is expanded reversibly and adiabatically in a nozzle from 15 bar and 350 K to a pressure of 4 bar. The inlet velocity in negligible and the process occurs under steady conditions. Calculate the exit velocity of the nozzle. Take $\gamma = 1.4$, and $c_p = -1.005$ kJ/kg K. *[5 marks]*

Question 2 (20 marks)

a) By considering the first law of thermodynamics, the definition of entropy, and the Helmholtz free energy (F = U – TS), obtain the following two Maxwell relations:

$$\left(\frac{\partial T}{\partial V}\right)_S = -\left(\frac{\partial P}{\partial S}\right)_V \quad \text{and} \quad \left(\frac{\partial P}{\partial T}\right)_V = \left(\frac{\partial S}{\partial V}\right)_T$$ *[14 marks]*

b) Using the Maxwell relations, determine relations for $\left(\frac{\partial S}{\partial V}\right)_T$ and $\left(\frac{\partial P}{\partial S}\right)_V$ for a gas whose equation of state is $(P - \frac{a}{v^2})(v - b) = RT$; where a and b are constants *[6 marks]*

Question 3 (20 marks)

A single acting, single stage, reciprocating compressor has a bore of 200 mm and a stroke of 300 mm. The speed of the compressor is 500 rev/min, clearance volume is 5% of the swept volume and polytropic index 1.3.

Inlet air at 97 kN/m^2, 20 ºC is compressed to 550 kN/m^2.

Determine the following:

i) The free air delivered in m^3/s at 1.013 bar and 15 ºC.

ii) The volumetric efficiency;

iii) The required power output of the drive motor if the mechanical efficiency of the compressor is 85%. *[20 marks]*

Question 4 (20 marks)

(a) Prove that the maximum discharge of fluid per unit area through a nozzle occurs when the ratio of fluid pressure at the throat to the inlet pressure is, $\left(\frac{2}{n+1}\right)^{\left(\frac{n}{n-1}\right)}$, where n is the index of adiabatic expansion. *[10 marks]*

(b) A convergent-divergent nozzle operates with 5 kg of steam per minute being discharged at 1 bar. If the steam is supplied to the nozzle at 8 bar and 250 ºC, for supersaturating expansion upto the throat then normal expansion, determine;

i. the steam state at the throat,

ii. the temperature at the throat,

iii. the throat area, neglect the inlet velocity to the nozzle.

For supersaturation take $pv^{1.3}$ = constant and $\frac{P}{T^{\frac{1.3}{0.3}}} = \text{constant}$. *[10 marks]*

Question 5 (20 marks)

A single stage impulse steam turbine has mean blade speed of 150 m/s; steam leaves nozzle with 680 m/s velocity at angle of 20º. The exit blade angle is 25º. If blade velocity coefficient is 0.9; for a steam flow rate of 5.5 kg/s, determine:

i. The power output,
ii. The specific steam consumption,
iii. The diagram efficiency. *[20 marks]*