First Semester Examination
2023/2024 Academic Session

February 2024

EMH 211 – Thermodynamics
(Termodinamik)

Duration: 3 hours
(Masa: 3 Jam)

Please check that this examination paper consists of SEVEN (7) pages of printed material before you begin the examination.

[Sila pastikan bahawa kertas peperiksaan ini mengandungi TUJUH (7) muka surat yang bercetak sebelum anda memulakan peperiksaan ini.]

Instructions: Answer ALL **FIVE (5)** questions.

*[**Arahan**: Jawab **LIMA (5)** soalan]*

Note:

1. Thermodynamic Formula Booklet is given in the Appendix.
2. Thermodynamic properties tables are provided

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1. Figure Q1 shows a 2D cross-section of a cylindrical nozzle.

   (a) Derive the steady flow energy equation for an open system based on the first law of thermodynamics.

   (30 marks)

   (b) Based on the steam inlet and outlet conditions given, calculate:

   (i) the steam mass flow rate, given that the inlet diameter of the nozzle, d_1, is 5 cm.

   (20 marks)

   (ii) the exit velocity of the steam, V_2. Assume adiabatic conditions.

   (50 marks)

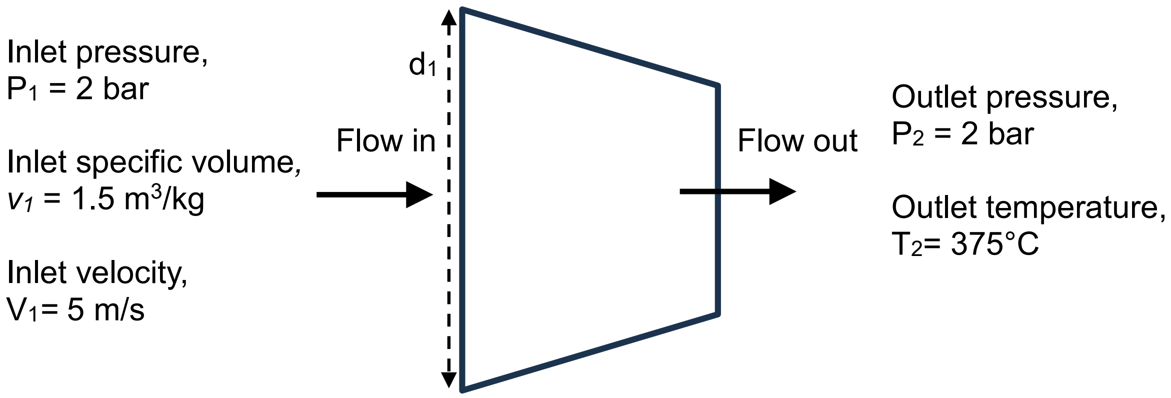

Figure 1

2. (a) Polytropic thermodynamics processes for a non-flow, closed system, in a gaseous system is governed by a simple formula $pV^n = constant$.

   State the thermodynamics processes and their respective terminologies for:

   n = 0, 1, γ, and ∞.

   (20 marks)

   (b) Air at temperature of 27°C and pressure of 1.03 bar is compressed following a polytropic process, $pV^n = constant$, until its pressure becomes 7.5 bar. Given that n = 1.2, γ = 1.4,

   (i) Sketch and label the process in a P-v diagram.

   (20 marks)

   (ii) Calculate the final temperature.

   (20 marks)

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(iii) Given that the mass of air is 10 kilograms, calculate the total work done and heat transfer. Indicate the direction of the work and heat in or out of the system to the environment.

(40 marks)

3. (a) The second law of thermodynamics involves heat pump and heat engine in reversible or irreversible processes. Briefly describe Clausius statement regarding heat pump and Kelvin-Planck statement regarding heat engine.

(20 marks)

(b) An externally insulated steam turbine is supplied with a steady flow steam at the inlet pressure of 80 bar and temperature of 600°C through to the exit as dry saturated steam at constant pressure of 2 bar. Neglect kinetic and potential energy losses. Given that the ambient temperature is 27°C, atmospheric pressure is 1 bar, the mass flow rate is 50 kg/s and mechanical efficiency is 90%:

(i) Sketch and label the process on a T-s diagram.

(10 marks)

Calculate:

(ii) isentropic efficiency of the process. **(20 marks)**

(iii) actual power output of the turbine. **(10 marks)**

(iv) exergy change in the process. **(10 marks)**

(v) second law efficiency of the process. **(10 marks)**

(vi) exergy of the steam at the inlet. **(10 marks)**

(vii) exergy conversion efficiency. **(10 marks)**

4. Heat is supplied to an air standard Otto cycle at 720 kJ/kg with the maximum and minimum temperatures of 1150°C and 28°C, respectively. Given that γ = 1.4, R = 0.287 kJ/kgK c_p= 1.005 kJ/kgK and c_v = 0.718 kJ/kgK:

(a) Sketch the cycle on a P-v diagram. **(20 marks)**

(b) Calculate:

(i) compression ratio. **(30 marks)**

(ii) thermal efficiency of the cycle. **(20 marks)**

(iii) ratio of maximum to minimum pressures in this cycle.

(30 marks)

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5. In a Rankine-based vapour power plant, steam is supplied to a two-stage turbine at 650°C and 80 bar. It expands isentropically in the first stage to the pressure of 4 bar. Then it is reheated to 500°C and expanded through the second-stage turbine to the condenser pressure of 0.035 bar. Assume the isentropic efficiency in the second stage of turbine to be equal to 0.72. The feed pump term is neglected in calculations.

   (a) Sketch the process in a T–s diagram showing the important points with proper labels.

   (10 marks)

   (b) Calculate:

   (i) total specific work of the turbine. **(30 marks)**

   (ii) cycle thermal efficiency. **(20 marks)**

   (iii) cycle specific steam consumption of the plant. **(10 marks)**

   (iv) Discuss two methods to improve Rankine cycle efficiency.

   (30 marks)

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APPENDIX 1

Thermodynamic Formulae Booklet 2024

First law for closed cycle

$\oint \delta Q = \oint \delta W \quad \Rightarrow Q_{net} = W_{net}$

Non-flow energy equation

$q - w = (u_2 - u_1)$

Enthalpy equation

$h = u + Pv$

specific heat equation

$q = c_p (T_2 - T_1)$

Joule Law

$du = c_v\, dT$

$dh = c_p\, dT$

Dryness Fraction equations

$v = v_f + x (v_f - v_g)$ or $v = x\, v_g$ (P<20bar)

$h = h_f + x\, h_{fg}$; $u = u_f + x\, u_{fg}$

$s = s_f + x\, s_{fg}$

Cycle efficiency

$$\eta = \frac{w_{net}}{q_h} = \frac{q_h - q_c}{q_h} = 1 - \frac{q_c}{q_h}$$

$$COP_{refrigerator} = \frac{q_c}{w_{net}}$$

$$COP_{heat\ pump} = \frac{q_h}{w_{net}}$$

Entropy

$q = T (s_2 - s_1)$; (Isothermal)

Gibbs Equation

$Tds = Pdv + du$

$Tds = dh - vdP$

$$\eta_{isentropic\ expantion} = \frac{W_{actual}}{W_{isentropic}}$$

$$\eta_{isentropic\ compression} = \frac{W_{isentropic}}{W_{actual}}$$

Ideal gas

Characteristics equation

$PV = mRT$

specific heat of an ideal gas

$$\gamma\ (or\ k) = \frac{Cp}{Cv}\ ;\ Cp = \frac{\gamma R}{\gamma - 1}\ ;$$

$$Cv = \frac{R}{\gamma - 1}$$

Polytrophic process $(PV^n = \text{constant})$

$$\frac{P_2}{P_1} = \left(\frac{V_1}{V_2}\right)^n \text{ and } \frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{n-1/n} = \left(\frac{V_1}{V_2}\right)^{n-1}$$

$$W(kJ) = \frac{P_2V_2 - P_1V_1}{1-n} = \frac{mR(T_2 - T_1)}{1-n};(n>1)$$

$$W(kJ) = P_1V_1.\ln\frac{V_2}{V_1} = mRT.\ln\frac{V_2}{V_1};(n=1)$$

$$Q(kJ) = W(\gamma - n)/(\gamma - 1);(n>1)$$

Adiabatic process $(PV^\gamma = \text{constant})$

Specific entropy of an ideal gas

$s_2 - s_1 = R \ln(v_2/v_1) + c_v \ln(T_2/T_1)$

$s_2 - s_1 = c_p \ln(v_2/v_1) + c_v \ln(P_2/P_1)$

$s_2 - s_1 = c_p \ln(T_2/T_1) - R \ln(P_2/P_1)$

Specific exergy of a closed system

$x = (u - u_o) + P_o(v - v_o) - T_o(s - s_o)$

Specific exergy of an open system

$x = (h - h_o) - T_o(s - s_o) + K.E + P.E$

Specific exergy change of the process

$\Delta x = x_2 - x_1 = (h_1 - h_2) - T_0(s_1 - s_2) + \Delta KE + \Delta PE$

Second Law Efficiency:

$$\eta_{II} = \frac{W_{irr}}{X} = \frac{\eta}{\eta_{rev}} = \frac{W}{W_{rev}} = \frac{COP_{rev}}{COP}$$

Carnot Cycle
$Q_{12} = m R T_1 \ln(v_1/v_2) = W_{12}$
$Q_{23} = m c_v (T_3 - T_2)$
$Q_{34} = mRT_3 \ln (v_4/v_3) = W_{34}$
$Q_{41} = m c_v (T_4 - T_1) = Q_{23}$
$$\eta_{carnot} = 1 - \frac{|Q_c|}{Q_h} = 1 - \frac{T_c}{T_h}$$

Stirling Cycle
$Q_c = Q_{12} = mRT_1 \ln (v_1/v_2) = W_{12}$
$Q_{23} = m c_v (T_3 - T_2)$
$Q_h = Q_{34} = mRT_3 \ln (v_4/v_3) = W_{34}$
$Q_{41} = mc_v (T_4 - T_1) = Q_{23}$
$$\eta_c = 1 - \frac{|Q_c|}{Q_h} = 1 - \frac{T_1}{T_3}$$
$$Work\ ratio = \frac{W_{34} - W_{12}}{W_{34}} = 1 - \frac{T_1}{T_3} = \eta_c$$

Ericsson Cycle
$Q_c = Q_{12} = mRT_1 \ln (P_2/P_1) = W_{12}$
$Q_{23} = m c_p (T_3 - T_2)$
$Q_h = Q_{34} = mRT_3 \ln (P_3/P_4) = W_{34}$
$Q_{41} = mc_p (T_1 - T_4)$
$$\eta_{ericsson} = 1 - \frac{|Q_c|}{Q_h} = 1 - \frac{T_1}{T_3}$$

Closed Brayton/Joule Cycle
$W_{12} = m c_p (T_1 - T_2)$
$Q_h = Q_{23} = m c_p (T_3 - T_2)$
$W_{34} = m c_p (T_3 - T_4)$
$Q_c = Q_{41} = m c_p (T_1 - T_4)$
$$\eta_c = \frac{W_{net}}{Q_h} = \frac{Q_{net}}{Q_h} = 1 - \frac{(T_1 - T_4)}{(T_3 - T_2)}$$
$\eta = 1 - \left(\frac{1}{r_p}\right)^{\frac{\gamma-1}{\gamma}}$ (Applicable for isentropic processes only)
$$Work\ ratio = \frac{W_{34} - W_{12}}{W_{34}} = 1 - \frac{T_1}{T_3}(r_p)^{\frac{\gamma-1}{\gamma}}$$

Otto Air Standard Cycle
$W_{12} = mc_v (T_1 - T_2)$
$Q_h = Q_{23} = m c_v (T_3 - T_2)$
$W_{34} = m c_v (T_3 - T_4)$
$Q_c = Q_{41} = m c_v (T_1 - T_4)$
$$\eta_c = 1 - \frac{|T_1 - T_4|}{(T_3 - T_2)}$$

Diesel Standard Air Cycle
$Q_{12} = Q_{34} = W_{41} = 0$
$Q_p = Q_{23} = mc_p(T_3 - T_2)$
$Q_s = Q_{41} = mc_v(T_1 - T_4)$
Cycle efficiency,
$$\eta_D = 1 - \frac{|Qs|}{Qp} = 1 - \frac{(T_4 - T_1)}{\gamma(T_3 - T_2)} = 1 - \frac{1}{r_v^{\gamma-1}}\left(\frac{\beta^\gamma - 1}{\gamma(\beta - 1)}\right)$$
$r_v = (v_1/v_2)$ = compression ratio
$\beta = (v_3/v_2)$ = volume ratio or cut-off ratio

Mixed Cycle (Dual combustion cycle)
$Q_{12} = 0$
$Q_{23} = mc_v (T_3 - T_2)$
$Q_{34} = mc_p (T_4 - T_3)$
$Q_{51} = mc_v (T_1 - T_5)$
$r_v = (v_1/v_2)$ = compression ratio
$r_p = (P_3/P_2)$ = pressure ratio
$\beta = (v_4/v_3)$ = volume ratio, cut-off ratio
Cycle efficiency,
$$\eta_m = 1 - \frac{|Q_c|}{Q_h} = 1 - \frac{|Q_{51}|}{(Q_{23} - Q_{34})}$$

Mean Effective Pressure – MEP (P_m)
$w_{net} = P_m (v_1 - v_2)$

Rankine Cycle (Simple & Superheated Cycle)
$w_{12} = -(h_2 - h_1)$
$q_{23} = -(h_3 - h_2)$
$w_{34} = -(h_4 - h_3) = -v_{f3}(P_4 - P_3)$
$q_{41} = h_1 - h_4$

Efficiency,
$$\eta = \frac{w_{12} - |w_{34}|}{q_{41}}$$
$$Work\ Ratio = \frac{w_{12} - |w_{34}|}{w_{12}}$$

Rankine Reheat Cycle:
$$\eta = \frac{(w_{12} + w_{78}) - |w_{34}|}{q_{41} + q_{27}}$$

Specific Steam Consumption = 1 /w_{net} (kg/kJ)

$\eta_o = \frac{w_{net}}{q_{net}} = 1 - \frac{q_c}{q_h}$ $\frac{T_2}{T_1} = \frac{T_3}{T_4} = \left(\frac{v_1}{v_2}\right)^{\gamma-1} = r_v^{\gamma-1}$ $pv^{\gamma} = Tv^{\gamma-1} = constant$ $r_v = \frac{Swept\ volume + Clearance\ volume}{Clearance\ volume} = \frac{v_1}{v_2}$ Otto cycle efficiency, $\eta = 1 - \frac{1}{r_v^{\gamma-1}}$	or Specific steam consumption=3600/w_{net} (kg/kWh) **Vapour Compression Cycle** $COP = \frac{\lvert q_{41} \rvert}{\lvert w \rvert} = \frac{h_1 - h_4}{h_2 - h_1}$ Refrigerating effect: $q_{41} = (h_1 - h_4)$ (kJ/kg)