TWO HOURS

Department of Mechanical, Aerospace & Civil Engineering

UNIVERSITY OF MANCHESTER

ENGINEERING THERMODYNAMICS

xxxxxx 2021

09:00 – 11:00

Special Instruction(s):

- ANSWER **ALL** QUESTIONS
- A FORMULA SHEET IS PROVIDED AT THE END OF THE PAEPR.
- MAKE USE OF THE '**PROPERTY TABLES AND CHARTS (SI UNITS)**', GIVEN AS APPENDIX OF 'THERMODYNAMICS-AN ENGINEERING APPROACH (SI VERSION) (9TH ED.) (MCGRAW HILL) CENGEL, BOLES AND KANOGLU.

Q1. A hot reservoir provides heat to a Carnot heat engine at 900°C at a rate of 0.8 MJ/min and the waste heat is rejected to the ambient air at 27°C. The total work from the heat engine is used to power a refrigerator operating between a refrigerated space kept at -5°C and the same ambient air at 27°C. You may assume that the heat engine and the refrigerator operate steadily.

(a) Sketch the heat engine/refrigerator in the question using a simple diagram and highlight all the main components. **[5 marks]**

(b) Calculate the thermal efficiency of the Carnot heat engine and its maximum power output. **[6 marks]**

(c) Calculate the Coefficient of Performance (COP) of the Carnot refrigerator and the maximum rate of heat removal in kJ/min from the refrigerated space. **[6 marks]**

(d) Calculate the total rate of heat rejection to the ambient air in kJ/min from both the heat engine and refrigerator. **[8 marks]**

Q2. A gas-turbine power plant shown in **Figure Q2**, which is based on a Brayton cycle, consists of a compressor, a combustion chamber and a turbine. Air enters the compressor at 0°C and 1 bar with a pressure ratio of 7. The compressor has an isentropic efficiency of 80%. The turbine has an isentropic efficiency of 90%. The temperature at the outlet of the combustion chamber is 1500 K. The net power output is 150 MW.

Assume steady operating conditions and constant properties for air at 300 K with c_v = 0.718 kJ/kgK, c_p = 1.005 kJ/kgK, R = 0.287 kJ/kgK, γ = 1.4. You may ignore any kinetic and potential energy changes and assume air as an ideal gas.

(a) Sketch the *T*-*s* diagram for the cycle. **[4 marks]**

(b) Calculate the exit temperature of the compressor. **[4 marks]**

(c) Calculate the exit temperature of the turbine. **[4 marks]**

(d) Calculate the mass flow rate through the power plant in kg/s and the volumetric flow rate of the air into the compressor in m^3/s. **[8 marks]**

(e) Assuming all parameters of the problem remain the same, explain the impact of raising the compressor inlet temperature on the inlet mass flow rate and net power output (for a fixed compressor inlet velocity and flow area). **[5 marks]**

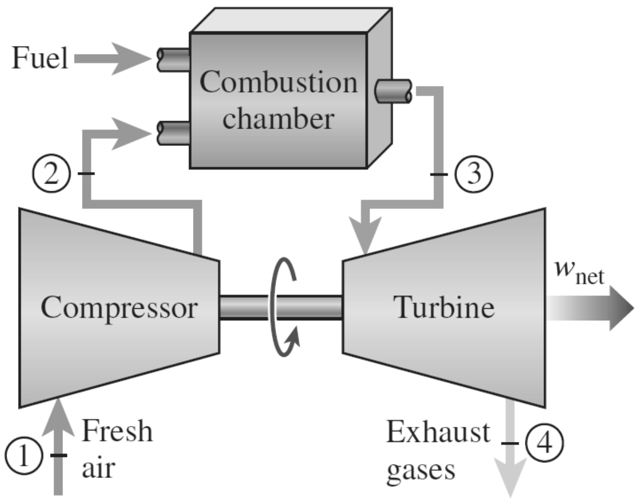

Figure Q2. A gas-turbine power plant

Q3. The mass-based composition of a hydrocarbon-based gas mixture is: 15% butane, 25% propane and 60% methane. By a reversible, isothermal, steady-flow compressor, the mixture, initially at 20°C, is compressed from 1 bar to 8 bar. Ignoring any kinetic and potential energy changes and assuming air as an ideal gas, calculate:

(a) the mole numbers of the component within the mixture. **[10 marks]**

(b) the gas constant of the mixture. **[5 marks]**

(c) the work input and heat transfer for this compression per unit mass of the mixture. **[10 marks]**

Q4. In a simple air-cooling unit depicted in **Figure Q4**, air enters at atmospheric pressure and temperature of 32°C with a relative humidity of 70% at the velocity of 120 m/min. The diameter of the cooling unit is 400 mm. The air is cooled by passing through a cold water cooling coil. The temperature of the water increases by 6°C as it cools the air. The air at the outlet of the cooling section is saturated at 20°C. Assuming a steady-flow process (i.e. constant mass flow rate for air), taking dry air and water vapour as ideal gases and ignoring the kinetic and potential energy changes, determine:

(a) the mass flow rate of air through the unit. **[7 marks]**

(b) the rate of heat transfer. **[6 marks]**

(c) the mass flow rate of the water. **[6 marks]**

(d) the exit velocity of the airstream. **[6 marks]**

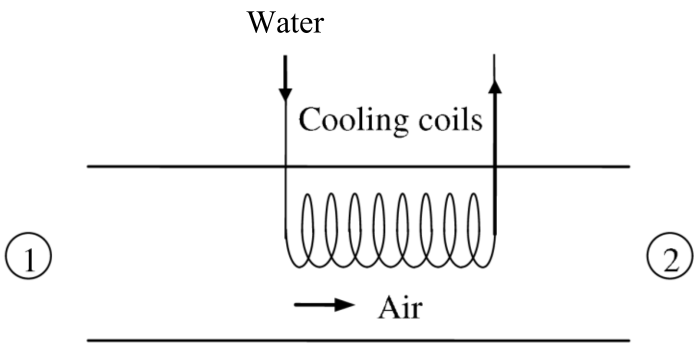

Figure Q4. Air cooling arrangement

END OF THE EXAMINATION PAPER

DATA SHEETS

1 Work

- **positive work:** is done by a system on the surroundings (a system does positive work if it can raise a weight)
- **negative work:** is done by the surroundings on a system.

Incremental piston, or displacement work , is $\delta W = p\mathrm{d}V$, and for a process in which the pressure varies with volume the work is $W = \int p\mathrm{d}V$

Constant pressure (isobaric) process: $pV^0 = c$

$$W_{12} = \int_1^2 pdV = p(V_2 - V_1)$$

Constant volume (isochoric) process: $pV^\infty = c$

$$W_{13} = \int_1^3 pdV = 0, \text{because} dV = 0$$

Process defined by $pV = c$

$$W_{14} = p_1V_1 \, ln\frac{V_4}{V_1} = p_1V_1 \, ln\frac{p_1}{p_4} = etc$$

Process defined by $pV^n = c$

$$W_{15} = \frac{p_1V_1 - p_5V_5}{n-1} = \frac{p_5V_5 - p_1V_1}{1-n}$$

2 First Law of Thermodynamics - closed systems

$$Q - W_s = m\left(u_2 + \frac{V_2^2}{2} + gz_2\right) - m\left(u_1 + \frac{V_1^2}{2} + gz_1\right)$$

First Law for a closed system in the absence of kinetic and potential energy

$$\delta Q = dU + \delta W$$

Specific heat at constant volume

$$c_v = \left(\frac{\partial u}{\partial T}\right)_v = \left(\frac{\partial u}{\partial t}\right)_v = \left(\frac{\partial Q}{\partial T}\right)_v$$

Enthalpy, H

$$H = U + pV$$

Specific enthalpy, h

$$h = \frac{H}{m} = \frac{U + pV}{m} = \frac{U}{m} + \frac{pV}{m} = u + pv$$

Specific heat at constant pressure

$$c_p = \left(\frac{\partial h}{\partial T}\right)_p = \left(\frac{\partial h}{\partial t}\right)_p = \left(\frac{\partial q}{\partial T}\right)_p$$

3 Steady flow energy equation

$$\dot{Q}-\dot{W}=\dot{m}\left(h_e-h_i+\frac{V_e^2-V_i^2}{2}+g(z_e-z_i)\right)$$

Stagnation enthalpy

$$h_0=h+\frac{V^2}{2}$$

Velocity at exit to a nozzle

$$V_2=\sqrt{2\left\{(h_1-h_2)+\frac{V_1^2}{2}\right\}}$$

Work from an adiabatic machine

$$-\dot{W}_s=\dot{m}(h_e-h_i)=\dot{m}(h_2-h_1).$$

4 Second Law of Thermodynamics

Efficiency

$$\textit{Thermal efficiency},\ \eta_{th}=\frac{\text{Useful work output}}{\text{Thermal energy input}},$$

for a heat engine operating in a cycle .

Thermal efficiency of heat engine

$$\text{Thermal efficiency},\ \eta_{th}=\frac{\text{Net work}}{\text{Heat supplied}} \qquad \eta_{th}=\frac{W_s}{Q_1}=\frac{Q_1-Q_2}{Q_1}=1-\frac{Q_2}{Q_1}$$

Coefficient of performance of refrigerator

$$\text{Coefficient of performance},\ \beta=\frac{\text{Heat transferred from cold reservoir}}{\text{Work done}},=\frac{Q_2}{W_s}=\frac{Q_2}{Q_1-Q_2}.$$

Coefficient of performance of heat pump

$$\text{Coefficient of performance},\ \beta'=\frac{\text{Heat transferred to hot reservoir}}{\text{Work done}},=\frac{Q_1}{W_s}=\frac{Q_1}{Q_1-Q_2}.$$

Relationship between coefficients of performance

$$\beta'=1+\frac{Q_2}{W_s}=1+\beta$$

Entropy

Entropy is denoted by the symbol - S; specific entropy is denoted by - s.

The change of entropy between states 1 and 2 is $S_2-S_1=\int_1^2\frac{\delta Q_R}{T}$

Central Equation of Thermodynamics

$$Tds=du+pdv=dh-vdp$$

Steady flow entropy equation for an adiabatic machine

$$\dot{S}_i=\dot{m}(s_e-s_i)\geq 0$$

5 Properties of pure substances

Dryness fraction, or quality

$$\text{Dryness fraction, } x = \frac{\text{Mass of dry vapour}}{\text{Total mass of liquid + vapour}}$$

$$v = xv_g + (1-x)v_f = v_f + xv_{fg}$$
$$u = xu_g + (1-x)u_f = u_f + xu_{fg}$$
$$h = xh_g + (1-x)h_f = h_f + xh_{fg}$$
$$s = xs_g + (1-x)s_f = s_f + xs_{fg}$$

6 Perfect gases, and mixtures of perfect gases

Ideal gas $\dfrac{pv}{T} = const,\ R$

Universal Gas Constant $\Re = MR$

S.I. units $\Re$ = 8.3145 kJ/kmol K

Imperial $\Re$ = 1545 ft.lbf/lb mol °R

= 1.986 Btu/lb mol °R

Molar Masses for Common Gases/Elements

Gas/Element	**M** (kg/kmol)
H_2	2
O_2	32
N_2	28
CO	28
CO_2	44
H_2O	18
C	12

Internal energy $u = \int_{T_o}^{T} c_v dT + u_o$, where u_0 is the value of u at temperature T_0

Enthalpy $h = u + pv = u + RT$

$h = \int_{T_0}^{T} c_p dT + h_0$, where h_0 is the enthalpy at temperature T_0.

Relationship between c_p and c_v

$$c_p = c_v + R \qquad \gamma = c_p/c_v$$

Entropy change

$$ds = \frac{c_v dT + pdv}{T} = c_v\frac{dT}{T} + \frac{p}{T}dv$$

$$s_2 - s_1 = \int_{T_1}^{T_2} \frac{c_v}{T} dT + R\ell n\frac{v_2}{v_1}$$

$$s_2 - s_1 = \int_{T_1}^{T_2} \frac{c_p}{T} dT - R\ell n\frac{p_2}{p_1}$$

7 Isentropic or process efficiencies

For compressors: $\eta_c = \dfrac{h_{2i} - h_1}{h_2 - h_1}$

For turbines: $\eta_t = \dfrac{h_1 - h_2}{h_1 - h_{2i}}$

where the process is from state 1 to state 2 and subscript *i* denotes ideal (isentropic) values

8 Ideal cycle efficiencies

Otto cycle: $\eta = 1 - r_v^{-(\gamma-1)}$

Diesel cycle: $\eta = 1 - r_v^{-(\gamma-1)} \dfrac{(r_c^{\gamma} - 1)}{\gamma(r_c - 1)}$

Dual cycle: $\eta = 1 - r_v^{-(\gamma-1)} \dfrac{(r_p r_c^{\gamma} - 1)}{(r_p - 1) + \gamma r_p (r_c - 1)}$

where r_v is the volumetric compression ratio
r_c is the volumetric cut-off ratio
r_p is the constant-volume heat input pressure ratio
γ is the ratio of specific heats

9 Mean effective pressures of reciprocating engine cycles

The indicated mean effective pressure (imep)

$$p_m = \frac{W_{net}}{V_s}$$

where W_{net} is the net cycle work, V_s is the swept volume

The brake mean effective pressure (bmep)

$$p_b = \frac{W_{net} - W_f}{V_s}$$

where W_f is the work lost to friction.

The friction mean effective pressure (fmep)

$$p_f = p_m - p_b$$