ESO 201A/202

End Sem Exam | 120 Marks | 3 h | 19 Nov 2014

Roll No. **Name** **Section**

Answer **Questions 1** and **2** on the Question Paper itself. Answer **Question 3**, **4** and **5** on the Answer Booklet provided. At the end of the examination, **RETURN BOTH** the Question Paper and the Answer Booklet. Please write your **Roll No.** on every sheet of the Question Paper.

Question 1. Tick (✓) the correct answer (True or False) for each of the following statements. Each correct answer carries **one mark.** There is **no** negative marking

(i) Weight of a system is an intensive property whereas specific weight and specific gravity are extensive properties. **TRUE/FALSE✓**

(ii) In the absence of gravitational effects, pressure and temperature have the same value everywhere for a simple compressible system in a state of thermodynamic equilibrium.

TRUE✓/FALSE

(iii) Blood pressure is measured using two different arm positions: *parallel* to the body (along the side) and *perpendicular* to the body (straight out). Reading in the parallel position will be higher than the same in the perpendicular position. **TRUE✓/FALSE**

(iv) Consider a single component simple compressible substance at its triple point. The number of independent intensive properties (other than the relative amount of each phase) required to fix the intensive state of the system is ZERO. **TRUE✓/FALSE**

(v) The boiling point (saturation) temperature of water increases with pressure, but the enthalpy of evaporation (latent heat of boiling) decreases with pressure and becomes zero at the critical point. **TRUE✓/FALSE**

(vi) If two bodies are in thermal equilibrium with a third body, they are not necessarily in thermal equilibrium with each other. **TRUE/FALSE✓**

(vii) The entropy of a perfectly ordered perfect crystal at absolute zero temperature is zero.

TRUE✓/FALSE

(viii) In the energy balance equation, $\Delta E = Q - W$, for a closed system, Q is the net heat input, W is the net work output and ΔE includes the changes in chemical and nuclear energies (if any) in addition to sensible or latent thermal energy changes.

TRUE✓/FALSE

(ix) The thermodynamic temperature scale is identical with the absolute gas temperature scale that utilizes an imaginary (hypothetical) gas that obeys the ideal gas equation of state at all temperatures. **TRUE✓/FALSE**

(x) Heat and work for a thermodynamic process are path functions and have inexact differentials, whereas P, V and T are point functions and have exact differentials.

TRUE✓/FALSE

(xi) If a closed system goes through a cyclic process, the net work done by the system is necessarily zero. **TRUE/FALSE✓**

(xii) For an incompressible substance ($v = constant$), the specific heat at constant pressure is identical with the specific heat at constant volume. **TRUE✓/FALSE**

(xiii) The relation $du = c_v dT$ is applicable only to a constant volume process and the relation $dh = c_p dT$ is applicable only to a constant pressure process. **TRUE/FALSE✓**

(xiv) An incompressible ($v = constant$), fluid flows steadily through an adiabatic horizontal pipe of constant cross section. Due to viscous friction, the temperature of the fluid rises by 1°C from inlet to exit. It follows that the enthalpy of the fluid at the exit is more than the enthalpy of the fluid at the inlet. **TRUE/FALSE✓**

(xv) In a nozzle the flow energy of the fluid is converted into its kinetic energy, whereas in a diffuser the kinetic energy of the fluid is converted into its flow energy.

TRUE✓/FALSE

(xvi) The relationship $(COP)_{HP} = (COR)_R + 1$ is true only for heat pumps and refrigerators working on the Carnot cycle. **TRUE/FALSE✓**

(xvii) If the thermal efficiency of a Carnot heat engine working between two temperature reservoirs is 1/3, the COP of a Carnot heat pump working between the same temperature will be 3. **TRUE✓/FALSE**

(xviii) A "1-ton" window air conditioner produces a cooling effect at the rate of 3.5 kW. If it rejects heat to the surroundings at the rate of 4.5 kW, its COP is 3.5.

TRUE✓/FALSE

(xix) A system undergoes a process between two fixed states first in a reversible manner and then in an irreversible manner. The entropy change is same for the two cases.

TRUE✓/FALSE

(xx) In an isothermal expansion of a gas, entropy of the gas increases. **TRUE✓/FALSE**

(xxi) For an internally irreversible process, the entropy change of a closed system must be greater than zero. **TRUE/FALSE✓**

(xxii) Useful work done by a closed system in going from state 1 to state 2 is less than the total work done by the system if $V_2 > V_1$. **TRUE✓/FALSE**

(xxiii) A refrigerator that has a higher COP necessarily has a higher second-law efficiency than one with a lower COP. **TRUE/FALSE✓**

(xxiv) A heat engine may have a higher second law efficiency than the first law efficiency.

TRUE✓/FALSE

(xxv) Consider a process during which no entropy is generated ($S_{gen} = 0$). **Exergy** destruction for this process is zero. **TRUE✓/FALSE**

(xxvi) **Exergy** of a closed system is either positive or zero. It is never negative even at low temperature ($T < T_0$) and/or low pressure ($P < P_0$) **TRUE✓/FALSE**

Roll No.

(xxvii) Heat is lost from a surface at 400 K to the environment at 300 K at the rate of 1 kW. The rate of **exergy** destruction in this irreversible heat transfer is 250 W.

TRUE✓/FALSE

(xxviii) The area enclosed by a cyclic process on a P-V diagram equals the area enclosed by the same cyclic process on T-S diagram. **TRUE✓/FALSE**

(xxix) A substance whose Joule-Thomson coefficient is negative is throttled to a lower pressure. During this process, the temperature of the substance will decrease.

TRUE/FALSE✓

(xxx) Consider the liquid-vapor saturation curve of a single-component pure substance on the P-T diagram. The slope of this curve at any point is proportional to the entropy change s_{fg} and inversely proportional to the volume change v_{fg} at that point.

TRUE✓/FALSE

In the following questions where needed you may use the following data/formulae:

$\bar{R} = 8.314$ kJ/kmol·K
Air ($M = 29$, $k = 1.4$, $R = 0.287$ kJ/kg·K) contains 3.76 mol of N_2 per mol of O_2.
For water at 25^{0}C, $\bar{h}_{fg} = 44$ MJ/kmol

$$\begin{aligned}\eta_{Otto} &= 1 - r^{1-k},\\ \eta_{Diesel} &= 1 - \frac{r_c^k - 1}{kr^{k-1}(r_c - 1)}\\ \eta_{Brayton} &= 1 - r_p^{(1-k)/k}\end{aligned}$$

Question 2. Among the multiple choices given with each part of this question, **only one** is correct. Please tick (✓) the **correct/closest to the correct answer.** Each correct answer carries **two marks**. There is **no** negative marking.

(i) Propane (C_3H_8) is burned with 150 percent theoretical air. The air-fuel mass ratio for this combustion process is

(a) 5.3 (b) 10.5 (c) 15.7 (d) 23.4✓ (e) 39.3

(ii) The higher heating value of a hydrocarbon fuel $C_nH_m$with $m = 8$ is given to be 1560 MJ/kmol of fuel. Then its lower heating value is

(a) 1384 MJ/kmol✓ (b) 1208 MJ/kmol (c) 1402 MJ/kmol
(d) 1514 MJ/kmol (e) 1551 MJ/kmol

(iii) A fuel is burned during a steady-flow combustion process. Heat is lost to the surroundings at 300 K at a rate of 1120 kW. The entropy of the reactants entering per unit time is 17 kW/K and that of the products is 15 kW/K. The total rate of exergy destruction during this combustion process is

(a) 520 kW✓ (b) 600 kW (c) 1120 kW (d) 340 kW (e) 739 kW

(iv) Consider a simple ideal Rankine cycle with fixed boiler and condenser pressures. If the steam is superheated to a higher temperature,

(a) the turbine work output will decrease.

(b) the amount of heat rejected will decrease.

(c) the cycle efficiency will decrease.

(d) the moisture content at turbine exit will decrease.✓

(e) the amount of heat input will decrease.

(v) Consider a simple ideal Rankine cycle with fixed boiler and condenser pressures. If the cycle is modified with reheating,

(a) the turbine work output will decrease.

(b) the amount of heat rejected will decrease.

(c) the pump work input will decrease.

(d) the moisture content at turbine exit will decrease.✓

(e) the amount of heat input will decrease.

(vi) Consider a simple ideal Rankine cycle with fixed boiler and condenser pressures. If the cycle is modified with regeneration that involves one open feed water heater (select the correct statement per unit mass of steam flowing through the boiler),

(a) the turbine work output will decrease.✓

(b) the amount of heat rejected will increase.

(c) the cycle thermal efficiency will decrease.

(d) the quality of steam at turbine exit will decrease.

(e) the amount of heat input will increase.

(vii) An Otto cycle with air as the working fluid has a compression ratio of 10.4. Under cold-air-standard conditions, the thermal efficiency of this cycle is

(a) 10% (b) 39% (c) 61%✓ (d) 79% (e) 82%

(viii) A Carnot cycle operates between the temperature limits of 300 and 2000 K, and produces 600 kW of net power. The rate of entropy change of the working fluid during the heat addition process is

(a) 0 (b) 0.300 kW/K (c) 0.353 kW/K✓ (d) 0.261 kW/K
(e) 2.0 kW/K

(ix) Air in an ideal Diesel cycle is compressed from 2 L to 0.13 L, and then it expands during the constant pressure heat addition process to 0.30 L. Under cold air standard conditions, the thermal efficiency of this cycle is

(a) 41% (b) 59%✓ (c) 66% (d) 70% (e) 78%

(x) In an ideal Otto cycle, air is compressed from 1.20 kg/m^3 and 2.2 L to 0.26 L, and the net work output of the cycle is 440 kJ/kg. The mean effective pressure (MEP) for this cycle is

(a) 612 kPa (b) 599 kPa✓ (c) 528 kPa (d) 416 kPa (e) 367 kPa

(xi) In an ideal Brayton cycle, air is compressed from 95 kPa and 25°C to 1100 kPa. Under cold-air-standard conditions, the thermal efficiency of this cycle is

(a) 45% (b) 50%✓ (c) 62% (d) 73% (e) 86%

(xii) A frictionless piston-cylinder device and a rigid tank contain 3 kmol of an ideal gas at the same temperature, pressure, and volume. Now heat is transferred, and the temperature of both systems is raised by 10°C. The amount of extra heat that must be supplied to the gas in the cylinder that is maintained at constant pressure is

(a) 0 kJ (b) 27 kJ (c) 83 kJ (d) 249 kJ✓ (e) 300 kJ

(xiii) A piston-cylinder device contains 5 kg of air at 400 kPa and 30°C. During a quasi-equilibrium isothermal expansion process, 15 kJ of boundary work is done by the system, and 3 kJ of paddle-wheel work is done on the system. The heat transfer during this process is

(a) 12 kJ✓ (b) 18 kJ (c) 2.4 kJ (d) 3.5 kJ (e) 60 kJ

(xiv) An ideal gas undergoes a constant volume (isochoric) process in a closed system. The heat transfer and work (per kg of gas) are, respectively

(a) $0, -c_v\triangle T$ (b) $c_v\triangle T, 0$✓ (c) $c_p\triangle T, R\triangle T$ (d) $R\, ln(T_2/T_1), R\, ln(T_2/T_1)$

(xv) An ideal gas undergoes a constant pressure (isobaric) process in a closed system. The heat transfer and work (per kg of gas) are, respectively

(a) $0, -c_v\triangle T$ (b) $c_v\triangle T, 0$ (c) $c_p\triangle T, R\triangle T$✓ (d) $R\, ln(T_2/T_1), R\, ln(T_2/T_1)$

Question 3. (*20 Marks*)

(a) Consider a steam power plant that operates on a simple ideal Rankine cycle and has a net power output of 45 MW. Steam enters the turbine at 7 MPa and 500°C and is cooled in the condenser at a pressure of 10 kPa by running cooling water from a lake through the tubes of the condenser at a rate of 2000 kg/s. **Show the cycle on a T-S diagram** with respect to saturation lines, and determine

(i) the thermal efficiency of the cycle,

(ii) the mass flow rate of the steam,

(iii) the temperature rise of the cooling water ($c = 4.18$ kJ/kg·K).

Where needed you may use the following data for water:

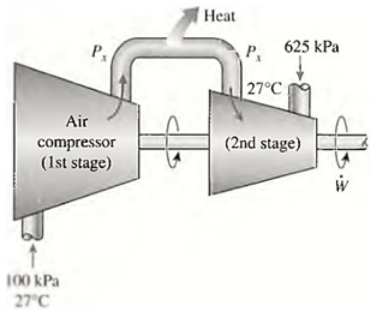
At 10 **kPa:** $h_f = 191.81$ kJ/kg, $h_{fg} = 2392.1$ kJ/kg, $s_f = 0.6492$ kJ/kg·K, $s_{fg} = 7.4996$ kJ/kg·K, $v_f = 0.00101$ m^3/kg,

At 7 **MPa and** 500^0**C:** $h = 3411.4$ kJ/kg, $s = 6.8000$ kJ/kg·K

(b) In the above Rankine cycle, if both the turbine and the pump have an efficiency of 87%, what would be the thermal efficiency of the cycle?

Question 4. (*20 Marks*)

(a) Air enters a two-stage compressor at 100 kPa and 27°C and is compressed to 625 kPa. The pressure ratio across each stage is the same, and the air is cooled to the initial temperature between the two stages. Assuming the compression process to be isentropic, determine the power input to the compressor for a mass flow rate of 0.15 kg/s. What would your answer be if only one stage of compression were used?



(b) An ideal Brayton cycle has a net work output of 150 kJ/kg and a back work ratio of 0.4. Calculate the net work output and the back work ratio of the cycle if both the turbine and the compressor had an isentropic efficiency of 85%.

Question 5. (*20 Marks*)

(a) (i) Define Joule-Thomson coefficient μ, and using the differential relation

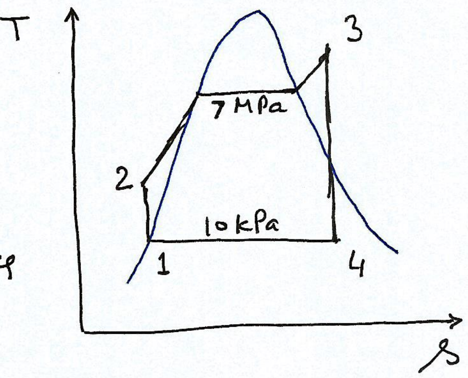
$$dh = c_p dT + \left[v - T\left(\frac{\partial v}{\partial T}\right)_P\right] dP,$$

obtain an expression for μ in terms of T, v, c_p, and β (volume expansivity).

(ii) Obtain an expression for μ for a substance whose equation of state is $P(v-b) = RT$.

(b) Estimate the **adiabatic** flame/combustion temperature for complete combustion of pure carbon with stoichiometric amount of air. The reactants are at the standard reference state and the following data is given: $\bar{h}_f^0(CO_2) = -393.52$ MJ/kmol, $\bar{c}_p(CO_2) = 54.3$ kJ/kmol·K and $\bar{c}_p(N_2) = 32.7$ kJ/kmol·K. *Assume that the given $\bar{c}_p$ values remain constant/represent average values over the temperature range of interest.*

Q.3 (a) $h_1 = 191.81 \text{ J/kg}$



$w_{pump} = v \Delta P = (0.00101)(6990)$

$= 7.06 \text{ kJ/kg}$

$h_2 = h_1 + w_{pump} = 198.87 \text{ kJ/kg}$

$h_3 = 3411.4 \text{ kJ/kg}$

$s_4 = s_3 = 6.8000 \text{ kJ/kg.K} = s_1 + x_4 s_{fg}$

$\Rightarrow x_4 = 0.8201$

$h_4 = h_1 + x_4 h_{fg} = 191.81 + 2392.1 \times 0.8201$

$= 2153.7 \text{ kJ/kg}.$

(i) $\eta = 1 - \dfrac{h_4 - h_1}{h_3 - h_2} = 1 - \dfrac{1961.9}{3212.53} = \boxed{38.9\%}$

$\eta \equiv 1 - \dfrac{q_{out}}{q_{in}} \rightarrow \eta =$

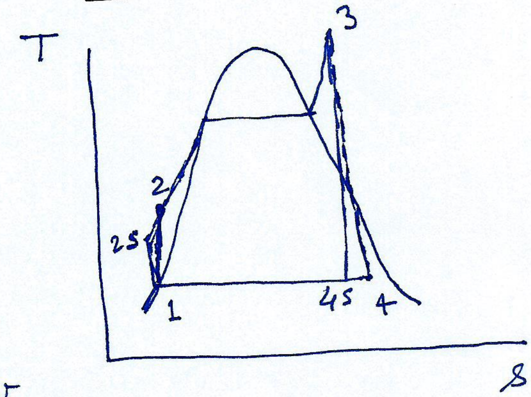
(ii) $\dot{m}_{steam}(q_{in} - q_{out}) = 45{,}000 \Rightarrow \boxed{\dot{m} = 36.0 \text{ kg/s}}$

(iii) $\dot{m}_{water} \cdot C \cdot \Delta T = q_{out} \Rightarrow \boxed{\Delta T = 8.4°C}$

(b) $w_T = 0.87(h_3 - h_{4s})$

$= 0.87(3411.4 - 2153.7)$

$= 1094.2 \text{ kJ/kg}.$



$w_p = \dfrac{v \Delta P}{0.87} = 8.115 \text{ kJ/kg}.$

$w_{Net} = 1085.1 \text{ kJ/kg}.$

$q_{in} = h_3 - h_2$ where $h_2 = h_1 + w_p$

$= 191.81 + 8.115 = 200 \text{ kJ/kg}.$

$= 3411.4 - 200 = 3211.4 \text{ kJ/kg}.$

$\eta = \dfrac{w_{net}}{q_{in}} = \dfrac{1085.1}{3211.4} \Rightarrow \boxed{\eta = 33.8\%}$

Q.4 (a) $P_i = P_{intermediate} = \sqrt{P_1 P_2} = \sqrt{100 \times 250}$

• Inlet to both stages is $T_1 = 300K$. $= 250 \text{ kPa}$

$$w_{comp,in} = 2 \cdot \frac{kRT_1}{k-1}\left[\left(\frac{P_i}{P_1}\right)^{\frac{k-1}{k}} - 1\right]$$

$$= 180.4 \text{ kJ/kg.}$$

Two stage

$$\dot{W}_{in} = \dot{m}\, w_{comp,in} = 0.15 \times 180.4 \Rightarrow \boxed{\dot{W}_{in} = 27.1 \text{ kW}}$$

<u>Single Stage</u> $w_{comp,in} = \frac{kRT_1}{(k-1)}\left[\left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} - 1\right]$

$$= 207.4 \text{ kJ/kg.}$$

$$\dot{W}_{in} = \dot{m} \times w_{in} = 0.15 \times 207.4 \Rightarrow \boxed{\dot{W}_{in} = 31.1 \text{ kW}}$$

Single stage.

(b) $w_{net} = w_T - w_c = w_T - 0.4\, w_T = 0.6\, w_T = 150$

$\Rightarrow w_T = 250 \text{ kJ/kg}$ $w_c = 100 \text{ kJ/kg.}$

$w'_T = 0.85 \times w_T = 0.85 \times 250 = 212.5 \text{ kJ/kg.}$

$w'_c = \frac{w_c}{0.85} = \frac{100}{0.85} = 117.65 \text{ kJ/kg.}$

$w'_{net} = w'_T - w'_c = 95.85 \text{ kJ/kg.}$

$$\boxed{w'_{net} = 95.85 \text{ kJ/kg}}$$

<u>New back work ratio</u> $= \frac{w'_c}{w'_T} \Rightarrow \boxed{0.554}$

Q 5 (a) (i) $\mu = \left(\frac{\partial T}{\partial P}\right)_h$; definition of μ.

$$0 = dh = c_p\, dT + \left[v - T\left(\frac{\partial v}{\partial T}\right)_P \right] dP$$

$$\Rightarrow \mu = \left(\frac{\partial T}{\partial P}\right)_h = \frac{1}{c_p}\left[T\left(\frac{\partial v}{\partial T}\right)_P - v \right]$$

$$\beta = \frac{1}{v}\left(\frac{\partial v}{\partial T}\right)_P \Rightarrow \boxed{\mu = \frac{v}{c_p}(T\beta - 1)}$$

(ii) $P(v-b) = RT \Rightarrow v = \frac{RT}{P} + b \Rightarrow \left(\frac{\partial v}{\partial T}\right)_P = \frac{R}{P}$

$$\beta = \frac{R}{vP} \Rightarrow \boxed{\mu = -b/c_p}$$

(b) $H_{prod} = H_{react}$. $C + O_2 + 3.76 N_2 = CO_2 + 3.76 N_2$

$$1 \cdot \bar{h}_f^\circ (CO_2) + \left[\bar{c}_p (CO_2) + 3.76\, \bar{c}_p (N_2)\right] \Delta T = 0$$

$$\Rightarrow \Delta T = \frac{393520}{54.3 + 3.76 \times 32.7}$$

$$= 2220\ ^\circ C$$

$$\boxed{T_{adiabatic\ flame} = 2245^\circ C}$$