Code Number :.............

THERMODYNAMICS QUALIFYING EXAM

August 2013

OPEN BOOK (only one book allowed) & CLOSED NOTES

Answer all four questions

All questions have equal weight

TIME: 3.0 hrs

Prepared by H.Schock & A. Engeda

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- **Take any required property from your book, approximate values if necessary.**
- **If you make any assumption to reach a solution state it clearly**

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Question # 1a

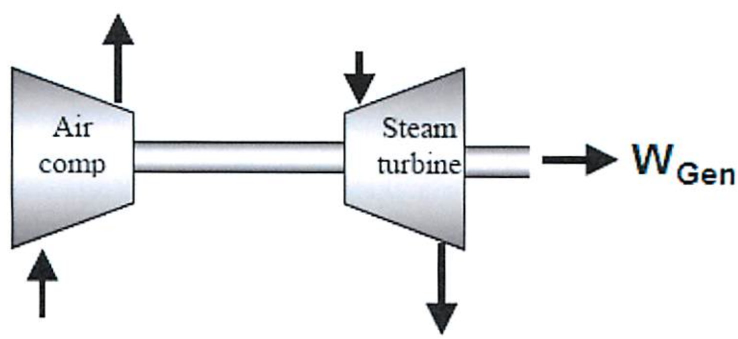
An adiabatic air compressor is to be powered by a direct-coupled adiabatic steam turbine that is also driving a generator, as shown in the figure below. Steam enters the turbine at 12.5 MPa and 500°C at a rate of 25 kg/s and exits at 10 kPa and a quality of 0.92. Air enters the compressor at 98 kPa and 295 K at a rate of 10 kg/s and exits at 1 MPa and 620 K.

Determine:

i) The net power developed by the steam turbine,

ii) The net power consumed by the compressor and

iii) The net power delivered to the generator by the turbine.



Question # 1b

Refrigerant 134a undergoes a closed process in a piston –cylinder device under the condition pv^n=constant. The initial and final states of the process are:

State 1: T_1= -10^{0}C & p_1= 200 kPa **State 2:** T_2= 50^{0}C & p_2= 1000 kPa

Determine:

i) The work transfer for the process in kJ/kg

ii) The heat transfer for the process in kJ/kg

iii) Sketch the process on a p-v diagram.

Question # 2a

Air at 500 kPa and 400 K enters an adiabatic nozzle at a velocity of 30 m/s and leaves at 300 kPa and 319 m/s. For enthalpy and entropy values use variable values from the tables.

Determine:

i) The exit temperature,

ii) The change in entropy

iii) Sketch the process on the T-S diagram

Question # 2b

Consider a non-insulated mixing chamber. Liquid water at 200 kPa, 20°C and 2.5 kg/s; and superheated steam at 200 kPa and 150°C enter the chamber and mix. The chamber is estimated to lose heat to the surrounding air at 25°C at a rate of 1200 kJ/min. The mixture leaves the mixing chamber at 200 kPa and 60°C.

Determine:

i) The mass flow rate of the superheated steam and

ii) The rate of entropy generation during this mixing process.

3. Air at 35C, 100kPa, 10% relative humidity passes through a chamber into which cooling water at 15 C is sprayed in a steady state steady flow process. The amount of water added is such that when it evaporates into the air stream, the exiting air-water vapor mixture will be 25 C, 100kPa. Calculate the exiting relative humidity.

4. An unknown hydrocarbon fuel is burned with air and a volumetric analysis of the combustion process yields the following percent composition on a dry basis.

CO_2 = 10.5%

O_2 = 5.3%

N_2 = 84.2 %

Determine the composition of fuel on a mass basis and the percentage of theoretical air used in the combustion process.

AE Solutions 1-a

Cengel & Boles 5th ed Problem 5.184

$$\left.\begin{array}{l} P_3 = 12.5\text{ MPa} \\ T_3 = 500°\text{C} \end{array}\right\} h_3 = 3343.6\text{ kJ/kg}$$

$$T_1 = 295\text{ K} \longrightarrow h_1 = 295.17\text{ kJ/kg}$$

$$T_2 = 620\text{ K} \longrightarrow h_2 = 628.07\text{ kJ/kg}$$

$$\left.\begin{array}{l} P_4 = 10\text{ kPa} \\ x_4 = 0.92 \end{array}\right\} h_4 = h_f + x_4 h_{fg} = 191.81 + (0.92)(2392.1) = 2392.5\text{ kJ/kg}$$

Compressor: $\dot{W}_{\text{comp, in}} + \dot{m}_{\text{air}} h_1 = \dot{m}_{\text{air}} h_2 \quad \rightarrow \quad \dot{W}_{\text{comp, in}} = \dot{m}_{\text{air}}(h_2 - h_1)$

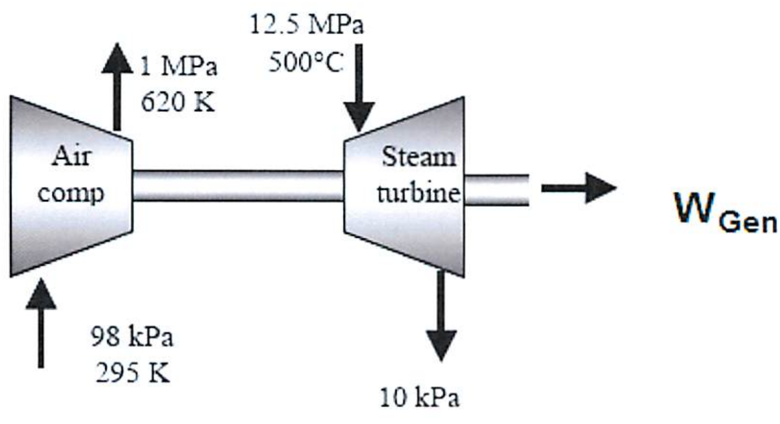
Turbine: $\dot{m}_{\text{steam}} h_3 = \dot{W}_{\text{turb, out}} + \dot{m}_{\text{steam}} h_4 \quad \rightarrow \quad \dot{W}_{\text{turb, out}} = \dot{m}_{\text{steam}}(h_3 - h_4)$

Substituting,

$$\dot{W}_{\text{comp,in}} = (10\text{ kg/s})(628.07 - 295.17)\text{ kJ/kg} = 3329\text{ kW}$$

$$\dot{W}_{\text{turb,out}} = (25\text{ kg/s})(3343.6 - 2392.5)\text{ kJ/kg} = 23{,}777\text{ kW}$$

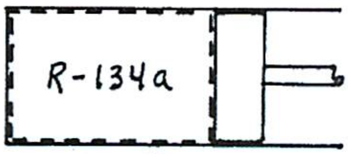
$$\dot{W}_{\text{net,out}} = \dot{W}_{\text{turb,out}} - \dot{W}_{\text{comp,in}} = 23{,}777 - 3329 = \mathbf{20{,}448\ kW}$$



AE Solutions 1-b

Moran & Shapiro3.53

SCHEMATIC & GIVEN DATA:



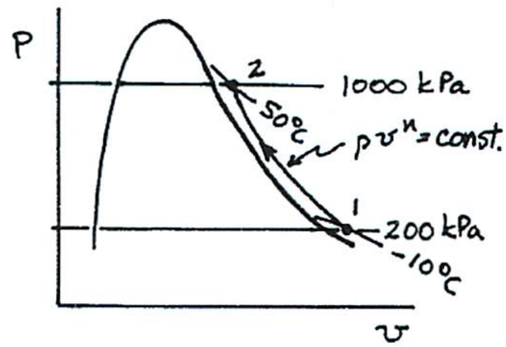
$pv^n = \text{const.}$

$p_1 = 200\,\text{kPa}$

$T_1 = -10°\text{C}$

$p_2 = 1000\,\text{kPa}$

$T_2 = 50°\text{C}$



$$\frac{W}{m} = \int_{v_1}^{v_2} p\,dv = \int_{v_1}^{v_2} \frac{\text{const.}}{v^n}\,dv$$

$$= \frac{p_2 v_2 - p_1 v_1}{1-n} \qquad (*)$$

To find the polytropic exponent n, we first must determine the initial and final specific volumes. Using Table.

$$p_1 = 200\,\text{kPa},\ T_1 = -10°\text{C} \Rightarrow v_1 = 0.09938\ \text{m}^3/\text{kg}$$

$$p_2 = 1000\,\text{kPa},\ T_2 = 50°\text{C} \Rightarrow v_2 = 0.02171\ \text{m}^3/\text{kg}$$

Thus, for the polytropic process

$$p_1 v_1^{\,n} = p_2 v_2^{\,n} \Rightarrow \log(p_2/p_1) = n \log(v_1/v_2)$$

$$n = \frac{\log(p_2/p_1)}{\log(v_1/v_2)} = \frac{\log(1000/200)}{\log(.09938/.02171)} = 1.058$$

Inserting values in Eq. (*)

$$\frac{W}{m} = \frac{(1000\,\text{kPa})(0.02171\ \text{m}^3/\text{kg}) - (200)(.09938)}{(1-1.058)} \left|\frac{10^3\,\text{N/m}^2}{1\,\text{kPa}}\right| \left|\frac{1\,\text{kJ}}{10^3\,\text{N}\cdot\text{m}}\right|$$

$$= -31.62\ \text{kJ/kg}$$

with $\Delta U = m(u_2 - u_1)$

$$\frac{Q}{m} = (u_2 - u_1) + \frac{W}{m}$$

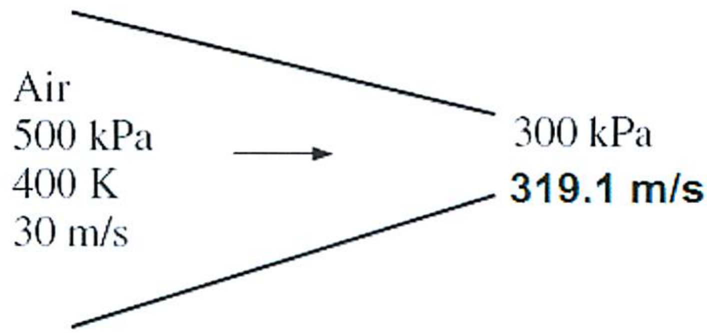
From Table ; $u_1 = 221.50\ \text{kJ/kg}$ and $u_2 = 258.48\ \text{kJ/kg}$

$$\frac{Q}{m} = (258.48 - 221.50) + (-31.62\ \text{kJ/kg})$$

$$= +5.36\ \text{kJ/kg}$$

AE Solutions 2-a

Cengel & Boles 5th ed Problem 7.167



The gas constant of air is $R = 0.287$ kJ/kg.K (Table A-1). For enthalpy values use table A-17

Energy balances on the control volume for the actual and isentropic processes give

$$h_1 + \frac{V_1^2}{2} = h_2 + \frac{V_2^2}{2}$$

$$400.98\ \text{kJ/kg} + \frac{(30\ \text{m/s})^2}{2}\left(\frac{1\ \text{kJ/kg}}{1000\ \text{m}^2/\text{s}^2}\right) = 350.49\ \text{kJ/kg} + \frac{V_2^2}{2}\left(\frac{1\ \text{kJ/kg}}{1000\ \text{m}^2/\text{s}^2}\right)$$

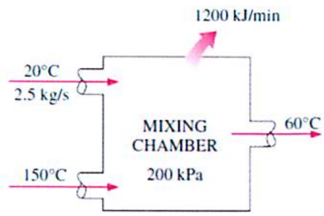
$$V_2 = \mathbf{319.1\ m/s}$$

$$\Delta s_{\text{air}} = s_2^0 - s_1^0 - R\ln\frac{P_2}{P_1}$$

$$= (1.85708 - 1.99194)\text{kJ/kg.K} - (0.287\ \text{kJ/kg.K})\ln\frac{300\ \text{kPa}}{500\ \text{kPa}}$$

$$= \mathbf{0.0118\ kJ/kg.K}$$

AE Solutions 2-b



7-145 Liquid water is heated in a chamber by mixing it with superheated steam. For a specified mixing temperature, the mass flow rate of the steam and the rate of entropy generation are to be determined.

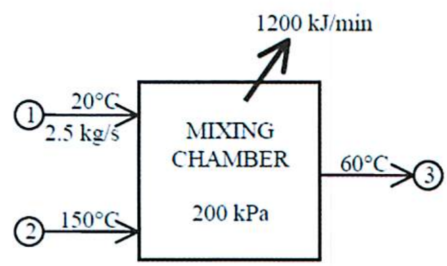
Assumptions **1** This is a steady-flow process since there is no change with time. **2** Kinetic and potential energy changes are negligible. **3** There are no work interactions.

Properties Noting that $T < T_{sat\ @\ 200\ kPa} = 120.21°C$, the cold water and the exit mixture streams exist as a compressed liquid, which can be approximated as a saturated liquid at the given temperature. From Tables A-4 through A-6,

$$\left.\begin{array}{l} P_1 = 200 \text{ kPa} \\ T_1 = 20°\text{C} \end{array}\right\} \begin{array}{l} h_1 \cong h_{f@20°C} = 83.91 \text{ kJ/kg} \\ s_1 \cong s_{f@20°C} = 0.2965 \text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_2 = 200 \text{ kPa} \\ T_2 = 150°\text{C} \end{array}\right\} \begin{array}{l} h_2 = 2769.1 \text{ kJ/kg} \\ s_2 = 7.2810 \text{ kJ/kg}\cdot\text{K} \end{array}$$

$$\left.\begin{array}{l} P_3 = 200 \text{ kPa} \\ T_3 = 60°\text{C} \end{array}\right\} \begin{array}{l} h_3 \cong h_{f@60°C} = 251.18 \text{ kJ/kg} \\ s_3 \cong s_{f@60°C} = 0.8313 \text{ kJ/kg}\cdot\text{K} \end{array}$$



Analysis (a) We take the mixing chamber as the system, which is a control volume. The mass and energy balances for this steady-flow system can be expressed in the rate form as

Mass balance: $\dot{m}_{in} - \dot{m}_{out} = \Delta \dot{E}_{system}^{\nearrow 0 \text{ (steady)}} = 0 \longrightarrow \dot{m}_1 + \dot{m}_2 = \dot{m}_3$

Energy balance:

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\substack{\text{Rate of net energy transfer}\\ \text{by heat, work, and mass}}} = \underbrace{\Delta \dot{E}_{system}^{\nearrow 0 \text{ (steady)}}}_{\substack{\text{Rate of change in internal, kinetic,}\\ \text{potential, etc. energies}}} = 0$$

$$\dot{E}_{in} = \dot{E}_{out}$$

$$\dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{Q}_{out} + \dot{m}_3 h_3$$

Combining the two relations gives $\dot{Q}_{out} = \dot{m}_1 h_1 + \dot{m}_2 h_2 - (\dot{m}_1 + \dot{m}_2) h_3 = \dot{m}_1 (h_1 - h_3) + \dot{m}_2 (h_2 - h_3)$

Solving for $\dot{m}_2$ and substituting, the mass flow rate of the superheated steam is determined to be

$$\dot{m}_2 = \frac{\dot{Q}_{out} - \dot{m}_1 (h_1 - h_3)}{h_2 - h_3} = \frac{(1200/60\text{kJ/s}) - (2.5 \text{ kg/s})(83.91 - 251.18)\text{kJ/kg}}{(2769.1 - 251.18)\text{kJ/kg}} = \mathbf{0.166 \text{ kg/s}}$$

Also, $\dot{m}_3 = \dot{m}_1 + \dot{m}_2 = 2.5 + 0.166 = 2.666$ kg/s

(*b*) The rate of total entropy generation during this process is determined by applying the entropy balance on an *extended system* that includes the mixing chamber and its immediate surroundings so that the boundary temperature of the extended system is 25°C at all times. It gives

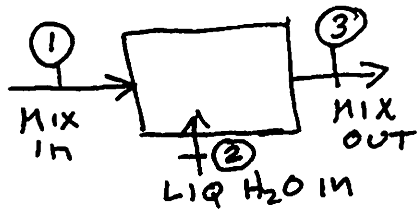
$$\underbrace{\dot{S}_{in} - \dot{S}_{out}}_{\substack{\text{Rate of net entropy transfer}\\ \text{by heat and mass}}} + \underbrace{\dot{S}_{gen}}_{\substack{\text{Rate of entropy}\\ \text{generation}}} = \underbrace{\Delta \dot{S}_{system}^{\nearrow 0}}_{\substack{\text{Rate of change}\\ \text{of entropy}}} = 0$$

$$\dot{m}_1 s_1 + \dot{m}_2 s_2 - \dot{m}_3 s_3 - \frac{\dot{Q}_{out}}{T_{b,surr}} + \dot{S}_{gen} = 0$$

Substituting, the rate of entropy generation during this process is determined to be

$$\begin{aligned}\dot{S}_{gen} &= \dot{m}_3 s_3 - \dot{m}_2 s_2 - \dot{m}_1 s_1 + \frac{\dot{Q}_{out}}{T_{b,surr}} \\ &= (2.666 \text{ kg/s})(0.8313 \text{ kJ/kg}\cdot\text{K}) - (0.166 \text{ kg/s})(7.2810 \text{ kJ/kg}\cdot\text{K}) \\ &\quad - (2.5 \text{ kg/s})(0.2965 \text{ kJ/kg}\cdot\text{K}) + \frac{(1200/60 \text{ kJ/s})}{298 \text{ K}} \\ &= \mathbf{0.333 \text{ kW/K}}\end{aligned}$$

3. **Air at 35C, 100kPa, 10% relative humidity passes through a chamber into which cooling water at 15 C is sprayed in a steady state steady flow process. The amount of water added is such that when it evaporates into the air stream, the exiting air-water vapor mixture will be 25 C, 100kPa. Calculate the exiting relative humidity.**



$$P_{v1} = \phi_1 P_{g_1} = 0.1 \times 5.628 = 0.5628 \text{ kPa}$$

$$\omega_1 = 0.622 \times \frac{0.5628}{(100 - 0.5628)} = 0.00352$$

$$\dot{Q}_{cv} = 0 = \dot{m}_a \left[(h_{a_3} - h_{a_1}) + \omega_3 h_{v_3} - \omega_1 h_{v_1} - (\omega_3 - \omega_1) h_{l_2} \right]$$

$$1.0035(25-35) + \omega_3 \times 2547.2 - 0.00352 \times 2565.3 - (\omega_3 - 0.00352) \times 62.99 = 0$$

$$\therefore \quad \omega_3 = 0.00759 = 0.622 \frac{P_{v_3}}{100 - P_{v_3}}$$

$$P_{v_3} = 1.2055$$

$$\phi_3 = \frac{P_{v_3}}{P_{g_3}} = \frac{1.2055}{3.169} = 0.38 \text{ or } 38\%$$

4. An unknown hydrocarbon fuel is burned with air and a volumetric analysis of the combustion process yields the following percent composition on a dry basis.

CO_2 = 10.5%

O_2 = 5.3%

N_2 = 84.2 %

Determine the composition of fuel on a mass basis and the percentage of theoretical air used in the combustion process.

$$C_a H_b + c\,O_2 + d\,N_2 \rightarrow 10.5\,CO_2 + e\,H_2O + 5.3\,O_2 + 84.2\,N_2$$

$C:\ a = 10.5$

$N_2:\ d = 84.2$

$O_2:\ c = 10.5 + \frac{e}{2} + 5.3$

$\frac{d}{c} = 3.76 \quad \therefore \quad c = 22.4$

$e = 2(22.4 - 15.8) = 13.2$

$H_2:\ \frac{b}{2} = e \quad \therefore \quad b = 26.4$

Mass basis $\%C = \frac{10.5 \times 12}{(10.5 \times 12) + (26.4 \times 1)} * 100 = 82.7\%$

& $\%H = 17.3\%$

$AF = c + d = 22.4 + 84.2 = 106.6$ kmole air / kmole fuel

Theoretical AF

$$C_{10.5}H_{26.4} + 17.1\,O_2 + 64.3\,N_2 \rightarrow 10.5\,CO_2 + 13.2\,H_2O + 64.3\,N_2$$

$\%$ Theor Air $= \frac{106.6}{(17.1 + 64.3)} = 131\%$