ME 200 Thermodynamics 1
Spring 2017 - Exam 3

Circle your instructor’s last name

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INSTRUCTIONS

• This is a closed book and closed notes exam. Equation sheets and all needed tables
  are provided.
• Significant credit for each problem is given if you identify your system and its boundary,
  draw the relevant EFD, start your analysis with the basic equations, list all relevant
  assumptions, and have appropriate units.
• Do not hesitate to ask if you do not comprehend a problem statement. For your own
  benefit, please write clearly and legibly. You must show your work to receive credit
  for your answers.
• Do not write on the back of any page because it won’t be scanned and therefore it
  won’t be graded. If you need extra paper raise your hand and a proctor will supply it.
• Place all solution pages in order. Do not, for instance, put a solution page from
  Problem 1 or from Problem 2 at the end of your exam.

IMPORTANT NOTE

The use of PDAs, Blackberry-type devices, cell phones, laptop computers, smart
watches or any other sources of communication (wireless or otherwise) is strictly
prohibited during examinations. Doing so is cheating. If you bring a smart watch, cell
phone, or other communication device to the examination, it must be turned off prior to
the start of the exam, placed in your backpack, and the backpack must be stored
below your seat. It shall be reactivated only after you leave the examination room
for the final time. Otherwise it is a form of cheating and will be treated as such.

SECOND IMPORTANT NOTE

The only calculators allowed for use on this exam are those of the TI-30X series. No
others are allowed.
<table>
<thead>
<tr>
<th>Problem</th>
<th>Possible</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
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1. You have been shown that the minimum steady flow mechanical work for a compressor does not occur for the reversible and adiabatic case, but instead for the reversible and isothermal case. What about the entropy generation? Is that also a minimum for the reversible isothermal case?

Consider that air at pressure 1.5 bar and temperature 310 K enters the compressor and exits at pressure 7.5 bar in both cases i.e. reversible and adiabatic (Case I) as well as reversible and isothermal (Case II).

Universal Gas Constant = 8.314 kJ/kmol-K  
Molecular Weight of Air = 29 kg/kmol

(a) Find the specific work input for both cases. Report your answers in kJ/kg. 
(b) Determine the specific heat transfer for both cases. Report your answers in kJ/kg. 
(c) Calculate the specific entropy generation for both cases. Assume the surroundings temperature is 300 K. Report your answers in kJ/kg-K.

System

**Assumptions**
- Steady state 
- One-dimensional flow 
- Quasi-equilibrium process 
- Ignore KE and PE changes 
- Air behaves as an ideal gas

**Basic Equations**
\[
\frac{dm}{dt}_{system} = \sum_{in} \dot{m}_{in} - \sum_{out} \dot{m}_{out} \Rightarrow \dot{m}_1 = \dot{m}_2 = \dot{m}_{air}
\]
\[
\frac{dE}{dt}_{system} = \dot{Q} - \dot{W} + \sum_{in} \dot{m}_{in} (h + ke + pe)_{in} - \sum_{out} \dot{m}_{out} (h + ke + pe)_{out}
\]
\[
\frac{dS}{dt}_{system} = \sum \frac{\dot{Q}}{T_{boundary}} + \sum_{in} \dot{m}_{in}s_{in} - \sum_{out} \dot{m}_{out}s_{out} + \sigma_{generation}
\]
Problem 1 (continued)

Solution
(a) For reversible and adiabatic (isentropic) process from 1.5 bar to 7.5 bar:

\[
\frac{p_{n_2}}{p_1} = \frac{P_{2s}}{P_1} = 1.5546 \times \frac{7.5 \text{ bar}}{1.5 \text{ bar}} = 7.773 \Rightarrow T_{2s} \approx 490 \text{ K}
\]

Alternatively:

\[
s_{2s}^0 - s_1^0 - R_{air} \ln \frac{P_{2s}}{P_1} = 0 \Rightarrow s_{2s}^0 = \left(1.73498 + 0.287 \ln \frac{7.5 \text{ bar}}{1.5 \text{ bar}}\right) \frac{\text{kJ}}{\text{kg-K}} = 2.19689 \frac{\text{kJ}}{\text{kg-K}} \Rightarrow T_{2s} \approx 490 \text{ K}
\]

For the reversible and adiabatic process, considering energy balance for the compressor:

\[
w_s = (h_1 - h_{2s}) = (310.24 - 492.74) \frac{\text{kJ}}{\text{kg}} \Rightarrow w_s = \frac{-182.5}{\text{kg}}
\]

For reversible and isothermal process from 1.5 bar to 7.5 bar:

\[
w_r = \int \frac{2}{1} v dP = \int \frac{2}{1} \frac{R_{air} T}{P} dP = -R_{air} (T_1 = T_2) \ln \frac{P_2}{P_1} = -0.287 \frac{\text{kJ}}{\text{kg-K}} \times 310 \text{ K} \times \ln \frac{7.5 \text{ bar}}{1.5 \text{ bar}} \Rightarrow w_r = \frac{-143.2}{\text{kg}}
\]

Alternatively:

\[
q_r = \int T ds = (T_1 = T_2) (s_2 - s_1) = (T_1 = T_2) \left(\frac{s_2^0 - s_1^0 - R_{air} \ln \frac{P_2}{P_1}}{s_2^0 - s_1^0 - R_{air} \ln \frac{P_2}{P_1}}\right) = -R_{air} (T_1 = T_2) \ln \frac{P_2}{P_1}
\]

(b) For reversible and adiabatic process, there is no heat transfer: \( q_s = 0 \frac{\text{kJ}}{\text{kg}} \)

For reversible and isothermal process, considering energy balance for the compressor:

\[
q_r = w_r + h_i \Rightarrow q_r = \frac{-143.2}{\text{kg}}
\]

(c) For reversible and adiabatic process:

\[
\sigma_s = 0 \frac{\text{kJ}}{\text{kg-K}}
\]

For reversible and isothermal process, considering entropy balance for the compressor:

\[
\sigma_r = -\frac{q_r}{T_{boundary} - T_{surrounding}} + (s_2 - s_1) = -\frac{q_r}{T_{boundary} - T_{surrounding}} + \left(\frac{s_2^0 - s_1^0 - R_{air} \ln \frac{P_2}{P_1}}{s_2^0 - s_1^0 - R_{air} \ln \frac{P_2}{P_1}}\right)
\]

\[
\sigma_r = \frac{-143.2}{300 \text{ K}} + \left(-0.287 \frac{\text{kJ}}{\text{kg-K}} \ln \frac{7.5 \text{ bar}}{1.5 \text{ bar}}\right) \Rightarrow \sigma_r = \frac{0.0154}{\text{kg-K}}
\]
2. A Rankine cycle power plant consists of a pump, a boiler, a turbine, and a condenser. Steam at 40 bar and 600°C exits the boiler and enters the turbine. The turbine isentropic efficiency is 95%. Saturated liquid at 25°C enters the pump and exits at 40 bar. Data at some states is provided in the table below.

<table>
<thead>
<tr>
<th>State</th>
<th>x</th>
<th>p, bar</th>
<th>T, °C</th>
<th>h, kJ/kg</th>
<th>s, kJ/kg-K</th>
</tr>
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<tr>
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<td></td>
<td>40</td>
<td>600</td>
<td>3674.4</td>
<td>7.3688</td>
</tr>
<tr>
<td>2s</td>
<td>0.0317</td>
<td></td>
<td>25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2a</td>
<td>0.0317</td>
<td></td>
<td>25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.00</td>
<td>0.0317</td>
<td>25</td>
<td>104.9</td>
<td>0.3674</td>
</tr>
<tr>
<td>4s</td>
<td></td>
<td>40</td>
<td></td>
<td>107.4</td>
<td>0.3674</td>
</tr>
<tr>
<td>4a</td>
<td></td>
<td>40</td>
<td></td>
<td>108.2</td>
<td>0.3710</td>
</tr>
</tbody>
</table>

(a) Find the missing information for states 2s and 2a in the table.
(b) Determine the isentropic efficiency of the pump. Report your answer as %.
(c) Compute the net specific work produced by this plant. Report your answer in kJ/kg.
(d) Compute the specific entropy generation for the pump and the turbine. Report your answers in kJ/kg-K.
(e) Make a recommendation as to which should be replaced first: pump or turbine? You must provide quantitative support to receive credit for your answer.
(f) Sketch the T-s diagram for the cycle. Label all states and constant pressure lines.
Problem 2 (continued)

Assumptions
- Steady state
- One-dimensional flow
- Quasi-equilibrium process
- Ignore KE and PE changes
- Insulated turbine and pump: $\dot{Q} = 0$

Basic Equations
\[
\frac{dm}{dt}_{\text{system}} = \sum_{\text{in}} \dot{m}_{\text{in}} - \sum_{\text{out}} \dot{m}_{\text{out}} \Rightarrow \dot{m}_1 = \dot{m}_2 = \dot{m}_3 = \dot{m}_4 = \dot{m}_{\text{steam}}
\]
\[
\frac{dE}{dt}_{\text{system}} = \dot{Q} - \dot{W} + \sum_{\text{in}} \dot{m}_{\text{in}} (h + ke + pe)_{\text{in}} - \sum_{\text{out}} \dot{m}_{\text{out}} (h + ke + pe)_{\text{out}}
\]
\[
\frac{dS}{dt}_{\text{system}} = \sum_{j} \frac{\dot{Q}}{T_{j,\text{boundary}}} + \sum_{\text{in}} \dot{m}_{\text{in}} s_{in} - \sum_{\text{out}} \dot{m}_{\text{out}} s_{out} + \sigma_{\text{generation}}
\]

Solution

(a) For isentropic process in the turbine: $s_{2s} = s_1 = 7.3688 \text{ kJ/kg-K} \Rightarrow \text{SLVM}$

\[
x_{2s} = \frac{s_{2s} - s_f}{s_g - s_f} = \frac{7.3688 - 0.3674}{8.5580 - 0.3674} \Rightarrow x_{2s} = 0.855 = \frac{h_{2s} - h_f}{h_{fg}} = \frac{h_{2s} - 104.89}{2442.3} \Rightarrow h_{2s} = 2193.1 \text{ kJ/kg}
\]

Isentropic turbine efficiency:

\[
\eta_{\text{turbine}} = 0.95 = \frac{w_{\text{actual}}}{w_{\text{isentropic}}} = \frac{h_1 - h_{2s}}{h_1 - h_{2a}} = \frac{3674.4 - h_{2a}}{3674.4 - 2193.1} \Rightarrow h_{2a} = 2267.2 \text{ kJ/kg}
\]

\[
x_{2a} = \frac{h_{2a} - h_f}{h_{fg}} = \frac{2267.2 - 104.89}{2442.3} \Rightarrow x_{2a} = 0.885 = \frac{s_{2a} - s_f}{s_g - s_f} = \frac{s_{2a} - 0.3674}{8.5580 - 0.3674} \Rightarrow s_{2a} = 7.6161 \text{ kJ/kg-K}
\]

(b) Isentropic pump efficiency:

\[
\eta_{\text{pump}} = \frac{w_{\text{isentropic}}}{w_{\text{actual}}} = \frac{h_3 - h_{4s}}{h_3 - h_{4a}} = \frac{107.4 - 104.9}{108.2 - 104.9} = -2.5 \text{ kJ/kg} \Rightarrow \eta_{\text{pump}} = 75.8\%
\]

(c) Considering energy balance for the turbine (CV I): $w_{\text{turbine}} = h_1 - h_{2a} = 1407.2 \text{ kJ/kg}$
Problem 2 (continued)

Considering energy balance for the pump (CV II): \[ w_{\text{pump}} = h_3 - h_{4a} = -3.3 \text{ kJ/kg} \]

Net specific work for the power plant: \[ w_{\text{net}} = w_{\text{turbine}} - |w_{\text{pump}}| \Rightarrow w_{\text{net}} = 1403.9 \text{ kJ/kg} \]

(d) Considering entropy balance for the turbine (CV I): \[ \sigma_{\text{turbine}} = s_{2a} - s_1 \Rightarrow \sigma_{\text{turbine}} = +0.2473 \text{ kJ/(kg-K)} \]

Considering entropy balance for the pump (CV II): \[ \sigma_{\text{pump}} = s_{4a} - s_3 \Rightarrow \sigma_{\text{pump}} = +0.0036 \text{ kJ/(kg-K)} \]

(e) **Turbine should be replaced** since \( \sigma_{\text{turbine}} > \sigma_{\text{pump}} \)

(f) T-s diagram for the cycle is shown below.
3. Answer the following questions by circling all (and only all) correct answers.

(a) The thermal efficiency of a reversible (ideal) power cycle is 100%.

Yes

\[ \eta_{\text{thermal, reversible}} = 1 - \frac{T_c}{T_H}; \ T_c \neq 0 \]

(b) A process violating the first law of thermodynamics necessarily violates the second law of thermodynamics.

Yes

No

(c) Can a process having heat transfer through a finite temperature difference ever be reversible?

Yes

No

Heat transfer requires finite temperature difference \( \Rightarrow \) irreversibility

(d) Consider two thermodynamic processes occurring between states 1 and 2: one irreversible (Process A) and the other reversible (Process B). Which of the following statement(s) is (are) true?

\[ S_A > \Delta S_B \quad \Delta S_A < \Delta S_B \]

\[ \sigma_A > \sigma_B \quad \sigma_A < \sigma_B \]

Entropy is a property \( \Rightarrow \Delta S \) is the same; for irreversible process: \( \sigma_A > 0 \), for reversible process \( \sigma_B = 0 \)

(e) Liquid water is compressed as it flows through a pump. If the process is isothermal, which of the following thermodynamic path(s) is (are) implied?

Adiabatic

Reversible

Isenthalpic

Isobaric

Incompressible: \( \Delta S = c \ln \left( \frac{T_2}{T_1} \right) = 0 \Rightarrow \text{isentropic (reversible and adiabatic)} \)