CIRCLE YOUR LECTURE BELOW:

<table>
<thead>
<tr>
<th>Time</th>
<th>First Name</th>
<th>Solution</th>
<th>Last Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>7:30 a.m.</td>
<td>Boregowda</td>
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<tr>
<td>8:30 a.m.</td>
<td>Boregowda</td>
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<td>10:30 a.m.</td>
<td>Braun</td>
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<td>3:30 p.m.</td>
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<td>4:30 p.m.</td>
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ME 200 Final Exam  
December 14, 2015  
8:00 a.m. to 10:00 a.m.

INSTRUCTIONS

1. This is a **closed book and closed notes examination**. You are provided with an equation sheet and all the needed property tables.
2. Do not hesitate to ask the instructor if you do not understand a problem statement.
3. Start each problem on the same page as the problem statement. Write on only one side of the page. Materials on the back side of the page will not be graded. There are blank pages following problems 2 and 3 for your work.
4. Put only one problem on a page. Another problem on the same page will not be graded.
5. Identify system boundary, list relevant assumptions, and provide solution with appropriate basic equations for problems 2 and 3. Do not specify “Given” or “Find” on these problems.
6. If you give multiple solutions, you will receive only a partial credit although one of the solutions might be correct. Delete the solution you do not want graded.
7. For your own benefit, please write clearly and legibly. Maximum credit for each problem is indicated below.
8. After you have completed the exam, at your seat **put your papers in order**. This may mean that you have to remove the staple and re-staple. **Do not turn in loose pages.**
9. Once time is called you will have three minutes to turn in your exam. Points will be subtracted for exams turned in after these three minutes.

<table>
<thead>
<tr>
<th>Problem</th>
<th>Possible</th>
<th>Score</th>
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<tbody>
<tr>
<td>1</td>
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<td></td>
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<tr>
<td>2</td>
<td>35</td>
<td></td>
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<td>3</td>
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<td><strong>Total</strong></td>
<td><strong>150</strong></td>
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</tbody>
</table>

1
Problem 1 (60 points) Answer the following questions. For Problem 1 only, assumptions need not be stated. No credit will be given without correct justification even if the answer is correct.

(a) Consider a lightbulb powered by electricity. Assume positive sign for heat transfer into the system and for work output from the system. Which of the following is true considering lightbulb as the system? Justify your answer. (6 points)

- \( W > 0, Q > 0 \)
- \( W > 0, Q < 0 \)
- \( W < 0, Q > 0 \)
- \( W < 0, Q < 0 \)

Work input (electrical work) and heat transfer out of the system

(b) What is the phase of water substance at 1 bar and 40\(^\circ\)C? Justify your answer for phase determination. (6 points)

Saturated Liquid
Sub-cooled Liquid \[+3\]
Saturated Vapor
Superheated Vapor

Table A-3 for water: \( T_{\text{sat}}(1 \text{ bar}) = 99.63^\circ\text{C} \Rightarrow T = 40^\circ\text{C} < T_{\text{sat}} \Rightarrow \text{sub-cooled liquid} \[+3\]
Table A-2 for water: \( P_{\text{sat}}(40^\circ\text{C}) = 0.07384 \text{ bar} \Rightarrow P = \text{bar} < P_{\text{sat}} \Rightarrow \text{compressed liquid} \]

(c) What is the specific entropy (kJ/kg-K) of water substance at 1 bar and 40\(^\circ\)C? Justify your answer with equation(s). (6 points)

1.3026
0.9376
0.5725 \[+3\]
Insufficient Information

For sub-cooled (compressed) liquid: \( s = s_f(T) \)
Table A-2 for water: \( s = s_f(40^\circ\text{C}) = 0.5725 \text{ kJ/kg-K} \[+3\]
Problem 1 (continued)

(d) An experimentalist measures the molecular weight, specific heat at constant volume, and specific heat at constant pressure of an ideal gas to be 8.314 kg/kmol, 2 kJ/kg-K, and 4 kJ/kg-K, respectively. Are the given measurements possible? Justify your answer with equation(s) and calculation(s). (6 points)

Yes  No  +2  Insufficient Information

For an ideal gas: \[ C_p - C_v = R = \frac{\overline{R}}{M} = \frac{8.314 \text{ kJ/kmol-K}}{8.314 \text{ kg/kmol}} = 1 \frac{\text{kJ}}{\text{kg-K}} \neq (4-2) \frac{\text{kJ}}{\text{kg-K}} \]

(e) A closed piston-cylinder device contains 2 kg of steam at 1 bar and 120°C. Steam is expanded at constant pressure with heat addition until the temperature increases to 160°C. What is the boundary work (kJ) during the expansion process? Justify your answer with equation(s) and calculation(s). (6 points)

19.1 kJ  38.1 kJ  28.6 kJ  Insufficient Information

\[ W_b = \int_{1}^{2} PdV = m(P_1 - P_2)(v_2 - v_1) = 2 \text{ kg} \times (1 \times 100) \text{kPa} \times (1.984 - 1.793) \frac{\text{m}^3}{\text{kg}} = 38.2 \text{ kJ} \]

(f) Is an isentropic process necessarily reversible? Justify your answer with equation(s). (6 points)

Yes  No  +2  Insufficient Information

\[ \Delta S = \frac{Q}{T_b} + \sigma \]

If heat rejection \((Q < 0)\) occurs such that \(\sigma = -\frac{Q}{T_b} > 0 \Rightarrow \Delta S = 0 \)
Problem 1 (continued)

(g) Consider a spherical balloon filled with air. The air inside the balloon is in thermal and mechanical equilibrium with the surroundings. At 8 a.m. in the morning, the surrounding temperature is 27°C and the balloon diameter is 30 cm. At 10 a.m. in the morning, the diameter of the balloon is measured to be 30.5 cm. The surrounding pressure remains constant at 1 bar from 8 to 10 a.m. Assume that the air pressure within the balloon remains constant for the small volume change during the process. Note that the volume of sphere is proportional to the cube of its diameter.

What is the temperature (°C) of the balloon surroundings at 10 a.m.? Justify your answer with equation(s) and calculation(s). (6 points)

28.4°C

42.25°C +2

32°C

Insufficient Information

For an ideal gas at constant pressure:

\[
\frac{T_2}{T_1} = \frac{V_2}{V_1} \Rightarrow T_2 = T_1 \left( \frac{D_2}{D_1} \right)^3 = \left( \frac{27 + 273}{30 \text{ cm}^3} \right) \times \left( \frac{30 \text{ cm}^3}{30 \text{ cm}^3} \right) = 315.25 \text{ K} = 42.25 \text{°C}
\]

(h) Consider an ideal gas with a constant specific heat ratio of \( k = \frac{C_p}{C_v} = 1.4 \). The gas is compressed from 1 bar and 27°C to 10 bar via an isentropic process.

What is the temperature (°C) of the gas after compression? Justify your answer with equation(s) and calculation(s). (6 points)

52.1°C

306.2°C +2

270°C

Insufficient Information

For an isentropic process of an ideal gas with constant specific heats:

\[
\frac{T_2}{T_1} = \left( \frac{P_2}{P_1} \right)^{\frac{k-1}{k}} \Rightarrow T_2 = (27 + 273) \text{ K} \times \left( \frac{10 \text{ bar}}{1 \text{ bar}} \right)^{0.4/1.4} = 579.2 \text{ K} = 306.2 \text{°C}
\]
Problem 1 (continued)

(i) Can the maximum thermal efficiency of a thermodynamic power cycle be 100% on the earth in the absence of any irreversibilities? Justify your answer with equation(s). (6 points)

Yes \[ \text{No} \quad +2 \] Insufficient Information

For a Carnot power cycle, the maximum efficiency:  \[ \eta_{\text{max}} = 1 - \frac{T_c}{T_H}; \quad T_c > 0 \Rightarrow \eta_{\text{max}} < 1 \]

(j) Consider a steady-flow, internally reversible compressor in which a gas is compressed either isothermally or isentropically. Ignore changes in KE and PE of the gas.

Is the work consumption during isothermal process less than the work consumption during isentropic process? Justify your answer with equation(s) and P-v diagram. (6 points)

Yes \[ +2 \] No \[ +2 \] Insufficient Information
**Problem 2 (35 points)** Consider a power plant operating steadily on the air-standard Brayton cycle shown below. Air enters the compressor at 1 bar and 280 K (State 1). Air is compressed to 20 bar (State 2) in a compressor having an isentropic efficiency of 90%. Compressed air then enters a constant-pressure heat exchanger in which heat is added to air and the heated air exits at 2200 K (State 3). Air expands to 1 bar (State 4) through a turbine having an isentropic efficiency of 90%. Consider variable specific heats for air.

Do not interpolate; use the closest values in property tables.

Molecular weight of air = 28.97 kg/kmol

(a) Complete the following table. Show any required calculations.

<table>
<thead>
<tr>
<th>State</th>
<th>Pressure (bar)</th>
<th>Temperature (K)</th>
<th>Specific Enthalpy (kJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>280</td>
<td>280.13</td>
</tr>
<tr>
<td>2s</td>
<td>20</td>
<td>650</td>
<td>659.84</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>690</td>
<td>702.03</td>
</tr>
<tr>
<td>3</td>
<td>20</td>
<td>2200</td>
<td>2503.2</td>
</tr>
<tr>
<td>4s</td>
<td>1</td>
<td>1080</td>
<td>1137.89</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>1200</td>
<td>1274.42</td>
</tr>
</tbody>
</table>

(b) Calculate the back work ratio of the cycle.

Identify system boundary, list assumptions, and provide solution with basic equations.
Problem 2 (continued)

Assumptions
- Steady state
- One-dimensional flow
- Ignore KE and PE changes
- No pressure drop across heat exchanger
- Heat exchanger: No work  $\dot{W}_{CV} = 0$
- Turbines and compressor: No heat transfer  $\dot{Q}_{CV} = 0$
- Air behaves as an ideal gas

Basic Equations
\[
\begin{align*}
\frac{dH}{dt} &= \sum_i \dot{m}_i - \sum_e \dot{m}_e \Rightarrow \dot{m}_1 = \dot{m}_2 = \dot{m}_3 = \dot{m}_4 = \dot{m}_{air} \\
\frac{dE}{dt} &= \dot{Q}_{CV} - \dot{W}_{CV} + \sum_i \dot{m}_i \left( h_i + \frac{V_i^2}{2} + gz_i \right) - \sum_e \dot{m}_e \left( h_e + \frac{V_e^2}{2} + gz_e \right) \\
\frac{dS}{dt} &= \frac{\dot{Q}_{CV}}{T_b} + \sum_i \dot{m}_i s_i - \sum_e \dot{m}_e s_e + \dot{\sigma}_{CV}
\end{align*}
\]

Solution
\begin{align*}
(a) & \text{ State 1: } P_1 = 1 \text{ bar}, \ T_1 = 280 \text{ K} \\
& \text{Table A-22 for air: } h_1 = 280.13 \text{ kJ/kg}, \ s_1^0 = 1.63279 \text{ kJ/kg-K}, \ p_{r1} = 1.0889 \\
\text{State 2s: } P_{2s} = P_2 = 20 \text{ bar}, \ s_{2s} = s_1 \text{ (isentropic)} \\
& \Rightarrow 0 = s_{2s}^0 - s_1^0 - R_{air} \ln \frac{P_{2s}}{P_1} \Rightarrow s_{2s}^0 = s_1^0 + R_{air} \ln \frac{P_{2s}}{P_1} + 2
\end{align*}

\[
R_{air} = \frac{\bar{R}}{M_{air}} = \frac{8.314 \text{ kJ/kmol-K}}{28.97 \text{ kg/kmol}} = 0.287 \text{ kJ/kg-K}
\]

\[
\Rightarrow s_{2s}^0 = 1.63279 + 0.287 \ln \frac{20 \text{ bar}}{1 \text{ bar}} = 2.49257 \text{ kJ/kg-K}
\]

Alternatively:
\[
\frac{P_{r2s}}{P_{r1}} = \frac{P_{2s}}{P_1} \Rightarrow P_{r2s} = P_{r1} \frac{P_{2s}}{P_1} = 1.0889 \times \frac{20 \text{ bar}}{1 \text{ bar}} = 21.78
\]

\begin{align*}
\text{Table A-22 for air: } T_{2s} &\approx 650 \text{ K}, \ h_{2s} &\approx 659.84 \frac{\text{kJ}}{\text{kg}}
\end{align*}
Problem 2 (continued)

State 2: \(P_2 = 20\) bar

Isentropic efficiency of the compressor: 
\[
\eta_{\text{compressor}} = \frac{\dot{w}_{\text{isentropic}}}{\dot{w}_{\text{actual}}} = \frac{h_1 - h_2}{h_1 - h_2_x} \Rightarrow 0.9 = \frac{280.13 - 659.84}{280.13 - h_2}
\]

\(h_2 = 702.03\text{ kJ/kg} \Rightarrow\) Table A-22 for air: \(T_2 \approx 690\) K 

\[+4\]

State 3: \(P_3 = P_2 = 20\) bar, \(T_3 = 2200\) K

Table A-22 for air: \(h_3 = 2503.2\) kJ/kg, \(s_3^0 = 3.91910\) kJ/kg-K, \(p_{r3} = 3138\) 

\[+1\ (\text{For } s_3^0 \text{ or } p_{r3})\]

State 4s: \(P_{4s} = 1\) bar, \(s_{4s} = s_3\) (isentropic)

\[
\Rightarrow 0 = s_{4s}^0 - s_3^0 - R_{\text{air}} \ln \frac{P_{4s}}{P_3} \Rightarrow s_{4s}^0 = s_3^0 + R_{\text{air}} \ln \frac{P_{4s}}{P_3} +2
\]

\[
\Rightarrow s_{4s}^0 = 3.91910 + 0.287 \text{ kJ/kg-K} \ln \frac{1}{20} = 3.05932 - \text{kJ/kg-K}
\]

Alternatively: 

\[
\Rightarrow \frac{P_{4s}}{P_{r3}} = \frac{P_{4s}}{P_3} \Rightarrow P_{r4s} = P_{r3} \frac{P_{4s}}{P_3} = 3138 \times \frac{1}{20} = 156.9
\]

Table A-22 for air: \(T_{4s} \approx 1080\) K, \(h_{4s} \approx 1137.89\) kJ/kg 

\[+1\ (\text{For } s_{4s}^0 \text{ or } p_{4s})\]

State 4: \(P_4 = 1\) bar

Isentropic efficiency of the turbine: 
\[
\eta_{\text{turbine}} = \frac{\dot{w}_{\text{actual}}}{\dot{w}_{\text{isentropic}}} = \frac{h_3 - h_4}{h_3 - h_{4s}} \Rightarrow 0.9 = \frac{2503.2 - h_4}{2503.2 - 1137.89}
\]

\(h_4 = 1274.42\text{ kJ/kg} \Rightarrow\) Table A-22 for air: \(T_4 \approx 1200\) K 

\[+4\]

(b) Considering energy balance for the compressor (CV I): 

\[
\dot{w}_{\text{compressor}} = \frac{\dot{w}_{\text{isentropic}}}{m_{\text{air}}} = (h_1 - h_2) = -421.9\text{ kJ/kg}
\]

Considering energy balance for the turbine (CV II): 

\[
\dot{w}_{\text{turbine}} = \frac{\dot{w}_{\text{isentropic}}}{m_{\text{air}}} = (h_3 - h_4) = +1228.78\text{ kJ/kg}
\]

Back work ratio of the cycle: 
\[
BWR = \frac{\dot{w}_{\text{compressor}}}{\dot{w}_{\text{turbine}}} = \frac{421.9\text{ kJ/kg}}{1228.78\text{ kJ/kg}} \Rightarrow BWR = 0.3435 \ [+2]
\]
Problem 3 (55 points) Consider a system shown below operating steadily. Steam at 80 bar and 520°C (State 1) with a mass flow rate of 2 kg/s enters a reversible, adiabatic (isentropic) high-pressure (HP) turbine and expands to a pressure of 7 bar (State 2). A fraction of the steam (y) is extracted at State 2 and the remaining steam \((1 - y)\) expands in a reversible, adiabatic (isentropic) low-pressure (LP) turbine to 0.08 bar (State 3). The remaining steam passes through a constant-pressure condenser and exits as saturated liquid at 0.08 bar (State 4). A reversible, adiabatic (isentropic) pump increases its pressure to 7 bar (State 5). Liquid (not saturated) leaving the pump at State 5 is mixed with the steam fraction \((y)\) extracted at State 2 in a rigid, insulated mixing chamber. Steam exits the mixing chamber as saturated liquid at 7 bar (State 6).
Problem 3 (continued)

Do not interpolate; use the closest values in property tables.

(a) Complete the following table. Show any required calculations.

<table>
<thead>
<tr>
<th>State</th>
<th>Pressure (bar)</th>
<th>Temperature (°C)</th>
<th>Specific Enthalpy (kJ/kg)</th>
<th>Specific Entropy (kJ/kg-K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>80</td>
<td>520</td>
<td>3447.7</td>
<td>6.7871</td>
</tr>
<tr>
<td>2</td>
<td>7</td>
<td>180</td>
<td>2799.1</td>
<td>6.7871</td>
</tr>
<tr>
<td>3</td>
<td>0.08</td>
<td>41.51</td>
<td>2122.8</td>
<td>6.7871</td>
</tr>
<tr>
<td>4</td>
<td>0.08</td>
<td>41.51</td>
<td>173.88</td>
<td>0.5926</td>
</tr>
<tr>
<td>5</td>
<td>7</td>
<td>165</td>
<td>697.22</td>
<td>1.9922</td>
</tr>
<tr>
<td>6</td>
<td>7</td>
<td>165</td>
<td>697.22</td>
<td>1.9922</td>
</tr>
</tbody>
</table>

(b) Determine the fraction of steam (y) extracted at State 2.
(c) Calculate the total power (kW) of the high-pressure and low-pressure turbine.
(d) Find the rate of entropy generation (kW/K) for the mixing chamber.
(e) Show the entire process on T-s diagram. Label states, indicate appropriate lines of constant pressure, and show property values. Critical temperature of water = 374.1°C.

Identify system boundary, list assumptions, and provide solution with basic equations.

Assumptions
- Steady state
- One-dimensional flow
- Ignore KE and PE changes
- Mixing chamber: No work $W_{cv} = 0$
- Mixing chamber, turbines, and pump: No heat transfer $\dot{Q}_{cv} = 0$
- Incompressible liquid water in pump

Basic Equations

$$\frac{dm_{cv}}{dt} = \sum_i m_i - \sum_e m_e$$

$$\frac{dE_{cv}}{dt} = \dot{Q}_{cv} - W_{cv} + \sum_i m_i \left( h_i + \frac{V_i^2}{2} + gz_i \right) - \sum_e m_e \left( h_e + \frac{V_e^2}{2} + gz_e \right)$$
Problem 3 (continued)

\[
\frac{dS}{dt} = \frac{\dot{Q}_V}{T_b} + \sum_i \dot{m}_i s_i - \sum_e \dot{m}_e s_e + \sigma_{CV} + 1
\]

Solution

(a) State 1: \( P_1 = 80 \) bar, \( T_1 = 520^\circ C \)

Table A-3 for water: \( T_{sat}(P_1) = 295.1^\circ C \Rightarrow T_1 > T_{sat}(P_1) \Rightarrow \) superheated vapor (SHV)

Table A-4 for superheated water vapor: \( h_1 = 3447.7 \frac{kJ}{kg}, s_1 = 6.7871 \frac{kJ}{kg} \)

State 2: \( P_2 = 7 \) bar, \( s_2 = s_1 = 6.7871 \frac{kJ}{kg-K} \) (isentropic)

Table A-3 for water: \( s_g(P_2) = 6.7080 \frac{kJ}{kg-K} \Rightarrow s_1 > s_g(P_2) \Rightarrow \) superheated vapor (SHV)

Table A-4 for superheated water vapor: \( T_2 \approx 180^\circ C, h_2 \approx 2799.1 \frac{kJ}{kg} \)

State 3: \( P_3 = 0.08 \) bar, \( s_3 = s_2 = s_1 = 6.7871 \frac{kJ}{kg-K} \) (isentropic)

Table A-3 for water: \( s_f(P_3) = 0.5926 \frac{kJ}{kg-K} \Rightarrow s_3 = s_f(P_3) \Rightarrow \) saturated liquid-vapor mixture (SLVM)

Table A-3 for superheated water vapor: \( T_3 = T_{sat}(P_3) = 41.51^\circ C \)

\[
x_3 = \frac{s_3 - s_f(P_3)}{s_g(P_3) - s_f(P_3)} = \frac{6.7871 - 0.5926}{8.2287 - 0.5926} = 0.811 = \frac{h_1 - h_f(P_3)}{h_g(P_3) - h_f(P_3)} = \frac{h_3 - 173.88}{2577 - 173.88} + 2
\]

\( h_3 = 2122.8 \frac{kJ}{kg} + 2 \)

State 4: \( P_3 = 0.08 \) bar, saturated liquid

Table A-3 for water: \( T_4 = T_{sat}(P_4) = 41.51^\circ C, v_4 = v_f(P_4) = 1.0084 \times 10^{-3} \frac{m^3}{kg} \)

\( h_4 = h_f(P_4) = 173.88 \frac{kJ}{kg}, s_4 = h_f(P_4) = 0.5926 \frac{kJ}{kg-K} \)

State 5: \( P_5 = 7 \) bar, \( s_5 = s_4 = 0.5926 \frac{kJ}{kg-K} \) (isentropic)

Table A-3 for water: \( s_f(P_5) = 1.9922 \frac{kJ}{kg-K} \Rightarrow s_5 < s_f(P_5) \Rightarrow \) sub-cooled (compressed) liquid

Considering energy balance for the pump (CV I): \( w_{pump} = (h_4 - h_5) = -\int_{4}^{5} \dot{v}dP \approx v_4 (P_5 - P_4) + 3 \)

\( \Rightarrow h_5 \approx h_4 + v_4 (P_5 - P_4) = 173.88 \frac{kJ}{kg} + 1.0084 \times 10^{-3} \frac{m^3}{kg} \times (7 - 0.08) \times 100 \text{ kPa} = 174.58 \frac{kJ}{kg} + 3 \)
Problem 3 (continued)

State 6: $P_6 = 7$ bar, saturated liquid

Table A-3 for water: $T_6 = T_{sat}(P_6) = 165^\circ C$, $h_6 = h_f(P_6) = 697.22$ $\frac{kJ}{kg}$, $s_6 = s_f(P_6) = 1.9922$ $\frac{kJ}{kg\cdot K}$

(b) Considering energy balance for the mixing chamber (CV II):

\[
\dot{m}_2 h_2 + \dot{m}_5 h_5 = \dot{m}_6 h_6 \Rightarrow y \dot{m}_{steam} h_2 + (1 - y) \dot{m}_{steam} h_5 = \dot{m}_{steam} h_6
\]

\[
\Rightarrow y = \frac{h_6 - h_5}{h_2 - h_5} = \frac{697.22 - 174.58}{2799.1 - 174.58} \Rightarrow y = 0.2
\]

(c) Considering energy balance for the high-pressure (CV III) and low-pressure turbine (CV IV), the total power output:

\[
\dot{W}_{total} = \dot{m}_{steam} (h_1 - h_2) + (1 - y) \dot{m}_{steam} (h_2 - h_3) = 2 \frac{kg}{s} \times \left[(3447.7 - 2799.1) + 0.8 \times (2799.1 - 2122.8)\right] \frac{kJ}{kg}
\]

\[
\dot{W}_{total} = 2379.3 \text{ kW}
\]

(d) Considering entropy balance for the mixing chamber, the rate of entropy generation:

\[
\dot{\sigma}_{mixing} = \dot{m}_{steam} s_6 - y \dot{m}_{steam} s_2 - (1 - y) \dot{m}_{steam} s_5 = 2 \frac{kg}{s} \times \left[1.9922 - 0.2 \times 6.7871 - 0.8 \times 0.5926\right] \frac{kJ}{kg\cdot K}
\]

\[
\dot{\sigma}_{mixing} = +0.32 \frac{kW}{K}
\]

(e) T-s diagram is shown below.

\[+1\text{ (State 1 above critical temperature)}\]

\[+1\text{ (Constant pressure lines)}\]

\[+3\text{ (Correct relative locations of all six states)}\]