ME 200  Thermodynamics I
Spring 2017 – Exam 1

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 makes it very easy for grading mistakes to occur. If you need extra paper raise your hand and a proctor will supply it.
• Maximum credit for each problem is indicated below.

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.
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1. A 7 kg mass of copper (Cu) is at 75ºC before being dropped into 10 liters of water at 25ºC. The final temperature of the water and Cu is 35ºC.

**Is the Cu-water system adiabatic?** You must provide quantitative support to receive credit for your answer.

Specific heat of copper: \( C_{\text{Cu}} = 0.39 \text{ kJ/kg-K} \)
Specific heat of water: \( C_{\text{water}} = 4.18 \text{ kJ/kg-K} \)

**System**

\[
\begin{align*}
\text{m}_{\text{Cu}} &= 7 \text{ kg} \\
C_{\text{Cu}} &= 0.39 \text{ kJ/kg-K} \\
T_{\text{Cu}} &= 75^\circ \text{C} \\
V_{\text{H}_2\text{O}} &= 10 \text{ liter} \\
C_{\text{H}_2\text{O}} &= 4.18 \text{ kJ/kg-K} \\
T_{\text{H}_2\text{O}} &= 25^\circ \text{C}
\end{align*}
\]

**Assumptions**
- No boundary or other work \( \Rightarrow W = 0 \)
- Adiabatic \( \Rightarrow Q = 0 \)
- Ignore KE and PE changes
- Solid (Cu) and liquid (H2O) are incompressible

**Basic Equations**

\[
\frac{dE}{dt} \bigg|_{\text{system}} = \dot{Q} - W + \sum_{\text{in}} m_{\text{in}} (h + ke + pe)_{\text{in}} - \sum_{\text{out}} m_{\text{out}} (h + ke + pe)_{\text{out}}
\]

Integrating:

\[
\dot{Q} - W = \Delta U + \Delta KE + \Delta PE
\]

\[
\Delta U = mC\Delta T
\]

**Solution**

Considering energy balance: \( \Delta U = 0 \Rightarrow \Delta U_{\text{Cu}} + \Delta U_{\text{water}} = 0 \)

\[
m_{\text{Cu}}C_{\text{Cu}} (T_{\text{final}} - T_{\text{Cu}}) + m_{\text{water}}C_{\text{water}} (T_{\text{final}} - T_{\text{water}}) = 0
\]

Final temperature for adiabatic system:

\[
T_{\text{final}} = \frac{m_{\text{Cu}}C_{\text{Cu}}T_{\text{Cu}} + m_{\text{water}}C_{\text{water}}T_{\text{water}}}{m_{\text{Cu}}C_{\text{Cu}} + m_{\text{water}}C_{\text{water}}}
\]
Problem 1 (continued)

Mass of liquid water: \[ m_{\text{water}} = \frac{V_{\text{water}}}{v_{\text{water}}(25^\circ \text{C})} = \frac{10 \times 10^{-3} \text{ m}^3}{1.0029 \times 10^{-3} \text{ m}^3/\text{kg}} = 9.98 \text{ kg} \]

Final temperature for adiabatic system:

\[ T_{\text{final}} = \frac{7 \text{ kg} \times 0.39 \frac{\text{kJ}}{\text{kg-K}} \times 75^\circ \text{C} + 9.98 \text{ kg} \times 4.18 \frac{\text{kJ}}{\text{kg-K}} \times 25^\circ \text{C}}{7 \text{ kg} \times 0.39 \frac{\text{kJ}}{\text{kg-K}} + 9.98 \text{ kg} \times 4.18 \frac{\text{kJ}}{\text{kg-K}}} = 28.1^\circ \text{C} \]

Since the given final temperature is 35°C, there must be energy added to the system by heat transfer i.e. the **Cu-water system is not adiabatic**

Alternatively

Calculate the actual change in internal energy of copper and water and prove that it is indeed non-zero i.e. the system is not adiabatic
2. A capped one liter plastic bottle is filled with water (no air, no CO₂, nothing but H₂O). There is a small space at the top that holds water vapor. Both the liquid water and water vapor are at 25°C, and their total mass is 0.95 kg.

(a) What is the pressure inside the bottle? Report your answer in bars.
(b) What is the quality? Report your answer in %.
(c) The temperature inside the bottle must remain below 60°C to adhere to the U.S. Department of Transportation guidelines. What is the corresponding pressure if the temperature increases to 60°C? Report your answer in bars.
(d) What is the change in the internal energy of water when the temperature rises from 25°C to 60°C? Report your answer in kJ/kg.
(e) Sketch the temperature increase process on the p-v axes provided below. Label initial and final states and constant temperature lines.
Problem 2 (continued)

Assumptions
Quasi-equilibrium

Basic Equations

\[ y_{\text{mixture}} = xy_g + (1-x)y_f \]

Solution

(a) Since liquid water and water vapor co-exist at 25°C, the corresponding pressure in the bottle must be equal to saturation pressure \( p_1 = p_{\text{sat}} \left( T_1 = 25^\circ \text{C} \right) = 0.0317 \text{ bar} \)

(b) Specific volume of saturated liquid-vapor mixture:

\[
 v_1 = \frac{1 \times 10^{-3} \text{ m}^3}{0.95 \text{ kg}} = 1.0526 \times 10^{-3} \frac{\text{ m}^3}{\text{ kg}} = x_1v_g + (1-x_1)v_f = x_1(43.36 \frac{\text{ m}^3}{\text{ kg}}) + (1-x_1)(1.0029 \times 10^{-3} \frac{\text{ m}^3}{\text{ kg}})
\]

Quality of the mixture: \( x_1 = 1.15 \times 10^{-6} \Rightarrow x_1 = 0.000115\% \)

(c) Specific volume does not change for rigid bottle with constant total mass.

\[ v_2 = v_1 = 1.0526 \times 10^{-3} \frac{\text{ m}^3}{\text{ kg}} \Rightarrow v_f \left( T_2 = 60^\circ \text{C} \right) < v_2 < v_g \left( T_2 = 60^\circ \text{C} \right) \]

\( \Rightarrow \) liquid water and water vapor co-exist at 60°C, the corresponding pressure in the bottle must be equal to saturation pressure \( p_2 = p_{\text{sat}} \left( T_2 = 60^\circ \text{C} \right) = 0.1994 \text{ bar} \)

(d) Specific internal energy of saturated liquid-vapor mixture at 25°C and 60°C:

\[
 u_1 = x_1u_g + (1-x_1)u_f = 1.15 \times 10^{-6} \times 2409.8 \frac{\text{ kJ}}{\text{ kg}} + (1-1.15 \times 10^{-6}) \times 104.88 \frac{\text{ kJ}}{\text{ kg}} = 104.88 \frac{\text{ kJ}}{\text{ kg}}
\]

\[
 v_2 = 1.0526 \times 10^{-3} \frac{\text{ m}^3}{\text{ kg}} = x_2v_g + (1-x_2)v_f = x_27.671 \frac{\text{ m}^3}{\text{ kg}} + (1-x_2)1.0172 \times 10^{-3} \frac{\text{ m}^3}{\text{ kg}}
\]

Quality of the mixture: \( x_2 = 4.62 \times 10^{-6} \)

\[
 u_2 = x_2u_g + (1-x_2)u_f = 4.62 \times 10^{-6} \times 2456.6 \frac{\text{ kJ}}{\text{ kg}} + (1-4.62 \times 10^{-6}) \times 251.11 \frac{\text{ kJ}}{\text{ kg}} = 251.11 \frac{\text{ kJ}}{\text{ kg}}
\]

Change in specific internal energy: \( \Delta u = u_2 - u_1 \Rightarrow \Delta u = 146.23 \frac{\text{ kJ}}{\text{ kg}} \)
3. The well-insulated dual-chamber device shown below is used to increase the pressure of air above that provided by a supply. In the system shown below, the larger 31.6 cm diameter lower piston surface is exposed to air at a pressure of 150 bar. The smaller 10.0 cm diameter upper piston compresses the air above it.

(a) What is the pressure of the air in the upper chamber? Report your answer in bar.
(b) The initial volume of air in the lower chamber is 0.02 m$^3$. The piston in the lower chamber moves a total distance of 25 cm along a polytropic path where $pv^n = \text{constant}$ with $n = 1.25$. What is the corresponding work for air in the lower chamber? Report your answer in kJ.
(c) What is the corresponding work for air in the upper chamber? Report your answer in kJ.

Assumptions
No other work except moving boundary work
Neglect friction
Quasi-equilibrium process
Well-insulated $\Rightarrow Q = 0$
Ignore KE and PE changes

Basic Equations
$W_{\text{boundary}} = \int pdV$
Problem 3 (continued)

Basic Equations (contd.)

\[
\frac{dE}{dt}_{\text{system}} = \dot{Q} - \dot{W} + \sum_{\text{in}} m_{\text{in}} (h + ke + pe)_{\text{in}} - \sum_{\text{out}} m_{\text{out}} (h + ke + pe)_{\text{out}}
\]

Integrating:

\[
\varphi - W = \Delta U + \Delta KE + \Delta PE
\]

Solution

(a) Considering force balance:

\[
p_1 \times \frac{\pi}{4} D_1^2 = p_{\text{upper}} \times \frac{\pi}{4} D_2^2 \Rightarrow p_{\text{upper}} = 150 \text{ bar} \left( \frac{31.6 \text{ cm}}{10.0 \text{ cm}} \right)^2
\]

Pressure of air in the upper chamber: \( p_{\text{upper}} = 1498 \text{ bar} \)

(b) Moving boundary work for air in the lower chamber undergoing polytropic process:

\[
W_{\text{lower}} = \int_1^2 p \, dV = \frac{p_1 V_1 - p_2 V_2}{n-1}
\]

Initial pressure of air in the lower chamber: \( p_1 = 150 \text{ bar} \)
Initial volume of air in the lower chamber: \( V_1 = 0.02 \text{ m}^3 \)

Final volume of air in the lower chamber:

\[
V_2 = V_1 + \frac{\pi}{4} D_1^2 L = 0.02 \text{ m}^3 + \frac{\pi}{4} \times (0.316)^2 \times 0.25 \text{ m}^3 = 0.04 \text{ m}^3
\]

Final pressure of air in the lower chamber:

\[
p_2 = p_1 \left( \frac{V_1}{V_2} \right)^{1.25} = 150 \text{ bar} \times \left( \frac{0.02 \text{ m}^3}{0.04 \text{ m}^3} \right)^{1.25} = 63 \text{ bar}
\]

Moving boundary work for air in the lower chamber:

\[
W_{\text{lower}} = \frac{(150 \times 100) \text{kPa} \times 0.02 \text{ m}^3 - (63 \times 100) \text{kPa} \times 0.04 \text{ m}^3}{1.25 - 1} \Rightarrow W_{\text{lower}} = +192 \text{ kJ}
\]

\( W_{\text{lower}} > 0 \) since the lower chamber air expands

(c) Considering energy balance: \( W = 0 \Rightarrow W_{\text{lower}} + W_{\text{upper}} = 0 \Rightarrow W_{\text{upper}} = -W_{\text{lower}} \)

\( W_{\text{upper}} = -192 \text{ kJ} \) \( W_{\text{upper}} < 0 \) since the upper chamber air is compressed