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ME 200 Thermodynamics 1
Fall 2017 – Exam 2

Circle your instructor's last name

Division 1: Naik **Division 2: Sojka**

Division 3: Wassgren **Division 4: Goldenstein**

Division 6: Braun **Division 7: Buckius**

Division 8: Meyer

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 energy flows on a diagram i.e. Energy Flow Diagram (EFD), start your analysis with the basic equations, list all relevant assumptions, and have appropriate units and use three significant figures. There is no need to re-write the given and find.
- 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 will not be scanned so will not be graded**. If you need extra paper raise your hand and a proctor will supply it.

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.

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1. [20 points] Circle all (and only all) correct answers.

(a) Can a constant mass of an ideal gas be compressed in an insulated piston-cylinder device using an isothermal process? Ignore KE and PE changes. <u>You must justify your answer with equation(s) to receive any credit on this problem.</u>

Yes

<u>No</u>

$\cancel{Q} - W = \Delta U + \Delta \cancel{KE} + \Delta \cancel{PE} \Rightarrow W = -\Delta U$

$U = f(T)$ only for an ideal gas $\Rightarrow$ $\Delta U = 0$ for isothermal process of an ideal gas

$\Rightarrow$ $W = 0$; however, compression requires work input $\Rightarrow$ process is not possible

(b) A constant mass of an ideal gas is heated from 300 K to 1000 K in a piston-cylinder device while maintaining the pressure constant either at 1 bar (Process A) or at 10 bar (Process B). Ignore KE and PE changes. Which of the following is true regarding heat transfer in the two processes? <u>You must justify your answer with equation(s) to receive any credit on this problem.</u>

<u>$Q_A = Q_B$</u>

$Q_A < Q_B$

$Q_A > Q_B$

Insufficient information

$Q - W = \Delta U + \Delta \cancel{KE} + \Delta \cancel{PE} \Rightarrow Q = W + \Delta U = P\Delta V + \Delta U = R\Delta T + +\Delta U$

$U = f(T)$ only for an ideal gas $\Rightarrow$ ΔU and $R\Delta T$ same for both processes

$\Rightarrow$ $Q_A = Q_B$

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Problem 1 (continued)

(c) Which of the following assumption(s) is (are) required to calculate the mass flow rate as: $\dot{m} = \rho AV$? No justification is required for the answer(s) on this problem.

Steady state

1-inlet, 1-exit

One-dimensional, uniform flow

No change in potential energy

(d) Which of the following assumption(s) is (are) required to obtain the relation for volume flow rate as: $A_1V_1 = A_2V_2$? You must justify your answer with equation(s) to receive any credit on this problem.

Steady state

1-inlet, 1-exit

Incompressible

No change in potential energy

$$\frac{dm_{CV}}{dt} = \sum_i \dot{m}_i - \sum_e \dot{m}_e$$

Steady 1-inlet, 1-exit (no summation)

$$\dot{m}_1 = \dot{m}_1 \Rightarrow \frac{A_1V_1}{v_1} = \frac{A_2V_2}{v_2} \Rightarrow A_1V_1 = A_2V_2 \quad if \;\; v_1 = v_2 \text{ (incompressible)}$$

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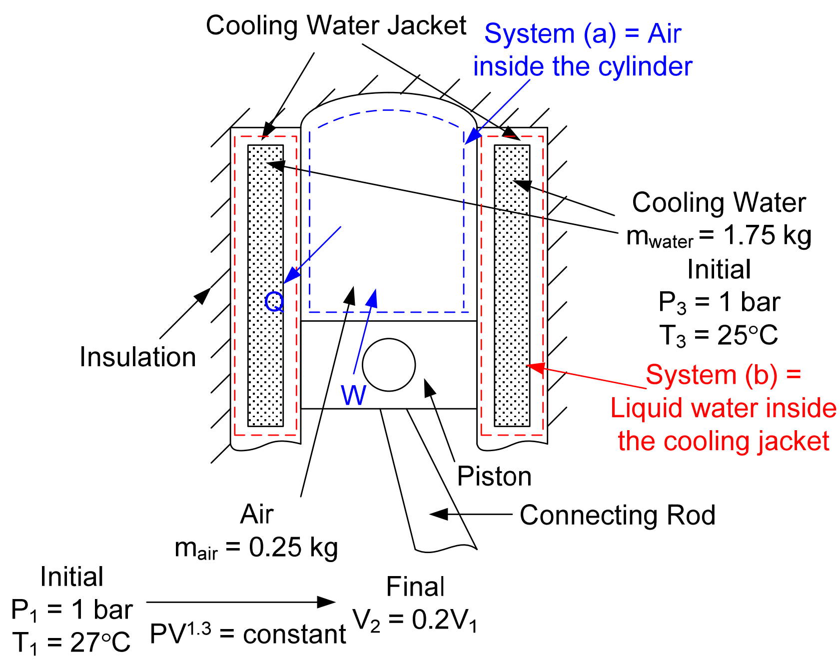
2. [40 points] A piston-cylinder device contains 0.25 kg of air initially at a temperature of 27°C and an absolute pressure of 1 bar (State 1). The air undergoes a compression process, where $PV^{1.3}$ = constant, until the volume is 20% of the initial volume (State 2). The cylinder is fitted with a cooling water jacket all around its outer wall. The cooling water jacket contains 1.75 kg of liquid water. The water is initially at a temperature of 25°C and an absolute pressure of 1 bar (State 3) at the start of the air compression process. Heat transfer occurs only between air in the cylinder and water inside the cooling jacket since the water jacket is perfectly insulated on its outside.



Molecular weight of air: 28.97 kg/kmol
Specific heat of liquid water: 4.18 kJ/kg-K
<u>Use the closest value in ideal gas table; do not interpolate.</u>

(a) Determine the boundary work (kJ) for air during the compression process.
(b) What is the temperature change (°C) of water during the compression process?

<u>Identify appropriate system or systems on the sketch provided, show mass/energy interactions (EFD), list any assumptions and basic equations, and provide your solution. There is no need to re-write the given and find.</u>

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Extra Space for Problem 2

Assumptions
Quasi-equilibrium
Ignore KE change
Ignore PE change
Neglect friction
No other work except boundary work
Air is an ideal gas
Liquid water is an incompressible liquid
Specific heat of liquid water remains constant with temperature change

Basic Equations

$$W_{boundary} = \int pdV$$

$$\left.\frac{dE}{dt}\right|_{system} = \dot{Q} - \dot{W} + \sum_{in} \dot{m}_{in}(h + ke + pe)_{in} - \sum_{out} \dot{m}_{out}(h + ke + pe)_{out}$$

Integrating:

$$Q - W = \Delta U + \Delta KE + \Delta PE$$

Solution

(a) Considering air inside the cylinder as the system, the boundary work during the compression process: $W_{12} = \int_{V_1}^{V_2} \frac{\text{constant}}{V^{1.3}} dV = \left(P_1 V_1^{1.3} = P_2 V_2^{1.3}\right)\left(\frac{V_2^{-n+1} - V_1^{-n+1}}{-n+1}\right) = \frac{P_1 V_1 - P_2 V_2}{n-1}$

Initial volume of air in the cylinder:

$$V_1 = \frac{m_{air} R_{air} T_1}{P_1} = \frac{m_{air}\left(\frac{\bar{R}}{M_{air}}\right) T_1}{P_1} = \frac{0.25 \text{ kg} \times 0.287 \frac{\text{kJ}}{\text{kg-K}} \times (27 + 273)\text{K}}{100 \text{ kPa}} = 0.21525 \text{ m}^3$$

Final volume of air in the cylinder: $V_2 = 0.2V_1 = 0.04305 \text{ m}^3$

$$W_{12} = \frac{100 \text{ kPa} \times (0.21525)^{1.3} \left(\text{m}^3\right)^{1.3} \left((0.04305)^{-0.3} - (0.21525)^{-0.3}\right)\left(\text{m}^3\right)^{-0.3}}{-1.3 + 1} \Rightarrow \mathbf{W_{12} = -44.5 \text{ kJ}}$$

(b) Considering air inside the cylinder as the system, heat transfer during the compression process: $Q_{12} - W_{12} = U_2 - U_1 = m_{air}(u_2 - u_1)$

Final temperature of air in the cylinder: $T_2 = \frac{P_2 V_2}{m_{air} R_{air}}$

For the polytropic process:

$$P_1 V_1^{1.3} = P_2 V_2^{1.3} \Rightarrow 1 \text{ bar} \times (0.21525)^{1.3} \left(\text{m}^3\right)^{1.3} = P_2 \times (0.04305)^{1.3} \left(\text{m}^3\right)^{1.3} \Rightarrow P_2 = 8.1 \text{ bar}$$

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Extra Space for Problem 2

Final temperature of air in the cylinder: $T_2 = \dfrac{810\ \text{kPa} \times 0.04305\ \text{m}^3}{0.25\ \text{kg} \times 0.287 \dfrac{\text{kJ}}{\text{kg-K}}} = 486\ \text{K}$

$u_1 = u\left(T_1 = 300\ \text{K}\right) = 214.1 \dfrac{\text{kJ}}{\text{kg}}$ and $u_2 \cong u\left(T_2 \cong 490\ \text{K}\right) = 352.1 \dfrac{\text{kJ}}{\text{kg}}$

$Q_{12} = -44.5\ \text{kJ} + 0.25\ \text{kg} \times \left(352.1 - 214.1\right) \dfrac{\text{kJ}}{\text{kg}} = -10\ \text{kJ}$

Considering liquid water inside the cooling jacket as the system during the polytropic compression process: $Q_{34} - \cancel{W_{34}} = U_4 - U_3 = m_{water}\left(u_4 - u_3\right) = m_{water} C_{water}\left(T_4 - T_3\right)$

Heat transfer from air occurs only to the liquid water in the cooling jacket since the outside of the cooling jacket is perfectly insulated $\Rightarrow Q_{34} = -Q_{12} = +10\ \text{kJ}$

Temperature change of liquid water during the compression process:

$\left(T_4 - T_3\right) = \dfrac{Q_{34}}{m_{water} C_{water}} = \dfrac{10\ \text{kJ}}{1.75\ \text{kg} \times 4.18 \dfrac{\text{kJ}}{\text{kg-K}}} = 1.38\ \text{K} \Rightarrow \underline{\boldsymbol{\left(T_4 - T_3\right) = 1.38\ ^\circ\text{C}}}$

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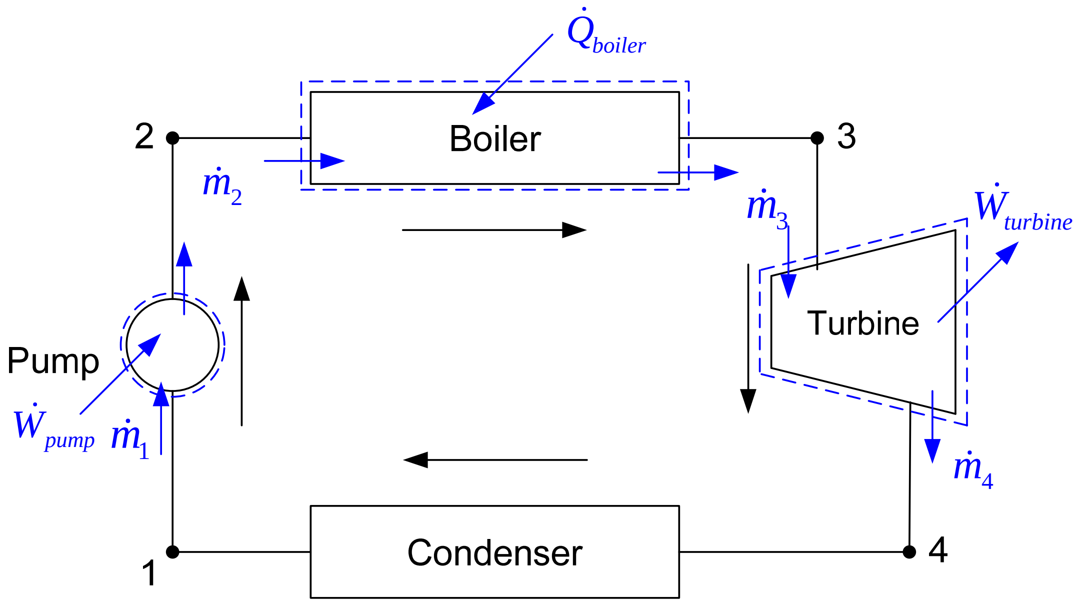
3. [40 points] A solar-powered steam power plant uses the sun's radiation to boil water. At peak operating conditions, the rate of radiation heat transfer into the boiler is 420 MW. The working fluid is water/steam, with data at each state provided in the table below; all the pressure values are absolute.



State	P, bar	T, °C	u, kJ/kg	h, kJ/kg	v, m^3/kg
1	**0.0123**	**10**	**42.0**	**42.0**	**0.00100**
2	**40**	**10**	**41.9**	**45.9**	**0.000998**
3	**40**	**600**	**3280**	**3670**	**0.0988**
4	**0.0123**	**10**	**2150**	**2270**	**95.7**

(a) Calculate the steam mass flow rate (kg/s) through the boiler
(b) Find the net power (MW) produced by the power plant.
(c) Determine thermal efficiency (%) of the power plant.
(d) Show the cycle on P-*v* diagram relative to the vapor dome and the relevant lines of constant temperature. Label the axes and four states and indicate the process directions with arrows. Critical temperature and pressure of water are 374°C and 221 bar, respectively. Saturated liquid water exits the condenser/enters the pump at State 1. Note that T_{sat} at 40 bar is 250.4°C.

<u>Identify appropriate system or systems on the sketch provided, show mass/energy interactions (EFD), list any assumptions and basic equations, and provide your solution. There is no need to re-write the given and find.</u>

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Extra Space for Problem 3

Assumptions
Quasi-equilibrium
Steady state, steady flow
One-dimensional, uniform flow
Ignore KE change
Ignore PE change
Boiler: $\dot{W}_{CV} = 0$
Turbine and Pump: $\dot{Q}_{CV} = 0$

Basic Equations

$$\left.\frac{dm}{dt}\right|_{system} = \sum_{in} \dot{m}_{in} - \sum_{out} \dot{m}_{out}$$

$$\left.\frac{dE}{dt}\right|_{system} = \dot{Q} - \dot{W} + \sum_{in} \dot{m}_{in}\left(h + ke + pe\right)_{in} - \sum_{out} \dot{m}_{out}\left(h + ke + pe\right)_{out}$$

Solution
(a) Mass balance for the boiler: $\dot{m}_2 = \dot{m}_3 = \dot{m}_{steam}$
Energy balance for the boiler: $\dot{Q}_{boiler} = \dot{m}_{steam}\left(h_3 - h_2\right)$

Mass flow rate of steam through the boiler: $\dot{m}_{steam} = \dfrac{\dot{Q}_{boiler}}{\left(h_3 - h_2\right)} = \dfrac{420\times 10^3 \dfrac{\text{kJ}}{\text{s}}}{\left(3670 - 45.9\right)\dfrac{\text{kJ}}{\text{kg}}} \Rightarrow$

$$\boldsymbol{\dot{m}_{steam} = 115.9 \frac{\text{kg}}{\text{s}}}$$

(b) Mass balance for the turbine: $\dot{m}_3 = \dot{m}_4 = \dot{m}_{steam}$
Energy balance for the turbine:

$$\dot{W}_{turbine} = \dot{m}_{steam}\left(h_3 - h_4\right) = 115.9\frac{\text{kg}}{\text{s}} \times \left(3670 - 2270\right)\frac{\text{kJ}}{\text{kg}} = +162,260\frac{\text{kJ}}{\text{s}}$$

Mass balance for the pump: $\dot{m}_1 = \dot{m}_2 = \dot{m}_{water(steam)}$

Energy balance for the pump: $\dot{W}_{pump} = \dot{m}_{water}\left(h_1 - h_2\right) = 115.9\dfrac{\text{kg}}{\text{s}} \times \left(42 - 45.9\right)\dfrac{\text{kJ}}{\text{kg}} = -452\dfrac{\text{kJ}}{\text{s}}$

Net power produced by the power plant:

$$\dot{W}_{net} = \dot{W}_{turbine} - \left|\dot{W}_{pump}\right| \Rightarrow \dot{W}_{net} = +161,808\frac{\text{kJ}}{\text{s}} \Rightarrow \boldsymbol{\dot{W}_{net} = +161.8 \text{ MW}}$$

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Extra Space for Problem 3

(c) Thermal efficiency of the power plant:

$$\eta_{thermal} = \frac{\dot{W}_{net}}{\dot{Q}_{in} = \dot{Q}_{boiler}} = \frac{161.8 \text{ MW}}{420 \text{ MW}} \Rightarrow \underline{\boldsymbol{\eta_{thermal} = 38.5\%}}$$

(d) P-v diagram