Thermodynamics 1 MECH 240:

Homework Assignment 1

Friday, Jan. 10, 2014  Due: Friday, Jan. 24, 2014 at end of the tutorial

Assigned Problems to be handed in:

Review of mechanical work:

1. Consider the following two situations:

   Case 1: The block moves up the incline and speeds up
   Case 2: The block moves down the incline and slows down

Tell whether the following quantities are positive, negative, or zero. Explain.

- The work done on the block by the hand
- The work done on the block by the earth
- The work done on the hand by the block (if there is no such work, state so).

Answer the above questions for a 3rd case in which the hand pushes down the incline as the block moves down with decreasing speed (there is friction between the block and incline in this case).
Expansion of a gas into a vacuum:

2. An insulated container is divided into two parts by a partition. One of these parts has a volume \( V_i \) and is filled with a dilute gas; the other part is empty. Remove the partition and wait until the final equilibrium condition is attained where the molecules of the gas are uniformly distributed throughout the entire container of volume \( V_f \).

(a) Has the total energy of the gas been changed? Use this result to compare the average energy per molecule and the average speed of a molecule in the equilibrium situations before and after the removal of the partition.

(b) What is the ratio of the pressure exerted by the gas in the final situation to that of the pressure exerted by it in the initial situation?

Fundamental Energy Transfer Processes:

3. A gas undergoes a thermodynamic cycle consisting of the following processes:

- Process 1-2: constant pressure, \( p = 1.4 \) bar, \( V_1 = 0.028 \) m\(^3\), \( W_{12} = 10.5 \) kJ
- Process 2-3: compression with \( pV \) constant, \( U_3 = U_2 \)
- Process 3-1: constant volume, \( U_1 - U_3 = -24.6 \) kJ

There are no significant changes in kinetic or potential energy.

(a) Sketch the cycle on a p-V diagram.
(b) Calculate the net work for the cycle, in kJ.
(c) Calculate the heat transfer for process 1-2, in kJ.

First Law Energy Analysis (write 1\(^{st}\) Law as a rate equation):

4. A gas is contained in a closed rigid tank fitted with a paddle wheel. The paddle wheel stirs the gas for 20 min, with the power (or rate of work done) varying with time according to \( \text{Power} = -10t \), where \( \text{Power} \) is in watts, and \( t \) is in min. Heat transfer from the gas to the surroundings takes place at a constant rate of 50 W. Determine

(a) the rate of change of energy of the gas at time \( t = 5 \) min, in watts.
(b) the net change in energy of the gas after 20 min, in kJ.

Heat pump cycle

5. The coefficient of performance of a heat pump cycle is 3.5, and the net work input is 5000 kJ. Determine the heat transfers \( Q_{\text{in}} \) and \( Q_{\text{out}} \), in kJ.
Additional problem to try if you need more practice: not to be handed in

6. A gas undergoes a thermodynamic cycle consisting of three processes:

   **Process 1-2**: constant volume, \( V = 0.028 \) m\(^3\), \( U_2 - U_1 = 264 \) kJ
   **Process 2-3**: expansion with \( pV \) constant, \( U_3 = U_2 \)
   **Process 3-1**: constant pressure, \( p = 1.4 \) bar, \( W_{31} = -10.5 \) kJ

   There are no significant changes in kinetic or potential energy.

   (a) Sketch the cycle on a \( p-V \) diagram
   (b) Calculate the net work for the cycle, in kJ (answer: 8.28 kJ)
   (c) Calculate the heat transfer for process 2-3, in kJ (answer: 18.78 kJ)
   (d) Calculate the heat transfer for process 3-1, in kJ (answer: -36.9 kJ)

   Is this a power cycle or a refrigeration cycle?

   Check your work:

   Question 3: \( W_{\text{cycle}} = -8.28 \) kJ; \( Q_{12} = 36.9 \) kJ

   Question 4: \( \frac{dE}{dt} = 50 \) W; \( \Delta E = 60 \) kJ

   Question 5: \( Q_{\text{out}} = 17,500 \) kJ; \( Q_{\text{in}} = 12,500 \) kJ
1. A gas contained within a piston-cylinder assembly is shown in the sketch in the text. Initially, the piston face is at \( x = 0 \), and the spring exerts no force on the piston. As a result of heat transfer, the gas expands, raising the piston until it hits the stops. At this point the piston face is located at \( x = 0.05 \) m, and the heat transfer ceases. The force exerted by the spring on the piston as the gas expands varies linearly with \( x \) according to \( F_{\text{spring}} = kx \), where \( k = 10,000 \) N/m. Friction between the piston and the cylinder wall can be neglected. The acceleration of gravity is \( g = 9.81 \) m/s\(^2\). Additional information is given in the sketch in the text, in particular, \( p_{\text{atm}} = 1 \) bar, \( A_{\text{pist}} = 0.0078 \) m\(^2\), \( m_{\text{pist}} = 10 \) kg, and \( m_{\text{gas}} = 0.5 \) g.

(a) What is the initial pressure of the gas, in kPa?
(b) Determine the work done by the gas on the piston, in J.
(c) If the specific internal energies of the gas at the initial and final states are 214 and 337 kJ/kg, respectively, calculate the heat transfer, in J.

2. A small, well-insulated cylinder and piston assembly contains an ideal gas at 10.13 bar and 294.13 K (see schematic below). A mechanical lock prevents the piston from moving. The length of the cylinder containing the gas is 0.305 m and the piston cross-sectional area is \( 1.858 \times 10^{-2} \) m\(^2\). The piston, which weighs 226 kg, is tightly fitted and when allowed to move, there are indications that considerable friction is present. When the mechanical lock is released, the piston moves in the cylinder until it impacts and is engaged by another mechanical stop; at this point, the gas volume has just doubled. The heat capacity per mole of the ideal gas is 20.93 J/gmmol-K, independent of temperature and pressure. Consider the heat capacity of the piston and cylinder walls to be negligible.

(a) What is the temperature and pressure of the gas after the expansion?
(b) Repeat the calculations if the cylinder were rotated both 90° and 180° before tripping the mechanical lock.
Additional problems to try if you need more practice: not to be handed in
(It is better to do a few of these problems thoroughly than to do many superficially – they all involve essentially the same type of analysis, i.e., application of the 1st Law to a closed system, evaluation of heat transfer and work interactions and the use of additional equilibrium conditions such as mechanical equilibrium or thermal equilibrium to solve for the unknown properties)

3. A piston \((A)\) and piston rod \((B)\) are fitted inside a cylinder of length 0.508 m and area \(6.45 \times 10^{-3} \text{ m}^2\) (see diagram below). Although the piston is quite thin, it weighs 9.07 kg; the piston rod is \(1.29 \times 10^{-3} \text{ m}^2\) in area and weighs 4.53 kg. On top of the rod, but outside the cylinder, an 18.14 kg weight \((C)\) is placed. Originally, gas in \(D\) is at atmospheric pressure while the piston is positioned in the middle of the cylinder. Gases \(D\) and \(E\) are helium and under these conditions may be considered ideal with a constant \(C_v = 12.6 \text{ J/gmmol K}\). The initial temperature everywhere is 311 K. Assume that the cylinder is insulated and the piston is a good conductor. Also assume that the cylinder, piston, and piston rod have negligible heat capacity. If weight \(C\) should fall off, what is the final state of the system when the piston has stopped and there is a balance of forces across the piston? Do not neglect the fact that during motion there may be some friction between moving parts.

4. Two tanks are connected by a valve. One tank contains 2 kg of carbon monoxide gas at 77°C and 0.7 bar. The other tank holds 8 kg of the same gas at 27°C and 1.2 bar. The valve is opened and the gases are allowed to mix while receiving energy by heat transfer from the surroundings. The final equilibrium temperature is 42°C. Using the ideal gas assumption, determine
   (a) the final equilibrium pressure, in bar, and
   (b) the heat transfer for the process, in kJ.
For carbon monoxide, \(c_v = 0.745 \text{ kJ/kgK}\).

Answers: (a) 1.05 bar, (b) 37.25 kJ.
5. Here is a problem very similar to the one done in class:

Two cylinders are attached as shown below. Both cylinders and pistons are adiabatic and have walls of negligible heat capacity. The connecting rod is nonconducting.

![Diagram of two cylinders connected by a connecting rod.](image)

The initial conditions and pertinent dimensions are as follows:

<table>
<thead>
<tr>
<th>Cylinder</th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial pressure (bar)</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>Initial temperature (K)</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>Initial volume (m³)</td>
<td>$6.28 \times 10^{-3}$</td>
<td>$1.96 \times 10^{-4}$</td>
</tr>
<tr>
<td>Piston area (m²)</td>
<td>$3.14 \times 10^{-4}$</td>
<td>$1.96 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

The pistons are, initially, prevented from moving by a stop on the outer face of piston $A$. When the stop is removed, the pistons move and finally reach an end state characterized by a balance of forces on the connecting rod. There is some friction in both piston-cylinders during this process. The gases $A$ and $B$ are ideal and have constant values of $c_v = 20.9$ J/mol K.

What are the final pressures in both $A$ and $B$? Do two cases, one where the ambient pressure is 0 bar and one where it is 1 bar.
6. *(This question is from an old exam).* A horizontal cylinder contains an explosive gas and an inert gas separated by a piston held by a spring as shown in the diagram below. The *relaxed* spring length is $L_0$ and the spring constant is $k$. The piston, spring and cylinder have negligible mass. The initial temperature and pressure of the explosive gas are $T_0$ and $p_0$, respectively. At time $t = 0$, the gas is ignited and a total amount of energy $Q$ is deposited in the gas, bringing the gas to a higher temperature prior to the piston moving (i.e., the explosion process is so rapid that the energy addition can be considered to be at constant volume). The gas then expands and the piston moves to a final equilibrium position after the oscillations stop. Neglect friction holding the piston in the final equilibrium position.

Assuming that the piston is a good heat conductor and that there is friction between the piston and the cylinder, find an equation involving the final position of the piston, $L$, in terms of the initial conditions (don’t try to find an explicit equation for $L$).

*Note: Define your system and clearly show the governing equations used.*
Thermodynamics I, MECH 240: PROBLEM SET 3

Friday, Jan. 31, 2014 Due: Friday, Feb. 14, 2014

Background Reading and Example Problems:

Study sections 3-1 to 3-7 of the text Cengel & Boles, and go through the example problems carefully. Section 3-7 covers the compressibility factor \( Z \); there is one problem related to this below, although you will not be given questions on compressibility factor on the exams in this course (this is covered more thoroughly in Thermo 2). Also, we will save the section on other equations of state (section 3-8) for Thermo 2. You can also read the discussion on vapor pressure and phase equilibria on p. 149.

Assigned Problems to be handed in:

Practice Using Steam Tables:

1. (i) The states of 1 kg of water substance are given below. Use steam tables or charts to determine the nature of the phase of the water: namely, compressed liquid, saturated liquid, wet (i.e., a 2-phase mixture of water vapor and liquid), dry saturated steam, or superheated steam.
   
   \[
   \begin{array}{ll}
   (a) p = 100 \text{ kPa}, T = 150\degree \text{C} & (b) p = 200 \text{ kPa}, T = 200\degree \text{C} \\
   (c) p = 300 \text{ kPa}, V = 0.1 \text{ m}^3 & (d) H = 2700 \text{ kJ}, p = 50 \text{ kPa} \\
   (e) H = 2100 \text{ kJ}, T = 50\degree \text{C} & (f) T = 100\degree \text{C}, x = 0.8 \\
   \end{array}
   \]

(ii) Determine the changes in the enthalpy, specific volume, quality, and temperature for the following processes. The initial pressure, \( p_i \), is 500 kPa. The final state is designated by subscript \( f \).

   \[
   \begin{array}{ll}
   (a) \text{Constant volume: } v_i = 0.3 \text{ m}^3/\text{kg}, p_f = 350 \text{ kPa} & (b) \text{Constant volume: } h_i = 2500 \text{ kJ/kg}, p_f = 190 \text{ kPa} \\
   (c) \text{Constant volume: } T_i = 200\degree \text{C}, p_f = 240 \text{ kPa} \\
   \end{array}
   \]

2. Sketch the following processes on \( P-v \) and \( P-T \) diagrams.

   \[
   \begin{array}{ll}
   (a) \text{Superheated vapor is cooled at constant pressure until liquid just begins to form.} \\
   (b) \text{A liquid-vapor mixture with a quality of 60% is heated at constant volume until its quality is 100%.} \\
   (c) \text{A liquid-vapor mixture of water with a quality of 50% is heated at a constant temperature of 200\degree \text{C until its volume is 4.67 times the initial volume.} } \\
   \end{array}
   \]
Comparison of constant heat capacity assumption, variable heat capacity and ideal gas tables

3. A rigid tank, with a volume of 0.05 m$^3$, contains air initially at 140 kPa, 300 K. A heat transfer of magnitude 6 kJ occurs to the air. Determine the final temperature, in K, and the final pressure, in kPa. Assume ideal gas behavior, and use

(a) a constant specific heat value from C&B Table A-2a (M&S, Table A-20),
(b) data from C&B Table A-2c (M&S, Table A-21), i.e., polynomial function $c_v(T)$ or $c_p(T)$, and
(c) data from C&B Table A-17 (M&S, Table A-22) - ideal gas table for air.

Compare the results with the different methods.

First Law Problems using Steam Tables

4. One kilogram of water substance is maintained in a weighted piston-cylinder assembly at 30 bar and 240˚C. The substance is slowly heated at constant pressure until the temperature reaches 320˚C. Determine (a) the work required to raise the weighted piston, and (b) the required heat input, in kJ/kg. Sketch the process on a $P$-$v$ diagram.

5. An isolated system consists of a 10-kg copper slab, initially at 30˚C, and 0.2 kg of saturated water vapor, initially at 130˚C. Assuming no volume change, determine the final equilibrium temperature of the isolated system, in ℃. (note that the specific heat for copper can be found in C&B Table A-3 or M&S Table A-19).

Answer: $T_2 = 98$˚C.

Compressibility Chart

6. Five kg of butane (C$_4$H$_{10}$) in a piston-cylinder assembly undergo a process from $p_1 = 5$ MPa, $T_1 = 500$ K to $p_2 = 3$ MPa, $T_2 = 450$ K during which the relationship between pressure and specific volume is $pv^n = $ constant. Determine the work, in kJ. Use the compressibility chart to evaluate the properties, as necessary.

Answer: $W = 120$ kJ.
Recommended extra problems to try but not to hand in:

First law problem with steam tables

7. One-tenth of a kilogram of water at 3 bar and 76.3% quality is contained in a rigid tank which is thermally insulated. A paddle-wheel inside the tank is turned by an external motor until the substance is a saturated vapor. Determine the work necessary to complete the process, and the final pressure and temperature of the water. Sketch the process on a P-v diagram.

8. A cylinder/piston arrangement contains 5 kg of water at 100°C with a quality, \( x = 20\% \) and the piston, with a mass of \( m_p = 75 \) kg, is resting on some stops as shown in the figure below. The outside pressure is 100 kPa, and the cylinder area is \( A = 24.5 \) cm\(^2\). Heat is now added to the water until the water reaches a saturated vapour state.

Sketch the process on a \( p-V \) diagram and also determine

a) the initial volume, in m\(^3\),
b) the final pressure, in kPa,
c) the work done by the water on the piston during this process, in kJ, and
d) the heat transfer to the water, in kJ.

9. A fixed amount of water vapor, initially at 20 MPa, 520°C, is cooled at constant volume until its temperature reaches 400°C. Using the compressibility chart, determine

(a) the specific volume of the water vapor in m\(^3\)/kg at the initial state.
(b) The pressure in MPa at the final state.

Compare the results of parts (a) and (b) with the values obtained from the superheated vapor table, C&B Table A-6 or M&S Table A-4.
Thermodynamics 1 MECH 240: PROBLEM SET 4

Posted: Friday, Feb. 14, 2014    Due: Monday, Feb. 24, 2014 (note assignment is due on Monday rather than Feb. 21 due to Midterm #1)

Example Problems:

Study the problems from the text for examples of energy analysis for steady-flow open system (examples in Cengel & Boles, sections 5-1 to 5-5 or Moran & Shapiro, sections 4.1 to 4.10).

Assigned Problems to be handed in:

1. **Conservation of Mass** A 0.03-m³ tank contains Refrigerant 134a, initially at 20°C, 4 bar. A leak develops, and refrigerant flows out of the tank at a constant mass flow rate of 0.0036 kg/s. The process occurs slowly enough that heat transfer from the surroundings maintains a constant temperature in the tank. Determine the time, in s, at which half of the mass has leaked out, and the pressure in the tank at that time, in bars. Use Tables C&B A-11 to A-13 (M&S A-12) to obtain the properties of R-134a.

2. **Heat Exchangers** Carbon dioxide gas is heated as it flows through a 2.5-cm-diameter pipe. At the inlet, the pressure is 2 bar, the temperature is 300 K, and the velocity is 100 m/s. At the exit, the pressure and velocity are 0.9413 bar and 400 m/s, respectively. The gas can be treated as an ideal gas with constant specific heat \( c_p = 0.94 \text{ kJ/kg·K} \). Neglecting potential energy effects, determine the rate of heat transfer to the carbon dioxide, in kW. **Answer:** heat transfer rate = 56.1 kW.

3. **Pump** A pump steadily delivers water through a hose terminated by a nozzle. The exit of the nozzle has a diameter of 0.6 cm and is located 10 m above the pump inlet pipe, which has a diameter of 1.2 cm. The pressure is equal to 1 bar at both the inlet and the exit, and the temperature is constant at 20°C throughout. The magnitude of the power input required by the pump is 1.5 kW, and the acceleration of gravity is \( g = 9.81 \text{ m/s}^2 \). Determine the mass flow rate delivered by the pump, in kg/s.

4. **Nozzle** A converging nozzle has an exit area of 0.001 m². Air enters the nozzle with negligible velocity at a pressure of 1.0 MPa and a temperature of 360K. For isentropic (i.e., adiabatic, frictionless) flow of an ideal gas with \( \gamma = 1.4 \), determine the mass flow rate, in kg/s, and the exit Mach number for “back” (i.e., exit) pressures of
   (a) 500 kPa and
   (b) 784 kPa.
   **Hint:** first use the given pressure ratio to determine if the flow is choked (if the flow is choked, \( M_{\text{exit}} = 1 \)).
5. **Combined System** The figure below shows a simple vapor power plant operating at steady state with water circulating through the components. Relevant data at key locations are given on the figure. The mass flow rate of the water through the power plant components is 109 kg/s. Kinetic and potential energy effects are negligible. Determine

(a) the thermal efficiency (note that the thermal efficiency is defined in general as the ratio of the desired effect to the required energy input, so in this case the efficiency is the ratio of the net work output of the combined system, or the work done by the turbine minus the work in to the pump, to the heat input to the steam generator).

(b) the mass flow rate of the cooling water passing through the condenser, in kg/s.

Answers: (a) efficiency = 0.332, (b) 3759 kg/s.
Extra problems to try if you need more practice, but not to hand in:

1. **Conservation of Mass** Carbon dioxide enters a steady-flow device at 27°C with a velocity of 25 m/s through an area of 4800 cm². At the exit of the device the pressure and temperature are 1.4 bars and 47°C, respectively, and the gas moves with a velocity of 9 m/s through an area of 7500 cm². Assuming ideal-gas behavior, determine
   (a) The mass flow rate in kg/s
   (b) The inlet pressure in bars.

2. **Heat Exchanger** A solar collector panel 20 m² in area receives solar energy at a rate of 750 W/m². It is estimated that 35% of the incident energy is lost to the surroundings. Water enters the panel at a steady flow rate of 0.05 kg/s and at 15°C. The water leaves the panel at an elevation 2 m higher than the inlet. Calculate the temperature of the water leaving the solar collector panel. The specific heat of water may be taken to be 4.18 kJ/kg-K.

3. **Turbine** Air enters a turbine at 6 bar, 740K, and 120 m/s. The exit conditions are 1 bar, 450K, and 220 m/s. A heat loss of 15 kJ/kg occurs as the air passes through the turbine. The inlet area is 4.91 cm².
   (a) Determine the kinetic energy change in kJ/kg.
   (b) Determine the power output in kilowatts.

4. **Pipe Flow** An ideal gas with constant specific heat (c_p = 0.86 J/gm-K) flows through a long, horizontal pipe of constant diameter. The gas enters the pipe at 2.8 bars and 37°C with a velocity of 70 m/s. The gas leaves the pipe at 1.4 bar and 37°C. Determine
   (a) The exit velocity in m/s,
   (b) The heat transfer in kJ/kg.

5. **Pump** A pump is employed to deliver 5000 kg/h of water from an elevation 10 m below the pump to an elevation 15 m above the pump. At the lower elevation (state 1) and the upper elevation (state 2) the known data are: \( D_1 = 4 \text{ cm, } p_1 = 0.7 \text{ bar, } T_1 = 20^\circ \text{C, } D_2 = 2 \text{ cm, } p_2 = 5 \text{ bar, and } T_2 = 20^\circ \text{C.} \)
   (a) Determine the magnitude of the shaft work in kJ/kg if the inlet velocity is 1 m/s and the pipe is insulated.
   (b) Determine the kilowatt rating of the pump.

6. **Diffuser** Air enters a diffuser at 0.80 bar and 20°C and leaves at 0.95 bar with a negligible velocity. If the inlet velocity is 300 m/s and the flow is adiabatic at a rate of 25 kg/s, compute
   (a) The exit temperature in °C,
   (b) The inlet area in square centimeters.

7. **Combined system** Air as an ideal gas flows through the turbine and heat exchanger arrangement as shown in the figure below. Data for the two flow streams are shown on the figure. Heat transfer to the surroundings can be neglected, as can all kinetic and potential energy effects. Determine temperature \( T_3 \), in K, and the power output of the second turbine, in kW, at steady state.
   **Answers:** \( T_3 = 1301.5 \text{ K, } \text{Power}_{\text{turbine2}} = 10,570 \text{ kW} \)
Sketch for problem #7
Thermo 1 MECH 240: PROBLEM SETS 5 and 6

Note: Problem Sets 5 & 6 both deal with open system, transient analysis. They are posted at the same time, so that you can work on them at your own pace. Some of the problems are more involved than in previous problem sets; don’t wait to the last minute to try them!

Prob. Set 5 (problems #1-3) and Prob. Set 6 (problems #6-7):

Due: Monday, Mar. 10, 2014 (just after Study Break)

Problem Set 5, assigned problems to be handed in:

1. **Compressors**: Hydrogen is compressed in a steady flow internally reversible compressor along a polytropic path for which the polytropic exponent is equal to 1.25. The inlet state of the hydrogen is 200 kPa, 30°C and the exit pressure is 900 kPa. Calculate the exit temperature of the hydrogen and the work per unit mass required to run the compressor.

2. **Open System Analysis** (including transient effects).
   The rigid tank shown below has a volume of 0.06 m³ and initially contains a two-phase liquid-vapor mixture of H₂O at a pressure of 15 bar and a quality of 20%. As the tank contents are heated, a pressure-regulating valve keeps the pressure constant in the tank by allowing saturated vapor to escape. Heating continues until no liquid remains in the tank. Neglecting kinetic and potential energy effects, determine

   (a) the amount of heat transfer, in kJ. (Answer: 3426 kJ)
   (b) the mass of vapor that escapes, in kg. (Answer: 1.744 kg)

[Diagram of pressure-regulating valve with tank and initial conditions]
3. A well-insulated piston-cylinder assembly is connected by a valve to an air supply line at 8 bars, as shown in the figure below. Initially, the air inside the cylinder is at 1 bar, 300 K, and the piston is located 0.5 m above the bottom of the cylinder. The atmospheric pressure is 1 bar, and the diameter of the piston face is 0.3 m. The valve is opened and air is admitted slowly until the volume of air inside the cylinder has doubled. The weight of the piston and the friction between the piston and the cylinder wall can be ignored. Using the ideal gas model, plot the final temperature, in K, and the final mass, in kg, of the air inside the cylinder for supply temperatures ranging from 300 to 500 K.

Extra problems not to be handed in:

4. The inlet conditions of a two-stage steady-flow compressor are 0.10 MPa and 27°C. The outlet pressure is 0.80 MPa, the stages are isentropic, and the intercooler cools the air to the initial temperature. Determine the total work input, in kJ/kg, if
(a) the pressure ratio across each stage is the same, and
(b) the pressure ratio across the first stage is twice that across the second stage.

5. A 1 m³ tank initially contains air at 300 kPa, 300 K. Air slowly escapes from the tank until the pressure drops to 100 kPa. The air that remains in the tank undergoes a process described by \( pv^{1.2} = \text{constant} \). For a control volume enclosing the tank, determine the heat transfer, in kJ. Assume ideal gas behavior with constant specific heats. (Answer: 83.39 kJ).

Schematic for problem 3
Problem Set 6, Assigned Problems to be handed in:

6. Two adiabatic tanks are interconnected through a valve. Tank A contains 0.2 m$^3$ of air at 40 bar and 90°C. Tank B contains 2 m$^3$ of air at 1 bar and 30°C. The valve is opened until the pressure in A drops to 15 bar. At this instant:

(a) what are the temperatures and pressures in both tanks, and
(b) how much mass has left tank A?

7. An air turbine operates between the atmosphere (1 bar, 300 K) and an evacuated tank of volume 1 m$^3$. When the tank pressure has risen to atmospheric, the turbine cannot be driven anymore. How much work can be obtained for the following processes if the turbine operates reversibly?

(Hint: You may need to consider several different open systems to solve the problem; when considering the turbine alone, remember that the work can be found using the expression $w_s = -\int v \, dp$.)

(1) The tank is adiabatic and the turbine operates isothermally (Answer: $p_oV/\gamma$),
(2) the tank is adiabatic and the turbine is adiabatic,
(3) the tank is diathermal (i.e., a very good conductor), and the turbine is adiabatic (Answer: $p_oV\gamma/(2\gamma - 1)$),
(4) and the tank is diathermal and the turbine is diathermal (Answer: $p_oV$).

For each case mentioned above, also find the temperature of the air in the tank at the end of the filling process as well as the heat interaction with the environment during the filling process.
Additional problems to try: not to be handed in:

Here are some more interesting problems that require some analysis. Try as many of these problems as you like until you feel confident using the First Law to analyze open and closed systems. Read them over carefully a few times to understand what the problem is all about, i.e., what is given and what you have to find, what are the processes involved, etc. Break down the problem into the basic elements and write down a procedure or method of solution before getting involved in the nitty gritty details (e.g., state assumptions, then give appropriate equations such as first law, ideal gas law, thermal or mechanical equilibrium and so on). Both closed and open systems are involved in these problems. If you like, work with a friend to discuss the problems and bounce ideas off each other to isolate any difficulties.

Note: extra problems 8a and 8b are similar. You may want to try 8a since it is in SI units and also is taken from a previous midterm in Thermodynamics 1. It illustrates an interesting problem in which the flow rate is steady (into and out of the bulge), but the system is not at steady state (the temperature of the gas in the bulge is increasing with time).
8a. (Taken from an old midterm in Thermo 1) A well-insulated pipe of 2.54 cm inside diameter carries air at 2 bar pressure and 366.5 K. It is connected to a 0.0283 m$^3$ insulated “bulge” as shown in the figure below.

The air in the bulge is initially at 1 bar pressure and 311 K. A and D are flow meters which accurately measure the mass rate of airflow. Valves B and C control the airflow into and out of the bulge. Connected to the bulge is a 0.283 m$^3$ rigid, adiabatic tank which is initially evacuated to a very low pressure.

At the start of the operation, valve B is opened to allow 4.54 g/s of air to flow into the bulge; simultaneously, valve C is operated to transfer air at exactly the same rate, i.e., 4.54 g/s, from the bulge into the tank. These flows are maintained constant as measured by the mass flow meters.

Air may be assumed an ideal gas with a constant heat capacity. Assume also that the gases, both in the bulge and large tank, are completely mixed so that there are no temperature or pressure gradients present.

(a) What is the temperature and pressure of the gas in the bulge after 6 s?

Answer: $T = 350$ K; $p = 1.124$ bar

(b) What is the temperature and pressure of the air in the large tank after 3 s?

Answer: $T = 455$ K; $p = 0.0628$ bar

For each part clearly state your assumptions and your choice of the system before carrying out your first law analysis.
8b. A well-insulated chamber of volume 1 ft$^3$ is shown in the figure below. Initially, the chamber contains air at 14.7 lbf/in.$^2$ and 100°F. Connected to the chamber are supply and discharge pipes equipped with valves that control the flow rates into and out of the chamber. The supply air is at 30 lbf/in.$^2$, 200°F. Both valves are opened simultaneously, allowing air to flow with a constant mass flow rate of 1 lb/min through each valve. The air within the chamber is well mixed, so the temperature and pressure at any time can be taken as uniform throughout. Determine the temperature, in °F, and the pressure, in lbf/in.$^2$, of the air in the chamber as functions of time. Neglect kinetic and potential energy effects and use the ideal gas model with constant specific heats.

Note: Either work out the problem using English units for practice, or convert to SI at the start.

Answers:

\[ T(t) = -100 \exp(-0.3291 \, t) + 200 \] \hspace{1cm} (T is in °F and \( t \) is in seconds)

\[ P(t) = -2.6258 \exp(-0.3291 \, t) + 17.3304 \] \hspace{1cm} (p in lbf/in.$^2$)

*Schematic for problem 8*
9. Bottles of compressed gases are commonly found in chemistry and chemical engineering laboratories. They present a serious safety hazard unless they are properly handled and stored. Oxygen cylinders are particularly dangerous. Pressure regulators for oxygen must be kept scrupulously clean, and no oil or grease should ever be applied to any threads or on moving parts within the regulator. The rationale for this rule comes from the fact that if oil were present - and if it were to ignite in the oxygen atmosphere - this hot spot could lead to ignition of the metal tubing and regulator and cause a disastrous fire and failure of the pressure container. Yet it is hard to see how a trace of heavy oil or grease could become ignited even in pure, compressed oxygen since ignition points probably are over 800 K if nonflammable synthetic greases are employed.

Let us model the simple act of opening an oxygen cylinder that is connected to a closed regulator (see figure on top of next page). Assume that the sum of the volumes of the connecting line and the interior of the regulator is \( V_R \). \( V_R \) is negligible compared to the bottle volume. Opening valve A pressurizes \( V_R \) from some initial pressure to full bottle pressure. Presumably, the temperature in \( V_R \) also changes. The question we would like to raise is: Can the temperature in \( V_R \) ever rise to a sufficiently high value to ignite any traces of oil or grease in the line or regulator?

**Data:** The oxygen cylinder is at 15.17 MN/m\(^2\) and 311 K. The connecting line to the regulator and the regulator interior (\( V_R \)) are initially at 0.101 MN/m\(^2\), 311 K, and contain pure oxygen. Assume no heat transfer to the metal tubing or regulator during the operation, independent of pressure or temperature.

(a) If the gas entering \( V_R \) mixes completely with the initial gas, what is the final temperature in \( V_R \)?

(b) An alternative model assumes that there is no mixing between the gas originally in \( V_R \) and that which enters from the bottle. In this case, after the pressures are equalized, we would have two identifiable gas slugs which presumably are at different temperatures. Assuming no axial heat transfer between the gas slugs, what is the final temperature of each?

(c) Comment on your assessment of the hazard of this simple operation of bottle opening. Do you think the models in (a) and (b) are realistic?
10. A 4 m³ storage tank (see schematic below) containing 2 m³ of liquid is to be pressurized with air from a large, high-pressure reservoir through a valve at the top of the tank to permit rapid ejection of the liquid. The air in the reservoir is maintained at 100 bar and 300 K. The gas space above the liquid contains initially air at 1 bar and 280 K. When the pressure in the tank reaches 5 bar, the liquid transfer valve is opened and the liquid is ejected at the rate of 0.2 m³/min while the tank pressure is maintained at 5 bar. What is the air temperature when the pressure reaches 5 bar and when the liquid has been drained completely?

Neglect heat interaction at the gas-liquid and gas-tank boundaries. It may be assumed that the gas above the liquid is well mixed and that air is an ideal gas with a constant value of $C_v = 20.9$ J/gm-mol K.

*Schematic for problem 10*
11. Advertised is a small toy that will send up a signal flare and the operation "is so simple that it is amazing" (see the figure below). Our examination of this device indicates that it is a sheet metal tube 2.13 m long and 645 mm$^2$ in area. A plug shaped into the form of a piston its into the tube and a mechanical trigger holds it in place 0.61 m above the bottom. The piston weighs 1.57 kg and contains the necessary parachute and pyrotechnics to make the show exciting. To operate the device, the volume below the piston is pumped up to a pressure of about 4.05 bar with a small hand pump, and then the trigger is depressed, allowing the piston to fly out the top. The pyrotechnic and parachute devices are actuated by the acceleration force during ejection.

When we operated this toy last summer, the ambient temperature was 305 K.

(a) Assuming no friction in the piston and no heat transfer or other irreversibilities in the operation, how high would you expect the piston to go? What would be the time required from the start to attain this height?

(b) Since you are an engineer who is never satisfied with a commercial object, suggest improvements to make the piston go even higher. What is the maximum height that could be obtained if it were limited to 4.05 bar pressure?

(c) Comment on the way you might analyze the expected performance if the restrictions in part (a) are removed.
12. To reduce gas storage costs, two companies, A and B, have built a common storage tank in the shape of a horizontal right circular cylinder 0.3 m in diameter and 30 m long as shown below. To decide how much gas each company uses between refills, a thin piston was placed in the tank. The piston moves freely, that is, there is essentially no friction present, and the pressure is the same on both sides. Thus, as company A uses gas, the piston moves left and as company B uses gas, the piston moves right.

When the gas company refills the tank, it must decide how much gas has been used by each company. It can easily measure the position of the piston and can, if necessary, install other instrumentation such as thermometers or pressure gauges in either or both ends of the tank.

Assume that (1) the gas is ideal; (2) the piston is adiabatic; (3) the walls are well insulated and have a low heat capacity; and (4) at the start of each month after filling the tank, the gas company positions the piston in the center of the tank, equalizes the temperature on both ends, and carefully meters the total amount of gas added.

List the minimum instrumentation that you would recommend, and show from this list how the amount of gas consumed by both companies could be determined at the time of refilling.
13. From the memoirs of a thermodynamicist: "while relaxing near a large tank of nitrogen gas (A) at 687 kN/m² and 298 K, I began reviewing some of my knowledge in thermodynamics. A rather interesting experiment suggested itself and I thought I would compare theory with real data. I obtained a small high-pressure vessel (B) and two valves (C) and (D). I first filled B with nitrogen gas at 101 kN/m² and 298 K and connected it as shown. Then working quickly, I opened valve C (with D closed) and allowed the pressures in B and A to equalize. Then, I quickly closed C and opened D to blow down vessel B to its original pressure. I repeated this sequence a number of times. Tank A was so large that I did not cause any significant drop in pressure in it by my experiments. Second, I pressurized and blew down B so rapidly that little heat transfer probably occurred during this time."

Nitrogen has a value of \( c_p = 29.33 \text{ J/mol K} \) and is an ideal gas, so \( c_p - c_v = R \).

(a) Guess the temperature of the gas in B after the second pressurization and after the second blowdown.

(b) What do you think these temperatures were after a very large number of cycles?

![Schematic for problem 13](image)

14. A spaceship cabin may be considered to be a rigid pressurized vessel, which contains the atmosphere required to support the life of its occupants. A puncture in the cabin when it is in space must be detected quickly, so that the cabin occupants can seal the puncture or switch to their individual life support systems. The time interval that elapses before a dangerously low pressure is reached is a critical quantity for designing the warning devices and countermeasure systems. Derive an equation giving an estimate for the pressure \( P \) after a puncture as a function of the time, \( t \), the initial pressure \( p_i \), the initial temperature \( T_i \), the area \( A \) of the puncture, and the volume \( V \) of the cabin.

Consider the atmosphere of the cabin to be a perfect gas. If the cabin atmosphere is air at an initial temperature of 300 K, determine the ratio \( p/p_i \) as a function of time with the ratio \( (A/V) \) as a parameter. Assume that for air, \( \gamma = 1.4 \) and \( R = 287.4 \text{ J/kg-K} \). (you can read up more details in a paper by S. T. Demetriedes "On the decompression of a punctured pressurized cabin in vacuum flight", *Jet Propulsion*, Vol. 24(1), 35-36, 1954).
1. What are the air-standard assumptions?

2. How is the mean effective pressure for reciprocating engines defined (check text or class notes)?

3. As a car gets older, will its compression ratio change? How about the mean effective pressure?

4. Can any ideal gas power cycle have a thermal efficiency greater than 55% when using thermal energy reservoirs at 627°C and 17°C?

5. What is the cutoff ratio for a diesel engine cycle? How does it affect the thermal efficiency of a Diesel cycle?

6. The compression ratio of an air-standard Otto cycle is 9.5. Prior to the adiabatic compression process, the air is at 100 kPa, 35°C, and 600 cm³. The temperature at the end of the adiabatic expansion process is 800 K. Using specific heat values at room temperature, determine (a) the highest temperature and pressure in the cycle; (b) the amount of heat transferred in, in kJ; (c) the thermal efficiency; and (d) the mean effective pressure.

   Answers: (a) 1969 K, 6072 kPa, (b) 0.59 kJ, (c) 59.4%, (d) 652 kPa.

7. A four-cylinder, four-stroke, 2.2-L gasoline engine operates with a cycle similar to the Otto cycle (except the adiabatic compression and expansion processes are replaced by polytropic compression and expansion processes) with a compression ratio of 10. The air is at 100 kPa and 60°C at the beginning of the compression process, and the maximum pressure in the cycle is 8 MPa. The compression and expansion processes may be modeled as polytropic with a polytropic constant of 1.3. Using constant specific heats at 850K, determine (a) the temperature at the end of the expansion process, (b) the net work output and the thermal efficiency, (c) the mean effective pressure, (d) the engine speed for a net power output of 70 kW, in revolutions/min (note that there are two revolutions in one cycle in four-stroke engines.), and (e) the specific fuel consumption, in g/kWh, defined as the ratio of the mass of the fuel consumed to the net work produced. The air-fuel ratio, defined as the amount of air divided by the amount of fuel intake, is 16.

   Properties: The properties of air at 850 K are $c_p = 1.110 \text{ kJ/kg} \cdot \text{K}$, $c_v = 0.823 \text{ kJ/kg} \cdot \text{K}$, $R = 0.287 \text{ kJ/kg} \cdot \text{K} \cdot \text{K}$, and $k = 1.349$ (Table A-2b).

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Thermodynamics 1 MECH 240: PROBLEM SET 8

Wednesday, March 19, 2014

**Due:** Please work through these problems as preparation for the final exam – there will be one question on the final exam which will have short answer questions similar to the ones below.

*It is not required to hand in this assignment. However, if you complete the assignment and hand it in during the tutorial on April 11, 2014 you will receive 1 bonus mark added to your term grade.*

**Review of Development of 2nd Law and Entropy:**

1. Read Chap. 6 of Cengel & Boles on the development of the 2nd Law of Thermodynamics (or Chapter 5 of Moran and Shapiro, paying particular attention to the discussion of reversible and irreversible processes in section 5.3).

2. Rewrite your notes or sections of the text on the 2nd Law, carefully explaining to your own satisfaction the important steps and assumptions. In the process, you should address the following questions:
   (i) What are the two usual statements of the second law (i.e., Kelvin-Planck and Clausius)?
   
   (ii) Prove the equivalence of the two statements (refer to your class notes)
   
   (iii) Think over very thoroughly and convince yourself that spontaneous heat flow from cold to hot reservoirs has something to do with a PMM2 (perpetual motion machine of the second kind).
   
   (iv) Is it absolutely impossible to have a PMM2 or spontaneous heat flow from cold to hot? If not, what do you think is the probability of such events?
   
   (v) Prove that a reversible Carnot heat engine is the most efficient engine that can operate between two given reservoirs (refer to class notes).
   
   (vi) Prove that all reversible engines between the same two heat reservoirs must have the same efficiencies (the proof follows in the same way as that for item (v) above, i.e., consider 2 reversible Carnot engines $C_1$ and $C_2$ operating between the same 2 temperature reservoirs; assume that either they generate the same amount of work or have the same heat input; now reverse one of the engines and use it to power the other; combine the two devices to show that either the K-P or Clausius statement is violated).
(vii) Prove that the efficiency of a reversible engine must depend on the temperature of both the hot and cold reservoirs (this proof is sketched out in the notes).

(viii) Prove that the ratio of the heat input to the heat rejected for a reversible engine can be used to derive an *absolute* temperature scale (this is discussed in Cengel & Boles, section 6-9 and Moran & Shapiro, section 5.4).

(ix) Prove Clausius' inequality for a general cyclic device (see class notes) and define (descriptively) what is entropy, why is it a state function and what does it represent or measure.

(x) State the second law in terms of the entropy and go back to explain the Kelvin-Planck and Clausius' statements in terms of entropy (i.e., show that a violation of K-P or Clausius's statements leads to a decrease in the entropy of the universe as demonstrated in class).

3. To calculate the change in entropy, in general, for a process that takes a system from an initial state to a final state, it is necessary to find a reversible process that connects the same two states, then use the definition of entropy to calculate the entropy change (i.e., $\Delta S = \int (\delta Q/T)_{\text{int. rev.}}$).

Work out in particular the entropy change for the following changes of state for a system. Consider one mole of N₂ at 1 bar and 300K as initial conditions.

(i) Isentropic compression to 10 bar.
(ii) Adiabatic compression to 10 bar, 650K. Since no heat transfer is involved in an adiabatic process, why is there an entropy change?
(iii) Reversible isothermal compression to 10 bars.
(iv) If the isothermal compression is irreversible (with friction) is entropy change of system the same? How about the environment?
(v) Constant volume heating to 2 bars.
(vi) Constant pressure heating to 600K.
(vii) If both the constant volume and constant pressure heating are carried out reversibly, what's the total change of entropy of the universe?
(viii) If the heating is carried out irreversibly by contact with a reservoir at 800K, what is the entropy increase in the universe?
(ix) It is still possible to carry out a reversible heat transfer process through a finite temperature difference between a reservoir and a system (i.e., by using a series of intermediate temperature reservoirs). Prove this by calculating the entropy change of the universe (i.e., reservoir and system).

4. Review the derivation and use of the TdS equations addressing the following points:
(i) An irreversible process brings the state of a system from 1 to 2. The first law can be written as \( \Delta U = Q - W \) (note that \( \Delta U = U_2 - U_1 \) can be written as \( \int dU \) since \( dU \) is a total differential). The same two states 1 and 2 can be connected by a reversible path (or a combination of reversible paths) if the first law is applied to the reversible path, then \( Q = \int (\delta Q)_{\text{rev}} = \int TdS \) and can choose the reversible paths so that \( W \) is \( pdV \) work, i.e., \( W = \int pdV \). Then the first law becomes

\[
\begin{align*}
\int_{U_1}^{U_2} dU &= \int_{S_1}^{S_2} TdS - \int_{V_1}^{V_2} pdV \\
U_1 &\quad S_1 &\quad V_1 \\
U_2 &\quad S_2 &\quad V_2
\end{align*}
\]

or if the two states are close together, \( dU = TdS - pdV \). This form of the first law now deals only with state functions (i.e., \( U, S, V \), etc.) and the paths do not come in. Think it over very thoroughly and understand what the \( TdS \) equations mean (i.e., \( TdS = dU + pdV \) or \( TdS = dH - Vdp \)).

(ii) Use the \( TdS \) equations and derive the expressions for the entropy change of a perfect gas in terms of \( P, T \), and \( V, T \) as independent variables (i.e., \( S(P,T) \), \( S(V,T) \)).

(iii) A system at temperature \( T \) receives \( Q \) (at constant volume) from a reservoir at temperature \( T + \Delta T \). Prove that if \( \Delta T/T \ll 1 \), the entropy change of the universe is zero (i.e., a reversible heat transfer process). If \( \Delta T/T \) is finite, then \( (\Delta S)_{\text{universe}} > 0 \).

(iv) Go back and use the \( TdS \) relations to calculate the entropy changes for the processes in problem 3 above and compare with the previous results.
Thermodynamics 1: MECH 240  PROBLEM SET 9

Wednesday, March 19, 2014  Due: Friday, April 4, 2014

Assigned Problems to be handed in:

Calculation of Entropy Changes:

1. An isentropic (i.e., constant entropy) steam turbine processes 5 kg/s of steam at 4 MPa, which is exhausted at 50 kPa and 100°C, as shown in the schematic below. Five percent of this mass flow is diverted for feedwater heating at 700 kPa. Determine the power produced by this turbine, in kW.

2. Consider two solid blocks, one hot and the other cold, brought into contact in an adiabatic container. After a while, thermal equilibrium is established in the container as a result of heat transfer. The first law requires that the amount of energy lost by the hot solid be equal to the amount of energy gained by the cold one. Does the second law require that the decrease in entropy of the hot solid be equal to the increase in entropy of the cold one?

3. A 25-kg iron block initially at 350°C is quenched in an insulated tank that contains 100 kg of water at 18°C. Assuming the water that vaporizes during the process condenses back in the tank, determine the total entropy change during this process. Take the specific heats of water and iron to be 4.18 kJ/kg-K and 0.45 kJ/kg-K, respectively. How could the iron block be cooled to 18°C will almost no change in entropy of the universe?
4. Two rigid tanks are connected by a valve as shown in the schematic below. Tank A is insulated and contains 0.2 m$^3$ of steam at 400 kPa and 80% quality. Tank B is uninsulated and contains 3 kg of steam at 200 kPa and 250°C. The valve is now opened, and steam flows from tank A to tank B until the pressure in tank A drops to 300 kPa. During this process 600 kJ of heat is transferred from tank B to the surroundings at 0°C. Assuming the steam remaining inside tank A to have undergone a reversible adiabatic process, determine

a) the final temperature in each tank, and  
b) the entropy generated during the process (i.e., the total entropy change of the universe).  

Answers: a) 133.5°C, 113.2°C, b) 0.916 kJ/K.

5. Consider a well-insulated horizontal rigid cylinder that is divided into two compartments by a piston that is free to move but does not allow either gas to leak into the other side. Initially, one side of the piston contains 1 m$^3$ of N$_2$ gas at 500 kPa and 80°C while the other side contains 1 m$^3$ of He gas at 500 kPa and 25°C. Now thermal equilibrium is established in the cylinder as a result of heat transfer through the piston. Using constant specific heats at room temperature, determine

a) the final equilibrium temperature in the cylinder and  
b) the total entropy change of the gases.

6. Sketch the Otto and Stirling cycles on both $p-V$ and $T-s$ diagrams. In each case, if an engine based on these cycles operates in an internally reversible manner, following one engine cycle, does the entropy of the working fluid change? Does the entropy of the environment change?
Assigned Problems to be handed in:

Exergy (or Availability) and Irreversibility:

1. (a) A block of copper has a mass of 9 kg and is at a temperature of 500K. The $c_p$ for copper is 0.383 kJ/kg-K. If the surroundings are at 27˚C, determine the exergy (or available work) of the block.
   (b) The copper block is now brought in thermal contact with 5 kg of water at 27˚C. Determine the loss of exergy (i.e., loss of available work) and the increase in the entropy of the universe, where $c_p$ for water = 4.18 kJ/kg-K.

2. A pressure vessel with a volume of 0.8 m³ contains air at 1000 kPa and 150˚C. Due to heat transfer to the surrounding air, which is at 25˚C, the temperature of the air in the tank drops to 25˚C. Determine
   (a) the change in the exergy (i.e., availability) of the air and (b) the irreversibility of the process.

3. (a) A tank of air at 2 bar and 300K has a volume of 3 m³. Heat is transferred to the air from a reservoir at 1000K until the temperature of the air in the tank is 600K. The surrounding atmosphere is at 17˚C and 1 bar. Calculate
   (a) the initial and final exergy (i.e., availability) of the air, in kJ, and
   (b) the maximum useful work (or reversible work $w_{\text{rev}}$) associated with the process, in kJ.
   (c) the irreversibility of the process.

4. Five kilograms of air is contained in a rigid storage vessel at an initial pressure and temperature of 200 kPa and 550˚C, respectively. A paddle wheel inserted through the side of the vessel is used to agitate the air. The paddle wheel is turned until a total of 70 kJ of work has been done on the air. During the process the temperature of the air is maintained constant by transferring heat from the air to a thermal-energy reservoir whose temperature is 400˚C. Determine the irreversibility associated with this process when
   (a) the air is considered to be the system,
   (b) the reservoir is considered to be the system, and
   (c) the combination of the air plus the reservoir is considered to be the system.
   Assume $T_o = 298K$ and $P_o = 100$ kPa.
5. **Open System Exergy (Availability)**

An adiabatic compressor operates with air initially at 1.0 bar, 300 K, and 70 m/s. The exit conditions are 5.0 bar, 540 K, and 150 m/s. Determine

a) the actual work input,

b) the reversible (minimum) work required for the same end states, and
c) the irreversibility of the actual process, all answers in kJ/kg

Assume that \( c_p \) is constant at 1.01 kJ/kg-K and that the atmosphere is at 1 bar and 17°C.

Answers: a) 251.2 kJ/kg; b) 212.8 kJ/kg; c) 38.4 kJ/kg.

**Additional problems to try (not to be handed in):**

6. Fifty kJ of heat is to be transferred from a thermal-energy reservoir at a temperature of 550K to a heat engine that produces 10 kJ of work while rejecting heat to (a) a thermal-energy reservoir at 400K and (b) the environment at 298K. For each case, determine the thermal efficiency of the engine and compare this result to the maximum theoretical thermal efficiency. Calculate the irreversibility and discuss its significance.

7. A well-insulated air storage tank initially contains 0.03 kg of air at 320K and 130 kPa. The tank is connected to a valve in order to charge the tank. The valve is opened, allowing supply air at 2 MPa and 680K to enter the tank. When the pressure of the air in the tank has reached 500 kPa, the valve is closed. Determine the irreversibility associated with this process. Assume \( T_0 \) is 25°C.