1. Answer the following questions. No Partial Credit!

1.1 Water at 10 bars and 90°C has an enthalpy (kJ/kg) of approximately

\[ h = h_e + u (p - p_{sat,T}) = 377.9 \quad + \quad 1 \times 10^{-5} (10 - 0.1) \times 100 \quad = \quad 377.9 \text{ kJ/kg} \]

1.2 A steady stream of air is expanded adiabatically in a turbine to a lower pressure. How would the temperature of the exit air for an irreversible turbine compare with that of a reversible turbine for the same inlet state and exit pressure:

\[ \Delta S = S_f - S_i = -R \ln \frac{P_f}{P_i} \Rightarrow S_f > S_i \]

1.3 A steady flow of air in a constant diameter pipe experiences a decrease in temperature from 500 K to 400 K due to heat loss, and a decrease in pressure from 5 bars to 4.5 bars due to friction. The velocity of the nitrogen:

\[ v = \frac{1}{\sqrt{T}} \]

1.4 One kilogram of saturated water vapor in a closed frictionless piston-cylinder device undergoes a quasi-static process at a constant pressure of 5 bars until all of the water is saturated liquid. The heat transfer (kJ/kg) for the process is:

\[ \Delta U = Q - W = Q - P \Delta V = Q = \Delta H = 1 \text{ kg} (\text{water}) \cdot 2-274.87) = -2108.5 \]

1.5 As a steady flow of liquid water passes through a horizontal, frictionless (i.e., internally reversible), adiabatic nozzle,

- water enthalpy is: (a) increased, (b) decreased, (c) constant, (d) unknown
- water velocity is: (a) increased, (b) decreased, (c) constant, (d) unknown
- water entropy is: (a) increased, (b) decreased, (c) constant, (d) unknown
- water temperature is: (a) increased, (b) decreased, (c) constant, (d) unknown
(4) 1.6 A steady flow of water at 1 bar and 100 C is pumped to a pressure of 60 bar at a flow rate of 1 kg/s. The minimum required power input if the pump is adiabatic (kW) is

\[ W_{min} = \dot{m} \left( \frac{P_2}{P_1} - 1 \right) = -1.0 \times 10^{-5} \times 10^0 \times 1 = -6.2 \text{ kW} \]

(a) -0.62  (b) -6.2  (c) -8.0  (d) -62

(3) 1.7 One kilogram of air is expanded isothermally in a closed system so that the volume doubles. The entropy change (kJ/K) for the air is approximately

\[ \Delta S = c_v \ln \frac{P_2}{P_1} + R \ln \frac{V_2}{V_1} = \frac{0.304 \times 2}{28.947} \ln 2 = 0.2 \text{ kJ/K} \]

(a) 0.69  (b) -0.20  (c) 0.0  (d) 0.20  (e) 5.76

(3) 1.8 Can an irreversible process be isentropic?

(a) Yes, if there is adequate heat gain.
(b) Never, because irreversibility generates entropy.
(c) Yes, if there is adequate heat loss.
(d) Can't tell from given information.

(3) 1.9 Propane has a molar mass of 44.09 and a critical pressure and temperature of 42.7 bars, 370K. Under which pressure, temperature conditions below would the ideal gas equation give the most accurate value for propane specific volume?

(a) 40 bar, 370 K,  \( P_k = \frac{P}{P_c} = \frac{3}{4} \rightarrow \)  \( \frac{T_k}{T_c} \sim 0.9, 1.0, 1.0 \)
(b) 4 bar, 370 K,  \( P_k = \frac{P}{P_c} = \frac{1}{10} \rightarrow \)  \( \frac{T_k}{T_c} \sim 0.05, 1.0 \)
(c) 2 bar, 740 K,  \( P_k = \frac{P}{P_c} = \frac{1}{2} \rightarrow \)  \( \frac{T_k}{T_c} \sim 1.0 \)

(3) 1.10 Equal mass flow rates of water at 15 C and 60 C and 1 bar are mixed at the junction where two pipes joined together. The outlet temperature and pressure are approximately

(a) 22.5 C, 1 bar  (b) 37.5 C, 1 bar  (c) 37.5 C, 2 bar

\[ \dot{m}_1 c_p T_1 + \dot{m}_2 c_p T_2 = \dot{m}_3 c_p T_3 \]
\[ \dot{m}_1 = \dot{m}_2 \rightarrow \dot{m}_3 = 2 \dot{m}_1 \]
\[ T_3 \sim \frac{T_1 + T_2}{2} \]
\[ P_3 \sim P_1 \]
(3) 1.11 Heat transfer at a rate of 10 kW is needed for a process operating at 300 K. How would the total rate of entropy generation change with increasing temperature of the heat source?

(a) It increases.
(b) It decreases.
(c) It doesn't change.
(d) Can't tell from given information.

\[ \frac{dS}{dt} = \frac{dS}{dt} + \frac{dS}{dt} = -\frac{Q}{T_H} + \frac{Q}{T_C} > 0 \]

Increase as \( T_H \) increases.

(3) 1.12 How would the rate of entropy production of an irreversible air compressor change with increasing pressure ratio?

(a) It increases.
(b) It decreases.
(c) It doesn't change.
(d) Can't tell from given information.

\[ s = m(s_2 - s_1) \]

Increase with \( P_2 \)

(3) 1.13 A throttle used in a refrigeration system throttles saturated liquid at the condensing pressure to the evaporation pressure. For the same inlet condition, how would the rate of entropy production change with decreasing evaporating temperature?

(a) It increases.
(b) It decreases.
(c) It doesn't change.
(d) Can't tell from given information.

(4) 1.14 A Carnot heat engine operates with thermal reservoirs at 500°C and 30°C, with a heat input of 1000 kJ per cycle. The net work output (kJ per cycle) is

(a) -608  
(b) 392  
(c) 1000  
(d) 608  
(e) 940

\[ T_{rev} = \frac{1 - T_2}{T_1} = 1 - \frac{273 + 50}{273 + 273} = 0.608 \]

\[ W = \frac{Q_1}{T_1} = 0.608 \]

(3) 1.15 The entropy change for the 500°C reservoir of problem 1.14 (kJ/K per cycle) is

(a) -2.000  
(b) 1.294  
(c) -1.294  
(d) 2.000  
(e) 0.0

\[ \Delta S = \frac{Q_1}{T_1} = \frac{-1000}{520 + 273} \]

\[ W_{in} < W_{out} \]

\[ T_1 - T_2 < T_1 - T_{25} \]

\[ T_1 - T_2 < T_1 - T_{25} \]
2. Consider a “novel” piston cylinder heat engine that is modeled as an air standard cycle that undergoes the four internally reversible processes depicted below. At the start of the compression process (state 1), the air is at 300 K and 100 kPa. The maximum temperature after the heat addition process (state 3) is 1500 K. The cylinder volumes at bottom dead center (BDC) and top dead center (TDC) are 0.01 m³ and 0.001 m³, respectively. With this information, do the following:

a) Show the processes that the air undergoes during the cycle on a T-s and a P-V diagram, labeling all four states.

b) Determine the unknown temperatures (K) and pressures (kPa) at states 2, 3, and 4.

c) Determine the compression work (kJ) per cycle.

d) Determine the overall thermal efficiency of the cycle.

You can assume that the air has constant specific heats with \( C_v = 0.72 \, \text{kJ/kg-K} \) and \( C_p = 1.01 \, \text{kJ/kg-K} \) and that \( M = 28.97 \).

\[ W_{12} \quad \text{BDC} \quad Q_{12} \quad \text{TDC} \quad Q_{23} \quad W_{34} \quad Q_{41} \]

1 to 2: reversible, isothermal compression
2 to 3: constant volume heat addition
3 to 4: reversible, adiabatic expansion
4 to 1: constant volume heat rejection

Assumptions:
1. Ideal gas
2. Const. spec. heats
3. \( \Delta KE = \Delta PE = 0 \) for all processes
(b) \[ T_2 = T_1 = 300 \text{ K} \]

\[ \frac{P_2 V_2}{T_2} = mR = \frac{P_1 V_1}{T_1} \Rightarrow P_2 = \frac{T_2}{T_1} \cdot \frac{V_2}{V_1} \cdot P_1 \]

\[ \Rightarrow P_2 = 1000 \text{ kPa} \]

\[ T_3 = 1500 \text{ K} \]

\[ \frac{P_3 V_3}{T_3} = \frac{P_2 V_2}{T_2} \Rightarrow P_3 = P_2 \cdot \frac{V_2}{V_3} \cdot \frac{T_3}{T_2} \]

\[ \boxed{P_3 = 5000 \text{ kPa}} \]

3 \rightarrow 4

\[ \frac{T_4}{T_3} = \left( \frac{V_3}{V_4} \right)^{k-1} \Rightarrow T_4 = 1500 \text{ K} \left( \frac{T_3}{T_0} \right)^{0.4} \Rightarrow T_4 = 597.2 \text{ K} \]

\[ P_4 = P_3 \cdot \frac{V_3}{V_4} \cdot \frac{T_4}{T_3} \Rightarrow P_4 = 199.1 \text{ kPa} \]

\[ W_{12} = \int P \, dV = - \int \frac{mRT}{V} \, dV = P_1 V_1 \ln \frac{V_2}{V_1} \]

\[ W_{12} = 100 \text{ kPa} \times 0.01 \text{ m}^3 \ln \frac{1}{10} \Rightarrow W_{12} = -2.303 \text{ kJ} \]

(d) \[ \eta = \frac{W_{net}}{Q_{in}} = \frac{W_{34} + W_{12}}{Q_{23}} \]

\[ W_{34} = Q_{34} - m(u_4 - u_3) = mC_v(T_3 - T_4) \]

\[ m = \frac{PV}{RT} = \frac{100 \text{ kPa} \times 0.01 \text{ m}^3}{8314 \text{ J/kmol} \cdot \text{K} \times 300 \text{ K}} \Rightarrow m = 0.0116 \text{ kg} \]

\[ W_{34} = 0.0116 \times 0.72 \times (1500 - 597.2) \Rightarrow W_{34} = 7.54 \text{ kJ} \]

\[ Q_{23} = m(u_3 - u_2) + \frac{W_{23}}{\eta} = mC_v(T_3 - T_2) \]

\[ = 0.0116 \times 0.72 \times (1500 - 300) \Rightarrow Q_{23} = 10.02 \text{ kJ} \]

\[ \eta = \frac{7.54 - 2.3}{10.02} \Rightarrow \boxed{\eta = 0.49} \]
3. Consider the vapor compression air conditioner depicted below with the given properties at each state. The air conditioner uses R-134a to cool a space that is at 70 F and rejects heat to an environment that is at 90 F. For a cooling rate of 8000 Btu/h and negligible pressure drops in the heat exchangers, do the following:

a) Show the process that the refrigerant undergoes on a T-s diagram with respect to saturation lines. Be sure to depict the correct condition of the refrigerant for each state.

b) Determine the overall COP.

c) Determine the compressor power requirement (Btu/h).

d) Determine the compressor isentropic efficiency.

e) Determine the total rate of entropy production associated with operating the vapor compression air conditioner (Btu/h-R).

\[ h = 118.5 \text{ Btu/lbm} \]
\[ s = 0.2222 \text{ Btu/lbm-R} \]
saturated liquid @ 140 psia

\[ \text{saturated vapor @ 50 psia} \]

**Assumptions**

1. **SSF**
   \[ \Delta h_e = \Delta h_f = 0 \text{ all components} \]
2. Ideal adiabatic compressor and throttle

\[ \dot{W}_c = \dot{m}(h_1 - h_2) \]

but
\[ \dot{Q}_{evap} = \dot{m}(h_1 - h_4) \Rightarrow \dot{m} = \frac{\dot{Q}_{evap}}{h_1 - h_4} \]

\[ \text{COP} = \frac{h_1 - h_4}{h_2 - h_1} \]

\[ h_1 = 107.4 \text{ Btu/lbm} \]
\[ h_4 = h_3 = 49.4 \text{ Btu/lbm} \]

\[ \Rightarrow \text{COP} = 5.68 \]
\[ m' = \frac{8000 \text{ Btu} \text{h}}{107.4 - 44.4} \quad \Rightarrow \quad m' = 127 \frac{\text{lbm}}{\text{n}} \]

\[ W_c = 127 \frac{\text{lbm}}{\text{n}} (107.4 - 118.5) \frac{\text{Btu}}{\text{lbm}} \quad \Rightarrow \quad W_c = -1409.7 \frac{\text{Btu}}{\text{hr}} \]

(4) \quad \eta_c = \frac{h_{2s} - h_1}{h_2 - h_1}

\[ s_1 = 0.2189 \frac{\text{Btu}}{\text{lbm} \cdot \text{R}} \quad \text{at} \quad P_2 = 140 \text{ psig} \quad \text{and} \quad S_2 = S_1 \]

\[ h_{2s} = 116.5 \]

\[ \eta_c = \frac{116.5 - 107.4}{116.5 - 107.4} \quad \Rightarrow \quad \eta_c = 0.82 \]

(e) \quad \dot{Q}_c = \dot{Q}_c^c - \dot{Q}_c^h + \dot{Q}_c^w

\[ \dot{Q}_c = \dot{W}_{\text{in}} + \dot{Q}_c = 9400.8 \frac{\text{Btu}}{\text{hr}} \]

\[ \dot{Q}_c^c = \frac{9400.8}{550} - \frac{8000}{530} \quad \Rightarrow \quad \dot{Q}_c = 2 \frac{\text{Btu}}{\text{hr} \cdot \text{R}} \]