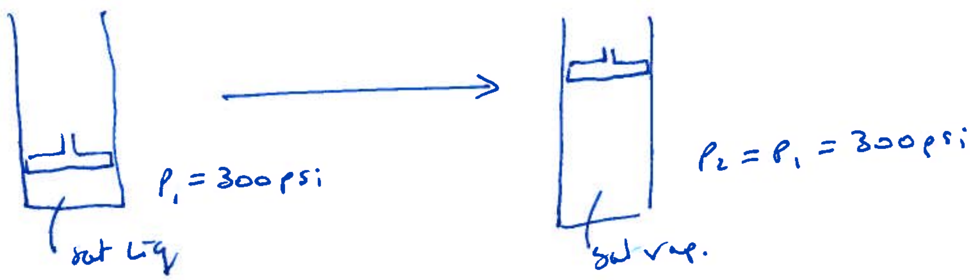
Question I *(16 Marks)*

A piston cylinder assembly initially contains saturated liquid water at 300 psi (lb_f/in^2).

a. What is the temperature (°F) of the water? *(1)*
b. To reach a quality of 1 at constant pressure, how much heat (Btu/lb) must be transferred? Kinetic and potential energy effects can be ignored. *(5)*
c. Sketch the process in b. on a *T-v* diagram and a *p-v* diagram. *(4)*
d. Using the compressibility charts, calculate the specific volume (ft^3/lb) of steam at 400 psi and 500°F. *(6)*



From Table A-3E $v_1 = 0.0189\ ft^3/lb$ $v_2 = 1.544\ ft^3/lb$, $T_1 = T_2 = 417.43°F$

(a) $T = 417.43°F$

(b) $\Delta KE + \Delta PE + \Delta U = Q - W.$

$\Delta U = m\Delta u$ $\therefore \frac{Q}{m} = \Delta u + \frac{W}{m}.$

$W = m\int_1^2 p\,dv$ $\frac{W}{m} = p(v_2 - v_1).$

$\frac{W}{m} = 300\frac{lbf}{in^2} \cdot \frac{144\ in^2}{1\ ft^2}(1.544 - 0.0189)\frac{ft^3}{lb} \cdot \frac{1\ Btu}{778.17\ lbf.ft}.$

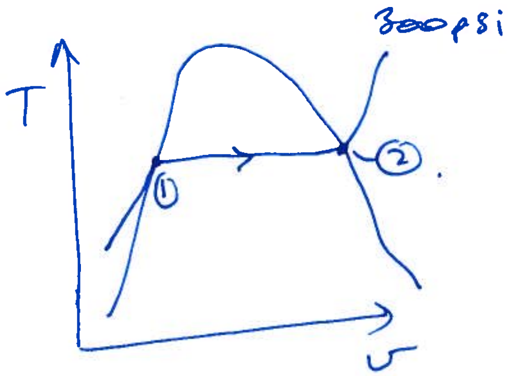
$\frac{W}{m} = 84.666\ Btu/lb.$

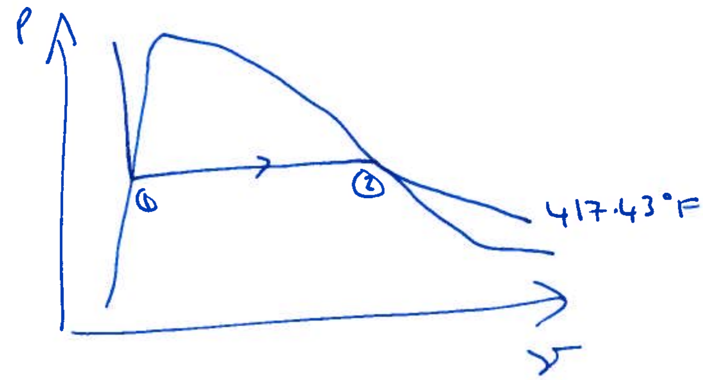
$\therefore \frac{Q}{m} = \Delta u + 84.666\frac{Btu}{lb}$

$u_2 = u_g = 1118.2\ Btu/lb$
$u_1 = u_f = 393.0\ Btu/lb$ } Table A-3E

$\left(\frac{Q}{m}\right) = 1118.2 - 393.0 + 84.666 = 809.9\ \frac{Btu}{lb}$

(c)





(d)

$T = 500°F$ $T_c = 1165\ °R$
$P = 400\,psi$ $P_c = 218\ atm$ } TABLE A-1E

$$P_R = \frac{400\ psi \cdot \frac{1\ atm}{14.696\ psi}}{218\ atm} = 0.12.$$

$$T_R = \frac{(459.67 + 500)°R}{1165\ °R} = 0.824$$

From figure A-1 $Z = 0.92$

$$v = \frac{ZRT}{P} \qquad R = \frac{1545\ \frac{ft.lbf}{lbmol.°R}}{18.02\ lb/lbmol}$$

(Table A-1E)

$$v = \frac{0.92 \cdot \left(\frac{1545}{18.02}\right)\frac{ft.lbf}{lb.°R} \cdot 959.67\ °R.}{400\frac{lbf}{in^2} \cdot \frac{144\,in^2}{1\,ft^2}}$$

$$v = 1.314\ \frac{ft^3}{lb.}$$

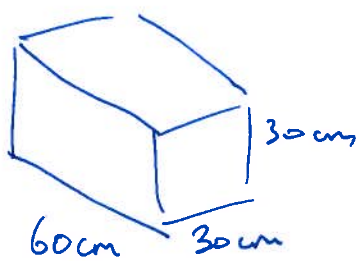
(compare to Table A-4E $v = 1.284\ \frac{ft^3}{lb.}$).

Question Number II *(16 Marks)*

Consider an insulated cooler that has internal dimensions of 60 cm wide, 30 cm deep, and 30 cm high. The walls are 2 cm thick with a thermal conductivity of 0.05 W/(m K). The cooler is left in the sun and gradually warms up so that the outside surface of the cooler is at a temperature of 27°C.

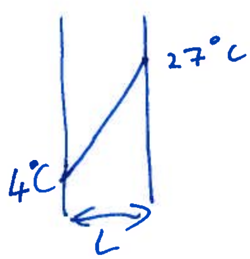
a. When the temperature in the cooler is 4°C, what is the rate of heat transfer (W) between the four sides of the cooler and the environment? Use the internal dimensions to calculate the area. *(5)*
b. If a device (e.g., chiller) could be attached to keep the cooler at 4°C, how much work (kJ) would the system do if the total heat transfer is 100 kJ? (Hint: clearly state what the system is.) *(3)*
c. What is the heat capacity (kJ/(kmol K)) of the air surrounding the cooler (i.e., at 27°C)? *(2)*
d. What force of friction (N) is required to prevent the top from popping off the cooler once the air inside the cooler reaches 27°C? For this question, assume that the cooler contains only air which cannot escape, the top of the cooler has a mass of 500 g and an area of 0.18 m^2, the atmospheric pressure is 0.89 bar, g is 9.81 m/s^2, and the air behaves like an ideal gas. *(6)*

(a).



$$\text{Area} = \left[(0.6 \times 0.3 \times 2) + (0.3 \times 0.3 \times 2)\right] m^2$$

$$A = 0.54\ m^2.$$



$$Q = -K \cdot A \cdot (T_{in} - T_{out}).$$

$$= -0.05 \frac{W}{mK} \cdot 0.54\ m^2 \, (4 - 27)\ K.$$

$$= 31.05\ W$$

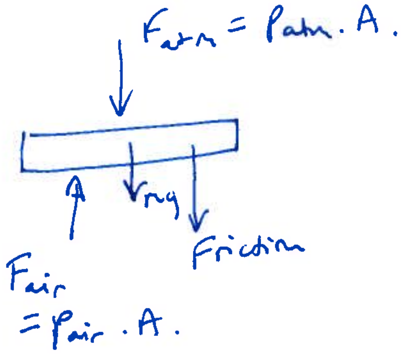
(b) Cooler is the system. Cooler at const. temp. so $\Delta U = 0$. Also $\Delta KE = \Delta PE = 0$.

so $Q = W = -100\,kW$ ie work is added to the cooler, heat is removed.

(c) Table A-20 $T = 300\,K$ $C_p = 1.005 \frac{kJ}{kg K} \times 28.97 \frac{kg}{kmol}$.

$$C_p = 29.11\ kJ/(kmol\,K).$$

(a) Force balance on lid:



$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}.$$

$$\frac{P_2}{P_1} = \frac{T_2}{T_1} \quad \therefore P_2 = P_1 \left(\frac{T_2}{T_1}\right).$$

assuming $P_1 = P_{atm} = 0.89$ bar

$$P_2 = 0.89 \text{ bar} \cdot \frac{300\text{K}}{277\text{K}} = 0.964 \text{ bar}.$$

$$F_{friction} = F_{air} - F_{atm} - mg$$

$$= A\left(P_{air} - P_{atm}\right) - mg.$$

$$= 0.18\,m^2 \left(0.964 - 0.89\right) \text{bar} \cdot \frac{10^5\,N/m^2}{1 \text{ bar}} - 0.5\,\text{kg} \cdot 9.81\,\frac{m}{s^2}$$

$$= 1327 \text{ N}.$$

Question Number III (*18 marks*)

A piston-cylinder assembly contains carbon dioxide (CO_2). The CO_2 undergoes a power cycle consisting of three processes in series:

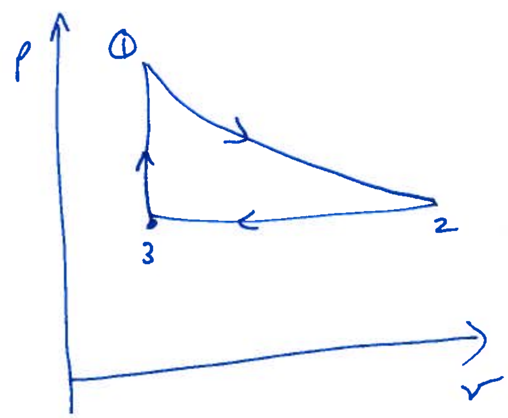
Process 1-2: Polytropic expansion with $n = 1.6$ from $p_1 = 0.5$ MPa to $p_2 = 0.35$ MPa, $V_1 = 0.1$ m^3

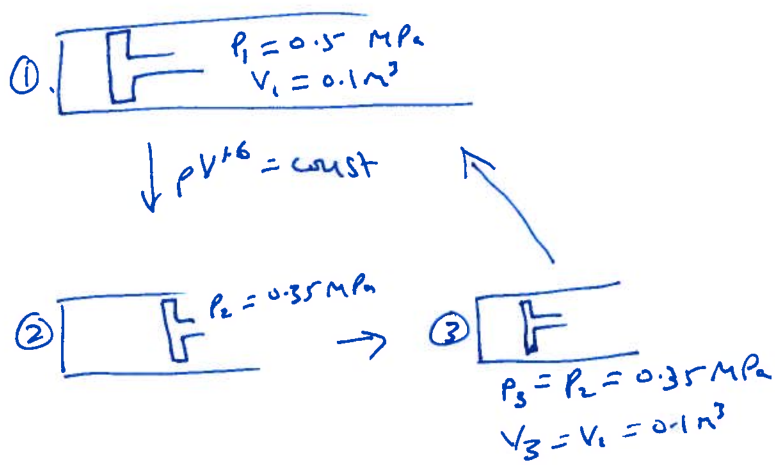
Process 2-3: Isobaric compression to V_1.

Process 3-1: Constant volume heating.

a. Sketch the processes on a *p-V* diagram. *(4)*
b. Calculate W_{12} (kJ). *(5)*
c. Calculate Q_{cycle} (kJ). *(4)*
d. If the pressure at state 1 was measured with a pressure gauge that had divisions of 10 kPa, what is the uncertainty in this pressure? *(1)*
e. The temperature is calculated at state 1 using the ideal gas law; $v = 10$ L/mol ± 0.1 L/mol. What are the temperature (°C) and its uncertainty? *(4)*

(a)





(b)

$$W_{12} = \frac{P_2 V_2 - P_1 V_1}{1-n}$$

$$P_2 V_2^{1.6} = P_1 V_1^{1.6}$$

$$V_2 = V_1 \cdot \left(\frac{P_1}{P_2}\right)^{\left(\frac{1}{1.6}\right)} = 0.1\,m^3 \left(\frac{0.5}{0.35}\right)^{\left(\frac{1}{1.6}\right)}$$

$$V_2 = 0.125\,m^3$$

$$W_{12} = \frac{0.35 \cdot 10^6 \frac{N}{m^2} \cdot 0.125\,m^3 - 0.5 \cdot 10^6 \frac{N}{m^2} \cdot 0.1\,m^3}{1 - 1.6}$$

$$W_{12} = 10417\,J = \underline{10.42\,kJ.}$$

(c)

$$Q_{cy.} = W_{cy} = W_{12} + W_{23} + W_{31}^{\nearrow 0}$$

$$W_{23} = p(V_3 - V_2).$$

$$= 0.35 \cdot 10^6 \frac{N}{m^2} \cdot (0.1\,m^3 - 0.125\,m^3)$$

$$W_{23} = -8750\,J.$$

$$Q_{cy} = (10417 - 8750) = 1667\,J$$

$$= \underline{1.67\,kJ.}$$

(d) Uncertainty $= \pm$ half increment.

$= \pm 5 \text{ kPa}$.

(e) $T = \frac{p\bar{v}}{\bar{R}} = \frac{0.5 \cdot 10^6 \frac{N}{m^2} \cdot 10 \frac{m^3}{kmol}}{8.314 \frac{kJ}{kmol\,K} \cdot \frac{1000\,J}{1\,kJ}}$

$T = 601.4\,K$.

$$\left(\frac{W_T}{T}\right)^2 = \left(\frac{W_p}{p}\right)^2 + \left(\frac{W_{\bar{v}}}{\bar{v}}\right)^2$$

$$\left(\frac{W_T}{601\,K}\right)^2 = \left(\frac{5\,kPa}{500\,kPa}\right)^2 + \left(\frac{0.1\,m^3/kmol}{10\,m^3/kmol}\right)^2$$

$W_T = \pm\left(601\sqrt{0.0002}\right) K$

$= \pm 8.5\,K \equiv \pm 8.5\,°C$.

$T = (601.4 - 273.15) \pm 8.5\,°C$.

$T = 328 \pm 8.5\,°C$.