Steady Flow Energy Equation
Open, steady flow thermodynamic system - a region in space

\[ Q = \dot{Q}E + W \]  
First Law

\[ W_{\text{flow in}} = \int p \, dV = p_1 V_1 \text{initial} - V_1 \text{final} = p_1 V_1 = m p_1 v_1 \]

\[ W_{\text{flow out}} = m p_2 v_2 \]

\[ W = W_{\text{shaft}} + W_{\text{flow in}} + W_{\text{flow out}} = W_{\text{shaft}} + m p_1 v_1 - m p_2 v_2 \]

\[ E = U(T) + KE + \Delta E = U(T) + \frac{V^2}{2} + \frac{\Delta h}{g} \]

\[ Q = m(u_1 + p_1 v_1 + \frac{V^2}{2} + \frac{\Delta h}{g}) - m(u_2 + p_2 v_2 + \frac{V^2}{2} + \frac{\Delta h}{g}) + W_{\text{shaft}} \]

\[ Q = m \times \Delta(u + pv + \frac{V^2}{2} + \frac{\Delta h}{g}) + W_{\text{shaft}} \]

\[ KE_{\text{ENGLISH}} = \frac{\text{ft}/\text{sec}^2 \times \text{lb}}{2 \times 32.2} = \frac{\text{ft}}{\text{lb}} \quad KE_{\text{METRIC}} = \frac{\text{m}^2/\text{sec}^2 \times \text{kJ}}{2 \times 1000 \text{kJ/kg}} = \frac{\text{kJ}}{\text{kg}} \]
Steady Flow Processes Devices

\[ Q = m\Delta(h + \frac{V^2}{2} + \phi gh) + W_{\text{shaft}} \]  
Steady Flow Energy Equation

Turbine, Compressor, Pump
\[ \Delta \text{Velocity}, \Delta \text{Elevation}, Q = 0 \]
\[ W = \nabla \phi H = m\Delta h \]
\[ W = m(h_{\text{in}} - h_{\text{out}}) \]

Boiler, Condenser, Heat Exchanger
\[ \nabla \phi \text{Velocity} \cong 0, \ nabla \phi \text{Elevation} \cong 0, \ \text{Work} = 0 \]
\[ Q = \nabla \phi H = m\nabla \phi h \]
\[ Q = m(h_{\text{in}} - h_{\text{out}}) \]

Diffuser, Nozzle
\[ \nabla \phi \text{Elevation} \cong 0, Q = 0, W = 0 \]
\[ h_1 + \frac{V_1^2}{2} = h_2 + \frac{V_2^2}{2} \]

Valve - throttling process
\[ \nabla \phi \text{Velocity} = 0, \ nabla \phi \text{Elevation} = 0, Q = 0, W = 0 \]
\[ \nabla \phi H = 0 \]
\[ H_{\text{in}} = H_{\text{out}} \]
\[ h_{\text{in}} = h_{\text{out}} \]
What range of 850 kPa steam quality can be measured with this device?

open thermodynamic system
Steady Flow Energy Equation

\[ Q = \varphi h + \frac{V^2}{2g} + \frac{1}{2} gh + W_{\text{shaft}} \]

\( \varphi KE = 0, \quad \varphi PE = 0, \quad W = 0, \quad Q = 0 \)

\( h_1 = h_2 (T_2, P_{\text{barometer}}) \)

\( h_2 @ \) maximum measurable quality = \( h_g @ (P_{\text{barometer}} = 100 \text{ kPa}) \)

\( h_2 @ \) maximum measurable quality = 2505.6 kJ/kg

@ 850 kPa

\( h_f = 731.95 \text{ kJ/kg} \)

\( h_{fg} = 2038.8 \text{ kJ/kg} \)

\[ x = \frac{h_2 - h_{1f}}{h_{1fg}} = \frac{2505.6 \text{ kJ/kg} - 731.95 \text{ kJ/kg}}{2038.8 \text{ kJ/kg}} \]

\[ x = .87, \quad 87\% \text{ to 100\% quality can be measured} \]
500 kg/sec of 60\(^\circ\)C water is mixed with 200 kg/sec 60\(^\circ\)C saturated steam in a tank at a pressure of 15kPa. What are the exit conditions?

open thermodynamic system
Mass Balance \( m_c = m_a + m_b \)
\( m_c = 500 \text{ kg/sec} + 200 \text{ kg/sec} \)
Steady Flow Energy Equation
\[ Q = mA(h + \frac{V^2}{2g} + \int gh) + \text{W}_{\text{shaft}} \]
\( Q = 0, \quad W = 0, \quad \Delta KE = 0, \quad \Delta PE = 0, \)
\( m \times h = \text{constant} \)
\( m_a h_a + m_b h_b = m_c h_c \)
\( h_a = h_f @ 60\(^\circ\)C = 251.18 \text{ kJ/kg} \)
\( h_b = h_v @ 60\(^\circ\)C = 2608.8 \text{ kJ/kg} \)
500 kg \times 251.18 \text{ kJ/kg} + 200 kg \times 2608.8 \text{ kJ/kg} = 700 kg \times h_c
\( h_c = 924.79 \text{ kJ/kg} \)
at 15 kPa \quad h_f = 225.94 \text{ kJ/kg}, \quad h_{fg} = 2373.3 \text{ kJ/kg}
\[ x = \frac{h - h_f}{h_{fg}} = \frac{924.79 - 225.94}{2372.3} = .29, \quad 29 \% \text{quality} \]
\[ T = T_{\text{saturation}} @ 15 \text{ kPa} = 53.97\(^\circ\)C \]
An adiabatic air compressor is to be powered by a direct coupled adiabatic steam turbine that is also driving a generator. Steam enters the turbine at 12.5 MPa and 500 C at a rate of 25 kg/sec and exits at 10 kPa and a quality of .92. Air enters the compressor at 98 kpa and 295 K at a rate of 10 kg/sec and exits at 1 MPa. Determine the net power delivered to the generator by the turbine.
An adiabatic air compressor is to be powered by a direct coupled adiabatic steam turbine that is also driving a generator. Steam enters the turbine at 12.5 MPa and 500 C at a rate of 25 kg/sec and exits at 10 kPa and a quality of .92. Air enters the compressor at 98 kpa and 295 K at a rate of 10 kg/sec and exits at 1 MPa and 620 K. Determine the net power delivered to the generator by the turbine.

\[ h_{c1} = \text{airtable}@(T = 295) = 295.17 \text{ kJ/kg} \quad \text{Table A - 17} \]
\[ h_{c2} = \text{airtable}@(T = 620) = 628.07 \text{ kJ/kg} \]
\[ h_{t1} = \text{superheat}@(T = 500, p = 12.5 \text{ Mpa}) = 3343.6 \text{ kJ/kg} \]
\[ h_{t2} = h_f @ 10kPa + xh_{fg} @ 10 \text{ kPa} \]
\[ h_{t2} = 191.81 + .92 \times 2392.1 = 2392.5 \text{ kJ/kg} \]

\[
W_{net} = W_{turbine} - W_{compressor} = m_t \left( h_{t1} - h_{t2} \right) - m_c \left( h_{c1} - h_{c2} \right)
\]

\[
W_{net} = 25 \frac{\text{kg}}{\text{sec}} \left( 3343.6 - 2392.5 \right) - 10 \frac{\text{kg}}{\text{sec}} \left( 628.07 - 295.17 \right)
\]

\[
W_{net} = +27,106.5 \text{ kJ/sec}
\]
Steam at 3Mpa and 400 C enters an adiabatic nozzle steadily with a velocity of 40 m/sec and leaves at 2.5 MPa and 300 m/sec. Determine (a) the exit temperature and (b) the ratio of inlet to exit area.
Steam at 3Mpa and 400 C enters an adiabatic nozzle steadily with a velocity of 40 m/sec and leaves at 2.5 MPa and 300 m/sec. Determine (a) the exit temperature and (b) the ratio of inlet to exit area.

Open thermodynamic system - a region in space

\[ h_1 \text{ & } v_1 = \text{superheat } @ \ (T = 400., P = 3. \text{Mpa}) \]
\[ h_1 = 3231.7 \text{ kJ/kg} \]
\[ v_1 = .09938 \text{ m}^3/\text{kg} \]

\[ h_1 + \frac{V_1^2}{2} = h_2 + \frac{V_2^2}{2} \quad \text{steady flow energy equation} \]
\[ h_2 = h_1 + \left( \frac{V_1^2}{2} - \frac{V_2^2}{2} \right) \]
\[ h_2 = 3231.71.9 \text{ kJ/kgm} + \left( \frac{40^2}{2} - \frac{300^2}{2} \right) \text{m}^2\text{sec}^{-2} \left( \frac{1 \text{kJ/kg}}{1000 \text{m}^2/\text{sec}^2} \right) \]
\[ h_2 = 3231.71 - 44.2 = 3187.5 \text{ kJ/kg} \]

\[ a) \quad T_2 @ (h = 3187.5, p = 2.5) \]
\[ T_2 = 376.5 \text{ C}, \quad v_2 @ (h = 3187.5, p = 2.5) \]
\[ v_2 = .11626 \]

\[ b) \quad m = \dot{\text{A}} \dot{V} \]
\[ \frac{A_1 \dot{V}_1}{v_1} = \frac{A_1 \dot{V}_2}{v_2} \]
\[ 3 A_1 \frac{40}{.09938} = 2.5 A_2 \frac{300}{.11626} \]
\[ A_2 = \frac{13.951}{74.535} = .1872 \]

\[ 4.65 \]
(a) Flow of steam into an evacuated tank

\[ P_i = 1 \text{ MPa} \]
\[ T_i = 300^\circ\text{C} \]
\[ m_1 = 0 \]
\[ P_2 = 1 \text{ MPa} \]
\[ T_2 = ? \]

(b) The closed-system equivalence

\[ P_2 = 1 \text{ MPa} \]
system consists of initial mass in the tank plus all the mass that will flow in, \( m_f = m_i + m_1 \)

\[
Q = \Delta E + W_{\text{flow}} + W_{\text{shaft}}
\]

\[
Q = E_f - E_i + W_{\text{flow}} + W_{\text{shaft}}
\]

\[
E_i = m_i u_i + (m_f - m_i) u_1
\]

\[
E_f = m_f u_f
\]

\[
W_{\text{flow}} = \int p \, dV
\]

\[
W_{\text{flow}} = m_1 p_1 \int dv = (m_f - m_i) p_1 (v_{\text{end}} - v_1)
\]

\[
W_{\text{flow}} = -(m_f - m_i) p_1 v_1
\]

\[
Q = m_f u_f - m_i u_i - (m_f - m_i) (u_1 + p_1 v_1) + W_{\text{shaft}}
\]

\[
\text{For:}
\]

\[
m_i = 0, \text{ a vacuum}
\]

\[
Q = 0
\]

\[
W_{\text{shaft}} = 0
\]

\[
u_f = h_1
\]

\[
c_v (T_f - T_o) = c_p (T_i - T_o)
\]

\[
c_p = \left( \frac{T_f - T_o}{T_i - T_o} \right)
\]

\( T_o \) is arbitrary, \( T_o = 0 \)

\( T_f = k T_1 \)
A 200 cubic ft tank contains 2 lbm carbon dioxide and .4 lbm helium at an initial temperature of 70 F. 3 lbm of air at 14.7 and 70 F are admitted to the tank.

What is the final temperature of the tank?

\[
Q = m_f u_f - m_i u_i - (m_f - m_i)(h_i)
\]
\[
m_f u_f = (3 \times .174 + 2 \times .1565 + .4 \times .745)T_f = 1.125T_f
\]
\[
m_i u_i = (2 \times .1565 + .4 \times .745) \times (460 + 70) = 323.83
\]
\[
(m_i - m_f) \times h_i = 3 \times .24 \times (460 + 70) = 381.6
\]
\[
Q = 1.125T_f - 323.83 - 381.6 = 0
\]
\[
T_f = 627^\circ R
\]
\[
T_f = 167^\circ F
\]
There initially are 2 kg of liquid water and 8 kg of vapor in an insulated vertical piston cylinder device. A constant pressure of 300 kPa is maintained by the piston weight. Steam at .5 Mpa and 350 C are added until the contents of the cylinder are all vapor. What is the final temperature in the cylinder and the mass of steam admitted?
the system is the mass finally in the cylinder, $m_f$

$$E_i = m_i u_i + (m_f - m_i) u_o$$

$$E_f = m_f u_f$$

$$W_{\text{flow}} = \int p \, dv = p_o (V_{oi} - V_{of})$$

$$W_{\text{flow}} = (m_f - m_i) p_o v_o$$

$$W_{\text{displace nt}} = \int p \, dv = p_f (V_f - V_i)$$

$$W_{\text{displace nt}} = p_f V_f - p_i V_i$$

$$W_{\text{displace nt}} = m_f p_f V_f - m_i p_i v_i$$

$$0 = E_f - E_i - W_{\text{flow}} + W_{\text{displace nt}} \quad \text{First Law}$$

$$0 = m_f u_f - m_i u_i - (m_f - m_i) u_o - (m_f - m_i) p_o v_o + m_f p_f v_f - m_i p_i v_i$$

$$0 = (m_f u_f + m_f p_f v_f) - (m_i u_i + m_i p_i v_i) - (m_f - m_i) u_o - (m_f - m_i) p_o v_o$$

$$0 = m_f h_f - m_i h_i - m_f h_o + m_i h_o$$

$$0 = m_f (h_f - h_o) + m_i (h_o - h_i)$$

$$m_f = m_i \frac{(h_o - h_i)}{(h_o - h_f)}$$

$$m_f = 10 \text{kg} \frac{(3168.1 \text{ kJ/kg} - 2292.23 \text{ kJ/kg})}{(3168.1 \text{ kJ/kg} - 2724.9 \text{ kJ/kg})} = 19.76 \text{ kg}$$

$$m_f - m_i = 19.76 \text{ kg} - 10 \text{ kg} = 9.76 \text{ kg}$$

@ 300 kPa

$$h_{\text{final}} = h_g = 2724.9 \text{ kJ/kg}$$

$$h_i = h_f + x \times h_{fg}$$

$$h_i = 561.43 + .8 \times 2163.5$$

$$h_i = 2292.23 \text{ kJ/kg}$$

@ .5 MPa, 350°C

$$h_o = 3168.1 \text{ kJ/kg}$$
First Law
Energy defined, Energy conserved
\[ E_{\text{in}} - E_{\text{out}} = \Delta E \]
E is all forms, Q, W, PE, KE, U
\[ (Q_{\text{in}} - Q_{\text{out}}) + (W_{\text{in}} - W_{\text{out}}) + (E_{\text{mass in}} - E_{\text{mass out}}) = U_2 - U_1 \]

CLOSED SYSTEM a contained quantity of mass
\[ (Q_{\text{in}} - Q_{\text{out}}) + (W_{\text{in}} - W_{\text{out}}) + (E_{\text{mass in}} - E_{\text{mass out}}) = U_2 - U_1 \]
\[ Q = U_2 - U_1 + W \]
\[ Q = \Delta E + W \]

OPEN SYSTEM a region in space
\[ (Q_{\text{in}} - Q_{\text{out}}) + (W_{\text{in}} - W_{\text{out}}) + (E_{\text{mass in}} - E_{\text{mass out}}) = U_2 - U_1 \]
\[ W = W_{\text{shaft}} + W_{\text{flow}} \]
\[ (Q_{\text{in}} - Q_{\text{out}}) + (W_{\text{in}} - W_{\text{out}}) = (E_{\text{mass out}} - E_{\text{mass in}}) \]
for \( W_{\text{net}} = 0 \), \[ Q = H_2 - H_1 = m(h_2 - h_1) \]
for \( Q_{\text{net}} = 0 \), \[ W = H_2 - H_1 = m(h_2 - h_1) \]
UNSTEADY SYSTEM

quantity of mass,  \( m_1 \) or \( m_2 \)

\[
(Q_{\text{in}} - Q_{\text{out}}) + (W_{\text{in}} - W_{\text{out}}) + (E_{\text{mass in}} - E_{\text{mass out}}) = U_2 - U_1
\]

\[
(Q_{\text{in}} - Q_{\text{out}}) + (W_{\text{bin}} - W_{\text{bout}}) + (W_{\text{flow in}} - W_{\text{flow out}}) = U_2 - U_1
\]

\[
(Q_{\text{in}} - Q_{\text{out}}) + (W_{\text{bin}} - W_{\text{bout}}) + (p_{o} V_{o})_{\text{in}} - (p_{o} V_{o})_{\text{out}} = U_2 - U
\]

\[
(Q_{\text{in}} - Q_{\text{out}}) + (W_{\text{bin}} - W_{\text{bout}}) + (m_2 - m_1)(p_{o} V_{o})_{\text{in}} - (m_2 - m_1)(p_{o} V_{o})_{\text{out}} =
\]

\[
m_2 u_2 - m_1 u_1 + (m_2 - m_1)u_{\text{out}} - (m_2 - m_1)u_{\text{in}}
\]

\[
(Q_{\text{in}} - Q_{\text{out}}) + (W_{\text{bin}} - W_{\text{bout}}) + (m_2 - m_1)h_{\text{in}} - (m_2 - m_1)h_{\text{out}} = m_2 u_2 - m_1 u_1
\]

with \( W_{\text{out}}, Q_{\text{in}}, + \)

\[ Q - W + (m_2 - m_1)h = m_2 u_2 - m_1 u_1 \]

UNSTEADY SYSTEM

region in space

\[
(Q_{\text{in}} - Q_{\text{out}}) + (W_{\text{in}} - W_{\text{out}}) + (E_{\text{mass in}} - E_{\text{mass out}}) = U_2 - U_1
\]

\[
(Q_{\text{in}} - Q_{\text{out}}) + (W_{\text{bin}} - W_{\text{bout}}) + (E_{\text{mass in}} - E_{\text{mass out}}) = U_2 - U_1
\]

\[
(Q_{\text{in}} - Q_{\text{out}}) + (W_{\text{bin}} - W_{\text{bout}}) + (m_2 - m_1)h_{\text{in}} - (m_2 - m_1)h_{\text{out}} = m_2 u_2 - m_1 u_1
\]