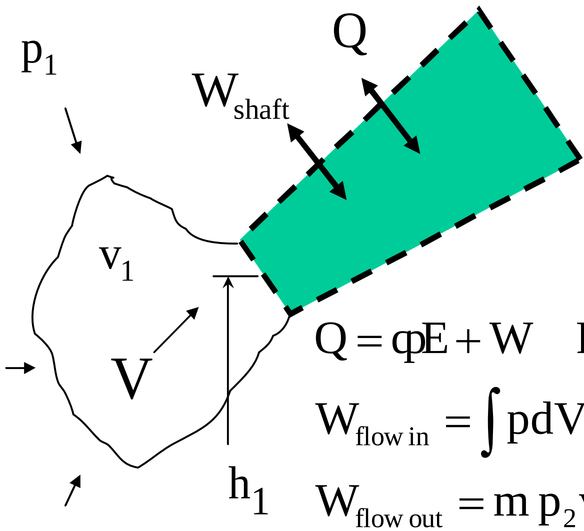
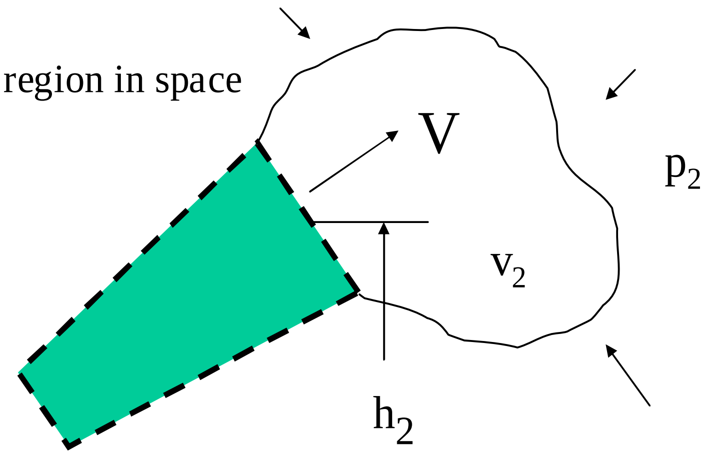
Steady Flow Energy Equation

Open, steady flow thermodynamic system - a region in space





$$Q = \Delta E + W \quad \text{First Law}$$

$$W_{\text{flow in}} = \int p\,dV = p_1\left(V_{1\ \text{initial}} - V_{1\ \text{final}}\right) = p_1 V_1 = m\, p_1 v_1$$

$$W_{\text{flow out}} = m\, p_2 v_2$$

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

$$E = U(T) + KE + PE = U(T) + \frac{V^2}{2} + \text{Ɉ}\, gh$$

$$Q = m(u_1 + p_1 v_1 + \frac{V^2}{2} + \text{Ɉ}\, gh_1) - m(u_2 + p_2 v_2 + \frac{V^2}{2} + \text{Ɉ}\, gh_1) + W_{\text{shaft}}$$

$$Q = m \times \Delta(u + pv + \frac{V^2}{2} + \text{Ɉ}\, gh) + W_{\text{shaft}}$$

$$KE_{\text{ENGLISH}} = \frac{(\text{ft/sec})^2}{2 \times 32.2} = \frac{\text{ft} - \text{lb}}{\text{lb}} \qquad KE_{\text{METRIC}} = \frac{(\text{m/sec})^2}{2 \times 1000 \frac{\text{m}^2/\text{sec}^2}{\text{kJ/kg}}} = \frac{\text{kJ}}{\text{kg}}$$

Steady Flow Processes Devices

$$Q = m\Delta\left(h + \frac{V^2}{2} + ȷ\,gh\right) + W_{shaft}$$ Steady Flow Energy Equation

Turbine, Compressor, Pump

$$\Delta\text{Velocity}, \Delta\text{Elevation}, Q = 0$$

$$W = \varphi H = m\Delta h$$

$$\mathbf{W} = \mathbf{m}\left(\mathbf{h_{in}} - \mathbf{h_{out}}\right)$$

Boiler, Condenser, Heat Exchanger

$$\varphi\text{Velocity} \cong 0, \varphi\text{Elevation} \cong 0, \text{Work} = 0$$

$$Q = \varphi H = m\varphi h$$

$$\mathbf{Q} = \mathbf{m}\left(\mathbf{h_{in}} - \mathbf{h_{out}}\right)$$

Diffuser, Nozzle

$$\varphi\text{Elevation} \cong 0, Q = 0, W = 0$$

$$\mathbf{h_1 + \frac{V_1^2}{2} = h_2 + \frac{V_2^2}{2}}$$

Valve - throttling process

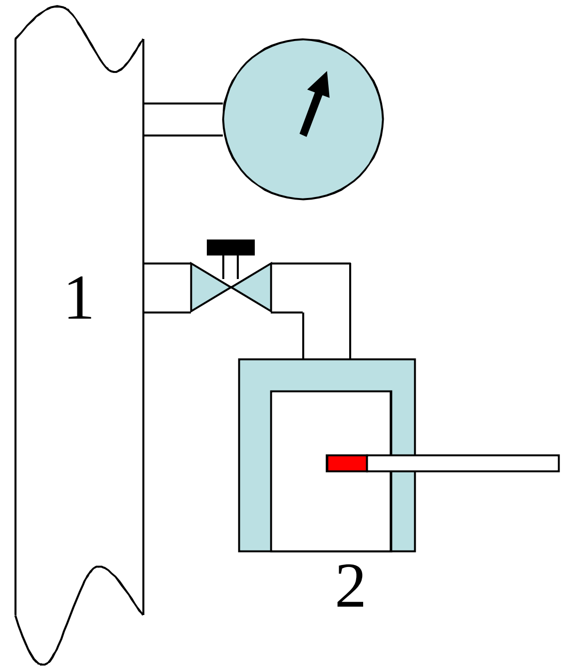
$$\varphi\text{Velocity} = 0, \varphi\text{Elevation} = 0, Q = 0, W = 0$$

$$\varphi H = 0$$

$$H_{in} = H_{out}$$

$$\mathbf{h_{in} = h_{out}}$$

What range of 850 kPa steam quality can be meaaured with this device?



open thermodynamic system

Steady Flow Energy Equation

$$Q = \varphi(h + \frac{V^2}{2g} + \jmath\, gh) + W_{shaft}$$

$$\varphi KE = 0, \quad \varphi PE = 0, \quad W = 0, \quad Q = 0$$

$$h_1 = h_2(T_{2,} P_{barometer})$$

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

$$h_2 @ \text{ maximum measurable quality} = 2505.6\ \text{kJ/kg}$$

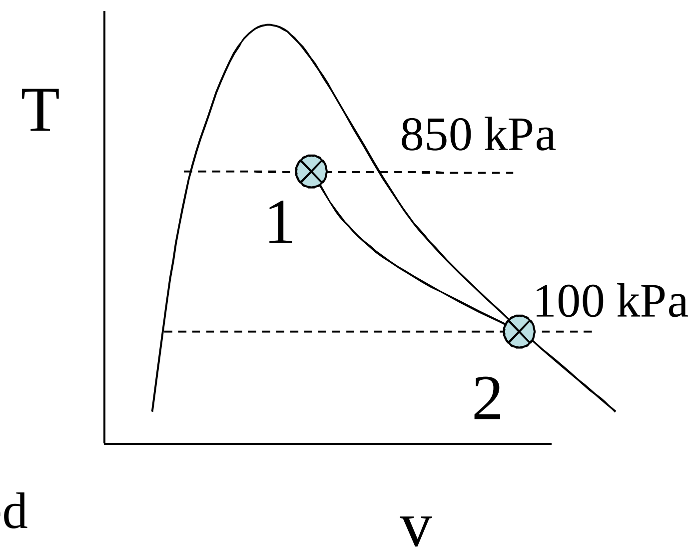
@ 850 kPa

$$h_f = 731.95\ \text{kJ/kg}$$

$$h_{fg} = 2038.8\ \text{kJ/kg}$$

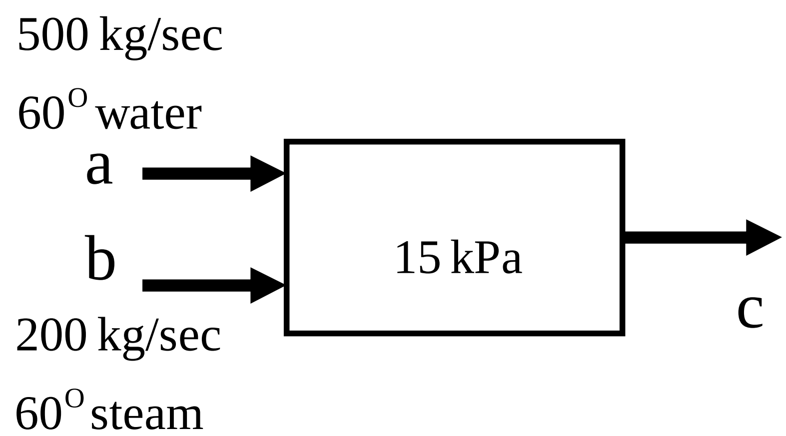
$$x = \frac{h_2 - h_{1f}}{h_{1fg}} = \frac{2505.6\ \text{kJ/kg} - 731.95\ \text{kJ/kg}}{2038.8\ \text{kJ/kg}}$$

$x = .87$, 87% to 100% quality can be measured



500 kg/sec of 60^{O} C water is mixed with 200 kg/sec 60^{O} 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

$$Q = m\Delta(h + \frac{V^2}{2g} + \jmath\, gh) + W_{shaft}$$

$Q = 0, \quad W = 0, \; \Delta KE = 0, \; \Delta PE = 0,$

$m \times h = \text{constant}$

$m_a h_a + m_b h_b = m_c h_c$

$h_a = h_f @ 60^{O} C = 251.18 \text{ kJ/kg}$

$h_b = h_v @ 60^{O} C = 2608.8 \text{ kJ/kg}$

$500 \text{ kg} \times 251.18 \text{ kJ/kg} + 200 \text{ kg} \times 2608.8 \text{ kJ/kg} = 700 \text{ kg} \times h_c$

$h_c = 924.79 \text{ kJ/kg}$

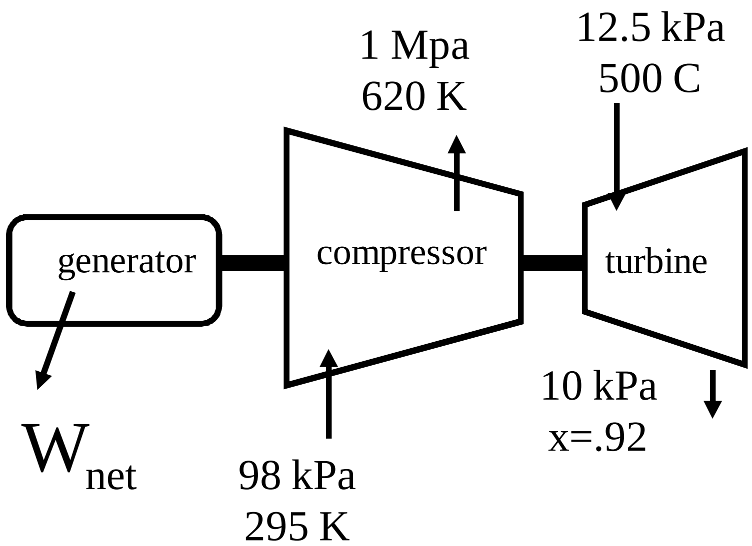
at 15 kPa $\quad h_f = 225.94 \text{ kJ/kg}, \quad h_{fg} = 2373.3 \text{ kJ/kg}$

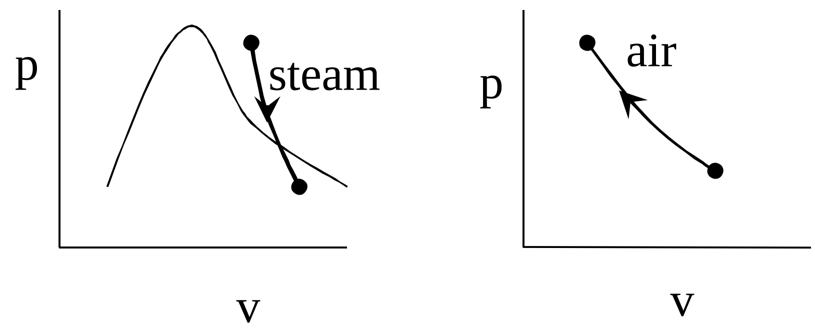
$$x = \frac{h - h_f}{h_{fg}} = \frac{924.79 - 225.94}{2372.3} = .29, \qquad 29\,\%\text{quality}$$

$T = T_{saturation} @ 15 \text{ kPa} = 53.97^{O} C$

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.





$$h_{c1} = \text{airtable}@(T = 295) = 295.17 \text{ kJ/kg} \quad \text{Table A-17}$$

$$h_{c2} = \text{airtable}@(T = 620) = 628.07 \text{ kJ/kg}$$

$$h_{t1} = \text{superheat}@(T = 500, p = 12.5 \text{ Mpa}) = 3343.6 \text{ kJ/kg}$$

$$h_{t2} = h_f@10\text{kPa} + x h_{fg}@10 \text{ kPa}$$

$$h_{t2} = 191.81 + .92 \times 2392.1 = 2392.5 \text{kJ/kg}$$

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

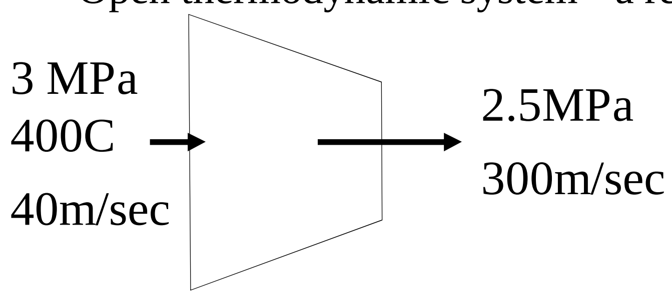
$$W_{net} = 25\frac{\text{kg}}{\text{sec}}\left(3343.6 - 2392.5\right) - 10\frac{\text{kg}}{\text{sec}}\left(628.07 - 295.17\right)$$

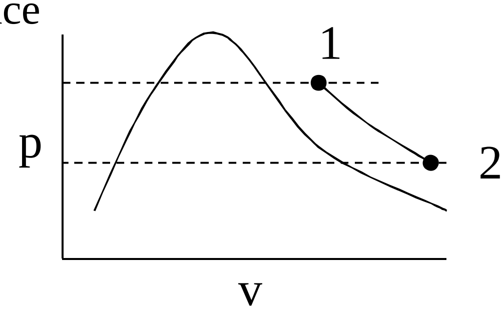
$$W_{net} = +27{,}106.5 \text{ kJ/sec}$$

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 & v_1 = superheat @ (T = 400., P = 3. Mpa)

$h_1 = 3231.7$ kJ/kg

$v_1 = .09938\ m^3/kg$

$$h_1 + \frac{V_1^2}{2} = h_2 + \frac{V_2^2}{2} \quad \text{steady flow energy equation}$$

$$h_2 = h_1 + \left(\frac{V_1^2}{2} - \frac{V_2^2}{2}\right)$$

$$h_2 = 3231.71.9\ \text{kJ/kgm} + \left(\frac{40^2}{2} - \frac{300^2}{2}\right)\frac{m^2}{sec^2}\left(\frac{1\ \text{kJ/kg}}{1000\ m^2/sec^2}\right)$$

$$h_2 = 3231.71 - 44.2 = 3187.5\ \text{kJ/kg}$$

a) T_2 @ (h = 3187.5, p = 2.5)

$T_2 = 376.5$ C,

v_2 @ (h = 3187.5, p = 2.5)

$v_2 = .11626$

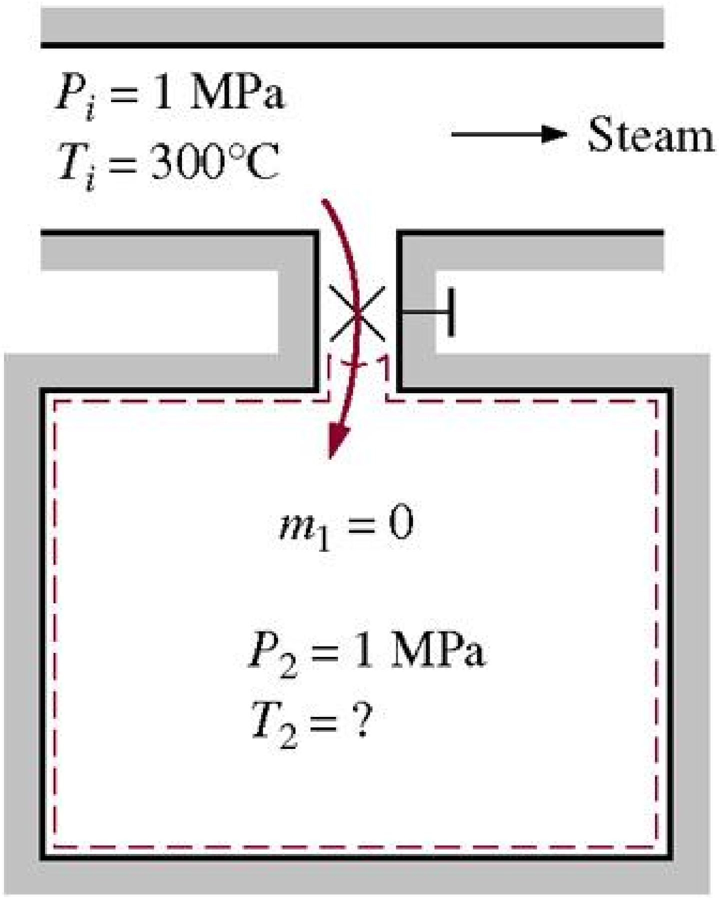
b) $m = ȷ AV$

$$\frac{A_1 V_1}{v_1} = \frac{A_1 V_2}{v_2}$$

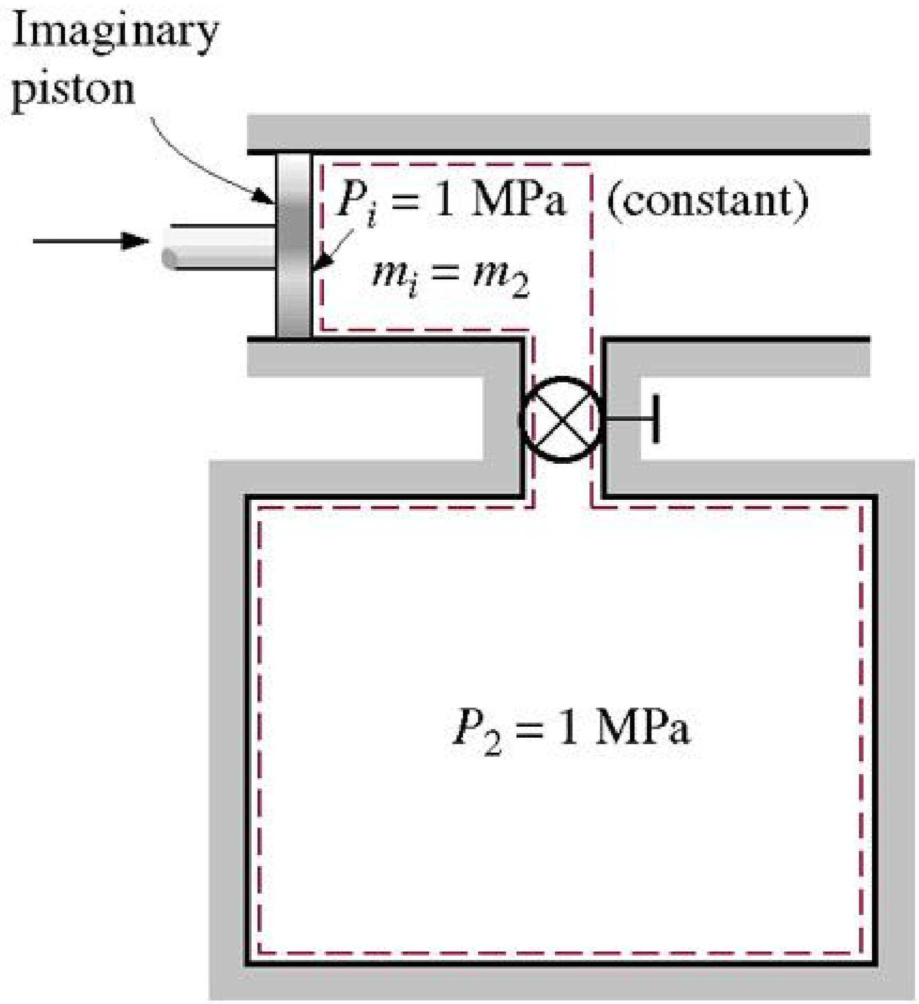
$$\frac{3\, A_1\, 40}{.09938} = \frac{2.5\, A_2\, 300}{.11626}$$

$$\frac{A_2}{A_1} = \frac{13.951}{74.535} = .1872$$

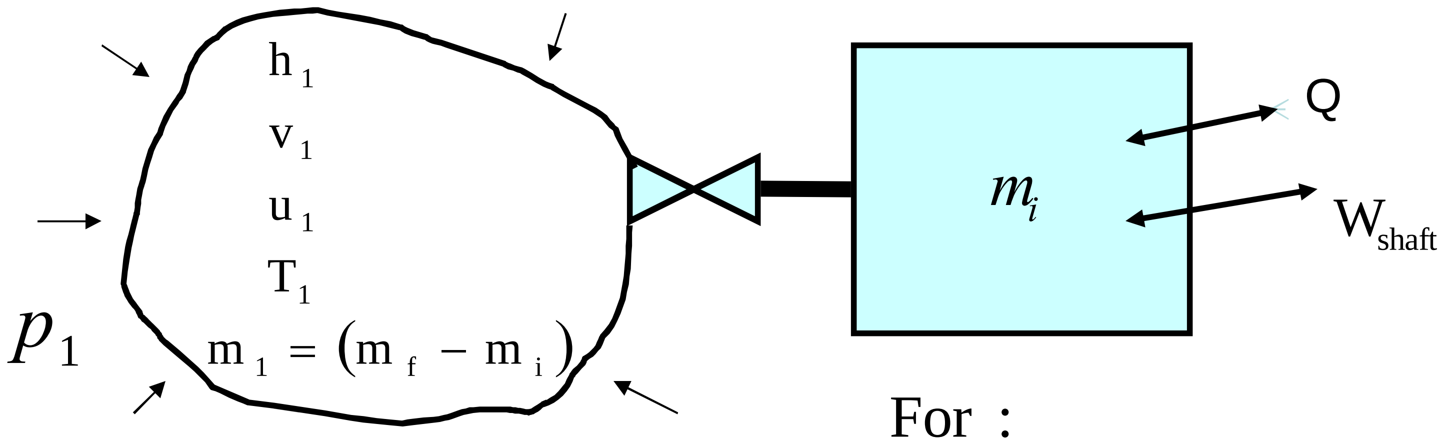
4.65



(*a*) Flow of steam into an evacuated tank



(*b*) The closed-system equivalence



system consists of initial mass in the tank plus all the mass that will flow in, $m_f = m_i + m_1$

$$Q = \varphi E + W_{flow} + W_{shaft}$$

$$Q = E_f - E_i + W_{flow} + W_{shaft}$$

W_{shaft}

$$E_i = m_i u_i + (m_f - m_i) u_1$$

$$E_f = m_f u_f$$

$$W_{flow} = \int p dV$$

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

$$W_{flow} = -(m_f - m_i) p_1 v_1$$

$$Q = m_f u_f - m_i u_i - (m_f - m_i)(u_1 + p_1 v_1) + W_{shaft}$$

$$Q = m_f u_f - m_i u_i - (m_f - m_i) h_1 + W_{shaft}$$

For :

$m_i = 0$, a vacuum

$$Q = 0$$

$$W_{shaft} = 0$$

$$u_f = h_1$$

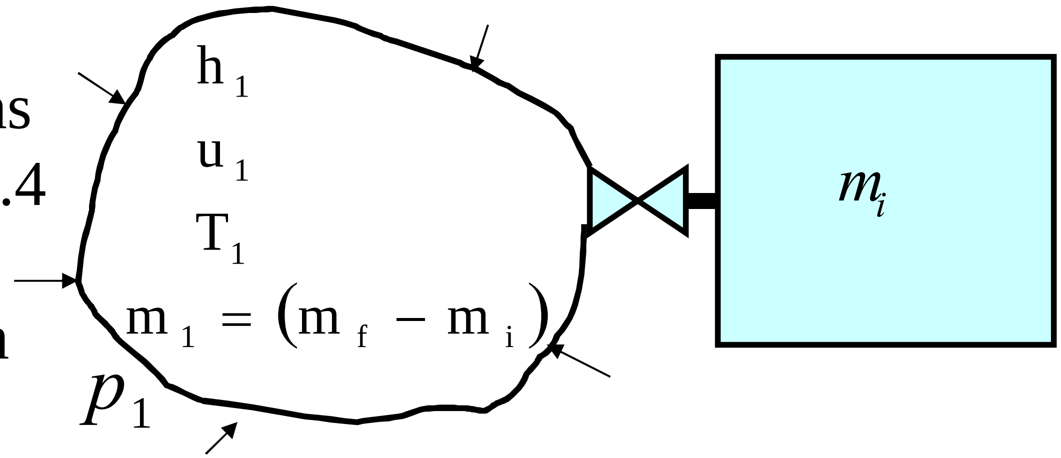
$$c_v (T_f - T_o) = c_p (T_i - T_o)$$

$$\frac{c_p}{c_v} = \left(\frac{T_f - T_o}{T_i - T_o} \right)$$

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?

$$Q = m_f u_f - m_i u_i - (m_f - m_i)(h_i)$$

$$m_f u_f = (3\times.174 + 2\times.1565 + .4\times.745)T_f = 1.125T_f$$

$$m_i u_i = (2\times.1565 + .4\times.745)\times(460+70) = 323.83$$

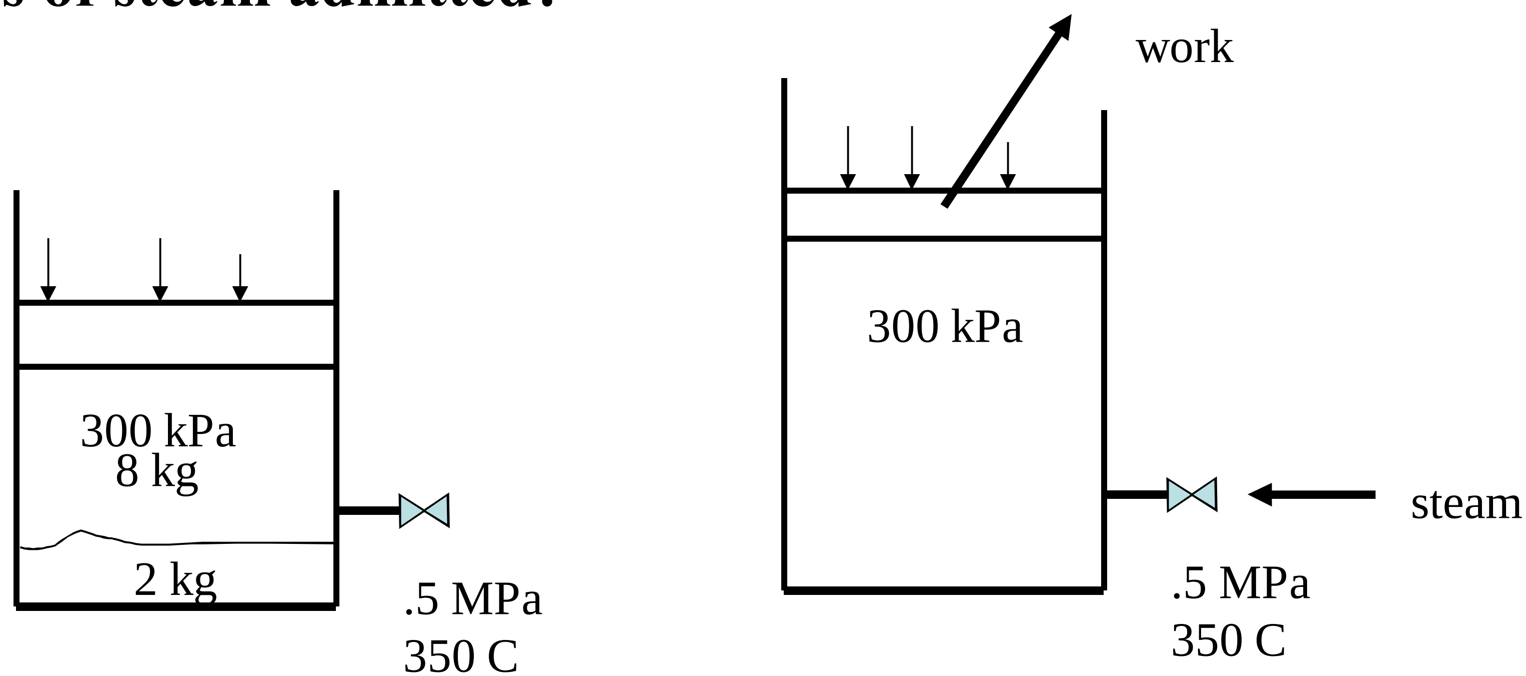
$$(m_i - m_f)\times h_1 = 3\times.24\times(460+70) = 381.6$$

$$Q = 1.125T_f - 323.83 - 381.6 = 0$$

$$T_f = 627^{o}R$$

$$T_f = 167^{o}F$$

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?



4-53

the system is the mass finally in the cylinder, m_f

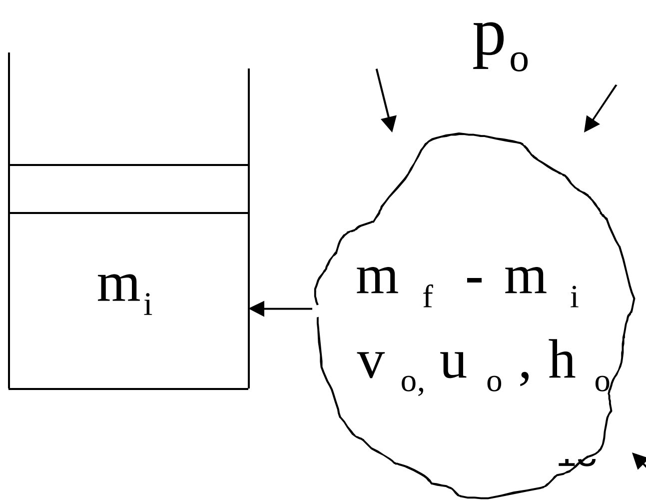
$$E_i = m_i u_i + (m_f - m_i) u_o$$
$$E_f = m_f u_f$$
$$W_{flow} = \int p dv = p_o (V_{oi} - V_{of})$$
$$W_{flow} = (m_f - m_i) p_o v_o$$
$$W_{displacement} = \int p dv = p_f (V_f - V_i)$$
$$W_{displacement} = p_f V_f - p_i V_i$$
$$W_{displacement} = m_f p_f v_f - m_i p_i v_i$$
$$0 = E_f - E_i - W_{flow} + W_{displacement} \quad \text{First Law}$$
$$0 = m_f u_f - m_i u_i - (m_f - m_i) u_o - (m_f - m_i) p_o v_o + m_f p_f v_f - m_i p_i v_i$$
$$0 = (m_f u_f + m_f p_f v_f) - (m_i u_i + m_i p_i v_i) - (m_f - m_i) u_o - (m_f - m_i) p_o v_o$$
$$0 = m_f h_f - m_i h_i - (m_f - m_i) h_o$$
$$0 = m_f h_f - m_i h_i - m_f h_o + m_i h_o$$
$$0 = m_f (h_f - h_o) + m_i (h_o - h_i)$$
$$m_f = m_i \frac{(h_o - h_i)}{(h_o - h_f)}$$
$$m_f = 10\text{kg} \frac{(3168.1 \text{ kJ/kg} - 2292.23 \text{ kJ/kg})}{(3168.1.7 \text{ kJ/kg} - 2724.9 \text{ kJ/kg})} = 19.76 \text{ kg}$$
$$m_f - m_i = 19.76 \text{ kg} - 10 \text{ kg} = 9.76 \text{ kg}$$

@ 300 kPa

$$h_{final} = h_g = 2724.9 \text{ kJ/kg}$$
$$h_i = h_f + x \times h_{fg}$$
$$h_i = 561.43 + .8 \times 2163.5$$
$$h_i = 2292.23 \text{ kJ/kg}$$

@.5 MPa, 350 ^oC

$$h_o = 3168.1 \text{ kJ/kg}$$



First Law

Energy defined , Energy conserved

$$E_{in} - E_{out} = \varphi E$$

E is all forms, Q, W, PE, KE, U

$$\left(Q_{in} - Q_{out}\right) + \left(W_{in} - W_{out}\right) + \left(E_{mass\ in} - E_{mass\ out}\right) = U_2 - U_1$$

CLOSED SYSTEM a contained quantity of mass

$$\left(Q_{in} - Q_{out}\right) + \left(W_{in} - W_{out}\right) + \left(E_{mass\ in} - E_{mass\ out}\right) = U_2 - U_1$$

0

$$\left(Q_{in} - Q_{out}\right) + \left(W_{in} - W_{out}\right) = U_2 - U_1$$

$$Q = U_2 - U_1 + W$$

$$Q = \varphi E + W$$

OPEN SYSTEM a region in space

$$\left(Q_{in} - Q_{out}\right) + \left(W_{in} - W_{out}\right) + \left(E_{mass\ in} - E_{mass\ out}\right) = U_2 - U_1$$

0

$$W = W_{shaft} + W_{flow}$$

$$\left(Q_{in} - Q_{out}\right) + \left(W_{in} - W_{out}\right) = \left(E_{mass\ out} - E_{mass\ in}\right)$$

$$\text{for } W_{net} = 0, \quad Q = H_2 - H_1 = m\left(h_2 - h_1\right)$$

$$\text{for } Q_{net} = 0, \quad W = H_2 - H_1 = m\left(h_2 - h_1\right)$$

UNSTEADY SYSTEM

quantity of mass, $\mathbf{m_1}$ or $\mathbf{m_2}$

$$\left(Q_{in} - Q_{out}\right) + \left(W_{in} - W_{out}\right) + \left(E_{mass\ in} - E_{mass\ out}\right) = U_2 - U_1$$

0

$$\left(Q_{in} - Q_{out}\right) + \left(W_{b\ in} - W_{b\,out}\right) + \left(W_{flow\ in} - W_{flow\ out}\right) = U_2 - U_1$$

$$\left(Q_{in} - Q_{out}\right) + \left(W_{b\,in} - W_{b\,out}\right) + \left(p_o V_o\right)_{in} - \left(p_o V_o\right)_{out} = U_2 - U$$

$$\left(Q_{in} - Q_{out}\right) + \left(W_{b\,in} - W_{b\,out}\right) + \left(m_2 - m_1\right)\left(p_o v_o\right)_{in} - \left(m_2 - m_1\right)\left(p_o v_o\right)_{out} =$$

$$m_2 u_2 - m_1 u_1 + \left(m_2 - m_1\right) u_{out} - \left(m_2 - m_1\right) u_{in}$$

$$\left(Q_{in} - Q_{out}\right) + \left(W_{b\,in} - W_{b\,out}\right) + \left(m_2 - m_1\right) h_{in} - \left(m_2 - m_1\right) h_{out} = m_2 u_2 - m_1 u_1$$

with W_{out}, Q_{in}, +

$$\mathbf{Q - W + \left(m_2 - m_1\right) h = m_2 u_2 - m_1 u_1}$$

UNSTEADY SYSTEM

region in space

$$\left(Q_{in} - Q_{out}\right) + \left(W_{in} - W_{out}\right) + \left(E_{mass\,in} - E_{mass\,out}\right) = U_2 - U_1$$

$$\left(Q_{in} - Q_{out}\right) + \left(W_{b\,in} - W_{b\,out}\right) + \left(E_{mass\,in} - E_{mass\,out}\right) = U_2 - U_1$$

$$\left(Q_{in} - Q_{out}\right) + \left(W_{b\ in} - W_{b\,out}\right) + \left(m_2 - m_1\right) h_{in} - \left(m_2 - m_1\right) h_{out} = m_2 u_2 - m_1 u_1$$