FIRST LAW IN OPEN SYSTEMS

Steady Flow Energy Equation

Open, steady flow thermodynamic system - a region in space

\[ Q = \Delta E + W \]  First Law

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

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

\[ E = u(T) + KE + PE = u(T) + \frac{V^2}{2} + gz \]

\[ Q = m \times (u_2 + p_2 v_2 + \frac{V_2^2}{2} + gz) - m \times (u_1 + p_1 v_1 + \frac{V_1^2}{2} + gz) + W_{\text{shaft}} \]

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

\[ Q = m\Delta(h + \frac{V^2}{2} + gz) + W_{\text{shaft}} \]  \hspace{1cm} (5-36)

the units of all the energy terms must be the same
Steady Flow Processes Devices

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

Turbine, Compressor, Pump

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

Boiler, Condenser, Heat Exchanger

\[ \Delta \text{Velocity} \cong 0, \Delta \text{Elevation} \cong 0, \text{Work} = 0 \]
\[ Q = \Delta H = m\Delta h \]
\[ Q = m(h_{\text{in}} - h_{\text{out}}) \]

Diffuser, Nozzle

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

Valve - throttling process

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

open thermodynamic system
Steady Flow Energy Equation

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

\[
\Delta KE = 0, \quad \Delta PE = 0, \quad W = 0, \quad Q = 0
\]

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

\[
h_2 = h_g@P_{\text{barometer}} = 100. \text{ kPa}
\]

\[
h_2\text{@maximum mesurable quality} = 2506.1 \text{ kJ/kg}
\]

@850 kPa

\[
h_v = 732.22 \text{ kJ/kg}
\]

\[
h_{fg} = 2039.4 \text{ kJ/kg}
\]

\[
x = \frac{h_2 - h_{1f}}{h_{1fg}} = \frac{2506.1 \text{ kJ/kg} - 732.22 \text{ kJ/kg}}{2039.4 \text{ kJ/kg}}
\]

\[x = .87, \quad 87\% \text{ to } 100\% \text{ quality can be measured}\]
500 kg/sec of 60°C water is mixed with 200 kg/sec 60°C saturated steam in a tank at a pressure of 15 kPa. 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
\[
Q = m\Delta h + \frac{V^2}{2g} + W_{\text{shaft}}
\]
\( Q = 0, \quad W = 0, \quad \Delta KE = 0, \quad \Delta PE = 0, \)
\( m_h = \text{constant} \)
\( m_a h_a + m_b h_b = m_c h_c \)
\( h_a = h_{l @ 60^0C} = 251.13 \text{ kJ/kg} \)
\( h_b = h_{v @ 60^0C} = 2373.1 \text{ kJ/kg} \)
500 kg \times 251.13 \text{ kJ/kg} + 200 \text{ kg} \times 2373.1 \text{ kJ/kg} = 700 \text{ kg} \times h_c
\( h_c = 924.98 \text{ kJ/kg} \)
at 15 kPa \( h_l = 225.94 \text{ kJ/kg}, \quad h_g = 2373.1 \text{ kJ/kg} \)
\[
x = \frac{925.98 - 225.94}{2373.1} = .29, \quad 29\% \text{ quality}
\]
\( T = 53.97^0C \)
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.

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

\[ W_{net} = 25 \frac{\text{kg}}{\text{sec}} \times (3341.8 - 2393.2) - 10 \frac{\text{kg}}{\text{sec}} \times (628.1 - 210.5) \]

\[ W_{net} = 19539 \text{ kJ/sec} \]
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.

Open thermodynamic system - a region in space

\[ p_1 = 3 \text{ MPa} \]
\[ T_1 = 400 \text{ C} \]
\[ v_1 = 40 \text{ m/sec} \]
\[ p_2 = 2.5 \text{ MPa} \]
\[ v_2 = 300 \text{ m/sec} \]

\[ h_1 & v_1 = \text{superheat } @ (T = 400., P = 3.) \]
\[ h_1 = 3203.9 \text{ kJ/kg} \]
\[ v_1 = 0.0936 \text{ m}^3/\text{kg} \]

\[ h_2 = h_1 + \frac{v_1^2}{2} = h_2 + \frac{v_2^2}{2} \text{ steady flow energy equation} \]
\[ h_2 = h_1 + \left( \frac{v_1^2}{2} - \frac{v_2^2}{2} \right) \]
\[ h_2 = 3203.9 \text{ kJ/kgm} + \left( \frac{40^2}{2} - \frac{300^2}{2} \right) \text{ m}^2/\text{sec}^2 \left( \frac{1 \text{ kJ/kg}}{1000 \text{ m}^2/\text{sec}^2} \right) \]
\[ h_2 = 3203.9 - 44.2 = 3159.7 \text{ kJ/kg} \]

a) \[ T_2 = \text{superheat } @ (h = 3159.7, p = 2.5) \]
\[ T_2 = 364.78 \text{ C} \]

b) \[ m = \rho AV = \left( \frac{p}{RT} \right) AV \]
\[ \left( \frac{p_1}{RT_1} \right) A_1 V_1 = \left( \frac{p_2}{RT_2} \right) A_1 V_2 \]
\[ \frac{3 A_1 40}{(400 + 273.15)} = \frac{2.5 A_2 300}{(364.78 + 273.15)} \]
\[ \frac{A_2}{A_1} = \frac{.1783}{1.1757} = .1517 \]
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

\[ h_1 \text{ & } v_1 = \text{superheat} @ (T = 400, P = 3. Mpa) \]

\[ h_1 = 3231.7 \text{ kJ/kg} \]

\[ v_1 = .09938 \text{ m}^3/\text{kg} \]

\[ h_1 + \frac{V_1^2}{2} = h_2 + \frac{V_2^2}{2} \]

steady flow energy equation

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

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

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

\[ a) \ T_2 @ (h = 3187.5, p = 2.5) \]

\[ T_2 = 376.5 \text{ C}, \]

\[ v_2 @ (h = 3187.5, p = 2.5) \]

\[ v_2 = .11626 \]

\[ b) \ m = \rho AV \]

\[ \frac{A_1 V_1}{v_1} = \frac{A_1 V_2}{v_2} \]

\[ 3 A_1 40 = 2.5 A_2 300 \]

\[ 0.09938 = .11626 \]

\[ A_2 = \frac{13.951}{74.535} = .1872 \]
FIRST LAW IN UNSTEADY SYSTEMS

(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

\[ m_i = m_2 \]

\[ P_i = 1 \text{ MPa} \]
\[ (constant) \]

Imaginary piston
\[ Q = \Delta E + W \]
\[ Q = E_f - E_i + (W_{\text{flow}} + W_{\text{boundary}}) \]
\[ E_i = m_i u_i + (m_f - m_i) u_1 \]
\[ E_f = m_f u_f \]
\[ W_f = \int p \, dV = (m_f - m_i) p_1 (v_{\text{end}} - v_1) \]
\[ W_f = -(m_f - m_i) \times p_1 v_1 \]
\[ Q = m_f u_f - m_i u_i - (m_f - m_i) \times (u_1 + p_1 v_1) + W_b \]
\[ Q = m_f u_f - m_i u_i - (m_f - m_i) \times h_1 + W_b \]

FIRST LAW FOR UNSTEADY SYSTEMS
\[ Q - W_b + H_{\text{in}} = \Delta U_{\text{contents}} \]

For:
\[ m_i = 0, \text{ adiabatic vacuum} \]
\[ Q = 0, \ W_b = 0 \]
\[ u_f = h_1 \]
\[ c_v (T_f - T_o) = c_p (T_i - T_o) \]
\[ \frac{c_p}{c_v} = \left( \frac{T_f - T_o}{T_i - T_o} \right) \]
\[ T_o \text{ is arbitrary, } T_o = 0 \]
\[ T_f = k \ T_i \]
A 200 cubic ft tank contains 2. lbm carbon dioxide and .1 mole 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?

\[ Q = m_f u_f - m_i u_i - (m_f - m_i)(h_i) \]
\[ m_f u_f = (3 \times .174 + 2 \times .1565 + .4 \times .745)T_f = 1.125T_f \]
\[ m_i u_i = (2 \times .1565 + .4 \times .745) \times (460 + 70) = 323.83 \]
\[ (m_i - m_f)h_i = 3 \times .24 \times (460 + 70) = 381.6 \]
\[ Q = 1.125T_f - 323.83 - 381.6 = 0 \]
\[ T_f = 627^\circ R \]
\[ T_f = 167^\circ F \]
8 kg liquid water and 2 kg vapor at 300 kPa are contained in an insulated piston cylinder. Steam at .5 MPa and 350 C are admitted until the piston cylinder contains only vapor. Determine the final temperature and the amount of steam admitted.

the system is the mass finally in the piston cylinder, $m_2$

$Q - W_{\text{boundary}} + (m_2 - m_1) h_o = m_2 u_2 - m_1 u_1$

$W_{\text{boundary}} = m_2 p_2 v_2 - m_1 p_1 v_1$

substituting for $W_{\text{boundary}}$,

$0 - (m_2 p_2 v_2 - m_1 p_1 v_1) + (m_2 - m_1) h_o = m_2 u_2 - m_1 u_1$

$0 = -m_2 h_o + m_1 h_o + m_2 u_2 - m_1 u_1 + m_2 p_2 v_2 - m_1 p_1 v_1$

$0 = -m_2 h_o + m_2 u_2 + m_2 p_2 v_2 + m_1 h_o - m_1 u_1 - m_1 p_1 v_1$

since $u = u + pv$,

$0 = m_2(h_2 - h_o) + m_1(h_o - h_1)$

$m_2 = m_1 \frac{(h_o - h_1)}{(h_o - h_1)}$

$m_2 = 10 kg \left( \frac{3167.7 \text{ kJ/kg} - 2292.51 \text{ kJ/kg}}{3167.7 \text{ kJ/kg} - 2725.3 \text{ kJ/kg}} \right) = 19.78 \text{ kg}$

$m_2 - m_1 = 19.78 \text{ kg} - 10 \text{ kg} = 9.78 \text{ kg}$

@ 300 kPa

$T_2 = T_{\text{saturation}}@300\text{kPa} = 133.55 \text{ C}$

$h_2 = v_g = 2725.3 \text{ kJ/kg}$

$h_1 = h_f + x \times h_{fg}$

$h_1 = 561.47 + .8 \times 2163.8$

$h_1 = 2292.51 \text{ kJ/kg}$

@ .5 MPa, 350°C

$h_o = 3167.7 \text{ kJ/kg}$
First Law
Energy defined, Energy conserved
\[ E_{in} - E_{out} = \Delta E \] (page 72)
E is all forms, Q, W, PE, KE, U
\[ (Q_{in} - Q_{out}) + (W_{in} - W_{out}) + (E_{massin} - E_{massout}) = U_2 - U_1 \] (2 - 32)

CLOSED SYSTEM a contained quantity of mass
\[ (Q_{in} - Q_{out}) + (W_{in} - W_{out}) + (E_{massin} - E_{massout}) = U_2 - U_1 \] (page 173)
\[ (Q_{in} - Q_{out}) + (W_{in} - W_{out}) = U_2 - U_1 \]
Q = U_2 - U_1 + W
Q = \Delta E + W

OPEN SYSTEM a region in space
\[ (Q_{in} - Q_{out}) + (W_{in} - W_{out}) + (E_{massin} - E_{massout}) = U_2 - U_1 \] (page 233)
\[ W = W_{shaft} + W_{flow} \]
\[ (Q_{in} - Q_{out}) + (W_{in} - W_{out}) = (E_{massout} - E_{massin}) \]
for \( W_{net} = 0 \), \( Q = H_2 - H_1 = m(h_2 - h_1) \)
for \( Q_{net} = 0 \), \( W = H_2 - H_1 = m(h_2 - h_1) \)
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

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

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

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

System
- open, closed, unsteady
- schematic at each system state

State Point
- property diagram
- locate points

Properties
- property values – tables, Ideal Gas Law
- what properties remain constant?

Cycle
- what remains constant?

Mass Balance

Identify Energy
- Forms
- Sources
- Uses

Energy Balance
- general equation
- from schematic
- specific for open system
- specific for closed system
- specific for unsteady system

From Chapter 1

Concepts
System
Properties
State Point
Process
Cycle
Kinetic Energy \[ \frac{V^2}{2} = \frac{m^2/\text{sec}^2}{2} \times \frac{1 \text{ kJ/kg}}{1000 \text{ m}^2/\text{sec}^2} \]

Kinetic Energy \[ \frac{V^2}{2g} = \frac{\text{ft}^2/\text{sec}^2}{2 \times 32.3 \text{ ft/sec}^2} \times \frac{1}{778 \text{ ft} - \text{lb}/\text{Btu}} \]

Work \[ \int \text{pdV} = \text{kPa} \times \text{m}^3 \times \frac{1 \text{ kJ}}{1 \text{ kPam}^3} = \text{kJ} \]

Work \[ \int \text{pdV} = \frac{\text{lb}}{\text{in}^2} \times \frac{144 \text{ in}^2}{\text{ft}^2} \times \text{ft}^3 \times \frac{1 \text{ Btu}}{778 \text{ft} - \text{lb}} = \text{Btu} \]