Fluid Systems

(Understanding Engineering Thermo—Octave Levenspiel)

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Two points I want to emphasis:

1. ΔU and ΔH
2. $W = W_{pv} + W_{sh}$

BATCH OF IDEAL GAS

Batch of ideal gas

- Constant volume

$$v_1 = v_2 \quad and \quad \frac{p_1}{T_1} = \frac{p_2}{T_2}$$

$$w_{rev} = \int p\,dv = 0$$

$$q_{rev} = \Delta u + w_{rev} = c_v \Delta T + 0 = c_v \Delta T \quad \text{J/mol}$$

- Constant pressure

$$p_1 = p_2 \quad and \quad \frac{v_1}{T_1} = \frac{v_2}{T_2}$$

$$w_{rev} = \int p\,dv = p(v_2 - v_1) = p_1 v_1 \left(\frac{T_2}{T_1} - 1 \right) = \frac{p_1 v_1}{T_1}(T_2 - T_1) = R\Delta T$$

$$q_{rev} = \Delta u + w_{rev} = c_v \Delta T + R\Delta T = c_p \Delta T \quad \text{J/mol}$$

Batch of ideal gas

- Constant temperature

$$T_1 = T_2 \quad and \quad p_1 v_1 = p_2 v_2$$

$$\Delta h = \Delta u + \Delta(pv) = 0$$

$$q_{rev} = w_{rev} = \int p\,dv = \int \frac{RT}{v}\,dv$$

$$= RT \ln \frac{v_2}{v_1} = RT \ln \frac{p_1}{p_2} \quad \text{J/mol}$$

Batch of ideal gas

- Adiabatic (q=0) reversible process with constant c_v

$$du = dq_{rev} - dw_{rev} = - p\,dv$$

$$c_v\,dT \qquad \frac{RT}{v}\,dv$$

- Integrate

$$\int_{T_1}^{T_2} \frac{dT}{T} = - \frac{R}{c_v} \int_{v_1}^{v_2} \frac{dv}{v}$$

- Assume constant c_v, hence constant c_p,
- Introduce symbol k,

$$k = \frac{c_p}{c_v} = 1 + \frac{R}{c_v}$$

- On integration,

$$\ln \frac{T_2}{T_1} = -(k - 1) \ln \frac{V_2}{V_1}$$

- therefore

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2} \right)^{k-1}$$

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1} \right)^{(k-1)/k}$$

$$\frac{p_2}{p_1} = \left(\frac{V_1}{V_2} \right)^{k}, \quad or \quad pv^{k} = \text{const.}$$

- For ideal adiabatic reversible batch process, $\Delta e_p = \Delta e_k = 0$, $q_{rev} = 0$,

$$w_{rev} = \int p\,dv = \int_{v_1}^{v_2} \frac{const.}{v^k}\,dv \qquad pv^k = \text{const.}$$

$$= \frac{p_1 v_1}{k-1}\left[1 - \left(\frac{p_2}{p_1}\right)^{(k-1)/k}\right] = \frac{RT_1}{k-1}\left[1 - \left(\frac{p_2}{p_1}\right)^{(k-1)/k}\right]$$

$$w_{rev} = -\Delta u = c_v(T_2 - T_1)$$

$$= -\frac{R}{k-1}(T_2 - T_1) \qquad k = \frac{c_p}{c_v} = 1 + \frac{R}{c_v}$$

$$= -\frac{p_2 v_2 - p_1 v_1}{k-1} \qquad pv = RT$$

$$dV^q = qV^{q-1}dV$$

$$-k = q-1$$

$$dV^{1-k} = \left(1-k\right)V^{-k}dV$$

$$\frac{dV^{1-k}}{1-k} = V^{-k}dV$$

$$\frac{const}{V^k}dV = \frac{p_1V_1^K}{1-k}dV^{1-k}$$

$$\int_{V_1}^{V_2}\frac{const}{V^k}dV = \frac{p_1V_1^K}{1-k}\left(V_2^{1-k} - V_1^{1-k}\right)$$

$$= \frac{p_1V_1}{1-k}V_1^{k-1}\left(V_2^{1-k} - V_1^{1-k}\right)$$

$$= \frac{p_1V_1}{k-1}\left(1 - \frac{V_2^{1-k}}{V_1^{1-k}}\right)$$

$$- \frac{p_2 V_2 - p_1 V_1}{k - 1} = \frac{p_1 V_1}{k - 1} \left(1 - \frac{p_2 V_2}{p_1 V_1} \right)$$

$$\frac{p_2 V_2}{p_1 V_1} = \left(\frac{V_1}{V_2} \right)^k \frac{V_2}{V_1} = \left(\frac{V_1}{V_2} \right)^{k-1} = \frac{T_2}{T_1} = \left(\frac{p_2}{p_1} \right)^{\frac{k-1}{k}}$$
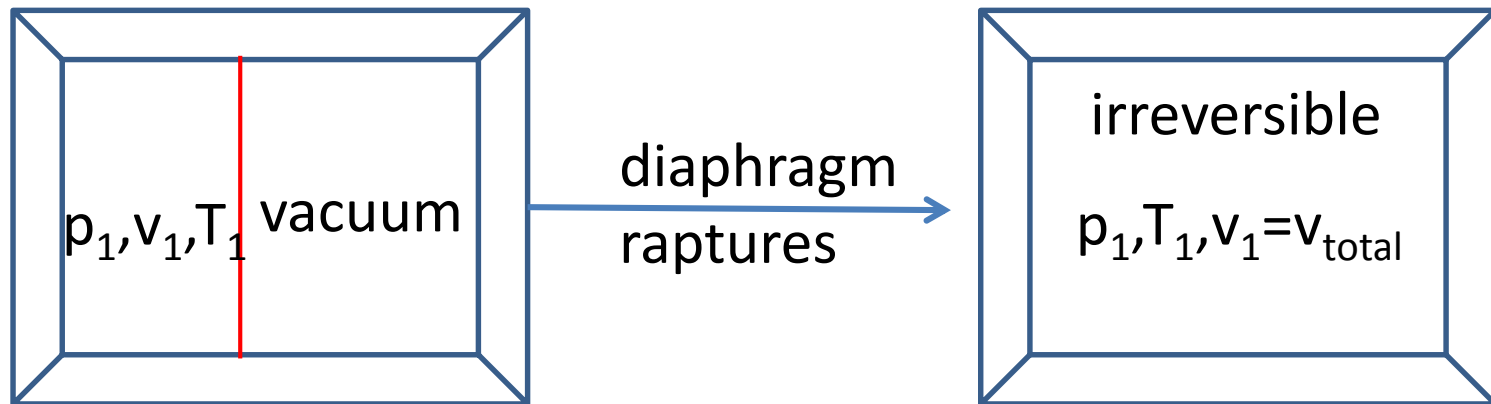
Example I

- Slow leak from an insulated tank

  The gas remaining in the tank experiences and

  adiabatic reversible expansion, therefore

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1} \right)^{(k-1)/k}$$

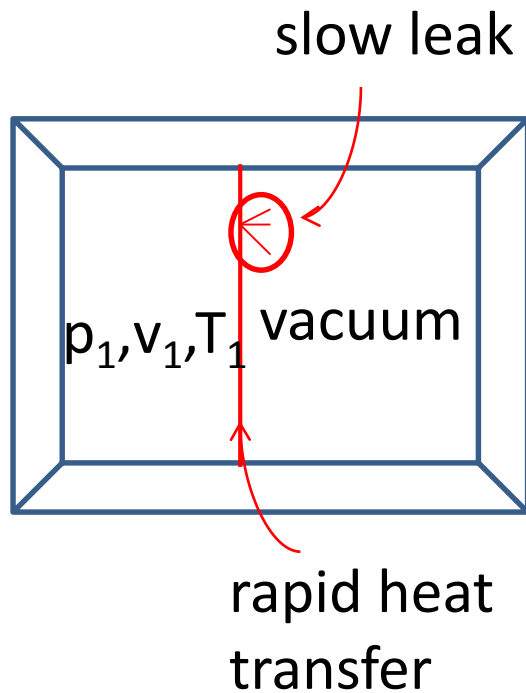# Example II

- Rupture of a diaphragm in an insulated tank

- Insulated and const volume

$$\Delta U = \cancelto{0}{Q} - \cancelto{0}{W}$$

$$T_2 = T_1 \quad and \quad \frac{p_2}{p_1} = \frac{V_2}{V_1}$$

Example III

- Slow leak between sections of an insulated tank

slow leak
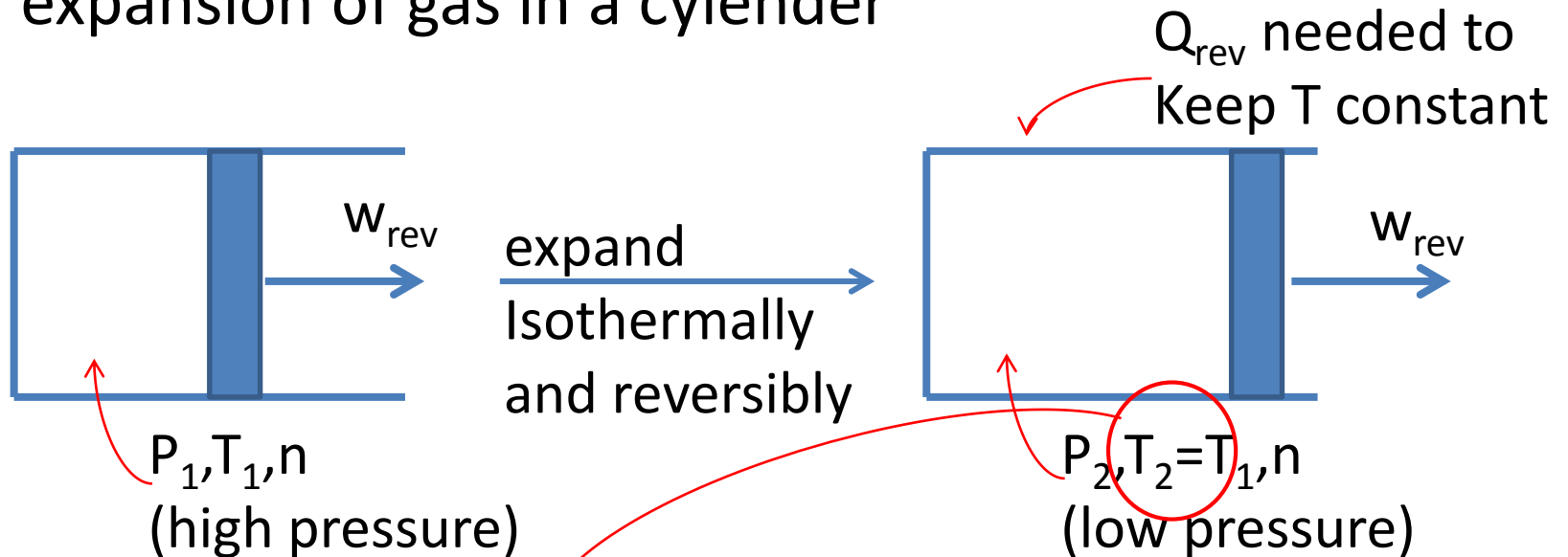
Insulated and const volume

p$_1$,v$_1$,T$_1$ vacuum

rapid heat transfer

$$\Delta U \quad = \quad \cancel{Q}^{0} \quad - \quad \cancel{W}^{0}$$

$$T_2 \quad = \quad T_1 \quad and \quad \frac{p_2}{p_1} \quad = \quad \frac{v_2}{v_1}$$

Example IV

- Heat involved in the slow isothermal reversible expansion of gas in a cylender

Q_{rev} needed to Keep T constant

w_{rev}

expand
Isothermally
and reversibly

w_{rev}

P_1,T_1,n
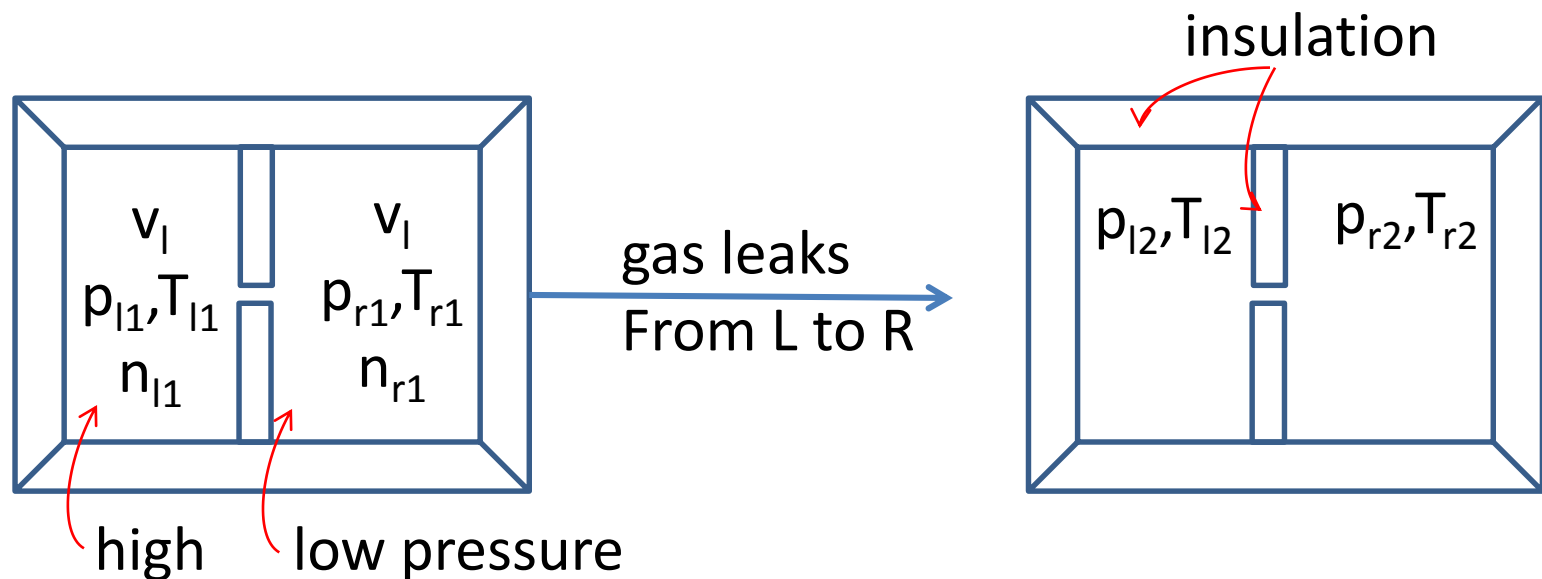(high pressure)

$P_2,T_2=T_1,n$
(low pressure)

$$0 = \Delta U = Q_{rev} - W_{rev}$$

$$Q_{rev} = W_{rev} = nRT \ln \frac{p_1}{p_2}$$

constant temperature process

Example V

- Leak between two interconnected insulated tanks

insulation

v_l
p_{l1}, T_{l1}
n_{l1}

v_l
p_{r1}, T_{r1}
n_{r1}

gas leaks
From L to R

p_{l2}, T_{l2}

p_{r2}, T_{r2}

high   low pressure

- The gas remaining on the left-hand side expands adiabatically and reversibly.

- Find how T_l, T_r, p_l and p_r change

$$n_{l1} = \left(\frac{pv}{RT} \right)_{l1} \qquad\qquad n_{l2} = \left(\frac{pv}{RT} \right)_{l2}$$

$$n_{l1}+n_{r1} = n_{total} \qquad\qquad n_{l2}+n_{r2} = n_{total}$$

$$n_{r1} = \left(\frac{pv}{RT} \right)_{r1} \qquad\qquad n_{r2} = \left(\frac{pv}{RT} \right)_{r2}$$

adiabatically and reversibly expansion,

$$\frac{T_{l2}}{T_{l1}} = \left(\frac{p_{l2}}{p_{l1}} \right)^{(k-1)/k}$$

$$\sum E_2 = \sum E_1 : (n_l u_l)_2 + (n_r u_r)_2 = (n_l u_l)_1 + (n_r u_r)_1$$

$$(n_l T_l)_2 + (n_r T_r)_2 = (n_l T_l)_1 + (n_r T_r)_1$$

$$u = c_v T$$

$$h = c_p T$$

Example VI

- Total work done by an expanding gas

A 2 liter plastic pop bottle contains air at 300K and 1.5 bar gauge pressure. How much work could be done by this gas if you could expand it down to 1 bar

  – Isothermally and reversibly?
  – Adiabatically and reversibly?

$$n = \frac{pv}{RT} = \frac{(12.5 \times 15^5)(0.002)}{(8.314)(300)} = 1.00 \text{ mol}$$

- Isothermal expansion

$$W_{rev} = nRT \ \ln \frac{p_1}{p_2}$$

$$W_{rev} = (1)(8.314)(300) \ln \frac{12.5}{1} = 6300 \ \text{J}$$

- Adiabatic expansion

$$W_{rev} = \frac{nRT_1}{k-1}\left[1 - \left(\frac{p_2}{p_1}\right)^{(k-1)/k}\right]$$

$$W_{rev} = \frac{(1)(8.314)(300)}{1.4-1}\left[1 - \left(\frac{1}{12.5}\right)^{0.4/1.4}\right] = 3205 \ \text{J}$$

Example VII

- Net work done by an expanding gas

  The previous example calculated the work done by an expanding gas. However, in doing so the gas had to push back the 1 bar atmosphere. Let us now account for this work, subtract it from the work done, and thereby evaluate the useful work (shaft work) that could be extracted by this
    - Isothermal expansion
    - Adiabatic expansion

- ## Isothermal expansion
  - The work needed to push back the atmosphere is

$$W_{pv} = p_0(v_2 - v_1)$$

$$= (1 \times 10^5)(12.5 \times 0.002 - 0.002) = 2300 \quad J$$

  - The reversible shaft work that can be extracted is

$$\boxed{W_{sh} = 6300 - 2300 = 4000 \quad J}$$

- ## Adiabatic expansion
  - Final temperature of the expanded air is not 300K, but

$$T_2 = T_1\left(\frac{p_2}{p_1}\right)^{(k-1)/k} = 300\left(\frac{1}{12.5}\right)^{0.4/1.4} = 146 \quad K$$

$$W_{pv} = p_0(v_2 - v_1)$$

$$= (1 \times 10^5)\left(12.5 \frac{146}{300} 0.002 - 0.002\right) = 1015 \quad J$$
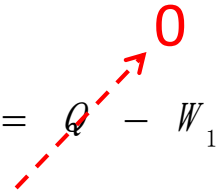
  - The reversible shaft work that can be extracted is

$$\boxed{W_{sh} = 3205 - 1015 = 2190 \quad J}$$

Example VIII

- Explosion: The popping pop bottle
  - reversible or irreversible?
  - Isothermal or adiabatic?
- From the first law, and adiabatic

$$\Delta U \;=\; \cancel{Q}^{\;0} \;-\; W_1$$

- Highly irreversible, all go to push back

$$W_2 \;=\; \int p\,dv \;=\; p_{surr}\,\Delta v$$

- Therefore,

$$W_1 = \Delta U = nc_v(T_{initial} - T_{final})$$

$$W_2 = p_{surr}(v_{finall} - v_{initial})$$

- Then

$$W_1 = (1)(29.099 - 8.314)(300 - T_{final})$$

$$W_2 = 1 \times 10^5 \left[12.5 \times 0.002 \left(\frac{T_{final}}{300} \right) - 0.002 \right]$$
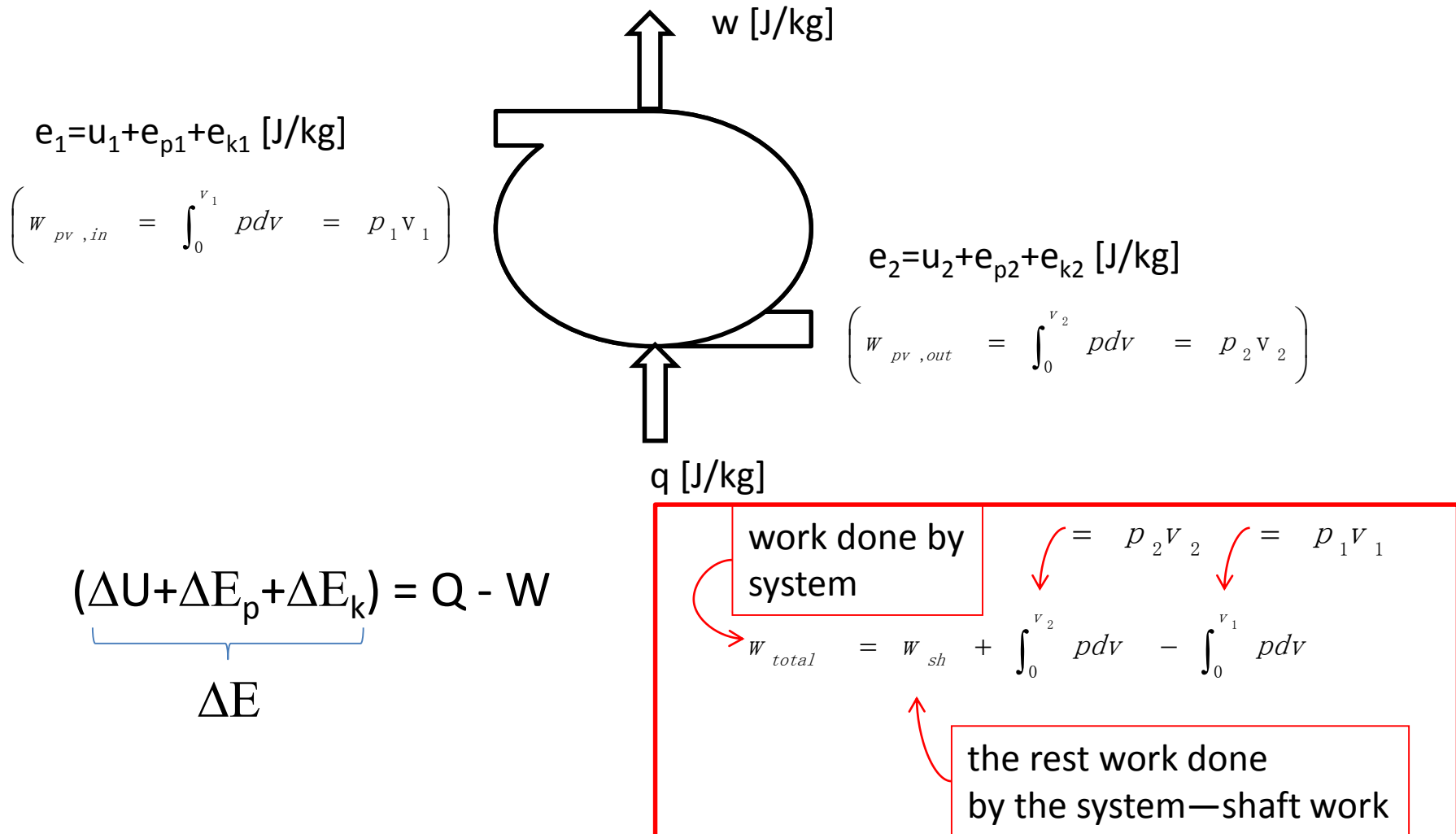
- Solving T$_{final}$ by equating W$_1$ = W$_2$
- Finally

$$T_{finall} = 221 \ K$$

$$W = 1642 \ J$$

STEADY STATE FLOW SYSTEMS

Steady State Flow System

w [J/kg]

$e_1 = u_1 + e_{p1} + e_{k1}$ [J/kg]

$$\left(W_{pv,in} = \int_0^{v_1} pdv = p_1 v_1 \right)$$

$e_2 = u_2 + e_{p2} + e_{k2}$ [J/kg]

$$\left(W_{pv,out} = \int_0^{v_2} pdv = p_2 v_2 \right)$$

q [J/kg]

$$(\Delta U + \Delta E_p + \Delta E_k) = Q - W$$

ΔE

work done by system $= p_2 v_2$ $= p_1 v_1$

$$W_{total} = W_{sh} + \int_0^{v_2} pdv - \int_0^{v_1} pdv$$

the rest work done by the system—shaft work

Steady State Flow System

- **Rearrange**

$$\left(u_2 + p_2 v_2 \right) - \left(u_1 + p_1 v_1 \right) + g \Delta z + \frac{1}{2} \Delta v^2 = q - w_{sh}$$

$\xrightarrow{\hspace{2cm}} 0$

h_2 $\qquad$ h_1

Δh

for the flow streams,
not the system

$RT_2 - RT_1 = R \Delta T$

$CvT_2 - CvT_1 + RT_2 - RT_1$

$= (Cv + R) \Delta T = Cp \Delta T$

Example I

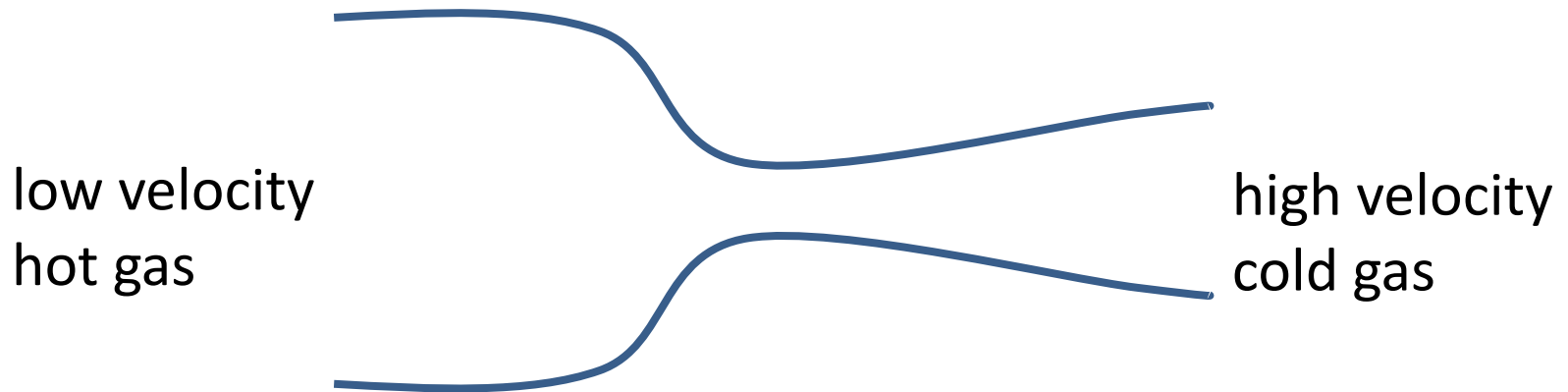- **The steam or water turbine and the steam engine**

steam in

high pressure

low pressure

w_{sh}

w_{sh}

steam out
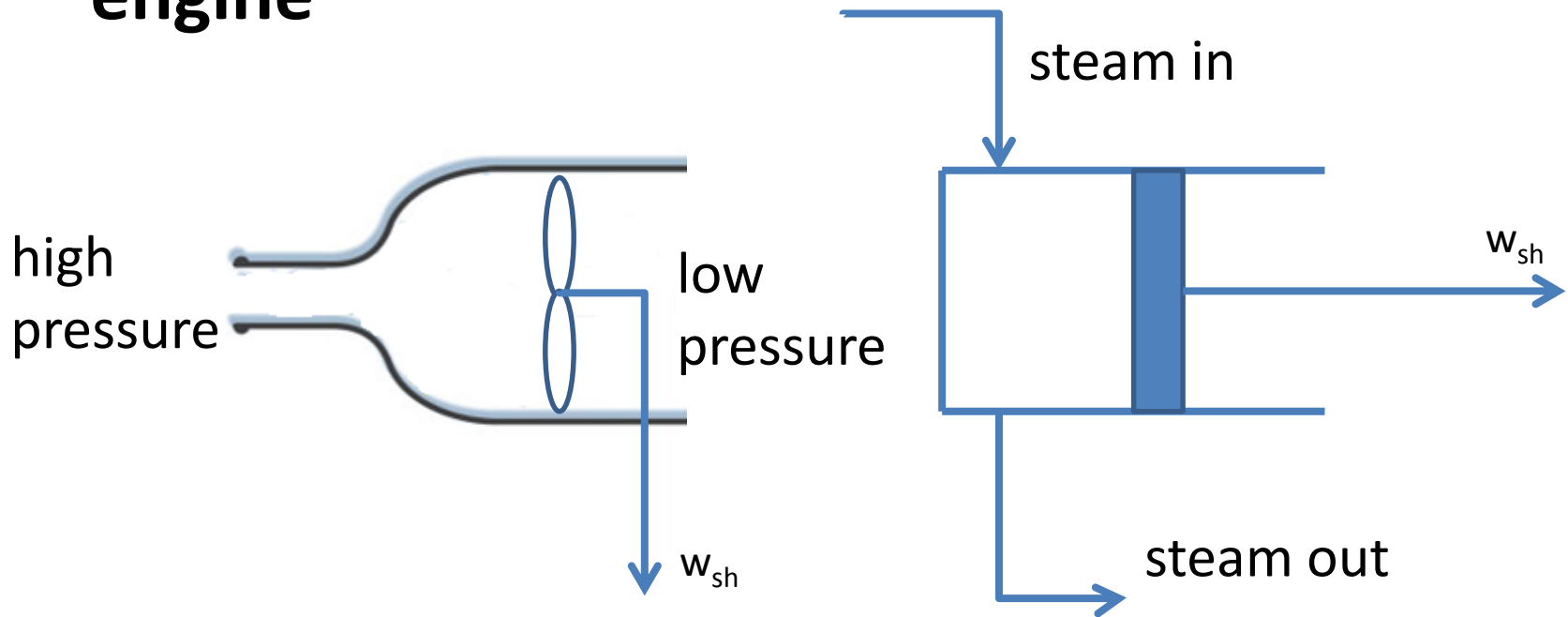
$$\dot{m}\Delta h \ = \ \dot{m}\left(h_2 \ - \ h_1\right) \ = \ -\dot{w}_{sh} \quad [W]$$

$$\Delta h \ = \ -w_{sh} \quad [J \ / \ kg]$$

Example II

- **The adiabatic flow nozzle**

low velocity
hot gas

high velocity
cold gas

$$\dot{m} \Delta h = - \frac{\dot{m}}{2} \underline{v}_2^2 \qquad [W]$$

$$\Delta h = - \frac{1}{2} \underline{v}_2^2 \qquad [\frac{J}{kg}]$$

Example III

- **The Joule-Thomson expansion**

pipe is well insulated

Across the slow leak or porous plug
$$\Delta h = h_2 - h_1 = 0$$

For ideal gas, from Jour Joule-Thompson expansion
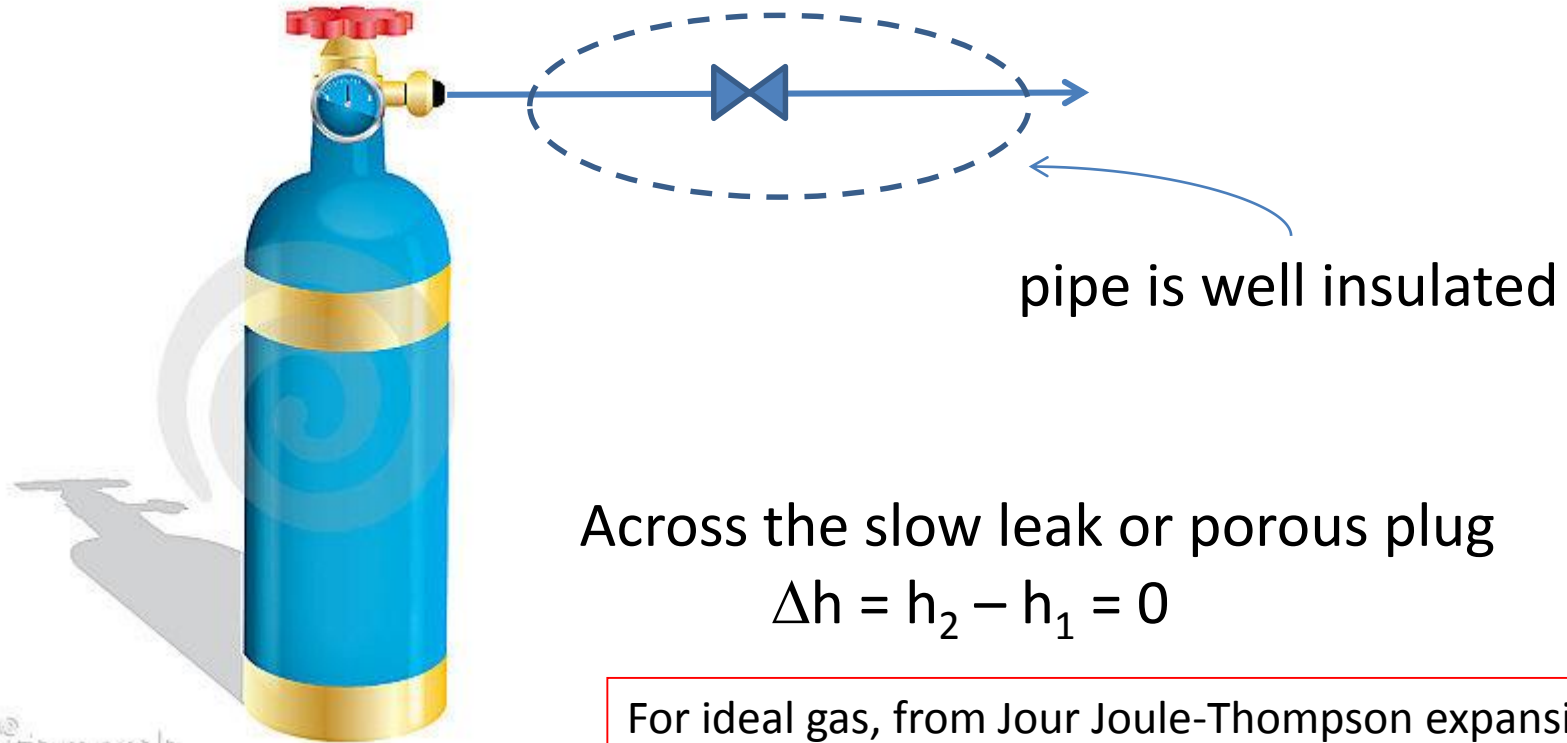
Example IV

- **The flow heater**

$$CvT_2 - CvT_1 + RT_2 - RT_1$$
$$= (Cv + R)\Delta T = Cp \Delta T$$

cold   warm

q (hot fluid)

$-w_{sh}$ (electricity)

$$\dot{m}\Delta h = \dot{q}$$
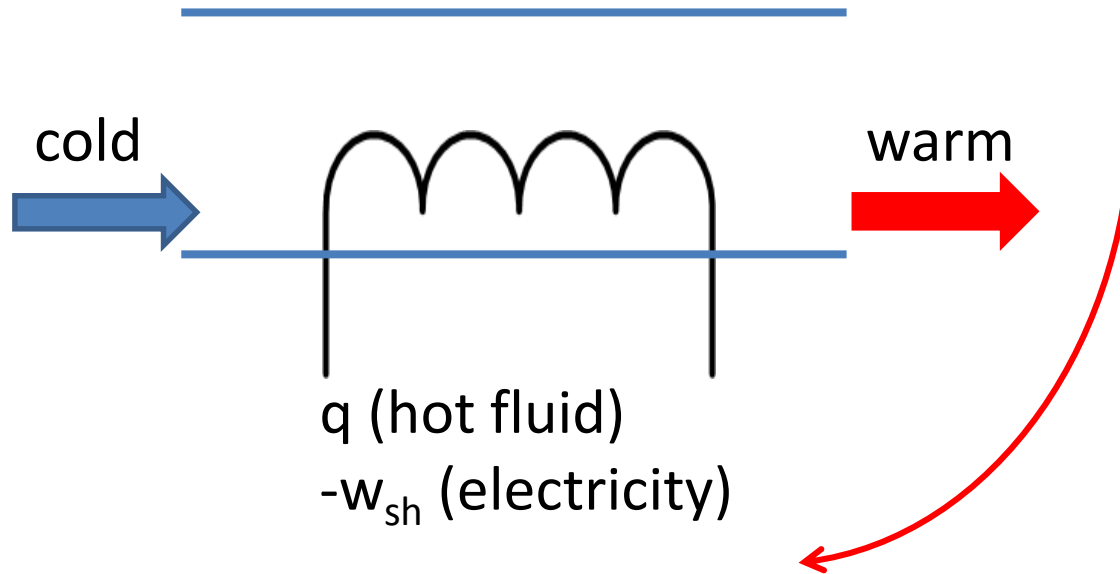
$$\dot{m}\Delta h = -\dot{w}_{sh}$$

heat or work done on fluid in the heater

Example V

- **Ideal piston-cylinder engine or ideal piston-cylinder pump**
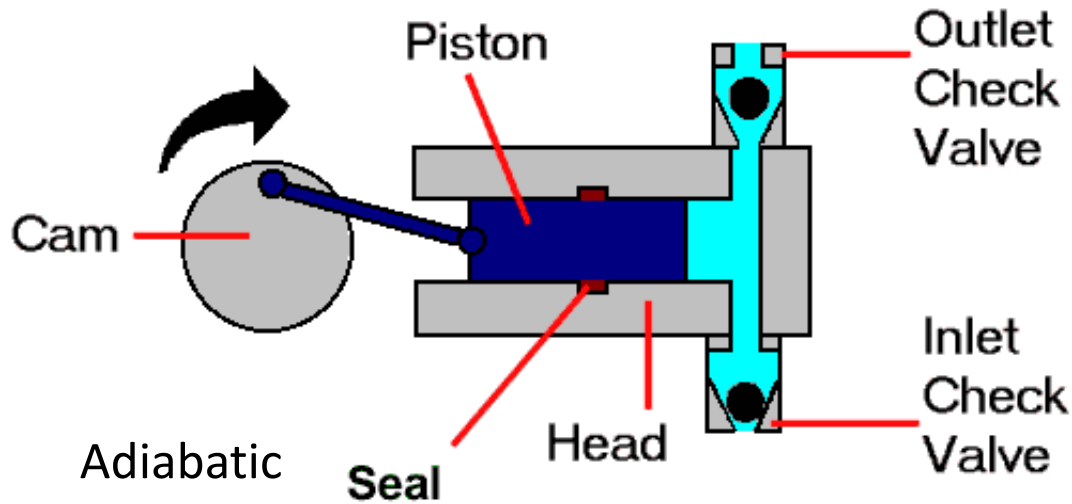
Example V
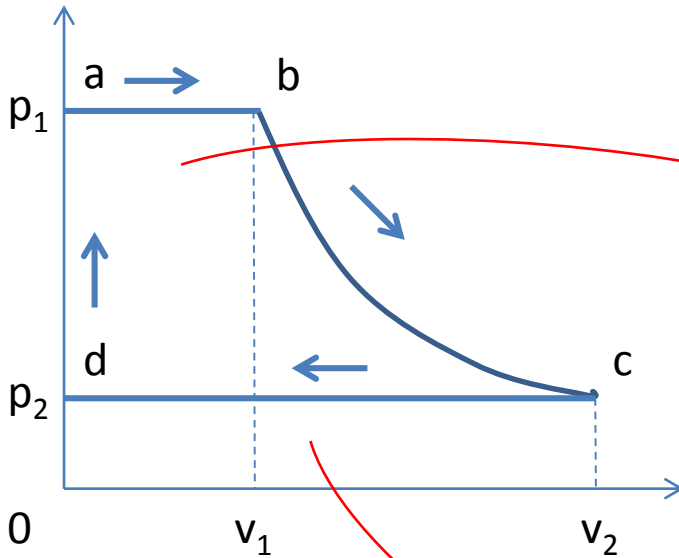
- a-b Introduce 1 kg of high pressure gas at p_1 and of volume v_1.

$$W_1 = \int_0^{V_1} p_1 \, dv = p_1 V_1$$

- b-c Expand the gas to the outlet pressure p_2. (both valves are closed)

$$W_2 = \int_{V_1}^{V_2} p \, dv$$

- c-d Push out all the gas in the cylinder.

$$W_3 = \int_{V_2}^{0} p_2 \, dv = p_2 V_2$$

- Net shaft work done by the fluid

$$W_{sh} = W_1 + W_2 + W_3$$

$$= p_1 v_1 + \int_{v_1}^{v_2} p\, dv - p_2 v_2$$

$$\boxed{\begin{array}{l} CvT_2 - CvT_1 + RT_2 - RT_1 \\[2mm] = (Cv + R)\,\Delta T = Cp\,\Delta T \end{array}}$$

- From the pv diagram

$$= -\int_{p_1}^{p_2} v\, dp$$

- Or $\quad d\left(pv\right) = p\, dv + v\, dp$

$$\int_1^2 d\left(pv\right) = p_2 v_2 - p_1 v_1 = \int p\, dv + \int v\, dp$$

$$\Delta h = -w_{sh} = +\int_1^2 v\, dp \qquad [\,J\ /\ kg\,]$$

Example VI

- Ideal turbine or compressor

P_2

P_1

adiabatic
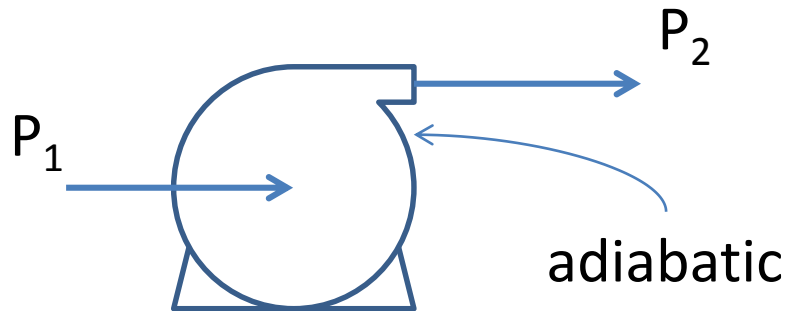
$$\Delta u \;+\; \Delta e_p \;+\; \Delta e_k \;=\; \cancel{q} \;-\; w \;=\; -\int pdv$$

$$\Delta u \;+\; \Delta e_p \;+\; \Delta e_k \;=\; -p_2 v_2 \;+\; p_1 v_1 \;+\; \int vdp$$

$$\Delta h \;+\; \Delta e_p \;+\; \Delta e_k \;=\; +\int vdp$$

From the previous slide

- If constant v

$$\Delta h \;+\; \Delta e_p \;+\; \Delta e_k \;=\; v\Delta p \;=\; \frac{\Delta p}{\rho}$$

$v \;\equiv\; V/m$

Example VII

$$CvT_2 - CvT_1 + RT_2 - RT_1$$
$$= (Cv + R) \Delta T = Cp \Delta T$$

- Ideal isothermal work-producing machine

low pressure

high pressure $p_2 T_2 = T_1$

$p_1 T_1$
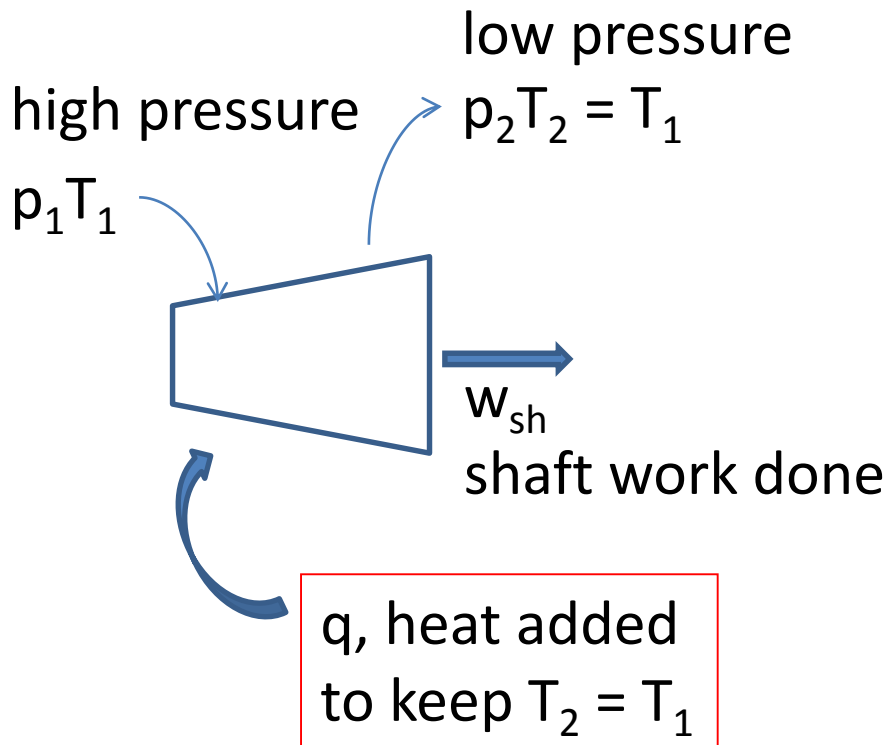
Assume $\Delta e_p = \Delta e_k = 0$
Noting that $T_1 = T_2$,
then $\quad P_1 v_1 = p_2 v_2$
$\quad\quad\quad \Delta h = 0$

w_{sh}
shaft work done

q, heat added
to keep $T_2 = T_1$

From the previous slide

$$w_{sh} = q = -\int v\,dp = RT \ln \frac{p_1}{p_2}$$

Or

$$\dot{W}_{sh} = \dot{Q} = \dot{n} RT \ln \frac{p_1}{p_2}$$

Example VIII

- Ideal gas frictionless adiabatic turbine or compressor

low pressure
$p_2 T_2 < T_1$

high pressure

$p_1 T_1$

w_{sh}

shaft work done
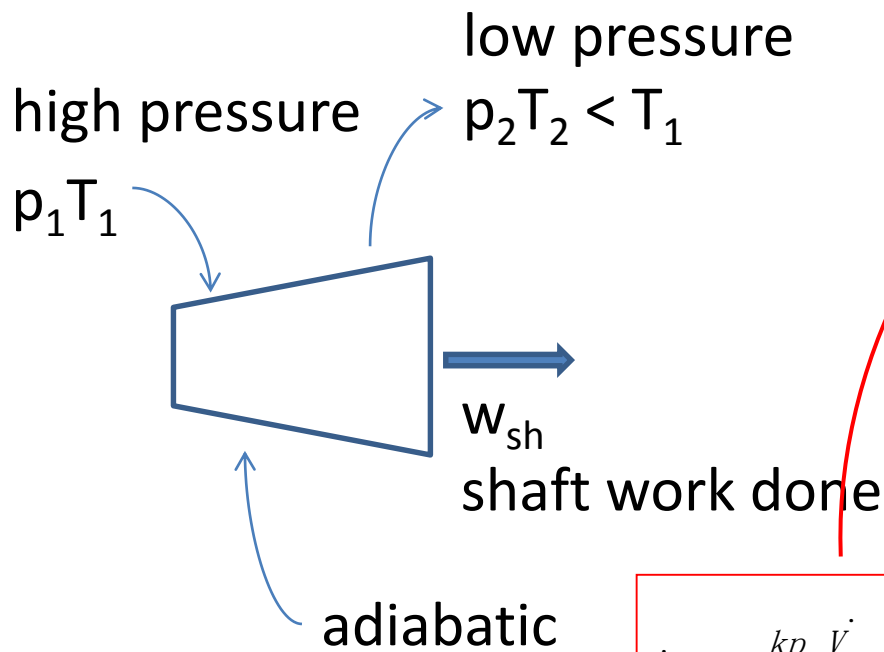
adiabatic

$w_{flow} = w_{batch} - \Delta pv$

$$W_{flow} = -\frac{(p_2 V_2 - p_1 V_1)}{k-1} - (p_2 V_2 - p_1 V_1)$$
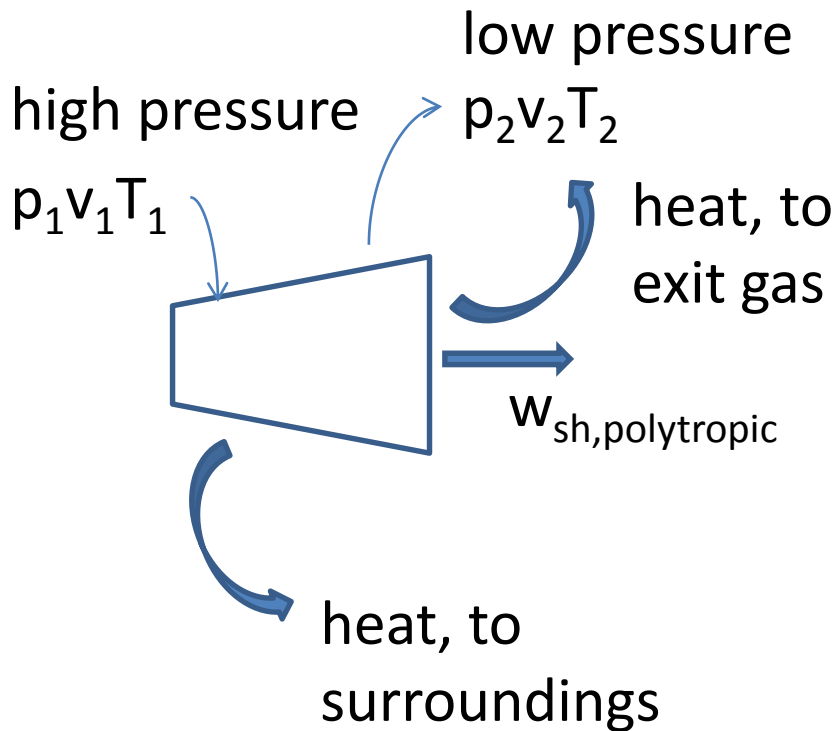
$$= -\frac{k}{k-1}(p_2 V_2 - p_1 V_1) = k w_{batch}$$

ideal gas
adiabatic reversible batch

$$\dot{W} = \frac{k p_1 \dot{V_1}}{k-1}\left[1 - \left(\frac{p_2}{p_1}\right)^{(k-1)/k}\right] = \dot{n} c_p T_1 \left[1 - \left(\frac{p_2}{p_1}\right)^{(k-1)/k}\right]$$

$$= \dot{n} c_p (T_2 - T_1) = -\frac{k}{k-1}(p_2 \dot{V_2} - p_1 \dot{V_1})$$

Example IX

- Real turbines and compressors

$$w_{sh,poly} = \gamma w_{batch}$$

high pressure

$p_1 v_1 T_1$

low pressure

$p_2 v_2 T_2$

heat, to exit gas

$w_{sh,polytropic}$

heat, to surroundings

$$w_{flow} = - \frac{(p_2 v_2 - p_1 v_1)}{k - 1} - (p_2 v_2 - p_1 v_1)$$

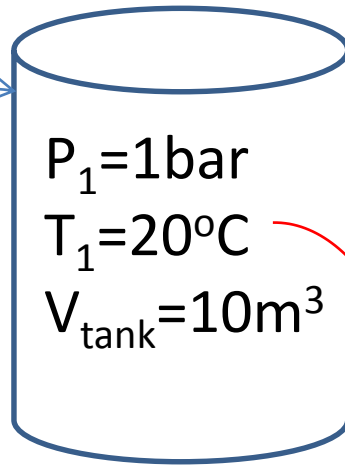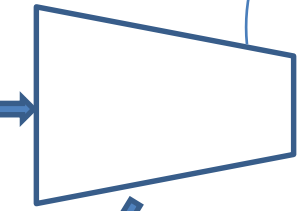$$= - \frac{k}{k - 1}(p_2 v_2 - p_1 v_1) = k w_{batch}$$

replace k with γ

Example X

- Pumping up a tank with an ideal gas
- A 10 m^3 tank is open to the surroundings at 20°C and 1 bar. A compressor connected the tank pumps air into the tank. The compressor operates isothermally.
  - Find the minimum work required to pressurize the tank to 10 bar.
  - Find the heat interchange at the compressor.

Visualize

P_1=1bar
T_1=20°C

-w_{sh}

-Q

P_1=1bar
T_1=20°C
V_{tank}=10m^3

isothermal

P_1=1bar
T_1=20°C

20°C

-w_{sh}

-Q

P_2=10bar
T_2=T_1=20°C
V_{tank}=10m^3
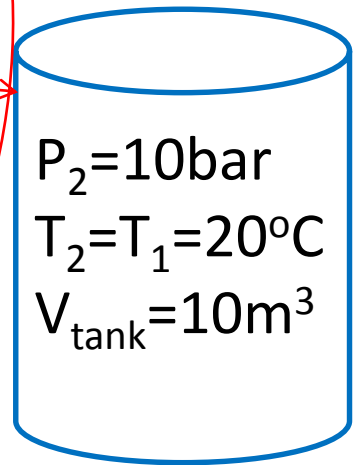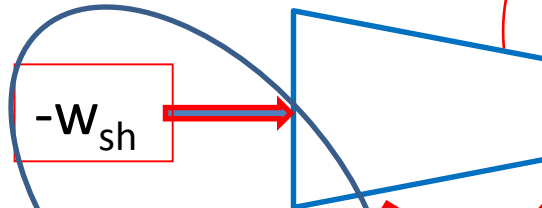
- Recall from example VII

$$w_{sh} = RT_1 \ln \frac{p_1}{p_2}$$

$$dw_{sh} = RT_1 d \ln p = RTd \ln p$$

$$w_{sh,\, p_1 \to p} = RT_1 \ln \frac{p_1}{p}$$

$$dW_{sh} = w_{sh}\, dn = RT_1 \ln \frac{p_1}{p}\, dn$$

$$dW_{sh} = V_{\text{tank}} \ln \frac{p_1}{p}\, dp$$

$$W_{sh} = 10\ m^3 \int_{10^5}^{10^6} \ln \frac{10^5}{p}\, dp = -13.5 \times 10^6\ \text{J}$$

- Ideal gas EOS

$$pv = nRT$$

$$n = \frac{V_{\text{tank}}\, p}{RT_1}$$

$$dn = \frac{V_{\text{tank}}}{RT_1}\, dp$$

$$m\left[\Delta h + \Delta e_p + \Delta e_k\right] = Q - W_{sh}$$

$$Q = W_{sh}$$

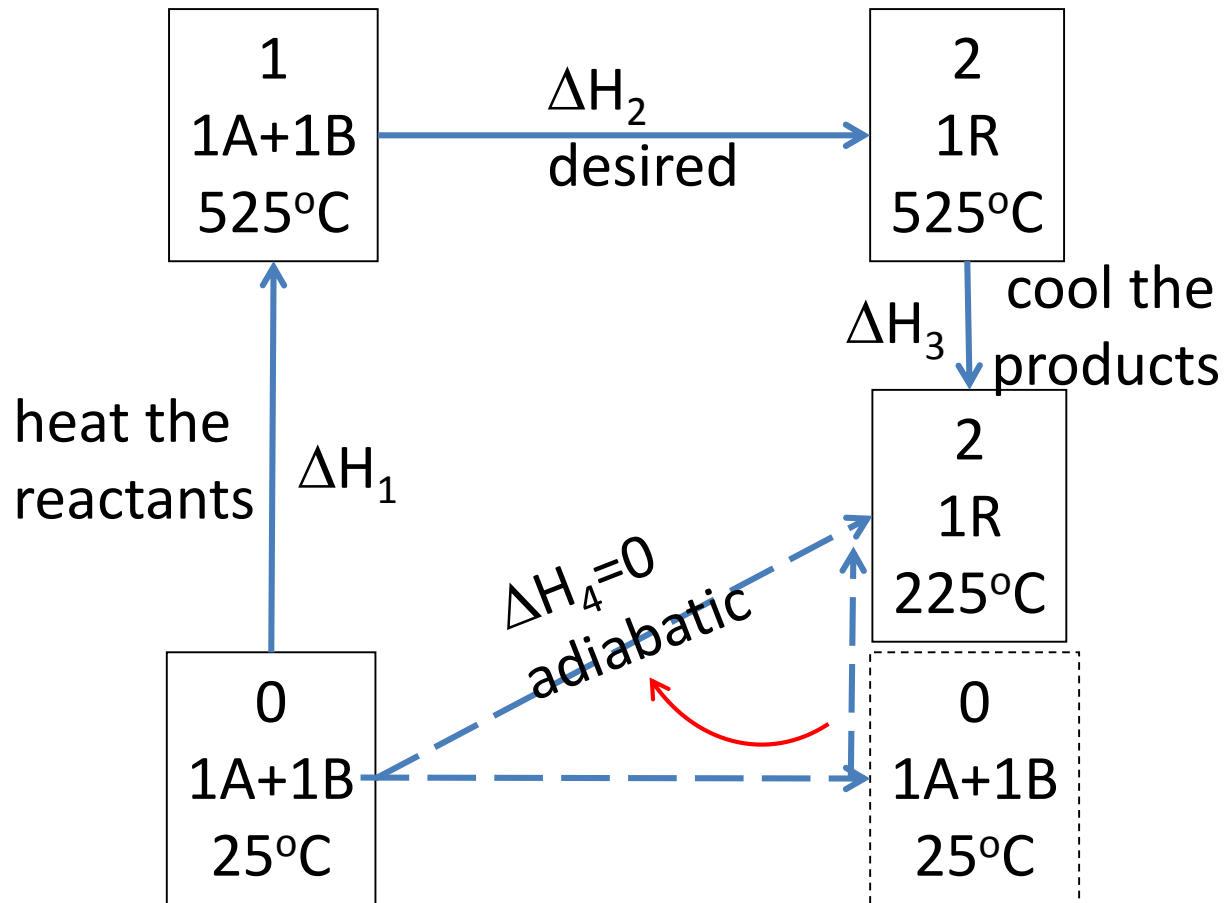$$\ln(1 + x) = x - \frac{x^2}{2} + \frac{x^3}{3} - \frac{x^4}{4} + \cdots$$
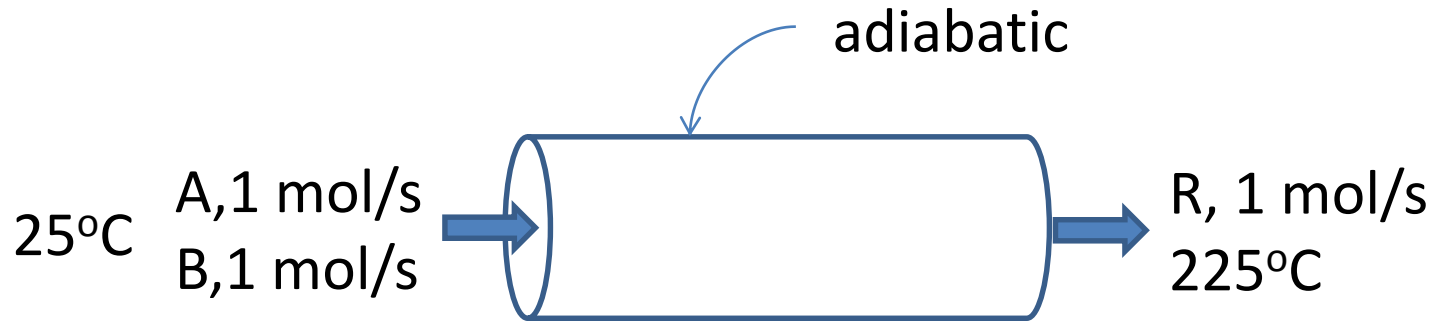
Example XI

- **The Flow Reactor** : 1 mol/s of gaseous A and 1 mol/s of gaseous B, both at 25°C, are pumped continuously into an adiabatic mixer-reactor. They react to completion according to the stoichiometry.

$$A + B \rightarrow R$$

- The product stream, also gaseous, leaves the reactor at 225°C. Find the ΔH_r for the above reaction at 525 ^{o}C.

- Data c_{pA} = 30, c_{pB} = 40, c_{pR} = 50 J/mol/K

$$\Delta H \ + \ \overline{(m\omega)}g\Delta z \ + \ \frac{\overline{(m\omega)}}{2}\Delta \mathbf{v}^2 \ = \ Q \ - \ W_{sh}$$

(red annotations: 0, 0, 0, 0 marking cancelled terms)

$$\Delta H_1 \ + \ \Delta H_2 \ + \ \Delta H_3 \ = \ \Delta H_4 \ = \ 0$$
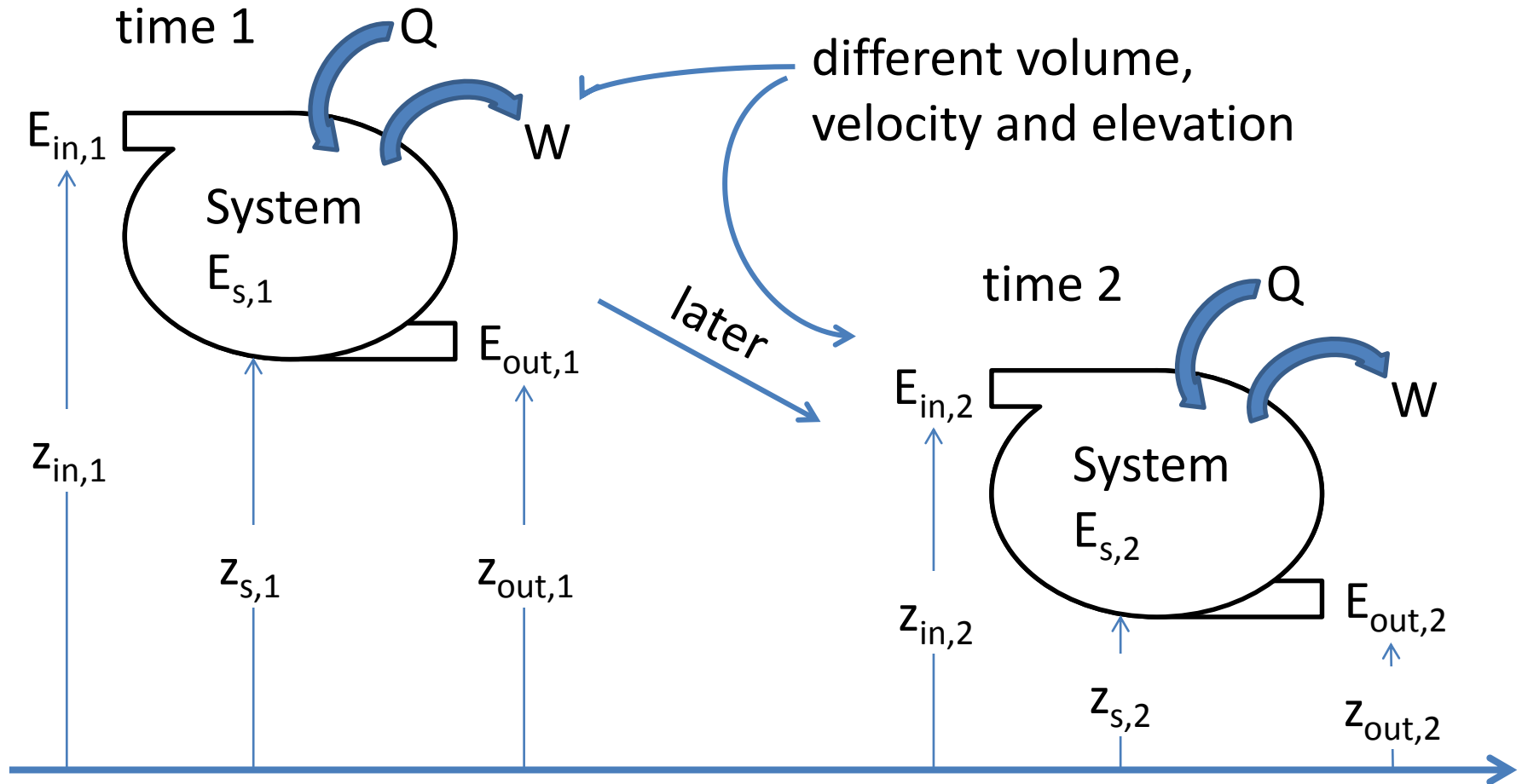
$$\Delta H_2 \ = \ -\Delta H_1 \ - \ \Delta H_3$$

$$= \ -\left[1 \cdot c_{pA}(T_1 \ - \ T_0) \ + \ 1 \cdot c_{pB}(T_1 \ - \ T_0)\right] - 1 \cdot c_{pR}(T_3 \ - \ T_2)$$

$$= \ -20 \ \ \text{kJ/mol}$$

UNSTEADY STATE FLOW SYSTEMS

Unsteady state flow systems

$\Delta \mathbf{E}_{system}$ = (all energy inputs) − (all energy outputs)

$\qquad = - \Delta \mathbf{E}_{streams} + Q - W$

$$m_2(u+e_p+e_k)_2 - m_1(u+e_p+e_k)_1 + m_{out}(u+e_p+e_k)_{out} - m_{in}(u+e_p+e_k)_{in}$$

$\qquad\qquad\underbrace{\qquad\qquad}_{system} \qquad\qquad\qquad\qquad \underbrace{\qquad\qquad}_{streams}$

$\qquad = Q - W$

where $\quad W = W_{sh} + W_{pv,system} + W_{pv,streams}$

$$m_2(u+e_p+e_k)_2 - m_1(u+e_p+e_k)_1 + m_{out}(h+e_p+e_k)_{out} - m_{in}(h+e_p+e_k)_{in}$$

$$\qquad = Q - (W_{sh} + W_{pv,system})$$

$$\qquad = Q - \left(W_{sh} + \int_{V_1}^{V_2} p_{system}\ dv\ \right)$$

volume change in system

Example I

- Filling a glass with water

Hot water (80°C) from a kettle is poured into a completely insulated styrofoam cup. Apply the general equation to the cup to find the temperature of the water in the cup.

water 1

$$(m_{cup}u_{cup})_2 + (m_{water}u_{water})_2 - (m_{cup}u_{cup})_1 - m_{kettle}h_{kettle} = Q - p_2v_2$$

assume $u_{cup1} = u_{cup2}$, Q=0, p_2 = 1 bar, v_2 = hot water

$$(m_{cup}u_{cup})_2 + (m_{water}u_{water})_2 - (m_{cup}u_{cup})_1 - m_{kettle}h_{kettle} = Q - p_2v_2$$

$$u_{water2} - h_{kettle} = -p_2v_{water2} \quad \text{or} \quad h_{water2} = h_{kettle}, \quad T_{water2} = T_{kettle} = 80^\circ C$$

$$\Delta h_{water} = 0, \quad \mathbb{C}p\,\Delta\,T_{water} = 0$$

Example II

- Filling an evacuated tank with an ideal gas

A valve on an evacuated insulated tank is opened. Air (an ideal gas) rushes in and the pressure equalizes. The valve is then quickly closed. What is the temperature of the gas in the tank if room temperature is 27^oC and pressure is 1 bar.

vacuum
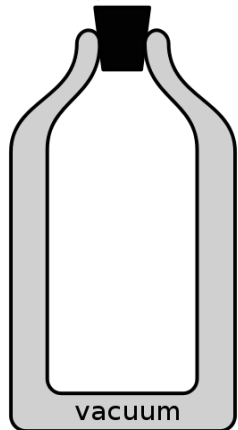
$$m_2(u+e_p+e_k)_2 - m_1(u+e_p+e_k)_1 + m_{out}(h+e_p+e_k)_{out} - m_{in}(h+e_p+e_k)_{in}$$

$$= Q - (W_{sh} + W_{pv,system})$$

$$m_2u_2 - m_{in}h_{in} = 0 \qquad u_2 = h_{in} \quad or \quad c_vT_2 = c_pT_{in}$$

$= m_2$,means stream in becomes part of system

$$T_2 = \left(\frac{29.1}{29.1 - 8.314} \right)(300) = 420K = 147\,^{\circ}C$$

An extension of the previous example has some fluid originally in the tank.

$$m_2(u+e_p+e_k)_2 - m_1(u+e_p+e_k)_1 + m_{out}(h+e_p+e_k)_{out} - m_{in}(h+e_p+e_k)_{in}$$
$$= Q - (W_{sh} + W_{pv,system})$$

$$m_2 u_2 - m_1 u_1 - (m_2 - m_1)\, h_{in} = 0$$

Since m_2 and u_2 are unknown, one may have to use trial and error to solve.

Example IV

- A large unused exhibition hall (50 m x 40 m x 10 m) is to be prepared for a show and has to be heated from 0^oC to 25^oC. How many 1.5 kW portable heaters operating for 24 hrs would be needed for this job?

- Assume the pressure stays at 1 bar, air leaks out of the hall. Only account for the heating of air not walls, fixtures and furniture.

$$n_2(u+e_p+e_k)_2 - n_1(u+e_p+e_k)_1 + n_{out}(h+e_p+e_k)_{out} - n_{in}(h+e_p+e_k)_{in}$$
$$= Q - (W_{sh} + W_{pv,system})$$

$$n_2 u_2 - n_1 u_1 + \int^{n_1 - n_2} h_{out}\, dn = Q$$

$$n_2 c_v T_2 - n_1 c_v T_1 + \int^{n_1 - n_2} c_p T\, dn = Q$$

changes as n changes

$$pv = nRT, \quad or \quad nT = \frac{pv}{R} = const. = n_1 T_1$$

$$dn_{in \atop vessel} = \frac{n_1 T_1}{- T^2}\, dT = -dn_{out}$$

$$n_2 c_v T_2 \left(\frac{n_1 T_1}{n_2 T} \right) - n_1 c_v T_1 + c_p \int_{T_2}^{T_1} T \left(\frac{n_1 T_1}{- T^2} \right) dT = Q$$

$$Q = \frac{c_p pV}{R} = \frac{29.1(10000 \quad 0)(20000)}{8.314} \ln \frac{298}{273}$$

$$= 613 \times 10^6 \text{ J/day.} \quad \boxed{\frac{613 \times 10^6 \text{ J/day}}{24 \times 3600 \text{ s/day}} \left(\frac{heater}{1500W} \right) \approx 5}$$