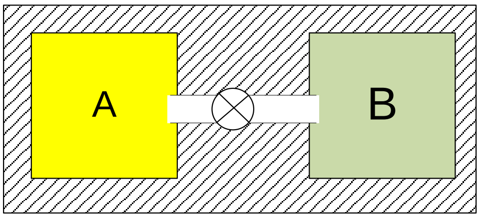
4-Open System –Irreversible:

4-1 free expansion:

Consider two vessels A&B, interconnected by short pipe with a valve, and perfectly insulated. Initially the vessel A is filled with a fluid at certain pressure, and let B will completely evacuated. When the valve is opened the fluid in A will expand rapidly to fill both A&B. This is known as free expansion. The process is highly irreversible.



$$Q = W + \Delta U$$

$$Q = 0 \, Adiabatic, \quad W = 0 \text{ Constant volume}$$

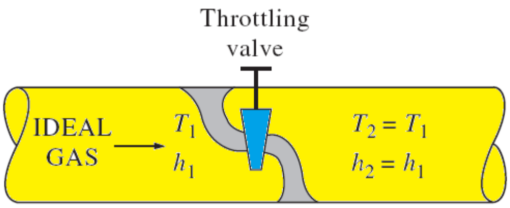
$$\therefore U_1 = U_2$$

or

$$T_1 = T_2 \text{ But not reversible process.}$$

4-2 Throttling process:

A flow of fluid is said to be throttled when there is some restriction to the flow, when the velocities before and after the restriction are either equals or negligibly, and when there is negligibly heat loss to the surroundings.



$$gz_1 + p_1v_1 + \frac{C_1^2}{2} + u_1 + q = gz_2 + p_2v_2 + \frac{C_2^2}{2} + u_2 + w$$

$$gz_1 + h_1 + \frac{C_1^2}{2} + q = gz_2 + h_2 + \frac{C_2^2}{2} + w$$

$$z_1 = z_2, \quad C_1 = C_2 \quad q = 0 \quad w = 0$$

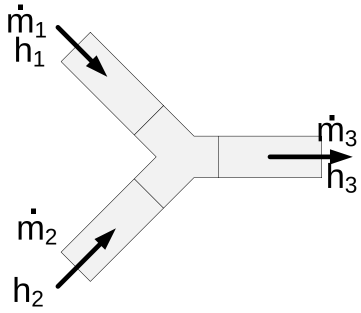
$$\therefore h_1 = h_2$$

or

$$T_1 = T_2 \quad \text{But not reversible}$$

4-3 adiabatic mixing:

$m_1+m_2=m_3$ mass conservation
$m_1h_1+m_2h_2=m_3h_3$
$m_1c_pT_1+ m_2c_pT_2= m_3c_pT_3$
if the gas mixed is at the same type.
$m_1T_1+ m_2T_2= m_3T_3$

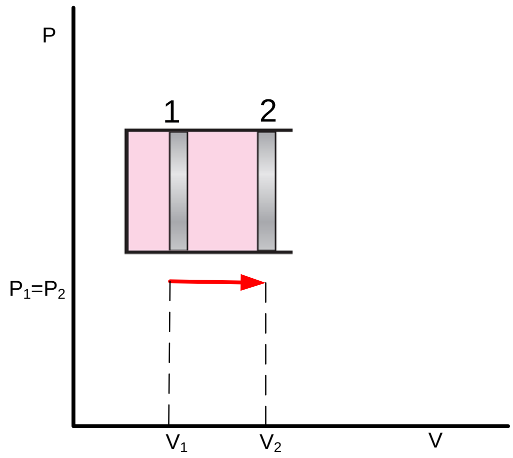


Example 1:

0.05 kg of air is heated at constant pressure of 2 bar until the volume occupied is 0.0658 m^3. Calculate the heat supplied and work done, when the initial temperature is 130 ^oC . Take c_p=1.005kJ/kgK, R=0.287 kJ/kgK.

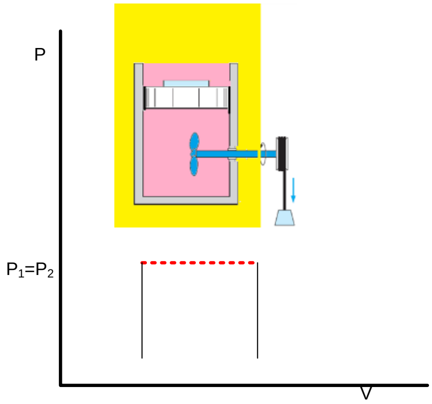
The non-flow energy equation

$$Q = W + \Delta U$$
$$W = P(V_2 - V_1) = mR(T_2 - T_1)$$
$$\Delta U = mc_v(T_2 - T_1)$$
$$Q = mR(T_2 - T_1) + mc_v(T_2 - T_1) = m(R + c_v)(T_2 - T_1)$$
$$Q = mc_p(T_2 - T_1) = m(h_2 - h_1)$$
$$P_2V_2 = mRT_2$$
$$T_2 = \frac{P_2V_2}{mR} = \frac{2\times10^2\times0.0658}{0.05\times0.287} = 912K$$
$$T_1 = 130 + 273 = 403K$$
$$Q = 0.05\times1.005\times(912 - 403) = 25.6kJ$$
$$W = mR(T_2 - T_1) = 0.05\times0.28\times(912 - 403) = 7.3kJ$$



Example 2:

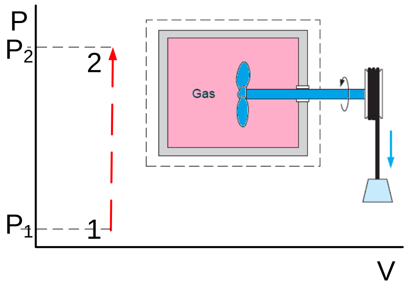
A constant pressure adiabatic system contains 0.13 kg of air at 1.3 bar. The system receives paddle work. The temperature of the air rises from 29 to 185 ^oC. Find the total work, mechanical work, change in internal energy and enthalpy. Take R=0.287 kJ/kgK, specific hears ratio 1.4.



$$Q = W + \Delta U + Wp$$
$$Q = 0 \quad adiabatic$$
$$W \neq \int pdV$$
$$But \quad W = P(V_2 - V_1) = mR(T_2 - T_1)$$
$$W = 0.13 \times 0.287 \times (185 - 29) = 5.82kJ$$
$$\Delta U = mc_v(T_2 - T_1)$$
$$c_v = \frac{R}{\gamma - 1} = \frac{0.287}{1.4 - 1} = 0.7175kJ/kgK$$
$$c_p = R + c_v = 0.287 + 0.7175 = 1.005kJ/kgK$$
$$\Delta U = 0.13 \times 0.7175 \times (185 - 29) = 14.5kJ$$
$$Q = W + \Delta U + Wp$$
$$0 = 5.82 + 14.5 + Wp$$
$$Wp = -20.32kJ$$
$$\Delta H = mcp(T_2 - T_1) = 0.13 \times 1.005 \times (185 - 29) = 20.3kJ$$

Example 3:

A closed constant volume system receives 10kJ of paddle work. The system contains oxygen at 3.5 bar 45^{o}C and occupied 0.04m3, Find the heat loss or gain if the final temperature is 185 ^{o}C, specific heats ratio is 1.4.



$$Q = W + \Delta U + Wp$$
$$W = 0 \rightarrow V = C$$
$$\Delta U = mc_v(T_2 - T_1)$$
$$R_{O_2} = \frac{8.314}{32} = 0.2598kJ/kgK$$
$$c_v = \frac{R}{\gamma - 1} = \frac{0.2598}{1.4 - 1} = 0.649kJ/kg$$
$$m = \frac{P_1 V_1}{RT_1} = \frac{3.5 \times 10^2 \times 0.04}{0.2598 \times (45 + 273)} = 0.16945kg$$
$$\Delta U = 0.16945 \times 0.649 \times (145 - 45) = 15kJ$$
$$Q = 0 + 15 - 10 = 5kJ$$

Example 4:

A piston cylinder containing air receives heat at constant temperature of 500K, and an initial pressure of 200kPa. The initial volume is 0.01m^3 and the final volume is 0.07 m^3 . Find the heat and the work. Take R=0.287kJ/kgK.

$$Q = W + \Delta U$$

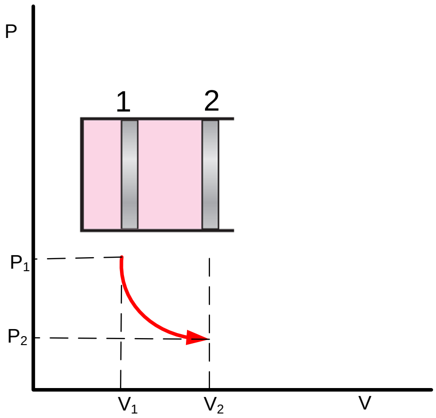
$$W = \int_1^2 P.dV = PV \ln \frac{V_2}{V_1} = mRT \ln \frac{V_2}{V_1}$$

$$m = \frac{P_1V_1}{RT_1} = \frac{200 \times 0.01}{0.287 \times 500} = 0.014kg$$

$$T = C \rightarrow \Delta U = 0$$

$$Q = W = mRT \ln \frac{V_2}{V_1} = 0.014 \times \ln \frac{0.07}{0.01}$$

$$Q = 3.9kJ$$



Example 5:

Air at 1.02 bar and 22^{o}C initially occupying a cylinder of 0.015m^3, is compressed reversibly and adiabatically by a piston to 6.8 bar. Calculate the final volume, the final temperature and the work one on the mass of air in the cylinder.

$$Q = W + \Delta U$$

$$Q = 0 \quad adiabatic$$

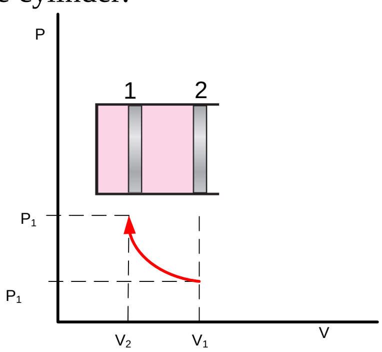
$$W = -\Delta U$$

$$P_1V_1^{\gamma} = P_2V_2^{\gamma}$$

$$V_2 = \left(\frac{P_2}{P_1}\right)^{\frac{1}{\gamma}} .V_1 = \left(\frac{1.02}{6.8}\right)^{\frac{1}{\gamma}} .0.015 = 3.86 \times 10^{-3} m^3$$

$$\frac{T2}{T1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}$$

$$T_2 = \left(\frac{6.8}{1.05}\right)^{\frac{1.4-1}{1.4}} .(22+273) = 507.25K$$



$$m = \frac{P_1V_1}{RT_1} = \frac{1.02 \times 10^2 \times 0.015}{0.287 \times 295} = 0.01807kg$$

$$\Delta U = m.c_v(T_2 - T_1) = 0.01807 \times 0.717 \times (507.25 - 295) = 2.749kJ$$

$$Q = -\Delta U = -2.749kJ$$

or

$$W = \frac{P_1V_1 - P_2V_2}{\gamma - 1} = \frac{1.02 \times 0.015 - 6.8 \times 3.86 \times 10^{-3}}{1.4 - 1} = -2.737kJ$$

Example 6:

One kg of a perfect gas is compressed from 1.1bar,27^{o}C according to a law $PV^{1.3}=C$ until the pressure is 6.6bar. Find the heat flow to or from the system when
a- the gas Ethan M=30, c_p=1.75kJ/kgK **b**-any M=30 c_p=0.515kJ/kgK **c**-the gas is Argon M=40 c_p=0.515kJ/kgK.

$$\gamma = \frac{c_p}{c_v}$$

$$R = \frac{8.314}{30} = 0.277$$

$$\gamma = \frac{1.75}{1.472} = 1.188 \therefore n \neq \gamma$$

The process is polytropic

$$Q = W + \Delta U$$

$$W = \frac{P_1V_1 - P_2V_2}{n-1} = \frac{mR(T_1 - T_2)}{n-1}$$

$$T_2 = \left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} .T_1 = \left(\frac{6.6}{1.1}\right)^{\frac{1.3-1}{1.3}} .300 = 453.6K$$

$$W = \frac{1\times 0.277\times(300-453.6)}{1.3-1} = -141.8kJ$$

$$\Delta U = mcv(T_2 - T_1) = 1\times 1.472\times(453.6-300)$$

$$\Delta U = 226kJ$$

$$Q = W + \Delta U = 84.3kJ$$

or

$$Q = \frac{\gamma - n}{\gamma - 1}.W = \frac{1.188-1.3}{1.188-1}(-141.8) = 84.47$$

b –

$$R = \frac{8.314}{70} = 0.11877kJ$$

$$c_v = c_p - R = 0.515 - 0.11877 = 0.3962kJ/kgK$$

$$\gamma = \frac{0.515}{0.396} = 1.299 \approx n \therefore adabatic\ process \rightarrow Q = 0$$

$$Q = W + \Delta U$$

$$W = -\Delta U$$

$$\Delta U = mc_v(T_2 - T_1)$$

$$T_2 = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} .T_1 = \left(\frac{6.6}{1.1}\right)^{\frac{1.3-1}{1.3}} .300 = 453.6K$$

$$\Delta U = 1\times 0.3962(453.6-300) = 226kJ$$

$$W = -226kJ$$

C –

$$R = \frac{8.314}{40} = 0.207kJ/kgK$$

$$c_v = 0.515 - 0.207 = 0.308kJ/kgK$$

$$\gamma = \frac{0.515}{0.308} = 1.67$$

$$n \neq \gamma\ polytropic$$

$$T_2 = \left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} .T_1 = \left(\frac{6.6}{1.1}\right)^{\frac{1.3-1}{1.3}} .300 = 453.6K$$

$$W = \frac{mR(T_1 - T_2)}{n-1} = \frac{1\times 0.207\times(300-453.6)}{1.3-1}$$

$$W = -105.98kJ$$

$$\Delta U = 1\times 0.308\times(453.6-300) = 47.3kJ$$

$$Q = W + \Delta U$$

$$Q = 58.67kJ$$

So when $\gamma > n$ heat is lost –Ve

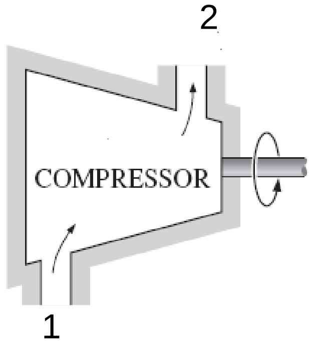
$\gamma = n$ no heat transfer

$\gamma < n$ heat is gain +Ve

Example 7:Compressor

A centrifugal air compressor of gas turbine receives air at 1 bar and 300K. At the discharge of the compressor the pressure is 4 bar , the temperature is 480K, and the velocity is 100m.s. The mass flow rate into the compressor is 15kg/s. Determine the power required to drive the compressor.

The steady flow energy equation is



$$gz_1 + (p_1v_1 + u_1) + \frac{C_1^2}{2} + q = gz_2 + (p_2v_2 + u_2) + \frac{C_2^2}{2} + w$$

$$gz_1 + h_1 + \frac{C_1^2}{2} + q = gz_2 + h_2 + \frac{C_2^2}{2} + w$$

$$z_1 = z_2, \quad C_1 = 0 \quad q = 0$$

$$w = (h_1 - h_2) - \frac{1}{2}(C_2)^2 \times 10^{-3} = c_p(T_1 - T_2) - \frac{1}{2}(C_1)^2 \times 10^{-3}$$

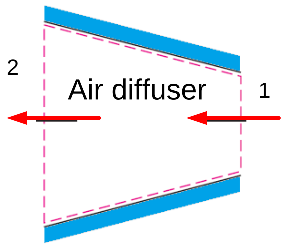
$$w = 1.005(300 - 480) - \frac{1}{2} \times (100)^2 \times 10^{-3} = -185.9kJ/kg$$

$$Power = W = m.w = 15 \times (-185.9) = -2788.5kW$$

Example 8: Diffuser

A diffuser receives Argon(cp=0.52kJ/kgK) at 100 kPa, 300K and 250m/s and the exit velocity is 25m/s. Determine the exit temperature.

The steady flow energy equation is



$$gz_1 + (p_1v_1 + u_1) + \frac{C_1^2}{2} + q = gz_2 + (p_2v_2 + u_2) + \frac{C_2^2}{2} + w$$

$$gz_1 + h_1 + \frac{C_1^2}{2} + q = gz_2 + h_2 + \frac{C_2^2}{2} + w$$

$$z_1 = z_2, \quad q = 0 \; w = 0$$

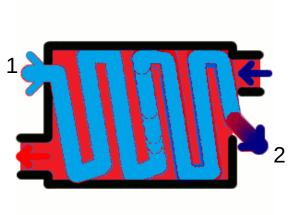
$$h_2 = h_1 + \frac{1}{2}(C_1^2 - C_2^2) \times 10^{-3} = 0.52 \times 300 + \frac{1}{2} \times (250^2 - 25^2) = 186.937kJ/kg$$

$$h_2 = c_pT_2$$

$$T_2 = \frac{h_2}{c_p} = \frac{186.937}{0.52} = 359.5K$$

Example 9: Heater

Carbon dioxide enters Steady State, Steady Flow(SSSF) heater at 300kPa& 15^{o}C and exit at 275kPa & 1200^{o}C, change in kinetic and potential energies are negligible. Calculate the required heat transfer per one kg cp=0.842kJ/kgK



$$gz_1 + (p_1v_1 + u_1) + \frac{C_1^2}{2} + q = gz_2 + (p_2v_2 + u_2) + \frac{C_2^2}{2} + w$$

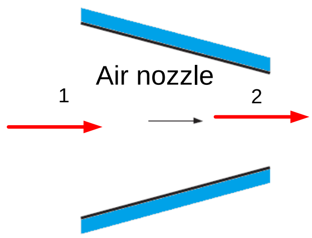
$$gz_1 + h_1 + \frac{C_1^2}{2} + q = gz_2 + h_2 + \frac{C_2^2}{2} + w$$

$$z_1 = z_2,\ w = 0\ C_1 = C_2$$

$$q = (h_2 - h_1) = c_p(T_2 - T_1) = 0.842 \times (1200 - 15) = 997.7kJ/kg$$

Example 10: Nozzle

Nitrogen gas flow into a nozzle at 200kPa and 400K with a very low velocity, it flow out at 100 kPa and 330K. If the nozzle is insulated, find the exit velocity, cp=1.042 kJ/kgK.



$$gz_1 + (p_1v_1 + u_1) + \frac{C_1^2}{2} + q = gz_2 + (p_2v_2 + u_2) + \frac{C_2^2}{2} + w$$

$$gz_1 + h_1 + \frac{C_1^2}{2} + q = gz_2 + h_2 + \frac{C_2^2}{2} + w$$

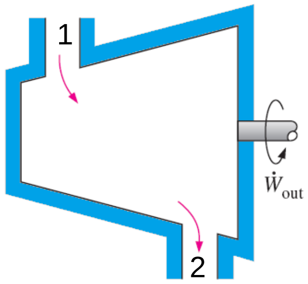
$$z_1 = z_2,\ w = 0\ C_1 = 0 \quad q = 0 \quad w = 0$$

$$\frac{C_2^2}{2} \times 10^{-3} = (h_1 - h_2)$$

$$C_2 = \sqrt{\frac{2cp(T_1 - T_2)}{10^{-3}}} = \sqrt{2 \times 10^3 \times 1.042 \times (400 - 330)} = 382m/s$$

Example 11 Turbine:

In a turbine 5000kg/min. of air expands polytropically from 4 bar & 1100^{o}C to 1 bar, the index of expansion is 1.75. Find the work done and heat transfer.



$$gz_1+(p_1v_1+u_1)+\frac{C_1^2}{2}+q=gz_2+(p_2v_2+u_2)+\frac{C_2^2}{2}+w$$

$$gz_1+h_1+\frac{C_1^2}{2}+q=gz_2+h_2+\frac{C_2^2}{2}+w$$

$$z_1=z_2,\ w=0\ C_1=C_2$$

$$h_1+q=h_2+w$$

$$q=w+\Delta h \quad Open\ system$$

$$\frac{T_2}{T_1}=\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}}$$

$$T_2=\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}}T_1=\left(\frac{1}{4}\right)^{\frac{1.75-1}{1.75}}1373=758K$$

$$Q=m.c_n.(T_2-T_1)$$

$$c_n=-c_v\frac{\gamma-n}{n-1}=-0.717\frac{1.4-1.75}{1.75-1}=0.3346kJ/kgK$$

$$Q=\frac{5000}{60}\times0.3346\times(758-17148)=-17148kW$$

$$Q=W+\Delta H$$

$$\Delta H=mcp(T_2-T_1)=\frac{5000}{60}\times0.1.005\times(758-17148)=-51506kW$$

$$W=Q-\Delta H=-17148-(-51506)=34358kW$$

<u>If we assumed another solution to the example as:</u>

$$W=\frac{P_1V_1-P_2V_2}{n-1}=\frac{mR(T_1-T_2)}{n-1}$$

$$W=\frac{\frac{5000}{60}\times0.287\times(1373-758)}{1.75-1}=19611.6kW??$$

$$Q=m.c_n.(T_2-T_1)=-17148kJ$$

$$\Delta U=mc_v(T_2-T_1)=\frac{5000}{60}\times0.717\times(758-1373)=36750$$

$$Q-W=-17148-(19611.6)=-36765.9kJ=\Delta U$$

$\therefore Q=W+\Delta U$ This for closed system???

This is not true because the system is open system, there for

$$Q=W+\Delta U \quad Closed$$

$$Q=W+\Delta H \quad Open$$

$W=\frac{P_1V_1-P_2V_2}{n-1}$ **For closed system only**

For open system polytropic:

$$Q=m.c_n.(T_2-T_1)$$

$$\Delta H=mc_p\Delta T$$

$$W=Q-\Delta H\neq\frac{P_1V_1-P_2V_2}{n-1}$$

Examples 12:

In a piston cylinder 0.5kg of air expand polytropically from 4 bar &1100 ^{o}C to 1 bar, the index of expansion is 1.75, find the work done and the heat transfer.

$$Q=W+\Delta U \quad or \quad Q=mc_n(T_2-T_1)$$

$$W=Q-\Delta U \quad or \quad W=\frac{P_1V_1-P_2V_2}{n-1}$$

$$cn=-cv\frac{\gamma-n}{n-1}=-0.717\times\frac{1.4-1.75}{1.75-1}=0.3346$$

$$T_2=\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}}.T_1=758K$$

$$Q=0.5\times0.3346\times(758-1373)=-103kJ$$

$$\Delta U=mcv(T_2-T_1)=0.5\times0.717\times(758-1373)=-220.5kJ$$

$$W=Q-\Delta U=-103-(-220.5)=117.5kJ$$

or

$$W=\frac{P_1V_1-P_2V_2}{n-1}=\frac{mR(T_2-T_1)}{n-1}=\frac{0.5\times0.287\times(758-1373)}{1.75-1}$$

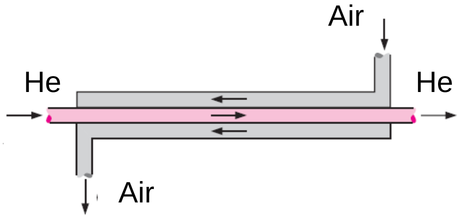
$$Q=\frac{\gamma-n}{\gamma-1}W=\frac{1.4-1.75}{1.4-1}\times117.67=-103kJ$$

Therefor all equations of polytropic process can be used for closed system, <u>while in open system the equation of work done $\frac{P_1V_1-P_2V_2}{n-1}$ cannot be used.</u>

Example 13: Heat exchanger

A simple tube to tube heat exchanger, has air flow in the outside tube cooling the Helium that flow in the inside tube. Assume the change in kinetic and potential energies are neglected. Determine the heat lost from the exchanger given the following information, air flow rate 150kg/hr enters at 5 ^oC and leaves at 60^oC, Helium flowing at 50kg/hr at 190^oC and leaves at 105 ^oC. take cp_{He} 5.16kJ/kgK.

Energy in =Energy Out



$$m_{a_i}h_{a_i}+m_{He_i}h_{He_i}=m_{a_o}h_{a_o}+m_{He_o}h_{He_o}$$

$$m_a=\frac{150}{3600}=0.0416kg/s$$

$$m_{He}=\frac{50}{3600}=0.0138kg/s$$

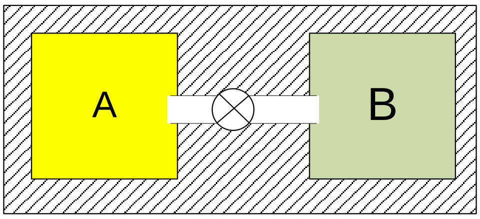
$$Q=m_a(h_{a_i}-h_{a_o})+m_{He}(h_{He_i}-h_{He_o})$$

$$Q=0.0416\times1.005\times(5-60)+0.0138\times5.16(190-105)$$

$$Q=3.8kW \quad lost$$

Example 14: Free expansion

Air at 20 bar is initially contained a vessel at volume 1 m^3 and connected with another vessel has the same volume and evacuated from the air, the two vessels are insulated, the valve between the two vessels is opened, the gas expands and fill the two vessels, calculate the final pressure of air.



$$Q=W+\Delta U$$

$$Q=0 \quad W=0$$

$$U_1=U_2$$

$$\therefore T_1=T_2$$

$$V2=V_A+V_B=2m^3$$

$$\frac{P_1V_1}{T_1}=\frac{P_2V_2}{T_2} \quad T_1=T_2$$

$$P_2=\frac{V_1}{V_2}\times P_1=\frac{1}{2}\times20=10bar$$