Thermodynamics

Chapter 4

Reversible Processes (Non-Flow & Steady Flow)

Irreversible Processes

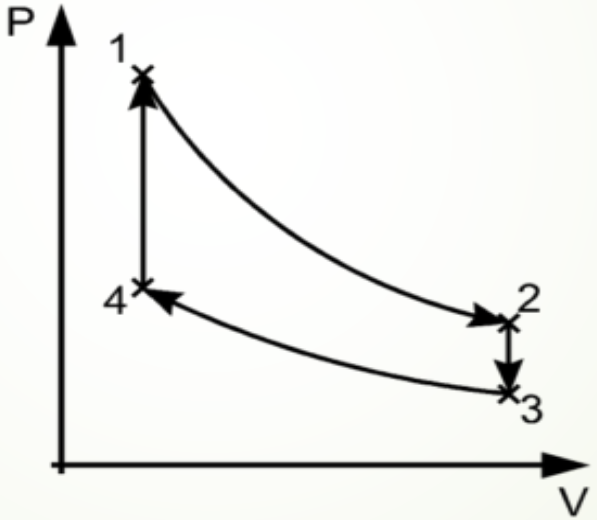
Non-Steady Flow Process

Dr. Sajid Hussein Alabbasi
Department of Mechanical Engineering
Engineering College – University of Basrah

Reversible Process

The reversible process is the ideal process which never occurs, while the irreversible process is the natural process that is commonly found in nature. When we tear a page from our notebooks, we cannot change this and ‘un-tear’. This is an irreversible process. Whereas when water evaporates, it can also be condensed in the form of rains. This is a reversible process. Let us study more about them below.

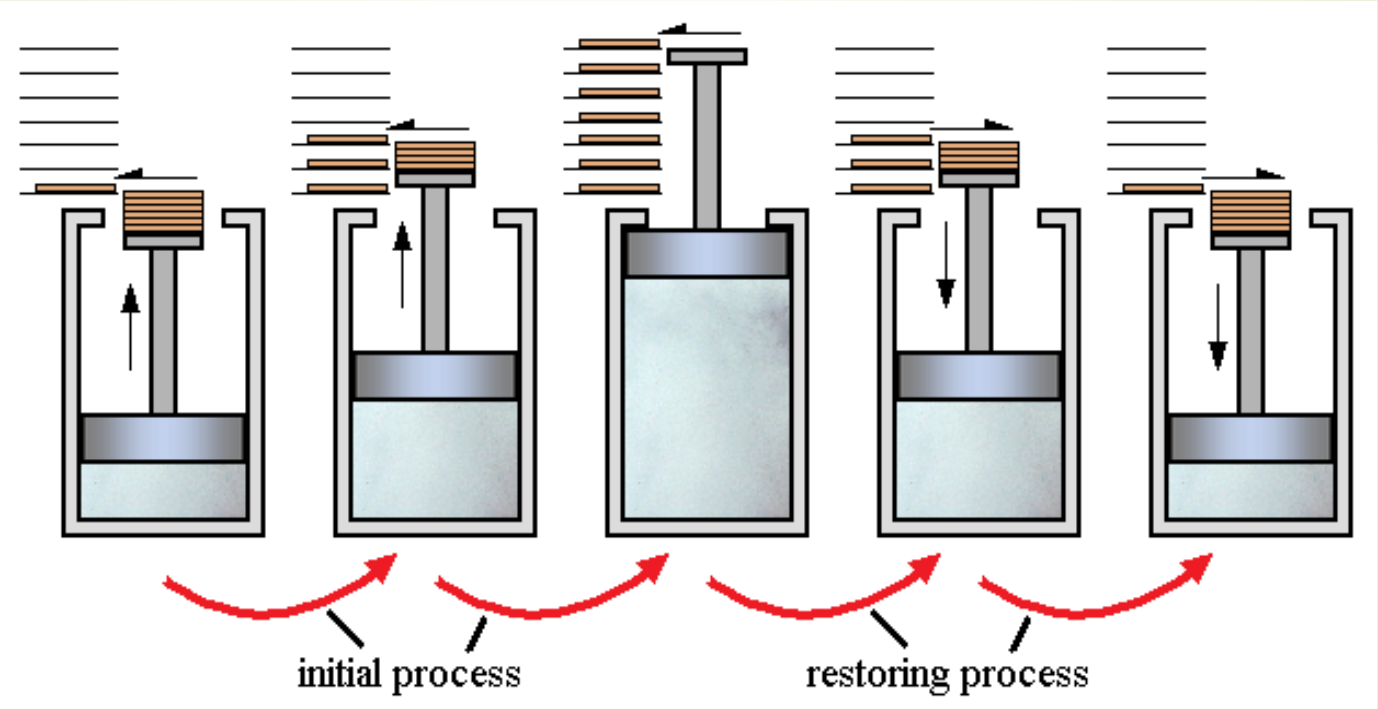
A thermodynamic process is reversible if the process can return back in such a that both the system and the surroundings return to their original states, with no other change anywhere else in the universe. It means both system and surroundings are returned to their initial states at the end of the reverse process.



In the figure above, the system has undergone a change from state 1 to state 2. The reversible process can reverse completely and there is no trace left to show that the system had undergone thermodynamic change. During the reversible process, all the changes in state that occur in the system are in thermodynamic equilibrium with each other.

A process can be reversible only when its satisfying two conditions

- Dissipative force must be absent.
- The process should occur in infinite small time.



In simple words, the process which can reverse back completely is a reversible process. This means that the final properties of the system can perfectly reverse back to the original properties. The process can be perfectly reversible only if the changes in the process are infinitesimally small. In practical situations it is not possible to trace these extremely small changes in extremely small time, hence the reversible process is also an ideal process. The changes that occur during the reversible process are in equilibrium with each other, friction effects can be assumed to be negligible and heat must never be transferred to or from the system through a finite temperature difference .

Non-Flow Reversible Processes :

(Heating/Cooling and Expansion/Compression of Gases)

Until now we have studied that thermodynamic system of a gas is used to convert heat energy into work energy or vice versa which is required in a number of practical applications.

Thermodynamic system is also of many types. Here we will study a closed system which can exchange energy with surroundings but not the mass. Thus mass does not flow in or out of the system and so the processes of heating/cooling/compression/expansion etc are undergone by this fix mass of gas confined in continuous closed boundary are called Non-flow processes. In these processes some property of the gas may change and some may not change based on which a particular process is characterized. By applying first law of thermodynamics, the various forms of energy exchange can be calculated considering the processes as reversible i.e. taking all internal/external losses due to friction etc as nil.

For this let us consider a fix quantity of an ideal gas filled in a metallic cylinder as shown in below figure, one side of which is covered or fixed by a solid end plate and other side is covered by a moving piston. The outer wall of piston matches with inner wall of cylinder such that it makes a leak proof sliding joint. This moving piston makes one of the boundaries of system as moving or flexible.

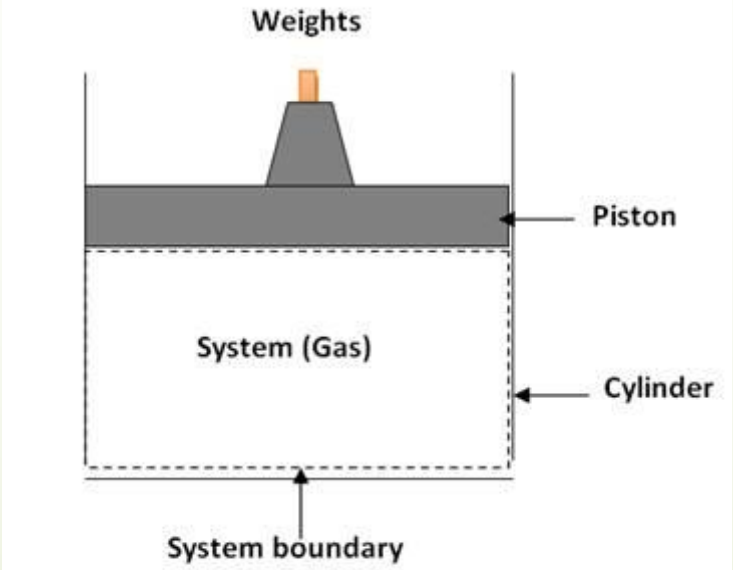


Fig. Closed system of gas filled in metallic cylinder

When infinitely small heat **δ**Q is supplied to gas from outside through the wall of cylinder, the gas tends to expand and forces the piston weight F to move up. Let piston moves by a short distance, *dl*. Then the infinitesimal work done can be calculated as

$$\delta W = F \times dl$$

$$= \frac{F}{A} \times dl \times A$$

$$= P.dV$$

Work = Pressure x Change in volume

Total work during a non-flow process 1-2 i.e. compression or expansion of gases can be calculated as taking integral of P.*dV*

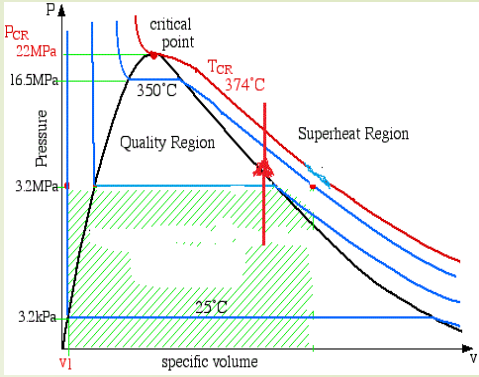
$$W = \int_1^2 P.dV$$

Thus, first law of thermodynamics can be written as :

$$\delta Q = P.dV + dU$$

All these reversible processes of heat exchange (Heating or Cooling) and work exchange (compression or expansion) by a system of ideal gas with its surroundings can take place in various ways as discussed below:

1 . Constant volume (Isochoric) heating/cooling process



Let the piston is fixed at one point in the walls of cylinder such that volume V = Constant

So the ideal gas law PV/T = Constant will reduce to

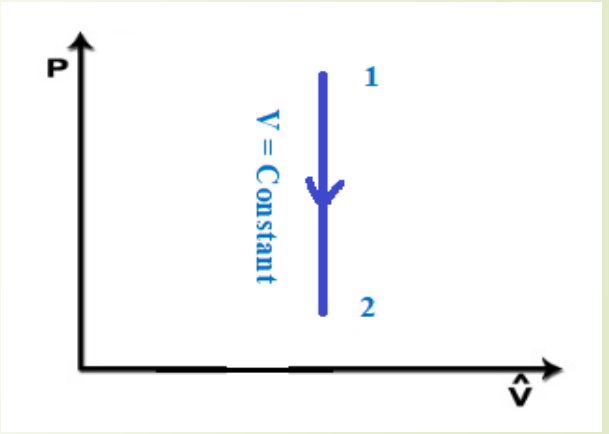
$$\frac{P}{T} = \text{Constant}$$

Now let a small increment of heat **δ**Q is supplied to the gas. According to the 1st law of thermodynamics,

$$\delta Q = \delta W + dU$$

$$\delta Q = P.dV + dU$$

As V = Constant, **δ**W = P . dV = 0, then the equation was written



For any work substance (fluid)

$$\mathbf{Q} = \Delta\mathbf{U}$$

And for perfect gas, the equation can be written as :

$$So \qquad \delta Q = \Delta U = mC_v\Delta T$$

Thus knowing the values of **δ**Q and C_v, ΔT (Increase in temperature) can be calculated and so ΔP can also be calculated from eq.

$$\frac{P}{T} = \text{Constant}$$

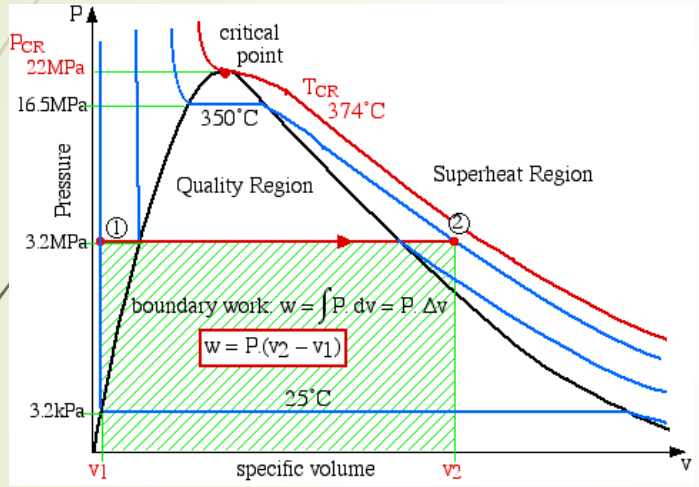
By measuring the small increment in temperature and pressure of system, the quantity **δ**Q & ΔU can also be calculated.

2 . Constant pressure (Isobaric) process

Let the piston is free to move in the cylinder and force, F or pressure, P on the piston remains constant. So now the boundaries of the system can move and so the gas can expand or can be compressed i.e. the system is able to exchange work.

Now let a small quantity of heat, **δ**Q is supplied to the gas through the walls of cylinder.

On absorbing this heat, the temperature of gas will tend to increase and simultaneously the gas will tend to expand against force F on the piston. Applying 1st law of thermodynamic to this process.



$$\delta Q = \delta W + dU$$

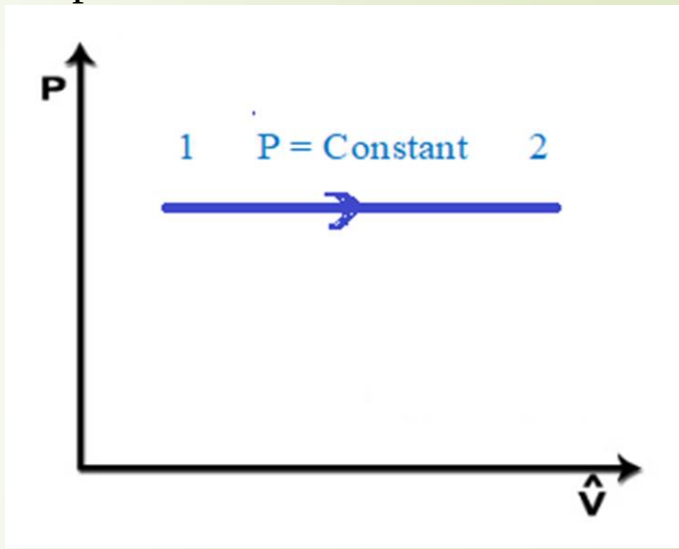
$$Or \qquad \delta Q = P.dV + m\,C_v\,dT$$

$$\mathbf{Q = P\,(V_2 - V_1) + (U_2 - U_1)}$$

$$\mathbf{Q = (U_2 + PV_2) - (U_1 + PV_1)}$$

For any working substance (fluid)

$$\mathbf{Q = H_2 - H_1}$$



And for perfect gas, the equation can be written as :

$$\mathbf{Q = C_P\,T_2 - C_P\,T_1}$$

$$\mathbf{Q = C_P\,(T_2 - T_1)}$$

$$\mathbf{Q = C_P\,\Delta T = C_P\,dT}$$

$$Q = P(V_2 - V_1) + mC_v(T_2 - T_1)$$

Also, work can be calculated for a perfect gas by equation :

$$W = P \int dV$$

$$W = P (V_2 - V_1) = PV_2 - PV_1 = m RT_2 - mRT_1 = mR (T_2 - T_1) = m \int R \, dT$$

Thus the increase in volume of gas due to expansion and increase in temperature are interrelated and if one can be measured the other can be found and the quantities W, ΔU and so Q can be calculated from equation as By ideal gas law

As pressure, P = Constant, the gas law reduce to V/T = Constant

$$\frac{PV}{T} = Constant = mR$$

And the fist law of thermodynamics

$$\delta Q = \delta W + dU$$

$$\delta Q = P.dV + m\, C_v\, dT$$

$$or \quad mC_p dT = mRdT + mC_v dT \qquad \left[\because \frac{P.dV}{dT} = mR\right]$$

$$or \quad C_p = R + C_v$$

$$or \quad C_p - C_v = R$$

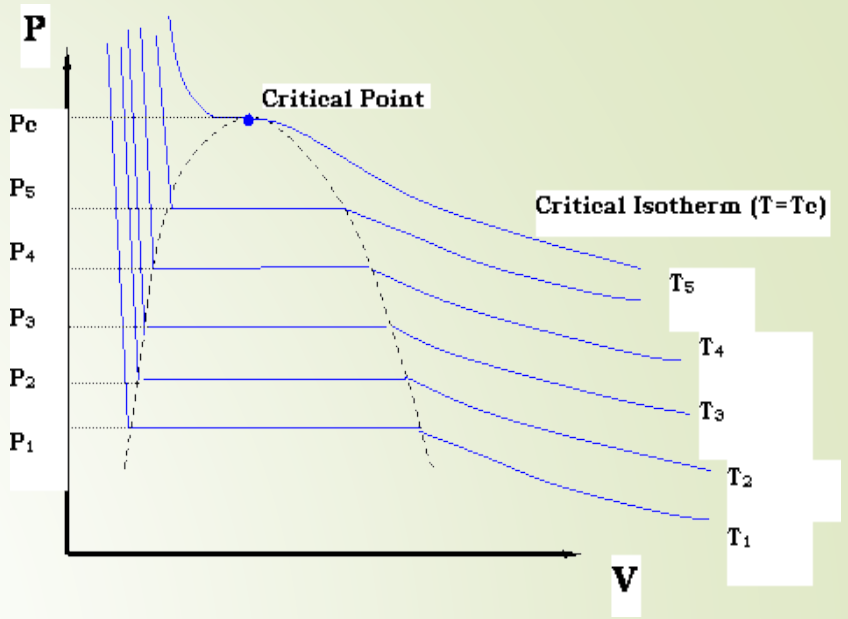
Thus characteristic gas constant of an ideal gas is the difference between specific heat at constant pressure (C_p) and at constant volume (C_v).

The ratio of specific heats $\mathbf{C_p / C_v}$ is denoted as $\boldsymbol{\gamma}$.

The physical meaning of R or γ can be taken as the characteristic of an ideal gas to expand under the influence of heat or we can say the increase in product of pressure and volume PV with increase in T.

3 . Constant temperature (Isothermal) Process

a. Steam



It can seen, that the isothermal process for a wet steam lay at the constant pressure line also. Thus the heat calculated by equation :

$$Q = H_2 - H_1$$

or

$$Q = U_2 - U_1 + W$$

b. Ideal gas (perfect gas)

The beauty of isothermal expansion or compression process (when the working substance is ideal gas) is that the internal energy remains constant and so whole of the heat exchange by system is converted to work and vice versa. However the process is difficult to visualize while thinking that when the system (gas filled behind piston in the cylinder) absorbs heat, its temperature should always increase. But what happens in the isothermal process that while absorbing heat, simultaneously the gas expands thus decrease in its pressure and temperature takes place and the net change in temperature is zero. While expanding, the gas gives positive work equal to the heat supplied. Conversely also if the gas is compressed by doing extra work on the gas, its pressure and temperature tends to increase, but simultaneously if the gas is cooled in such proportion that the net change in temperature remains zero, the compression process becomes isothermal. In this isothermal compression process, again the work supplied to the gas is given away by the system in the form of heat. Applying first law of thermodynamics to this isothermal process in which

$$du = 0, \text{ because } dt = 0$$

$$\delta Q = \delta W = P.\, dV$$

$$Q = W = \int_1^2 P.\, dV$$

From ideal gas law

$$\frac{PV}{T} = \text{constant}$$

At T= constant

Gas law reduces to PV = constant or $P_1V_1 = P_2V_2 = PV$

Putting this in equation

$$Q = W = \int_1^2 \frac{P_1V_1}{V}.dV = P_1V_1\int_1^2 \frac{dV}{V}$$

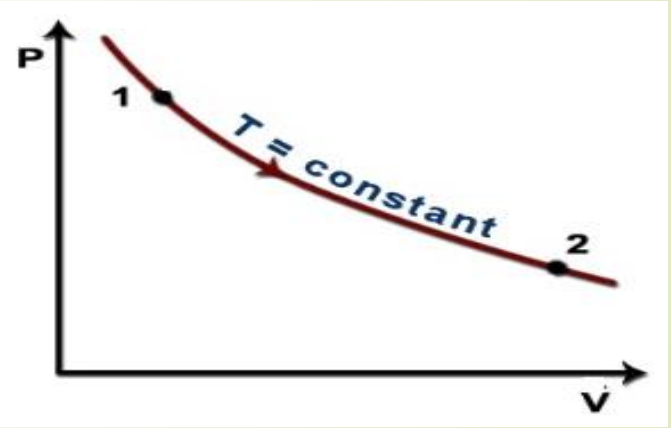
$$\mathbf{Q = W = P_1\,V_1\,ln\ \frac{v_2}{v_1}}$$

By using this equation we can calculate the work exchange or heat exchange during isothermal process if we know the change in volume.

Also in case of Isothermal process we know that

$$P_1V_1 = P_2V_2$$

$$\frac{V_2}{V_1} = \frac{P_1}{P_2}$$



Putting in eq.

$$Q = W = P_1\,V_1\,\ln\frac{p_1}{p_2}$$

By using this equation, we can calculate the work exchange or heat exchange if we know the change in pressure.

4. Adiabatic Process

- The system does not exchange heat with the surrounding
- System is completely insulated from surrounding

From non – flow equation (first law of thermodynamics)

$$\mathbf{Q = U_2 - U_1 + W}$$

$$\mathbf{Q = 0}$$

Thus, for any adiabatic process whether it is reversible or not, and for a vapour undergoing a reversible adiabatic process the work done can be found by :

$$\mathbf{U_1 - U_2 = W}$$

And for an ideal gas, where Q = 0 , The non flow equation is :

$$\mathbf{dq = du + dw = 0}$$

$$\mathbf{dq = du + p\,dv = 0}$$

$$\mathbf{du + p\,dv = 0}$$

For unit mass

$$\mathbf{P\,V = R\,T}$$

$$P = \frac{R\,T}{V}$$

$$du + \frac{R\,T\,dV}{V} = 0$$

$$C_v\,dT + \frac{R\,T\,dV}{V} = 0$$

$$C_v\,\frac{dT}{T} + R\,\frac{dV}{V} = 0$$

$$C_v\,Ln\,T + R\,Ln\,V = Constant$$

Where $T = \frac{P\,V}{R}$

$$[\ Cv\,Ln\,\frac{P\,V}{R} + R\,Ln\,V = Constant\ ]$$ divided by C_v

$$Ln\,\frac{P\,V}{R} + \frac{R}{Cv}\,Ln\,V = Constant$$

Where $Cv = \frac{R}{\gamma - 1}$, $\gamma - 1 = \frac{R}{Cv}$

$$Ln\,\frac{P\,V}{R} + (\gamma - 1)\,Ln\,V = Constant$$

$$Ln\,\frac{P\,V}{R} + Ln\,V^{(\gamma-1)} = Constant$$

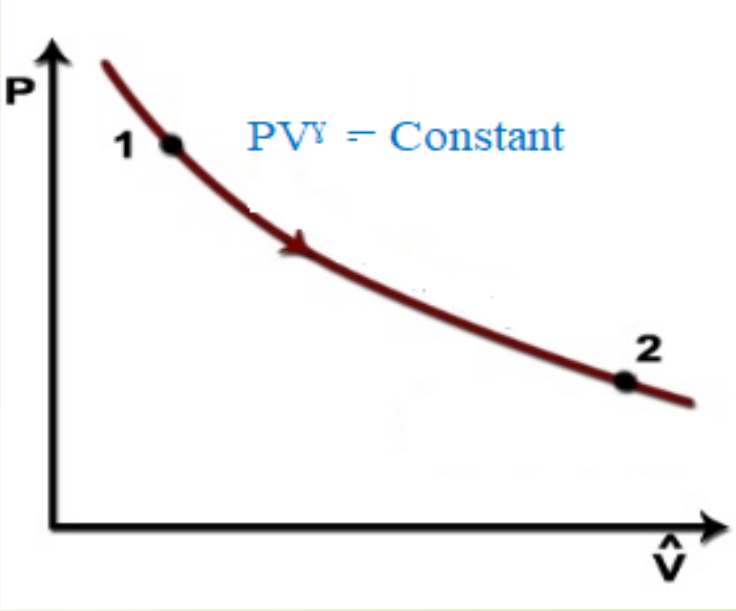
$$Ln\,\frac{P\,V^{\gamma}}{R} = Constant \qquad Then \qquad \frac{P\,V^{\gamma}}{R} = e^{constant}$$

$$PV^{\gamma} = Constant$$

Thus perfect gas expand / compress according to the equation :

$$PV^{\gamma} = \text{Constant}$$

$$P = \frac{C}{V^{\gamma}}$$



Then the work found by :

$$W = U_1 - U_2 = \int_1^2 P\, dV$$

$$W = C_v\, dT = C_v\, (T_2 - T_1)$$

or $$W = \int_1^2 \frac{C}{V^{\gamma}}\, dV = C \int_1^2 \frac{dV}{V^{\gamma}}$$

$$W = C \left[\frac{V^{1-\gamma}}{1-\gamma} \right]_1^2 = PV^{\gamma} \left[\frac{V^{1-\gamma}}{1-\gamma} \right]_1^2 = \frac{P_2V_2 - P_1V_1}{1-\gamma}$$

$$W = \frac{P_1V_1 - P_2V_2}{\gamma - 1}$$

By equations $PV^{\gamma} = \text{Constant}$, and $\frac{PV}{T} = \text{Constant}$, can found

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

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

5. Polytropic Process

It is found that many processes in practice approximate to reversible law of the form $\mathbf{PV^n = Constant}$, where n is a constant. The index n depends only on the heat and work quantities during the process . Both vapours and perfect gases obey this type of closely in many non-flow processes. Such processes are internally reversible. Thus perfect gas expand / compress according to the law :

$$\mathbf{PV^n = Constant, \quad then\ P = \frac{C}{V^n}}$$

Then the work found by :

$$\mathbf{W = {}_1\int^2 P\, dV}$$

$$\mathbf{W = {}_1\int^2 \frac{C}{V^n}\, dV = C\ {}_1\int^2 \frac{dV}{V^n}}$$

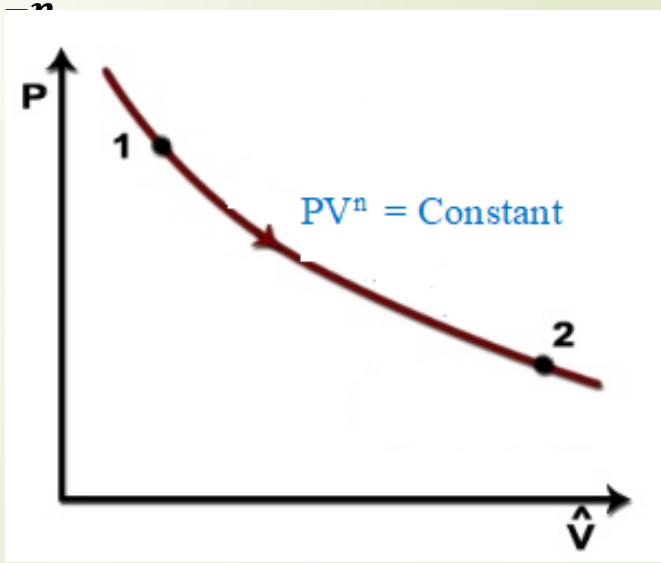
$$\mathbf{W = C\left[\frac{V^{1-n}}{1-n}\right]_1^2 = PV^n\left[\frac{V^{1-n}}{1-n}\right]_1^2 = \frac{P_2V_2 - P_1V_1}{1-n}}$$

$$\mathbf{W = \frac{P_1V_1 - P_2V_2}{n-1}}$$

By equations $\mathbf{PV^n = Constant,}$ **and** $\mathbf{\frac{PV}{T} = Constant}$, can found

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

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



$$W = \frac{P_1V_1 - P_2V_2}{n-1}$$

For unit mass , the work is

$$w = \frac{R(T_1 - T_2)}{n-1}$$

While the total work is

$$W = \frac{m\,R(T_1 - T_2)}{n-1}$$

$$Q = U2 - U1 + W = Cv(T_1 - T_2) + \frac{R(T_1 - T_2)}{n-1}$$

Where $Cv = \frac{R}{\gamma - 1}$,

$$Q = \frac{R(T_1 - T_2)}{n-1} - \frac{R}{\gamma - 1}(T_1 - T_2)$$

$$Q = R(T_1 - T_2)\left[\frac{1}{n-1} - \frac{1}{\gamma - 1}\right]$$

$$Q = \left[\frac{\gamma - n}{\gamma - 1}\right]\frac{R(T_1 - T_2)}{n-1} = \left[\frac{\gamma - n}{\gamma - 1}\right]W$$

There are 2-types of specific heats:

1. Specific Heat at Constant Volume C_v :

It is the amount of heat required to rise the temperature of unit mass of a gas through one degree when the volume is constant.
If a unit mass of a gas is taken in a closed vessel and is heated, the volume of the gas remains constant, but the temperature increases. As the volume remains constant, there is no external work done by the gas and as temperature of the gas increases, there is increase in internal energy of the gas.
Therefore heat supplied to the gas is completely utilized in increasing the I.E. of the gas,

2. Specific Heat at Constant Pressure C_p:

It is the amount of heat required to rise the temperature of unit mass of a gas through one degree when the pressure is kept constant.
Consider a unit mass of a gas in a cylinder fitted with a frictionless piston. When the gas is heated, the piston moves up, maintaining the same pressure. But the volume and temperature of the gas increases during heating.
As there is increase in volume, there is external work done by the gas and there is increase in temperature, there is increase in I.E.
Thus heat supplied when the pressure is constant, is utilized for two purposes:
(a) To do some external work.
(b) To increase the I.E of the gas.
Whereas in case of constant volume heating, the heat supplied is completely utilized for increasing the I.E.
∴ Specific heat at constant pressure is greater than specific heat at constant volume.

i.e., $C_P > C_V$ and, $C_P = \left[\frac{\delta q}{dT}\right]_P$

Also $C_P = \left[\frac{dh}{dT}\right]_P$

Therefore, C_p is also defined as, the rate of change of specific enthalpy with respect to temperature when the pressure is kept constant.

6. Adiabatic Index:

It is the ratio of specific heat at constant pressure to the specific heat at constant volume and is given by,

$$K \text{ or } \gamma = \frac{C_p}{C_v}$$

Note: For air, $C_p = 1.005 \frac{kJ}{kg-K}$ and $C_v = 0.718 \frac{kJ}{kg-K}$ and $\gamma = 1.4$

Internal Energy of an Ideal Gas

We will show that the internal energy of an ideal gas is a function of temperature only. This makes physical sense because there is an assumption in ideal gas behavior that there is no interaction between the molecules when we write

Start with a reversible process for an ideal gas:

$$P\overline{V} = RT$$

$$dU = dq + dw = dq - PdV$$

Consider two processes: one occurring at constant volume, the other occurring at constant pressure.

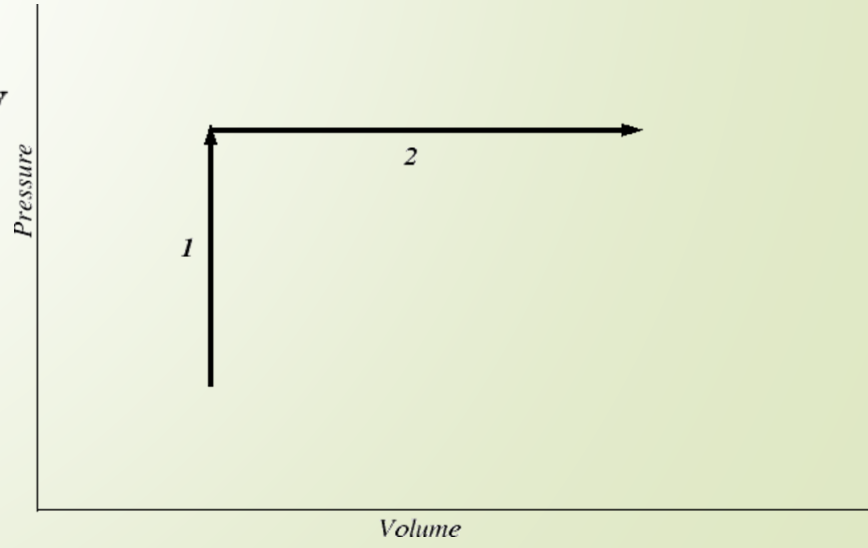


Figure : Two consecutive processes, constant volume followed by constant pressure.

For process 1: At constant V (PdV = 0)

$$dU = C_V dT + 0$$

i.e U is f (T) only $dU = C_v\, dT$

This can be integrated because T is the only thing that is changing on the right hand side (C_v is assumed to be independent of T and V).

For process 2:

$$dU = C_P dT - PdV$$

P is constant (i.e., not a function of T or V) so it can be integrated directly. Using the ideal gas law:

$$PV = nRT$$

For one mole of gas (i.e n = 1)

$$PdV + VdP = RdT$$

At constant P (VdP = 0)

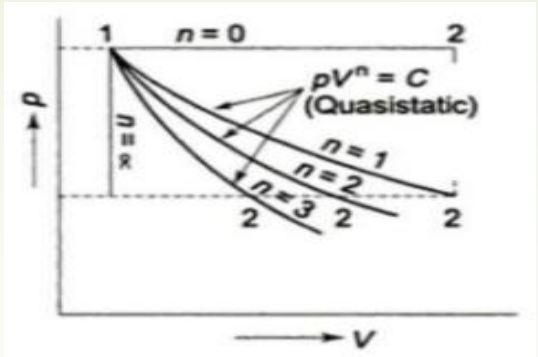
$$PdV = RdT$$

Then

$$dU = C_p\,dT - RdT$$

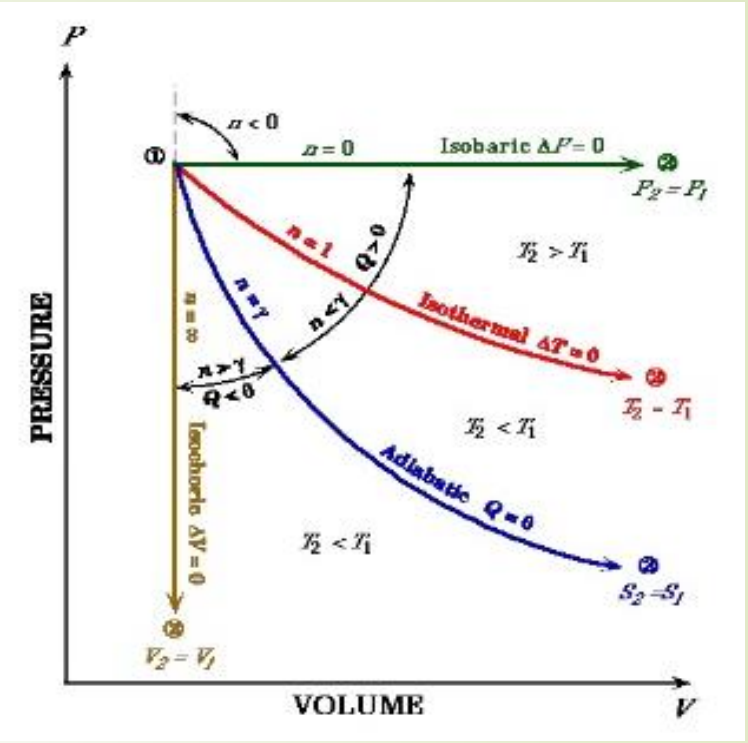
$$dU = (C_p - R)\,dT$$

So $C_v = C_p - R$



Then $dU = C_v\,dT$ or $dU = \frac{Cp}{\gamma}\,dT$, U is f (T) only.

Note : that $\gamma = \frac{Cp}{Cv}$, $C_v = \frac{R}{\gamma - 1}$ and $C_p = \frac{\gamma R}{\gamma - 1}$



Summary

A perfect gases obey this type of closely in many non-flow processes. Such processes are internally reversible according to the law : $PV^{index} = Constant.$ And $\frac{PV}{T} = Constant.$

1. If index = ∞ , the process is to be called Isochoric process i.e V = Constant $(P)^{(1/\infty)}$ = Constant. If the gas is an ideal gas. Then, P / T = Constant
2. If index = 1 , the process is to be called Isothermal process i.e T = Constant. Then, PV = Constant
3. If index = 0 , the process is to be called Isobaric process i.e P = Constant. Then $\frac{V}{T}$ = Constant .
4. If index = ɤ , the process is to be called adiabatic process. Then, PV^{γ} = Constant
5. If index = n , the process is to be called polytropic process. Then, PV^n = Constant

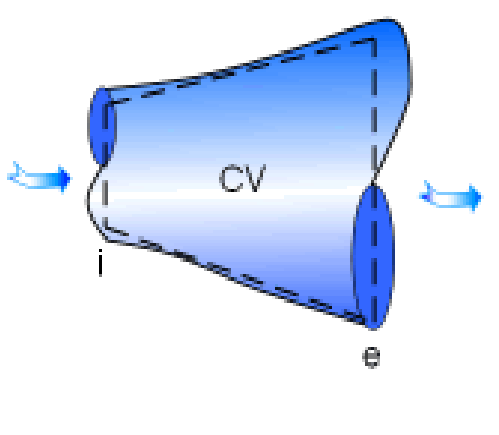
Steasdy Flow Reversible Processes :

The energy balance for a steady-flow device (nozzle, compressor, turbine and pump) with one inlet and one exit is:

$$K E_1 + P E_1 + I E_1 + W E_1 + Q = K E_2 + P E_2 + I E_2 + W E_2 + W$$

$$\frac{C_1^2}{2} + g Z_1 + U_1 + P_1 V_1 + Q = \frac{C_2^2}{2} + g Z_2 + U_2 + P_2 V_2 + W$$

One-inlet-one-exit Nozzle



$$\frac{C_1^2}{2} + g Z_1 + H_1 + Q = \frac{C_1^2}{2} + g Z_1 + H_2 + W$$

$$Q - W = \Delta H + \Delta K E + \Delta P E$$

Its differential form is:

$$dq - dw = dh + dke + dpe$$

If the device undergoes an internally reversible process, the heat transfer term δq can be replaced by dh - vdP since

$$h = u + pv$$

$$dh = du + p\,dv + v\,dp$$

$$dh - v\,dp = du + p\,dv$$

$$dq = du + p\,dv$$

$$dq = dh - v\,dp$$

Then the energy balance becomes

$$\mathbf{dh - v\,dp - dw = dh + dke + dpe}$$

By rearranging the above equation, the reversible steady-flow work can be expressed as

$$\mathbf{-dw_{reversible} = v\,dp + dke + dpe}$$

Integrating it form location 1 to location 2 yields

$$w_{rev} = -\int_1^2 v\,dP - \Delta ke - \Delta pe$$

The above equation is the relation for the reversible work output associated with an internally reversible process in a steady-flow device. When the changes in kinetic and potential energies are negligible, the relation reduces to

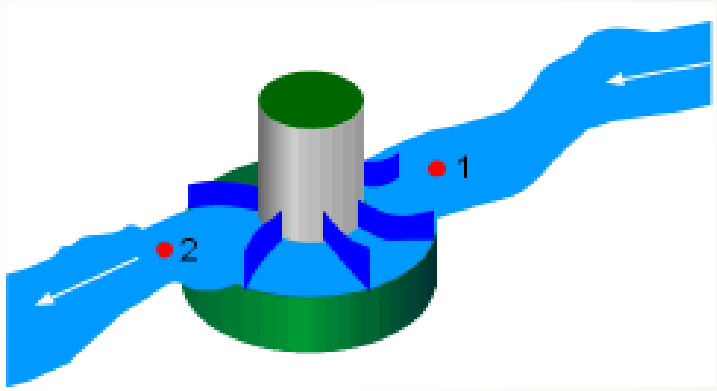
$$w_{rev} = -\int_1^2 v\,dP$$

The above equation states that the larger the specific volume, the larger the reversible work produced or consumed by a steady-flow device. To minimize the work input during a compression process, one should keep the specific volume of the working fluid as small as possible. In the same manner, to maximize the work output during an expansion process, one should keep the specific volume of the working fluid as large as possible.

One needs to know the relationship between the specific volume v and the pressure P for the given process to perform the integration in the above relation. If an incompressible fluid is used as the working fluid, the specific volume v is a constant. The relation for the reversible work output associated with an internally reversible process in a steady-flow device is simplified to give

$$W_{rev.} = -V(P_2 - P_1) - dke - dpe$$

Hydraulic turbines used in hydroelectric power plants run in a steady-flow process with incompressible fluid, i.e., water, as the working fluid.



Water Flowing through a Hydraulic Turbine

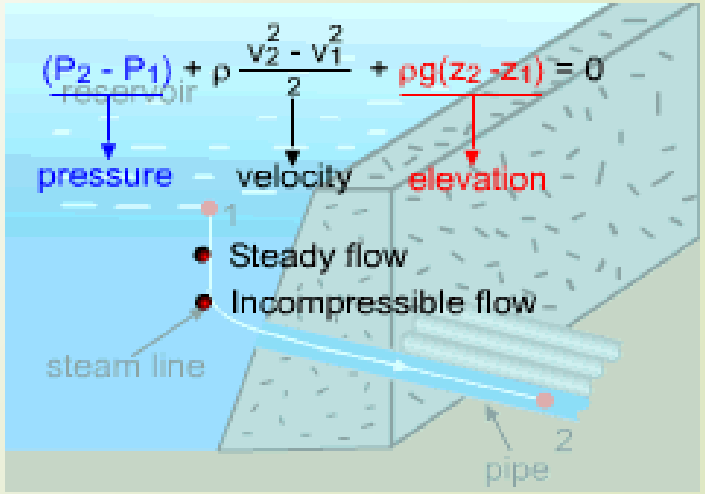
If no work interactions are involved, like nozzle or pipe section, the above equation is reduced to

$$v(P_2 - P_1) + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1) = 0$$

or

$$(P_2 - P_1) + \rho\frac{V_2^2 - V_1^2}{2} + \rho g(z_2 - z_1) = 0$$

where V is the velocity of the fluid. This equation is known as the Bernoulli equation in fluid mechanics.



Reversible Steady – flow Devices produce Most and Consume Least Work

The steady-flow devices deliver the most and consume the least work when it undergoes a reversible process. Consider two steady-flow devices, one is reversible and the other is irreversible (actual process), operating between the same inlet and exit states. The differential forms for the energy balance of these two devices are

$$\delta q_{act} - \delta w_{act} = dh + dke + dpe$$

$$\delta q_{rev} - \delta w_{rev} = dh + dke + dpe$$

The right hand sides of these two equations are the same. It gives,

$$q_{act} - \delta w_{act} = q_{rev} - \delta w_{rev}$$

Rearranging this equation gives,

$$\delta w_{rev} - \delta w_{act} = q_{rev} - q_{act}$$

Since $q_{rev} = Tds$, the above equation becomes,

$$\delta w_{rev} - \delta w_{act} = Tds - q_{act}$$

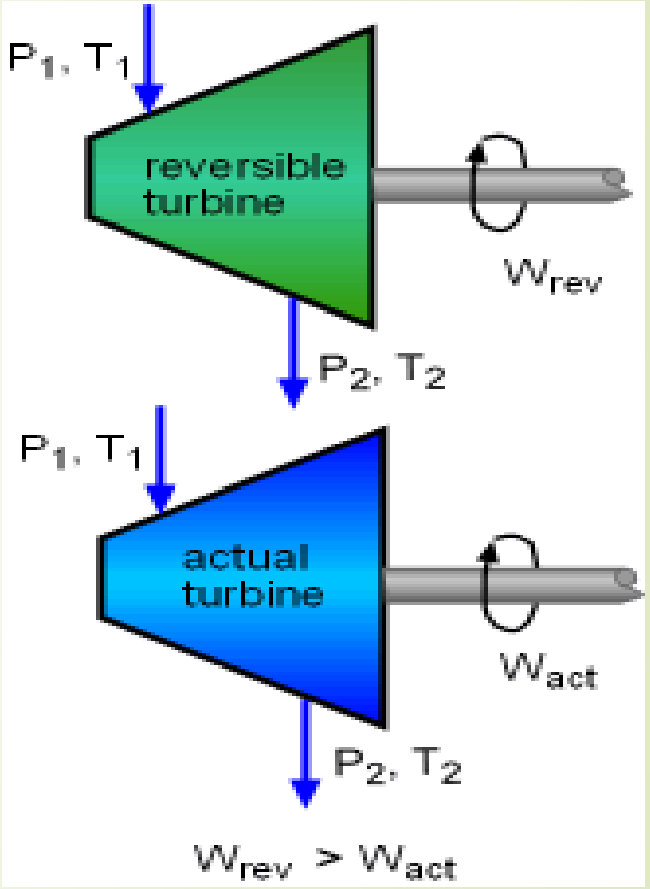
the increase of entropy principle gives

$$ds \geq \frac{\delta q_{act}}{T}$$

Thus,

$$\delta w_{rev} - \delta w_{act} \geq 0 \qquad \text{or} \qquad \delta w_{rev} \geq \delta w_{act}$$

.



Reversible Turbine Delivers more Work than Actual Turbine

That is, for the same inlet and exit conditions, when the device undergoes a reversible process, a work-produce device like turbine produces the most work (w is positive), or a work-consuming device like compressor consumes the least work (w is negative).

Some work is done on or by the gas by virtue of the forces acting between the moving gas and it's surrounding, us For reversible adiabatic flow process for a perfect gas, for the flow equation :

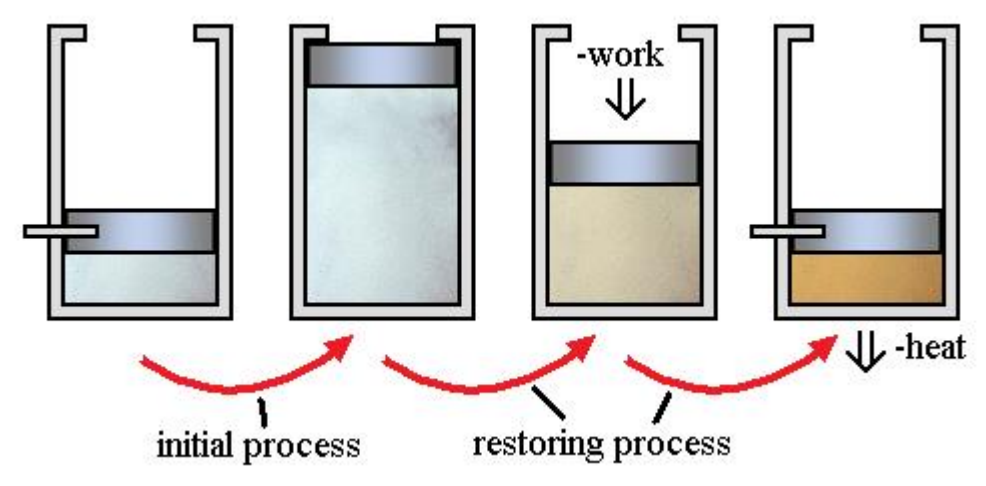
$$\frac{C_1^2}{2} + g Z_1 + H_1 + Q = \frac{C_1^2}{2} + g Z_1 + H_2 + W$$

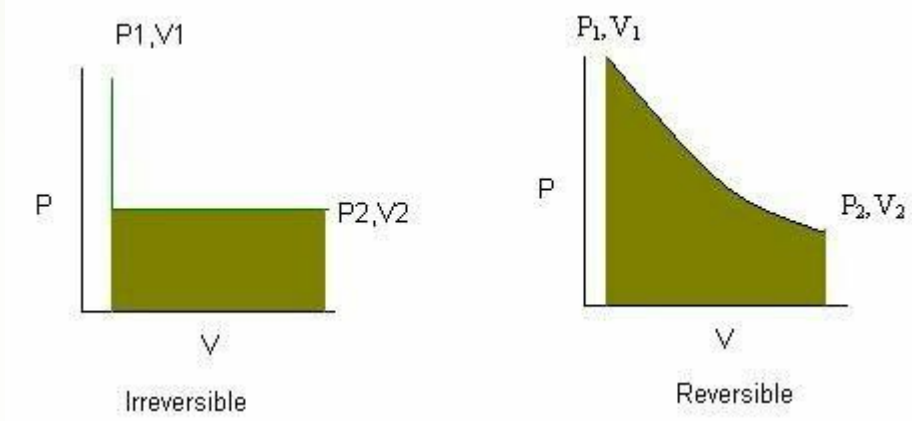
Adiabatic means, **Q = 0, & same elevation** $Z_1 = Z_2$

$$W = (h_1 - h_2) + \left(\frac{C_1^2 - C_2^2}{2} \right)$$

Irreversible Process

Irreversible processes are a result of straying away from the curve, therefore decreasing the amount of overall work done. An irreversible process is a thermodynamic process that departs from equilibrium. In terms of pressure and volume, it occurs when the pressure (or the volume) of a system changes dramatically and instantaneously that the volume (or the pressure) do not have the time to reach equilibrium.





A classic example of an irreversible process is allowing a certain volume of gas to release into a vacuum. By releasing pressure on a sample and allowing it to occupy a large space, the system and surroundings are not in equilibrium during the expansion process.

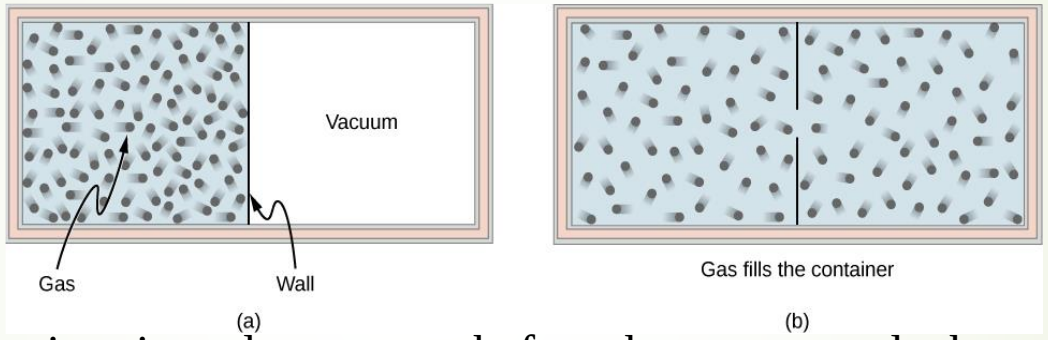
Here little work occurs. However, there is a requirement of significant work, with a corresponding amount of energy dissipation as heat flows to the environment. This is in order to reverse the process.

Non-Flow Irreversible Processes :

free expansion

Consider an ideal gas that is held in half of a thermally insulated container by a wall in the middle of the container. The other half of the container is under vacuum with no molecules inside. Now, if we remove the wall in the middle quickly, the gas expands and fills up the entire container immediately, as shown in (Figure).

A gas expanding from half of a container to the entire container (a) before and (b) after the wall in the middle is removed.



Because half of the container is under vacuum before the gas expands there, we do not expect any work to be done by the system that is, **W = 0** because no force from the vacuum is exerted on the gas during the expansion. If the container is thermally insulated from the rest of the environment, we do not expect any heat transfer to the system either, so **Q = 0** . Then the first law of thermodynamics leads to the change of the internal energy of the system,

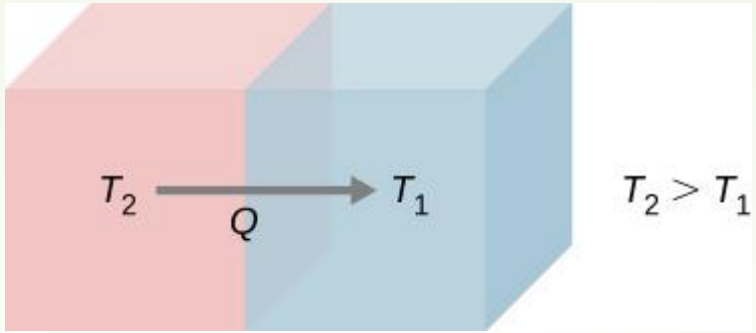
$$\Delta U = Q - W$$

For an ideal gas, if the internal energy doesn't change, then the temperature stays the same i.e $T_1 = T_2$. Thus, the equation of state of the ideal gas gives us the final pressure of the gas,

$$PV = nRT \quad \text{then} \quad PV = \text{Constant} \qquad \text{i.e} \qquad \frac{P_1}{P_2} = \frac{V_2}{V_1}$$

Where P_O is the pressure of the gas before the expansion. The volume is doubled and the pressure is halved, but nothing else seems to have changed during the expansion.

Let us see another example of irreversibility in thermal processes. Consider two objects in thermal contact: one at temperature and the other at temperature $T_2 > T_1$, as shown in (Figure)



Spontaneous heat flow from an object at higher temperature T_2 to another at lower temperature T_1. We know from common personal experience that heat flows from a hotter object to a colder one. For example, when we hold a few pieces of ice in our hands, we feel cold because heat has left our hands into the ice. The opposite is true when we hold one end of a metal rod while keeping the other end over a fire.

Steady Flow Irreversible Processes :

Throttling Process (Isenthalpic Process)

A throttling process is a thermodynamics process, in which the enthalpy of the gas or medium remains constant **(h = constant)**. In fact, the throttling process is one of isenthalpic processes **(S = Constant)**. During the throttling process no work is done by or on the system **(dW = 0)**, and usually there is no heat transfer (adiabatic) from or into the system **(dQ = 0)**. On the other the throttling process cannot be isentropic, it is a fundamentally irreversible process. Characteristics of throttling process:

1. No Work Transfer
2. No Heat Transfer
3. Irreversible Process
4. Isenthalpic Process

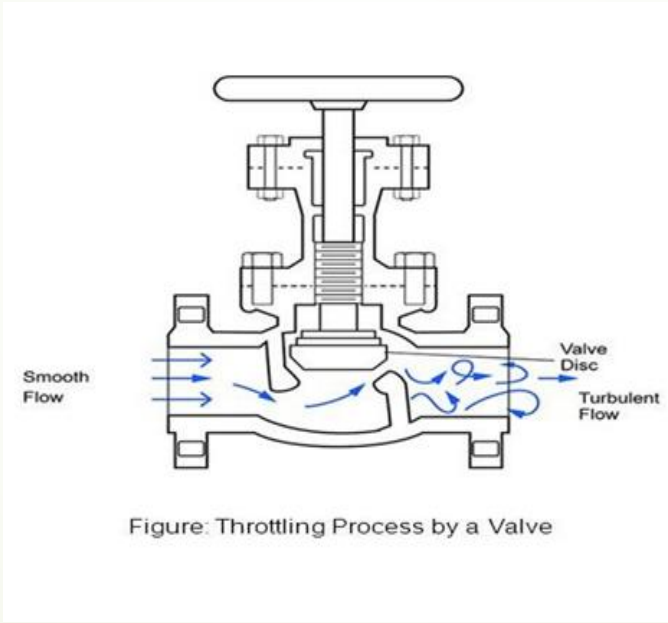
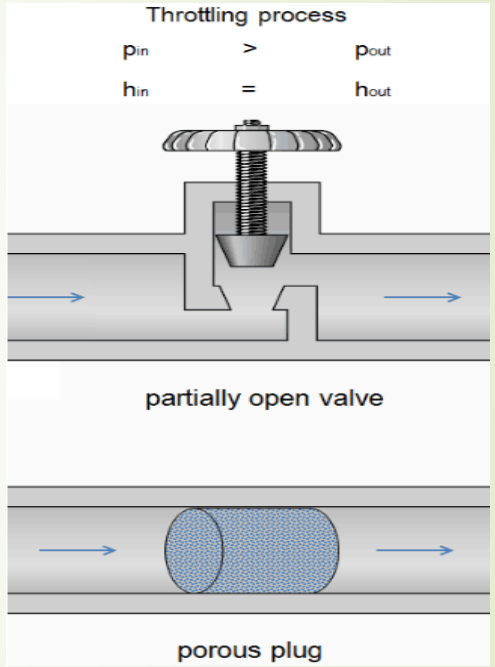
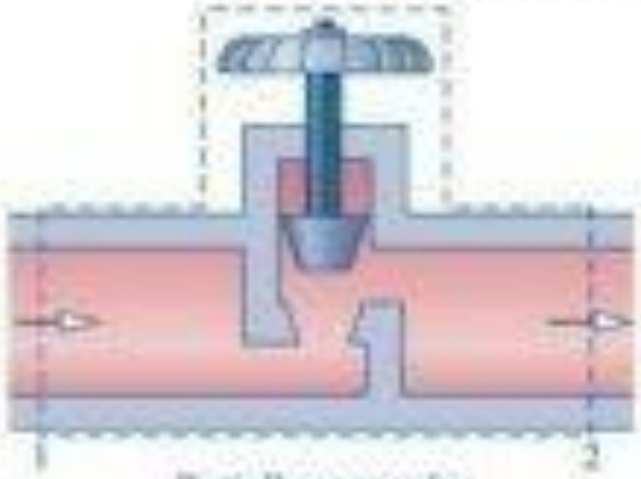


Figure: Throttling Process by a Valve



A throttling of the flow causes significant reduction in pressure, because a throttling device causes a local pressure loss. A throttling can be achieved simply by introducing a restriction into a line through which a gas or liquid flows. This restriction is commonly done by means of a partially open valve or a porous plug. Such pressure losses are generally termed minor losses, although they often account for a major portion of the head loss. The minor losses are roughly proportional to the square of the flow rate .

Throttling devices



Partially open valve

Flow restriction

Porous plug

Capillary tube expansion valve used to drop refrigerant pressure and temperature

- Slow flows, ΔKE effects can be neglected

Throttling is an isenthalpic process.

Fundamentally, non-quasiequilibrium.

Negligible heat transfer (small devices) ($\propto$ surface area)

$$\dot{m}\left(h_2 - h_1 + \frac{V_2^2 - V_1^2}{2}\right) = 0$$

$$h_2 = h_1$$

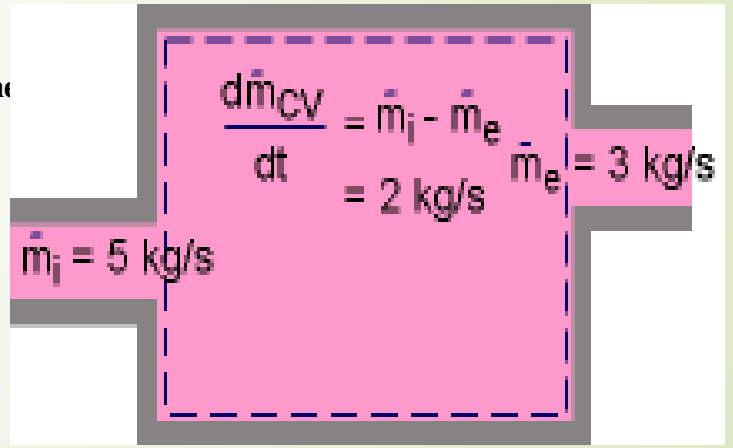
Non-Steady Flow Process

In the previous sections, it was noted that nozzles, diffusers, turbines, compressors and other devices undergo a steady flow process because of their long-time running consideration. But their start up and shutdown periods undergo transient operations since their states change with time. The flow processes involved are called unsteady-flow processes, or transient-flow processes. Unlike steady-flow processes, unsteady-flow processes start and end over some finite time period (Δt). An additional example of an unsteady-flow process is filling or discharging a tank (internal energy as well as mass of the tank changes with time). Anther example is the condition of water in the cylinder jacket of an Internal Combustion engine (is time dependant).

In a steady flow process we have assumed that the mass and energy within the system remain constant and do not vary with time. In an unsteady flow process, mass and energy within the control volume vary continuously.

During an unsteady-flow process, the mass in the control volume changes with time. The mass balance for a system undergoing any process, can be used for control volume as

$$\Sigma m_i - \Sigma m_e = m_2 - m_1 = \Delta m_{\text{control volume}}$$



where

m_i = the mass flow into the control volume through one inlet
m_e = the mass flow out of the control volume through one exit
m_1 = the mass of the fluid in the control volume before process
m_2 = the mass of the fluid in of the control volume after process

Or in rate form (mass per time $\frac{\text{kg}}{\text{sec}}$)

$$\Sigma m'_i - \Sigma m'_e = \frac{dm_{cv}}{dt} = dm'_{CV}$$

where

m'_i = the mass flow rate into the control volume through one inlet

m'_e = the mass flow rate out of the control volume through one exit

dm'_{CV} = the rate of change of mass within the control volume

The energy can be transferred by heat, work, and mass only, the energy balance can be rewritten as :

$$\delta Q + \delta m_i (K E_i + P E_i + I E_i + W E_i) - \delta W - \delta m_e (K E_e + P E_e + I E_e + W E_e) = \Delta I E_{CV}$$

Where $\Delta I E_{cv} = m_2 U_2 - m_1 U_1$ is the change of internal energy of the system (control volume)

$$Q - W + \delta m_i \left(\frac{C_i^2}{2} + g z_i + u_i + p_i v_i \right) - \delta m_e \left(\frac{C_e^2}{2} + g z_e + u_e + p_e v_e \right) = m_2 u_2 - m_1 u_1$$

$$Q - W + \delta m_i \left(\frac{C_i^2}{2} + g z_i + h_i \right) - \delta m_e \left(\frac{C_e^2}{2} + g z_e + h_e \right) = \Delta U_{CV}$$

Where $\Delta U_{CV} = U_2 - U_1 = m_2 u_2 - m_1 u_1$

$h = u + p v$

Note that any term can be negligible depending on the application of device . For example of the non steady flow process is the case in which a vessel is opened to large space and fluid is allowed to escape . There is no work done and in this case $m_i = 0$ since no mass enters the system, neglecting changes in potential energy and applying above equation :

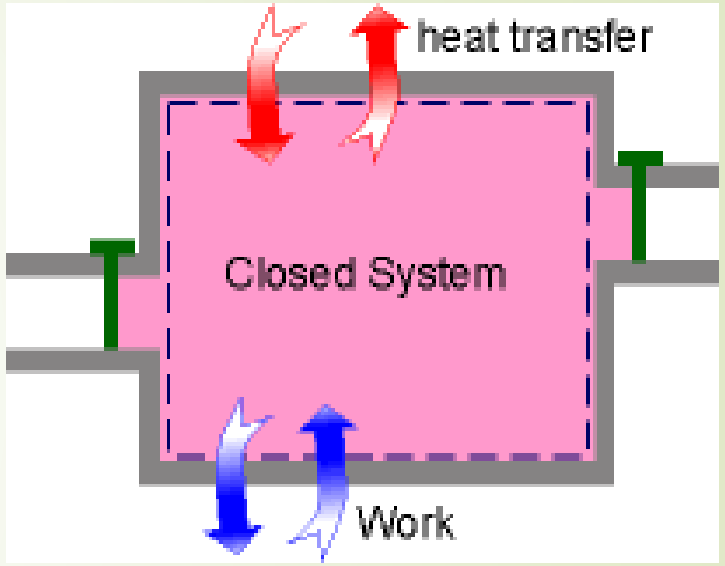
$$Q - \delta m_e \left(\frac{C_e^2}{2} + h_e \right) = \Delta U_{CV}$$

When no mass is entering or leaving the control volume, and the kinetic and potential energy changes associated with the control volume are negligible, the energy equation can be reduced to the first law relation for closed system.

$$m_2 = m_1 = m$$

$$Q - W = \sum m_e\left(h_e + \frac{v_e^2}{2} + gz_e\right) - \sum m_i\left(h_i + \frac{v_i^2}{2} + gz_i\right) + \left[m_2(u + ke + pe)_2 - m_1(u + ke + pe)_1\right]$$

$$Q - W = m(u_2 - u_1)$$



System Reduces to a Closed System

When all the Inlets and Exits are Closed

Thank You