Thermodynamics

Chapter 4

Reversible Processes (Flow & Steady Flow)
Irreversible Processes

Dr. Mahmood Shaker Jamel
Department of Engineering of Mechanics
Engineering College – University of Basrah

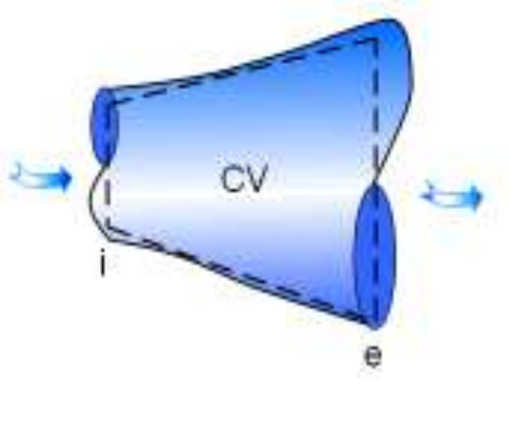
Steasdy Flow Reversible Processes :

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

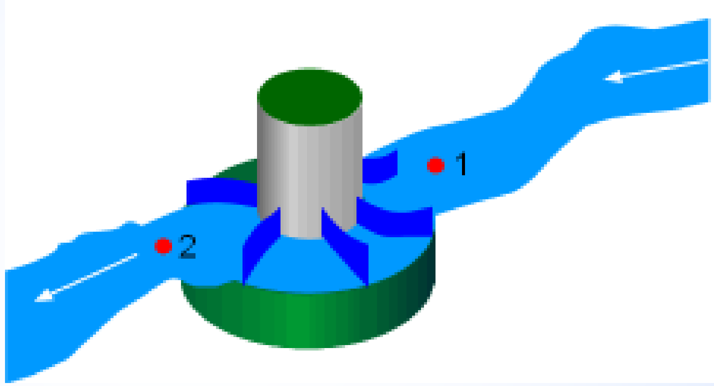
$$w_{rev} = -\int_1^2 v\,dP$$

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

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

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

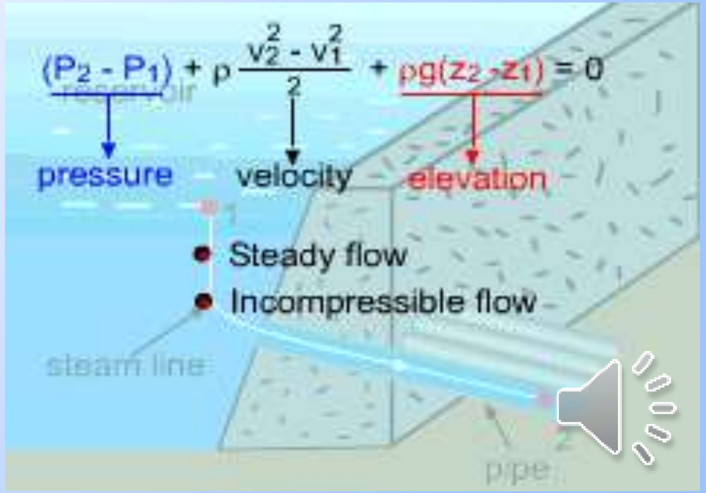
If no work interactions are involved, like nozzle or pipe section, the above equation is reduced to

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

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,

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

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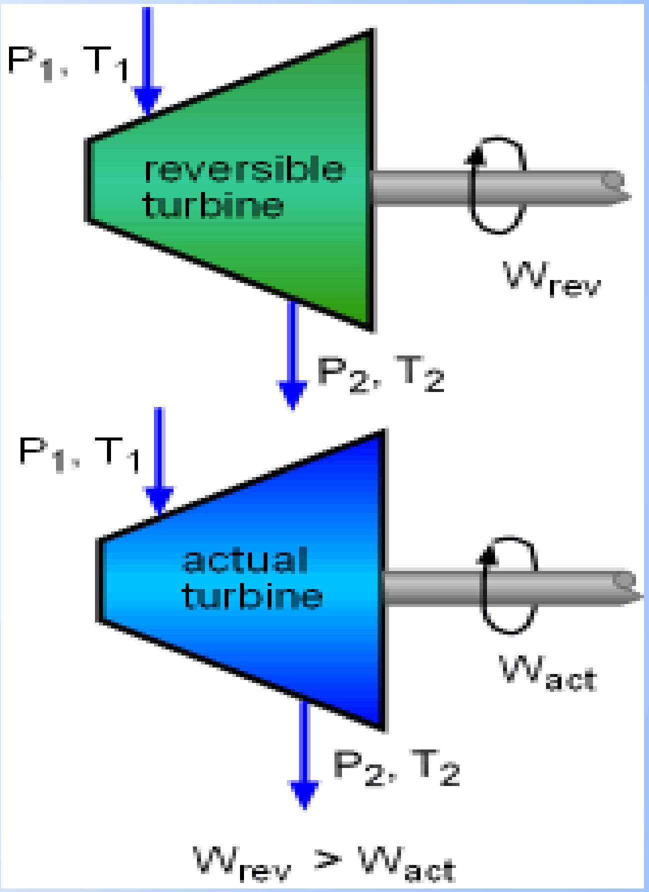


Reversible Turbine Delivers more Work than Actual Turbine

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 :

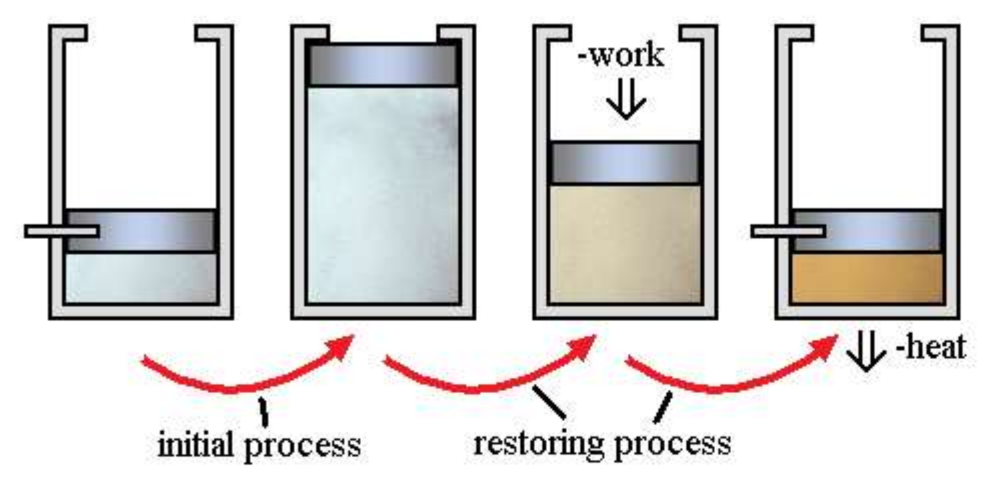
$$\frac{C_1^2}{2} + g\,Z_1 + H_1 + Q = \frac{C_1^2}{2} + g\,Z_1 + H_2 + W$$

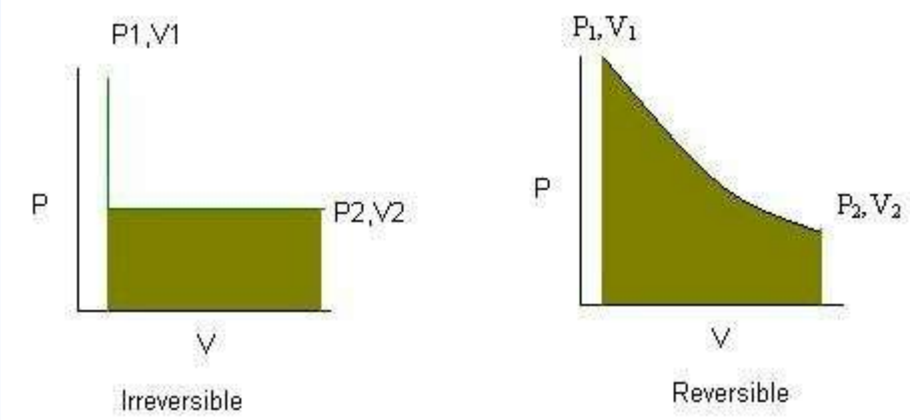
Adiabatic means, **Q = 0, & same elevation** $Z_1 = Z_2$

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

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.

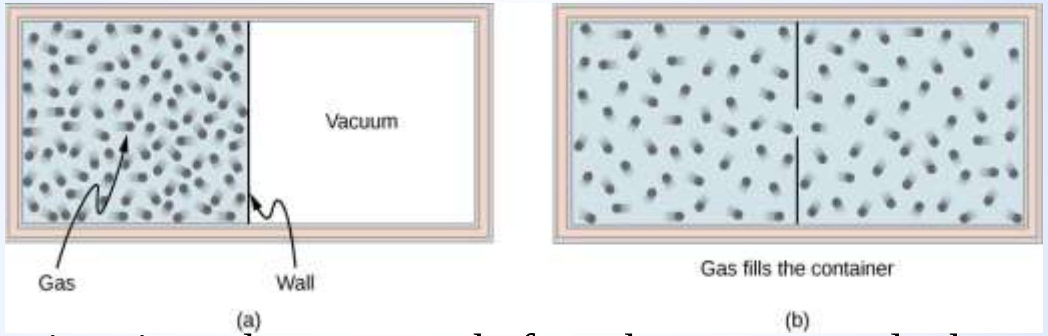
Here little work occurs. However, there is a requirement of significant work, with a corresponding amount of energy dissipation as heat flows to the environment. This is in order to reverse the process.

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,

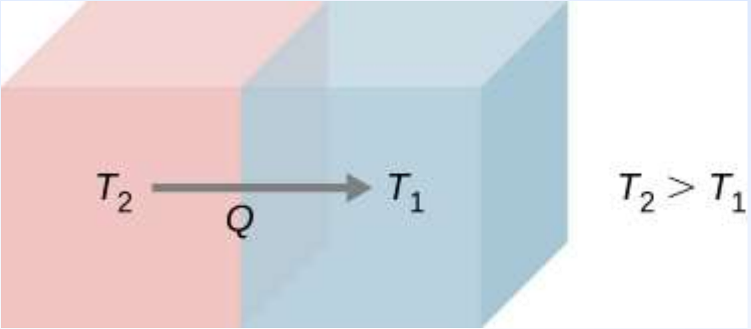
$$\Delta U = Q - W$$

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,

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

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

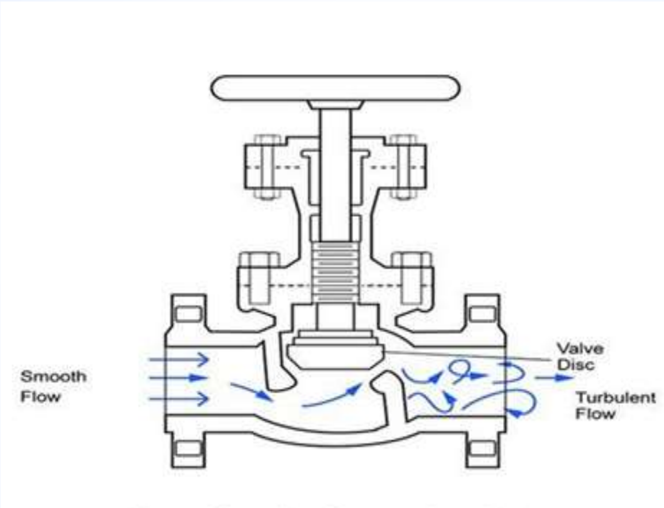
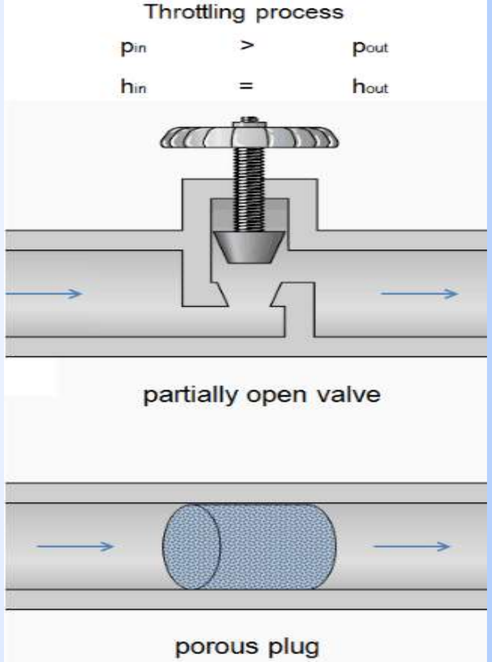
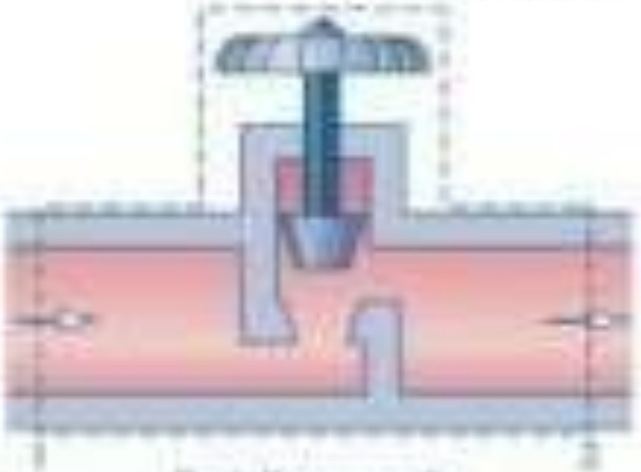


Figure: Throttling Process by a Valve



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

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

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

$$h_2 = h_1$$

Throttling is an isenthalpic process.

Fundamentally, non-quasiequilibrium.