- Recap: Lecture 6: 20th January 2014, 1130-1230 hrs.
  - First law for a cycle
  - First law for a system undergoing a change of state
  - First law for an isolated system
  - Perpetual Motion Machines of the First Kind (PMM1)

First law of thermodynamics for open systems

- First law process applied to flow process
  - System approach: Lagrangian
  - Control volume approach: Eulerian
- Steady flow processes
- Unsteady flow processes

First law of thermodynamics for open systems

- Steady flow processes: rates of flow of mass, energy are constant across the system boundary
  - eg. Turbines, compressors, heat exchangers etc
- Unsteady flow processes: rates of mass, energy are not constant across the system boundary
  - eg. Charging and discharging process (tanks, pipelines etc.)

Conservation of mass

- Conservation of mass principle
  - Total mass entering the system - Total mass leaving the system = Net change in mass within the system

$$m_{in} - m_{out} = \Delta m_{CV}$$

$$\dot{m}_{in} - \dot{m}_{out} = dm_{CV}/dt$$

Total mass within the CV: $m_{CV} = \int_{CV} \rho \, dV$

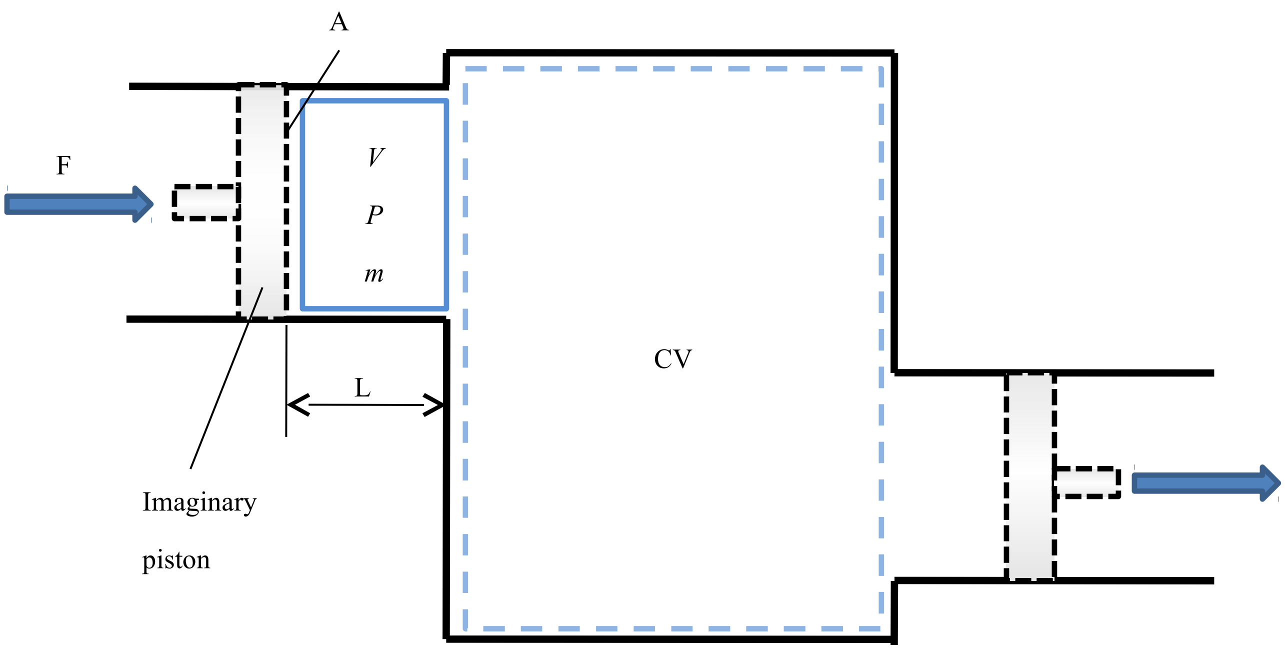
Rate of change of mass within the CV: $\dfrac{dm_{CV}}{dt} = \dfrac{d}{dt}\int_{CV} \rho \, dV$

Flow work and the energy of a flowing fluid

- Work required to push the mass into or out of the control volume: flow work or flow energy.
- Consider a fluid element of volume V.
- Let fluid pressure be P, the cross-sectional area be A, L is the distance through which the imaginary piston must move.
- The work done in pushing the fluid element across the system boundary is

$$W_{flow} = FL = PAL = PV$$

Flow work and the energy of a flowing fluid



Total energy of a flowing fluid

- The fluid entering or leaving a control volume possesses an additional form of energy—the flow energy, Pv
- The total energy of a flowing fluid on a unit-mass basis (denoted by θ) becomes

$$\theta = e + Pv = (u + ke + pe) + Pv$$

- Since $u+Pv=h$,

$$\theta = h + ke + pe \qquad (kJ/kg)$$

- Therefore, enthalpy, h, takes care of the flow work in addition to the internal energy.

Total energy of a flowing fluid

Non flowing fluid :

$$e = u + ke + pe = u + \frac{V^2}{2} + gz$$

Flowing fluid :

$$\theta = h + ke + pe = u + Pv + \frac{V^2}{2} + gz$$

The total energy consists of three parts for a non flowing fluid and four parts for a flowing fluid.

Energy transport by mass

- θ is total energy per unit mass, the total energy of a flowing fluid of mass m is simply $m\theta$, for uniform properties of the mass m.

Amount of energy transport, E_{mass}

$$E_{mass} = m\theta = m\left(h + \frac{V^2}{2} + gz\right) \quad (\mathrm{kJ})$$

Rate of energy transport, $\dot{E}_{mass}$

$$\dot{E}_{mass} = \dot{m}\theta = \dot{m}\left(h + \frac{V^2}{2} + gz\right) \quad (\mathrm{kW})$$

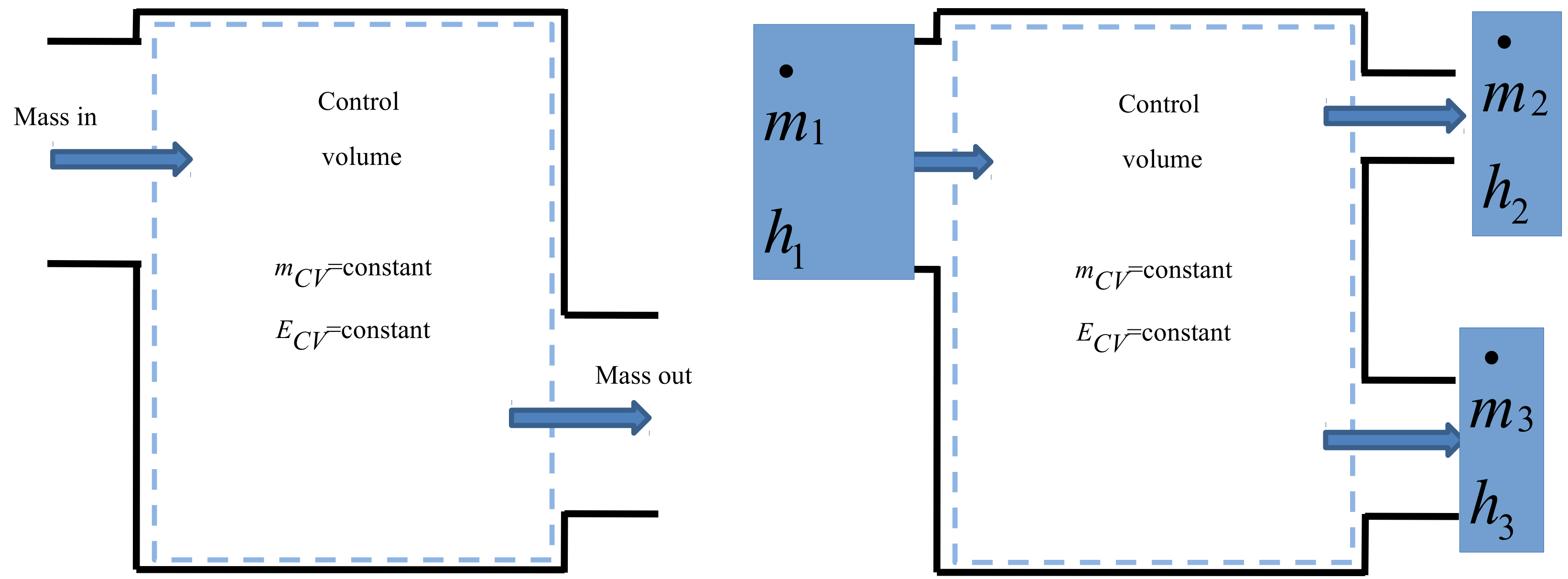
Energy analysis of steady flow systems

- Several engineering devices can be approximated to operate as steady flow devices: turbine, compressors, nozzles etc.
- During a steady-flow process, no intensive or extensive properties within the control volume change with time.
- The boundary work is zero for steady-flow systems (since V_{CV} =constant).
- The total mass or energy entering the control volume must be equal to the total mass or energy leaving it.

Energy analysis of steady flow systems

- Properties of steady flow processes
  - No properties within the control volume change with time.
  - No properties change at the boundaries of the CV with time.
  - The rates of flow of energy and mass across the control surface is constant.
  - Thermodynamic property has a fixed value at a particular location and do not change with time.

Energy analysis of steady flow systems



Under steady-flow conditions, the fluid properties at an inlet or exit remain constant (do not change with time).

<u>Energy analysis of steady flow systems</u>

- For a steady flow system, the amount of energy entering a control volume in all forms (by heat, work, and mass) must be equal to the amount of energy leaving it.
- Energy balance for a steady flow system

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\substack{\text{Rate of net energy transfer} \\ \text{by heat, work and mass}}} = \underbrace{dE_{system} / dt}_{\substack{\text{Rate of change in internal, kinetic} \\ \text{potential etc. energies}}} \quad \text{(kW)}$$

$$\text{or Energy balance:} \quad \underbrace{\dot{E}_{in}}_{\substack{\text{Rate of net energy transfer} \\ \text{in by heat, work and mass}}} = \underbrace{\dot{E}_{out}}_{\substack{\text{Rate of net energy transfer} \\ \text{out by heat, work and mass}}} \quad \text{(kW)}$$

Energy analysis of steady flow systems

- Energy balance for a steady flow system written more explicitly,

$$\dot{Q}_{in} - \dot{W}_{in} + \sum_{in} \dot{m}\theta = \dot{Q}_{out} - \dot{W}_{out} + \sum_{out} \dot{m}\theta$$

or,

$$\dot{Q}_{in} - \dot{W}_{in} + \sum_{in} \dot{m} \underbrace{\left(h + \frac{V^2}{2} + gz \right)}_{\text{for each inlet}} = \dot{Q}_{out} - \dot{W}_{out} + \sum_{out} \dot{m} \underbrace{\left(h + \frac{V^2}{2} + gz \right)}_{\text{for each exit}}$$

Energy analysis of steady flow systems

- The energy equation is also written as:

$$\dot{Q}-\dot{W}=\sum_{out}\dot{m}\underbrace{\left(h+\frac{V^2}{2}+gz\right)}_{\text{for each exit}}-\sum_{in}\dot{m}\underbrace{\left(h+\frac{V^2}{2}+gz\right)}_{\text{for each inlet}}$$

where, $\dot{Q}$ is the net heat input to the system and

$\dot{W}$ is the net work output from the system

Energy analysis of steady flow systems

- For single entry and exit devices,

$$\dot{Q} - \dot{W} = \dot{m}\left[h_2 - h_1 + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)\right]$$

or per unit mass,

$$\dot{q} - \dot{w} = h_2 - h_1 + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)$$

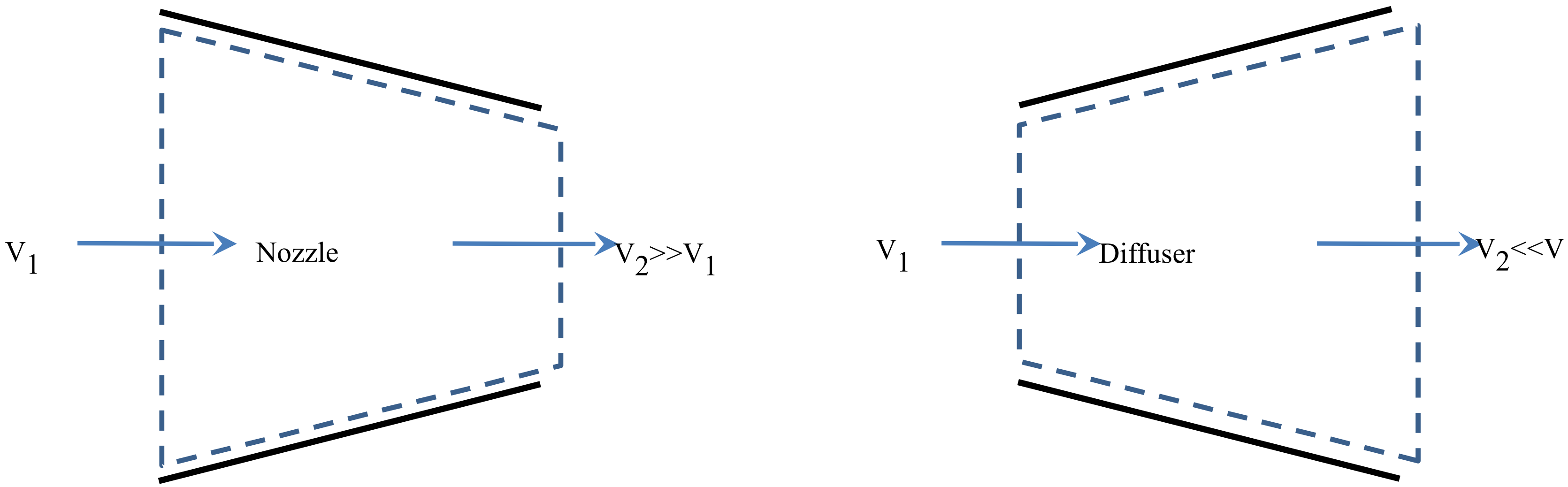
Steady flow energy equation for common engineering devices

- Some commonly used steady flow engineering devices:
  - Nozzles and diffusers
  - Compressors and turbines
  - Throttling devices
  - Mixing chambers
  - Heat exchangers

Nozzles and diffusers

- A nozzle is a device that increases the velocity of a fluid at the expense of pressure.
- A diffuser is a device that increases the pressure of a fluid by slowing it down.
- The cross-sectional area of a nozzle decreases in the flow direction for subsonic flows and increases for supersonic flows. The reverse is true for diffusers.

Nozzles and diffusers



Nozzles and diffusers are shaped so that they cause large changes in fluid velocities and thus kinetic energies.

Nozzles and diffusers

$$\dot{E}_{in} = \dot{E}_{out}$$

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

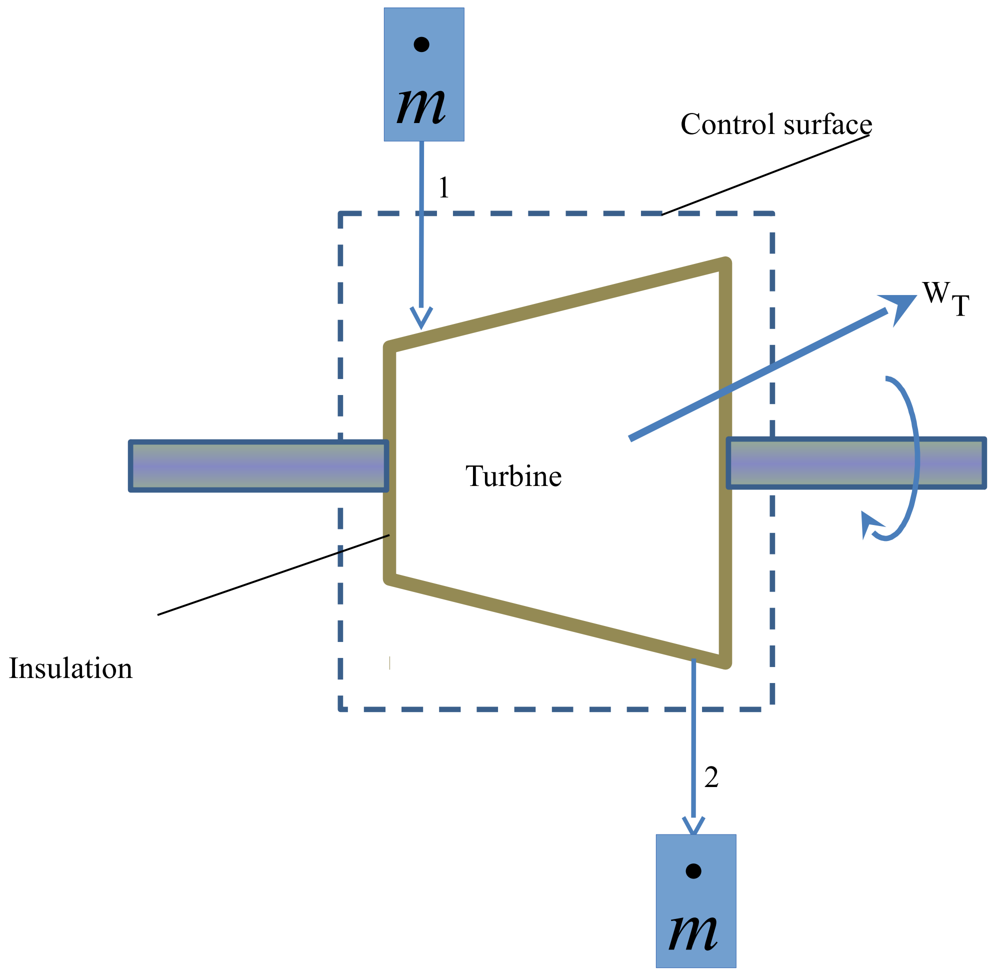
$$(\text{since } \dot{Q} \cong 0,\ \dot{W} = 0 \text{ and } \Delta PE \cong 0)$$

$$h_2 = h_1 - \frac{V_2^2 - V_1^2}{2}$$

Turbines and compressors

- Pumps, compressors and fans: used to increase the pressure of a fluid and require work input.
- Turbines generate work.
- *Q*, *KE* and *PE* may or may not be zero.
- Usually *PE* is negligibly small.

Turbines and compressors



Turbines and compressors

- For a turbine for eg., the energy equation would be:

$$\dot{m}\left(h_1 + \frac{V_1^2}{2} + gz_1\right) = \dot{W}_{out} + \dot{m}\left(h_2 + \frac{V_2^2}{2} + gz_2\right)$$

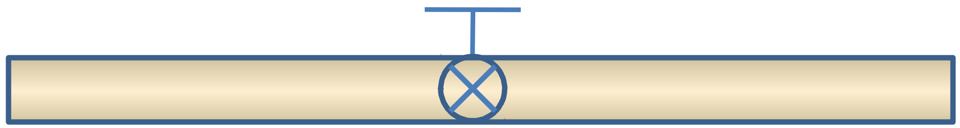
$$\text{If KE and PE are negligible,}$$

$$\dot{W}_{out} = \dot{m}(h_1 - h_2)$$

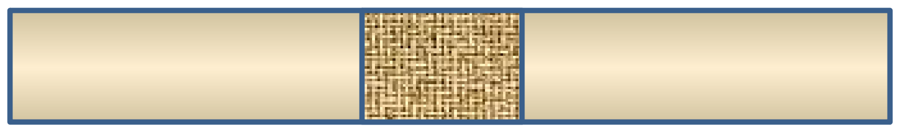
Throttling device

- Throttling valves are any kind of flow-restricting devices that cause a significant pressure drop in the fluid.
- Eg: capillary tubes, valves
- Unlike turbines, they produce a pressure drop without involving any work.
- The pressure drop in the fluid is often accompanied by a large drop in temperature.
- Hence throttling devices are commonly used in refrigeration and air-conditioning applications.

<u>Throttling device</u>



An adjustable valve



A porous plug

A capillary tube

Throttling device

For throttling devices,

$q \cong 0,\ w = 0,\ \Delta pe \cong 0,\ \Delta ke \cong 0$

The energy equation therefore reduces to,

$h_2 \cong h_1$

Throttling processes are isenthalpic processes.

It follows that,

$\mathrm{u}_1 + P_1 v_1 = \mathrm{u}_2 + P_2 v_2$

or, Internal energy + flow energy = constant

Throttling device

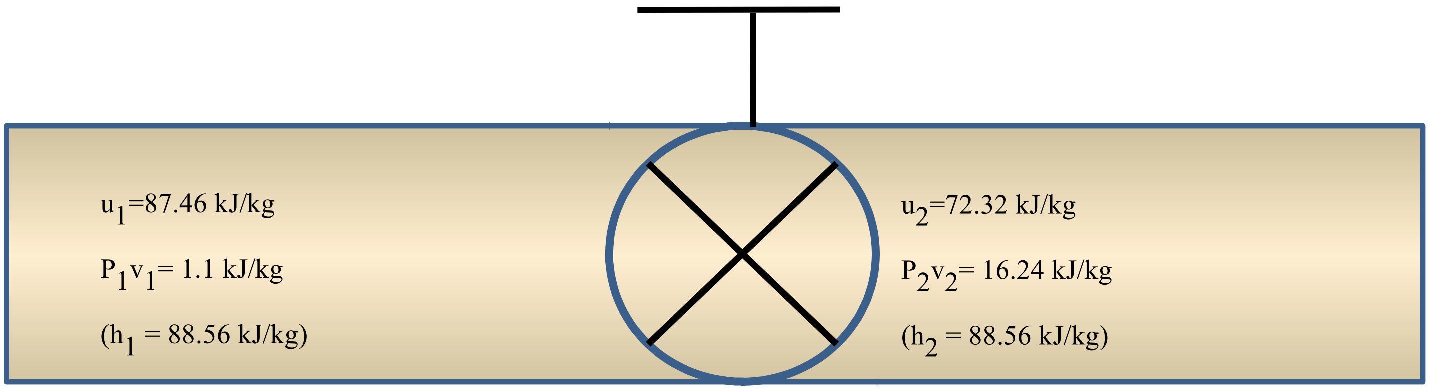
If $P_2 v_2 > P_1 v_1$, $u_2 < u_1$

Therefore, if flow energy increases, temperature decreases and vice - versa.

For an ideal gas, $h = h(T)$.

Therefore temperature has to remain constant during a throttling process.

Throttling device



During a throttling process, the enthalpy (flow energy + internal energy) of a fluid remains constant. But internal and flow energies inter-convertible.

Mixing chambers

- The section where the mixing process takes place is commonly referred to as a mixing chamber.
- Eg.: mixing of hot and cold water at the T joint of a shower.

$$\dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{m}_3 h_3 \quad (\text{Since } \dot{\mathrm{q}} \cong 0, \dot{w} \cong 0, ke \,\&\, pe \cong 0)$$

Combining energy and mass balances,

$$\dot{m}_1 h_1 + \dot{m}_2 h_2 = \left(\dot{m}_1 + \dot{m}_2 \right) h_3$$