ME 209
Basic Thermodynamics
Analysis of Open Systems-2

Kannan Iyer
Kiyer@me.iitb.ac.in

Department of Mechanical Engineering
Indian Institute of Technology, Bombay

Review of Lecture 16

- Identified that Open Systems are of engineering importance
- Derived the Conservation of Mass
- Understood the concept of flow work
- Derived the Conservation of Energy
- Most engineering devices have one inlet and one exit and operate in steady mode and the relevant equations are $\dot{m}_i = \dot{m}_e = \dot{m}$

$$0 = \dot{Q}_{CV} - \dot{W}_{CV} + \dot{m}\left((h_i - h_e) + \frac{V_i^2 - V_e^2}{2} + g(z_i - z_e) \right)$$

- Today, we shall look at the various engineering devices, make relevant assumptions and apply the First law of thermodynamics (Energy Equation)

Approximations in Open Systems

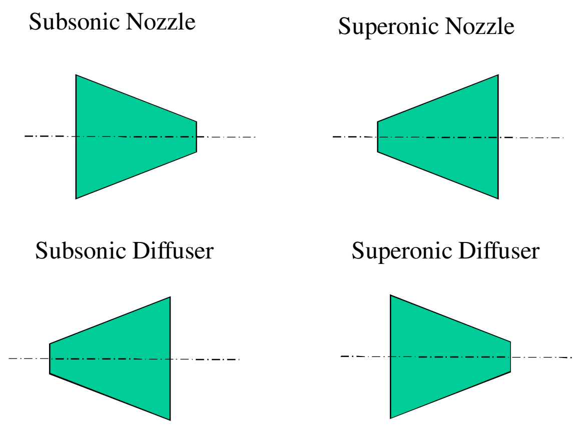
Common Approximations

- Velocity and temperature are uniform at the inlet and exit.
- At each location equilibrium property relations apply
- Heat transfer is assumed zero for cases, when
  - Control surface is insulated
  - Exposed area is small
  - ΔT between system and surroundings small
- No work transfer, if
  - No rotating shafts
  - No movement of system boundaries

Kinetic Energy Transfer Devices-I

- In applications like rocket motors, steam ejectors, there is a need to accelerate a fluid to very high velocity
- At times, a high velocity fluid has to be decelerated to lower velocity
- A device that accelerates fluid velocity is called a nozzle and that which reduces velocity is called a diffuser
- Everyday experience of watering the garden suggests that the area has to be decreased to increase velocity. However, in Fluid Mechanics, you will learn that at supersonic conditions it is just the opposite

Kinetic Energy Transfer Devices-II



Kinetic Energy Transfer Devices-III

No moving shaft

$$0 = \dot{Q}_{CV} - \dot{W}_{CV} + \dot{m}\left((h_i - h_e) + \frac{V_i^2 - V_e^2}{2} + g(z_i - z_e)\right)$$

Device area small

Change in elevation negligible

$$\Rightarrow (h_i - h_e) = \frac{V_e^2 - V_i^2}{2}$$

Many occasions this is negligible

$$\Rightarrow V_e = \sqrt{2(h_i - h_e)}$$

Work Transfer Devices

- In many application, work is supplied to increase the fluid pressure
- The most common ones are
  - Compressor (Gas, High Δp, but low flow)
  - Blower (Gas, High Flow, but low Δp)
  - Pump (Liquid, all Δp)

Change in KE negligible

$$0 = \dot{Q}_{CV} - \dot{W}_{CV} + \dot{m}\left((h_i - h_e) + \frac{V_i^2 - V_e^2}{2} + g(z_i - z_e)\right)$$

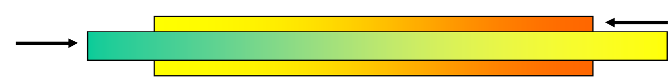
Negligible

Change in elevation negligible

$$\frac{\dot{W}_{CV}}{\dot{m}} = (h_i - h_e)$$

Heat Transfer Devices-I

- There are many heat transfer devices
- The most common ones are
  - Boiler (To produce steam)
  - Condenser (To condense steam)
  - Heat Exchanger (To heat/cool fluids)
- The construction varies from device to device, but they can be idealized as two concentric tubes



Heat Transfer Devices-II

- First Law can be simplified for any one tube as

Change in KE negligible

$$0 = \dot{Q}_{CV} - \dot{W}_{CV} + \dot{m}\left((h_i - h_e) + \frac{V_i^2 - V_e^2}{2} + g(z_i - z_e) \right)$$

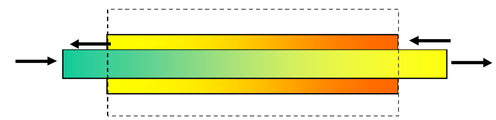
No shaft

Change in elevation negligible

$$\dot{Q}_{CV} = \dot{m}(h_e - h_i) = \dot{m}c_p(T_e - T_i)$$

Heat Transfer Devices-III

- If we combine both the tubes together in our control volume, it becomes multiple inlet

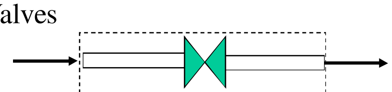


$$0 = \dot{Q}_{CV} - \dot{W}_{CV} + \sum \dot{m}_i \left(h_i + \frac{V_i^2}{2} + gz_i \right) - \sum \dot{m}_e \left(h_e + \frac{V_e^2}{2} + gz_e \right)$$

$$= \dot{m}_1(h_{e1} - h_{i1}) = \dot{m}_2(h_{i2} - h_{e2})$$

Pressure Reduction Device

- In many application the pressure of a flowing fluid is to be reduced to control the flow. These are called Valves



No shaft

Change in KE negligible

$$0 = \dot{Q}_{CV} - \dot{W}_{CV} + \dot{m}\left((h_i - h_e) + \frac{V_i^2 - V_e^2}{2} + g(z_i - z_e) \right)$$

Negligible

Change in elevation negligible

$$\Rightarrow h_i = h_e$$

- This isenthalpic process is also called throttling

Flow Measuring Device-I

- A convergent divergent device operating at low velocities is called a venturimeter and is used to measure flow
- Prior to showing the basis, let us get back the so called Bernoulli's equation from First law

$$0 = \dot{Q}_{CV} - \dot{W}_{CV} + \dot{m}\left((h_i - h_e) + \frac{V_i^2 - V_e^2}{2} + g(z_i - z_e) \right)$$

$$h_i + \frac{V_i^2}{2} + gz_i = h_e + \frac{V_e^2}{2} + gz_e$$

$$\Rightarrow u_i + \frac{p_i}{\rho_i} + \frac{V_i^2}{2} + gz_i = u_e + \frac{p_e}{\rho_e} + \frac{V_e^2}{2} + gz_e$$

Flow Measuring Device-II

- If the velocities are low, then in such cases flow can be approximated to be isothermal

$$\Rightarrow \not{u}_i + \frac{p_i}{\rho_i} + \frac{V_i^2}{2} + gz_i = \not{u}_e + \frac{p_e}{\rho_e} + \frac{V_e^2}{2} + gz_e$$

- Further, when velocities are low, even a gas flow can be considered incompressible

$$\Rightarrow \frac{p_i}{\rho} + \frac{V_i^2}{2} + gz_i = \frac{p_e}{\rho} + \frac{V_e^2}{2} + gz_e$$

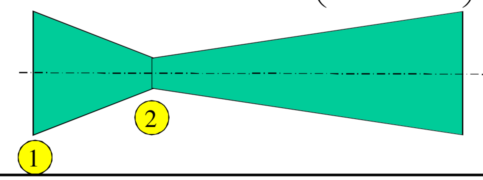
The above is incompressible Bernoulli's Equation

Flow Measuring Device-III

- Now we can deduce the expression for flow in terms of measured pressures at 1 and 2

$$\Rightarrow \frac{p_1}{\rho} + \frac{V_1^2}{2} + g\not{z}_1 = \frac{p_2}{\rho} + \frac{V_2^2}{2} + g\not{z}_2$$

$$\Rightarrow \frac{p_1 - p_2}{\rho} = \frac{V_2^2 - V_1^2}{2} = V_2^2\left(\frac{1 - A_2^2/A_1^2}{2}\right)$$



Flow Measuring Device-IV

- Thus, the final expression for Velocity at 2 is

$$\Rightarrow V_2 = \sqrt{\frac{2(p_1 - p_2)}{\rho\left(1 - A_2^2/A_1^2\right)}}$$

- The volumetric flow rate or mass flow rate can now be obtained easily by multiplying by area or the product of area and density