CHAPTER

6

MEC Thermodynamics

FIRST LAW OF THERMODYNAMICS

MASS & ENERGY ANALYSIS OF CONTROL VOLUME

Conservation of Mass

- Conservation of mass is one of the most fundamental principles in nature. We are all familiar with this principle, and it is not difficult to understand it!

- For closed system, the conservation of mass principle is implicitly used since the mass of the system remain constant during a process.

- However, for control volume, mass can cross the boundaries. So the amount of mass entering and leaving the control volume must be considered.

Mass and Volume Flow Rates

- Mass flow through a cross-sectional area per unit time is called the mass flow rate. Note the dot over the mass symbol indicates a time rate of change. It is expressed as

$$\dot{m} = \int \rho V . dA$$

- If the fluid density and velocity are constant over the flow cross-sectional area, the mass flow rate is

$$\dot{m} = \rho AV = \frac{AV}{v}$$

$$where\, v = \frac{1}{\rho}$$

$$v\; is\, called\;\; specific\; voulme$$

Principal of Conservation of Mass

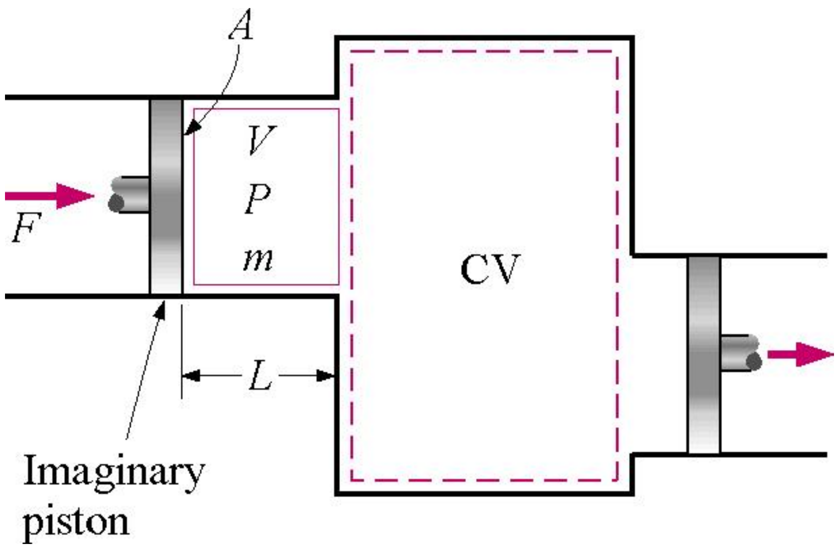
- The conservation of mass principle for a control volume can be expressed as

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

- For a steady state, steady flow process the conservation of mass principle becomes

$$\dot{m}_{in} = \dot{m}_{out} \quad \text{(kg/s)}$$

Flow Work & The Energy of a Flowing Fluid



- As the fluid upstream pushes mass across the control volume, work done on that unit of mass is

$$\delta W_{flow} = F\,dL = F\,dL\frac{A}{A} = P\,dV = Pv\delta m$$

$$\delta w_{flow} = \frac{\delta W_{flow}}{\delta m} = Pv$$

Total Energy of a Flowing Fluid

- The total energy carried by a unit of mass as it crosses the control surface is the sum of the internal energy + flow work + potential energy + kinetic energy

$$\sum energy = u + Pv + \frac{V^2}{2} + gz = h + \frac{V^2}{2} + gz$$

- The first law for a control volume can be written as

$$\dot{Q}_{net} - \dot{W}_{net} = \sum_{out} \dot{m}_{out}\left(h_{out} + \frac{V_{out}^{\ 2}}{2} + gz_{out} \right) - \sum_{in} \dot{m}_{in}\left(h_{in} + \frac{V_{in}^{\ 2}}{2} + gz_{in} \right)$$

Total Energy of a Flowing Fluid

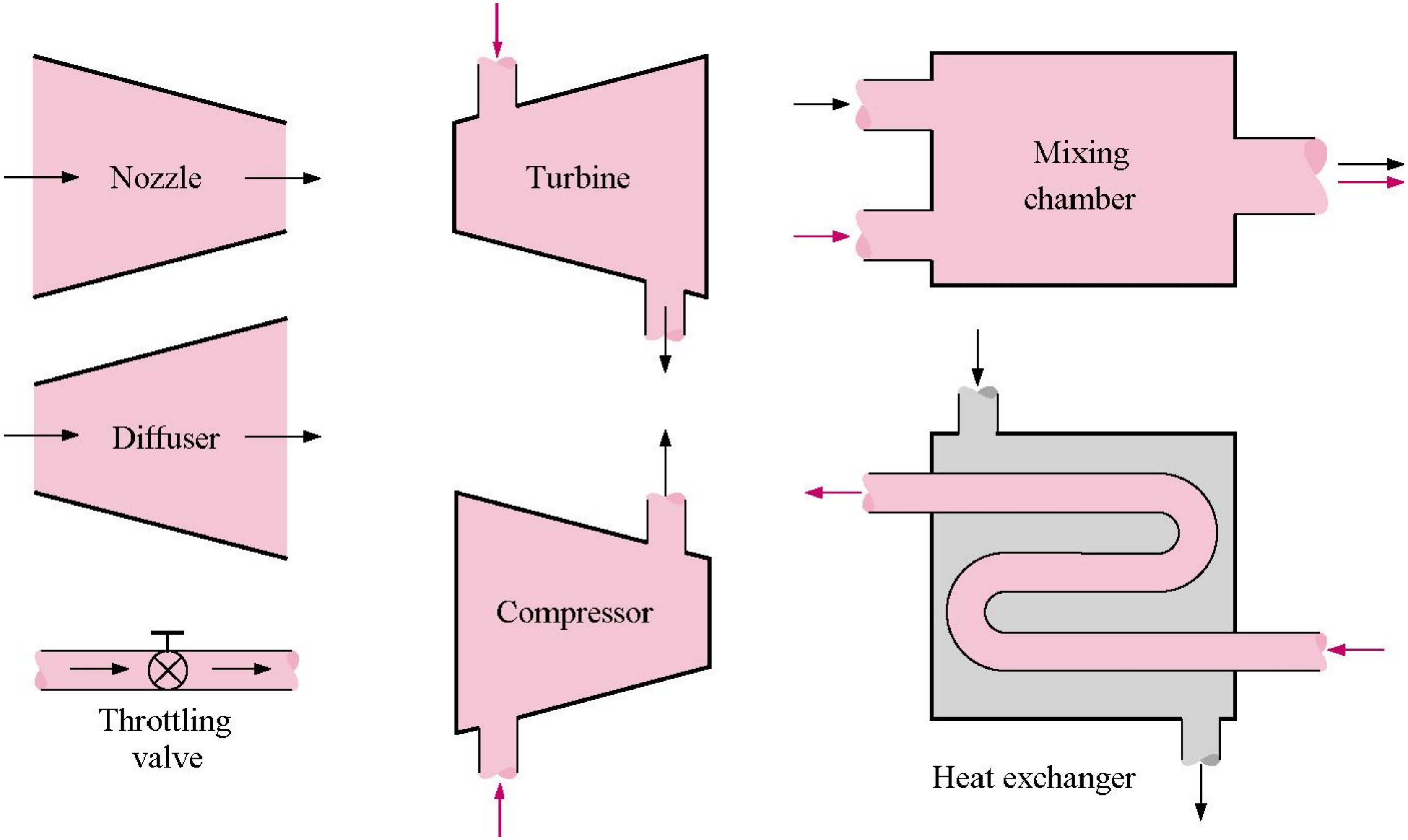
- The steady state, steady flow conservation of mass and first law of thermodynamics can be expressed in the following forms

$$q_{net} - w_{net} = \left(h_2 - h_1 + \frac{V_2^{\ 2} - V_1^{\ 2}}{2000} + \frac{g(z_2 - z_1)}{1000} \right) \qquad (kJ/kg)$$

$$Q_{net} - W_{net} = m\left(h_2 - h_1 + \frac{V_2^{\ 2} - V_1^{\ 2}}{2000} + \frac{g(z_2 - z_1)}{1000} \right) \qquad (kJ)$$

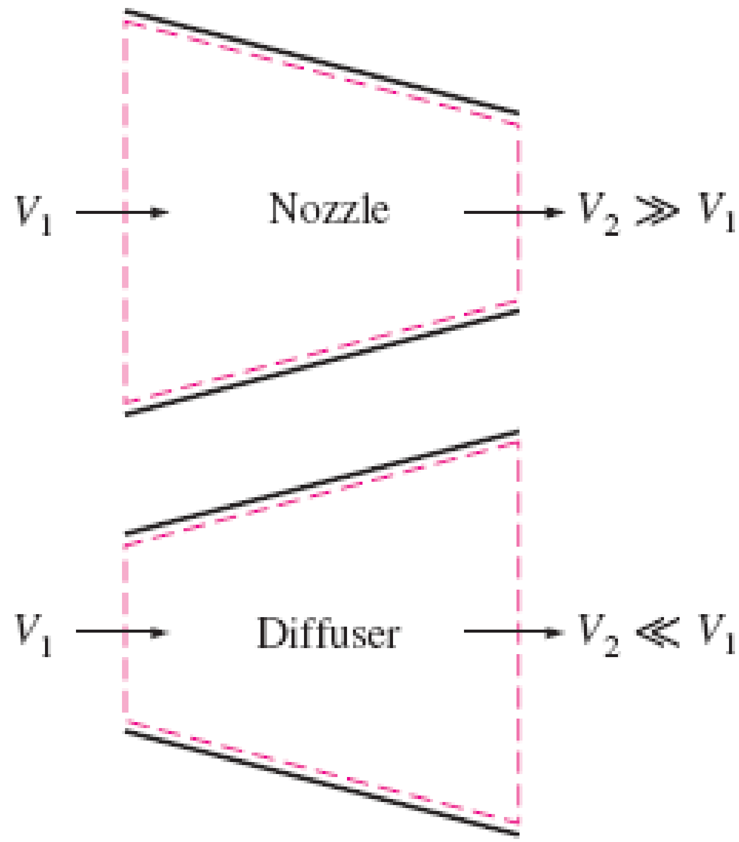
$$\dot{Q}_{net} - \dot{W}_{net} = \dot{m}\left(h_2 - h_1 + \frac{V_2^{\ 2} - V_1^{\ 2}}{2000} + \frac{g(z_2 - z_1)}{1000} \right) \qquad (kW)$$

Steady-flow Engineering Devices



Nozzle & Diffuser

- Nozzle - device that increases the velocity fluid at the expense of pressure.
- Diffuser - device that increases pressure of a fluid by slowing it down.
- Commonly utilized in jet engines, rockets, space-craft and even garden hoses.
- Q = 0 (heat transfer from the fluid to surroundings very small
- W = 0 and ΔPE = 0



- Energy balance (nozzle & diffuser):

$$\dot{Q}_{in} + \dot{W}_{in} + \sum_{in} \dot{m}_{in}\left(h_{in} + \frac{V_{in}^{\;2}}{2} + gz_{in} \right) = \dot{Q}_{out} + \dot{W}_{out} + \sum_{out} \dot{m}_{out}\left(h_{out} + \frac{V_{out}^{\;2}}{2} + gz_{out} \right)$$

$$\dot{m}_{in}\left(h_{in} + \frac{V_{in}^{\;2}}{2} \right) = \dot{m}_{out}\left(h_{out} + \frac{V_{out}^{\;2}}{2} \right)$$

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

Example 3.6

Steam at 0.4 MPa, 300ºC, enters an adiabatic nozzle with a low velocity and leaves at 0.2 MPa with a quality of 90%. Find the exit velocity.

Solution:

State 1	State 2
$P_1 = 0.4\,MPa$	$P_2 = 0.2\,MPa$
$T_1 = 300^o C$	$x_2 = 0.9$
$V_1 \approx 0$	

- Simplified energy balance:

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

State 1

$$\left.\begin{aligned} P_1 &= 0.4\,MPa \\ T_1 &= 300^o C \end{aligned}\right\} \begin{aligned} &h_1 = 3067.1\tfrac{kJ}{kg} \\ &(\text{superheated}) \end{aligned}$$

State 2

$$\left.\begin{aligned} P_2 &= 0.2\,MPa \\ x_2 &= 0.9 \end{aligned}\right\} \begin{aligned} &h_2 = h_f + x_2 h_{fg} \\ &h_2 = 2486.1\tfrac{kJ}{kg} \end{aligned}$$

- Exit velocity:

$$V_2 = \sqrt{2000(3067.1 - 2486.1)}$$

$$= \underline{\underline{1078\,m/s}}$$

Example 3.7

Air at 10°C and 80 kPa enters the *diffuser* of a jet engine steadily with a velocity of 200 m/s. The inlet area of the diffuser is 0.4 m^2. The air leaves the diffuser with a velocity that is very small compared with the inlet velocity. Determine (a) the mass flow rate of the air and (b) the temperature of the air leaving the diffuser.

State 1

$$P_1 = 80\,kPa$$

$$T_1 = 10^o C$$

$$V_1 = 200 m/s$$

$$A_1 = 0.4\,m^2$$

State 2

$$V_2 \approx 0$$

Solution:

- Simplified energy balance:

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

- From Ideal Gas Law:

$$v_1 = \frac{RT_1}{P_1} = 1.015 \tfrac{m^3}{kg}$$

- Mass flow rate

$$\dot{m} = \frac{1}{v_1} V_1 A_1$$

$$= \left(\frac{1}{1.015}\right)(200)(0.4)$$

$$= \underline{\underline{78.8 \tfrac{kg}{s}}}$$

- Enthalpy at state 1

$$h_1 = C_p T_1 = 1.005(283)$$

$$= 284.42 \tfrac{kJ}{kg}$$

- From energy balance:

$$h_2 = h_1 + \frac{V_1^2}{2000}$$

$$= 284.42 + \frac{200^2}{2000}$$

$$= 304.42 \tfrac{kJ}{kg}$$

$$T_2 = \frac{h_2}{C_p}$$

$$= \frac{304.42}{1.005}$$

$$= \underline{\underline{302.9\, K}}$$