ESO201A

Lecture#18

(Class Lecture)

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By

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Steady-Flow Process

The fluid properties can change from point to point within the control volume, but at any fixed point they remain the same during the entire process.

1. No properties (intensive or extensive) within the control volume change with time.

   Thus, intensive properties like pressure, velocity, temperature, density do not change with time in the cv.

   Also, extensive properties like volume, mass and total energy are invariant with time in the cv.

   Hence, V_{cv}, m_{cv}, E_{cv} remain unchanged.

2. Boundary work, that is, $\int P dV = 0$ since V_{cv} is constant.

3. Total mass or energy entering the cv must be equal to total mass or energy leaving it since $m_{cv} = $ constant and $E_{cv} =$ constant.

Hence, $\dot{E}_{in} = \dot{E}_{out}$ and $\dot{m}_{in} = \dot{m}_{out}$.

4. The fluid properties at an inlet or exit remain constant during a steady-flow process. The properties may, however, be different at different openings.

5. The rate of heat and work interactions between a steady-flow system and its surroundings do not change with time.
Thus, $\frac{\delta \dot{Q}}{dt}$ and $\frac{\delta \dot{W}}{\delta t}$ are zero.

Mass Balance

The mass balance for a general steady-flow system is:

$$\sum_{in} \dot{m} = \sum_{out} \dot{m} \quad (1)$$

The mass balance for a single inlet and single outlet is:

$$\dot{m}_1 = \dot{m}_2 \quad (2)$$

$$\Rightarrow \rho_1 A_1 v_1 = \rho_2 A_2 v_2$$

The subscripts 1 and 2 denote the inlet and the exit states, respectively, ρ is the density, V is the average flow velocity in the flow direction, and A is the cross-sectional area normal to the flow direction.

Energy Balance

$$\underbrace{\dot{E}_{in}}_{\substack{\text{Rate of}\\\text{energy}\\\text{in by}\\\text{heat, work}\\\text{and mass}}} - \underbrace{\dot{E}_{out}}_{\substack{\text{Rate of}\\\text{energy}\\\text{out}\\\text{by heat,}\\\text{work}\\\text{and}\\\text{mass}}} = \underbrace{\cancelto{0 \text{ steady}}{\frac{dE_{system}}{dt}}}_{\substack{\text{Rate of}\\\text{change in}\\\text{internal,}\\\text{kinetic, potential}\\\text{etc., energies}}} \approx 0 \qquad (3)$$

$$\text{or} \quad \dot{E}_{in} = \dot{E}_{out}$$

$$\text{or} \quad \dot{Q}_{in} + \dot{W}_{in} + \sum_{in} \dot{m}\theta$$

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

(Note that at the inlet and the outlet there are no heat or work interactions. $\dot{Q}$ and $\dot{W}$ occur only at the boundary of the control volume.)

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

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

$$\text{or} \quad \overbrace{\left(\dot{Q}_{in} - \dot{Q}_{out}\right)}^{\dot{Q}} - \overbrace{\left(\dot{W}_{out} - \dot{W}_{in}\right)}^{\dot{W}}$$

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

$$- \underbrace{\sum_{in} \dot{m}\left(h + \frac{V^2}{2} + gz\right)}_{\text{for each inlet}} \qquad (4)$$

The subscripts 'in' and 'out' for $\dot{Q}$ and $\dot{W}$ represent heat and work transfer, respectively, to or from the boundary of the control volume. Do not confuse them with inlet and outlet.

For single-stream devices (that is, single inlet and single outlet) the energy balance equation becomes

$$\dot{Q} - \dot{W} = \dot{m}\left[h_2 - h_1 + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)\right] \quad (5)$$

$$\text{or} \quad q - w = h_2 - h_1 + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1) \quad (6)$$

where $q = \frac{\dot{Q}}{\dot{m}}$ and $w = \frac{\dot{W}}{\dot{m}}$

When $\Delta ke = 0$, $\Delta pe = 0$,

$$q - w = h_2 - h_1 \quad (7)$$

The various terms appearing in the foregoing equations are as follows.

$\dot{Q} = \dot{Q}_{in} - \dot{Q}_{out}$ = Net rate of heat transfer between the CV and the surroundings. If the CV is well insulated (i.e. adiabatic) then $\dot{Q} = 0$.

$\dot{W} = \dot{W}_{out} - \dot{W}_{in}$ = Net power delivered or consumed.

Many steady-flow devices, such as turbines, compressors and pumps, transmit power through a shaft, and $\dot{W}$ simply becomes the shaft power for these devices.

If the control volume surface is crossed by electric wires, $\dot{W}$ represents the electric work done per unit time.

If neither is present,

$\dot{W} = 0$.

$\Delta h = h_2 - h_1$.

The enthalpy change of a fluid can easily be determined by reading the enthalpy values at the exit and inlet states from property tables.

For ideal gases,

$\Delta h = c_{p,avg} (T_2 - T_1)$.

$$\Delta ke = \frac{V_2^2 - V_1^2}{2}.$$

The unit of kinetic energy is m^2/s^2, which is equivalent to J/kg.

A velocity of 45 m/s corresponds to a kinetic energy of 1 kJ/kg, which is very small compared with the enthalpy values encountered in practice. Thus, KE at low velocities can be neglected.

At high velocities, however, small changes in velocities may cause significant change in kinetic energy.

$$\Delta Pe = g(z_2 - z_1).$$

A potential energy change of 1 kJ/kg corresponds to an elevation difference of 102 m. For most devices, the elevation difference between the inlet and exit is much smaller and hence ΔPE is neglected.

The only time the PE term is significant is when a process involves pumping a fluid to high elevations and we are interested in the required pumping power.