Course Title:

Fundamental of Thermodynamics and Heat Transfer

Lecture 8 (Week 8):

First Law of Thermodynamics

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Learning Objective of Lecture:

To impart a great deal of knowledge to undergraduate students on the topics:

- ✓ First Law of Thermodynamics for Control Volume (Open System/Flow Process)
- ✓ Conservation of Mass for a Control Volume
- ✓ Expression for Mass Flow Rate
- ✓ Conservation of Energy for a Control Volume
- ✓ Analysis of Control Volume
- ✓ Steady State Analysis
- ✓ Unsteady State Analysis

4.3. First Law of Thermodynamics for a Control Volume (Open System)

As discussed earlier, a control volume or an open system is a region in space which is to be studied in a particular analysis. The surface that bounds the control volume is called a boundary or a *control surface*. Mass and energy can cross the control surface of the control volume which may be fixed or may deform. Hence, in contrary to a control mass (closed system) in addition to the energy transfer (i.e. heat and work transfer), another type of energy transfer can also occur due to mass transfer namely the energy carried by the mass when it enters or exists the control volume (open system).

4.3.1. Conservation of Mass for a Control Volume

A control volume (open system) can interact with its surroundings by energy transfer as well as mass transfer. Let us consider an open system or control volume undergoing a process during which m_{in} amount of total mass is entering the control volume and m_{out} amount of total mass is leaving it. If total mass entering the system during the process is greater than total mass leaving the system then the mass of the system increases; whereas if total mass entering the system during the process is less than total mass leaving the system then the mass of the system decreases. Moreover, if total mass entering the system during the process is equal to total mass leaving the system then the mass of the system remains constant. This explanation can be generalized as conservation of mass for a control volume and summarized in a statement as

The change in mass within a control volume is equal to the total mass entering the control volume minus the total mass leaving the control volume [1].

Mathematically,

$$dm_{cv} = m_{in} - m_{out} \qquad \text{……….(4.29)}$$

and on a rate basis considering the time interval *Δt,* the conservation of mass is,

$$\frac{dm_{CV}}{dt} = \dot{m}_{in} - \dot{m}_{out} \qquad \text{………. (4.30)}$$

where $\dot{m}_{in}$ is the total mass flow rate or summation of mass flow rates at each inlet and $\dot{m}_{out}$ is the total mass flow rate or summation of mass flow rates at each outlet, i.e.

$$\dot{m}_{in} = \sum_{in} \dot{m} \qquad \text{……………(4.31)}$$

$$\dot{m}_{out} = \sum_{out} \dot{m} \quad \text{……………(4.32)}$$

To illustrate it, let us consider a control volume shown in figure 4.2 consisting of three inlets and two outlets. Total mass flow rates $\dot{m}_{in}$ at inlets and $\dot{m}_{out}$ at outlets for the system are given as

$$\dot{m}_{in} = \dot{m}_1 + \dot{m}_2 + \dot{m}_3 \quad \text{...……………..(4.33)}$$

$$\dot{m}_{out} = \dot{m}_4 + \dot{m}_5 \quad \text{……..………(4.34)}$$

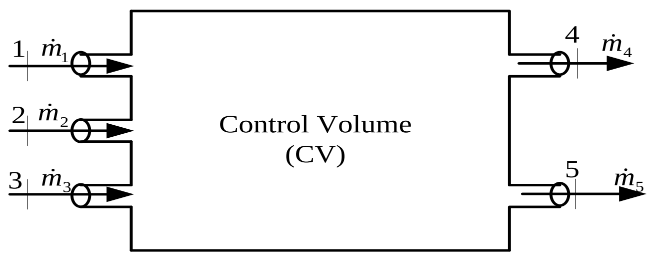


Figure 4.2. Mass interactions between a control volume and surroundings

Now, the conservation of mass for control volume can be alternately stated as

The rate of change in mass within a control volume is equal to the total mass flow rate entering the control volume minus the total mass flow rate leaving the control volume.

Expression for Mass Flow Rate

The inlet and outlet mass flow rates at the boundaries can be expressed in terms of density, velocity of a fluid and cross-sectional area of a port. To do this, let us consider a fluid flowing through a port having a uniform cross sectional area A, where it crosses ΔL distance in time interval Δt as shown in figure 4.3.

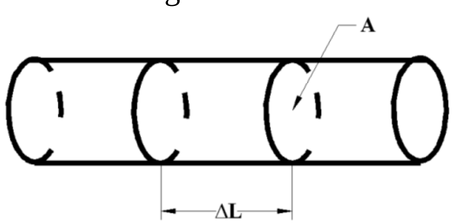


Figure 4.3. Mass flow at a port (inlet or outlet)

Total mass of the fluid crossing the section of length ΔL is given by

$$m = \rho V_{swept} \quad \text{…..……… (4.35)}$$

where, ρ is the density of the fluid and V_{swept} is the volume swept away by the fluid in the given time interval Δt.

Putting $V_{swept} = A\Delta L$, into equation (4.35), we get

$$m = \rho A \Delta L \quad \text{.............. (4.36)}$$

Dividing both sides of equation (4.36) by time interval Δt, the mass flow rate is then

$$\dot{m} = \rho A \frac{\Delta L}{\Delta t} = \rho A \bar{V} = \rho \dot{V} \quad \text{.............. (4.37)}$$

which can also be expressed in terms of specific volume as

$$\dot{m} = \frac{A\bar{V}}{v} = \frac{\dot{V}}{v} \quad \text{.............. (4.38)}$$

where $\dot{V}$ is the volumetric flow rate of the fluid.

Equation (4.30) can then be expressed in terms of properties of the fluid at inlets and outlets as

$$\frac{dm_{CV}}{dt} = \sum_{in} (\rho A\bar{V}) - \sum_{out} (\rho A\bar{V}) \quad \text{... ... ... (4.39)}$$

Or,

$$\frac{dm_{CV}}{dt} = \sum_{in} \left(\frac{A\bar{V}}{v}\right) - \sum_{out} \left(\frac{A\bar{V}}{v}\right) \quad \text{.......... (4.40)}$$

When there is no mass entering or leaving the control volume, the conservation of mass becomes

$$dm_{cv} = 0 \Rightarrow m_{cv} = constant \quad \text{..........(4.41)}$$

which is exactly the expression of the conservation of mass for a control mass.

4.3.2. Conservation of Energy for a Control Volume

In a control volume there is not only the heat transfer and work transfer (like in a control mass), but also the mass transfer and the mass entering and leaving the control volume (open system) also carries energy with it. The net energy transported by the fluid into the control volume is equal to total energy entering the control volume through the inlets minus total energy leaving mass transfer also affects the total energy of a control volume. Mass entering into the control volume increases the total energy of the system where as mass leaving from the control volume decreases the total energy of the system.

Let us consider an opened system or control volume undergoing a process during which E_{in} amount of total energy is entering the control volume through different inlets and E_{out} amount of total energy is leaving it through different outlets. If total energy entering the system during the process is greater than the total energy leaving the system then total energy of the system increases; whereas if total energy entering the system during the process is less than that leaving the system then the total energy of the system decreases. Similarly, if total energy entering the system during the process is equal to the total energy leaving the system then the total energy of the system remains constant. This explanation can be generalized as conservation of energy for a control volume and summarized in a statement as

The change in total energy within a control volume is equal to the net energy transported by the fluid into the control volume plus the heat supplied to the control volume minus the work done by the control volume [1].

Mathematically,

$$dE_{CV} = E_{net} + Q - W \qquad \text{……..…….(4.42)}$$

where E_{CV} is the total energy within the control volume and $E_{net} = (E_{in} - E_{out})$ is the net energy transported by the fluid into the control volume, i.e. difference of energy entering through the inlets and leaving through the outlets, Q is the heat supplied to the control volume, and W is the work done by the control volume as shown in figure (4.4)

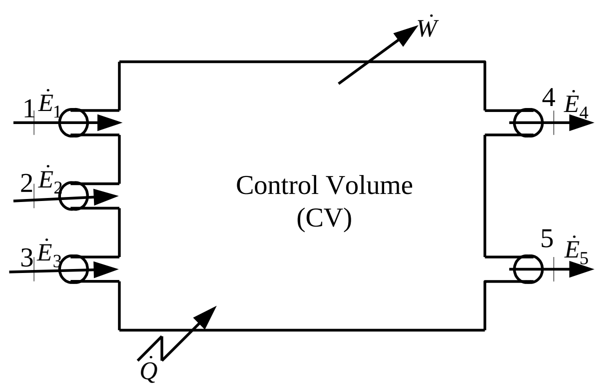


Figure 4.4. Energy interactions between a control volume and surroundings

On a rate basis considering the time interval Δt, the conservation of energy is

$$\frac{dE_{CV}}{dt} = \dot{E}_{net} + \dot{Q} - \dot{W} \qquad \text{............ (4.43)}$$

Putting $\dot{E}_{net} = \dot{E}_{in} - \dot{E}_{out}$, we get

$$\frac{dE_{CV}}{dt} = \dot{E}_{in} - \dot{E}_{out} + \dot{Q} - \dot{W} \qquad \text{................ (4.44)}$$

Where

$$\dot{E}_{in} = \sum_{in} \left\{ \dot{m} \left(u + \frac{1}{2}\bar{V}^2 + gz \right) \right\} \qquad \text{... ... ... (4.45)}$$

$$\dot{E}_{out} = \sum_{out} \left\{ \dot{m} \left(u + \frac{1}{2}\bar{V}^2 + gz \right) \right\} \qquad \text{... ... ... (4.46)}$$

Contribution of heat transfer

Heat transfer to the control volume is the transfer of energy without transfer of mass across the boundary because of the temperature difference between the control volume and the surroundings which is the same as that in the case of the control mass. Hence, we can write

$$\dot{Q} = \dot{Q}_{CV} \qquad \text{... .... (4.47)}$$

Contribution of work transfer

The work transfer associated with a control volume includes various types of works such as flow work, shaft work, displacement work (expansion or compression of boundary), electrical work and other work forms. Thus, the work transfer can be divided into two main types of work forms namely flow work due to fluid flow at inlets/outlets (W_{flow}) and work transfer across the boundary rather than flow work (W_{CV}). Therefore, the rate of work done by the control volume is the sum of the rate of the flow work and all other forms of work transfer across the boundary rather than the flow work, i.e.

$$\dot{W} = \dot{W}_{flow} + \dot{W}_{CV} \qquad \text{.......... (4.48)}$$

where the term $\dot{W}_{flow}$ is the rate of flow work of the fluid and $\dot{W}_{CV}(= \dot{W}_{shaft} + \dot{W}_{gen})$ includes the rate of shaft work, and general forms of work like displacement work ($P.dV$), electrical work etc [2].

Flow work is the energy required to get the flowing fluid into the control volume through the inlets or work performed by the fluid coming out from the control volume through outlets. By using the sign convention, the flow work at the inlets (work done on the system) is taken as negative and the flow work at the outlets (work done by the system) is taken as positive.

To obtain an expression for flow work at an inlet or outlet, let us consider a fluid element of volume V entering the control volume through an inlet with a cross sectional area of A, where it crosses ΔL distance in time interval Δt as shown in figure 4.5.

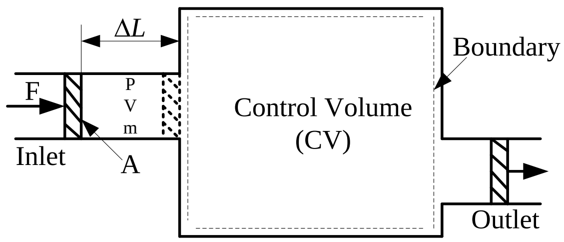


Figure 4.5. Schematic diagram for flow work at inlet and outlet

Energy required or work done in pushing the entire fluid element into the control volume through a distance ΔL (i.e., the flow work) is

$$W_{flow} = F.\Delta L \qquad \text{………… (4.49)}$$

where F is the force acting on the fluid element, which is calculated as the product of the fluid pressure P and the cross sectional area A of the inlet.

Putting $F = PA$ into Equation (4.49),

$$W_{flow} = PA.\Delta L = PV \qquad \text{… ……… (4.50)}$$

Flow work per unit mass or specific flow work can be obtained by dividing both sides of the equation (4.50) by the mass of the fluid element as

$$w_{flow} = Pv \qquad \text{…..……… (4.51)}$$

This specific flow work expression for the fluid element is the same whether it is pushed into or out of the control volume. The only difference between them is the flow work for pushing the fluid into the control volume is considered as negative and the flow work for pushing the fluid out of the control volume is considered as positive according to the sign convention of the work transfer.

The rate of flow work is then calculated with the help of the mass flow rate as

$$\dot{W}_{flow} = \dot{m}w_{flow} = \dot{m}Pv \qquad \text{.……….. (4.52)}$$

Now, the total flow work for the control volume is the sum of the flow work at the inlets and the flow wok at the outlets with consideration of sign convention and it is expressed as

$$\dot{W}_{flow} = -\sum_{in}(\dot{m}Pv) + \sum_{\text{out}}(\dot{m}Pv) \qquad \text{… … … … … … . (4.53)}$$

Shaft work is the contribution resulting from the rotation of a shaft which interacts with the fluid through a shearing motion within the control volume and crosses the boundary so as to transfer energy between the control volume and the surroundings. The shaft work is associated with the work produced by the shaft by consuming energy carried by a fluid like in turbine or work consumed by the shaft to increase the fluid energy like in compressor or pump.
Putting $\dot{W}_{flow}$ from equation (4.53) in equation (4.48), we get

$$\dot{W} = -\sum_{in}(\dot{m}Pv) + \sum_{out}(\dot{m}Pv) + \dot{W}_{CV} \qquad \text{… … … … … (4.54)}$$

Putting equations (4.47) and (4.54) in equation (4.44), we get

$$\frac{dE_{CV}}{dt} = \sum_{in}\left\{\dot{m}\left(u + \frac{1}{2}\bar{V}^2 + gz\right)\right\} - \sum_{out}\left\{\dot{m}\left(u + \frac{1}{2}\bar{V}^2 + gz\right)\right\}$$
$$+ \sum_{in}(\dot{m}Pv) - \sum_{out}(\dot{m}Pv) + \dot{Q}_{CV} - \dot{W}_{CV}$$

Or, $$\frac{dE_{CV}}{dt} = \sum_{in}\left\{\dot{m}\left(u + Pv + \frac{1}{2}\bar{V}^2 + gz\right)\right\} - \sum_{out}\left\{\dot{m}\left(u + Pv + \frac{1}{2}\bar{V}^2 + gz\right)\right\} + \dot{Q}_{CV} - \dot{W}_{CV}$$

……….(4.55)

Enthalpy is defined as $h = u + Pv$, so equation (4.55) becomes

$$\frac{dE_{CV}}{dt} = \sum_{in}\left\{\dot{m}\left(h + \frac{1}{2}\bar{V}^2 + gz\right)\right\} - \sum_{out}\left\{\dot{m}\left(h + \frac{1}{2}\bar{V}^2 + gz\right)\right\} + \dot{Q}_{CV} - \dot{W}_{CV} \qquad \text{… … … … (4.56)}$$

Equation (4.56) represents the general energy equation for a control volume which implies in short, *what stays within the control volume is equal to what goes in it minus what goes out of it.*

Here the expression $\left\{\dot{m}\left(h+\frac{1}{2}\bar{V}^2+gz\right)\right\}$ indicates the energy carried by the fluid and is called flow energy.

For the special case of no mass entering or leaving the control volume all "m" terms are zero, then equation (4.56) reduces to

$$\frac{dE_{CV}}{dt}=\dot{Q}_{CV}-\dot{W}_{CV} \qquad \dots\dots\dots\dots(4.57)$$

which is the conservation principle of energy of a control mass. If there is no energy interactions between the system and the surroundings, then

$$\frac{dE_{CV}}{dt}=0 \qquad \dots\dots\dots\dots\dots(4.58)$$

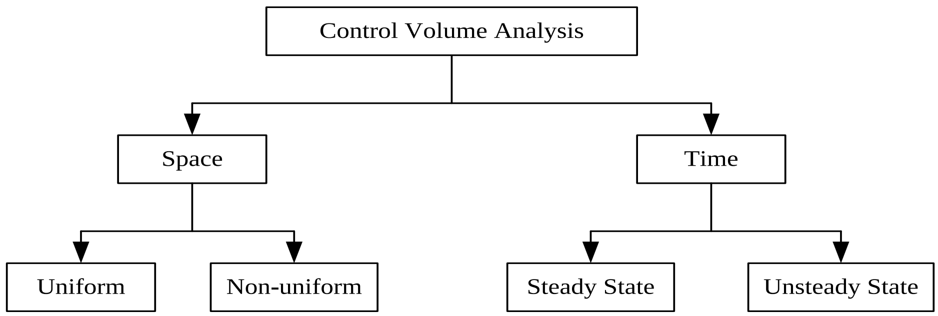
which is the conservation principle of energy of an isolated system.

4.4. Analysis of Control Volume

The analysis of a control volume or an open system requires detailed consideration of the inlets and outlets to the control volume as well as the state within the control volume. The spatial and time variations of the system properties are addressed at both inlets and outlets, and within the control volume itself.

A control volume can be analyzed by using two methods: the spatial consideration or the time consideration. When a control volume is analyzed with respect to space, it can be classified in two different types namely a uniform system and a non-uniform system. If the properties of the system at a particular instant of time do not vary with space i.e. all elements within the control volume have the same value for the properties at any time, such a system is called a uniform system and those properties are defined as uniform properties. Hence, uniform properties are spatially constant but may vary with time. If the properties of the system at a particular instant of time vary with space, such a system is called a non-uniform system and those properties are defined as non-uniform properties. So, non-uniform properties vary spatially [2].

When a control volume is analyzed with respect to time, it can also be classified in two different types namely a steady state system or an unsteady state system. If the properties of the system at a particular point do not vary with time, such a system is called a steady state system and those properties are defined as steady state properties. Hence, steady state properties are independent on time at a particular space. If the properties of the system at a particular point vary with time such a system is called an unsteady state system and those properties are defined as unsteady state properties. So, unsteady properties are function of time. These are shown in following chart.



We will do only uniform steady state and uniform unsteady state analysis in the following.

4.4.1. Steady State Analysis

The analysis of the long-term operation of an open system or a control volume can be considered as a steady state analysis where no mass or energy accumulates or dissipates within the control volume. Thus, for the steady state operation of a control volume, its properties (total mass and total energy) should not change with time. Mathematically,

$$\frac{dm_{CV}}{dt} = 0 \qquad \text{………. (4.59)}$$

and

$$\frac{dE_{CV}}{dt} = 0 \qquad \text{………. (4.60)}$$

Putting equation (4.59) in equation (4.30),

$$0 = \dot{m}_{in} - \dot{m}_{out}$$

$$\therefore \quad \dot{m}_{in} = \dot{m}_{out} \qquad \text{………. (4.61)}$$

Substituting equation (4.60) in equation (4.56), we get

$$0 = \sum_{in} \left\{ \dot{m}(h + \frac{1}{2}\bar{V}^2 + gz) \right\} - \sum_{out} \left\{ \dot{m}\left(h + \frac{1}{2}\bar{V}^2 + gz\right) \right\} + \dot{Q}_{CV} - \dot{W}_{CV}$$

$$\therefore \qquad \sum_{in}\left\{\dot{m}\left(h+\frac{1}{2}\bar{V}^2+gz\right)\right\}+\dot{Q}_{CV}=\sum_{out}\left\{\dot{m}(h+\frac{1}{2}\bar{V}^2+gz)\right\}+\dot{W}_{CV} \qquad \text{... ... ... (4.62)}$$

These equations (4.61) and (4.62) are the basis of much of the cycle analysis. In short, both these expressions state that for the steady state operation, incoming mass should be equal to outgoing mass and incoming energy should be equal to outgoing energy.

Most common examples of steady state devices are turbine, compressor, pump, nozzle, diffuser etc. These devices have single inlet and single outlet. If we denote inlet section by 1 and outlet section by 2, i.e.,

$$\dot{m}_{in}=\dot{m}_1 \qquad \text{and} \qquad \dot{m}_{out}=\dot{m}_2$$

Then equation (4.61) reduces to

$$\dot{m}_1=\dot{m}_2=\dot{m} \qquad \text{………. (4.63)}$$

Similarly, equation (4.62) reduces to

$$\dot{m}_1\left(h_1+\frac{1}{2}\bar{V}_1{}^2+gz_1\right)+\dot{Q}_{CV}=\dot{m}_2\left(h_2+\frac{1}{2}\bar{V}_2{}^2+gz_2\right)+\dot{W}_{CV}$$

or

$$\dot{m}\left(h_1+\frac{1}{2}\bar{V}_1{}^2+gz_1\right)+\dot{Q}_{CV}=\dot{m}\left(h_2+\frac{1}{2}\bar{V}_2{}^2+gz_2\right)+\dot{W}_{CV}$$

,

$$\therefore \qquad \dot{Q}_{CV}-\dot{W}_{CV}=\dot{m}\left[(h_2-h_1)+\frac{1}{2}\left(\bar{V}_2{}^2-\bar{V}_1{}^2\right)+g(z_2-z_1)\right] \qquad \text{…………(4.64)}$$

4.4.2. Unsteady State Analysis

Unsteady state analysis is performed when there is an accumulation (storage) or dissipation of the mass or energy within the control volume and their time variations at the inlets and outlets. Time variations of the mass or energy occur in filling and discharging problems as well as in start-up and shut-down considerations. Hence, during the unsteady state operation of a control volume, its properties (e.g., total mass and total energy) change with time, i.e., total mass and total energy of the system is function of time. Mathematically,

$$\frac{dm_{CV}}{dt}\neq 0 \qquad \text{or} \qquad m_{CV}=f_1(t) \qquad \text{………. (4.65)}$$

And

$$\frac{dE_{CV}}{dt} \neq 0 \qquad \text{or} \qquad E_{CV} = f_2(t) \qquad \text{.........} \ (4.66)$$

Then, the generalized equations of the mass and energy conservation principles for the unsteady state operation of the devices can be derived by integrating equations (4.30) and (4.56) respectively with respect to time for the required interval.

For any process $1-2$ between state 1 (instant t_1) and state 2 (instant t_2), equation of mass conservation principle reduces to

$$\int_{t_1}^{t_2} \left(\frac{dm_{CV}}{dt}\right) dt = \int_{t_1}^{t_2} \dot{m}_{in} dt - \int_{t_1}^{t_2} \dot{m}_{out} dt$$

$$\therefore \quad (m_{CV})_2 - (m_{CV})_1 = m_{in} - m_{out} \qquad \text{.........} \ (4.67)$$

where $(m_{CV})_1$ and $(m_{CV})_2$ are the masses of the control volume at state 1 and state 2 respectively; m_{in} and m_{out} are the total mass that is entering into the control volume and leaving out from the control volume during the time interval $(t_2 - t_1)$ respectively.

Similarly, integrating equation (4.56) of energy conservation principle,

$$\int_{t_1}^{t_2} \left(\frac{dE_{CV}}{dt}\right) dt = \int_{t_1}^{t_2} \sum_{in} \left\{\dot{m}\left(h + \frac{1}{2}\bar{V}^2 + gz\right)\right\} dt - \int_{t_1}^{t_2} \sum_{out} \left\{\dot{m}\left(h + \frac{1}{2}\bar{V}^2 + gz\right)\right\} dt + \int_{t_1}^{t_2} \dot{Q}_{CV} dt - \int_{t_1}^{t_2} \dot{W}_{CV} dt$$

$$\therefore (E_{CV})_2 - (E_{CV})_1 = m_{in}\left(h_{in} + \frac{1}{2}\bar{V}_{in}{}^2 + gz_{in}\right) - m_{out}\left(h_{out} + \frac{1}{2}\bar{V}_{out}{}^2 + gz_{out}\right) + Q_{12} - W_{12}$$

..........(4.68)

where E_{CV1} and E_{CV2} are the total energies of the control volume at state 1 and state 2 respectively; Q_{12} and W_{12} are the total heat transferred to the control volume and total work done by the control volume during the time interval $(t_2 - t_1)$ respectively.

Equation (4.68) includes the unsteady storage term within the control volume and all inlet and outlet flow terms. In short, the conservation of energy states that

The change of total energy within the control volume is equal to energy entering the control volume minus energy leaving the control volume.

Lecture Highlights

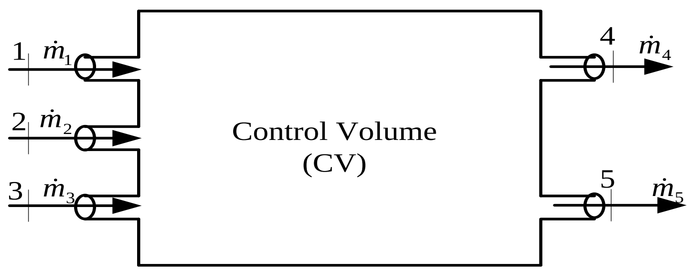
- *Conservation of mass for control volume:* "The change in mass within a control volume is equal to mass entering the control volume minus mass leaving the control volume". Mathematically,

$$dm_{cv} = \sum m_{in} - \sum m_{out}$$

On rate basis, $\frac{dm_{cv}}{dt} = \sum \dot{m}_{in} - \sum \dot{m}_{out}$

where $\dot{m}_{in} = \dot{m}_1 + \dot{m}_2 + \dot{m}_3$ is the sum of mass flow rate at each inlet and

$\dot{m}_{out} = \dot{m}_4 + \dot{m}_5$ is the sum of mass flow rate at each outlet.



- *Mass flow rate* is given by: $\dot{m} = \frac{A\overline{V}}{v} = \rho A\overline{V}$

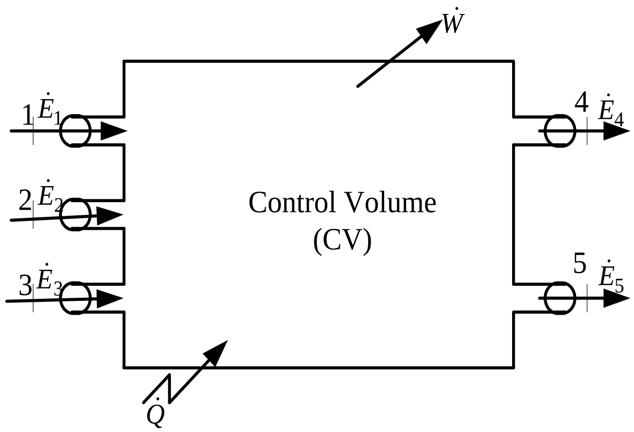
where A = Area of inlet or outlet, $\overline{V}$ = velocity of fluid, v = specific volume of fluid and ρ = density of fluid

- *Conservation of energy for a control volume:* "The change in total energy of a control volume is equal to net energy transported by the fluid into the control volume plus the heat supplied to the control volume minus the work produced by the control volume". Mathematically,

$$dE_{cv} = E_{net} + \delta Q - \delta W$$

On rate basis, $\frac{dE_{cv}}{dt} = \dot{E}_{net} + \dot{Q} - \dot{W}$

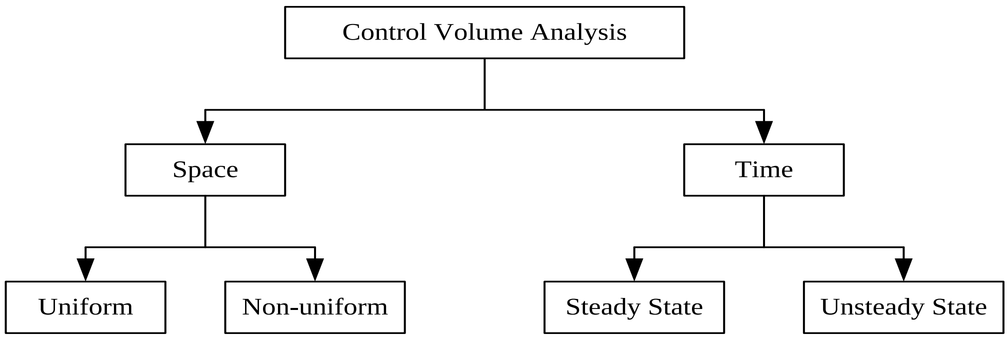
where $\dot{E}_{net} = \sum \dot{E}_{in} - \sum \dot{E}_{out}$ and $\dot{E} = \dot{m}(u + \frac{1}{2}\overline{V}^2 + gz)$



- The general energy equation for control volume is

$$\frac{dE_{cv}}{dt} = \sum[\dot{m}(h + \frac{1}{2}\bar{V}^2 + gz)]_{in} - \sum[\dot{m}(h + \frac{1}{2}\bar{V}^2 + gz)]_{out} + \dot{Q}_{cv} - \dot{W}_{cv}$$

- *Analysis of a control volume*: Any control volume can be analyzed with reference to either space or time.



- *Uniform control volume*: It is defined as the system whose properties do not vary with space at a particular instant of time.
- *Non-uniform control volume:* It is defined as the system whose properties vary with space at a particular instant of time.
- *Steady state control volume*: It is the system whose properties at a particular point do not vary with time.
- *Unsteady state control volume*: It is the system whose properties at a particular point vary with time.
- For *steady state control volume* it reveals:

$$\frac{dm_{cv}}{dt} = 0 \quad \text{and} \quad \frac{dE_{cv}}{dt} = 0$$

- The *steady state mass equation for control volume* is:

$$\sum \dot{m}_{in} = \sum \dot{m}_{out}$$

- The *steady state energy equation for control volume* is:

$$\sum [\dot{m}(h + \frac{1}{2}\overline{V}^2 + gz)]_{in} + \dot{Q}_{cv} = \sum [\dot{m}(h + \frac{1}{2}\overline{V}^2 + gz)]_{out} + \dot{W}_{cv}$$

- *Differences between steady state and unsteady control volume:*

Steady state control volume	Unsteady state control volume
1. The properties of the system within control volume do not change with time. 2. The properties at the boundaries of the control volume do not change with time. 3. The mass and energy interactions (heat and work) between the system and surroundings do not change with time. 4. The system continues indefinitely. 5. For examples: Common devices such as Turbine, compressor, pump, fan, nozzle, diffuser, heat exchanger etc. at their normal operation.	1. The properties of the system within control volume change with time. 2. The properties at the boundaries of the control volume change with time. 3. The mass and energy interactions (heat and work) between the system and surroundings do not change with time. 4. The system starts and stops over some finite time. 5. For examples: Discharging and filling of a gas cylinder, Balloons, during start up and shut down period of devices such as turbine, compressor, pump, fan etc.

References

[1] *Fundamentals of Thermodynamics & Heat Transfer*: Luintel M.C., Heritage Publishers & Distributors Pvt. Ltd., Kathmandu, Nepal, 2016.

[2] *Fundamentals of Engineering Thermodynamics*: Howell J. R. and Buckius R. O., McGraw-Hill, New York, 1992.