Course Title:

Fundamental of Thermodynamics and Heat Transfer

Lecture 9 (Week 9):

First Law of Thermodynamics

Lecturer: Assoc. Prof. Dr. Lila Raj Koirala

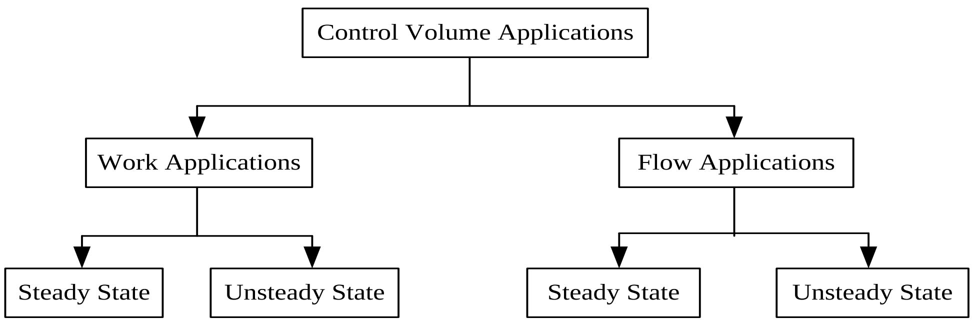
Learning Objective of Lecture:

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

- ✓ Control Volume Applications
- ✓ Steady State Work Applications
- ✓ Steady State Flow Applications
- ✓ Unsteady State Work Applications
- ✓ Unsteady State Flow Applications
- ✓ Other Statements of First Law of Thermodynamics

4.5. Control Volume Applications

As discussed earlier, operation and performance of the control volume applications or common devices such as turbine, compressor, pump, fan, nozzle, diffuser, heat exchanger, throttling valve etc can be studied or analyzed with respect to mass conservation and energy conservation principles. The common control volume applications can be divided into four groups depending upon their operation and function: steady state work applications, steady state flow applications, unsteady state work applications and unsteady state flow applications as shown in following chart.



4.5.1. Steady State Work Applications

Typical devices which operate under steady state conditions and have a work interaction with the surroundings, i.e. either produce or consume work are called steady state work applications. The common examples of steady state work applications are turbine, compressor, pump, fan, etc. These devices generally have a single inlet denoted by 1 and a single outlet denoted by 2. Therefore, equations for conservation of mass and conservation of energy for the steady state operation of these devices are given as

$$\dot{m}_1 = \dot{m}_2 = \dot{m} \qquad \text{..........(4.69)}$$

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

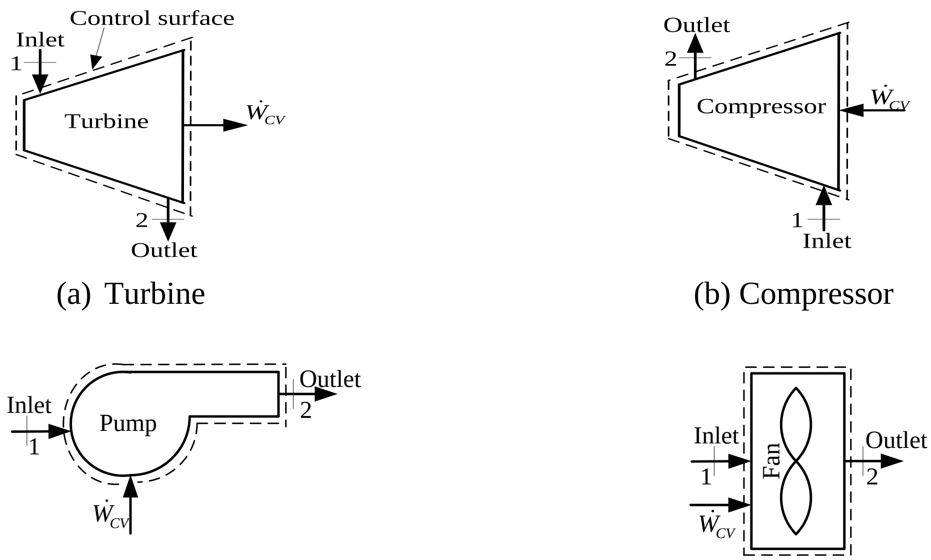
Or,

$$q_{CV} - w_{CV} = \left[(h_2 - h_1) + \frac{1}{2}\left(\bar{V}_2{}^2 - \bar{V}_1{}^2\right) + g(z_2 - z_1)\right] \qquad \text{............(4.70)}$$

Schematic diagrams of common steady state work applications or devices such as turbine, compressor, pump and fan are shown in figure 4.6. In case of these devices, the kinetic and potential energy changes between the inlet and outlet are usually, but not always, small. Moreover, some part of the energy carried by the fluid is lost as a heat transfer from their boundary or control surface to the surroundings. If their control surface is perfectly insulated and heat loss from the surface is negligible in comparison to the work produced or consumed, they are called adiabatic devices. Therefore, for an adiabatic device or steady state work application the equation of the energy conservation reduces to

$$\dot{W}_{CV} = \dot{m}\left[(h_1 - h_2) + \frac{1}{2}\left(\bar{V}_1^{\,2} - \bar{V}_2^{\,2}\right) + g(z_1 - z_2)\right] \qquad \text{...........(4.71)}$$

A turbine as shown in figure 4.6 (a), is a device which produces work (or power) by consuming energy carried by a fluid and does work through the rotation of a shaft. The fluid having high pressure expands to a low pressure thereby doing work against the turbine blades. In thermodynamics, it is frequently dealt with steam turbine or gas turbine.



(a) Turbine (b) Compressor

(c) Pump (d) Fan

Figure 4.6. Steady state work applications or devices [1]

All other three devices namely compressor, pump and fan increase fluid energy by consuming mechanical work. Compressor, as shown in figure 4.6(b), requires a work input to produce a high pressure of a fluid at the outlet from the low pressure at the inlet. It is usually used for a gaseous working substance. Pump, as shown in figure 4.7(c), requires a work input to increase pressure or potential energy of the liquid working substance. Fan, as shown in figure 4.6(d), also requires a work input to increase kinetic energy of the fluid by increasing its velocity rather than produce large pressure changes. It is employed to move fluid.

While using energy equations (4.70) and (4.71) for energy consuming devices like compressor, pump and fan, we have to put negative sign for the magnitude of work input. Similarly, we have to put negative sign for the magnitude of heat loss from the control surface when using energy equation (4.70) in case of all steady state work devices.

4.5.2. Steady State Flow Applications

Equipment or devices which operate under steady state conditions and have no work interaction with the surroundings, i.e. do not produce or consume work ($\dot{W}_{CV} = 0$) are known as steady state flow applications. Heat exchanger, evaporator (steam generator or boiler), condenser, nozzle, diffuser, throttling valve, pipe etc are the common examples of steady state flow applications. These devices have a single inlet denoted by 1 and a single outlet denoted by 2 and therefore, general equations for mass and energy conservation are expressed when $\dot{W}_{CV} = 0$ as

$$\dot{m}_1 = \dot{m}_2 = \dot{m} \qquad \text{……….(4.72)}$$

$$\dot{Q}_{CV} = \dot{m}\left[(h_2 - h_1) + \frac{1}{2}\left(\bar{V}_2{}^2 - \bar{V}_1{}^2\right) + g(z_2 - z_1)\right] \qquad \text{……….(4.73)}$$

Schematic diagrams of common steady state flow applications or devices such as heat exchanger, evaporator, condenser, nozzle, diffuser, throttling valve and pipe are shown in figure 4.7. Most of these devices experience very small changes in potential energy.

A heat exchanger, as shown in figure 4.7 (a)**,** is a device used to transfer heat energy from one fluid to another. The analysis of the heat exchanger is very dependent on the selection of the control volume. In the figure 4.7 (a) three possible control volumes *A*, *B* and *C* are indicated by boundary dotted lines where *1h* is inlet of hot fluid, *2h* is outlet of hot fluid, *1c* is inlet of cold fluid and *2c* is outlet of cold fluid. The control volume A or B can be analyzed to determine the magnitude of heat transfer or heat exchange $\dot{Q}_{CV}$. We have to analyze the control volume C if the effect of heat exchange on the properties of hot or cold fluid has to be studied. In case of heat exchanger, the changes in potential energy and kinetic energy are small and therefore, are negligible in comparison to the change in enthalpy. Hence, the equation of the energy conservation for the control volume A is given as

$$\dot{Q}_{CV} = \dot{m}_h(h_{2h} - h_{1h}) \qquad \text{……….(4.74)}$$

where $\dot{m}_h$ is the mass flow rate of hot fluid, h_{1h} is the enthalpy of hot fluid at the inlet and h_{2h} is the enthalpy of hot fluid at the outlet.
Similarly, the equation of energy conservation for control volume C is given as

$$\dot{m}_h h_{1h} + \dot{m}_c h_{1c} = \dot{m}_h h_{2h} + \dot{m}_c h_{2c} \qquad \text{……….(4.75)}$$

where $\dot{m}_c$ is the mass flow rate of cold fluid, h_{1c} is the enthalpy of cold fluid at the inlet and h_{2c} is the enthalpy of cold fluid at the outlet.

An evaporator, as shown in figure 4.7 (b), and a condenser, as shown in figure 4.7 (c), are special types of heat exchangers that perform a specific task. An evaporator converts a liquid into a high-temperature vapor (saturated or superheated) by absorbing heat energy from the surroundings. A condenser converts a high-quality mixture or superheated vapor into the liquid state by rejecting heat energy to the surroundings. The equation of energy conservation for the evaporator and condenser is given as

$$\dot{Q}_{CV} = \dot{m}(h_2 - h_1) \qquad \text{……….(4.76)}$$

Nozzle and diffuser are used to control the velocity of the fluid. These devices are simply area changing devices. A nozzle, as shown in figure 4.7(d), is a device with decreasing cross sectional area and is used to increase the velocity of the fluid thereby decreasing the pressure. A diffuser, as shown in figure 4.7(e), is a device with increasing cross sectional area and is used to decrease the velocity of the fluid thereby increasing the pressure.

Since the kinetic energy is typically important in the nozzle and diffuser, the change in the potential energy is usually negligible in comparison to the change in the kinetic energy or the change in the enthalpy. Hence, the equation of energy conservation for the nozzle and diffuser is given by

$$\dot{Q}_{CV} = \dot{m}\{(h_2 - h_1) + \tfrac{1}{2}\left(\bar{V}_2{}^2 - \bar{V}_1{}^2\right)\} \qquad \text{…….(4.77)}$$

If these devices are operating under adiabatic condition ($\dot{Q}_{CV} = 0$), the above equation reduces to

$$(h_2 - h_1) + \tfrac{1}{2}\left(\bar{V}_2{}^2 - \bar{V}_1{}^2\right) = 0 \qquad \text{………(4.78)}$$

which can also be written as

$$h_1 + \tfrac{1}{2}\bar{V}_1{}^2 = h_2 + \tfrac{1}{2}\bar{V}_2{}^2 \qquad \text{………(4.79)}$$

A throttling valve, as shown in figure 4.7(f), is simply a flow obstruction (partially opened valve or a small orifice) placed in the fluid flow passage which reduces pressure of the fluid without performing work. Generally, the heat transfer is small. The change in potential energy and kinetic energy are also negligible. Then the equation of the energy conservation for the throttling valve yields

$$h_2 - h_1 = 0$$

$$\therefore \quad h_2 = h_1 \qquad \text{…………(4.80)}$$

Hence, enthalpy remains constant during a throttling process.

One of the steady state flow applications or devices is a simple pipe as shown in figure 4.7(g). In a pipe the change in potential energy between the inlet and outlet is important and there is no work. Assuming that the control surface of the pipe is adiabatic, the equation of energy conservation reduces to

$$(h_1 - h_2) + \frac{1}{2}\left(\bar{V}_1^{\ 2} - \bar{V}_2^{\ 2}\right) + g(z_1 - z_2) = 0 \qquad \text{………..(4.81)}$$

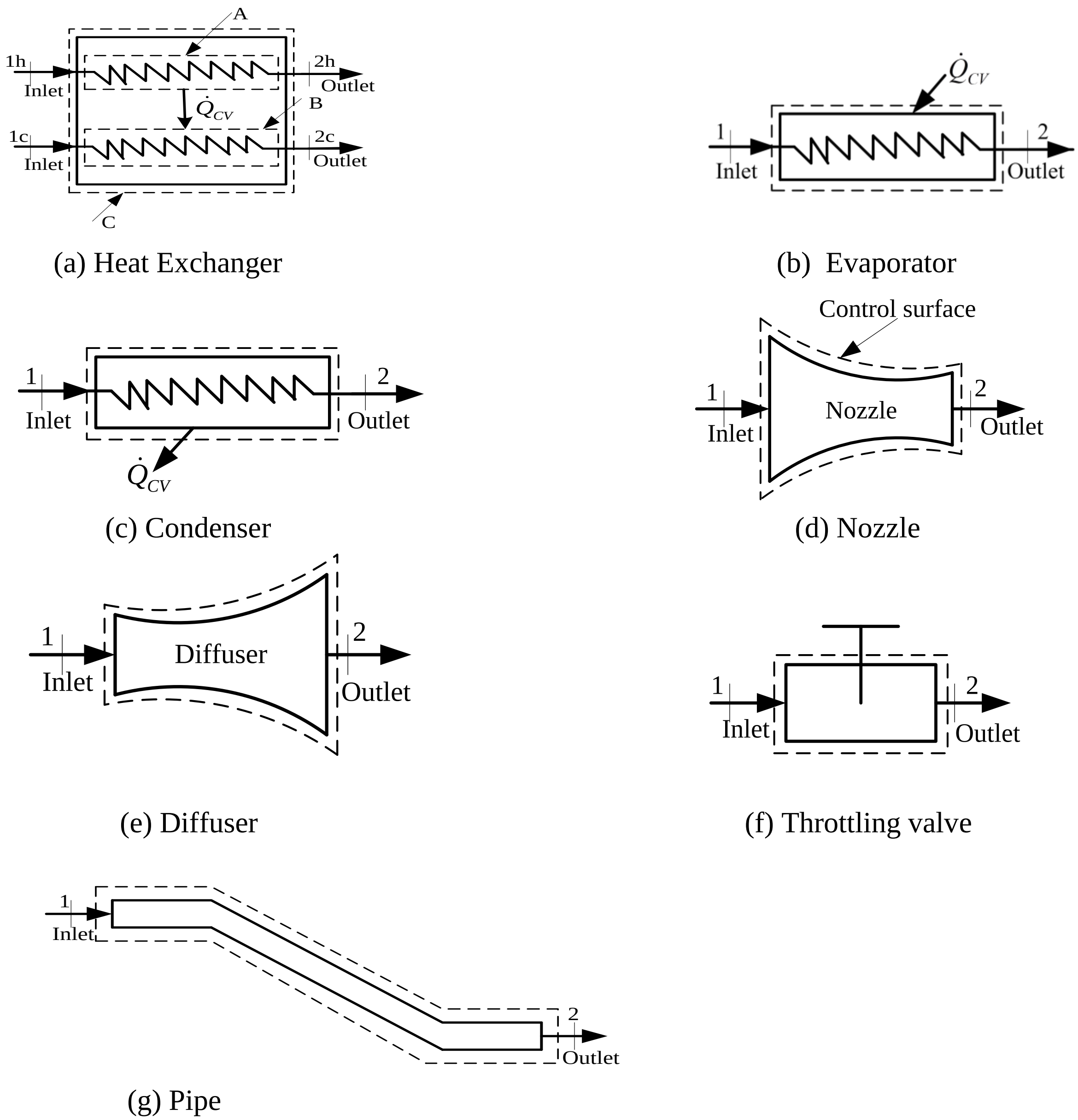


Figure 4.7. Steady State Flow Applications [1]

4.5.3. Unsteady State Work Applications

Work applications or devices such as turbine, compressor, pump, fan etc operate in steady state condition at their normal operation. But these devices operate in unsteady state condition during the start-up and shut-down period and therefore, require unsteady state analysis.

(a) Fluid entering an open system (b) Fluid leaving an open system

Figure 4.8. Unsteady state work applications

Let us consider an open system, as shown in figure 4.8 (a), to have general idea about the unsteady state work applications. In this system, a fluid is supplied into a piston cylinder device through a valve. When the valve is opened, the fluid enters the system boundary (control surface). Therefore, there is continuous increase of the mass and then total energy of the fluid with time within the system which can produce a displacement work by moving the piston upwards. Here, the work is taken as positive because it is done by the system.

Using the equations (4.67) and (4.68), the equations of mass and energy conservation for this special device are given as

$$(m_{CV})_2 - (m_{CV})_1 = m_{in} \qquad \text{………. (4.82)}$$

$$(E_{CV})_2 - (E_{CV})_1 = m_{in}\left(h_{in} + \frac{1}{2}\bar{V}_{in}^{\;2} + gz_{in}\right) + Q_{12} - W_{12} \qquad \text{………. (4.83)}$$

In case of piston cylinder device, changes in potential energy and kinetic energy are negligible in comparison to change in internal energy. Therefore, the equation (4.83) reduces to

$$(m_{CV}u_{CV})_2 - (m_{CV}u_{CV})_1 = m_{in}\left(h_{in} + \frac{1}{2}\bar{V}_{in}^{\;2} + gz_{in}\right) + Q_{12} - W_{12} \qquad \text{………. (4.84)}$$

A similar device can be considered where a fluid is released from a tank or piston cylinder device through a valve as shown in figure 4.8 (b). When the valve is opened, the fluid goes out of the system boundary (control surface), and therefore, there is continuous decrease of the mass and then total energy of the fluid with time within the system which causes a displacement work by moving the piston downwards. Here, the work is taken as negative because it is done on the system.

Similarly, the equations of mass and energy conservation for this special arrangement are given as

$$(m_{CV})_2 - (m_{CV})_1 = -m_{out} \quad \text{……….(4.85)}$$

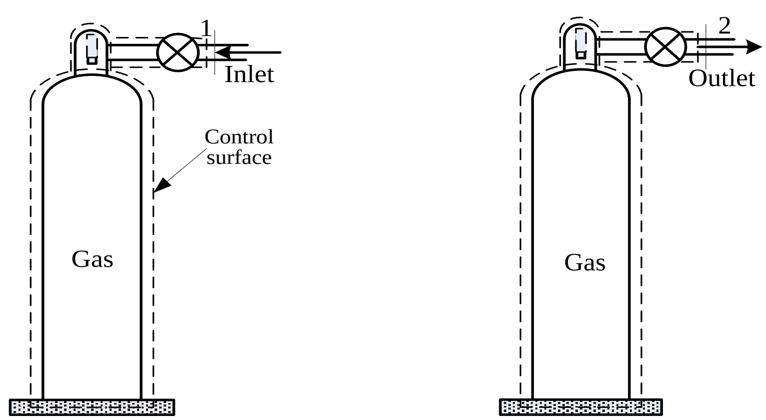
$$(m_{\text{CV}}u_{\text{CV}})_2 - (m_{\text{CV}}u_{\text{CV}})_1 = -m_{out}\left(h_{out} + \frac{1}{2}\bar{V}_{out}{}^2 + gz_{out}\right) + Q_{12} - W_{12} \quad \text{……...(4.86)}$$

4.5.4. Unsteady State Flow Applications

In many applications or devices such as in the filling or discharging of a tank, the total energy as well as mass of the tank changes with time thereby producing or consuming no work. Such devices are referred to as unsteady state flow applications.

4.5.4.1. Tank Filling Process

Let us consider a tank or gas cylinder as shown in figure 4.9 (a). During the filling of a gas cylinder, gas enters the control volume (gas cylinder) through a valve and therefore, the mass and total energy of the control volume continuously increases with time. However, there is no any work interaction with the surroundings. Hence, it can be regarded as an unsteady state flow application.



(a) Filling of a gas cylinder (b) Discharging of a gas cylinder

Figure 4.9. Unsteady state flow applications

Using the equations (4.67) and (4.68), equations of mass and energy conservation for the tank filling process are given as

$$(m_{CV})_2 - (m_{CV})_1 = m_{in} \quad \text{.......(4.87)}$$

$$(E_{CV})_2 - (E_{CV})_1 = m_{in}\left(h_{\text{in}} + \frac{1}{2}\bar{V}_{in}^{\ 2} + gz_{in}\right) + Q_{12} \quad \text{.......(4.88)}$$

In this case also, changes in potential energy and kinetic energy are negligible in comparison to the change in internal energy within the control volume. Therefore, equation (4.88) becomes

$$(m_{CV}u_{CV})_2 - (m_{CV}u_{CV})_1 = m_{in}\left(h_{in} + \frac{1}{2}\bar{V}_{in}^{\ 2} + gz_{in}\right) + Q_{12} \quad \text{.......... (4.89)}$$

4.5.4.2. Tank Discharging Process

In contrary to the tank filling process, let us consider a tank or gas cylinder as shown in figure 4.9(b). During the cooking of a certain food, gas is consumed and mass as well as total energy of the system continuously decreases with time. Moreover, it does not produce or consume any work. Therefore, it is an unsteady state flow application.

Applying the equations (4.67) and (4.68), equations of mass and energy conservation for the tank discharging process are given as

$$(m_{CV})_2 - (m_{CV})_1 = -m_{out} \quad \text{.......... (4.90)}$$

$$(E_{CV})_2 - (E_{CV})_1 = -m_{out}\left(h_{out} + \frac{1}{2}\bar{V}_{out}^{\ 2} + gz_{out}\right) + Q_{12} \quad \text{.......... (4.91)}$$

Neglecting the changes in potential energy and kinetic energy in comparison to change in internal energy yields

$$(m_{\text{CV}}u_{\text{CV}})_2 - (m_{\text{CV}}u_{\text{CV}})_1 = -m_{out}\left(h_{out} + \frac{1}{2}\bar{V}_{out}^{\ 2} + gz_{out}\right) + Q_{12} \quad \text{.......... (4.92)}$$

4.6. Other Statements of First Law of Thermodynamics

The first law of thermodynamics has many different forms. Their mathematical expressions and statements can be derived for different specific processes or systems with the help of the equations of the conservation of the energy mentioned earlier.

4.6.1. First Law of Thermodynamics for an Isolated System

Total energy of an isolated system always remains constant or never changes [2].

As described earlier, the conservation principle of the energy or first law of thermodynamics for a control mass undergoing a process is

$$dE = \delta Q - \delta W \qquad \text{………(4.93)}$$

This equation expresses the change in total energy of a control mass due to the energy transfer (heat and work transfer) between the system and the surroundings. If the control mass is isolated from its surroundings, i.e. if there is no interaction in terms of the energy transfer between the system and the surroundings ($\delta Q = \delta W = 0$), then equation of the energy conservation for a isolated system is given as

$$dE = 0$$

or, $E = \text{constant}$ ……. (4.94)

Hence, the total energy is constant for an isolated system.

4.6.2. First Law of Thermodynamics for a Control Mass Undergoing an Adiabatic Process

An increase in total energy of a control mass during an adiabatic process is equal to the work done on the control mass [2].

Alternately,

A decrease in total energy of a control mass during an adiabatic process is equal to the work done by the control mass.

If the boundary of the control mass is adiabatic or completely insulated ($i.e.\ \delta Q = 0$), then energy equation (4.93) becomes

$$dE = -\delta W \qquad \text{………. (4.95)}$$

Therefore, the work done on a control mass is equal to the change in total energy of a control mass undergoing an adiabatic process.

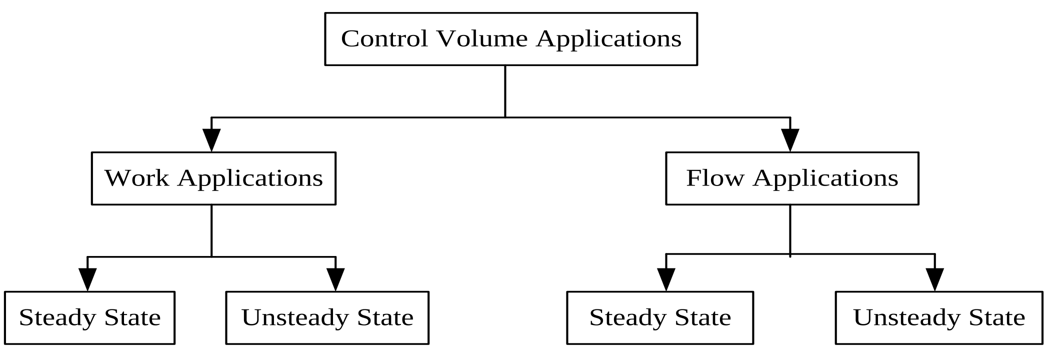
4.6.3. Perpetual Motion Machine of the First Kind

A machine which produces a continuous supply of work without absorbing any energy from the surroundings is called a perpetual motion machine of the first kind (PMM-I). However, perpetual motion or continuously running machine is impossible in nature because of the presence of friction. Hence, we cannot take continuous useful output effect without corresponding supply of input energy.

If a device or machine has no interaction with the surroundings in terms of energy transfer, then $\delta Q = 0 \; and \; \delta W = 0$. Thus, it is not possible to have the change in total energy *(dE)* equal anything but zero.

Lecture Highlights

- Depending upon the operation and functions of devices, *control volume applications* can be classified into four groups:
  (i) Steady state work applications
  (ii) Steady state flow applications
  (iii) Unsteady state work applications
  (iv) Unsteady state flow applications



- *Differences between steady state work applications and steady state flow applications*:

Steady state work applications	Steady state flow applications
1. They are any devices which operate under steady state conditions and either produce or consume work. 2. For examples: Devices such as Turbine, compressor, pump, fan etc.	1. They are any devices which operate under steady state condition and neither produce nor consume work. 2. For examples: Devices such as nozzle, diffuser, heat exchanger, boiler, condenser, throttling valve etc.

- *Differences between steady state work applications and steady state flow applications*:

Unsteady state work applications	**Unsteady state flow applications**
1.They are any devices which operate under unsteady state conditions and either produce or consume work.	1. They are any devices which operate under unsteady state condition and neither produce nor consume work.
2. For examples: During start up and shut down period of devices such as turbine, compressor, pump, fan etc.	2. For examples: Discharging a gas cylinder e.g. during cooking and filling of cylinder by gas etc.

- *Turbine:* It is a device which produces the shaft work (mechanical work) at the expense of the energy of the working fluid.
- *Compressor, pump and fan*: They are the devices which increase the fluid energy by consuming mechanical work. Compressor increases the pressure of a gas, pump increases the pressure of a liquid and fan increases the kinetic energy or velocity of the fluid.
- For the common steady state work devices such as turbine, compressor, pump and fan having single inlet "1" and single outlet "2", steady state energy equation becomes

$$\dot{Q}_{cv} - \dot{W}_{cv} = \dot{m}[(h_2 - h_1) + \frac{1}{2}(\overline{V}_2^2 - \overline{V}_1^2) + (z_2 - z_1)]$$

where $\dot{Q}_{cv} = 0$, if devices are adiabatic, $\dot{W}_{cv}$ is positive for turbine and $\dot{W}_{cv}$ is negative for compressor, pump and fan.

- *Nozzle and diffuser*: A nozzle is a device with decreasing cross-sectional area which increases the velocity of a fluid at the expense of pressure. A diffuser is a device with increasing cross-sectional area which decreases the velocity of a fluid thereby increases the pressure of a fluid.
- For the steady state flow devices ($\dot{W}_{cv} = 0$) such as nozzle and diffuser having single inlet "1" and single outlet "2", *steady state energy equation* becomes

$$\dot{Q}_{cv} = \dot{m}[(h_2 - h_1) + \frac{1}{2}(\overline{V}_2^2 - \overline{V}_1^2) + (z_2 - z_1)]$$

For these devices change in potential energy between inlet and outlet is negligible as compare to the change in kinetic energy and enthalpy, then for adiabatic ($\dot{Q}_{cv} = 0$) nozzle and diffuser above equation reduces to

$$h_1 + \frac{1}{2}\overline{V}_1^2 = h_2 + \frac{1}{2}\overline{V}_2^2$$

- *Heat exchanger*: It is a flow device in which two moving hot and cold fluid streams having different temperatures exchange heat without mixing. In this device, the change in kinetic and potential energy between inlet and outlet are negligible in comparison to the change in enthalpy. Hence, the steady state energy equation for the hot fluid is given by

$$\dot{Q}_{cv} = \dot{m}_h(h_{2h} - h_{1h})$$

Similarly, the steady state energy equation for the cold fluid is given by

$$\dot{Q}_{cv} = \dot{m}_c (h_{2c} - h_{1c})$$

If both hot and cold fluids together are taken as a system, then the steady state energy equation for the combined system is given by

$$\dot{m}_h h_{1h} + \dot{m}_c h_{1c} = \dot{m}_h h_{2h} + \dot{m}_c h_{2c}$$

where subscripts *1h* and *1c* denote inlet of hot and cold fluids respectively. Likewise, subscripts *2h* and *2c* denote outlet of hot and cold fluids respectively. $\dot{m}_h$ and $\dot{m}_c$ are mass flow rates of hot and cold fluids respectively.

- *Evaporator and condenser:* Evaporator is a special type of heat exchanger which converts liquid into vapor by absorbing heat from the surroundings, whereas condenser is also a special type of heat exchanger which converts vapor into liquid by rejecting heat to the surroundings. The steady state energy equation for these two devices is expressed as

$$\dot{Q}_{cv} = \dot{m}(h_2 - h_1)$$

- *Throttling valve:* It is a flow device which reduces pressure of a fluid without performing work. For this device, change in kinetic and potential energy between inlet and outlet as well as heat transfer are assumed to be negligible. Hence, the steady state energy equation for the throttling valve reduces to

$$h_1 = h_2$$

which indicates the throttling process is an isenthalpic process.

- *Pipe*: In a pipe the change in potential energy between the inlet and outlet is important and there is no work. Assuming that the control surface of the pipe is adiabatic, the equation of energy conservation reduces to

$$(h_1 - h_2) + \frac{1}{2}\left(\bar{V}_1{}^2 - \bar{V}_2{}^2\right) + g(z_1 - z_2) = 0$$

- *Mass conservation equation for any unsteady process* between two states 1 and 2 is

$$m_{cv2} - m_{cv1} = m_{in} - m_{out}$$

where m_{cv1} and m_{cv2} are the masses of the control volume at state 1 and state 2 respectively. m_{in} is the total mass entering the control volume and m_{out} is the total mass exiting from the control volume during time interval t_1 to t_2.

- *Energy conservation equation for any unsteady process* between two states 1 and 2 is

$$E_{cv2} - E_{cv1} = [\dot{m}(h + \frac{1}{2}\overline{V}^2 + gz]_{in} - [\dot{m}(h + \frac{1}{2}\overline{V}^2 + gz)]_{out} + Q_{12} - W_{12}$$

where E_{cv1} and E_{cv2} are the total energy of the control volume at state 1 and state 2 respectively. Q_{12} is the total heat transfer to the control volume and W_{12} is the total work done by the control volume during time interval t_1 to t_2.

The above energy equation is used for unsteady state work applications and it is also applied for the flow applications like discharging of a gas cylinder by putting $W_{12} = 0$.

- *First law of thermodynamics for an isolated system:* Total energy of a control mass remains constant when it is isolated from its surroundings, i.e.

$$dE = 0 \text{ as } \delta Q = 0 \text{ and } \delta W = 0.$$

- *First law of thermodynamics for a control mass undergoing an adiabatic process:* The increase in total energy of a control mass during an adiabatic process is equal to the work done on the control mass, i.e.

$$dE = -\delta W \text{ as } \delta Q = 0.$$

- *Perpetual motion (continuously running) machine of the first kind (PMM-I)* is impossible due to friction.

References

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

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