Course Title:

Fundamental of Thermodynamics and Heat Transfer

Lecture 7 (Week 7):

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:

- ✓ First Law of Thermodynamics for Control Mass (Closed System)
- ✓ Applications of First Law of Thermodynamics for Non – Flow Processes: Isochoric Process, Isobaric Process, Isothermal Process, and Polytropic Process
- ✓ First Law of Thermodynamics for Control Mass Undergoing Cyclic Process

4.1. First Law of Thermodynamics for a Control Mass

Conservation principles form the foundation of thermodynamics. The concept of conservation of energy and hypothesis that "*energy can neither be created nor be destroyed but it can be transformed from one form to another*" was developed by the scientists as the law of conservation of energy which came to be known as the first law of thermodynamics [1]. This implies energy is conserved in any process involving a thermodynamic system and its surroundings. In other words, if something enters into the system, it comes out in any other form but does not vanish.

First law of thermodynamics is based on the conservation principles namely mass and energy conservation principles. It is a mathematical expression for the effect of the interactions between the system and surrounding on the stored energy or total energy (internal energy, kinetic energy and potential energy) of the system. In closed system or control mass, interactions can take place only in the form of energy transfer (e.g., work transfer and heat transfer) but no mass transfer occurs between the system and surroundings. Therefore, first law of thermodynamics for a control mass can be explained with reference to conservation of energy only whereas in an open system or control volume, interactions can take place both by the mass transfer and energy transfer. Hence, the first law of thermodynamic for a control volume is explained with reference to both mass conservation and energy conservation principles.

The first law of thermodynamics cannot be proved mathematically, but no experiment has violated it. The first law of thermodynamics applies to reversible as well as irreversible energy conversion processes.

4.1.1. Conservation of Mass for a Control Mass (Closed System)

A control mass (closed system) is defined as a system in which energy transfer in terms of heat and work transfer can take place but no mass transfer occurs between the system and surroundings. Hence, it is a system which contains a fixed mass of a working substance within its boundary that can undergo transition, rotation and deformation. Conservation of mass for a control mass states that

Total mass of a control mass always remains constant or never changes[2].

Mathematically,

$$m = \text{constant}$$

$$\Rightarrow \quad dm = 0 \qquad \text{..........(4.1)}$$

For any process between state 1 and 2,

$$m_2 - m_1 = 0$$

$$\Rightarrow \qquad m_2 = m_1 \qquad \text{..........(4.2)}$$

Equation (4.1) can also be expressed on a rate basis as

$$\frac{dm}{dt} = 0 \qquad \text{......... (4.3)}$$

4.1.2. Conservation of Energy for a Control Mass (Closed System)

Let us consider a closed system or control mass undergoing a process during which δQ amount of heat is supplied to the control mass and δW amount of work is done by it. If heat supplied to the system during the process is greater than the work done by the system then total energy of the system increases; whereas if heat supplied to the system during the process is less than the work done by the system then the total energy of the system decreases. Similarly, if heat supplied to the system during the process is equal to the work done by the system then the total energy of the system remains constant. This explanation can be generalized as conservation of energy for a control mass and summarized in a statement as

A change in total energy of a control mass is equal to the heat supplied to the control mass minus the work done by the control mass [2].

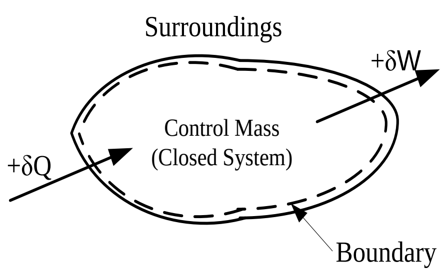

Figure 4.1. Conservation of energy for a control mass (closed system)

Mathematically,

$$dE = \delta Q - \delta W \qquad \text{......... (4.4)}$$

which can also be expressed on rate basis as

$$\frac{dE}{dt} = \dot{Q} - \dot{W} \qquad \text{………. (4.5)}$$

For any process $1 - 2$ between state 1 and 2,

$$E_2 - E_1 = Q_{12} - W_{12} \qquad \text{………. (4.6)}$$

where Q_{12} and W_{12} are the total heat supplied to the control mass and total work done by the control mass during the process, respectively.

Replacing the total energy by the sum of internal, kinetic and potential energies from equation (2.4) in equation (4.6),

$$(U + KE + PE)_2 - (U + KE + PE)_1 = Q_{12} - W_{12}$$

$$\Rightarrow \left(U + \frac{1}{2}m\bar{V}^2 + mgz\right)_2 - \left(U + \frac{1}{2}m\bar{V}^2 + mgz\right)_1 = Q_{12} - W_{12} \qquad \text{… … … . . (4.7)}$$

If the mass within the control mass is uniform and as the mass is constant in a control mass, above equations (4.4), (4.6) and (4.7) are alternately expressed on a specific basis by dividing both sides by mass *(m*) as

$$de = \delta q - \delta w \qquad \text{……….(4.8)}$$

$$e_2 - e_1 = q_{12} - w_{12} \qquad \text{....…….(4.9)}$$

$$(u + \frac{1}{2}\bar{v}^2 + gz)_2 - (u + \frac{1}{2}\bar{v}^2 + gz)_1 = q_{12} - w_{12} \qquad \text{……..(4.10)}$$

Most common example of a control mass is a piston cylinder device and for a stationary piston cylinder device the changes in potential energy and kinetic energy are negligible in comparison to the change in internal energy. Therefore, for the piston cylinder devices, equation (4.7) becomes

$$U_2 - U_1 = Q_{12} - W_{12} \qquad \text{………. (4.11)}$$

Equation (4.9) can also be rearranged for the heat transfer as

$$Q_{12} = (\Delta U)_{12} + W_{12} \qquad \text{………. (4.12)}$$

4.1.3. Applications of First Law of Thermodynamics for Control Mass in Non-flow Processes

Equation (4.12) can be applied to derive the expressions for heat transfer for different non-flow processes in a control mass as follows:

4.1.3.1. Isochoric (Constant Volume) Process

For an isochoric or a constant volume process ($dV = 0$), there is no displacement work transfer, i.e., $W_{12} = 0$. Putting this value into equation (4.12), we get

$$Q_{12} = (\Delta U)_{12} \qquad \text{………. (4.13)}$$

Equation (4.13) implies heat supplied to a control mass during an isochoric or a constant volume process is equal to the increase in internal energy of the control mass (closed system).

4.1.3.2. Isobaric (Constant Pressure) Process

For an isobaric or a constant pressure process, displacement work transfer is given as

$$W_{12} = P(V_2 - V_1) \qquad \text{……,,,(4.14)}$$

where $P_1 = P_2 = P$.

Putting in equation (4.12), we get

$$\begin{aligned} Q_{12} &= (\Delta U)_{12} + P(V_2 - V_1) \\ &= (U_2 - U_1) + (P_2V_2 - P_1V_1) \\ &= (U_2 + P_2V_2) - (U_1 + P_1V_1) \\ \therefore \quad Q_{12} &= (U + PV)_2 - (U + PV)_1 \end{aligned} \qquad \text{………. (4.15)}$$

The expression $U + PV$ occurs so frequently in thermodynamics that it has been given a special name enthalpy and symbol H, i.e.,

$$H = U + PV \qquad \text{………. (4.16)}$$

Putting the value of H from equation (4.16) into equation (4.15),

$$Q_{12} = H_2 - H_1 = (\Delta H)_{12} \qquad \text{………. (4.17)}$$

Equation (4.17) implies heat supplied to a control mass during an isobaric a constant pressure process is equal to the increase in enthalpy of the control mass (closed system).

4.1.3.3. Isothermal (Constant Temperature) Process for an Ideal Gas

For an isothermal or a constant temperature process, displacement work transfer is given as

$$W_{12} = P_1 V_1 ln\left(\frac{V_2}{V_1}\right) \quad \text{……….} (4.18)$$

The change in internal energy of an ideal gas during an isothermal or a constant temperature process is zero, i.e.

$$(\Delta U)_{12} = mc_V(T_2 - T_1) = 0 \quad \text{………..}(4.19)$$

Putting $(\Delta U)_{12}$ and W_{12} in equation (4.10), we get

$$Q_{12} = W_{12} = P_1 V_1 ln\left(\frac{V_2}{V_1}\right) \quad \text{……….} (4.20)$$

Equation (4.20) implies heat supplied to a control mass consisting of an ideal gas during an isothermal or constant temperature process is equal to the work done by the control mass (closed system).

4.1.3.4. Polytropic Process for an Ideal Gas

Work transfer and the change in internal energy of an ideal gas during a polytropic process are given as

$$W_{12} = \frac{P_2 V_2 - P_1 V_1}{1 - n} = \frac{mR(T_2 - T_1)}{1 - n}$$

$$(\Delta U)_{12} = mc_V(T_2 - T_1) \quad \text{……….}(4.21)$$

Putting $(\Delta U)_{12}$ and W_{12} in equation (4.12),

$$Q_{12} = m\left(c_V + \frac{R}{1 - n}\right)(T_2 - T_1) \quad \text{……….} (4.22)$$

Equation (4.22) can also be expressed in simpler from as

$$Q_{12} = mc_n(T_2 - T_1) \quad \text{………}(4.23)$$

where, $c_n = c_V + \frac{R}{1 - n}$

is the polytropic specific heat.

By using the relation, $c_v = R/(\gamma - 1)$, equation (4.22) becomes

$$Q_{12} = \frac{mR}{1-n}\left(\frac{\gamma - n}{\gamma - 1}\right)(T_2 - T_1) = \left(\frac{\gamma - n}{\gamma - 1}\right) \times W_{12} \quad \text{..........(4.24)}$$

4.2. First Law of Thermodynamics for a Control Mass Undergoing Cyclic Process

For the control mass undergoing a cyclic process, taking cyclic integral of equation (4.4),

$$\oint dE = \oint \delta Q - \oint \delta W \quad \text{....... (4.25)}$$

As the total energy is a thermodynamic property and initial and final states are identical for a cyclic process, the change in the total energy for a cycle is zero, i.e., $\oint dE = 0$, but $\oint \delta Q \neq 0$ and $\oint \delta W \neq 0$. Then equation (4.25) becomes

$$\oint \delta Q = \oint \delta W \quad \text{........(4.26)}$$

Equation (4.26) can also be expressed in the equivalent form as

$$\sum Q = \sum W \quad \text{.......... (4.27)}$$

For a cycle consisting of three individual processes such as $1-2$, $2-3$ and $3-1$, equation (4.27) can be expanded as

$$Q_{12} + Q_{23} + Q_{31} = W_{12} + W_{23} + W_{31} \quad \text{..........(4.28)}$$

Hence, according to the equation (4.27) first law of thermodynamics for a control mass undergoing a cyclic process can be stated as

(i) for a power cycle

When a control mass is undergoing a cyclic process then the heat supplied to the control mass is equal to the net work done by the control mass [2].

(ii) for a refrigeration cycle

When a control mass is undergoing a cyclic process then the heat rejected by the control mass is equal to the net work done on the control mass [2].

Lecture Highlights

- *First law of thermodynamics:* It is based on the mass and energy conservation principles. It provides the effect of the interactions between the system and surroundings on the total energy of the system.
- Since in a *closed system (control mass)* interactions can take place only in terms of energy transfer, first law of thermodynamics for a closed system is explained with reference to conservation of energy alone.
- Since in an open *system (control volume) interactions* can take place in terms of both mass and energy transfer, first law of thermodynamics for an open system is explained with reference to both mass and energy conservation principles.
- *Conservation of mass for a control mass:* "The total mass of a control mass always remains constant". Mathematically, $dm = 0$.
- *Conservation of energy for a control mass*: "The change in total energy of a control mass is equal to the heat supplied to the control mass minus the work produced by the control mass".

  Mathematically, $dE = \delta Q - \delta W$

  On the rate basis, $\frac{dE}{dt} = \dot{Q} - \dot{W}$

  For any process from state 1 to state 2: $E_2 - E_1 = Q_{12} - W_{12}$

  where Q_{12} and W_{12} are the total heat transferred to the control mass and total work transferred by the control mass respectively.

  Then, heat transferred to the control mass

  $Q = \Delta E + W = \Delta U + W$, when neglecting kinetic energy and potential energy.
- *Applications of first law of thermodynamics for non-flow processes*:
  - *Isochoric process:* For a control mass, heat transfer during a constant volume process is equal to the increase in internal energy of the system. Mathematically,

    As $W = 0$, $Q = \Delta U = U_2 - U_1 = mc_v(T_2 - T_1)$.
  - *Isobaric process*: For a control mass, heat transfer during a constant pressure process is equal to the increase in enthalpy of the system. Mathematically,

    As $W = P(V_2 - V_1)$,

    $Q = \Delta U + W = U_2 - U_1 + P(V_2 - V_1) = H_2 - H_1 = mc_P(T_2 - T_1)$.
  - *Isothermal Process:* For a control mass, heat transfer during a constant temperature process is equal to the work done by the system. Mathematically,

    As $\Delta U = 0$, $Q = W = P_1V_1 \ln(V_2/V_1)$
  - *Adiabatic process:* For a control mass, heat transfer during an adiabatic process is equal to zero. Mathematically,

    As $Q = 0$, $W = -\Delta U$

    This means work is done by the system at the expense of the reduction in the internal energy during an adiabatic process.

- *Polytropic process*: For a control mass, heat transfer during an polytropic process with polytropic index *n* is equal to

$$Q = \left(\frac{\gamma - n}{\gamma - 1} \right) \times W \text{ where } W = \frac{mR(T_2 - T_1)}{1 - n} \text{ and } \gamma = c_p / c_v$$

- First law of thermodynamics for a *control mass undergoing cyclic process* ($\oint \delta E = 0$) can be expressed as: $\oint \delta Q = \oint \delta W$ or, $\sum Q = \sum W$.
- First law of thermodynamics for a *power cycle*: "Whenever a control mass is undergoing cyclic process, then net heat supplied to the control mass is equal to net work produced by the control mass."
- First law of thermodynamics for a *refrigeration cycle*: "Whenever a control mass is undergoing a cyclic process, then net work supplied to the control mass is equal to the net heat rejected by the control mass."

References

[1] *Thermodynamics: An Engineering Approach:* Cengel Y. A. and Boles M. A., McGraw-Hill Education, New York, 2018.

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