Module

2

Lecture

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Asansol Engineering College

Department of Mechanical Engineering

Thermodynamics

Temperature and Zeroth Law of Thermodynamics

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COROLLARIES OF THE FIRST LAW OF THERMODYNAMICS

Corollary-1:

There exists a property of a closed system such that a change in its value is equal to the difference between heat supplied and work done during the change of state.

Proof:

Let the system be taken from state 1 to state 2 by the two different processes 1-a-2 and 1-b-2 as shown in Fig. 1.

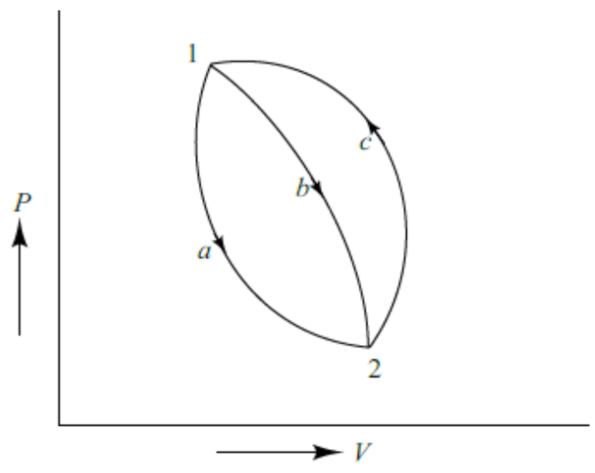

Fig. 1: P-V diagram

Let us consider,

$$(\delta Q - \delta W)_a \neq (\delta Q - \delta W)_b$$

where δQ the net heat is supplied to the system and δW is the net work done by the system during a process. Let the system be taken from state 2 to 1 through path 2-c-1.Now the processes 1-a-2 and 2-c-1 together constitute a cycle. From the first law of thermodynamics for a cyclic process, we can write

$$\oint \delta Q = \oint \delta W$$

$$\delta Q_a + \delta Q_c = \delta W_a + \delta W_c$$

$$(\delta Q - \delta W)_a = -(\delta Q - \delta W)_c$$

- Similarly, the processes 1-a-2 and 2-c-1 together constitute a cycle for which the first law of thermodynamics becomes

$$\oint \delta Q = \oint \delta W$$

$$\delta Q_b + \delta Q_c = \delta W_b + \delta W_c$$

$$(\delta Q - \delta W)_b = -(\delta Q - \delta W)_c$$

- **From above equations, we can conclude that $(\delta Q - \delta W)$ is same for both cycles and hence independent of the path the system follows during a change of state. If the property is denoted by U, then corollary can be expressed as $\delta Q - \delta W = dU$. The property U is called internal energy of the system.**

Corollary-2:

The internal energy of a closed system remains unchanged if the system is isolated from the surroundings.

Proof:

A system which exchanges neither mass nor energy with the surroundings is called an isolated system. It is thus a closed system having no energy interaction ($\delta Q = 0, \delta W = 0$) with the surroundings.

Then the first law of thermodynamics in differential form becomes

$dU = 0$

or, $U = \text{Constant}$

Corollary-3:

A perpetual motion machine of first kind is impossible.

Proof:

- A hypothetical device which would produce work continuously without absorbing any energy from its surroundings is called a perpetual motion machine of the first kind. A perpetual motion machine of the first kind must operate on a cycle to produce work continuously. If it does not operate on a cycle, its state would change continuously and it could not go on indefinitely. For such a device there cannot be any energy transfer in the form of heat from the surroundings, hence $\oint \delta Q = 0$ herefore, $\oint \delta W = 0$,, that means the work delivered by it is zero. Therefore, it is impossible to construct a perpetual motion machine of the first kind. A perpetual motion machine of the first kind is a machine which violates the first law of thermodynamics.
- It is always possible to devise a machine to deliver a limited (certain) quantity of work without requiring a source of energy in the surroundings. For example, a compressed gas in a piston-cylinder arrangement will expand and do work at the expense of the internal energy of the gas. Such a device can not produce work continuously.

FIRST LAW OF THERMODYNAMICS FOR DIFFERENT PROCESSES

1) Constant Volume Process (Isochoric)

- An isochoric process is one during which the volume remains constant, implying that the work done by the system will be zero. It therefore follows that any heat energy transferred to the system externally will be absorbed as internal energy. An isochoric process is also known as an isometric process or an isovolumetric process and is represented by a vertical line in the P-V diagram.

- Consider a gas confined in a rigid vessel of volume V as the system. Since the vessel has rigid walls, the displacement work done by the system is zero. Let the system be brought into contact with a heat source so that it can exchange energy in a quasi-equilibrium manner.
- First law of thermodynamics for the constant volume process in differential form becomes

$$\delta Q = dU$$

- When the system changes its state from 1 to 2, Then

$$Q_{1-2} = U_2 - U_1$$

Hence, the heat interaction is equal to the change in the internal energy of the system.

For constant C_v, we get

$$Q_{1-2} = mC_v(T_2 - T_1)$$

2) Constant Pressure Process (Isobaric)

- Consider a certain quantity of gas in a cylinder bounded by a piston as a system. Let the system undergoes a quasi-equilibrium constant-pressure heating process without changes in potential and kinetic energy. The only work done associated with the process is the displacement work done, which is

$$W_{1-2} = P(V_2 - V_1)$$

- The heat transfer is found by applying the first of thermodynamics for a constant-pressure quasi equilibrium process as

$$Q_{1-2} = H_2 - H_1$$

- The heat transfer in the constant pressure quasi-equilibrium process is equal to the change in enthalpy. It includes the change in internal energy and the work for the process.
- For constant C_p , we get

$$Q_{1-2} = mC_p(T_2 - T_1)$$

3) Constant Temperature Process (Isothermal)

- Consider certain quantity of gas in a cylinder bounded by a piston as a system. The system is allowed to undergo a quasi-equilibrium expansion process while in contact with a constant temperature bath.
- Let the system change its state from 1 to 2. Applying the first law of thermodynamics for the path 1-2, we get

$$Q_{1-2} - W_{1-2} = \Delta U$$

Suppose the gas under consideration is an ideal gas. Since, for an ideal gas the internal energy is a function of temperature only, change in internal energy for constant temperature process is zero, that is

$$\Delta U = 0$$

- Then the equation becones

$$Q_{1-2} = W_{1-2}$$

The heat transfer as well as the work transfer for a quasi-equilibrium process can be written as

$$Q_{1-2} = W_{1-2} = P_1V_1 \ln\frac{V_2}{V_1} = mRT_1 \ln\frac{V_2}{V_1} = m\, mRT_1 \ln\frac{P_1}{P_2}$$

4) Polytropic Process

Consider certain quantity of gas in a cylinder bounded by a piston as a system. The system is allowed to undergo a quasi-equilibrium expansion process in such a way that the functional relationship between pressure and volume during the expansion process follow the relation constant $PV^n = Constant$. Such process in thermodynamics is called as polytropic process. For a polytropic process ($PV^n = Constant$) between two end states 1 and 2, the work done is calculated as

$$W_{1-2} = \int_{V_1}^{V_2} PdV = \int_{V_1}^{V_2} \frac{C}{V^n} dV \quad (\text{where } C = P_1V_1^n = P_2V_2^n)$$

$$= C\frac{V_2^{-n+1} - V_1^{-n+1}}{1-n}$$

$$= \frac{CV_1^{-n+1} - CV_2^{-n+1}}{n-1}$$

$$= \frac{P_1V_1^nV_1^{-n+1} - P_2V_2^nV_2^{-n+1}}{n-1}$$

$$W_{1-2} = \frac{P_1V_1 - P_2V_2}{n-1}$$

- By applying the first law of thermodynamics to a quasi-equilibrium polytropic process between states 1 and 2, we get

$$Q_{1-2} = \Delta U + \int_1^2 PdV = (U_2 - U_1) + \frac{P_2V_2 - P_1V_1}{1-n}$$

$$Q_{1-2} = mC_v(T_2 - T_1) + \frac{P_2V_2 - P_1V_1}{1-n}$$

Since $U_2 - U_1 = mC_v(T_2 - T_1)$ for an ideal gas with constant specific heats. Using the ideal gas equation $PV = mRT$, the equation becomes

$$Q_{1-2} = mC_v(T_2 - T_1) + \frac{mR(T_2 - T_1)}{1-n}$$

$$= m\left(C_v + \frac{R}{1-n}\right)(T_2 - T_1)$$

Using the relationships $C_p - C_v = R$ and $\gamma = \frac{C_p}{C_v}$, it yields

$$Q_{1-2} = m\left(C_v + \frac{C_p - C_v}{1-n}\right)(T_2 - T_1)$$

$$Q_{1-2} = m\left(1 + \frac{\gamma - 1}{1-n}\right)C_v(T_2 - T_1) = m\left(\frac{1 - n + \gamma - 1}{1-n}\right)C_v(T_2 - T_1)$$

$$Q_{1-2} = m\left(\frac{\gamma - n}{1-n}\right)C_v(T_2 - T_1)$$

- Solved Examples:

Air is contained in a 1 m^3 rigid volume at 40°C and 200 kPa. Calculate the heat transfer needed to increase the pressure to 500 kPa. The C_v for air is constant and equal to 0.718 kJ/kg-°C.

Solution The mass of air (considering an ideal gas) is found to be

$$m = \frac{PV}{RT} = \frac{(200\ \text{kPa})(1\ \text{m}^3)}{(0.287\text{kJ/kg.K})(313\text{K})} = 2.226\ \text{kg}$$

The work is zero for this constant-volume process. Consequently, the first law of thermodynamics gives

$$Q = m\Delta u = mC_v\Delta T = mC_v(T_2 - T_1)$$

The ideal-gas law, $PV = mRT$, allows us to write

$$\frac{P_1}{T_1} = \frac{P_2}{T_2}$$

or, $$\frac{200}{313} = \frac{500}{T_2}$$

$$\therefore T_2 = 782.5 \text{ K}$$

The heat transfer is then found from Eq. (3.40) as

$$Q = (2.226 \text{ kg})(0.718 \text{ kJ/kg-K})(782.5 - 313) \text{ K} = 750.39 \text{ kJ}$$

The gas in a system receives heat which causes expansion against a constant pressure of 4 bar. An agitator in the system is driven by an electric motor using 200 W. For 6 kJ of heat supplied, the volume increase of the system in 30 s is 0.05 m^3. Estimate net change in the energy of the system.

Solution The rate of work on the system through agitator is = –200 W = –200 J/s (According to the sign convention of work transfer, work done on the system is negative).

Thus, during the 30 s of operation the work done is $= -200 \times 30 = -6000 \text{ J} = -6 \text{ kJ}$

Quasi-equilibrium expansion work is

$$W_{1-2} = P(V_2 - V_1) = 4 \times 10^5 \times 0.05 = 20 \times 10^3 \text{ N-m} = 20 \text{ kJ}$$

Net work done is therefore = 20 – 6 =14 kJ

From first law of thermodynamics, we can write

$$Q_{1-2} = \Delta U + W_{1-2}$$

or, $$6 = \Delta U + 14$$

or, $$\Delta U = -8 \text{ kJ}$$

Note that the negative sign indicates that the energy of the system decreases.

A mass of 8 kg gas expands within a flexible container so that the P-V relationship is of the form $PV^{1.2}$ = constant. The initial pressure is 1000 kPa and the initial volume is 1 m^3. The final pressure is 5 kPa. If specific internal energy of the gas decreases by 40 kJ/kg, find the heat transfer in magnitude and direction.

Solution From the given data, we have

$P_1 = 1000 \text{ kPa}$, $V_1 = 1 \text{ m}^3$, and $P_2 = 5 \text{ kPa}$

Final volume can be found as follows

$$P_1 V_1^{1.2} = P_2 V_2^{1.2}$$

or,

$$V_2 = 82.7 \text{ m}^3$$

Work done during polytropic expansion is

$$W_{1-2} = \frac{P_1 V_1 - P_2 V_2}{n-1}$$

$$= \frac{1000 \times 1 - 5 \times 82.7}{1.2 - 1}$$

$$= 2932.5 \text{ kJ}$$

Change in internal energy is $\Delta U = 8 \times (-40 \text{ kJ}) = -320 \text{ kJ}$ (Negative sign signifies that the energy decreases)

From first law of thermodynamics, we get

$$Q_{1-2} = \Delta U + W_{1-2}$$

$$= -320 + 2932.5 = 2612.5 \text{ kJ}$$

Since heat transfer is positive, heat is transferred to the gas.

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Thank You