5. The First Law of Thermodynamics

The first law of thermodynamics is one of the most important mathematical equations in the field of power engineering, as it can be applied to solve many problems regarding flow and non-flow systems alike. The first law of thermodynamics is a version of the law of conservation of energy adapted for thermodynamic systems.

The first law may be stated as follows: whenever a system undergoes a cyclic change, the algebraic sum of heat transfers is equal to the algebraic sum of work transfers.

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

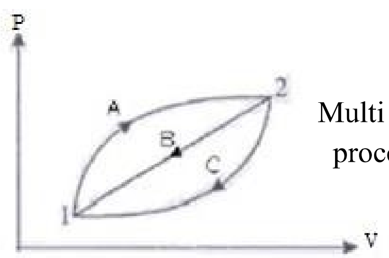
where: Q = heat transfer

W = work transfer

The circles on the integral symbols in the above equation indicate that these are integrals for all the processes of a cycle.

The First Law Applied to a Closed System Process

One very important consequence of the first law of thermodynamics is that the energy of the system is a property. To prove this, consider a closed system undergoing a change of state from 1 to 2 as shown in figure below. The system may proceed from state 1 to state 2 along the path and then return to the original state 1 along two paths B and C.



Multi path process

For cycle 1-A-2-B-1, we have:

$$\oint (\delta Q - \delta W) = 0$$

or

$$\oint_1^2 (\delta Q - \delta W)_A + \oint_2^1 (\delta Q - \delta W)_B = 0 \qquad \dots\dots\dots\dots\dots\dots (5.1)$$

For cycle 1-A-2-C-1, we have:

$$\oint_1^2 (\delta Q - \delta W)_A + \oint_2^1 (\delta Q - \delta W)_C = 0 \qquad \dots\dots\dots\dots\dots\dots (5.2)$$

Comparing Equations (5.1) and (5.2), we get:

$$\oint_2^1 (\delta Q - \delta W)_B = \oint_2^1 (\delta Q - \delta W)_C \qquad \dots\dots\dots\dots\dots\dots (5.3)$$

Equation (5.3) suggests that when a system operates between states 1 and 2, the quantity $\oint_2^1 (\delta Q - \delta W)$ is constant irrespective of the path along which the system proceeds. Thus the value $\oint_1^2 (\delta Q - \delta W)$ is solely fixed by the end states and is independent of the path of the process. Therefore, the quantity $\oint_1^2 (\delta Q - \delta W)$ is a property, as it is a point function. This is called the total energy E of the system and is an exact differential.

$$\int_1^2 (\delta Q - \delta W) = \int_1^2 dE = E_2 - E_1 \qquad \ldots\ldots\ldots\ldots\ldots\ldots (5.4)$$

or

$$\delta Q - \delta W = dE \qquad \ldots\ldots\ldots\ldots\ldots\ldots (5.5)$$

Neglecting kinetic and potential energies, and considering internal energy only ($E = U$), we have:

$$\delta Q - \delta W = dU \qquad \ldots\ldots\ldots\ldots\ldots\ldots (5.6)$$

Therefore, the first law of thermodynamics enables us to define a property of the system called internal energy. The last equation is called the non-flow energy equation and can be applied on any closed system.

Integrating both parts, we get:

$$Q - W = \Delta U \qquad \ldots\ldots\ldots\ldots\ldots\ldots (5.7)$$

For a unit mass, we get:

$$q - w = \Delta u \qquad \ldots\ldots\ldots\ldots\ldots\ldots (5.8)$$

Energy of an isolated system

An isolated system is one in which there is no interaction of the system with the surroundings. For an isolated system, $dQ = 0, dW = 0$. So the first law gives:

$$dE = 0 \qquad \text{or} \qquad E = \text{Constant}$$

Thus the energy of an isolated system is always constant. This conclusion is very important, since the universe is considered an isolated system, then energy is conserved in the universe which leads to the principle of conservation of energy. The principle of conservation of energy states that energy can neither be created nor destroyed rather, it transforms from one form to another.

Perpetual motion machine of the first kind

According to the first law of thermodynamics, energy is neither created nor destroyed, but only gets transformed from one form to another. There can be no machine which would continuously supply mechanical work without some other form of energy disappearing simultaneously. Such a fictitious machine is called a perpetual motion machine of the first kind (PMM 1). A (PMM 1) is thus impossible.

Specific Heat of Gases

1. Specific heat at constant volume (C_v): from the first law of thermodynamic for a closed system at constant volume:

$$Q - W = \Delta U$$

Since the volume is constant:

$$W = \int PdV = 0 \qquad \dots\dots\dots\dots\dots\dots\dots (5.9)$$

Then:

$$Q = \Delta U \qquad \dots\dots\dots\dots\dots\dots\dots (5.10)$$

and

$$Q = mC_v\Delta T \qquad \dots\dots\dots\dots\dots\dots\dots (5.11)$$

So:

$$\Delta U = mC_v\Delta T \qquad \dots\dots\dots\dots\dots\dots\dots (5.12)$$

Then:

$$U = mC_vT \qquad \dots\dots\dots\dots\dots\dots\dots (5.13)$$

For a unit mass:

$$u = C_vT \qquad \dots\dots\dots\dots\dots\dots\dots (5.14)$$

2. Specific heat at constant pressure (C_p): from the first law of thermodynamic for a closed system at constant pressure:

$$Q - W = \Delta U$$

Since the pressure is constant:

$$W = \int PdV = P(V_2 - V_1) \qquad \dots\dots\dots\dots\dots\dots\dots (5.15)$$

and

$$Q = mC_p\Delta T \qquad \dots\dots\dots\dots\dots\dots\dots (5.16)$$

So:

$mC_p\Delta T - P(V_2 - V_1) = (U_2 - U_1)$ ... ... (5.17)

$(U_2 - U_1) + P(V_2 - V_1) = mC_p\Delta T$ ... ... (5.18)

$(U_2 + P_2V_2) - (U_1 + P_1V_1) = mC_p\Delta T$ ... ... (5.19)

Since $H = U + PV$, then:

$H_2 - H_1 = mC_p\Delta T$

$\Delta H = mC_p\Delta T$ ... ... (5.20)

Then:

$H = mC_pT$ ... ... (5.21)

For a unit mass:

$h = C_pT$ ... ... (5.22)

Relationship between C_v and C_p

We know that the enthalpy may be given as:

$H = U + PV$

Since $H = mC_pT$, $U = mC_vT$ and $PV = mRT$, then:

$mC_pT = mC_vT + mRT$ ... ... (5.23)

Dividing by mT, we get:

$C_p = C_v + R$

$R = C_p - C_v$ ... ... (5.24)

Also

$\gamma = \frac{C_p}{C_v}$ ... ... (5.25)

where γ is the adiabatic index.

Example (5.1): In an internal combustion engine, during the compression stroke the heat rejected to the cooling water is 50 kJ/kg and the work input is 100 kJ/kg. Calculate the change in internal energy of the working fluid stating whether it is a gain or loss.

Solution:

Applying the first law of thermodynamics:

$q - w = \Delta u$

Since heat is rejected, then it will have a negative sign. Also work input will have a negative sign. Hence:

$(-50) - (-100) = \Delta u$

$\boldsymbol{\Delta u = 50}$ **kJ/kg** **Ans.**

So the working fluid gains internal energy.

Example (5.2): 0.3 kg of nitrogen gas at 40°C is contained in a cylinder. The piston is moved compressing nitrogen until the temperature becomes 160°C. The work done during the process is 30 kJ. Calculate the heat transferred from the nitrogen to the surroundings. Take C_v for nitrogen = 0.75 kJ/kg.K.

Solution:

The absolute temperatures: $T_1 = 40 + 273 = 313$ K

$T_2 = 160 + 273 = 433$ K

Applying the first law of thermodynamics:

$Q - W = \Delta U$

Since $\Delta U = mC_v \Delta T$, then:

$Q - W = mC_v(T_2 - T_1)$

$Q - (-30) = 0.3 \times 0.75 \times (433 - 313)$

$\boldsymbol{Q = -3}$ **kJ** **Ans.**

The First Law of Thermodynamics for Non-Flow Processes

The energy equation for non-flow processes is written as:

$Q - W = \Delta U$

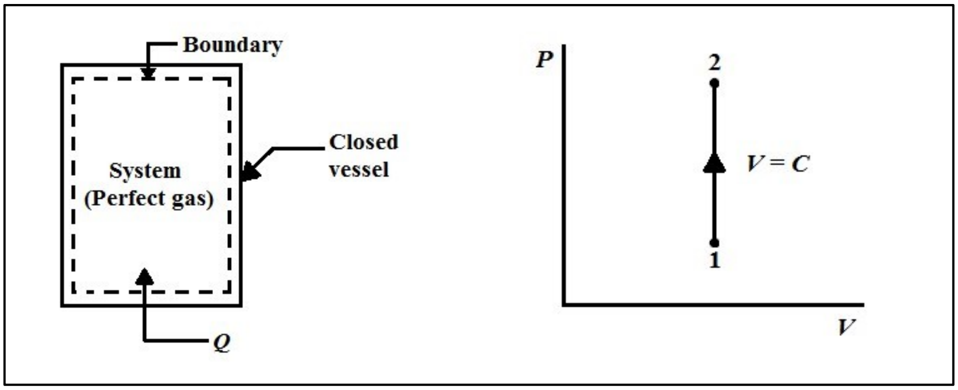
$q - w = \Delta u$ (per unit mass)

Since $U = mC_v T$, then:

$Q - W = mC_v \Delta T$

$q - w = C_v \Delta T$ (per unit mass)

1. Constant volume (Isochoric) process: consider a completely closed vessel filled with a perfect gas as shown in figure below. Let Q units of heat be supplied to the system. This results in an increase in the pressure and temperature of the system at constant volume as presented by process 1-2 on the (P-V) diagram shown below. Since there is no change in volume, therefore:



Applying the first law of thermodynamics:

$Q - W = \Delta U = mC_v(T_2 - T_1)$

For a constant volume process, no work is done on the system. Hence:

$W = \int PdV = 0$ ... ... (5.26)

Then:

$Q = mC_v(T_2 - T_1)$ ... ... (5.27)

For a unit mass, we get:

$q = C_v(T_2 - T_1)$ ... ... (5.28)

Example (5.3): 1 kg of air enclosed in a rigid container, is initially at 4.8 bar and 150°C. The container is heated until the temperature becomes 200°C. Calculate the final pressure of the air and the heat supplied during the process.

Solution:

The absolute temperatures: $T_1 = 150 + 273 = 423$ K

$T_2 = 200 + 273 = 473$ K

Since we have a rigid container, then the volume is constant.

$W = 0$

For a constant volume process:

$\frac{P_1}{T_1} = \frac{P_2}{T_2} \rightarrow \frac{4.8}{423} = \frac{P_2}{473}$