## Chapter two

## Conservation of Energy and The first Law of Thermodynamics

## Principle of energy conservation:-

State that energy can be neither created nor destroyed but can only convert from one form to another.

## The first law of thermodynamics:-

"When a system undergoes a thermodynamics cycle then the net heat supplied to the system from its surroundings is equal to the net work done by the system on its surroundings".

In symbols;

$$
\sum \mathrm{d} Q=\sum \mathrm{d} W \quad \text { for cycle }
$$

where;
$\Sigma$ : represents the sum for a complete cycle.
(i.e.) when a system possessing a certain intrinsic energy is made to undergo a cycle by heat and work transfer, then the net heat supplied is equal to the net work output.

## Example 2.1:

In a certain steam plant the turbine develops 1000 kW . The heal supplied to the steam in the boiler is $2800 \mathrm{~kJ} / \mathrm{kg}$, the heal rejected by the steam to the cooling water in the condenser is $2100 \mathrm{~kJ} / \mathrm{kg}$ and the feed-pump work required to pump the condensate back into the boiler is 5 kW . Calculate the steam flow rate round the cycle in $\mathrm{kg} / \mathrm{s}$.
solution:

$$
\Sigma \mathrm{d} Q=2800-2100=700 \mathrm{~kJ} / \mathrm{kg}
$$

Let the steam flow be $\dot{m} \mathrm{~kg} / \mathrm{s}$. Therefore

$$
\sum \mathrm{d} Q=700 \mathrm{~m} \mathrm{~kW}
$$

and

$$
\begin{aligned}
& \sum \mathrm{d} W=5-1000=-995 \mathrm{~kW} \\
& \sum \mathrm{~d} Q+\sum \mathrm{d} W=0 \\
& 700 \dot{m}-995=0
\end{aligned}
$$



## therefore

$$
\dot{m}=995 / 700=1.421 \mathrm{~kg} / \mathrm{s}
$$

i.e. Steam mass flow rate required $=1.421 \mathrm{~kg} / \mathrm{s}$

## (A) The non-flow equation:-

For any process (not a cycle) and closed system in which the intrinsic energy of the system is finally greater than the initial intrinsic energy. The difference between the net heat supplied and the net work output has increased the intrinsic energy of the system.
i.e. Gain in intrinsic energy $=$ Net heat supplied - Net work output

Note: When a fluid is not in motion then its intrinsic energy is known as the internal energy of the fluid and is given the symbol U .

The gain in internal energy in changing from state 1 to state 2 .
$U_{2}-U_{1}=\sum_{1}^{2} d Q-\sum_{1}^{2} d W$
$U_{2}-U_{1}=Q-W \quad$ For a non-flow process
Where;
$Q$ :heat flow (kJ)
$W$ :work done (kJ)
$U$ :the internal energy ( kJ )
$Q=\left(U_{2}-U_{1}\right)+W$
Or for 1 kg .

$$
\begin{equation*}
Q=\left(u_{2}-u_{1}\right)+W \tag{2.2}
\end{equation*}
$$

$$
u=U / m \quad \text { (specific internal energy) }
$$

**: For a small amount of heat supplied $d Q$, a small amount of work done by the fluid $d W$, and a small gain in internal energy $d u$, then.

$$
\begin{equation*}
d Q=d u+d W \tag{2.3}
\end{equation*}
$$

Process $(1 \rightarrow 2) Q_{l \rightarrow 2}=U_{2}-U_{l}+W_{l \rightarrow 2}$
Process $(2 \rightarrow 3) Q_{2 \rightarrow 3}=U_{3}-U_{2}+W_{2 \rightarrow 3}$
Process $(3 \rightarrow 1) Q_{3 \rightarrow 1}=U_{1}-U_{3}+W_{3 \rightarrow 1}$

$Q_{1 \rightarrow 2}+Q_{2 \rightarrow 3}+Q_{3 \rightarrow 1}=U_{2}-U_{1}+W_{l \rightarrow 2}+U_{3}-U_{2}+W_{2 \rightarrow 3}+U_{1}-U_{3}+W_{3 \rightarrow 1}$
$Q_{1 \rightarrow 2}+Q_{2 \rightarrow 3}+Q_{3 \rightarrow 1}=W_{l \rightarrow 2}+W_{2 \rightarrow 3}+W_{3 \rightarrow 1}$

$$
\sum \mathrm{d} Q=\sum \mathrm{d} W \quad \text { for any cycle }
$$

A: $\Delta u=u_{2}-u_{1}$
B: $\Delta u=u_{2}-u_{1}$
C: $\Delta u=u_{2}-u_{1}$
The property does not depend on the path


## Example 2.2:

In the compression stroke of an internal-combustion engine the heat rejected to the cooling water is $45 \mathrm{~kJ} / \mathrm{kg}$ and the work input is $90 \mathrm{~kJ} / \mathrm{kg}$. Calculate the change in specific internal energy of the working fluid stating whether it is a gain or a loss.

## Solution:

$Q=-45 \mathrm{~kJ} / \mathrm{kg}$ (heat is reject)
$W=-90 \mathrm{~kJ} / \mathrm{kg}$ (work input to the system)
$Q=\left(u_{2}-u_{1}\right)+W$
$-45=\Delta u-90$
$\Delta u=-45+90=45 \mathrm{~kJ} / \mathrm{kg}$
Gain in internal energy

## Example 2.2:

In the cylinder of an air motor the compressed air has a specific internal energy of $420 \mathrm{~kJ} / \mathrm{kg}$ at the beginning of the expansion and a specific internal energy of 200 $\mathrm{kJ} / \mathrm{kg}$ after expansion. Calculate the beat flow to or from the cylinder when the work done by the air during the expansion is $100 \mathrm{~kJ} / \mathrm{kg}$.

## Solution:

$u_{1}=420 \mathrm{~kJ} / \mathrm{kg}, u_{2}=200 \mathrm{~kJ} / \mathrm{kg}, Q=$ ?, $W=100 \mathrm{~kJ} / \mathrm{kg}$
$Q=\left(u_{2}-u_{1}\right)+W$
$Q=(200-420)+100=-220+100=-120 \mathrm{~kJ} / \mathrm{kg}$
The heat rejected by the air $=120 \mathrm{~kJ} / \mathrm{kg}$
Note:- It is important to note that equations (2.1), (2.2) and (2.3) are true whether the process is reversible or not and these are called energy equations.
H.W: A tank containing of fluid is stirred by a paddle wheel, the power input to the paddle wheel is 3000 W . Heat is transferred from the tank at the rate of $6300 \mathrm{~kJ} / \mathrm{hr}$. Considering the tank and the fluid as the system, determine the change in internal energy of the system.
(B) The steady flow equation:-

Consider 1 kg of a fluid flowing in steady flow through a piece of apparatus as shown in figure below, with internal energy, $u$ is moving with velocity C and is a height Z above a datum level.


Energy required to push element across boundary $=\left(\mathrm{p}_{1} \mathrm{~A}_{1}\right)^{*} l$

$$
=\mathrm{p}_{1}{ }^{*}(\text { volume of fluid element })
$$

Energy required for 1 kg of fluid $=\mathrm{p}_{1} \mathrm{v}_{1}$
Total energy entering the system = Total energy leaving the system
$u_{1}+p_{1} v_{1}+\frac{C_{1}^{2}}{2}+g Z_{1}+Q=u_{2}+p_{2} v_{2}+\frac{C_{2}^{2}}{2}+g Z_{2}+W$
Where;
$u$ : internal energy
$p v$ : flow energy per unit mas
$C^{2} / 2$ :kinetic energy per unit mass
$g Z$ : potential energy per unit mass
$Q$ : heat supplied per unit mass
$W$ : work done by the system per unit mass
Flow energy:- the energy required to push the fluid through the control volume surface.
$h=u+p v$
where;
$h$ : enthalpy of fluid
$H=m h$ (the enthalpy of mass $m$ )
$h_{1}+\frac{C_{1}^{2}}{2}+Q=h_{2}+\frac{C_{2}^{2}}{2}+W$ (the steady flow energy equation)

Note:- In steady flow the rate of mass flow of fluid at any section is the same as at any other section.

Mass flow rate;

$$
m^{\cdot}=\frac{C A}{v}=\rho C A
$$

$$
m^{\cdot}=\frac{C_{1} A_{1}}{v_{1}}=\frac{C_{2} A_{2}}{v_{2}} \quad(\mathrm{~kg} / \mathrm{s})
$$

Volumetric flow rate $=C A\left(\mathrm{~m}^{3} / \mathrm{s}\right)$

## Note:-

Work done $\left\{\begin{array}{l}+ \text { ve by the system } \\ - \text {-ve on the system }\end{array}\right.$


## Application of open system:-

1-Turbine: is a device used to convert the energy of the vapor to mechanical work. (rotating the shaft of the turbine)
$W=+\mathrm{ve}, \quad Q=-\mathrm{ve}$
$h_{1}+\frac{C_{1}^{2}}{2}+g Z_{1}-Q=h_{2}+\frac{C_{2}^{2}}{2}+g Z_{2}+W$
2-Boiler (steam generator): is a heat exchanger used to convert liquid water to vapor.
$W=0, \quad Q=+\mathrm{ve}$
$h_{1}+\frac{C_{1}^{2}}{2}+g Z_{1}+Q=h_{2}+\frac{C_{2}^{2}}{2}+g Z_{2}$
3-Condenser: is a heat exchanger used to convert vapor to liquid.
$W=0, \quad Q=-\mathrm{ve}$
$h_{1}+\frac{C_{1}^{2}}{2}+g Z_{1}-Q=h_{2}+\frac{C_{2}^{2}}{2}+g Z_{2}$
4-Compressor: is device used to increase the pressure of the fluid.
$W=-\mathrm{ve}, \quad Q=-\mathrm{ve}$
$h_{1}+\frac{C_{1}^{2}}{2}+g Z_{1}-Q=h_{2}+\frac{C_{2}^{2}}{2}+g Z_{2}-W$
5-Nozzle: is a device used to increase the velocity of fluid.
$W=0, \quad Q=0, \quad Z_{1}=Z_{2}$
$h_{1}+\frac{C_{1}^{2}}{2}=h_{2}+\frac{C_{2}^{2}}{2}$

## 6-throttling:

$W=0, \quad Q=0, \quad Z_{1}=Z_{2}, \quad C_{1}=C_{2}$
$h_{1}=h_{2}$


## Example 2.3:

In the turbine of a gas turbine unit the gases flow through the turbine at 17 kg /, and the power developed by the turbine is 14000 kW , The specific enthalpies of the gases at inlet and outlet are $1200 \mathrm{~kJ} / \mathrm{kg}$ and $360 \mathrm{~kJ} / \mathrm{kg}$ respectively, and the velocities of the gases at inlet and outlet are $60 \mathrm{~m} / \mathrm{s}$ and $150 \mathrm{~m} / \mathrm{s}$ respectively. Calculate the rate at which heat is rejected from the turbine. Find also the area of the inlet pipe given that the specific volume of the gases at inlet is $0.5 \mathrm{~m}^{3} / \mathrm{kg}$.

## Solution:

$h_{1}+\frac{C_{1}^{2}}{2}+Q=h_{2}+\frac{C_{2}^{2}}{2}+W$
Kinetic energy at inlet $=\frac{C_{1}^{2}}{2}=\frac{(60)^{2}}{2}=1800 \frac{\mathrm{~m}^{2}}{\mathrm{~s}^{2}} * \frac{\mathrm{~kg}}{\mathrm{~kg}}=1800 \frac{\mathrm{~N} \cdot \mathrm{~m}}{\mathrm{~kg}}=1.8 \frac{\mathrm{~kJ}}{\mathrm{~kg}}$
Kinetic energy at outlet $=\frac{C_{2}^{2}}{2}=\frac{(150)^{2}}{2}=11250 \frac{\mathrm{~N} \cdot \mathrm{~m}}{\mathrm{~kg}}=11.25 \frac{\mathrm{~kJ}}{\mathrm{~kg}}$
Power $=W * m$.

$$
W=14000 / 17=823.5 \mathrm{~kJ} / \mathrm{kg}
$$

$$
1200+1.8+Q=360+11.25+823.5
$$

$Q=-7.05 \mathrm{~kJ} / \mathrm{kg}$
heat rejected $=7.05 * 17=119.85 \mathrm{~kW}$

$m^{\cdot}=\frac{C_{1} A_{1}}{v_{1}}$
$A_{1}=(17 * 0.5) / 60=0.142 \mathrm{~m}^{2}$

## Example 2.3:

Air flows steadily at the rate of $0.4 \mathrm{~kg} / \mathrm{s}$ through an air compressor, entering at $6 \mathrm{~m} / \mathrm{s}$ with a pressure of 1 bar and a specific volume of $0.85 \mathrm{~m}^{3} / \mathrm{kg}$, and leaving at $4.5 \mathrm{~m} / \mathrm{s}$ with a pressure of 6.9 bar and a specific volume of $0.16 \mathrm{~m}^{3} / \mathrm{kg}$. The specific internal energy of the air leaving is $88 \mathrm{~kJ} / \mathrm{kg}$ greater than that of the air entering. Cooling water
in a jacket surrounding the cylinder absorbs heat from the air at the rate of 59 kW . Calculate the power required to drive the compressor and the inlet and outlet pipe cross-sectional areas.

## Solution:

$$
\begin{aligned}
& u_{1}+p_{1} v_{1}+\frac{C_{1}^{2}}{2}+Q=u_{2}+p_{2} \mathrm{v}_{2}+\frac{C_{2}^{2}}{2}+W \\
& \frac{C_{1}^{2}}{2}=\frac{(6)^{2}}{2}=18 \frac{\mathrm{~J}}{\mathrm{~kg}} \\
& \frac{C_{2}^{2}}{2}=\frac{(4.5)^{2}}{2}=10.125 \frac{\mathrm{~J}}{\mathrm{~kg}} \\
& p_{1} \mathrm{v}_{1}=1 * 10^{5} * 0.85=85000 \mathrm{~J} / \mathrm{kg} \\
& \mathrm{p}_{2} \mathrm{v}_{2}=6.9 * 10^{5} * 0.16=110400 \mathrm{~J} / \mathrm{kg} \\
& u_{2}-u_{1}=88000 \mathrm{~J} / \mathrm{kg} \\
& Q=-59 * 10^{3} / 0.4=-147.5 * 10^{3}
\end{aligned}
$$



$$
85000+18-147500=88000+110400+10.125+W
$$

$$
W=-260.9 \mathrm{~kJ} / \mathrm{kg}
$$

Work input required $=260.9 * 0.4=104.4 \mathrm{~kJ} / \mathrm{s}$

$$
\begin{aligned}
& m^{\bullet}=\frac{C_{1} A_{1}}{v_{1}}, \quad A_{1}=\left(0.4^{*} 0.85\right) / 6=0.057 m^{2} \\
& m^{\bullet}=\frac{C_{2} A_{2}}{v_{2}}, A_{2}=\left(0.4^{*} 0.16\right) / 4.5=0.014 m^{2}
\end{aligned}
$$

