

## UNIT 1

# Steady and Unsteady Flow Processes.

### BASIC CONCEPTS AND DEFINITIONS

Thermodynamics is the science of energy transfer which deals with the relations among heat, work and properties of systems.

The name 'thermodynamics' is derived from the Greek words therme, meaning 'heat' and dynamis meaning power. Thus, thermodynamics is basically the study of heat and power.

### Application Area of Thermodynamics

Energy transfer is present in almost all the engineering activities. Hence, the principles of thermodynamics are playing vital role in designing all the engineering equipments such as internal combustion engines, rockets, jet engines, thermal and nuclear power plants, refrigerators etc.

### WORK AND HEAT

The different thermodynamic systems and their characteristics were discussed. To undergo a change of state, the system has to interact with its surroundings. Work and heat transfers across the boundaries cause these changes.

### Work as Defined in Mechanics

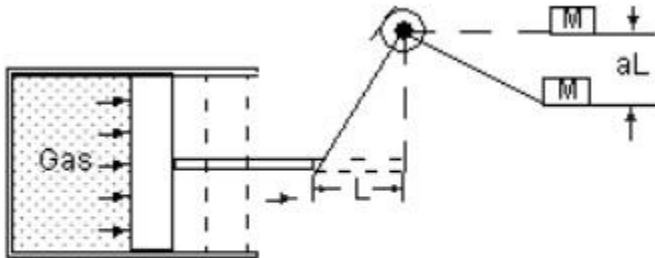
Work is done when the point of application of a force moves in the direction of the force. The product of the force and the distance moved in the direction of the force is equal to the amount of the work done.

This simple definition of work confines only to the area of mechanics and can not be extended to the more complex problems in thermodynamics. Hence a new definition should be introduced to cover mechanical as well as the other forms of work.

### The Thermodynamic Definition of Work

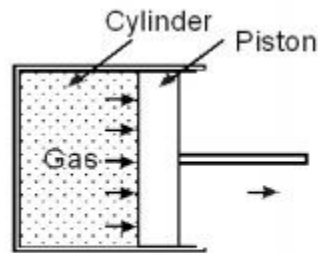
*Positive work is done by a system, during a given process, when sole effect external to the system could be reduced to the lifting of a mass.*

Consider a gas expanding in a piston cylinder arrangement as given in Figure 2.1. Here no mass is actually lifted against gravity. But if the existing surroundings is fitted with an arrangement as given in the Figure 2.2, there is a possibility of lifting the mass. Hence work is said to be done by the system.



**Figure 2.2 Expansion with actual lifting of mass**

While exploring the possibility of lifting a mass the effects that are external to the system alone must be taken into account. For example, a lift with a person and a suitcase is considered as a system. If the person lifts the suitcase, it should not be taken into account, because this event occurs within the system.



**Figure 2.1 Expansion without actual lifting of mass**

## Units of Work and Power

In the international system (SI), the unit of force is Newton (N) and that of distance is metre (m). Hence the unit of work is Nm which is also given a special name Joule. In most of the applications large quantity of work is involved. Therefore kJ is commonly used.

Rate of doing work is known as power. Hence its unit is Nm/S or J/S which is again given a special name Watts(W).

## Sign Convention of Work

- Work done by the system on the surroundings is considered as positive work.

□

Work done on the system by the surroundings is taken as negative work.

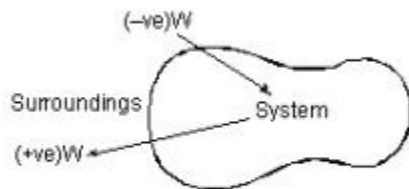


Figure 2.3 Sign Convention of work

## Displacement Work

Consider a piston cylinder arrangement as given in the Figure 2.4. If the pressure of the fluid is greater than that of the surroundings, there will be an unbalanced force on the face of the piston. Hence, the piston will move towards right.

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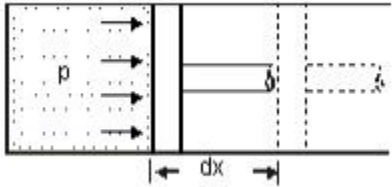


Figure 2.4 Displacement work

Force acting on the piston = Pressure  $\times$  Area

$$= pA$$

$\therefore$  Work done = Force  $\times$  distance

$$= pA \times dx$$

$$= pdV$$

where  $dV$  - change in volume.

This work is known as displacement work or  $pdV$  work corresponding to the elemental displacement  $dx$ . To obtain the total work done in a process, this elemental work must be added from the initial state to the final state. Mathematically, .

## Evaluation of Displacement Work

### Constant Pressure Process

Figure 2.5 shows a piston cylinder arrangement containing a fluid. Let the fluid expands such that the pressure of the fluid remains constant throughout the process. Figure 2.6 shows the process in a  $p$ - $V$  diagram.

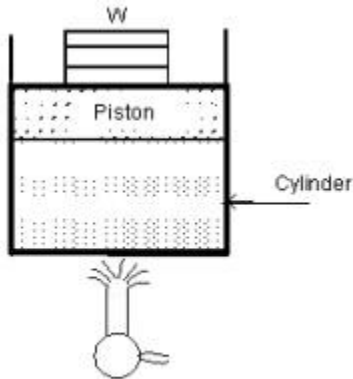


Figure 2.5

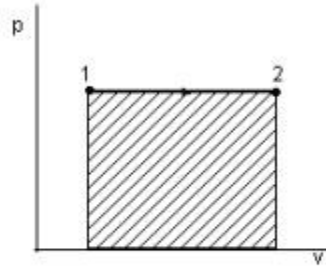


Figure 2.6

$$\begin{aligned}
 {}_1W_2 &= \int_1^2 p dV \\
 &= \int_1^2 C dV \text{ where } C=pV \\
 &= C \int_1^2 \frac{1}{V} dV \\
 &= C \ln(V_2/V_1) \\
 &= p_1 V_1 \ln(V_2/V_1) \text{ (or) } p_2 V_2 \ln(V_2/V_1) \quad \dots(2.2)
 \end{aligned}$$

The mathematical expression for displacement work can be obtained as follows:

$$=p(V_2 - V_1) \quad \dots(2.1)$$

This expression shows that the area under a curve in a p-V diagram gives work done in the process.

### Constant volume process

Consider a gas contained in a rigid vessel being heated. Since there is no change in volume, the displacement work .

### Hyperbolic process

Let the product of pressure and volume remains constant at all the intermediate states of a process. In the p-V diagram it will be a hyperbola as given in Figure 2.7.

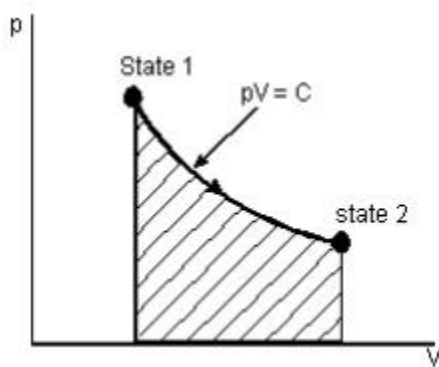


Figure 2.7

For Ideal gases when temperature remains constant,  $pV$  will be constant i.e., isothermal process are hyperbolic processes for an ideal gas.

## Polytropic Process

Any process can be represented by the general form  $pV^n = \text{constant}$ . Based on the value of  $n$ , the process differs as given below; For other values of  $n$ , the process is known as polytropic process. Figure

2.8 shows the polytropic process on p-V coordinates of various. Expression possible for displacements work for a polytropic process can be obtained as follows :

$$\begin{aligned}
{}_1W_2 &= \int_1^2 p dV \\
&= \int_1^2 \frac{C}{V^n} dV \quad \text{where } C = pV^n \\
&= C \int_1^2 V^{-n} dV \\
&= C \left[ \frac{V^{-n+1}}{-n+1} \right]_1^2 \\
&= \left[ \frac{CV_2^{-n+1} - CV_1^{-n+1}}{-n+1} \right]_1^2 \\
&= \left[ \frac{p_2 V_2^n V_2^{-n+1} - p_1 V_1^n V_1^{-n+1}}{-n+1} \right] \quad \text{since } C = p_1 V_1^n = p_2 V_2^n \\
&= \left[ \frac{p_2 V_2 - p_1 V_1}{-n+1} \right]
\end{aligned}$$

## Work is a Path Function

Consider a working substance initially occupying  $0.2 \text{ m}^3$  at 1 bar as represented by state 1 in the Figure 2.9. Let the system changes its state such that the final volume is  $0.05 \text{ m}^3$  and pressure 2 bar. The change of state may occur along the paths 1A2, 1B2 or 1C2. As mentioned earlier, area under the curve representing the process in a p-V diagram gives the work done in the process. Comparing the area under the paths 1A2, 1B2 and 1C2, it is clear that the work done in these paths are different. Hence it can be concluded that the amount of work done is not only a function of the end states of a process, but also the path followed between the states. Therefore work is a path function.

## Additivity of Work Over Processes

If a system is taken through two or more number of processes, the total work done is the sum of work done in the individual processes.

Let a system executes three processes as shown in Figure 2.10. The total work done,

$${}_1W_4 = {}_1W_2 + {}_2W_3 + {}_3W_4$$

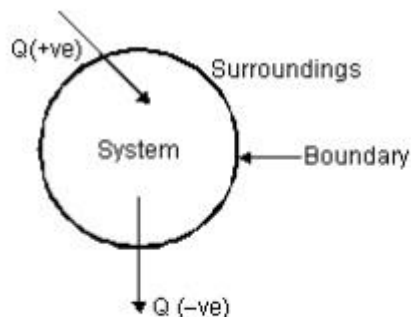
## Heat

Heat is the interaction between systems which occurs by virtue of their temperature difference when they communicate.

If a system, at a given temperature is brought in contact with another system (or surroundings) at a lower temperature, it can be observed that heat is transferred from the system at the higher temperature to the system at lower temperature. This heat transfer occurs solely because of the temperature difference between the two systems. Another important aspect of the definition of heat is that a body never contains heat. Rather, heat can be identified only as it crosses the boundary. Similar to work, heat is also a form of energy transfer occurring at the boundary of the system and is a path function.

### Sign Convention of Heat

- Heat given into a system is positive
- Heat coming out of the system is negative



**Fig. 2.8 Sign convention of work**

### Modes of Heat Exchange



Conduction, convection and radiation are the three possible modes of heat transfer between systems and between system and its surroundings.

Conduction occurs without bulk movement of molecules. Energy transfer in conduction is due to lattice vibration and free electron movement. It is the predominant mode of heat transfer in solids.

Convection occurs with bulk movement of molecules and therefore, occurs in gases and liquids. If the bulk movement or flow is due to an external device, it is known as forced convection. In the absence of an external device the flow is due to the difference in density caused by the temperature difference. This mode is known as natural convection.

Bodies separated by a distance may exchange heat in the form of electromagnetic waves without the participation of the intervening medium. It is known as radiation. It is generally a surface phenomenon. Sometimes as in the case of gas mixtures containing carbon dioxide and water vapour it is a volume phenomenon.

## Sensible and Latent Heat

It is known that a substance can exist in three phases namely solid, liquid and gas. When a substance is heated or cooled temperature of the substance increases or decreases respectively unless there is any phase change. Quantity of heat added or removed to change the temperature by unit degree is known as specific heat. For solids and liquids same quantity of heat is required to cause unit degree rise for both constant pressure heating as well as constant volume heating as they are incompressible. But for gases there is appreciable difference in the quantity of heat required to cause unit difference in temperature between constant volume and constant pressure processes. Accordingly, they are known as specific heat at constant volume ( $C_v$ ) and specific heat at constant pressure ( $C_p$ ). Thus to increase the temperature of  $m$  kg of the given substance by  $\Delta T$  degree, amount of heat required is given by

$$Q = mC_v\Delta T \text{ at Constant Volume}$$

$$Q_1 = mC_p\Delta T \text{ at Constant Pressure}$$

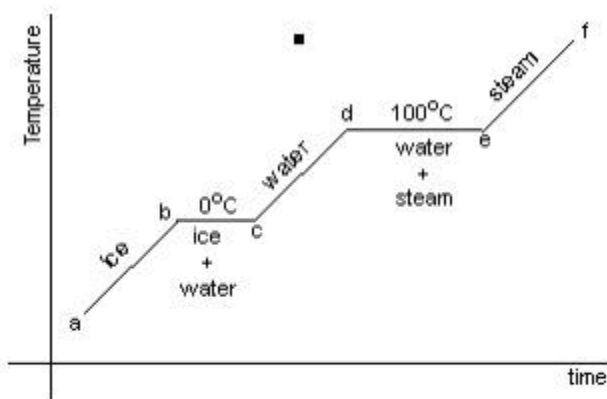
$$Q = mC_v\Delta T \text{ at Constant Volume} \quad \dots(2.5)$$

$$Q_1 = mC_P\Delta T \text{ at Constant Pressure} \quad \dots(2.6)$$

If a certain single component system is undergoing phase change at constant pressure, temperature of the system remains constant during heating or cooling. Quantity of heat removed or added to cause the change of phase of unit mass of the substance is known as latent heat. For example latent heat of fusion of water is the amount of heat to be removed to solidify 1 kg of water into 1 kg of ice at a given temperature.

Let us consider a process of converting 1 kg of ice at  $-30^\circ\text{C}$  to system to steam at  $250^\circ\text{C}$  at atmospheric pressure. We know that ice melts at  $0^\circ\text{C}$  and water evaporates at  $100^\circ\text{C}$  at atmospheric pressure.

For a constant rate of heating, if temperature at different instants are plotted we will get a graph as shown in Figure 2.9.



**Figure 2.9 Illustration for sensible and latent heat**

Figure 2.9 Illustration for sensible and latent heat

The total heat required can be obtained as follows:

$$Q = Q_{ab} + Q_{bc} + Q_{cd} + Q_{de} + Q_{ef} \dots(2.7)$$

$$Q_{ab} = mC_{ice} (t_b - t_c) \quad \dots(2.8)$$

$Q_{bc}$  = Latent heat of melting of ice at  $0^\circ\text{C}$

$$Q_{cd} = mC_{water} (t_d - t_c) \quad \dots(2.9)$$

$Q_{de}$  = Latent heat of evaporation of water at  $100^\circ\text{C}$

$$Q_{ef} = mC_{P\text{Steam}} (t_f - t_e) \quad \dots(2.10)$$

Where  $C_{ice}$  = Specific heat of ice

$C_{water}$  = Specific heat of water

$C_{P\text{Steam}}$  = Specific heat of steam at constant pressure

## Reversible Adiabatic Process

A reversible process during which, the system and the surroundings do not exchange any heat across the boundary is known as reversible adiabatic process. For such a process, pressure and volume variation is governed by the law :

$$pV = \text{constant} \quad \dots(2.11)$$

Where

$C_p$  is the specific heat at constant pressure

$C_v$  is the specific heat at constant volume

Detailed discussion on these specific heats is presented in the next chapter.

A wall which does not permit the heat flow across it is known as adiabatic wall, whereas the wall that permits the heat is known as diathermic wall. In an adiabatic process the only possible energy interaction across the boundary of the system is work transfer to or from the system.

Displacement work involved in a reversible adiabatic process can be expressed as

$$W = \left[ \frac{p_2 V_2 - p_1 V_1}{-\gamma + 1} \right] \quad \dots(2.12)$$

## Comparison between work and heat

- Both heat and work are boundary phenomena, that is, they occur only at the boundary.

- The interaction due to the temperature difference is heat and all other interactions are to be taken as work.
- Both work and heat are path functions, that is, they are inexact differentials.

## THE FIRST LAW OF THERMODYNAMICS

Energy interactions between a system and its surroundings across the boundary in the form of heat and work have been discussed separately in the previous chapter. So far, no attempt has been made to relate these interactions between themselves and with the energy content of the system.

First law of thermodynamics, often called as law of conservation of energy, relating work, heat, and energy content of the system will be discussed in detail in this chapter.

### First Law of Thermodynamics

In its more general form, the first law may be stated as follows

*“When energy is either transferred or transformed, the final total energy present in all forms must precisely equal the original total energy”.*

It is based on the experimental observations and can not be proved mathematically. All the observations made so far, confirm the correctness of this law.

### First Law of Thermodynamics for a Closed System Undergoing a Process

First law can be written for a closed system in an equation form as

$$\left[ \begin{array}{l} \text{Energy entered} \\ \text{into the system} \end{array} \right] + \left[ \begin{array}{l} \text{Energy left} \\ \text{the system} \end{array} \right] = \left[ \begin{array}{l} \text{Change in the energy} \\ \text{content of the system} \end{array} \right]$$

For a system of constant mass, energy can enter or leave the system only in two forms namely work and heat.

Let a closed system of initial energy  $E_1$  receives  $Q$  units of net heat and gives out  $W$  units of work during a process. If  $E_2$  is energy content at the end of the process as given in Figure 3.1, applying first law we get

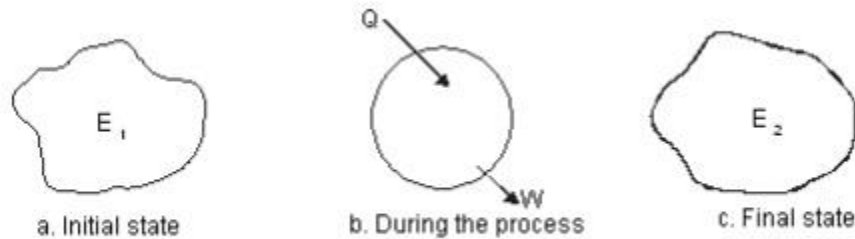


Figure 3.1 First Law for a closed system

$$Q - W = (E_2 - E_1)$$

Where the total energy content

Internal Energy + Kinetic energy + Potential energy

$$E = \text{Internal Energy} + \text{Kinetic energy} + \text{Potential energy}$$

$$= U + \frac{1}{2} \frac{mC^2}{g_c} + mgz$$

The term internal energy usually denoted by the letter  $U$  is the energy due to such factors as electron spin and vibrations, molecular motion and chemical bond.

Kinetic energy term is due to the system movement with a velocity  $C$ . For stationary systems this term will be zero. The term  $g_c$  is a constant of value 1 in SI unit. It will be dropped here after since SI unit is followed throughout the book.

Potential energy term is due to the location of the system in the gravitational field. It remains constant for a stationary system. The unit of energy in SI is kJ.

## The Thermodynamic Property Enthalpy

Consider a stationary system of fixed mass undergoing a quasi-equilibrium constant pressure process

Applying first law

$$Q_{12} - {}_1W_2 = E_2 - E_1$$

$$\text{where } E_2 - E_1 = (U_2 - U_1) + m(C_2^2 - C_1^2) + mg(Z_2 - Z_1)$$

$$= U_2 - U_1 \quad \text{since it is a stationary system.}$$

$$\text{also } {}_1W_2 = p(V_2 - V_1)$$

$$= p_2V_2 - p_1V_1$$

$$\therefore Q_{12} = (p_2V_2 - p_1V_1) + (U_2 - U_1)$$

$$= (U_2 + p_2V_2) - (U_1 + p_1V_1)$$

The terms within brackets are all properties depending on the end states. This combination of properties may be regarded as a single property known as enthalpy. It is usually denoted by the letter H.

$$\text{ie } H = U + pV$$

$$\text{(or) } h = u + pv$$

Where  $h$  is specific enthalpy in kJ/kg

$u$  is specific internal energy in kJ/kg and

$v$  is specific volume in m<sup>3</sup>/kg

## Flow Energy

Flow energy is defined as the energy required to move a mass into the a control volume against a pressure. Consider a mass of volume  $V$  entering into a control volume as given in the Figure 3.2 against a pressure  $p$ .

The Flow energy = Work done in moving the mass

$$= \text{Force} \times \text{distance}$$

$$= pA \times dx$$

$$=p \times (A dx)$$

$$=pV$$

Therefore, Enthalpy = Internal energy + Flow energy

### First Law of Thermodynamics for a Control Volume

Mass simultaneously entering and leaving the system is a very common phenomenon in most of the engineering applications. Control volume concept is applied to these devices by assuming suitable control surfaces.

To analyze these control volume problems, conservation of mass and energy concepts are to be simultaneously considered.

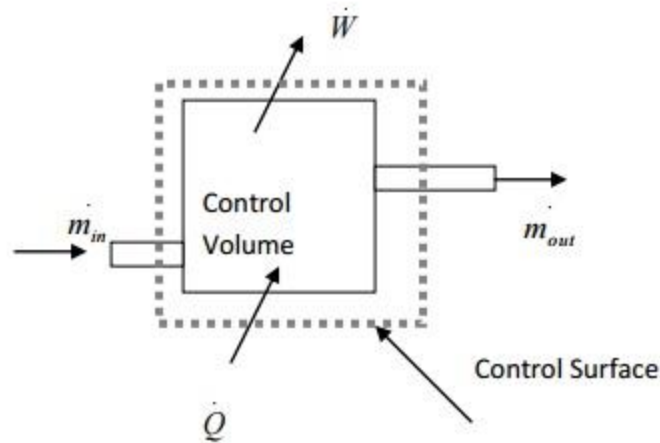
Energy may cross the control surface not only in the form of heat and work but also by total energy associated with the mass crossing the boundaries. Hence apart from kinetic, potential and internal energies, flow energy should also be taken into account.

### Conservation of mass

$$\left[ \begin{array}{l} \text{Total mass} \\ \text{entering the} \\ \text{control volume} \end{array} \right] + \left[ \begin{array}{l} \text{Total mass} \\ \text{leaving the} \\ \text{control volume} \end{array} \right] = \left[ \begin{array}{l} \text{Net change in the} \\ \text{mass content of the} \\ \text{control volume} \end{array} \right]$$

### Conservation of energy

$$\left[ \begin{array}{l} \text{Net energy crossing the} \\ \text{boundary in the} \\ \text{form of heat} \\ \text{and work} \end{array} \right] + \left[ \begin{array}{l} \text{Total energy} \\ \text{associated with the} \\ \text{mass entering} \\ \text{the control volume} \end{array} \right] - \left[ \begin{array}{l} \text{Total energy} \\ \text{associated with the} \\ \text{mass leaving} \\ \text{the control volume} \end{array} \right] = \left[ \begin{array}{l} \text{Net change} \\ \text{in the energy} \\ \text{content of the} \\ \text{control volume} \end{array} \right]$$



**Figure 3.3 First Law of Thermodynamics Applied to a control Volume**

**Figure 3.3 First Law of Thermodynamics Applied to a control Volume**

As a rate equation, it becomes

$$[\dot{Q} - \dot{W}] + \sum_{in} \dot{m}_in \left[ h + \frac{C^2}{2} + Zg \right] - \sum_{out} \dot{m}_{out} \left[ h + \frac{C^2}{2} + Zg \right] = [\Delta E_{CV}]$$

## The Steady-state Flow Process

When a flow process is satisfying the following conditions, it is known as a steady flow process.

1. The mass and energy content of the control volume remains constant with time.



2. The state and energy of the fluid at inlet, at the exit and at every point within the control volume are time independent.
3. The rate of energy transfer in the form of work and heat across the control surface is constant with time.

Therefore for a steady flow process

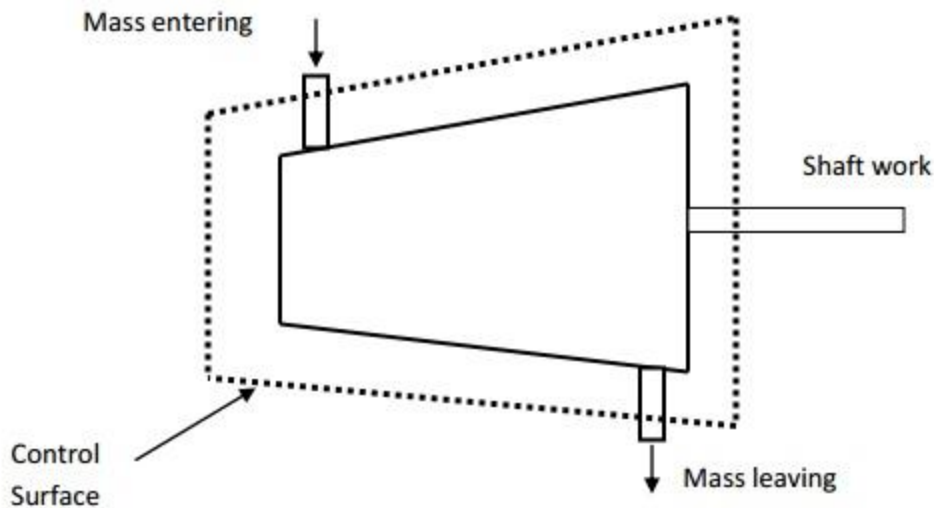
This equation is commonly known as steady flow energy equation (SFEE).

### **Application of SFEE**

SFEE governs the working of a large number of components used in many engineering practices. In this section a brief analysis of such components working under steady flow conditions are given and the respective governing equations are obtained.

### **Turbines**

Turbines are devices used in hydraulic, steam and gas turbine power plants. As the fluid passes through the turbine, work is done on the blades of the turbine which are attached to a shaft. Due to the work given to the blades, the turbine shaft rotates producing work.



**Figure 3.4 Schematic Representation of a Turbine**

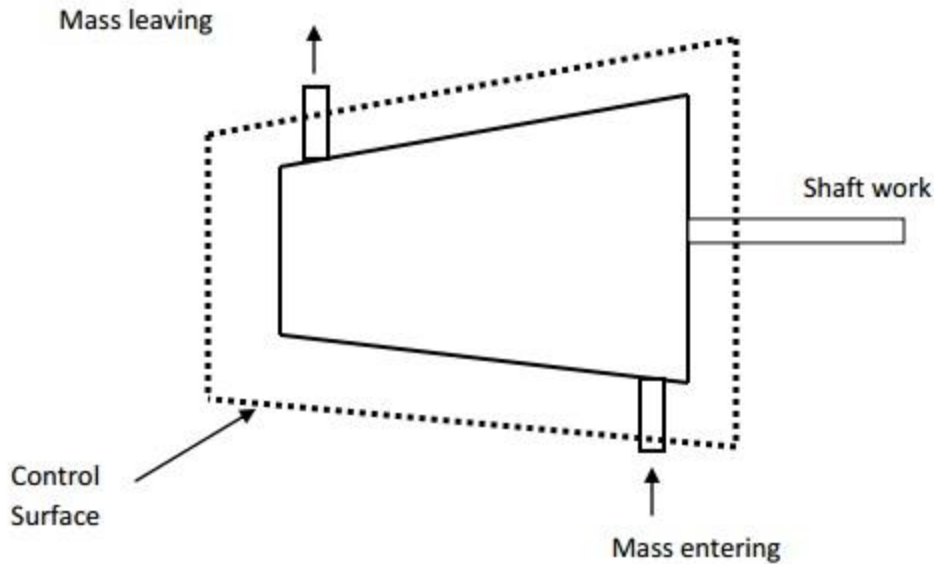
### General Assumptions

1. Changes in kinetic energy of the fluid are negligible
2. Changes in potential energy of the fluid are negligible.

$$[Q - W] = m[(h_2 - h_1)]$$

### Compressors

Compressors (fans and blowers) are work consuming devices, where a low-pressure fluid is compressed by utilising mechanical work. Blades attached to the shaft of the turbine imparts kinetic energy to the fluid which is later converted into pressure energy.



**Figure 3.5 Schematic Representation of a Compresso**

### General Assumptions

1. Changes in the kinetic energy of the fluid are negligible
2. Changes in the potential energy of the fluid are negligible

### Governing Equation

Applying the above equations SFEE becomes

$$[Q - W] = m[(h_2 - h_1)]$$

### Pumps

Similar to compressors pumps are also work consuming devices. But pumps handle incompressible fluids, whereas compressors deal with compressible fluids.

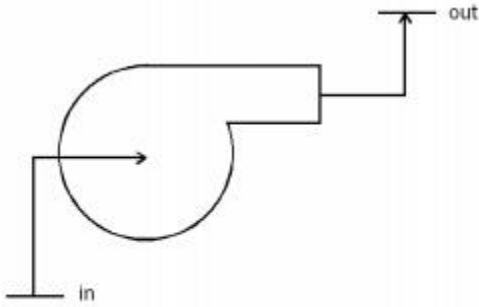


Figure 3.6 Schematic diagram of a pump

### General Assumptions

1. No heat energy is gained or lost by the fluids;
2. Changes in kinetic energy of the fluid are negligible.

### Governing Equation

$$[-\dot{W}] = \dot{m}[(h_2 - h_1) + (Z_2 - Z_1)g] \dots(3.13)$$

As the fluid passes through a pump, enthalpy of the fluid increases, (internal energy of the fluid remains constant) due to the increase in  $pv$  (flow energy). Increase in potential energy of fluid is the most important change found in almost all pump applications.

### Nozzles

Nozzles are devices which increase the velocity of a fluid at the expense of pressure. A typical nozzle used for fluid flow at subsonic\* speeds is shown in Figure 3.7.

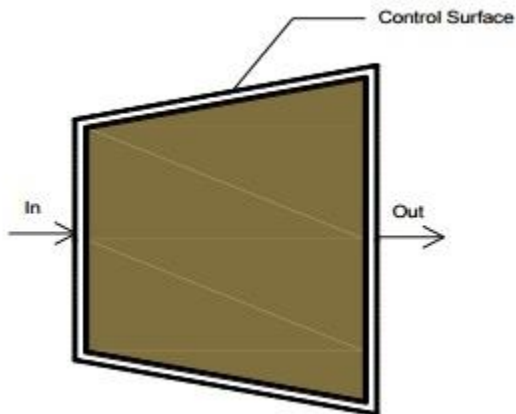
### General Assumptions

1. In nozzles fluids flow at a speed which is high enough to neglect heat lost or gained as it crosses the entire length of the nozzle. Therefore, flow through nozzles can be regarded as adiabatic. That is  $=0$ .

2. There is no shaft or any other form of work transfer to the fluid or from the fluid; that is  $\dot{W} = 0$

$\dot{Q} = 0$ .

Changes in the potential energy of the fluid are negligible.



### Governing Equation

$$\left[ (h_2 - h_1) + \left( \frac{C_2^2 - C_1^2}{2} \right) \right] = 0$$

$$\left( \frac{C_2^2 - C_1^2}{2} \right) = (h_1 - h_2)$$

### Diffusers

Diffusers are (reverse of nozzles) devices which increase the pressure of a fluid stream by reducing its kinetic energy.

### General Assumptions

Similar to nozzles, the following assumptions hold good for diffusers.

1. Heat lost or gained as it crosses the entire length of the nozzle. Therefore, flow through nozzles can be regarded as adiabatic. That is  $Q = 0$
2. There is no shaft or any other form of work transfer to the fluid or from the fluid; that is  $W = 0$ .
3. Changes in the potential energy of the fluid are negligible

### Governing Equation

$$\left[ (h_2 - h_1) + \left( \frac{C_2^2 - C_1^2}{2} \right) \right] = 0$$

$$(h_2 - h_1) = \left( \frac{C_1^2 - C_2^2}{2} \right)$$

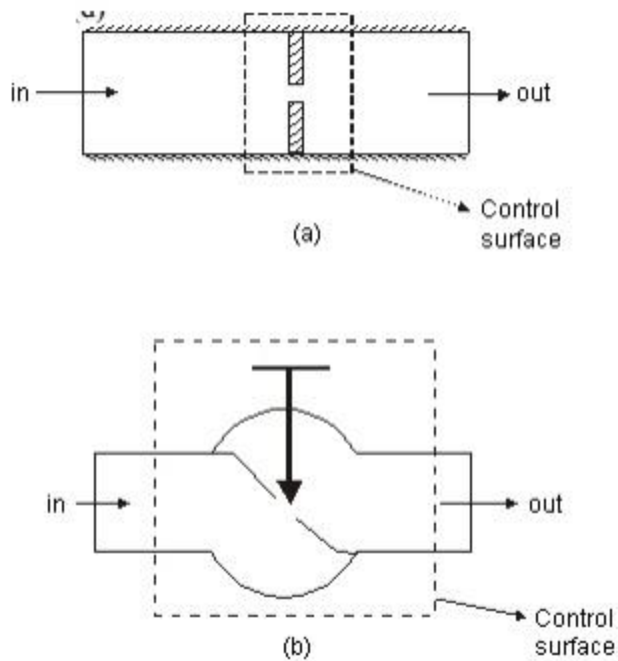
### Heat Exchangers

Devices in which heat is transferred from a hot fluid stream to a cold fluid stream are known as heat exchangers.

### Throttling

A throttling process occurs when a fluid flowing in a line suddenly encounters a restriction in the flow passage. It may be

- a plate with a small hole as shown in Figure 3.10 (a)
- 
- a valve partially closed as shown in Figure 3.10 (b)
- a capillary tube which is normally found in a refrigerator as shown in Figure 3.10 (c)
- 
- a porous plug as shown in Figure 3.10 (d)



### First Law for a Cyclic Process

In a cyclic process the system is taken through a series of processes and finally returned to its original state. The end state of a cyclic process is identical with the state of the system at the beginning of the cycle. This is possible if the energy level at the beginning and end of the cyclic process are also the same. In other words, the net energy change in a cyclic process is zero.

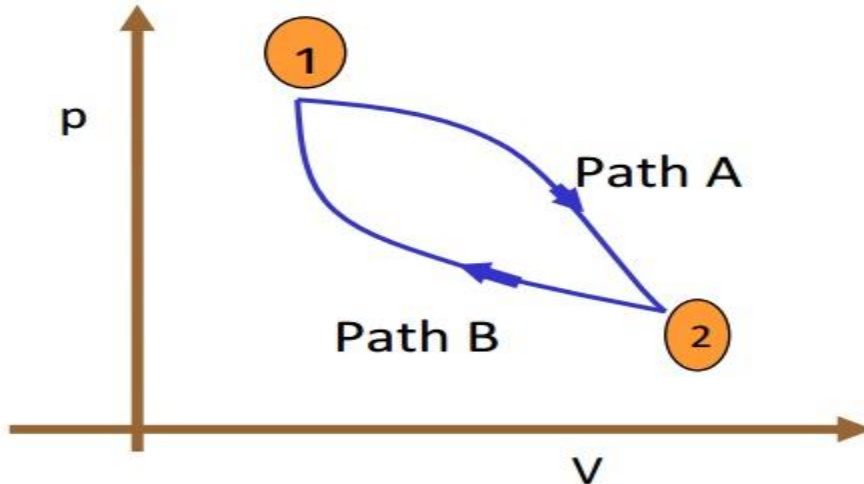


Figure 3.11 First Law for a Cyclic Process

### Figure 3.11 First Law for a Cyclic Process

Consider a system undergoing a cycle consisting of two processes A & B as shown in Figure 3.11 Net energy change

$$\Delta E_A + \Delta E_B = 0 \quad \dots(3.17)$$

$$(Q_A - W_A) + (Q_B - W_B) = 0 \quad \dots(3.18)$$

ie  $Q_A - Q_B = W_A - W_B \quad \dots(3.19)$

$$\text{(or)} \quad \oint dQ = \oint dW \quad \dots(3.20)$$

*Hence for a cyclic process algebraic sum of heat transfers is equal to the algebraic sum of work transfer.*

This was first proved by Joule, based on the experiments he conducted between 1843 and 1858, that were the first quantitative analysis of thermodynamic systems.

### Energy is a property of a system

Consider a system undergoing a process from state 1 to state 2 along path A as shown in Figure 3.12. Let the system be taken back to the initial state 1 along two possible paths B and C. Process A, combined separately with process B and C forms two possible cycles.



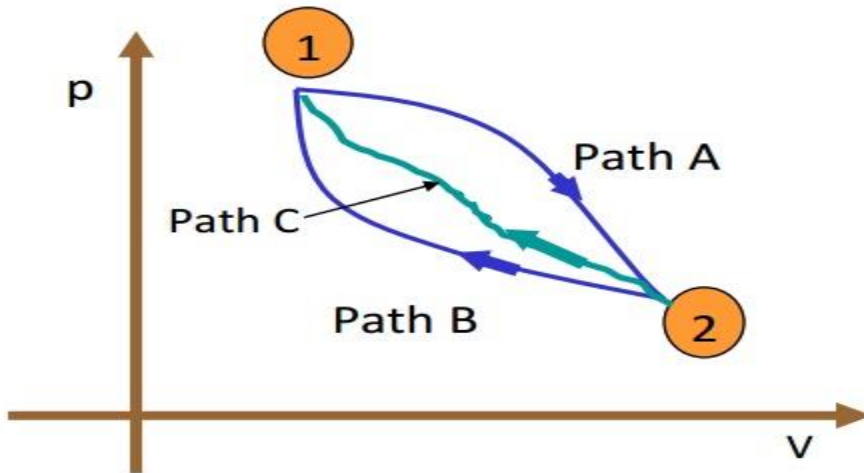


Figure 3.12 Illustration to show that energy is property

### Cycle 1A2B1

$$Q_A + Q_B = [W_A + W_B]$$

$$Q_A - W_A = -[Q_B - W_B]$$

$$\Delta E = -\Delta E \quad \dots(3.21)$$

### Cycle 1A2C1

$$Q_A + Q_C = [W_A + W_C]$$

$$Q_A - W_A = -[Q_C - W_C]$$

$$\Delta E_A = -\Delta E_C \quad \dots(3.22)$$

From Equation (3.21) and (3.22) it can be concluded that energy change in path B and path C are equal and hence energy is a point function depending only on the end states.

It has been already shown that all the properties are point functions and hence energy is also a property of the system.

### Specific Heat at Constant Volume and at Constant Pressure

Specific heat at constant volume of a substance is the amount of heat added to rise the temperature of unit mass of the given substance by 1 degree at constant volume

From first law for a stationary closed system undergoing a process

$$dQ = pdV + dU \text{ or } dq = pdv + du$$

For a constant volume process

$$dQ = dU \text{ or } dq = du$$

$$du = C_v dT \quad \dots(3.23)$$

Similarly specific heat at constant pressure is the quantity of heat added to rise the temperature of unit mass of the given substance by 1 degree at constant pressure

where  $dQ = pdV + dU$

$$= pdV + d(H - PV)$$

$$dQ = pdV + dH - Vdp - pdV \quad dQ = dH - Vdp$$

For a constant pressure process  $dp = 0$

Hence  $dQ = dH$  or  $dq = dh$

$\therefore$

or  $dh = C_p dT$

- The difference in specific heats  $C_p - C_v = R$
- The ratio of sp. heat  $\gamma = C_p / C_v$
- Since  $h$  and  $u$  are properties of a system,  $dh = C_p dT$  and  $du = C_v dT$ , for all processes.

### Work Interaction in a Reversible Steady Flow Process

In a steady flow process the work interaction per unit mass between an open system and the surroundings can be expressed in differential form as

$$dq - dw = dh + CdC + gdz$$

$$dw = dq - (dh + CdC + gdz)$$

$$dq - du + pdv \text{ (or) } dh - vdp$$

$$dw - dh - vdp - (dh + CdC + gdz)$$

$$- vdp - (CdC + gdz)$$

For a stationary

$$W = -\int_1^2 v dp - \left( \frac{C_2^2 - C_1^2}{2} \right) - g(z_2 - z_1) \text{ system}$$

$$W = -\int_1^2 v dp \quad 3.26)$$

### First law for an open system under unsteady flow conditions

Many processes of engineering interest involve unsteady flow, where energy and mass

content of the control volume increase or decrease.

Example for such conditions are:

- 1) Filling closed tanks with a gas or liquid.
- 2) Discharge from closed vessels.
- 3) Fluid flow in reciprocating equipments during an individual cycle.

To develop a mathematical model for the analysis of such systems the following assumptions are

made.

instant of time the state is uniform throughout the entire control volume.

- 3) The state of the mass crossing each of the areas of flow on the control surface is constant with time although the mass flow rates may be time varying.

Unlike in steady flow system, duration of observation  $\Delta t$  plays an important role in transient analysis. Let mass of the working fluid within the control volume before and after the observation be  $m_1$  and  $m_2$  respectively. Applying mass balance we get,

$$(m_2 - m_1)_{cv} = \sum m_i - \sum m_o \quad \dots(3.27)$$

Where  $\sum m_i$  is the mass entered the control volume during the interval  $\Delta t$  seconds.

$\sum m_o$  is the mass left the control volume during the interval  $\Delta t$  seconds.

By applying energy balance we get,

$$[Q_{cv} - W_{cv}] + \sum_{in} m_{in} \left[ h + \frac{C^2}{2} + Zg \right] - \sum_{out} m_{out} \left[ h + \frac{C^2}{2} + Zg \right] = \Delta E_{cv} \quad \dots(3.28)$$

Where  $E_{cv}$  is the change in energy content of the control volume in  $\Delta t$  seconds.

$Q_{cv}$  is the heat energy entered into the control volume in  $\Delta t$  seconds.

$W_{cv}$  is the work energy left the control volume in  $\Delta t$  seconds.

$h_i$  &  $h_o$  are specific enthalpy of the inlet and outlet streams respectively.

$\frac{C_i^2}{2}$  &  $\frac{C_o^2}{2}$  are the kinetic energy of the inlet and outlet streams respectively.

$Z_i g$  &  $Z_o g$  are the potential energy of inlet and outlet streams respectively.

## Perpetual Motion Machine – I

An engine which could provide work transfer continuously without heat transfer is known as perpetual motion machine of first kind. It is impossible to have such an engine as it violates first law of thermodynamics.

1.A turbine operating under steady flow conditions receives steam at the following state: Pressure 13.8bar; Specific volume 0.143 Internal energy 2590 KJ/Kg; Velocity 30m/s. The state of the steam leaving the turbine is: Pressure 0.35bar; Specific Volume 4.37 Internal energy 2360KJ/Kg; Velocity 90m/s. Heat is lost to the surroundings at the rate of 0.25KJ/s. If the rate of steam flow is 0.38Kg/. What is the power developed by the turbine.

**Given:**

**At steam Entering,**

$$P_1 = 13.8 \text{ bar} = 13.8 \times 10^2 \text{ KN/m}^2$$

$$V_1 = 0.143 \text{ m}^3/\text{kg}$$

$$U_1 = 2590 \text{ KJ/Kg}$$

$$C_1 = 30\text{m/s}$$

**At steam Leaving,**

$$P_2 = 0.35 \text{ bar} = 0.35 \times 10^2 \text{ KN/m}^2$$

$$V_2 = 4.37 \text{ m}^3/\text{kg}$$

$$U_2 = 2360 \text{ KJ/Kg}$$

$$C_2 = 90\text{m/s}$$

$$\text{Heat lost, } Q = 0.25 \text{ KJ/s}$$

$$\text{Steam rate, } m = 0.38 \text{ Kg/s}$$

**To find:**

$$\text{Power (P) =?}$$

**Solution:**

The equation of steady state is,

$$gz_1 + \frac{C_1^2}{2} + (U_1 + P_1 V_1) + Q = gz_2 + \frac{C_2^2}{2} + (U_2 + P_2 V_2) + W$$

Assume  $z_1 = z_2$

$$[9.81 + \frac{30^2}{2} + (2590 + (13.8 \times 10^2 \times 0.143))] - 0.25 = [9.81 + \frac{90^2}{2} + (2360 + (0.35 \times 10^2 \times 4.37))] + W$$

$$W = -3325.6\text{KJ}$$

$P_1$  = Pressure of working substance entering the system

$V_1$  = Specific volume of working substance

$U_1$  = Specific Internal Energy

$C_1$  = Velocity of working substance

$Z_1$  = Height above the datum level

$P_2, V_2, U_2, C_2, Z_2$  = Corresponding values of working substance

$Q$  = Heat supplied to system

$W$  = Work developed by system

Total energy at Entering = P.E + K.E + U.E + F.E + Heat energy

$$= gz_1 + \frac{C_1^2}{2} + (U_1 + P_1 V_1) + Q$$

Total energy at Leaving = P.E + K.E + U.E + F.E + Work done

$$= gz_2 + \frac{C_2^2}{2} + (U_2 + P_2 V_2) + W$$

Total energy entering and leaving,

$$gz_1 + \frac{C_1^2}{2} + (U_1 + P_1 V_1) + Q = gz_2 + \frac{C_2^2}{2} + (U_2 + P_2 V_2) + W$$

We know that,

$$H = U + PV$$

$$gz_1 + \frac{C_1^2}{2} + H_1 + Q = gz_2 + \frac{C_2^2}{2} + H_2 + W$$

Multiply 'm' on both sides,

$$m [gz_1 + \frac{C_1^2}{2} + H_1 + Q] = m [gz_2 + \frac{C_2^2}{2} + H_2 + W]$$

$P_1$  = Pressure of working substance entering the system

$V_1$  = Specific volume of working substance

$U_1$  = Specific Internal Energy

$C_1$  = Velocity of working substance

$Z_1$  = Height above the datum level

$P_2, V_2, U_2, C_2, Z_2$  = Corresponding values of working substance

$Q$  = Heat supplied to system

$W$  = Work developed by system

Total energy at Entering = P.E + K.E + U.E + F.E + Heat energy

$$= gz_1 + \frac{C_1^2}{2} + (U_1 + P_1 V_1) + Q$$

Total energy at Leaving = P.E + K.E + U.E + F.E + Work done

$$= gz_2 + \frac{C_2^2}{2} + (U_2 + P_2 V_2) + W$$

Total energy entering and leaving,

$$gz_1 + \frac{C_1^2}{2} + (U_1 + P_1 V_1) + Q = gz_2 + \frac{C_2^2}{2} + (U_2 + P_2 V_2) + W$$

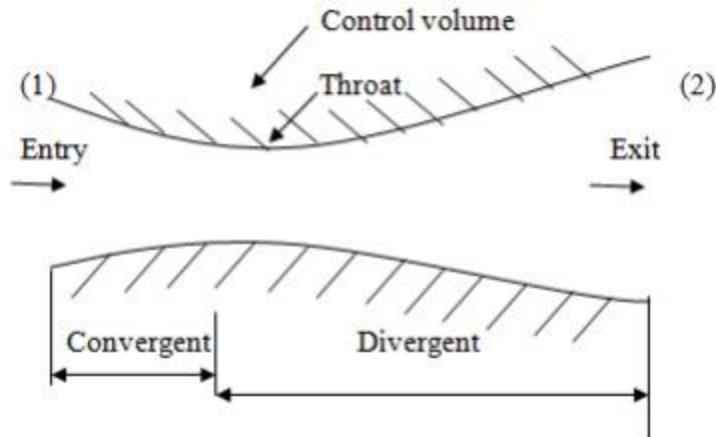
We know that,

$$H = U + PV$$

$$gz_1 + \frac{C_1^2}{2} + H_1 + Q = gz_2 + \frac{C_2^2}{2} + H_2 + W$$

Multiply 'm' on both sides,

$$m [gz_1 + \frac{C_1^2}{2} + H_1 + Q] = m [gz_2 + \frac{C_2^2}{2} + H_2 + W]$$

**Fig. Nozzle**

$$C_2^2 - C_1^2 = 2(h_1 - h_2)$$

$$C_2 = \sqrt{2(h_1 - h_2) + C_1^2}$$

$$C_2 = \sqrt{2(h_1 - h_2)}$$

$$C_2 = \sqrt{2C_p(T_1 - T_2) + C_1^2} \quad [h=C_p\Delta T]$$

$$C_2 = \sqrt{2C_p \left( T_1 - T_1 \left[ \frac{p_2}{p_1} \right]^{\frac{\gamma-1}{\gamma}} \right) + C_1^2}$$

$$[\text{For isentropic process: } T_2 = T_1 \left[ \frac{p_2}{p_1} \right]^{\frac{\gamma-1}{\gamma}}]$$

$$C_2 = \sqrt{2C_p T_1 \left( 1 - \left[ \frac{p_2}{p_1} \right]^{\frac{\gamma-1}{\gamma}} \right) + C_1^2} \quad \text{m/s.}$$

3. 0.25kg of air at a pressure of 1 bar occupies a volume of 0.3 . If this air expands isothermally to a volume of 0.9 . Find

- i. The initial temperature
- ii. Final temperature
- iii. External work done
- iv. Heat absorbed by the air



**Change in internal energy. Assume  $R=0.29 \text{ KJ/Kg K}$ .**

**Given:**

$$m=0.25\text{kg}$$

$$P_1 = 1 \text{ bar}$$

$$V_1 = 0.3\text{m}^3$$

$$V_2 = 0.9\text{m}^3$$

**To find:**

$$T_1, T_2, W, Q, \Delta U$$

**Solution**

**The initial temperature**

We know that,

$$P_1 V_1 = mRT_1$$

$$T_1 = \frac{P_1 V_1}{mR} = \frac{100 \times 0.3}{0.25 \times 0.287} = 418.12\text{K}$$

**Final temperature**

For constant temperature (isothermal) process

$$T_1 = T_2$$

$$T_2 = 418.12\text{K}$$

**External work done**

For isothermal Process,

$$W = P_1 V_1 \ln \left( \frac{V_2}{V_1} \right)$$

$$W = 100 \times 0.3 \ln \left( \frac{0.9}{0.3} \right)$$

$$W = 32.96 \text{KJ}$$

**Heat absorbed by the air**

$$Q = W$$

$$Q = 32.96 \text{KJ}$$

**Change in internal energy**

For isothermal process,

$$\Delta U = 0.$$

**1.5kg of certain gas at a pressure of 8 bar and 20°C occupies the volume of 0.5 . It expands adiabatically to a pressure of 0.9 bar and volume 0.73 . Determine the work done during the process. Gas constant, ratio of specific heat, values of two specific heats, change in internal energy and change in enthalpy.**

**Given:**

$$m = 1.5\text{kg}$$

$$P_1 = 8\text{bar} = 800\text{KN/m}^2$$

$$T_1 = 20^\circ\text{C} = 20 + 273 = 293\text{K}$$

$$V_1 = 0.15\text{m}^3$$

$$P_2 = 0.9\text{bar}$$

$$V_2 = 0.73\text{m}^3$$

**To find:**

$$W, R, \frac{C_p}{C_v}, C_p, C_v, \Delta U, \Delta H$$

**Gas constant**

From the characteristic equation,

$$P_1 V_1 = mRT_1$$

$$R = \frac{P_1 V_1}{mT_1} = \frac{800 \times 0.15}{1.5 \times 293} = 0.273\text{KJ/Kg K}$$

**Ratio of specific heat**

$$\gamma = \frac{C_p}{C_v}$$

$$\gamma = \frac{\log_{10} \left( \frac{P_2}{P_1} \right)}{\log_{10} \left( \frac{V_1}{V_2} \right)}$$

$$\gamma = \frac{\log_{10} \left( \frac{90}{800} \right)}{\log_{10} \left( \frac{0.15}{0.73} \right)}$$

$$\gamma = 1.38$$

$$C_p = 1.38 C_v$$

$$R = C_p - C_v$$

$$= 1.38 C_v - C_v$$

$$0.273 = 0.38 C_v$$

$$C_v = 0.718 \text{ KJ/Kg K}$$

$$C_p = 1.38 C_v = 1.38 \times 0.718 = 0.99 \text{ KJ/Kg K}$$

### Change in Internal energy

$$\Delta U = m C_v (T_2 - T_1)$$

Now we find  $T_2$

; K

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{\gamma-1}$$

$$T_2 = 293 \times \left(\frac{0.15}{0.73}\right)^{1.38-1}$$

$$T_2 = 160.59 \text{ K}$$

$$\Delta U = m C_v (T_2 - T_1)$$

$$= 1.5 \times 0.718 (160.59 - 293)$$

$$\Delta U = -142.5 \text{ KJ}$$

### Change in enthalpy

$$\Delta H = m C_p (T_2 - T_1)$$

$$= 1.5 \times 0.99 (160.59 - 293)$$

$$\Delta H = -196.6 \text{ KJ}$$

### Work done

$$W = \frac{P_1 V_1 - P_2 V_2}{\gamma - 1} = \frac{(800 \times 0.15) - (90 \times 0.73)}{1.38 - 1}$$

$$W = 142.89 \text{ KJ}$$

5. A cylinder contains 1 of gas at 100kpa and 100°C, the gas is polytropically compressed to a volume of 0.25 . The final pressure is 100kpa. Determine

- Mass of the gas
- The value of index 'n' for compression
- Change in internal energy of the gas
- Heat transferred by the gas during compression. Assume  $R = 0.287\text{KJ/Kg K}$ ;  $\gamma = 1.4$ .

**Given:**

$$V_1 = 1\text{m}^3$$

$$P_1 = 100\text{kpa}$$

$$T_1 = 100^\circ\text{C}$$

$$V_2 = 0.25\text{m}^3$$

$$P_2 = 600\text{kpa} = 600\text{KN/m}^2$$

$$R = 0.287\text{KJ/Kg K}$$

$$\gamma = 1.4$$

**To find:**

$$m, n, \Delta U, Q$$

**Solution:**

**Mass of the gas**

We know that characteristics gas equation,

$$P_1 V_1 = mRT_1$$

$$m = \frac{P_1 V_1}{RT_1} = \frac{100 \times 1}{0.287 \times 373} = 0.93\text{kg}$$

**Value of index 'n'**

$$n = \frac{\log_{10} \left( \frac{P_2}{P_1} \right)}{\log_{10} \left( \frac{V_1}{V_2} \right)} = \frac{\log \left( \frac{600}{100} \right)}{\log \left( \frac{1}{0.25} \right)} = 1.29$$

**Change in internal energy of the gas**

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

For polytropic process,

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}}$$

$$T_2 = 373 \times \left(\frac{600}{100}\right)^{\frac{1.21-1}{1.21}}$$

$$T_2 = 558\text{K}$$

$$\Delta U = mC_v (T_2 - T_1) = 0.93 \times 0.718(558-373)$$

$$\Delta U = 123.53\text{KJ}$$

**Heat transferred by the gas during compression Q**

$$Q = W \left(\frac{\gamma-n}{\gamma-1}\right)$$

Now finding W,

$$W = \frac{mR(T_1 - T_2)}{n-1} = \frac{0.93 \times 0.287 \times (373 - 558)}{1.29-1} = -170.19\text{KJ}$$

Heat transfer,

$$Q = W \left(\frac{\gamma-n}{\gamma-1}\right) = -170.19 \left(\frac{1.4-1.29}{1.4-1}\right)$$

$$Q = -46.802\text{KJ}$$