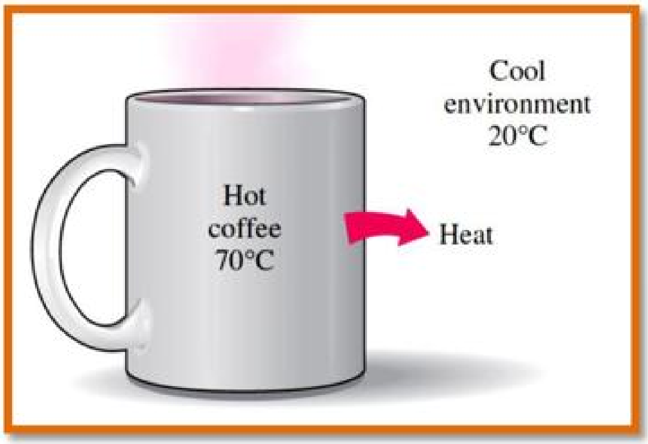
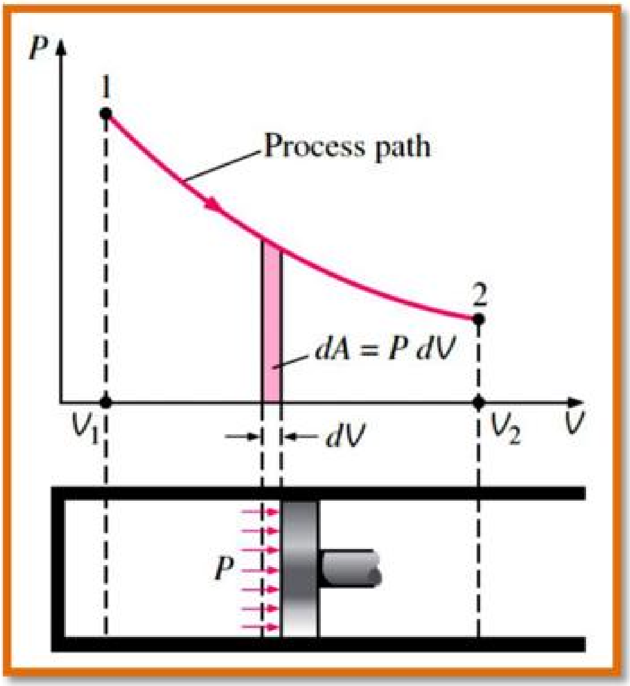
UNIT-I

BASIC CONCEPTS





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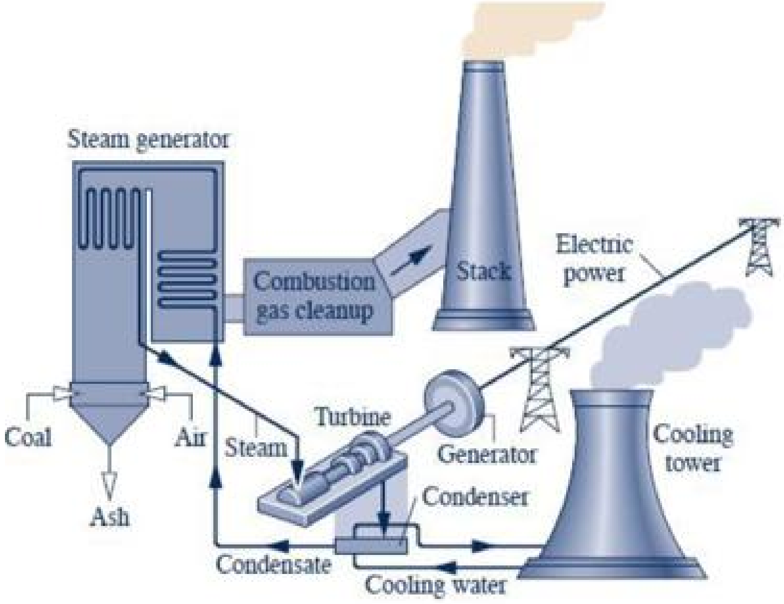
1.1 Introduction to Engineering Thermodynamics

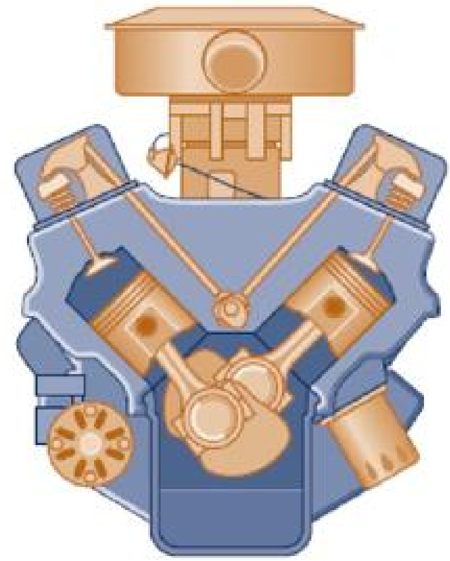
- ***Thermodynamics*** is the branch of science that deals with energy transfer and its effect on the state or condition of the system.
- Thermodynamics, basically entails four laws known as Zeroth, First, Second and Third law of thermodynamics.
  - ✓ ***Zeroth law*** deals with thermal equilibrium, relates to the concept of equality of temperature.
  - ✓ ***First law*** pertains to the conservation of energy and introduces the concept of internal energy.
  - ✓ ***Second law*** relates the direction of flow of heat, dictates limits on the conversion of heat into work and introduces the principle of increase of entropy.
  - ✓ ***Third law*** defines the absolute zero of entropy
- These laws are based on experimental observations and have ***No Mathematical Proof***.

Application Areas of Engineering Thermodynamics

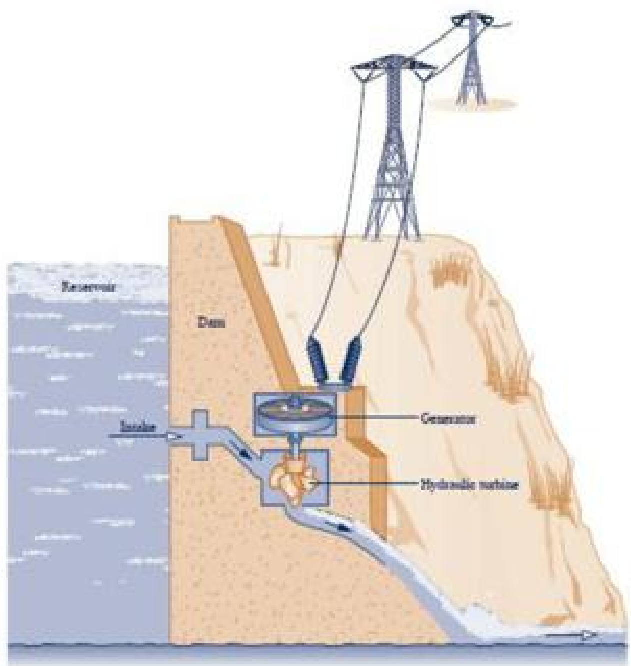
- All activities in nature involve some interaction between energy and matter; thus, it is hard to imagine an area that does not relate to thermodynamics in some manner.
- Thermodynamics is commonly encountered in many engineering systems and other aspects of life, and one does not need to go very far to see some application areas of it. In fact, one does not need to go anywhere. The heart is constantly pumping blood to all parts of the human body, various energy conversions occur in trillions of body cells, and the body heat generated is constantly rejected to the environment. The human comfort is closely tied to the rate of this metabolic heat rejection. We try to control this heat transfer rate by adjusting our clothing to the environmental conditions.
- Some of the selected areas of application of engineering thermodynamics are:
  - Automobile engines
  - Turbines, Compressors & Pumps
  - Propulsion system for aircraft and rockets
  - Combustion systems
  - HVAC systems: Vapor compression & absorption refrigeration, Heat pumps
  - Cooling of electronic equipments
  - Power stations: Nuclear, Thermal, etc.
  - Alternative energy systems
  - Biomedical applications: Life-support systems, Artificial organs



Thermal Power Station

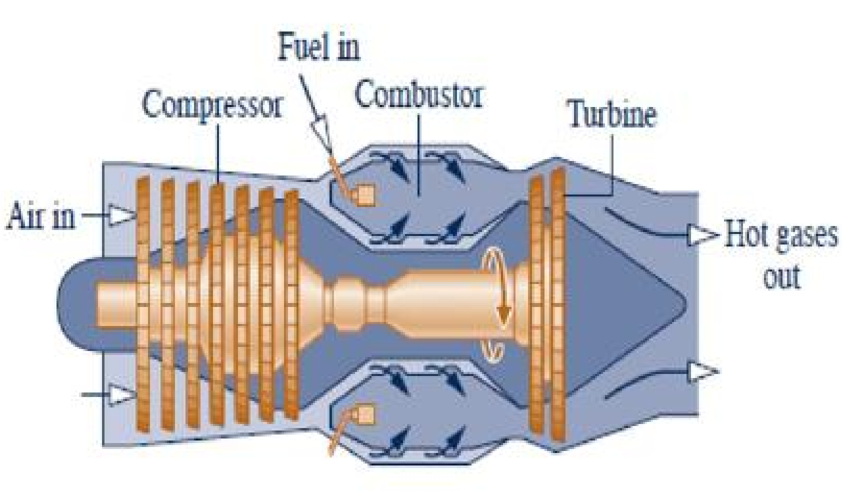


Vehicle Engine

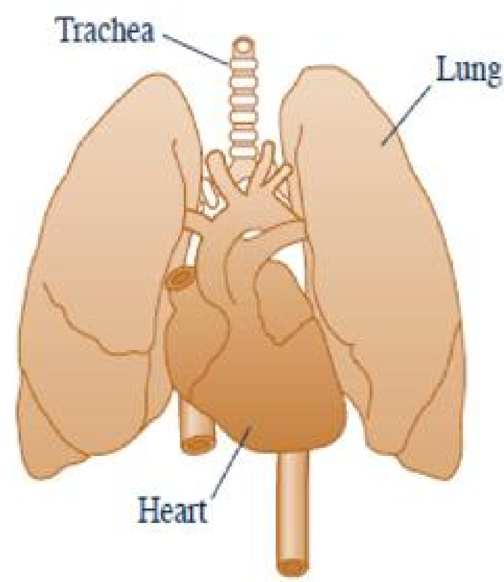


Hydro Power Station

Refrigerator



Turbo Jet Engine



Biomedical Applications

Fig. 1.1 Application areas of engineering thermodynamics

1.2 Macroscopic and Microscopic Point of View

- It is well known that every substance is composed of a large number of molecules. The properties of the substance depend on the behavior of these molecules.
- The behavior of a system may be investigated from either a microscopic (Micro means small) or macroscopic (Macro means big or total) point of view.
- These approaches are discussed below in a comparative way:

Sr. No.	Macroscopic Approach	Microscopic Approach
1	In this approach a certain quantity of matter is considered without taking into account the events occurring at molecular level.	The matter is considered to be comprised of a large number of tiny particles known as molecules, which moves randomly in chaotic fashion. The effect of molecular motion is considered.
2	Analysis is concerned with overall behavior of the system.	The Knowledge of the structure of matter is essential in analyzing the behavior of the system.
3	This approach is used in the study of classical thermodynamics.	This approach is used in the study of statistical thermodynamics.
4	A few properties are required to describe the system.	Large numbers of variables are required to describe the system.
5	The properties like pressure, temperature, etc. needed to describe the system, can be easily measured.	The properties like velocity, momentum, kinetic energy, etc. needed to describe the system, cannot be measured easily.
6	The properties of the system are their average values.	The properties are defined for each molecule individually.
7	This approach requires simple mathematical formulas for analyzing the system.	No. of molecules are very large so it requires advanced statistical and mathematical method to explain any change in the system.

- The macroscopic properties are the average properties of a large number of microscopic characteristics. Obviously, when both the methods are applied to a practical system, they give the same result.

1.3 Thermodynamic System and Control Volume

Thermodynamic System

"It is defined as a quantity of matter or a region in the space upon which attention is concentrated for the investigation or analysis of the thermodynamic problems i.e. heat transfer, work transfer, etc."

Surroundings or Environment

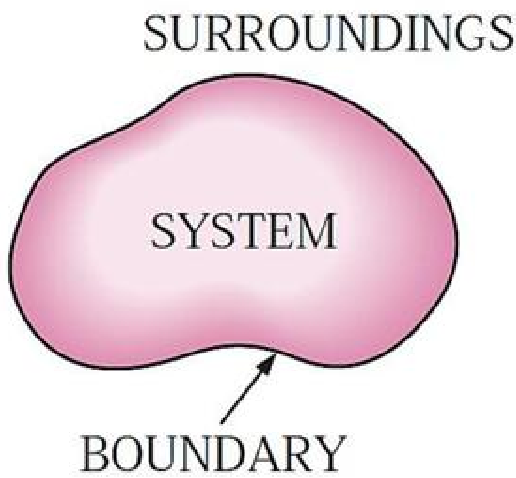
"It is the matter or region outside the system"

Boundary

"The system and surroundings are separated by an envelope called boundary of the system"

Types of boundary

- Fixed or moving boundary
- Real or imaginary boundary



System + Surrounding = Universe

Fig. 1.2 System, Surroundings and Boundary

Types of Thermodynamic System

A. Open System

- In an open system mass and energy (in form of heat and work) both can transfer across the boundary.
- Most of the engineering devices are open system.
- **Examples:** Boiler, Turbine, Compressor, Pump, I.C. Engine, etc.

B. Closed System

- A closed system can exchange energy in the form of heat and work with its surroundings but there is **no mass transfer** across the system boundary.
- The mass within the system remains constant though its volume can change against a flexible boundary.
- Further, the physical nature and chemical composition of the mass may change.
- **Examples:** Cylinder bounded by a piston with certain quantity of fluid, Pressure cooker and Bomb calorimeter, etc.

C. Isolated System

- There is no interaction between system and surroundings.
- It is of fixed mass and energy, and hence there is no mass and energy transfer across the system boundary.
- **Examples:** The Universe and Perfectly insulated closed vessel (Thermo flask).

D. Adiabatic System

- Boundaries do not allow heat transfer to take place across them.
- An adiabatic system is thermally insulated from its environment.
- It can exchange energy in the form of work only. If it does not, it becomes isolated.
- **Example:** A perfectly insulated piston-cylinder arrangement.

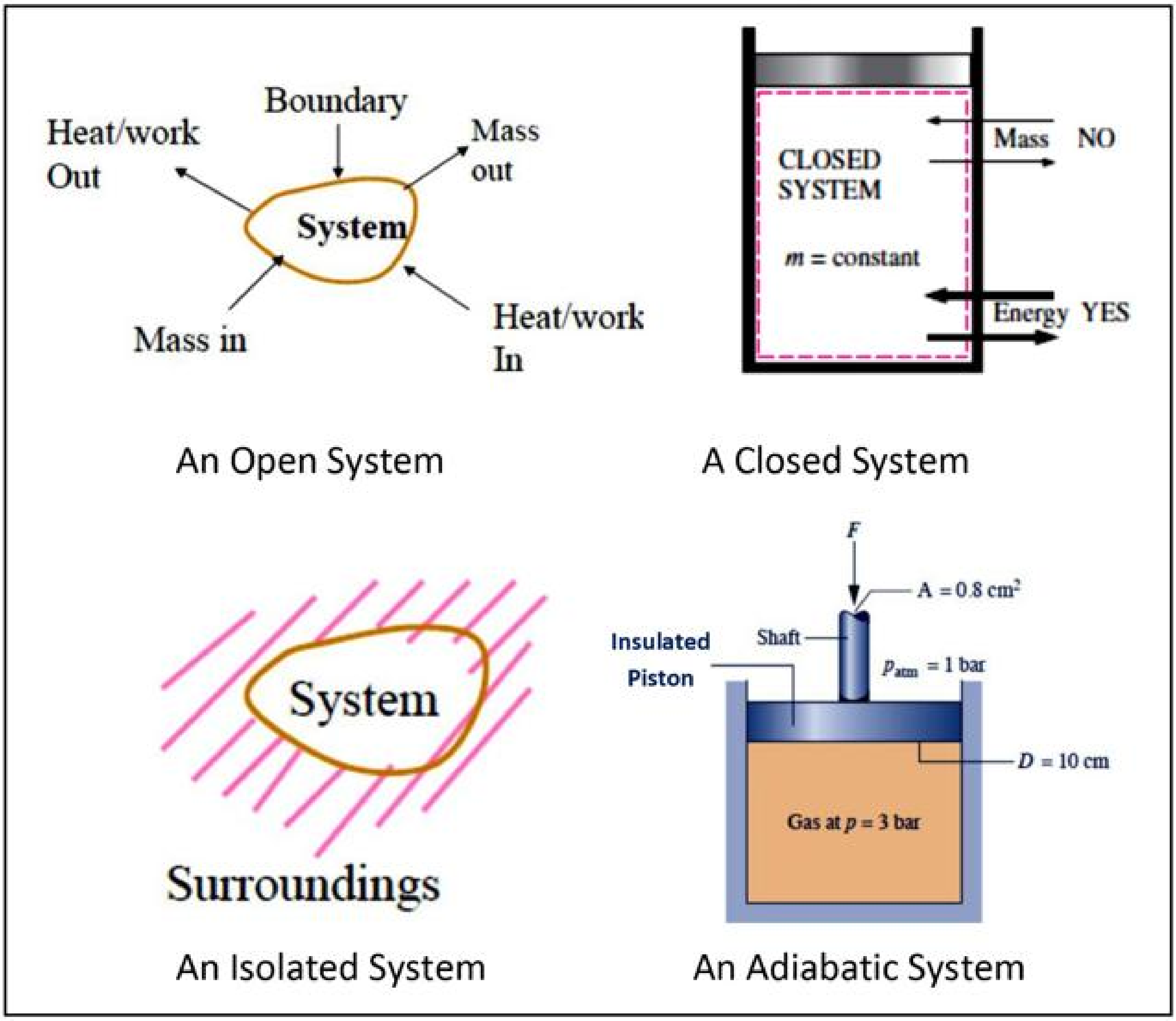


Fig. 1.3 Types of thermodynamic systems

E. Homogeneous & Heterogeneous System

<u>Homogeneous System</u>

"A system which consists of a single phase is termed as homogeneous system."

Examples:

- Mixture of air and water vapor
- Water + Nitric acid

<u>Heterogeneous System</u>

"A system which consists of two or more phases is called a heterogeneous system."

Examples:

- Water + Steam
- Ice + Water
- Water + Oil

Control Volume Concept

- For thermodynamic analysis of an open system, such as an air compressor, turbine, etc. attention is focused on a certain volume in space surrounding the system, known as **control volume**.
- The control volume bounded by the surface is called "**Control Surface**".
- Both mass and energy can cross the control surface. It may be physical or imaginary.

Example of Control Volume:

- Consider an air compressor (open system) as shown in Fig. 1.4. Since compressed air will leave the compressor and be replaced by fresh air, it is not convenient to choose a fixed mass as our system for the analysis.
- Instead we can concentrate our attention on the volume formed by compressor surfaces and consider the compressed air and fresh air streams as mass leaving and entering the control volume.

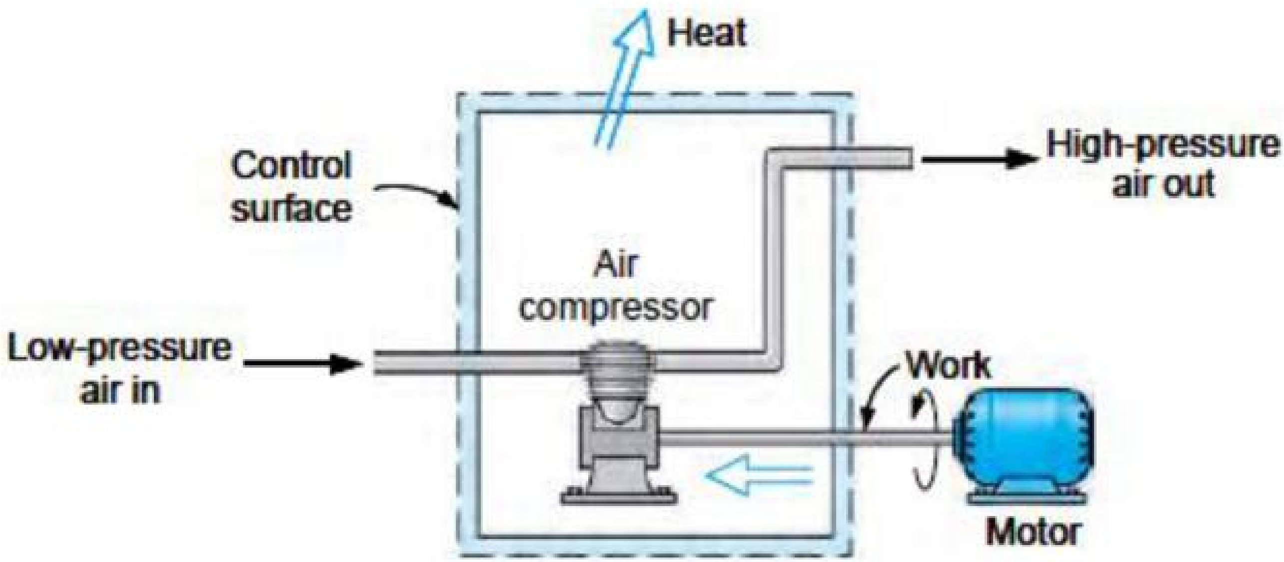


Fig. 1.4 An example of control volume

Difference between System and Control Volume

Sr. No.	System	Control Volume
1	A system is a defined quantity of matter which is considered to analyze the problem.	A control volume is a certain volume which is considered to analyze the problem.
2	The system is separated from its surrounding by a boundary which may be real or imaginary and may change shape, volume and position relative to observer.	The C.V. is separated from its surrounding by a control surface which may be real or imaginary and normally fixed in shape & position relative to observer.

1.4 Thermodynamic Properties, Processes and Cycles

Thermodynamic Properties

"A thermodynamic property refers to the characteristics which can be used to describe the physical condition or state of a system."

Examples of thermodynamic properties are: Temperature, Pressure, Volume, Energy, Mass, Viscosity, Thermal conductivity, Modulus of elasticity, velocity, etc.

Salient Aspects of a Thermodynamic Property

- It is a *macroscopic characteristic* of the system.
- It has a unique value when the system is in a particular state, and this value does not depend on the previous states that the system passed through; that is, it is not a *path function but it is a point function.*
- Since a property is not dependent on the path, any change depends only on the initial and final states of the system. *Hence its differential is exact*.

Types of Thermodynamic Properties

1. **Intensive Property**

– Intensive property is Independent of the mass of the system. Its value remains same whether one considers the whole system or only a part of it.

– **Examples:** Pressure, Temperature, Density, Viscosity, Thermal conductivity, Electrical potential, etc.

2. **Extensive Property**

– Extensive property depends on the mass of the system.

– **Examples:** Mass, Energy, Enthalpy, Volume, Entropy, etc.

3. **Specific Property**

– Extensive properties per unit mass are called specific properties.

– **Examples:** Specific volume $\left(v = \frac{V}{m}\right)$ and specific total energy $\left(e = \frac{E}{m}\right)$.

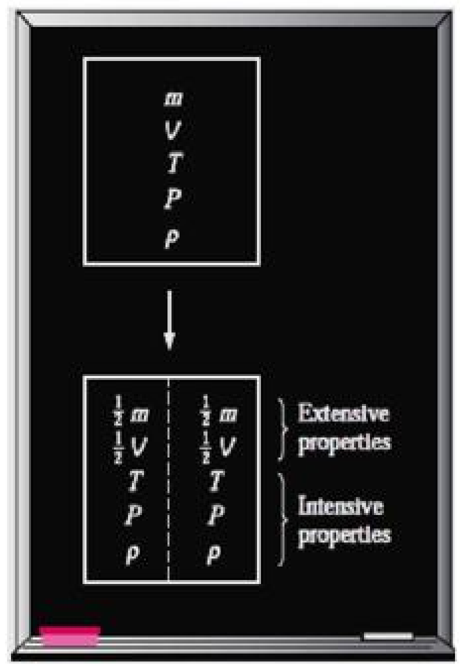


Fig. 1.5 Criterion to differentiate intensive and extensive properties

> ❖ **Note:**
> An easy way to determine whether a property is intensive or extensive is to divide the system into two equal parts with an imaginary partition, as shown in Fig. 1.5. Each part will have the same value of intensive properties as the original system, but half the value of the extensive properties.

State

- "***State*** refers to the condition of a system as described by its properties." It gives a complete description of the system. At a given state, all the properties of a system have fixed values.
- If the value of even one property changes, the state will change to a different one, any such kind of operation is called ***Change of state***.

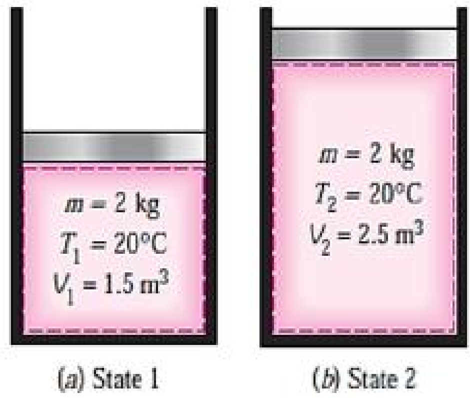


Fig. 1.6 A system at two different states

Process and Path

- Any change that a system undergoes from one equilibrium state to another is called a ***process***, and the series of states through which a system passes during a process is called the ***path*** of the process.
- To describe a process completely, one should specify the initial and final states of the process, as well as the path it follows, and the interactions with the surroundings.
- There are infinite ways for a system to change from one state to another state.

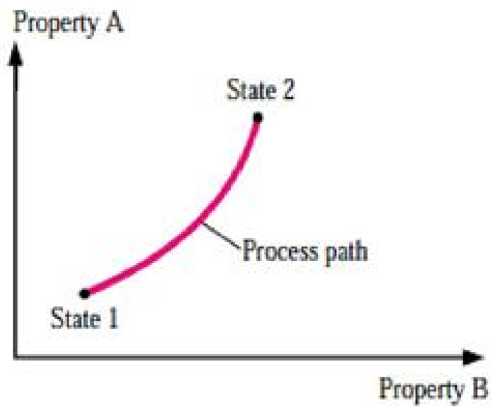


Fig. 1.7 A process between states 1 and 2 and a process path

Cycle

- When a system in a given initial state goes through a number of different changes of state or processes and finally returns to its initial state, the system has undergone a **cycle**. Thus for a cycle the initial and final states are identical.
- **Example:** Steam (water) that circulates through a steam power plant undergoes a cycle.

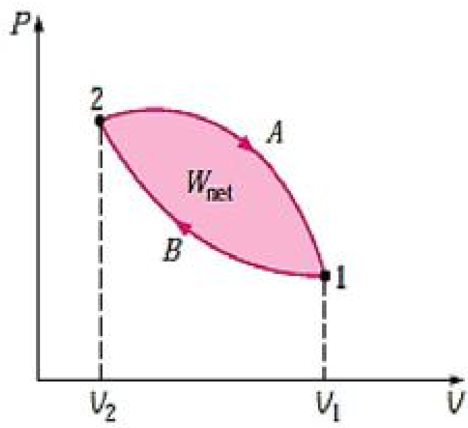


Fig. 1.8 Cycle of operations

Point Function

- When two properties locate a point on the graph (Co-ordinate axis) then those properties are called as Point Function.
- Examples: Pressure, Volume, Temperature, etc.
- It can be represented by an exact differential. i.e. $\int_1^2 dV = V_2 - V_1$

Path Function

- There are certain quantities which cannot be located on a graph (Co-ordinate axis) by a point but are given by the area or so, on that graph.
- In that case, the area on the graph, pertaining to the particular process, is a function of the path of the process, such quantities are called Path Functions.
- **Examples:** Heat, Work, etc.
- It can be represented by an inexact differential. Their change can not be written as difference between their end states.
- Thus,

$$\int_1^2 \delta W \neq W_2 - W_1 \text{ and is shown as } W_{1-2}$$

$$\int_1^2 \delta Q \neq Q_2 - Q_1 \text{ and is shown as } Q_{1-2}$$

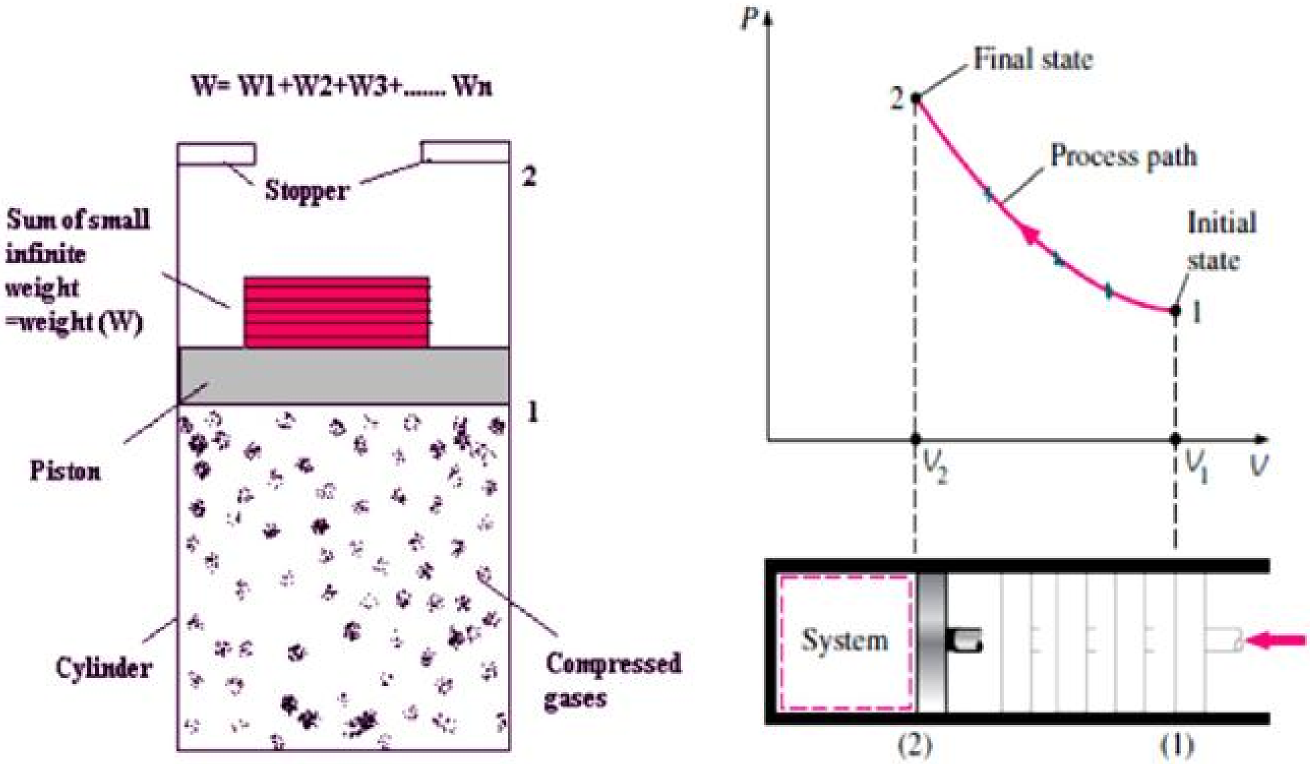
> ❖ **Note:**
> The operator δ is used to denote inexact differentials and d is used to denote exact differentials.

1.5 Thermodynamic Equilibrium

- A system is said to be in a state of thermodynamic equilibrium, if the conditions for the following three types of equilibrium are satisfied simultaneously:
  - ✓ **Mechanical Equilibrium:** There are no unbalanced forces within the system or between the surroundings. The pressure in the system is same at all points and does not change with respect to time.
  - ✓ **Thermal Equilibrium:** The temperature of the system does not change with time and has same value at all points of the system.
  - ✓ **Chemical Equilibrium:** No chemical reaction takes place in the system and the chemical composition which is same throughout the system does not vary with time.
- A system in thermodynamic equilibrium does not deliver anything.

1.6 Quasi-Static Process ***OR*** Quasi-Equilibrium Process

- ***"Quasi"*** means Almost slow or Infinitely slow.
- Consider a system of gas contained in a cylinder fitted with a piston upon which many very small pieces of weights are placed as shown in Fig.1.9(a).
- The upward force exerted by the gas just balances the weights on the piston and the system is initially in equilibrium state identified by pressure P_1, volume V_1 and temperature T_1.



(a) (b)

Fig. 1.9 (a) Quasi-Static Process (b) p-v diagram of a compression process

- When these weights are removed slowly, one at a time, the unbalanced potential is infinitesimally small.
- The piston will slowly move upwards and at any particular instant of piston travel, the system would be almost close to state of equilibrium.
- Every state passed by the system will be an equilibrium state.
- ***The locus of a series of such equilibrium states is called a "Quasi-Static or Quasi-Equilibrium process."***
- It should be pointed out that a quasi-equilibrium process is an idealized process and is not a true representation of an actual process. But many actual processes closely approximate it, and they can be modeled as quasi-equilibrium with negligible error.
- Engineers are interested in quasi-equilibrium processes for two reasons. First, they are easy to analyze; second, work-producing devices deliver the most work when they operate on quasi-equilibrium processes. Therefore, quasi-equilibrium processes serve as standards to which actual processes can be compared.
- Fig. 1.9(b) shows the p-v diagram of a compression process of a gas.
- A quasi-static process is also called a reversible process. This process is a succession of equilibrium states and ***infinite slowness*** is its characteristic feature.

1.7 Heat and Work

- Energy can cross the boundary of a closed system in two distinct forms: heat and work. It is important to distinguish between these two forms of energy.

Heat

- "***Heat*** is defined as the form of energy that is transferred between two systems (or a system and its surroundings) by virtue of a temperature difference." Then it follows that there cannot be any heat transfer between two systems that are at the same temperature.
- The ***temperature difference*** is the ***driving potential*** for heat transfer.
- A process during which there is no heat transfer is called an *adiabatic process*. In an adiabatic process, energy content and the temperature of a system can be changed by other processes, such as work.
- All heat interaction need not to be result in temperature changes e.g. Evaporation and Condensation.

Work

- "An energy interaction between a system and its surroundings during a process can be considered as work transfer, if its sole effect on everything external to the system could have been to raise a weight."
- It is also a form of energy in transit like heat.

Sign Convention for Heat & Work

- Heat and Work are directional quantity, and its specification requires magnitude and direction both. Universally accepted sign convections for heat and work energy are shown in Fig. 1.10.
  1. Heat transferred to a system (heat supply) and Work done by a system is considered ***positive.***
  2. Heat transferred from a system (heat rejection) and Work done on a system is considered ***negative.***

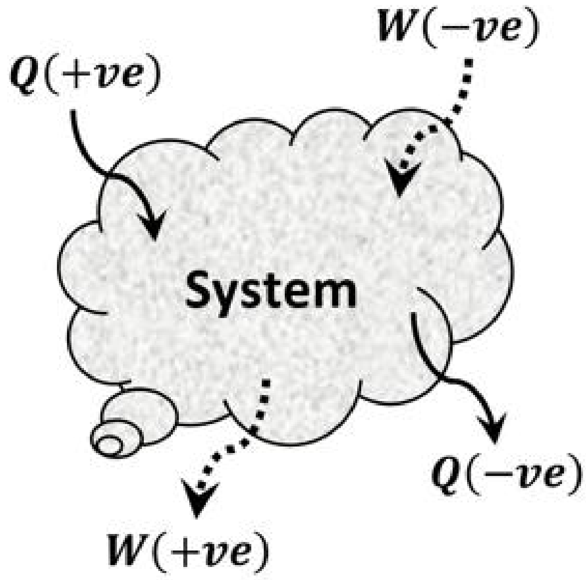


Fig. 1.10 Sign convention for heat & work

Comparison of Heat and Work

Similarities:

1. Both are recognized at the boundaries of a system as they cross the boundaries. That is, both heat and work are boundary phenomena.
2. Systems possess energy, but not heat or work.
3. Both are associated with a process, not a state. Unlike properties, heat or work has no meaning at a state.
4. Both are path functions (i.e. their magnitudes depend on the path followed during a process as well as the end states).

Dissimilarities:

1. In heat transfer temperature difference is required.
2. In a stable system there cannot be work transfer, however, there is no restriction for thetransfer of heat.
3. The sole effect external to the system could be reduced to rise of a weight but in the caseof a heat transfer other effects are also observed.

Different Forms of Work Transfer

1. Electrical work
2. **Mechanical work**
3. **Moving boundary work**
4. **Flow work**
5. Gravitational work
6. Acceleration work
7. Shaft work
8. Spring work

- Some of the important forms of work transfer are discussed here:

Mechanical Work

- In mechanics work done by a system is expressed as a product of force (F) and displacement (s)

$$W = F \times s$$

- If the force is not constant, the work done is obtained by adding the differential amounts of work,

$$W = \int_1^2 F \, ds$$

- The ***pressure difference*** is the ***driving force*** for mechanical work.

Moving Boundary Work / Displacement Work / pdV - Work

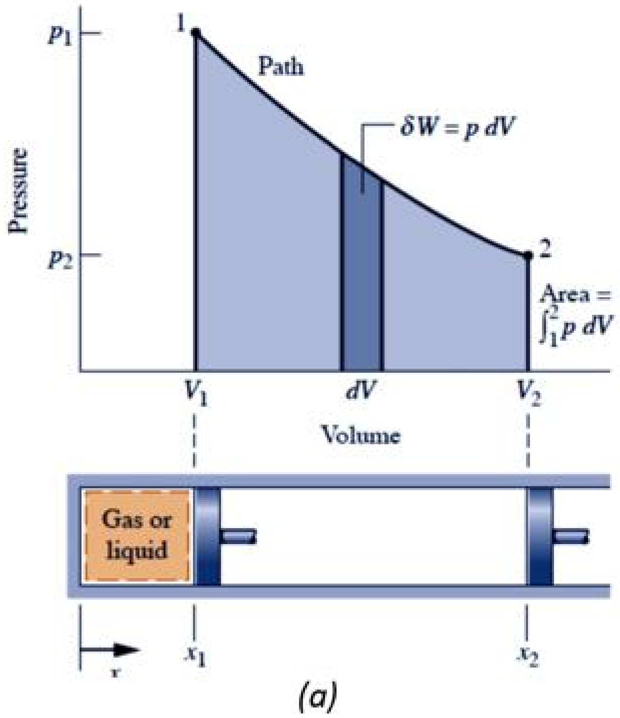
- In many thermodynamic problems, mechanical work is the form of moving boundary work. The moving boundary work is associated with real engines and compressors.

- Consider the gas enclosed in a frictionless piston cylinder arrangement as shown in Fig. 1.11. Let the initial gas pressure p_1 and volume V_1. The piston is the only boundary which moves due to gas pressure. Let the piston moves out to a new final position 2, specified by pressure $p_2$and volume V_2. At any intermediate point in the travel of the piston, let the pressure be p, volume V and piston cross sectional area is A. When the piston moves through and infinitesimal distance ds in a quasi-equilibrium manner, the force applied on piston is,

$$F = p \times A$$

- Then differential work transfer through a displacement of ds during this process,

$$\delta W = F \times ds = p \times A \times ds = p \times dV$$



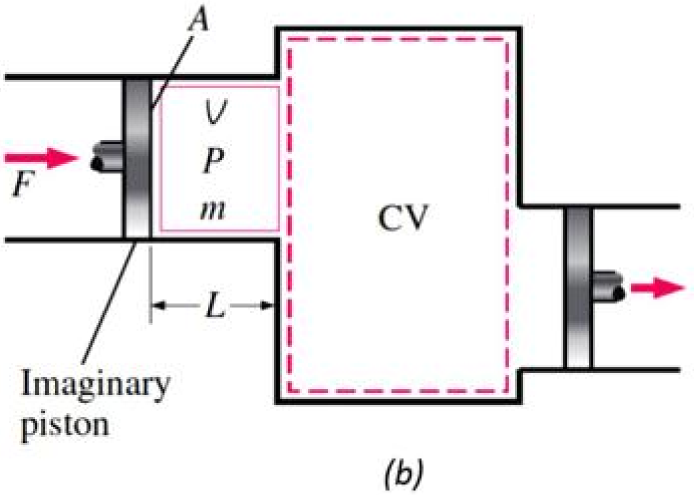


Fig. 1.11 (a) Displacement work and (b) Flow work

- When piston moves out from initial state 1 to final state 2 with volume changing from V_1 to V_2, The total boundary work done by the system will be,

$$W_{1-2} = \int_{V_1}^{V_2} pdV \ \ (kJ)$$

or

$$W_{1-2} = \int_{V_1}^{V_2} pdv \ \ (kJ/kg)$$

- This work transfer during a process is equal to the area under the curve on a $p - V$ diagram as shown in Fig. 1.11 (a).

Flow Work

- Flow energy or flow work refers to work required to push a certain mass of fluid into and out of the control volume. It is necessary for maintaining continuous flow through a control volume.
- Consider a fluid element of volume V, entering the control volume through a cross-sectional area A as shown in Fig. 1.11 (b).
- If p is the fluid pressure acting uniformly at the imaginary piston at the entrance of the control volume, the force applied on the fluid element by imaginary piston is,

$$F = p \times A$$

- If the fluid is pushed by a distance L, then the flow work will be,

$$W_f = p \times A \times L = p \times V$$

✓ Flow work at the entrance, $W_{f1} = p_1 V_1$

✓ Flow work at the exit, $W_{f2} = p_2 V_2$

Specific Heat

- "It is defined as heat energy required to change the temperature of the unit mass of a substance by one degree." It is designated as C and measured in kJ/kg-K.
- In general, the specific heat can be calculated as,

$$C = \frac{1}{m}\left(\frac{\delta Q}{dT}\right) = \frac{\delta q}{dT}$$

- Gases have two specific heats, C_p and C_v but for liquids and solids, the specific volume is very small and its change with pressure and temperature is negligible, thus they have only one specific heat.

Zeroth Law of Thermodynamics

- It states that if two bodies are in thermal equilibrium with a third body, they are also in thermal equilibrium with each other.
- The Zeroth law was first formulated and labeled by R. H. Fowler in 1931.

1.8 References

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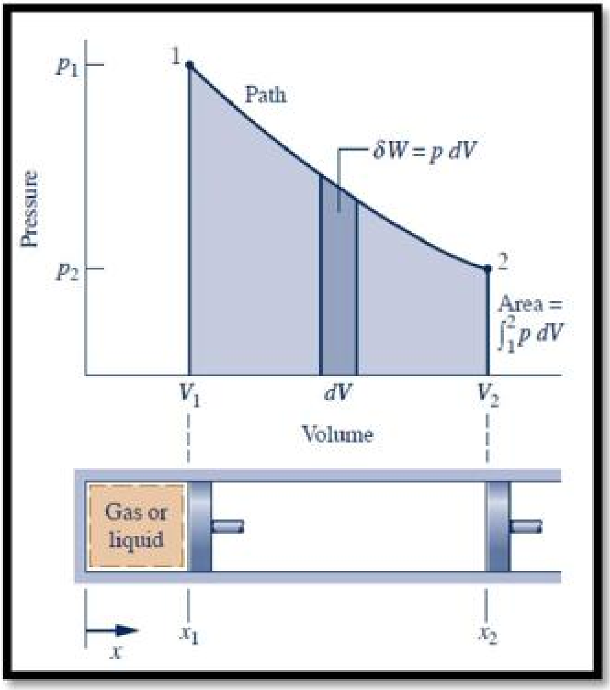
"Have no fear of perfection, You will never reach it"

FIRST LAW OF THERMODYNAMICS



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2.1 Introduction to 1st Law of Thermodynamics

- The first law of thermodynamics, also known as the conservation of energy principle. It states that *"Energy can neither be created nor destroyed; it can only change its form."*
- Total energy of an isolated system in all its form remains constant.
- The first law of thermodynamics cannot be proved mathematically but no process in nature is known to have violated the first law of thermodynamics.
- It is the relation of energy balance and is applicable to any kind of system (open or closed) undergoing any kind of process.

2.2 First Law Applied to a Cyclic Process – Joule's Experiment

- **Cyclic Process:** *"A process is cyclic if the initial and final states of the system executing the process are identical."*
- A system represented by a state point 1 undergoes a process 1-a-2, and comes back to initial state following the path 2-b-1.
- All properties of the system are restored, when the initial state is reached.

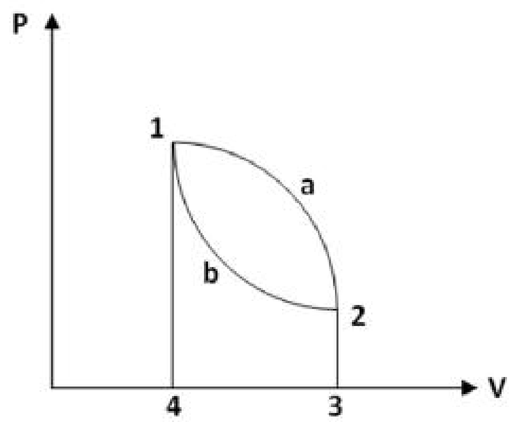


Fig. 2.1 Cyclic process

- During the execution of these processes:
  i. Area 1-a-2-3-4-1 represents the work done by the system (W_1) during expansion process 1-a-2.
  ii. Similarly area 2-3-4-1-b-2 gives work supplied to the system (W_2) during compression process 2-b-1.
  iii. Area 1-a-2-b-1 represents the net work $(W_1 - W_2)$ delivered by the system.
- Since the system regains its initial state, there is no change in the energy stored by the system.
- For a cyclic process, the First Law of Thermodynamics can be stated as follows :

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

  Mathematically,

$$\oint \delta Q = \oint \delta W \text{ --------- } (2.1)$$

Joule's Experiment

- The first law can be illustrated by considering the following experiment (Fig. 2.2).

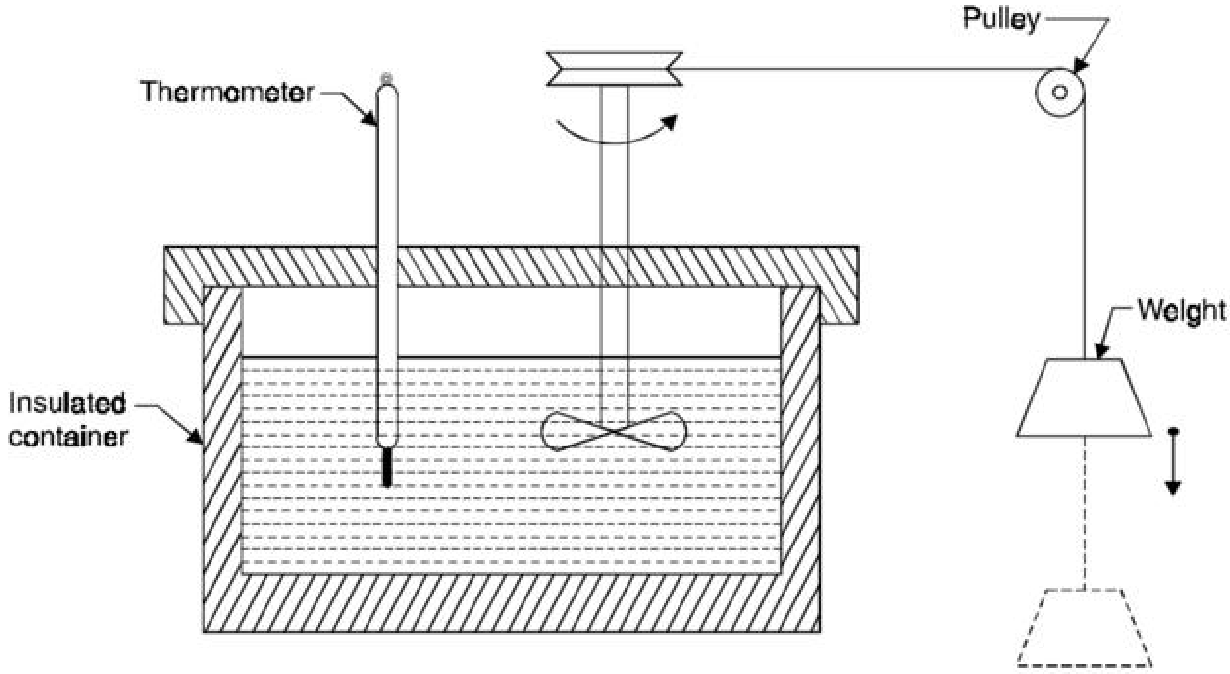


Fig. 2.2 Joule's paddle-wheel experiment

- A known mass of water is taken into a rigid and well insulated container provided with a paddle wheel.
- The insulation is provided to prevent any heat interaction with surroundings.
- The work input to the paddle wheel is measured by the fall of weight while the corresponding temperature rise of the liquid in the insulated container is measured by the thermometer.
- Joule conducted a number of experiments involving different types of work interactions and found that the work expended was proportional to increase in thermal energy, i.e.

$$Q \propto W$$

$$\therefore Q = \frac{W}{J}$$

$$\therefore W = JQ$$

Where,

J = Joule's equivalent or mechanical equivalent of heat

- In SI system of units, both heat and work are measured in Joules.

2.3 First Law Applied to a Process

- The first law of thermodynamics is often applied to a process as the system changes from one state to another.
- According to first law of thermodynamics,

$$\Delta E = Q - W --------(2.2)$$

Where,

$\Delta E = \Delta U + \Delta KE + \Delta PE + other\ forms\ of\ energy =$ Net change in total energy of the system

- If a ***closed system*** undergoes a change of state during which both heat and work transfer are involved, the net energy transfer will be stored or accumulated within the system. If Q is the heat transfer to the system and W is the work transferred from the system during process, the net energy transfer $(Q - W)$ will be stored in the system. Energy in storage is neither heat nor work and is given the name "***Internal Energy***" or "***Stored Energy***" of the system.

$$\therefore Q - W = \Delta U --------(2.3)$$

- Most closed systems in practice are stationary, i.e. they do not involve kinetic energy and potential energy during the process. Thus the stationary systems are called non-flow systems and the first law of thermodynamics is reduced to equation 2.3.
- In differential form first law of thermodynamics for a process can be written as,

$$\delta Q - \delta W = dE --------(2.4)$$

- Also for a ***cyclic process*** $\Delta U = 0$, as the system regains its original state hence,

$$Q - W = 0$$

$$\therefore Q = W --------(2.5)$$

2.4 Internal Energy: A Property of the System

- Consider a closed system which changes from state 1 to state 2 by path A and returns back to original state 1 by one of the following path as shown in Fig.2.3:
(i) 2-B-1 (ii) 2-C-1 (iii) 2-D-1

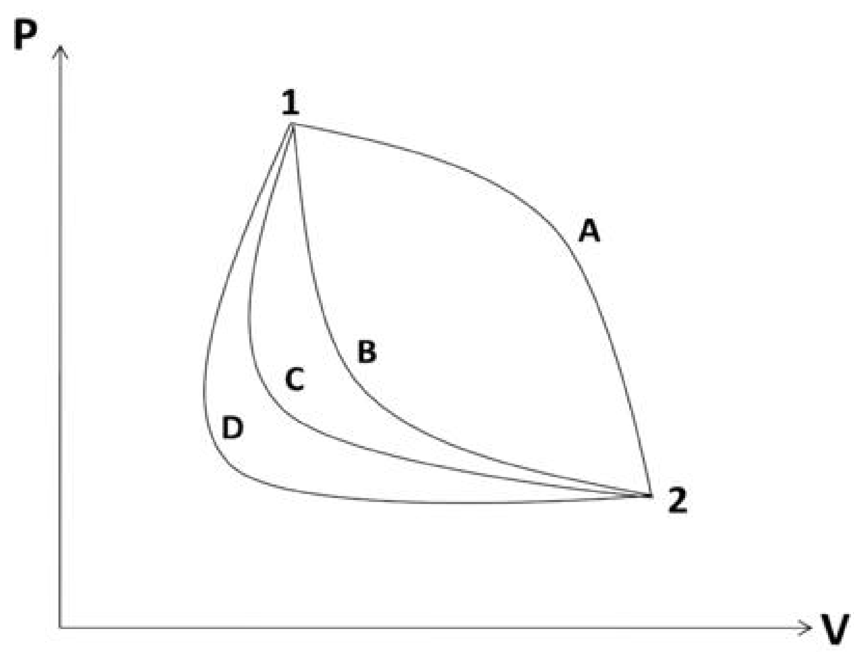


Fig. 2.3 Cyclic process with different paths

- Applying the 1st law for the cyclic process 1-A-2-**B**-1,

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

$$\therefore \int_{1,via\ A}^{2} (\delta Q - \delta W) + \int_{2,via\ B}^{1} (\delta Q - \delta W) = 0 - - - - - - - - - (2.6)$$

Similarly,

- Applying the 1st law for the cyclic process 1-A-2-**C**-1,

$$\therefore \int_{1,via\ A}^{2} (\delta Q - \delta W) + \int_{2,via\ C}^{1} (\delta Q - \delta W) = 0 - - - - - - - - - (2.7)$$

And,

- Applying the 1st law for the cyclic process 1-A-2-**D**-1,

$$\therefore \int_{1,via\ A}^{2} (\delta Q - \delta W) + \int_{2,via\ D}^{1} (\delta Q - \delta W) = 0 - - - - - - - - - (2.8)$$

- Comparing equations 2.6, 2.7 and 2.8, we get,

$$\int_{2,via\ B}^{1} (\delta Q - \delta W) = \int_{2,via\ C}^{1} (\delta Q - \delta W) = \int_{2,via\ D}^{1} (\delta Q - \delta W)$$

- Since B, C and D represents arbitrary paths between the state point 2 and state point 1, it can be concluded that the integral $\int_2^1 (\delta Q - \delta W)$
  - (i) Remains the same irrespective of the path along which the system proceeds,
  - (ii) Is solely dependent on the initial and final states of the system; ***is a point function and hence property***.
- The integral $\int_2^1 (\delta Q - \delta w)$ is called energy of the system and is given by a symbol *E*.
- Further the energy is a property of the system; its differential is exact and is denoted by *dE*.
- Thus for a process,

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

- The energy, E is an extensive property.
- The specific energy $\left(e = \frac{E}{m}\right)$ is an intensive property.

2.5 First Law Applied to Steady Flow Processes

Conservation of Mass Principle – Continuity Equation

- Conservation of mass is one of the most fundamental principles for flow systems. ***"It states that the mass of a system can neither be created nor destroyed but its amount remains constant during any process. It only changes its form (phase)."***
- The conservation of mass principle for a control volume (CV) can be expressed as,

  Total mass entering CV – Total mass leaving CV = Net change in mass within CV

- The amount of mass flowing through a cross-section per unit time is called the ***mass flow rate*** and it is calculated as,

$$\dot{m} = \frac{AC}{v} - - - - - - - - -(2.9)$$

Where,
$\dot{m}$ = Mass flow rate in kg/sec,
A = Cross-sectional area of flow in m^2,
v = Specific volume of fluid in m^3/kg,
C = Fluid velocity in m/sec.
Further,

$$Specific\ volume = \frac{1}{Density}$$

$$\therefore v = \frac{1}{\rho}$$

Equation (2.9) can be expressed as,

$$\dot{m} = \rho AC - - - - - - - - -(2.10)$$

- The volume flow rate through a cross-sectional area per unit time is called fluid ***discharge*** rate (Q),

$$Q = AC$$

- For a ***steady flow***,

$$\dot{m} = Constant = \rho_1 A_1 C_1 = \rho_2 A_2 C_2 - - - - - - - - -(2.11)$$

Steady and Un-steady Flow Process

- A flow process is said to be steady when the fluid parameters (P) at any point of the control volume remains constant with respect to time; the parameters may, however, be different at different cross-section of the flow passage.

$$\therefore \frac{\partial P}{\partial t} = 0$$

- A flow process is un-steady when the conditions vary with respect to time.

$$\therefore \frac{\partial P}{\partial t} \neq 0$$

Steady Flow Energy Equation (SFEE)

- ***Assumptions***

  The following assumptions are made in the steady flow system analysis:

  a) The mass flow through the system remains constant.

  b) Fluid is uniform in composition.

  c) The only interaction between the system and surroundings are work and heat.

  d) The state of fluid at any point remains constant with time.

  e) In the analysis only potential, kinetic and flow energies are considered.

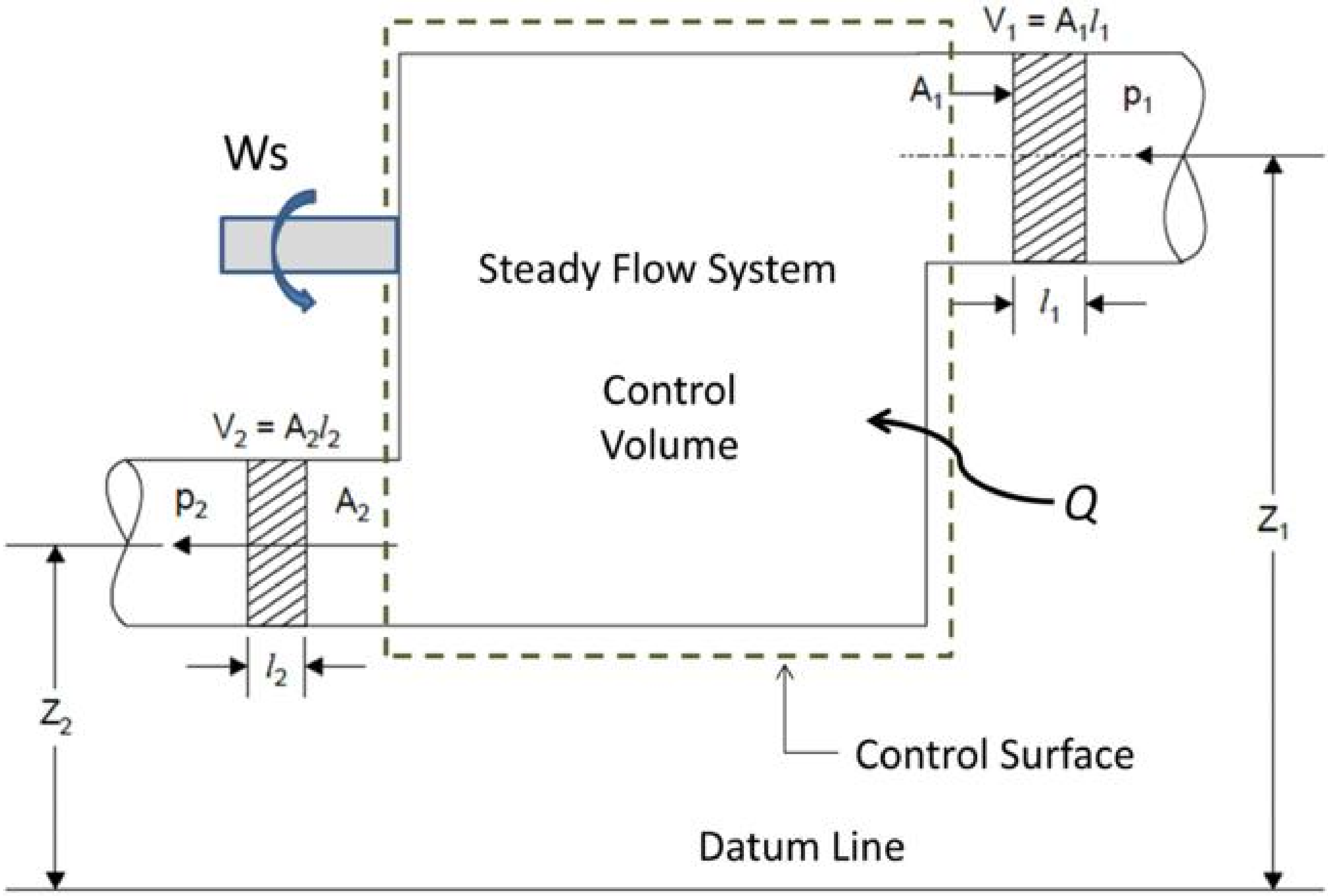


Fig. 2.4 Schematic flow process for an open system

- Consider a flow of fluid through an open system as shown in Fig. 2.4.
- During a small time interval dt there occurs a flow of mass and energy into the fixed control volume; entry is at section 1 and exit occurs at section 2.
- The fluid enters the control volume at section 1 with average velocity C_1, Pressure P_1, Specific volume v_1, and Specific internal energy u_1.
- The corresponding values at the exit section 2 are C_2, P_2, v_2 and u_2.
- Further during, the fluid flow between the two selected sections, heat (Q) and mechanical or shaft work (W_s) may also cross the control surface.
- The following species of energy are taken into account while drawing up the energy balance:

A. Internal energy stored by the fluid $= U$

B. Kinetic energy $= \frac{1}{2}mC^2$

C. Potential energy $= mgZ$

D. Flow work $= P_1V_1$

E. Heat interaction $= Q$

F. Work interaction i.e. shaft work $= W_s$

- According to 1st law of thermodynamics, energy balance in the symbolic form may be written as,

$$m_1\left(u_1 + P_1v_1 + \frac{C_1^2}{2} + gZ_1\right) + Q = m_2\left(u_2 + P_2v_2 + \frac{C_2^2}{2} + gZ_2\right) + W_s$$

$$---------(2.12)$$

- Equation (2.12) is the general steady flow energy equation (SFEE) and is equally applicable to compressible and incompressible; ideal and real fluids, liquids and gases.

- But according to assumption (1),

$$m = m_1 = m_2$$

Also enthalpy,

$$h = u + Pv$$

$$\therefore m\left(h_1 + \frac{C_1^2}{2} + gZ_1\right) + Q = m\left(h_2 + \frac{C_2^2}{2} + gZ_2\right) + W_s$$

- SFEE can be written on the basis of unit mass or on the basis of unit time.

- **SFEE on unit mass basis:**

$$h_1 + \frac{C_1^2}{2} + gZ_1 + q = h_2 + \frac{C_2^2}{2} + gZ_2 + w_s \quad --------(2.13)$$

Here, all the terms represents energy flow per unit mass of the fluid (J/kg)

6 SFEE Applied to Engineering Applications

- The SFEE applies to flow processes in many of the engineering applications, such as Turbines, Compressors, Pumps, Heat exchangers and flows through nozzles and diffusers.

- In certain flow processes, some of the energy terms in SFEE are negligibly small and can be omitted without much error.

1. Nozzles and Diffusers

- A nozzle is a device for increasing the velocity of a steadily flowing steam at the expense of its pressure and hence enthalpy.
- A diffuser is a device that increases the pressure of a fluid by slowing it down. That is nozzles and diffusers perform opposite task.
- Nozzles and diffusers are commonly utilized in jet engines, rockets, spacecraft, and even garden hoses. Fig. 2.5 shows a commonly used convergent-divergent nozzle.

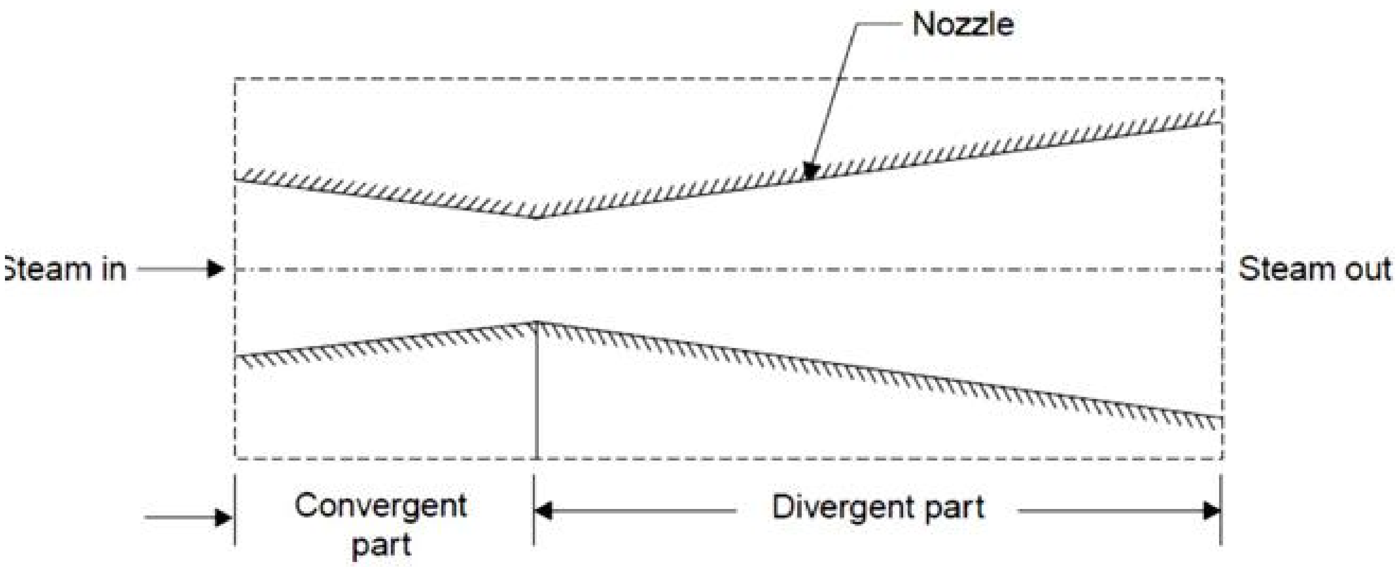


Fig. 2.5 A convergent-divergent nozzle

- Applying Steady Flow Energy Equation (SFEE),

$$m\left(h_1 + \frac{C_1^2}{2} + gZ_1\right) + Q = m\left(h_2 + \frac{C_2^2}{2} + gZ_2\right) + W_s$$

- The characteristic features of the flow through a ***nozzle*** are:
  - No shaft work; $W_s = 0$
  - If walls are thermally insulated; $Q = 0$
  - Nozzle is horizontal i.e No elevation difference between inlet and exit; $Z_1 = Z_2$
- Hence, the SFEE is reduced to

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

$$\therefore \frac{C_2^2}{2} - \frac{C_1^2}{2} = h_1 - h_2$$

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

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

If, $C_1 <<<< C_2$, then,

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

- Similar way SFEE can be reduced for diffusers also.

2. Heat Exchangers

- Condensers and Evaporators are the main types of heat exchangers.
- These are the devices where the objective is to transfer heat energy between hot and cold fluids. Therefore the heat transfer rate cannot be taken as zero.
- These devices are widely used in refrigeration system, air conditioning system, thermal power plant and various industries.
- A ***steam condenser*** is also a heat exchanger in which steam losses heat as it passes over the tubes through which cold fluid is flowing.
- An ***evaporator*** is also a heat exchanger and is used to extract heat from the cold places or fluids.
- **Boiler** is a type of evaporator and hence heat exchanger; used for the generation of steam. Thermal energy released by combustion of fuel is transferred to water which vaporizes and gets converted into steam at the desired pressure and temperature.

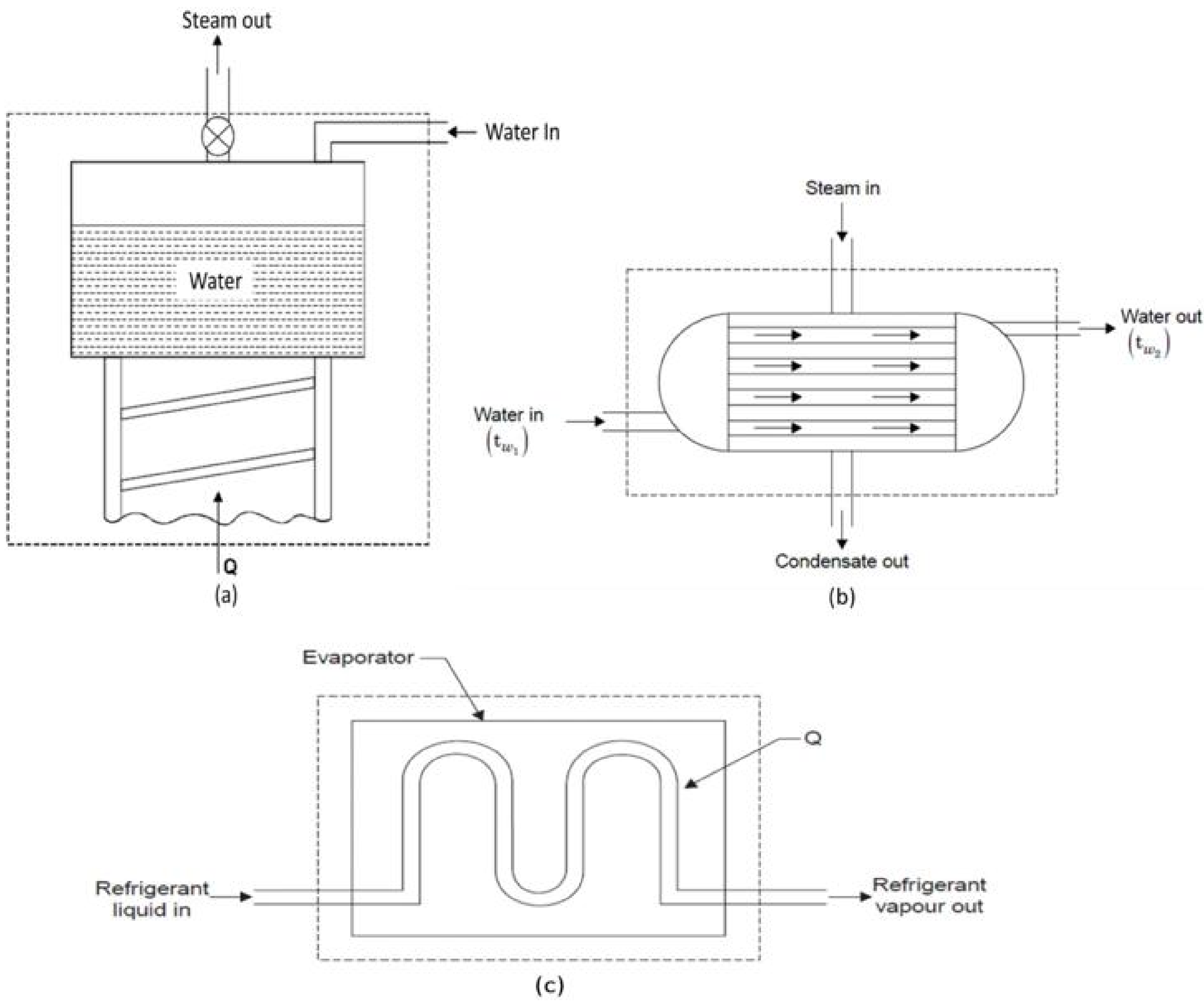


Fig. 2.6 Schematic diagram of (a) Boiler (b) Condenser (c) Evaporator

- Applying Steady Flow Energy Equation (SFEE),

$$m\left(h_1 + \frac{C_1^2}{2} + gZ_1\right) + Q = m\left(h_2 + \frac{C_2^2}{2} + gZ_2\right) + W_s$$

- The characteristic features of the flow through a ***heat exchangers*** are:
  - No shaft work; $W_s = 0$
  - Heat transfer, $Q \neq 0$ (Compulsory)
  - Change in kinetic energy is negligible (compare to change in enthalpy);

$$\frac{C_2^2}{2} - \frac{C_1^2}{2} = 0$$

  - Change in potential energy is negligible (i.e. No elevation difference between inlet and exit); $Z_1 = Z_2$
- Hence, SFEE is reduced to,

$$mh_1 + Q = mh_2$$
$$\therefore Q = m(h_2 - h_1)$$

- For condenser and evaporator, from energy balance equation,

$$Heat\ lost\ by\ the\ steam = Heat\ gained\ by\ the\ cooling\ water$$
$$m_s(h_{si} - h_{so}) = m_w(h_{wo} - h_{wi})$$

Where,

$m_s =$ Mass flow of steam

$m_w =$ Mass flow of cooling water

3. Steam or Gas Turbine

- A turbine is a device for obtaining work from a flow of fluid expanding from high pressure to low pressure.

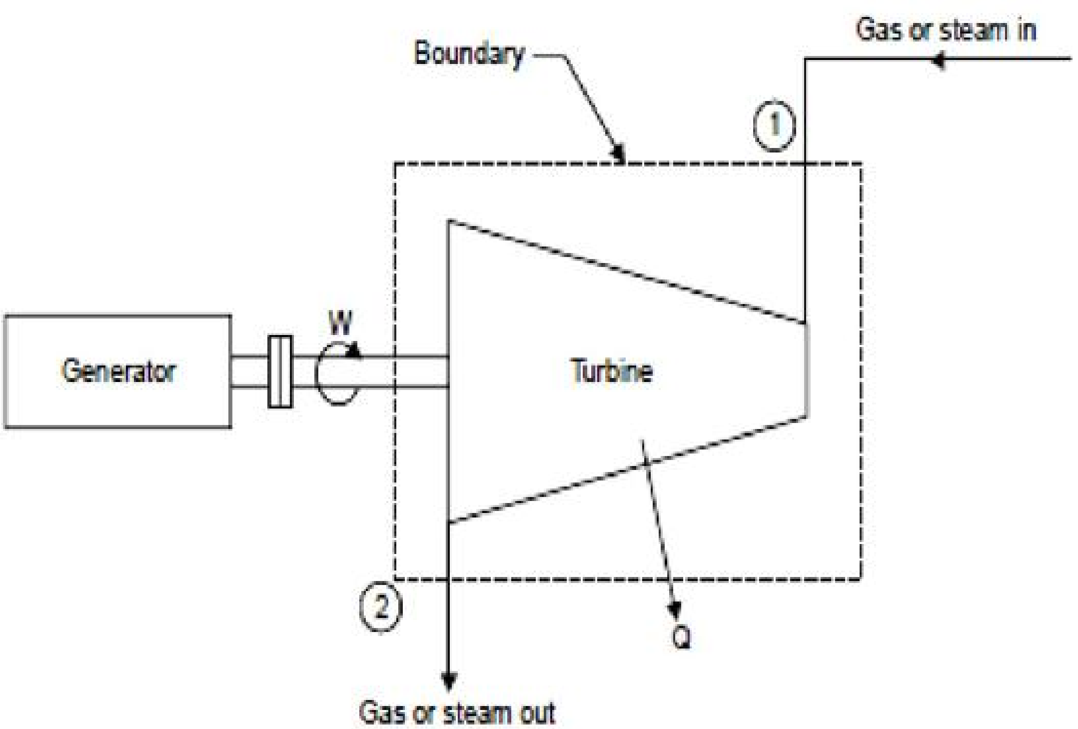


Fig. 2.7 Schematic of steam or gas turbine

- Applying Steady Flow Energy Equation (SFEE),

$$m\left(h_1+\frac{C_1^2}{2}+gZ_1\right)+Q=m\left(h_2+\frac{C_2^2}{2}+gZ_2\right)+W_s$$

- The characteristic features of flow through a ***steam or gas turbine*** are:
  - Shaft work produced; $W_s = +ve$
  - Negligible velocity change in the flow of fluid; $C_1 = C_2$
  - Negligible potential energy change; $Z_1 = Z_2$
  - No transfer of heat as its walls are thermally insulated; $Q = 0$
- Hence, SFEE is reduced to,

$$m(h_1)+0=m(h_1)+W_s$$
$$W_s=m(h_1-h_2)$$

- Apparently work is done at the expense of enthalpy.

4. Hydraulic Turbine

- A hydraulic turbine or water turbine is a device which takes in water from a height. The water enters into the turbine, a part of its potential energy is converted into useful work (shaft work), which is used to generate electric power in a generator.

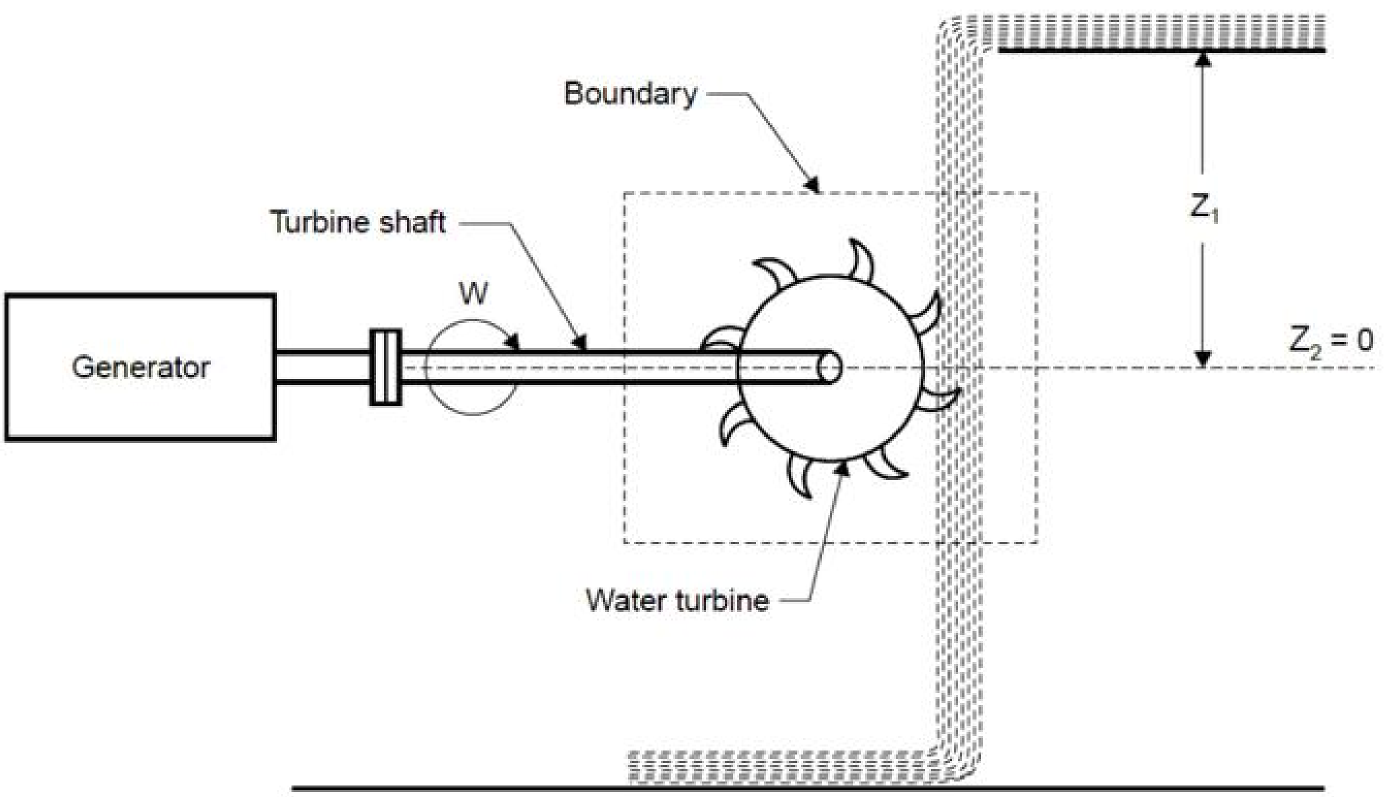


Fig. 2.8 Schematic of hydraulic turbine

- Applying Steady Flow Energy Equation (SFEE),

$$m\left(u_1+P_1v_1+\frac{C_1^2}{2}+gZ_1\right)+Q=m\left(u_2+P_2v_2+\frac{C_2^2}{2}+gZ_2\right)+W_s$$

- The characteristic features of flow through a ***hydraulic turbine*** are:
  - Shaft work produced; $W_s = +ve$

- Negligible change in temperature of water so,
  - Heat transfer rate from turbine; $Q = 0$
  - Change in specific internal energy; $\Delta u = u_2 - u_1 = 0$
- As water is an incompressible fluid, its specific volume and hence density will remain constant; $v_1 = v_2 = v$

– Hence, SFEE is reduced to,

$$W_s = m\left[(P_1 v_1 - P_2 v_2) + \left(\frac{C_1^2}{2} - \frac{C_2^2}{2}\right) + g(Z_1 - Z_2)\right]$$

5. Centrifugal Water Pump

– A centrifugal water pump is a device that transfers the mechanical energy of a motor or an engine into the pressure energy of incompressible fluid like water.

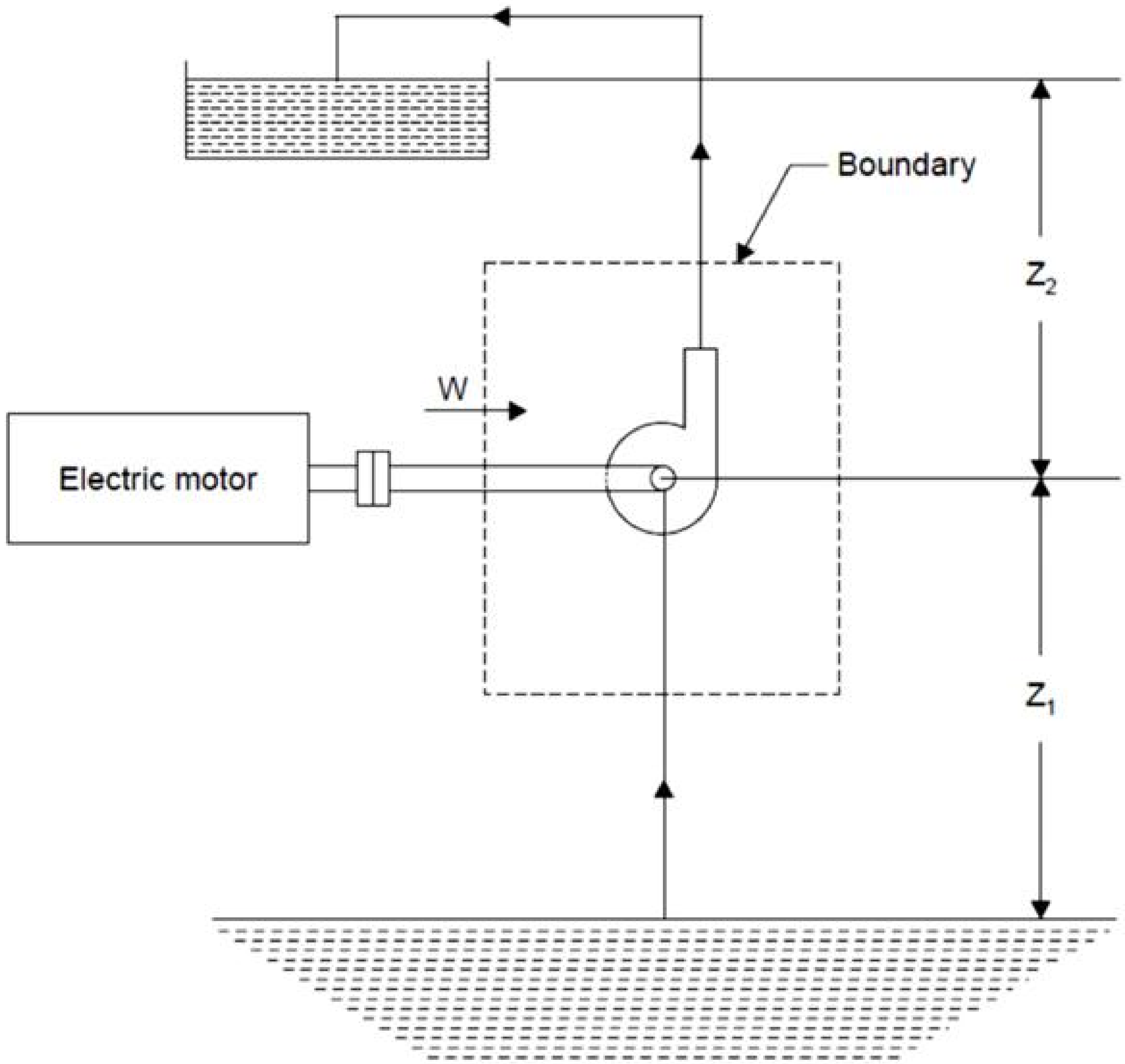


Fig. 2.9 Schematic of centrifugal water pump

– Applying Steady Flow Energy Equation (SFEE),

$$m\left(u_1 + P_1 v_1 + \frac{C_1^2}{2} + gZ_1\right) + Q = m\left(u_2 + P_2 v_2 + \frac{C_2^2}{2} + gZ_2\right) + W_s$$

– The characteristic features of flow through a ***centrifugal water pump*** are:

- Shaft work required; $W_s = -ve$
- Negligible change in temperature of water so,
  - Heat transfer rate from turbine; $Q = 0$
  - Change in specific internal energy; $\Delta u = u_2 - u_1 = 0$
- As water is incompressible fluid, its specific volume and hence density will remain constant; $v_1 = v_2 = v$

– Hence, SFEE is reduced to,

$$m\left(P_1 v_1 + \frac{C_1^2}{2} + gZ_1\right) = m\left(P_2 v_2 + \frac{C_2^2}{2} + gZ_2\right) - W_s$$

$$W_s = m\left[(P_2 v_2 - P_1 v_1) + \left(\frac{C_2^2}{2} - \frac{C_1^2}{2}\right) + g(Z_2 - Z_1)\right]$$

6. Reciprocating Compressor

– A reciprocating compressor is used for increasing the pressure of a fluid and has a piston cylinder mechanism as the primary element.

– The unit sucks in definite quantity of fluid, compresses through a required pressure ratio and then delivers the compressed air/gas to a receiver.

– Reciprocating compressors are used when small quantity of fluid with high pressure is required.

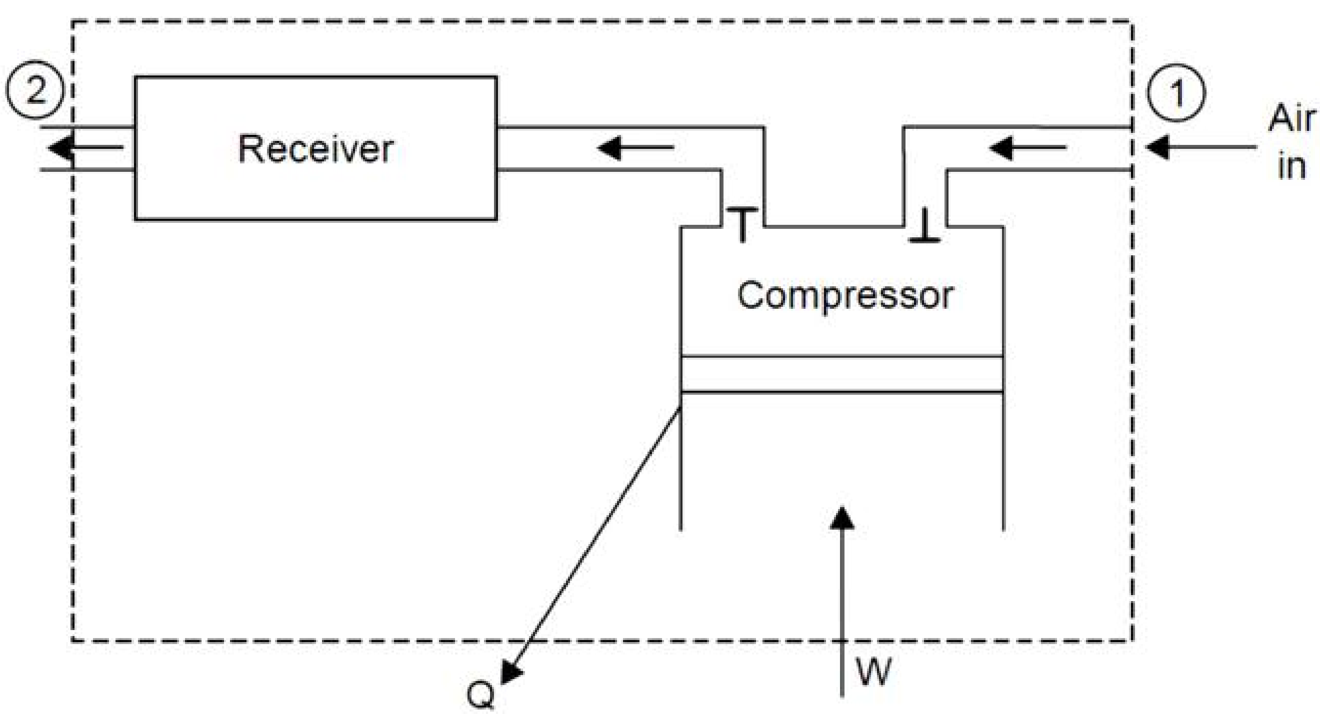


Fig. 2.10 Schematic of reciprocating compressor

– Applying Steady Flow Energy Equation (SFEE),

$$m\left(h_1 + \frac{C_1^2}{2} + gZ_1\right) + Q = m\left(h_2 + \frac{C_2^2}{2} + gZ_2\right) + W_s$$

– The characteristic features of flow through a ***reciprocating compressor*** are:

- Shaft work required; $W_s = -ve$
- Negligible velocity change in the flow of fluid; $C_1 = C_2$
- Negligible potential energy change; $Z_1 = Z_2$
- Appreciable amount of heat transfer is involved; heat is lost from the system as it gets sufficient time to interact with surrounding because of low speed; $Q \neq 0$ and $Q = -ve$

– Hence, SFEE is reduced to,

$$mh_1 - Q = mh_2 - W_s$$
$$\therefore W_s = Q + m(h_2 - h_1)$$

7. Rotary Compressor

– Rotary compressors are used for increasing the pressure of a fluid and have a rotor as the primary element.

– Rotary compressors are employed where high efficiency, medium pressure rise and large flow rate are the primary considerations.

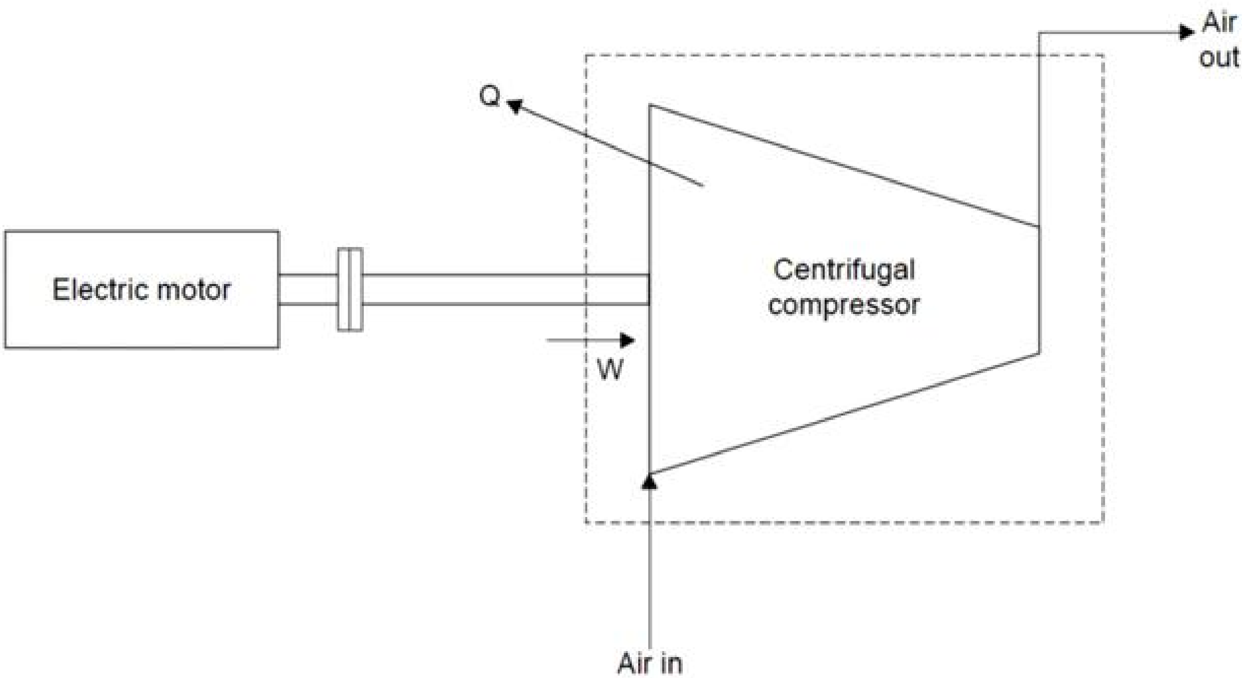


Fig. 2.11 Schematic of rotary compressor

– Applying Steady Flow Energy Equation (SFEE),

$$m\left(h_1 + \frac{C_1^2}{2} + gZ_1\right) + Q = m\left(h_2 + \frac{C_2^2}{2} + gZ_2\right) + W_s$$

– The characteristic features of flow through a ***rotary compressor*** are:

- Shaft work required; $W_s = -ve$
- Negligible velocity change in the flow of fluid; $C_1 = C_2$
- Negligible potential energy changes; $Z_1 = Z_2$
- Flow process is treated as adiabatic due to vary high flow rates; $Q = 0$

– Hence, SFEE is reduced to,

$$mh_1 = mh_2 - W_s$$
$$\therefore W_s = m(h_2 - h_1)$$

8. Throttling Process

- Throttling is the expansion of fluid from high pressure to low pressure. This process occurs when fluid passes through an obstruction (partially opened valve, porous plug or a small orifice) placed in the fluid flow passage.
- The throttling process is commonly used for the following purposes :
  I. For determining the condition of steam (dryness fraction).
  II. For controlling the speed of the turbine.
  III. Used in refrigeration plant for reducing the pressure of the refrigerant before entry into the evaporator.
- Fig. 2.12 shows the schematic of porous plug experiment performed by Joule and Thomson in 1852. A stream of incompressible fluid is made to pass steadily through a porous plug placed in an insulated and horizontal pipe.

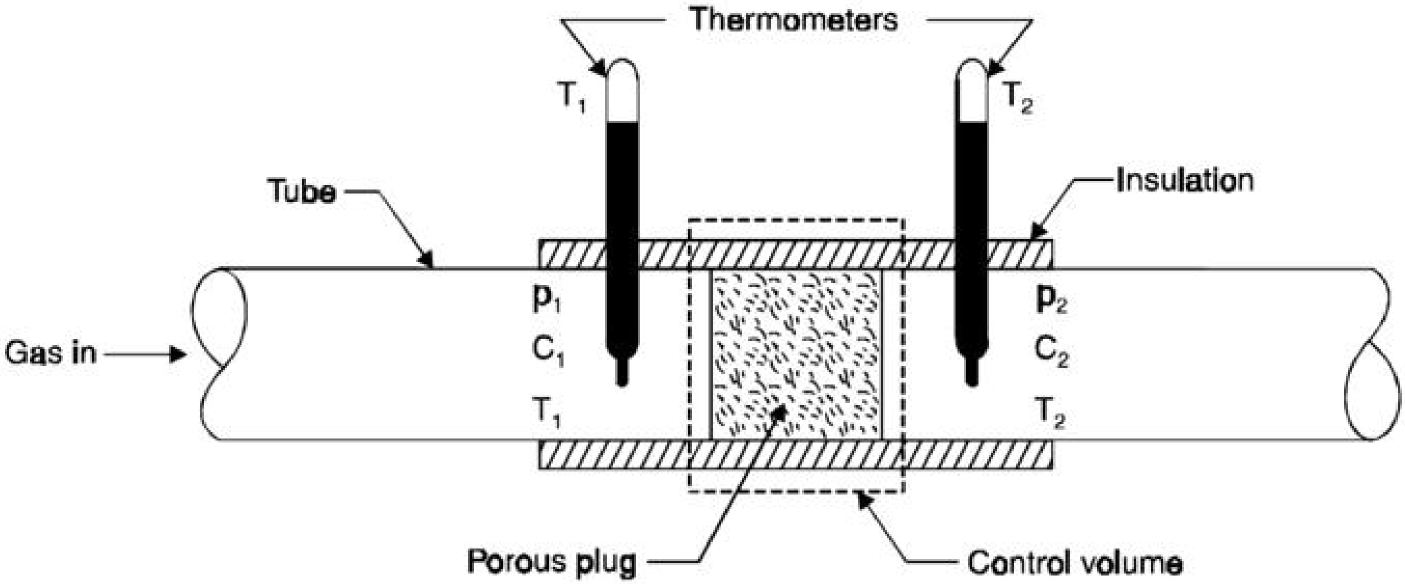
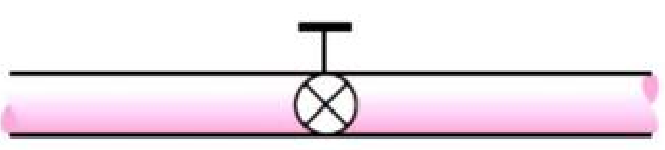
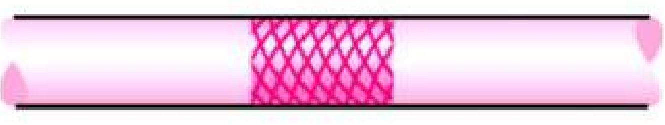


Fig. 2.12 The Joule – Thomson porous plug experiment



(a) An adjustable valve



(b) A porous plug

Fig. 2.13 Throttling devices (a) An adjustable valve (b) A porous plug

- Applying Steady Flow Energy Equation (SFEE),

$$m\left(h_1+\frac{C_1^2}{2}+gZ_1\right)+Q = m\left(h_2+\frac{C_2^2}{2}+gZ_2\right)+W_s$$

- The characteristic features of a ***throttling process*** are:
  - No shaft work required; $W_s = 0$
  - No heat interaction as pipe is thermally insulated; $Q = 0$
  - Negligible velocity change in the flow of fluid; $C_1 = C_2$
  - Negligible potential energy changes as the pipe is placed horizontally; $Z_1 = Z_2$
- Hence steady flow energy equation reduced to,

$$h_1 = h_2$$

- Enthalpy of fluid remains constant during throttling process. Thus the throttling expansion process is an ***isenthalpic process***.
- For a perfect gas,

$$C_pT_1 = C_pT_2$$
$$\therefore T_1 = T_2$$

- Thus for a perfect gas, the temperature before and after throttling is always same.

2.7 Unsteady Flow Processes: Filling and Emptying Process

- In engineering practice, the variable flow process applications are as common as the steady flow process. The rate of energy and mass transfer into and out of the control volume are not same in the case of unstable (or variable or transient or unsteady) flow process.
- Following two cases only will be discussed :
  1. Tank Filling Process.
  2. Tank Emptying Process ***or*** Tank Discharge Process

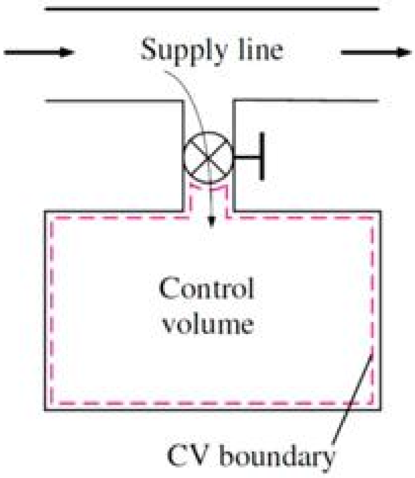


Fig. 2.14 Tank/ CV filling process

1. Tank Filling Process

- The tank/bottle initially contains fluid having mass m_i, at the state P_i, v_i *and* T_i. The corresponding values after the filling operation are m_f, P_f, v_f *and* T_f.
- In addition there may be heat and work interactions with the surroundings.
- The work interaction is possible by change in volume of the bottle or by internal electrical or mechanical devices.

- Mass of fluid entering $= m_f - m_i$
- Energy of entering fluid $= (m_f - m_i)e$
- Energy balance gives,

$$(m_f - m_i)e + Q = (m_f u_f - m_i u_i) + W$$

Where,

u_f & u_i = Final & Initial sp. Internal energy of fluid mass

- In a filling process of a tank from a large reservoir (pipeline), the properties of the entering fluid stream are essentially constant and so will be the energy e_p accompanying unit mass of fluid at entrance to control volume.

$$e_p = u_p + P_p v_p + \frac{C_p^2}{2} = h_p + \frac{C_p^2}{2}$$

$$\therefore (m_f - m_i)\left(h_p + \frac{C_p^2}{2}\right) + Q = (m_f u_f - m_i u_i) + W$$

The suffix 'p' refers to state of fluid in the pipe line.

- In the absence of any work interaction $(W = 0)$ and when the tank is thermally insulated $(Q = 0)$.

$$\therefore (m_f - m_i)\left(h_p + \frac{C_p^2}{2}\right) = (m_f u_f - m_i u_i)$$

- Neglecting kinetic energy of the incoming fluid,

$$(m_f - m_i)(h_p) = (m_f u_f - m_i u_i)$$

- If the tank is initially empty,

$$m_f h_p = m_f u_f$$

$$\therefore h_p = u_f$$

- Thus the specific internal energy of fluid charged into empty insulated tank is equal to the specific enthalpy of the filling fluid in the charging pipe line.
- If the fluid is an ideal gas, then temperature of gas in the tank after it is charged is given by,

$$C_p T_p = C_v T_2$$

$$\therefore T_2 = \gamma T_p$$

2. Tank Emptying Process

- The tank emptying process is the reverse of filling process, i.e. there is flow of fluid from the tank to the surrounding.
- The surroundings are much larger than the tank being emptied and so the energy $e_p = h_p + \frac{C_p^2}{2}$ accompanying unit mass of fluid at exit from the control volume will be constant.

- Energy balance gives,

$$(m_i - m_f)\left(h_p + \frac{C_p^2}{2}\right) + Q = (m_i u_i - m_f u_f)$$

- For no heat transfer and negligible exit velocity,

$$(m_i - m_f)(h_p) = (m_i u_i - m_f u_f)$$

- Further if the tank is to be fully emptied $(m_f = 0)$

$$\therefore m_i h_p = m_i u_i$$

$$\therefore h_p = u_i$$

2.8 First Law Applied to Non Flow Processes

- Following are the important non-flow processes, which are commonly used in engineering applications:

  A. Constant Volume Process (Isochoric)

  B. Constant Pressure Process (Isobaric)

  C. Constant Temperature Process (Isothermal)

  D. Adiabatic Process $(Q = 0)$ ***or*** Isentropic Process (Reversible Adiabatic; $S = C$)

  E. Polytropic Process

- Fig. 2.15 to 2.19 shows schematic and P-v diagram for all the processes listed above.

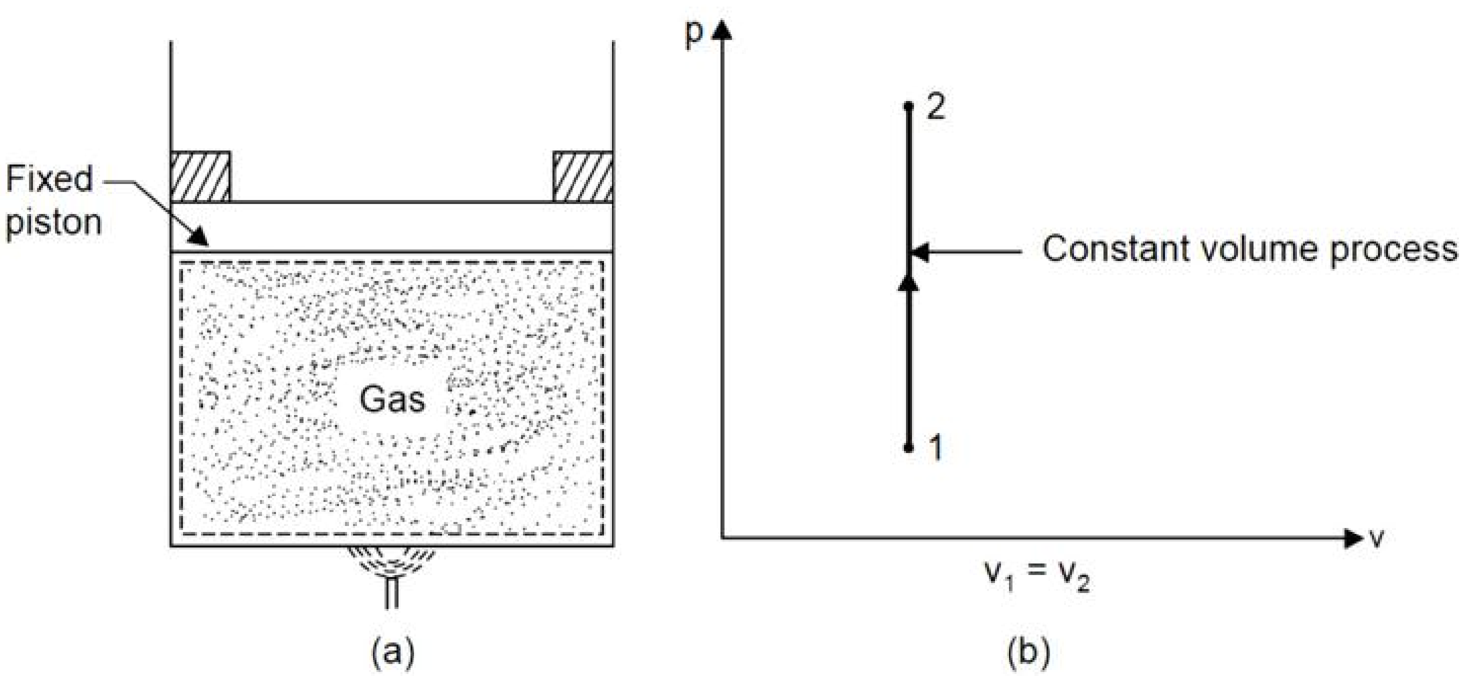


Fig. 2.15 Constant volume process (Isochoric)

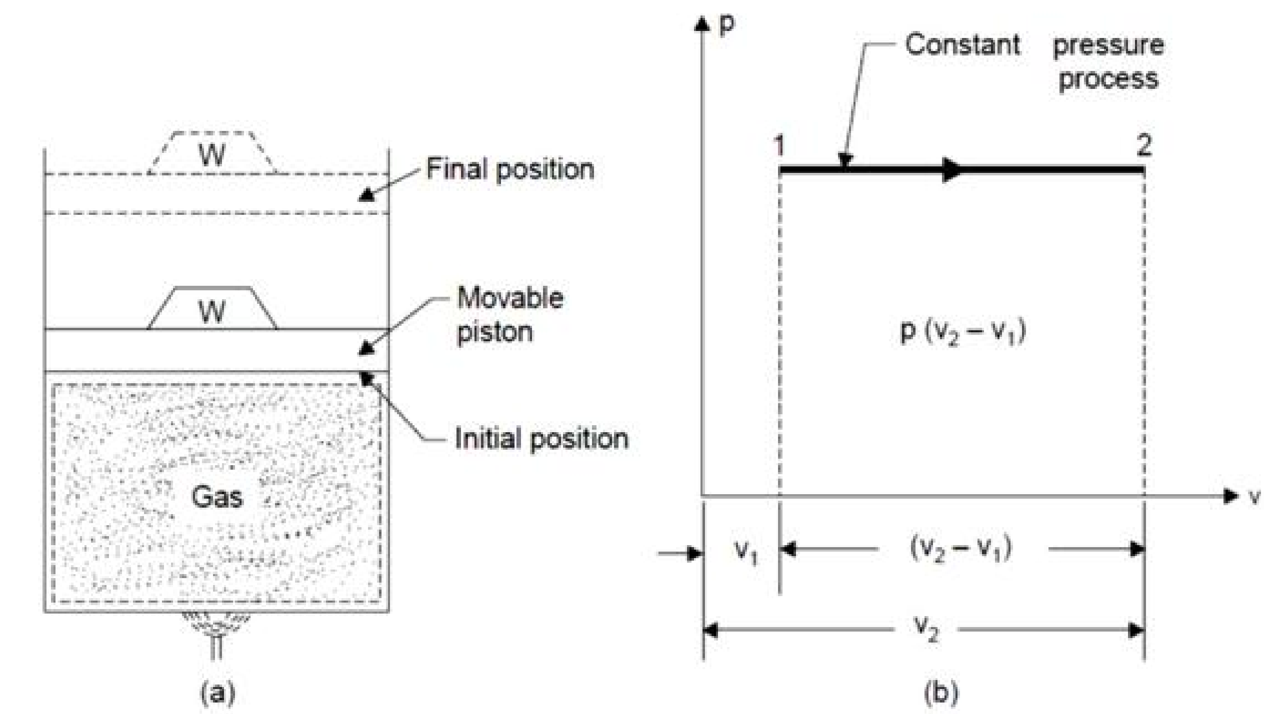


Fig. 2.16 Constant pressure process (Isobaric)

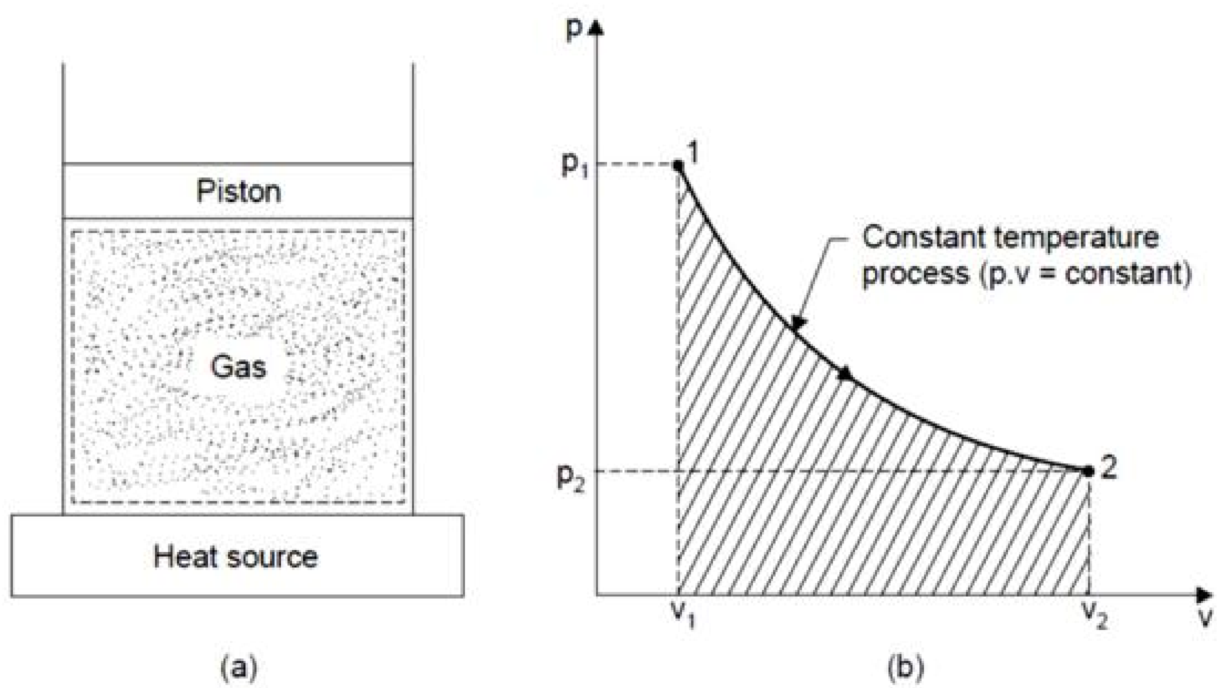


Fig. 2.17 Constant temperature process (Isothermal)

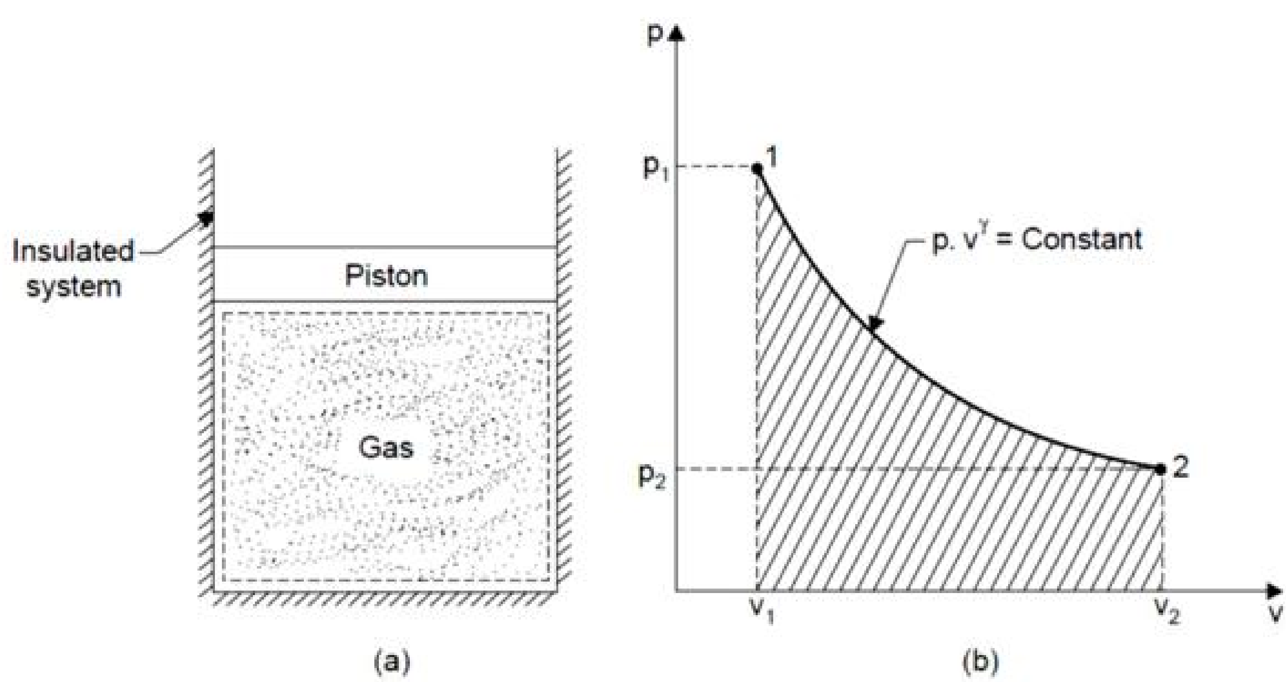


Fig. 2.18 Reversible Adiabatic Process (Isentropic process)

— In a Polytropic process, the index n depends only on the heat and work quantities during the process. The various processes considered earlier are special cases of Polytropic process for a perfect gas. This is illustrated on P-v diagram in Fig. 2.19.

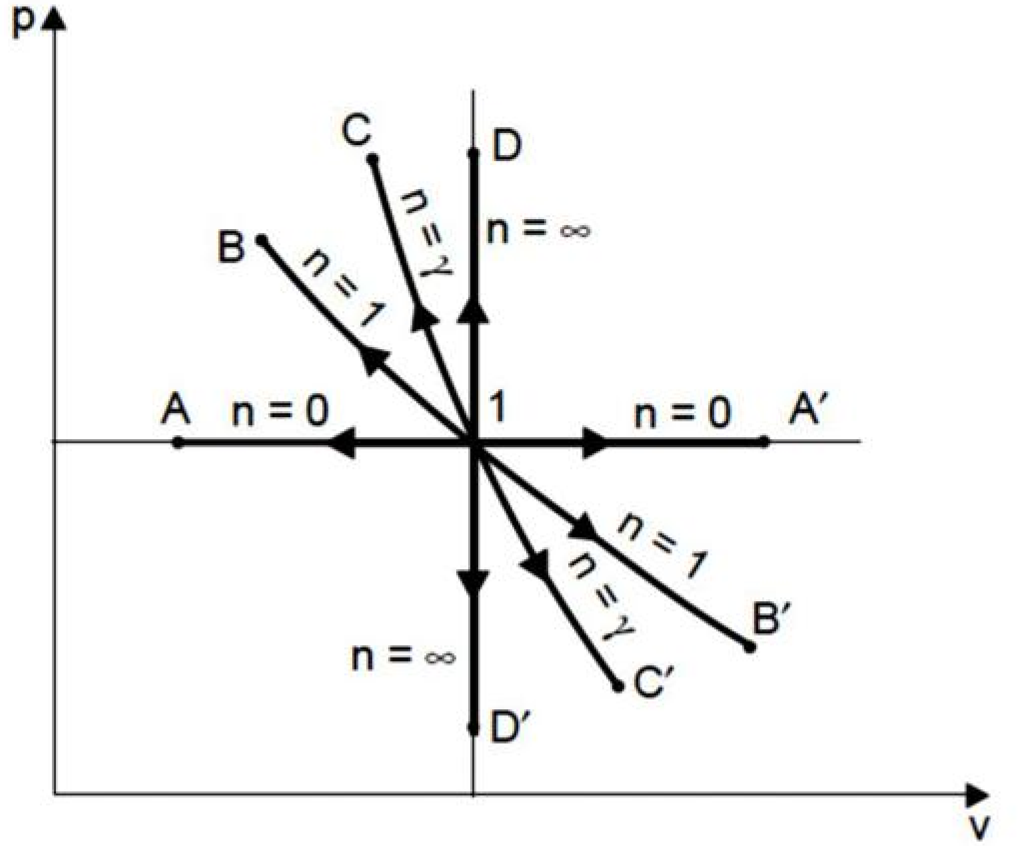


Fig. 2.19 Polytropic process for different values on index 'n'

For Air (Perfect Gas)

$R = 0.287\ KJ/kg - k$

$C_p = 1.005\ KJ/kg - k$

$C_v = 0.718\ KJ/kg - k$

$\gamma = 1.4$

Relationship between R, C_p, C_v and γ

$R = C_p - C_v$

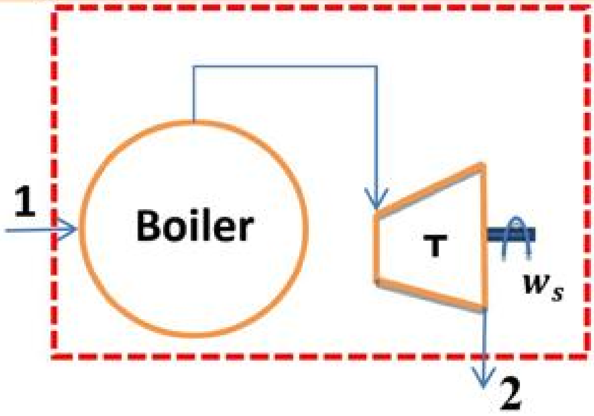
$\gamma = \frac{C_p}{C_v}$

2.9 Solved Numerical

Ex 2.1.

In steam power plant 1 kg of water per second is supplied to the boiler. The enthalpy and velocity of water entering the boiler are 800 kJ/kg and 5 m/s. the water receives 2200 kJ/kg of heat in the boiler at constant pressure. The steam after passing through the turbine comes out with a velocity of 50 m/s, and its enthalpy is 2520 kJ/kg. The inlet is 4 m above the turbine exit. Assuming the heat losses from the boiler and the turbine to the surroundings are 20 kJ/sec. Calculate the power developed by the turbine. Consider the boiler and turbine as single system.

Solution:



<u>Given Data:</u>

$\dot{m}_w = 1\ kg/sec$

$h_1 = 800\ kJ/kg$

$C_1 = 5\ m/s$

$q_s = 2200\ kJ/kg$

$C_2 = 50\ m/s$

$h_2 = 2520\ kJ/kg$

$Z_1 - Z_2 = 4\ m$

$\dot{q}_r = -20\ kJ/sec$

$\therefore q_r = \dfrac{\dot{q}_r}{\dot{m}_w} = \dfrac{-20}{1}$

$\therefore q_r = -20\ kJ/kg$

<u>To be Calculated:</u>

$P = ?$

⇨ Net Heat Transfer to the System,

$$q_{net} = q_s - q_r$$
$$\therefore q_{net} = 2200 - 20$$
$$\therefore q_{net} = 2180\ kJ/kg$$

⇨ Apply Steady Flow Energy Equation,

$$h_1 + \frac{C_1^2}{2} + gZ_1 + q_{net} = h_2 + \frac{C_2^2}{2} + gZ_2 + w_{net}$$
$$\therefore w_{net} = (h_1 - h_2) + \left(\frac{C_1^2}{2} - \frac{C_2^2}{2}\right) + g(Z_1 - Z_2) + q_{net}$$
$$\therefore w_{net} = (800 - 2520) \times 10^3 + \left(\frac{5^2}{2} - \frac{50^2}{2}\right) + 9.81(4) + (2180 \times 10^3)$$
$$\therefore w_{net} = 458801.74\ J/kg$$
$$\therefore w_{net} = 458.801\ kJ/kg$$

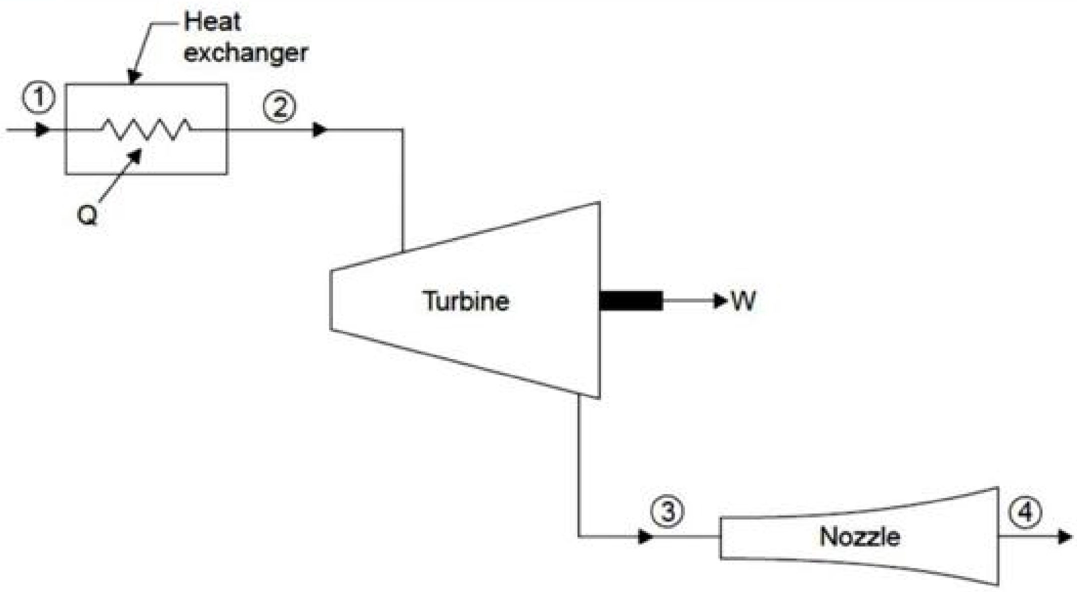
⇨ **Power Developed by the Turbine:**

$$P = \dot{m}_w \times w_{net}$$
$$\therefore P = 1 \times 458.801$$
$$\therefore \boldsymbol{P = 458.801\ kW}$$

Ex 2.2.

Air at a temperature of 15°C passes through a heat exchanger at velocity of 30 m/s, where temperature is raised to 800°C. It then enters a turbine with same velocity of 30m/s and expands until temperature falls to 650°C. On leaving the turbine the air is taken at velocity of 60m/s to a nozzle where it expands until the temperature has fallen to 500°C, If the air flow rate is 2kg/s, calculate (a) rate of heat transfer to air in the heat exchanger, (b) power output from turbine assuming no heat loss and (c) velocity at exit from the nozzle. Assuming no heat loss.

Solution:



Given Data:

$\dot{m}_a = 2\ kg/sec$

$C_1 = C_2 = 30\ m/s$

$T_1 = 15\ °C$

$T_2 = 800\ °C$

$T_3 = 650\ °C$

$C_3 = 60\ m/s$

$T_4 = 500\ °C$

To be Calculated:

a) $\dot{q}_s = ?$

b) $P = ?$

c) $C_4 = ?$

[1] Heat Exchanger

⇨ For H.E.

$$w_{net} = 0$$
$$Z_1 = Z_2\ (Assume)$$

Also,

$$C_1 = C_2\ (Given)$$

⇨ Apply Steady Flow Energy Equation to Heat Exchanger (1 – 2),

$$h_1 + \frac{C_1^2}{2} + gZ_1 + q_{net} = h_2 + \frac{C_2^2}{2} + gZ_2 + w_{net}$$
$$\therefore q_{net} = (h_2 - h_1)$$
$$\therefore q_{net} = C_p(T_2 - T_1)$$
$$\therefore q_{net} = 1.005(800 - 15)$$
$$\therefore q_{net} = 788.925\ kJ/kg$$

⇨ **Rate of Heat transfer:**

$$\dot{q}_{net} = \dot{m}_a \times q_{net}$$
$$\dot{q}_{net} = 2 \times 788.925$$
$$\boldsymbol{\dot{q}_{net} = 1577.85\ kW}$$

[2] Turbine

⇨ For Turbine,

$$q_{net} = 0\ (No\ heat\ loss)$$

$$Z_2 = Z_3\ (Assume)$$

⇨ Apply Steady Flow Energy Equation to Turbine (2 – 3),

$$h_2 + \frac{C_2^2}{2} + gZ_2 + q_{net} = h_3 + \frac{C_3^2}{2} + gZ_3 + w_{net}$$

$$\therefore w_{net} = (h_2 - h_3) + \left(\frac{C_2^2}{2} - \frac{C_3^2}{2}\right)$$

$$\therefore w_{net} = C_p(T_2 - T_3) + \left(\frac{C_2^2}{2} - \frac{C_3^2}{2}\right)$$

$$\therefore w_{net} = 1.005 \times 10^3 \times (800 - 650) + \left(\frac{30^2}{2} - \frac{60^2}{2}\right)$$

$$\therefore w_{net} = 149400\ J/kg$$

⇨ **Power Output from Turbine:**

$$P = \dot{m}_a \times w_{net}$$
$$P = 2 \times 149400$$
$$\boldsymbol{P = 298800\ W}$$

[3] Nozzle

⇨ For Nozzle.

$$w_{net} = 0$$
$$Z_1 = Z_2\ (Assume\ that\ nozzle\ is\ horizontal)$$
$$q_{net} = 0\ (No\ heat\ loss)$$

⇨ Apply Steady Flow Energy Equation to Nozzle (3 – 4),

$$h_3 + \frac{C_3^2}{2} + gZ_3 + q_{net} = h_4 + \frac{C_4^2}{2} + gZ_4 + w_{net}$$

$$\therefore \frac{C_4^2}{2} = (h_3 - h_4) + \frac{C_3^2}{2}$$

$$\therefore \frac{C_4^2}{2} = C_p(T_3 - T_4) + \frac{C_3^2}{2}$$

$$\therefore \frac{C_4^2}{2} = 1.005 \times 10^3 \times (650 - 500) + \frac{60^2}{2}$$

$$\therefore \frac{C_4^2}{2} = 152550$$

$$\therefore \boldsymbol{C_4 = 552.358\ m/sec}$$

2.10 References

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4. Thermal Science and Engineering by D. S. Kumar, S K Kataria and Sons Publications.
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