

FCME006

Basics of Mechanical Engineering

UNIT-IV Introduction to Thermodynamics

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Introduction to Thermodynamics

- Thermodynamic system, Cycle, Path, Thermodynamic properties, Extensive and intensive properties, Thermodynamic equilibrium, Reversible and irreversible processes, isochoric, Isothermal, Isobaric, Isentropic and Polytropic processes, First law of thermodynamics applied to a cycle and process, Kelvin-Planck and Clausius statements of Second law of thermodynamics, Carnot cycle, Entropy, Clausius inequality, Internal combustion (IC) engines, IC engines terminology, Spark ignition (SI) and Compression ignition (CI) engines, Two and four stroke engines, Air standard cycles such as Otto, Diesel, Dual and Brayton cycles, Numerical problems

Introduction

- ❖ ***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.***

THERMODYNAMICS AND ENERGY

- **Thermodynamics:** The science of *energy*.
- **Energy:** The ability to cause changes.
- The name *thermodynamics* stems from the Greek words *therme* (heat) and *dynamis* (power).
- **Conservation of energy principle:** During an interaction, energy can change from one form to another but the total amount of energy remains constant.
- Energy cannot be created or destroyed.
- **The first law of thermodynamics:** An expression of the conservation of energy principle.
- The first law asserts that *energy* is a thermodynamic property.

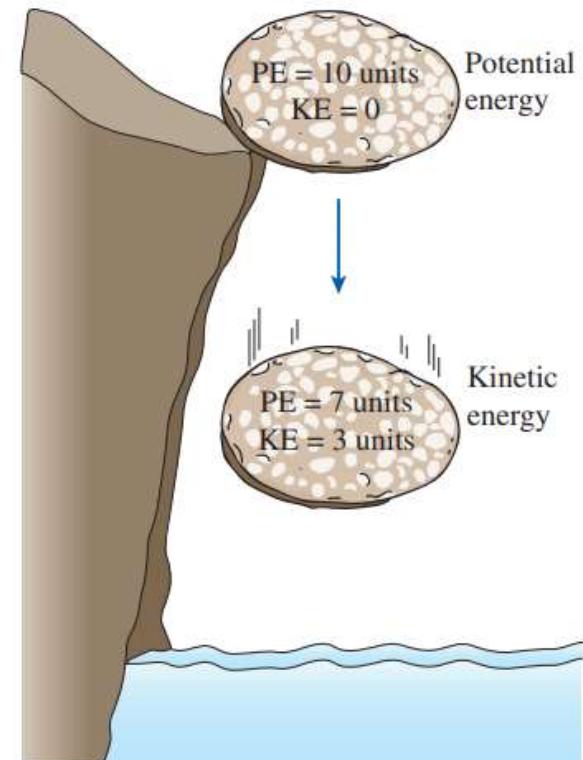


FIGURE Energy cannot be created or destroyed; it can only change forms (the first law).

- **The second law of thermodynamics:** It asserts that energy has *quality* as well as *quantity*, and actual processes occur in the direction of decreasing quality of energy.
- A person who has a greater energy input (food) than energy output (exercise) will gain weight (store energy in the form of fat), and a person who has a smaller energy input than output will lose weight
- **Classical thermodynamics:** A macroscopic approach to the study of thermodynamics that does not require a knowledge of the behavior of individual particles.
- It provides a direct and easy way to the solution of engineering problems and it is used in this text.
- **Statistical thermodynamics:** A microscopic approach, based on the average behavior of large groups of individual particles.
- It is used in this text only in the supporting role.

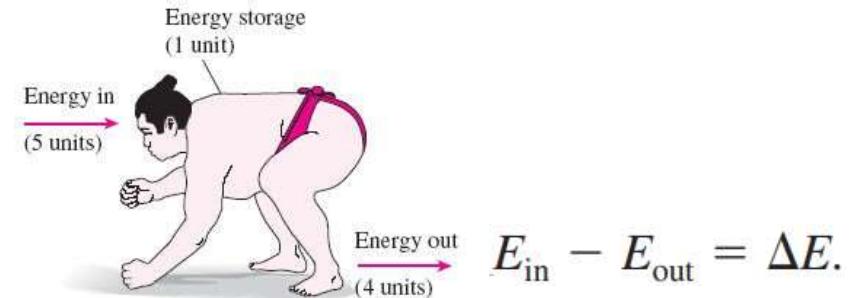


FIGURE 1–2
Conservation of energy principle
for the human body.



FIGURE 1–3
Heat flows in the direction
of decreasing temperature.

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.

Application Areas of Thermodynamics

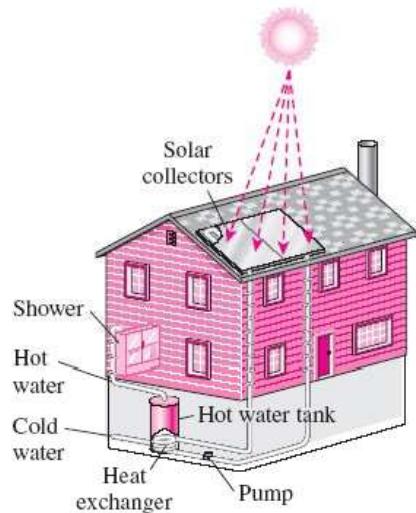


FIGURE 1-4

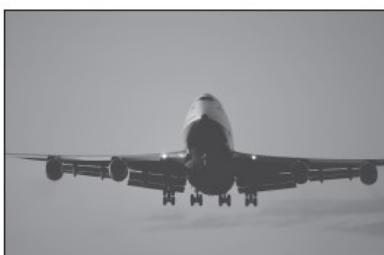
The design of many engineering systems, such as this solar hot water system, involves thermodynamics.



Refrigeration systems



Boats



Aircraft and spacecraft



Power plants

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.



Refrigerator

© McGraw-Hill Education, Jill Braaten



Boats

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Aircraft and spacecraft

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Power plants

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Human body

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Cars

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Wind turbines

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Food processing

Glow Images RF

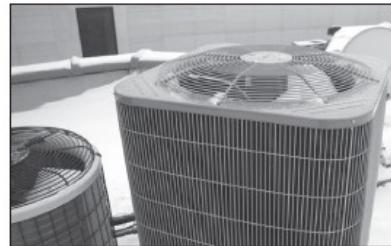


A piping network in an industrial facility.

Courtesy of UMDE Engineering Contracting and Trading. Used by permission



Wind turbines



Air conditioning systems



Industrial applications



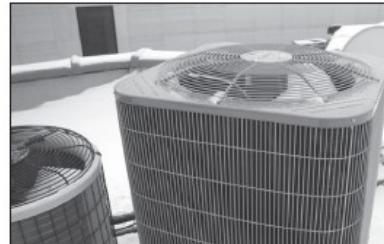
Human body



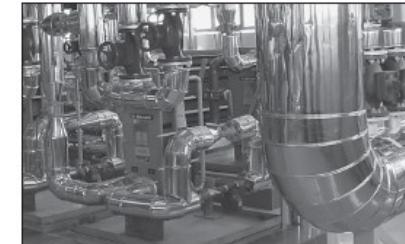
Cars



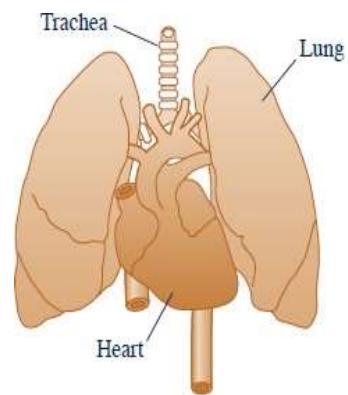
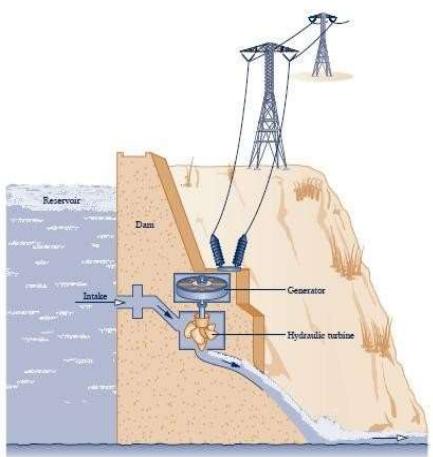
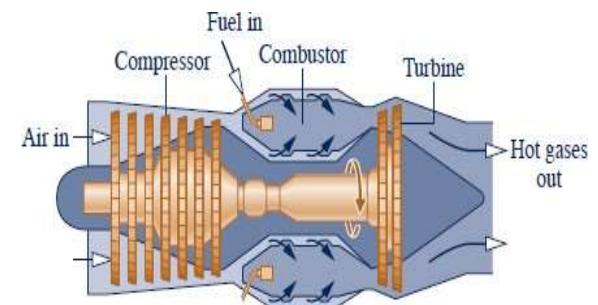
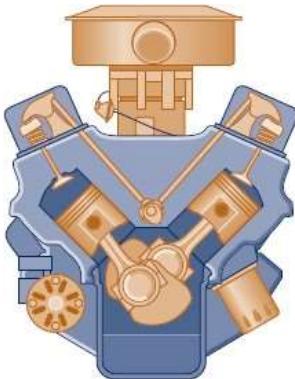
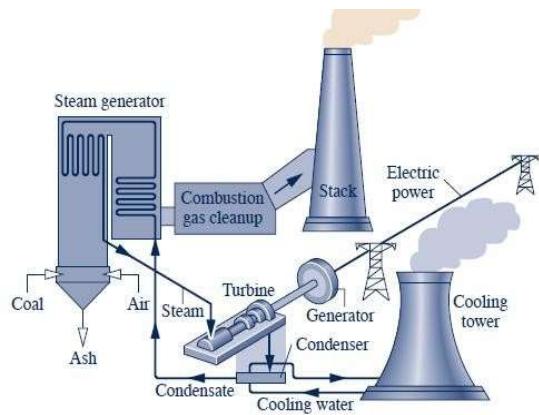
Wind turbines



Air conditioning systems



Industrial applications



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.
- ❖ 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.

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.

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

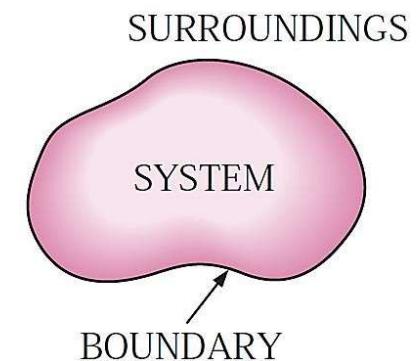
“It is the matter or region outside the system”

Boundary

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

Types of boundary

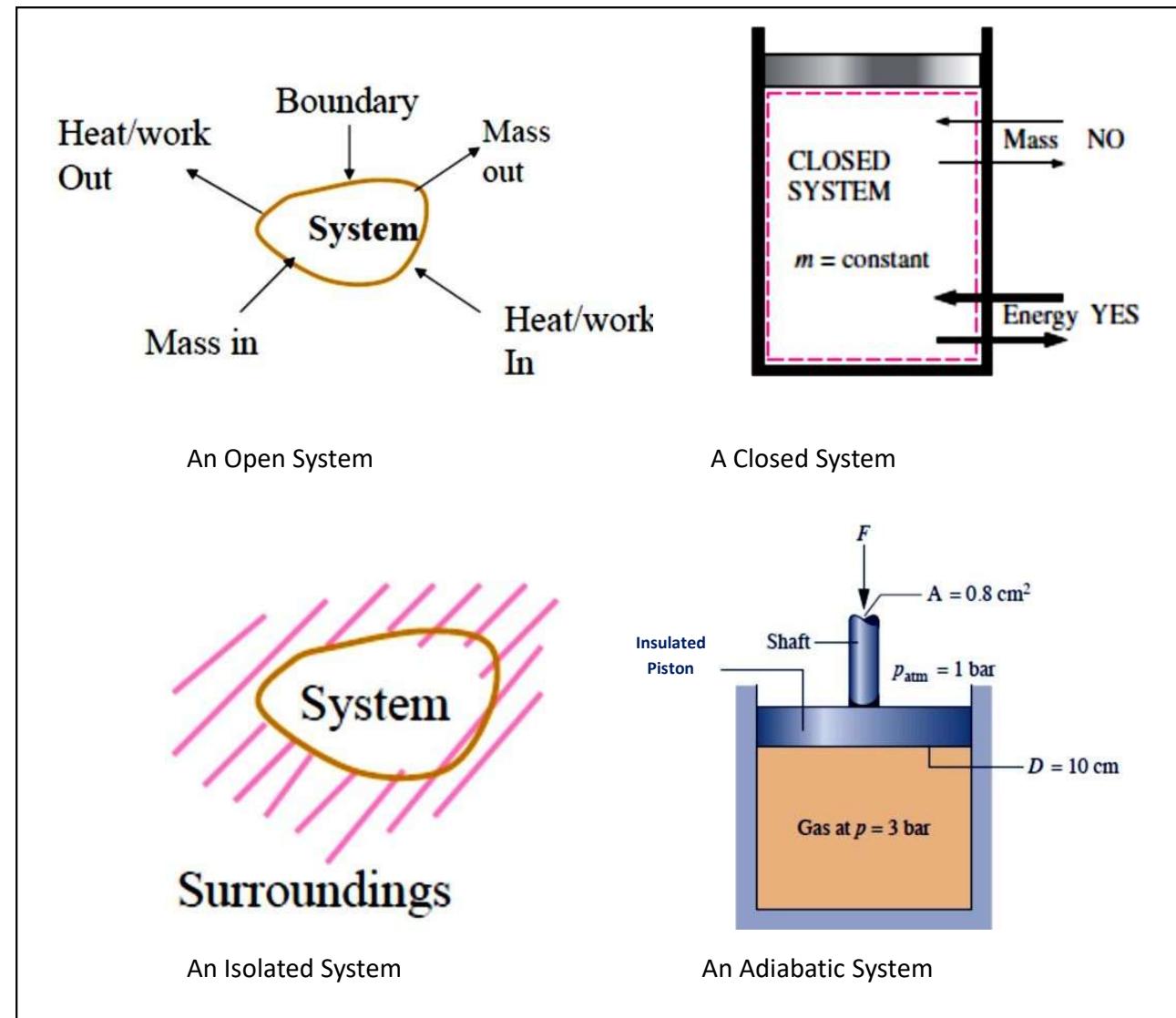
- Fixed or moving boundary
- Real or imaginary boundary



•Fig. 1.2 System, Surroundings and Boundary

System + Surrounding = Universe

Types of Thermodynamic System



Open System and Closed 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.

Isolated Systems and Adiabatic System

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.

Homogeneous and Heterogeneous System

E. Homogeneous & Heterogeneous

Homogeneous System

- ❖ “A system which consists of a single phase is termed as homogeneous system.”
- ❖ Examples:
 - ❖ Mixture of air and water vapor
 - ❖ Water + Nitric acid

Heterogeneous System

- ❖ “A system which consists of two or more phases is called a heterogeneous system.”

Examples:

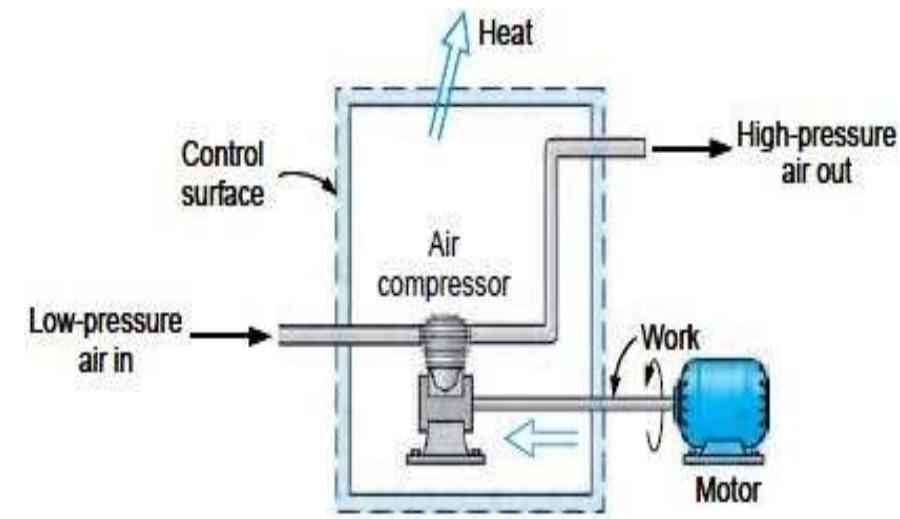
- ❖ Water + Steam
- ❖ Ice + Water
- ❖ Water + Oil

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. 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.

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.



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.*

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 ($v = V/m$)
and specific total energy ($e = E/m$)

❖ 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.

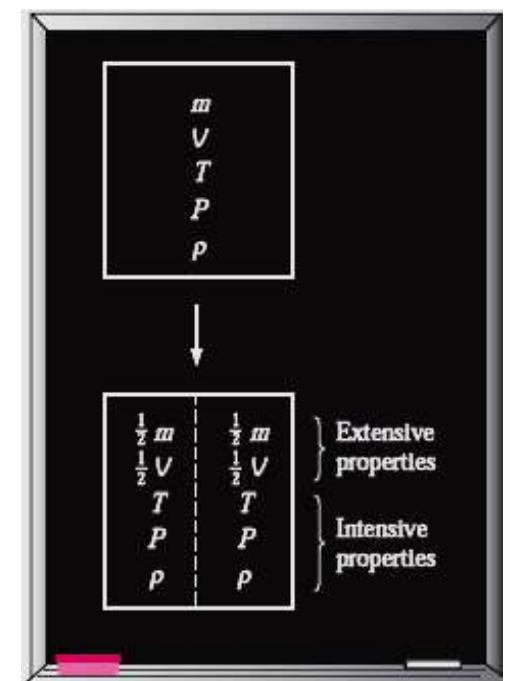


Fig. Criterion to differentiate intensive and extensive properties

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.

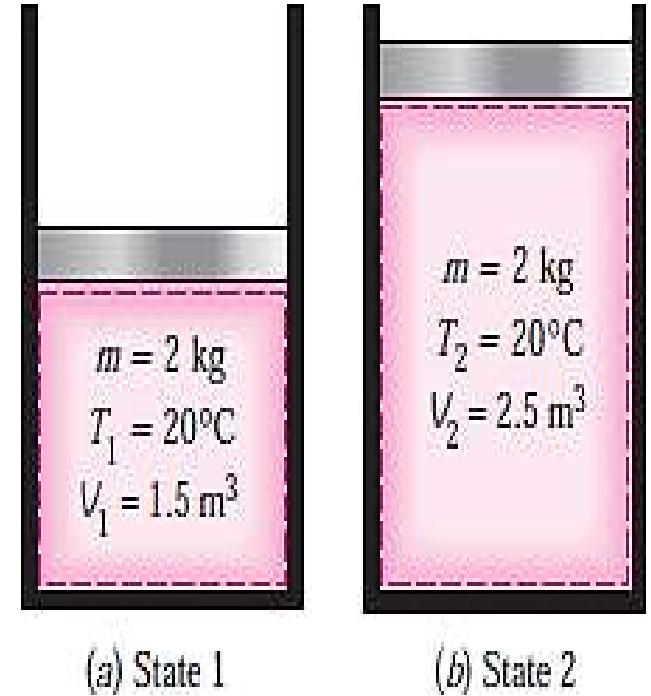


Fig. A system at two different states

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.

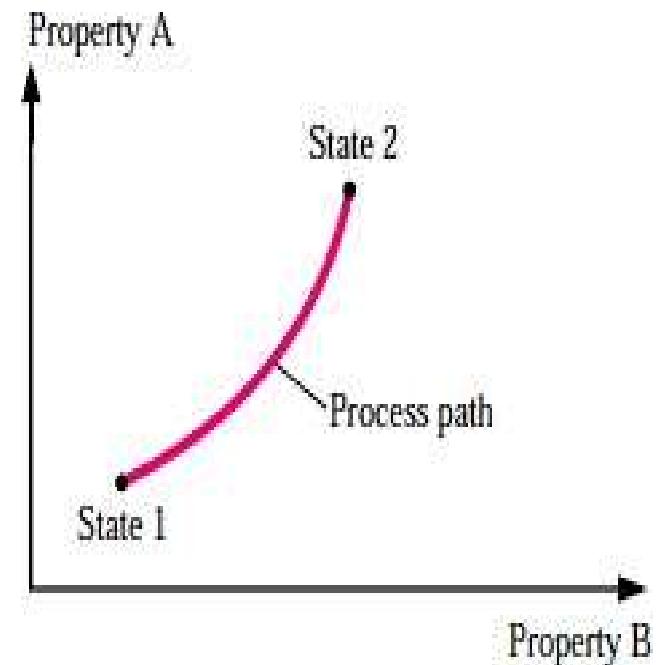


Fig. A process between states 1 and 2 and a process path

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.

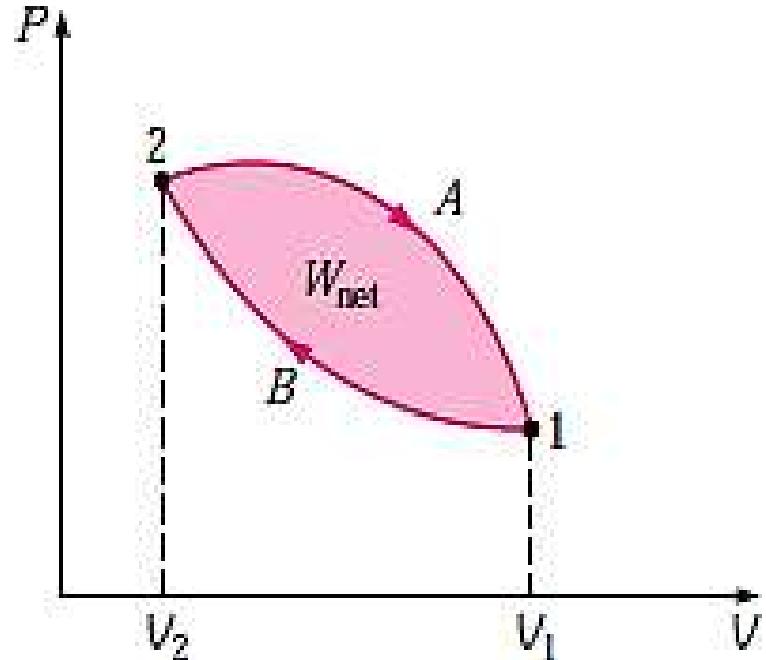


Fig. Cycle of operations

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 (Coordinate 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.

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

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

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.

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.(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 .
- 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.”

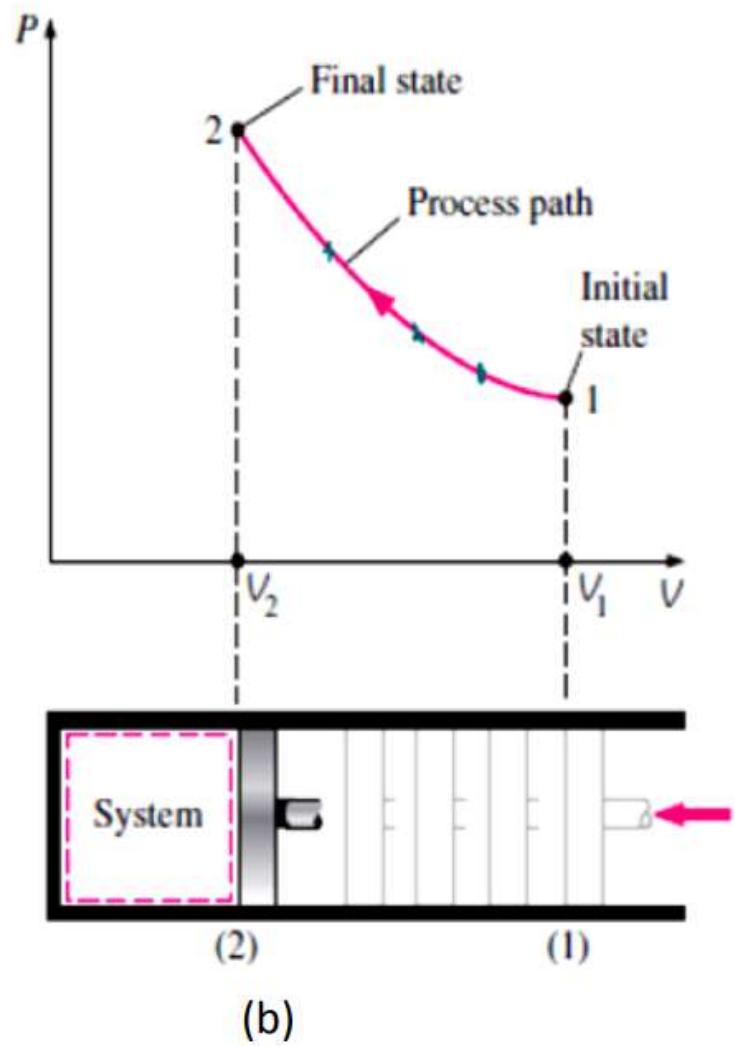
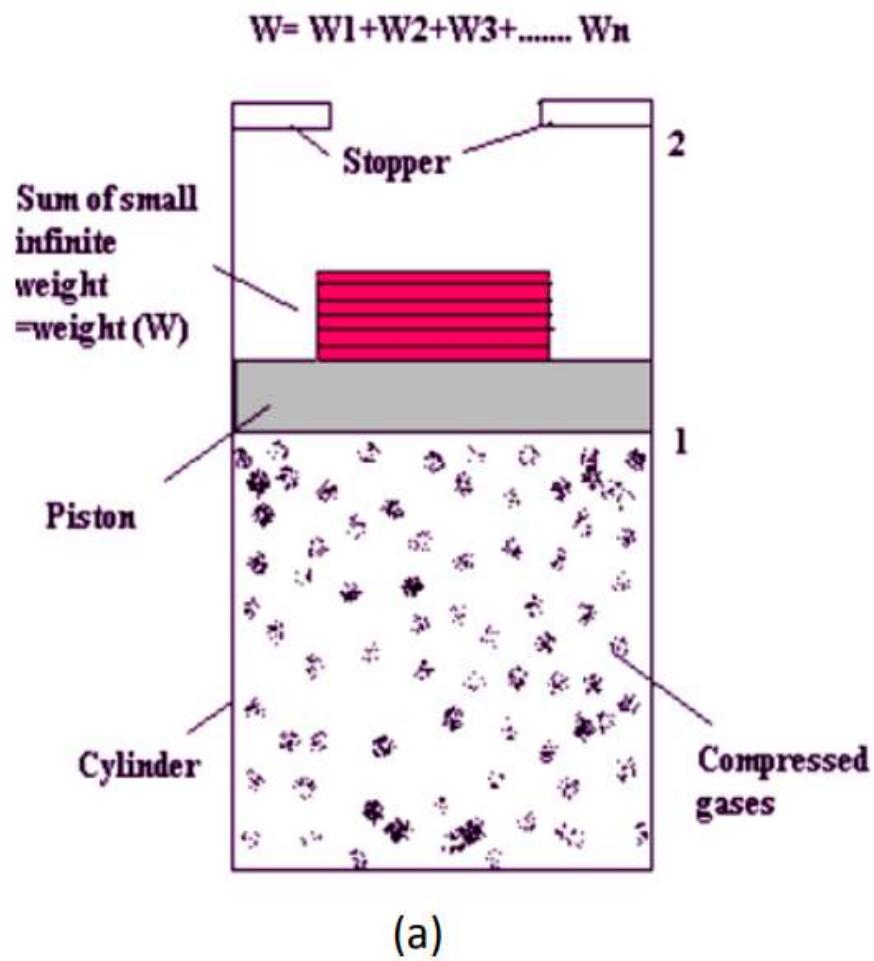


Fig. (a) Quasi-Static Process (b) p-v diagram of a compression process

- 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.
- Fig. (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.

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 conventions for heat and work energy are shown in Fig.
 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**.

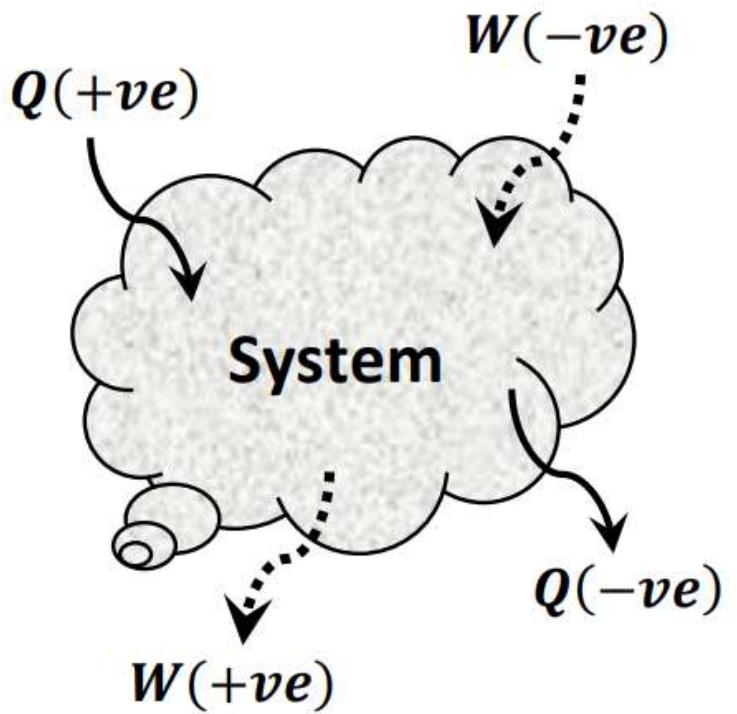


Fig. Sign convention
for heat & work

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 the transfer of heat.
3. The sole effect external to the system could be reduced to rise of a weight but in the case of 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

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 / $p dV$ - 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.

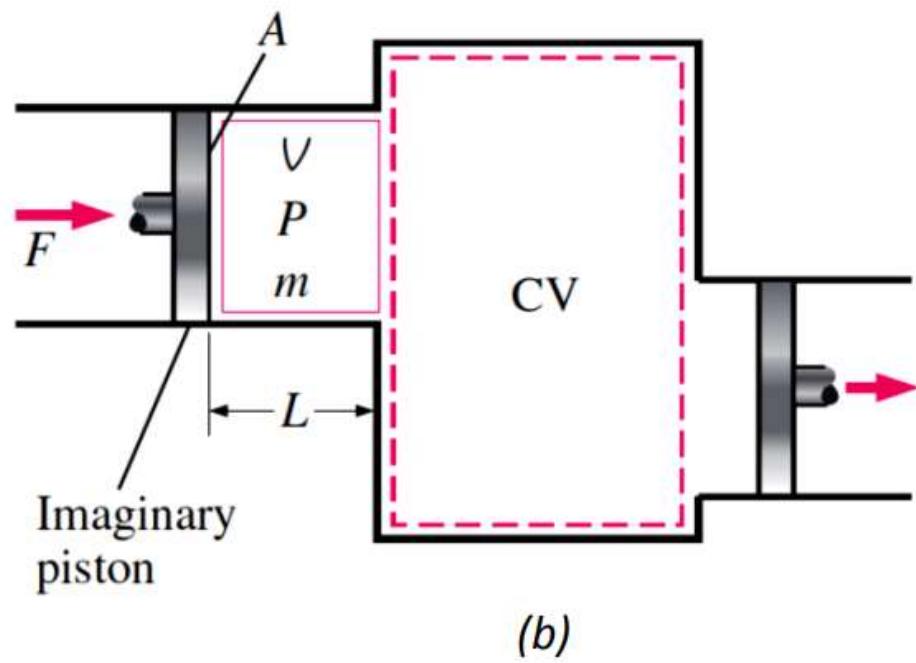
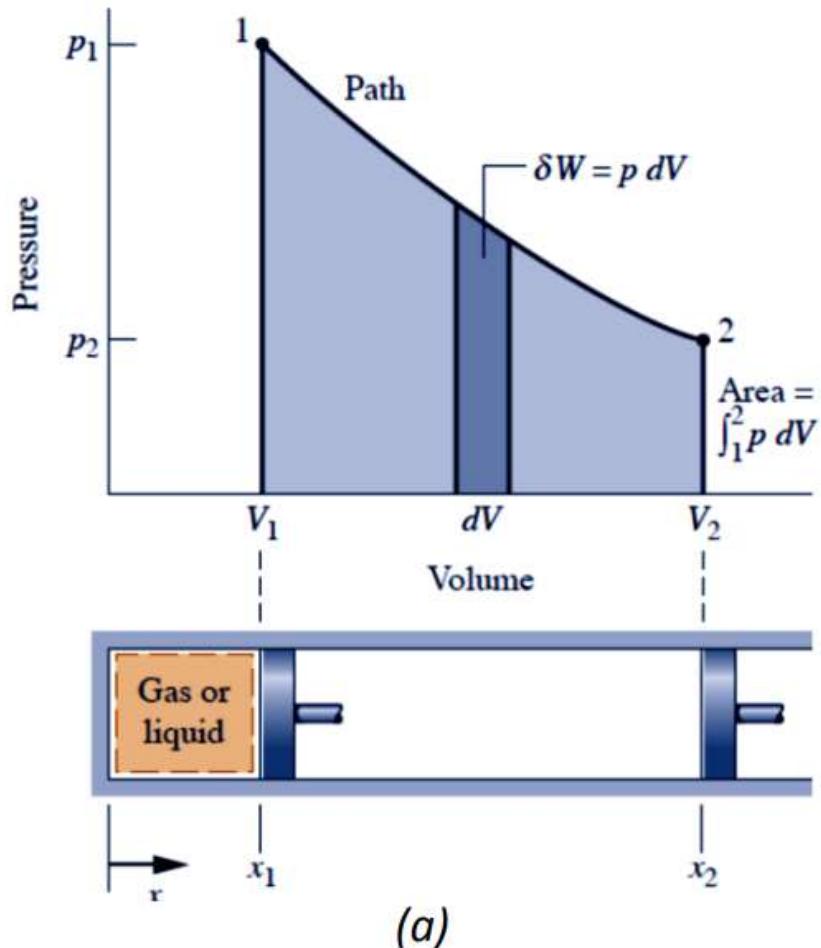


Fig. (a) Displacement work and (b) Flow work

- 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 an 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,

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

- 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,

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

or

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

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

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. (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 im

$$F = p \times A$$

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, $W_{f2} = p_2 V_2$

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.

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.

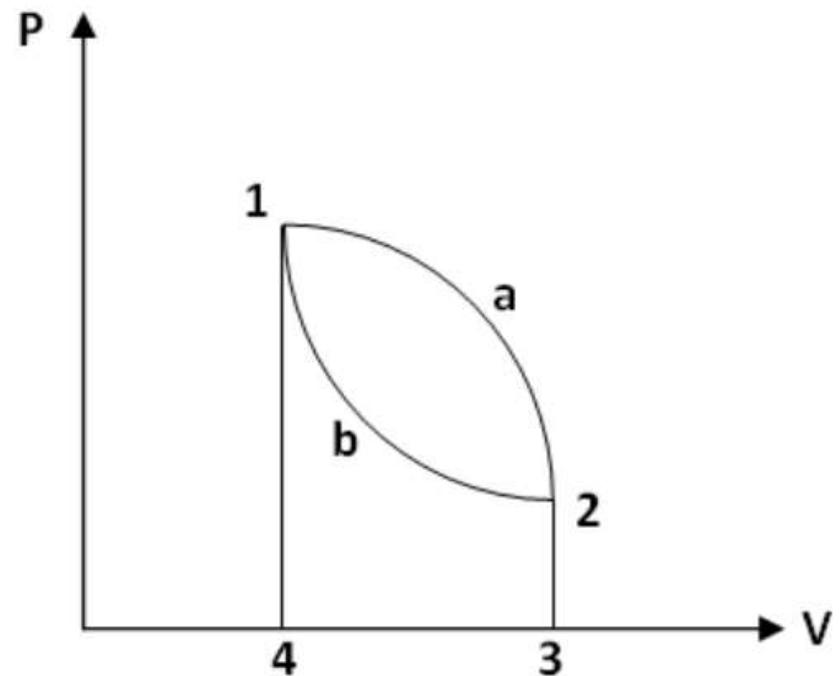


Fig. Cyclic process

- 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,

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

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,

$$\Delta E = Q - W$$

Where,

$\Delta E = \Delta U + \Delta KE + \Delta PE + \text{other forms of energy}$ = 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.

$$\therefore Q - W = \Delta U$$

- 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 nonflow systems and the first law of thermodynamics is reduced to equation.
- In differential form first law of thermodynamics for a process can be written as

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

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

$$Q - W = 0$$

$$\therefore Q = W$$

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.:
(i) 2-B-1 (ii) 2-C-1 (iii) 2-D-1

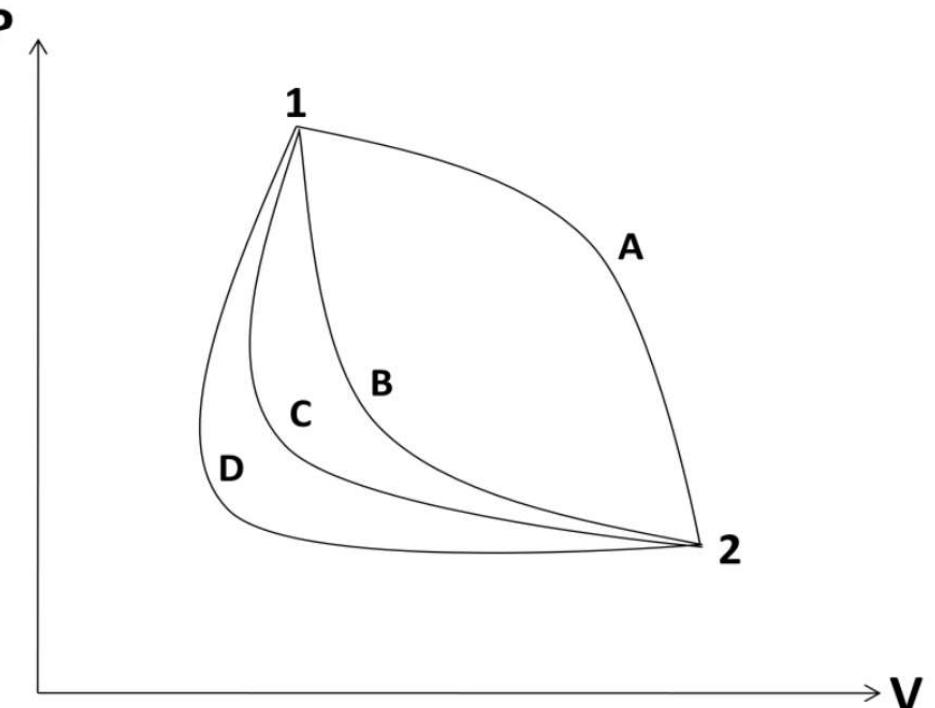


Fig. Cyclic process with different paths

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

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

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

Similarly,

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

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

And,

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

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

- Comparing equations we get,

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

- 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 $(e = \frac{E}{m})$ is an intensive property.

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,

$$\dot{m} = \frac{AC}{v}$$

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,

$$\text{Specific volume} = \frac{1}{\text{Density}}$$
$$\therefore v = \frac{1}{\rho}$$

Equation can be expressed as,

$$\dot{m} = \rho AC$$

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

$$Q = AC$$

- For a **steady flow**,

$$\dot{m} = \text{Constant} = \rho_1 A_1 C_1 = \rho_2 A_2 C_2$$

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.

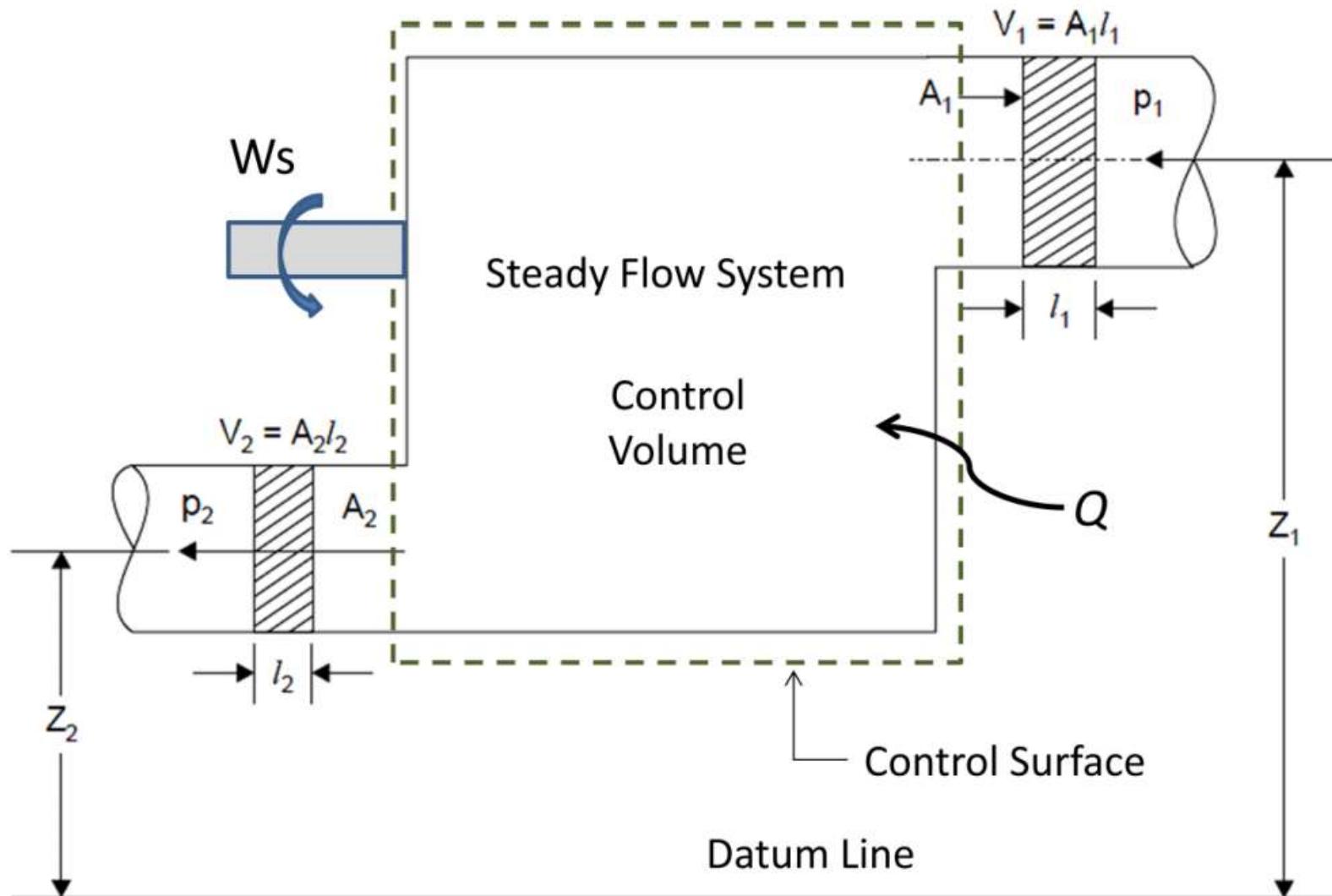


Fig. Schematic flow process for an open system

- Consider a flow of fluid through an open system as shown in Fig.
- 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 = $\frac{1}{2} m C^2$
- C. Potential energy = mgZ
- D. Flow work = $P_1 V_1$
- 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,

$$m_1 \left(u_1 + P_1 v_1 + \frac{C_1^2}{2} + g Z_1 \right) + Q = m_2 \left(u_2 + P_2 v_2 + \frac{C_2^2}{2} + g Z_2 \right) + W_s$$

- Equation 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:**

$$h_1 + \frac{C_1^2}{2} + gZ_1 + q = h_2 + \frac{C_2^2}{2} + gZ_2 + w_s$$

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

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. Nozzle and diffuser
 2. Heat Exchangers
 3. Steam or Gas turbines
 4. Hydraulic turbine
 5. Centrifugal water pump
 6. Reciprocating compressor
 7. Rotary compressor
 8. Throttling process

PERPETUAL MOTION MACHINE OF THE FIRST KIND—PMM 1

- The first law of thermodynamics states the general principle of the conservation of energy. Energy is neither created nor destroyed, but only gets transformed from one form to another. There can be no machine which would continuously supply mechanical work without some form of energy disappearing simultaneously (Fig.). Such a fictitious machine is called a perpetual motion machine of the first kind, or in brief, PMM 1. A PMM 1 is thus impossible.

The converse of the above statement is also true, i.e., there can be no machine which would continuously consume work without some other form of energy appearing simultaneously

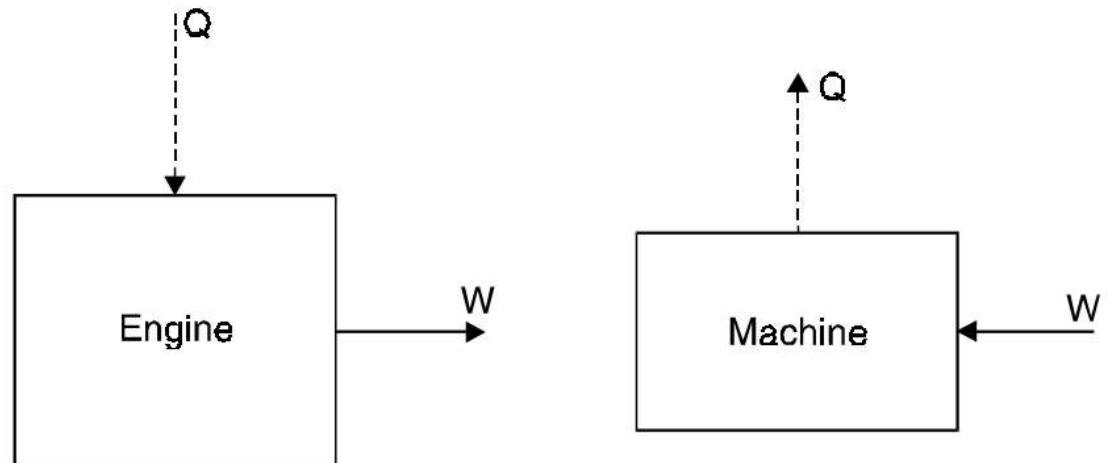


Fig. A PMM 1.

Fig. The converse of PMM 1.

ENERGY OF AN ISOLATED SYSTEM

An isolated system is one in which there is no interaction of the system with the surroundings.

For an isolated system,

$$dQ = 0, \quad dW = 0$$

The first law of thermodynamics gives

$$dE = 0$$

$$E = \text{constant}$$

or

The energy of an isolated system is always constant.

THE PERFECT GAS

The Characteristic Equation of State

- At temperatures that are considerably in excess of critical temperature of a fluid, and also at very low pressure, the vapour of fluid tends to obey the equation

$$\frac{pv}{T} = \text{constant} = R$$

- In practice, no gas obeys this law rigidly, but many gases tend towards it. An imaginary ideal gas which obeys this law is called a **perfect gas**, and the equation

$$\frac{pv}{T} = R,$$

is called the **characteristic equation of a state of a perfect gas**.

- The constant R is called the gas constant.
- Each perfect gas has a different gas constant.

Units of R are Nm/kg K or kJ/kg K.

Usually, the characteristic equation is written as

$$pv = RT$$

or for m kg, occupying V m³

$$pV = mRT$$

Specific Heat

- The specific heat of a solid or liquid is usually defined as the heat required to raise unit mass through one degree temperature rise.

For small quantities, we have

$$dQ = mcdT$$

where m = mass,

c = specific heat, and

dT = temperature rise.

- For a gas there are an infinite number of ways in which heat may be added between any two temperatures, and hence a gas could have an infinite number of specific heats. However, only two specific heats for gases are defined.

Specific heat at constant volume, c_v

and,

Specific heat at constant pressure, c_p .

We have

$dQ = m c_p dT$ For a reversible non-flow process at *constant pressure*

and,

$dQ = m c_v dT$ For a reversible non-flow process at *constant volume*

The values of c_p and c_v , for a perfect gas, are constant for any one gas at all pressures and temperatures. Hence, integrating eqns. we have

Flow of heat in a reversible constant pressure process

$$= mc_p (T_2 - T_1)$$

Flow of heat in a reversible constant volume process

$$= mc_v (T_2 - T_1)$$

In case of *real gases*, c_p and c_v vary with temperature, but a suitable *average value* may be used for most practical purposes.

For Air (Perfect Gas)

$$R = 0.287 \text{ KJ/kg} - \text{k}$$

$$C_p = 1.005 \text{ KJ/kg} - \text{k}$$

$$C_v = 0.718 \text{ KJ/kg} - \text{k}$$

$$\gamma = 1.4$$

Relationship between R , C_p , C_v and γ

$$R = C_p - C_v$$

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

Enthalpy

- One of the fundamental quantities which occur invariably in thermodynamics is the sum of internal energy (u) and pressure volume product (pv). This sum is called **Enthalpy** (h).

i.e.,

$$h = u + pv$$

- The enthalpy of a fluid is the property of the fluid, since it consists of the sum of a property and the product of the two properties. Since enthalpy is a property like internal energy, pressure, specific volume and temperature, it can be introduced into any problem whether the process is a flow or a non-flow process.

The total enthalpy of mass, m , of a fluid can be

$$H = U + pV, \text{ where } H = mh.$$

For a **perfect gas**,

Referring equation

$$h = u + pv$$

APPLICATION OF FIRST LAW OF THERMODYNAMICS TO NON-FLOW OR CLOSED SYSTEM

1. Reversible Constant Volume (or Isochoric) Process ($v = \text{constant}$)
2. Reversible Constant Pressure (or Isobaric) Process ($p = \text{constant}$)
3. Reversible Temperature (or Isothermal) Process ($pv = \text{constant}$, $T = \text{constant}$)
4. Reversible Adiabatic Process $pv^\gamma = \text{constant}$
5. Polytropic Reversible Process ($pvn = \text{constant}$)

Reversible Constant Volume (or Isochoric) Process ($v = \text{constant}$)

- In a constant volume process the working substance is contained in a rigid vessel, hence the boundaries of the system are immovable and no work can be done on or by the system, other than paddle-wheel work input. It will be assumed that 'constant volume' implies zero work unless stated otherwise.

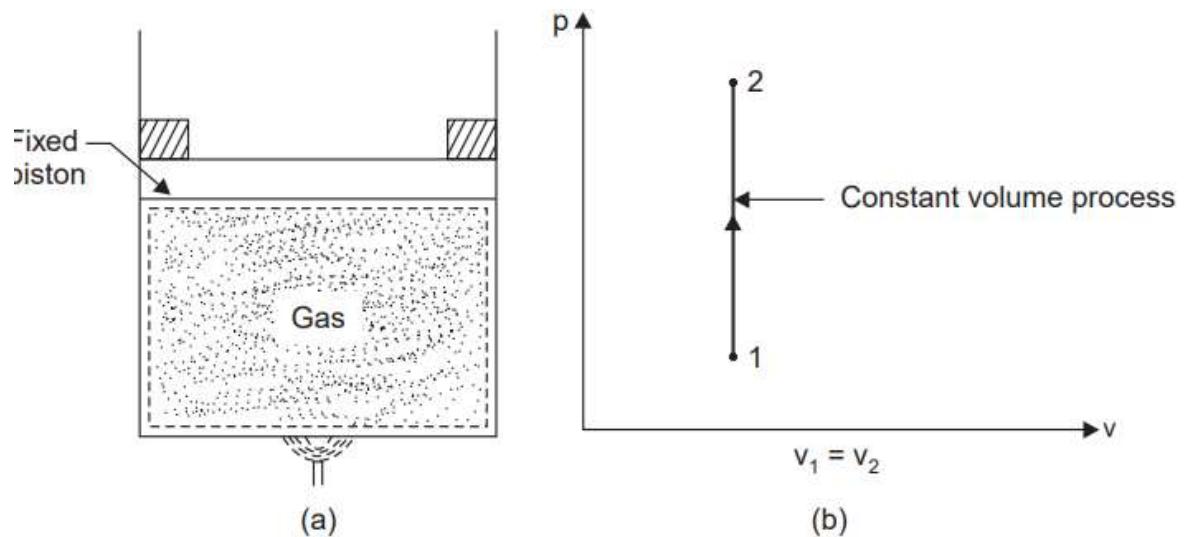


Fig. Reversible constant volume process.

Considering mass of the working substance *unity* and applying first law of thermodynamics to the process

$$Q = (u_2 - u_1) + W$$

The work done $W = \int_1^2 pdv = 0$ as $dv = 0$.

$$\therefore Q = (u_2 - u_1) = c_v(T_2 - T_1)$$

where c_v = Specific heat at constant volume.

For mass, m , of working substance

$$Q = U_2 - U_1 = mc_v(T_2 - T_1)$$

$$[\because mu = U]$$

Reversible Constant Pressure (or Isobaric) Process ($p = \text{constant}$)

- It can be seen from Fig. (b) that when the boundary of the system is inflexible as in a constant volume process, then the pressure rises when heat is supplied.
- Hence for a constant pressure process, the boundary must move against an external resistance as heat is supplied ; for instance a gas [Fig. (a)] in a cylinder behind a piston can be made to undergo a constant pressure process.
- Since the piston is pushed through a certain distance by the force exerted by the gas, then the work is done by the gas on its surroundings.

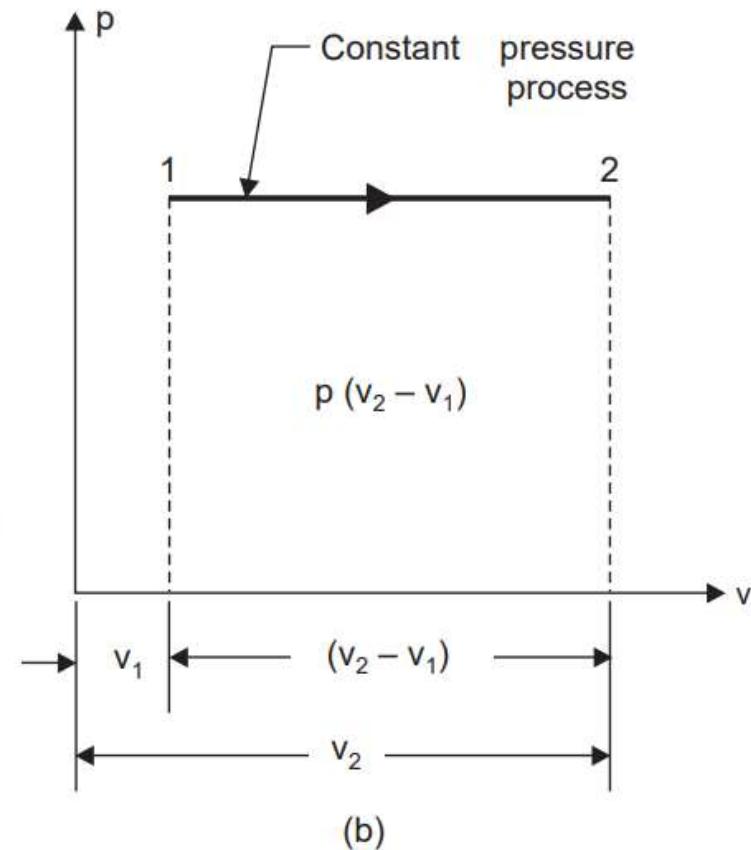
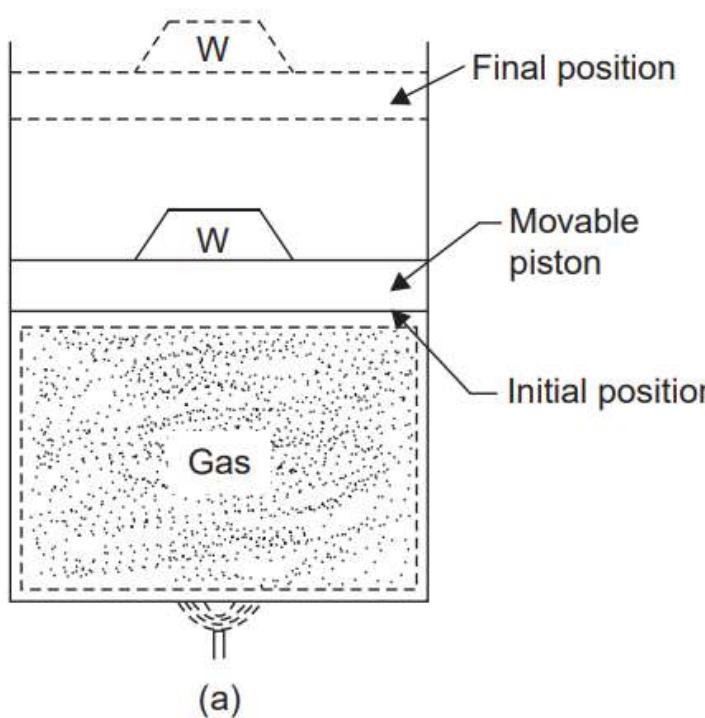


Fig. Reversible constant pressure process.

Considering unit mass of working substance and applying first law of thermodynamics to the process

$$Q = (u_2 - u_1) + W$$

The work done, $W = \int_1^2 pdv = p(v_2 - v_1)$

$$\therefore Q = (u_2 - u_1) + p(v_2 - v_1) = u_2 - u_1 + pv_2 - pv_1$$

$$= (u_2 + pv_2) - (u_1 + pv_1) = h_2 - h_1$$

[$\because h = u + pv$]

or

$$Q = h_2 - h_1 = c_p (T_2 - T_1)$$

where h = Enthalpy (specific), and

c_p = Specific heat at constant pressure.

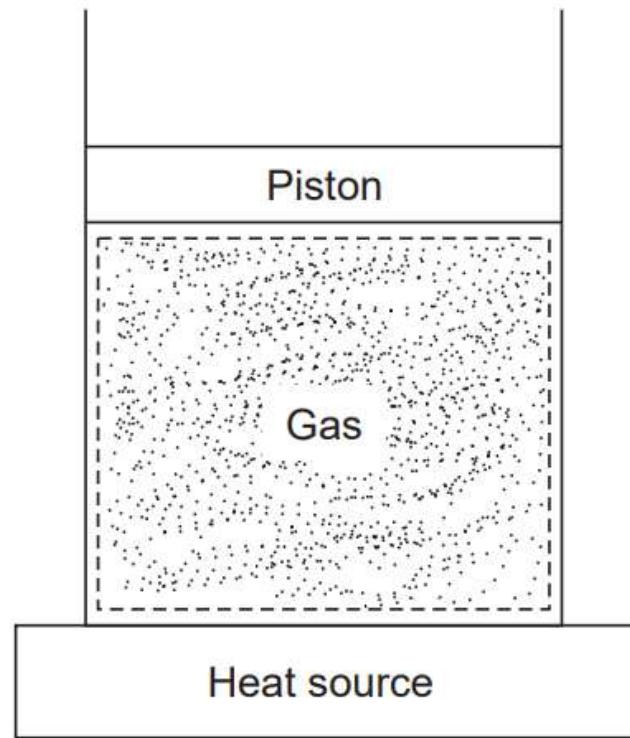
For mass, m , of working substance

$$Q = H_2 - H_1 = mc_p (T_2 - T_1)$$

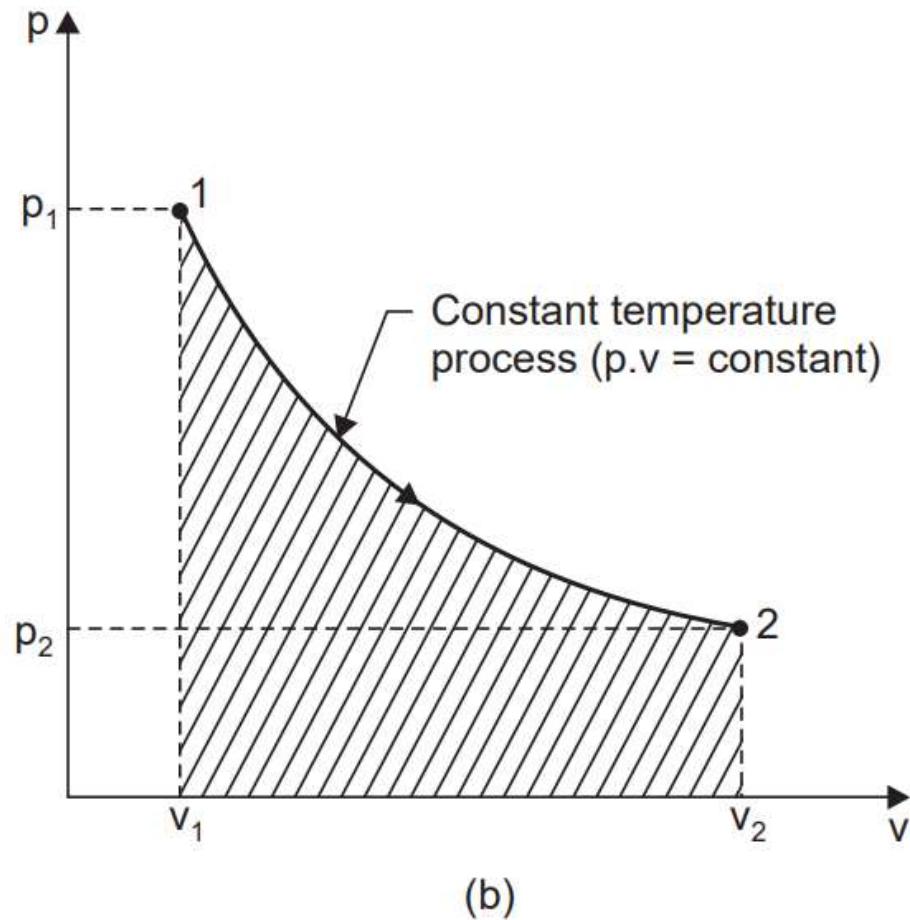
[$\because mh = H$]

Reversible Temperature (or Isothermal) Process ($pV = \text{constant}$, $T = \text{constant}$)

- A process at a constant temperature is called an isothermal process. When a working substance in a cylinder behind a piston expands from a high pressure to a low pressure there is a tendency for the temperature to fall. In an isothermal expansion heat must be added continuously in order to keep the temperature at the initial value. Similarly in an isothermal compression heat must be removed from the working substance continuously during the process.



(a)



(b)

Fig. Reversible isothermal process.

Considering unit mass of working substance and applying first law to the process

$$\begin{aligned} Q &= (u_2 - u_1) + W \\ &= c_v (T_2 - T_1) + W \\ &= 0 + W \quad [\because T_2 = T_1] \end{aligned}$$

The work done, $W = \int_1^2 pdv$

In this case $pv = \text{constant}$ or $p = \frac{C}{v}$ (where $C = \text{constant}$)

$$\therefore W = \int_{v_1}^{v_2} C \frac{dv}{v} = C \left[\log_e v \right]_{v_1}^{v_2} = C \log_e \frac{v_2}{v_1}$$

The constant C can either be written as p_1v_1 or as p_2v_2 , since

$$p_1v_1 = p_2v_2 = \text{constant}, C$$

i.e.,

$$W = p_1v_1 \log_e \frac{v_2}{v_1} \text{ per unit mass of working substance}$$

or

$$W = p_2v_2 \log_e \frac{v_2}{v_1} \text{ per unit mass of working substance}$$

∴

$$Q = W = p_1v_1 \log_e \frac{v_2}{v_1}$$

For mass, m , of the working substance

$$Q = p_1V_1 \log_e \frac{V_2}{V_1}$$

or

$$Q = p_1V_1 \log_e \frac{p_1}{p_2} \quad \left[\because \frac{V_2}{V_1} = \frac{p_1}{p_2} \right]$$

Reversible Adiabatic Process $(pv^\gamma) = \text{constant}$

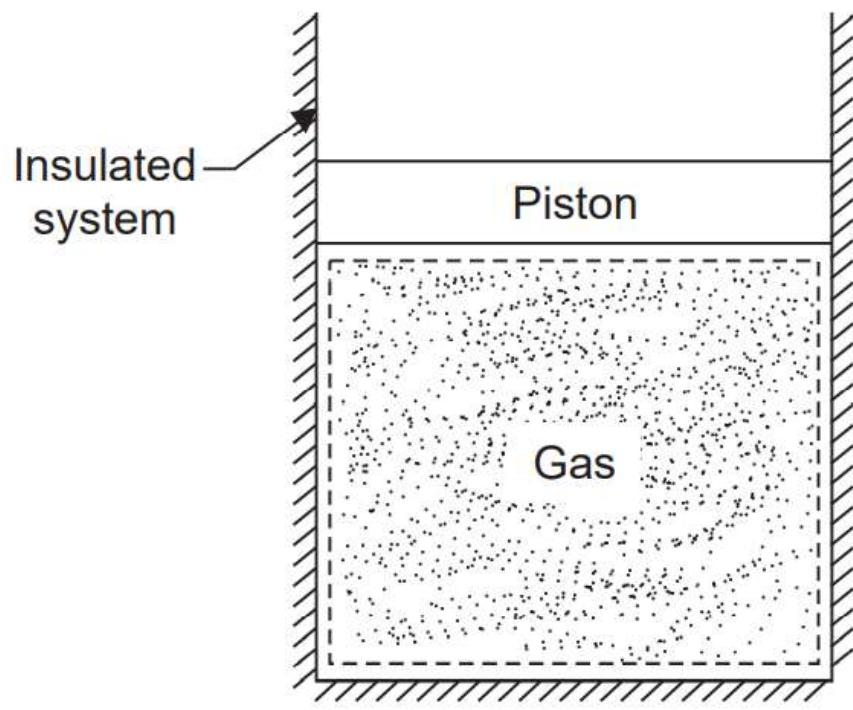
- An adiabatic process is one in which no heat is transferred to or from the fluid during the process. Such a process can be reversible or irreversible. The reversible adiabatic non-flow process will be considered in this section. Considering unit mass of working substance and applying first law to the process

$$Q = (u_2 - u_1) + W$$

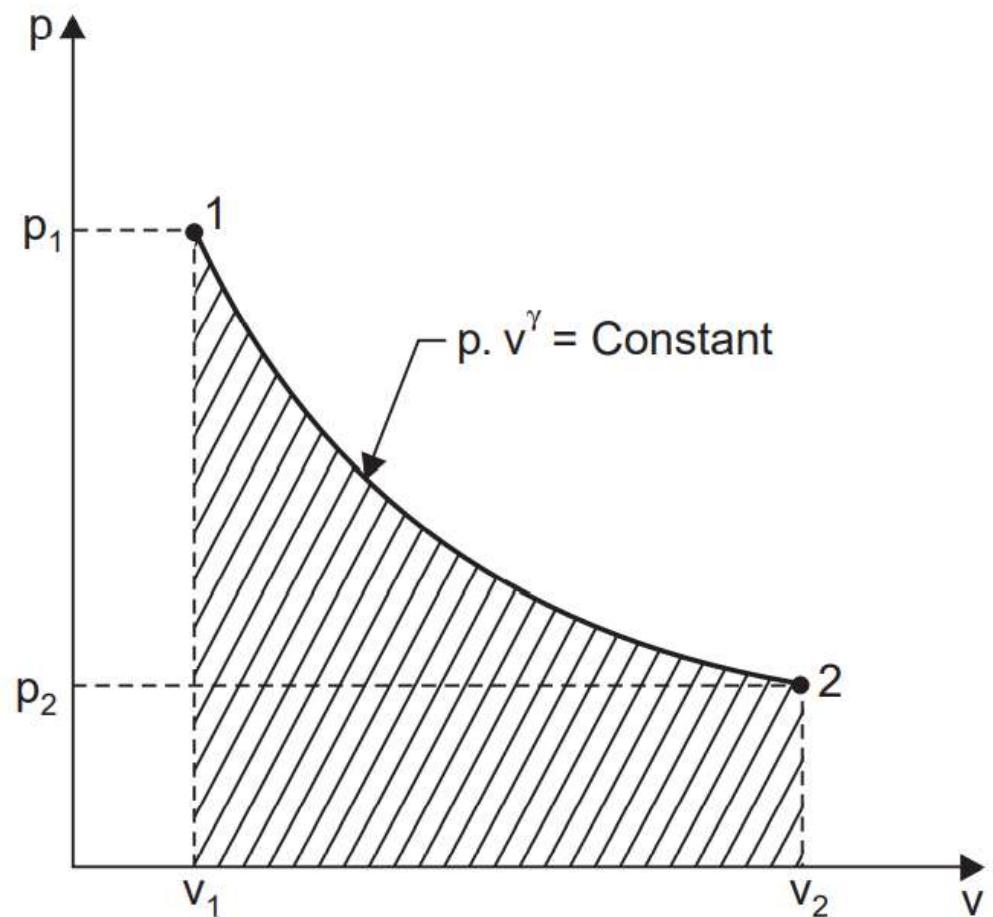
$$Q = 0 + W$$

$$W = (u_1 - u_2) \text{ for any adiabatic process}$$

- The above eqn. is true for an adiabatic process whether the process is reversible or not. In an adiabatic expansion, the work done W by the fluid is at the expense of a reduction in the internal energy of the fluid. Similarly in an adiabatic compression process all the work done on the fluid goes to increase the internal energy of the fluid.



(a)



(b)

Fig. Reversible adiabatic process.

i.e.,

$$W = \int_{v_1}^{v_2} p \, dv$$

Therefore, since $pv^\gamma = \text{constant}$, C , then

$$W = \int_{v_1}^{v_2} C \frac{dv}{v^\gamma}$$

$$\left[\because p = \frac{C}{v^\gamma} \right]$$

i.e.,

$$W = C \int_{v_1}^{v_2} \frac{dv}{v^\gamma} = C \left| \frac{v^{-\gamma+1}}{-\gamma+1} \right|_{v_1}^{v_2}$$

$$= C \left(\frac{v_2^{-\gamma+1} - v_1^{-\gamma+1}}{1-\gamma} \right) = C \left(\frac{v_1^{-\gamma+1} - v_2^{-\gamma+1}}{\gamma-1} \right)$$

The constant in this equation can be written as $p_1 v_1^\gamma$ or as $p_2 v_2^\gamma$. Hence,

$$W = \frac{p_1 v_1^\gamma v_1^{-\gamma+1} - p_2 v_2^\gamma v_2^{-\gamma+1}}{\gamma-1} = \frac{p_1 v_1 - p_2 v_2}{\gamma-1}$$

i.e.,

$$W = \frac{p_1 v_1 - p_2 v_2}{\gamma-1}$$

or

$$W = \frac{R(T_1 - T_2)}{\gamma-1}$$

By using equation $pv = RT$, the relationship between T and v , and T and p , may be derived as follows :

i.e.,

$$pv = RT$$

∴

$$p = \frac{RT}{v}$$

Putting this value in the equation $pv^\gamma = \text{constant}$

$$\frac{RT}{v} \cdot v^\gamma = \text{constant}$$

i.e.,

$$Tv^{\gamma-1} = \text{constant}$$

Also $v = \frac{RT}{p}$; hence substituting in equation $pv^\gamma = \text{constant}$

$$p \left(\frac{RT}{p} \right)^\gamma = \text{constant}$$

∴

$$\frac{T^\gamma}{p^{\gamma-1}} = \text{constant}$$

or

$$\frac{T}{\underline{\gamma - 1}} = \text{constant}$$

$$(p)^{\underline{\gamma}}$$

Therefore, for a reversible adiabatic process for a perfect gas between states 1 and 2, we can write :

From Eqn.

$$p_1 v_1^\gamma = p_2 v_2^\gamma \quad \text{or} \quad \frac{p_2}{p_1} = \left(\frac{v_1}{v_2} \right)^\gamma$$

From Eqn.

$$T_1 v_1^{\gamma-1} = T_2 v_2^{\gamma-1} \quad \text{or} \quad \frac{T_2}{T_1} = \left(\frac{v_1}{v_2} \right)^{\gamma-1}$$

From Eqn.

$$\frac{T_1}{(p_1)^{\frac{\gamma-1}{\gamma}}} = \frac{T_2}{(p_2)^{\frac{\gamma-1}{\gamma}}} \quad \text{or} \quad \frac{T_2}{T_1} = \left(\frac{p_2}{p_1} \right)^{\frac{\gamma-1}{\gamma}}$$

From eqn. the work done in an adiabatic process per kg of gas is given by $W = (u_1 - u_2)$. The gain in internal energy of a perfect gas is given by equation :

$$u_2 - u_1 = c_v (T_2 - T_1) \quad (\text{for } 1 \text{ kg})$$

$$\therefore W = c_v (T_1 - T_2)$$

Also, we know that

$$c_v = \frac{R}{\gamma - 1}$$

Hence substituting, we get

$$W = \frac{R (T_1 - T_2)}{\gamma - 1}$$

Using equation, $pv = RT$

$$W = \frac{p_1 v_1 - p_2 v_2}{\gamma - 1}$$

Polytropic Reversible Process ($pv^n = \text{constant}$)

- It is found that many processes in practice approximate to a reversible law of form $pv^n = \text{constant}$, where n is a constant. Both vapours and perfect gases obey this type of law closely in many non-flow processes. Such processes are internally reversible.

We know that for any reversible process,

$$W = \int p \, dv$$

For a process in $pv^n = \text{constant}$, we have

$$p = \frac{C}{v^n}, \text{ where } C \text{ is a constant}$$

$$\therefore W = C \int_{v_1}^{v_2} \frac{dv}{v^n} = C \left| \frac{v^{-n+1}}{-n+1} \right| = C \left(\frac{v_2^{-n+1} - v_1^{-n+1}}{-n+1} \right)$$

i.e.,

$$W = C \left(\frac{v_1^{-n+1} - v_2^{-n+1}}{n-1} \right) = \frac{p_1 v_1^n v_1^{-n+1} - p_2 v_2^n v_2^{-n+1}}{n-1}$$

(since the constant C , can be written as $p_1 v_1^n$ or as $p_2 v_2^n$)

i.e.,

$$\text{Work done, } W = \frac{p_1 v_1 - p_2 v_2}{n - 1}$$

or

$$W = \frac{R(T_1 - T_2)}{n - 1}$$

Eqn. (4.39) is true for any working substance undergoing a reversible polytropic process. It follows also that for any polytropic process, we can write

$$\frac{p_2}{p_1} = \left(\frac{v_1}{v_2} \right)^n$$

The following relations can be derived (following the same procedure as was done under reversible adiabatic process)

$$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2} \right)^{n-1}$$

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1} \right)^{\frac{n-1}{n}}$$

Heat transfer during polytropic process (for perfect gas $pV = RT$)

Using non-flow energy equation, the heat flow/transfer during the process can be found,

i.e.,

$$\begin{aligned} Q &= (u_2 - u_1) + W \\ &= c_v(T_2 - T_1) + \frac{R(T_1 - T_2)}{n-1} \end{aligned}$$

i.e.,

$$Q = \frac{R(T_1 - T_2)}{n-1} - c_v(T_1 - T_2)$$

Also

$$c_v = \frac{R}{(\gamma - 1)}$$

On substituting,

i.e.,

$$\begin{aligned} Q &= \frac{R}{n-1}(T_1 - T_2) - \frac{R}{(\gamma - 1)}(T_1 - T_2) \\ Q &= R(T_1 - T_2) \left(\frac{1}{n-1} - \frac{1}{\gamma-1} \right) \\ &= \frac{R(T_1 - T_2)(\gamma - 1 - n + 1)}{(\gamma - 1)(n - 1)} = \frac{R(T_1 - T_2)(\gamma - n)}{(\gamma - 1)(n - 1)} \end{aligned}$$

∴

$$Q = \frac{(\gamma - n)}{(\gamma - 1)} \frac{R(T_1 - T_2)}{(n - 1)}$$

or

$$Q = \left(\frac{\gamma - n}{\gamma - 1} \right) W \quad \left[\because W = \frac{R(T_1 - T_2)}{(n - 1)} \right]$$

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. For example,

When $n = 0$ $pv^0 = \text{constant}$ i.e., $p = \text{constant}$

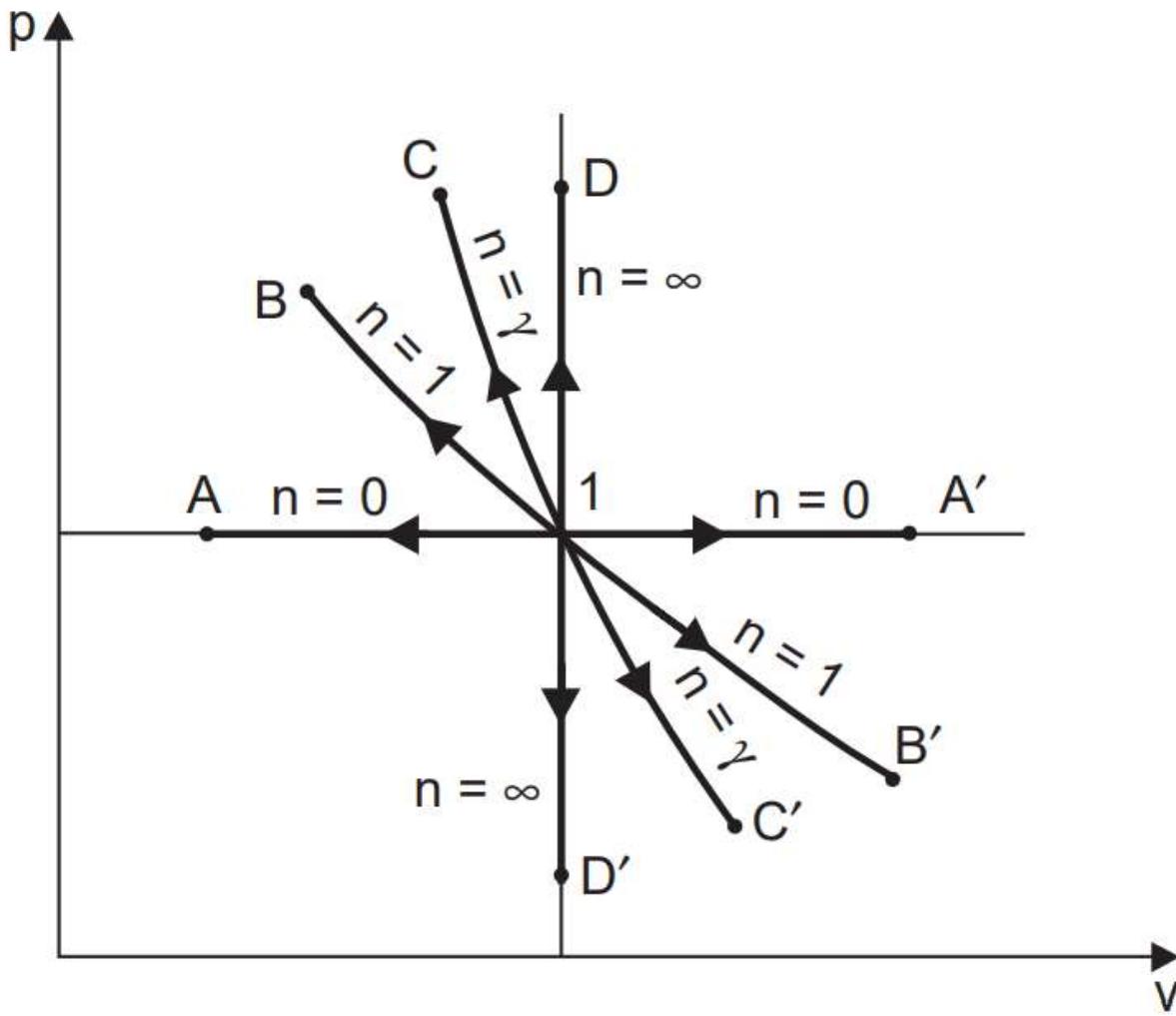
When $n = \infty$ $pv^\infty = \text{constant}$

or $p^{1/\infty} v = \text{constant}$, i.e., $v = \text{constant}$

When $n = 1$ $pv = \text{constant}$, i.e., $T = \text{constant}$

[since $(pv)/T = \text{constant}$ for a perfect gas]

When $n = \gamma$ $pv^\gamma = \text{constant}$, i.e., reversible adiabatic



This is illustrated on a p - v diagram in Fig.

- (i) State 1 to state A is *constant pressure cooling* ($n = 0$).
- (ii) State 1 to state B is *isothermal compression* ($n = 1$).
- (iii) State 1 to state C is *reversible adiabatic compression* ($n = \gamma$).
- (iv) State 1 to state D is *constant volume heating* ($n = \infty$).

Similarly,

- (i) State 1 to state A' is *constant pressure heating* ($n = 0$).
- (ii) State 1 to state B' is *isothermal expansion* ($n = 1$).
- (iii) State 1 to state C' is *reversible adiabatic expansion* ($n = \gamma$).
- (iv) State 1 to state D' is *constant volume cooling* ($n = \infty$).

It may be noted that, since γ is always greater than unity, than process 1 to C must lie between processes 1 to B and 1 to D ; similarly, process 1 to C' must lie between processes 1 to B' and 1 to D' .

Summary of Processes for Perfect Gas (Unit mass)

<i>Process</i>	<i>Index n</i>	<i>Heat added</i>	$\int_1^2 pdv$	<i>p, v, T relations</i>	<i>Specific heat, c</i>
Constant pressure	$n = 0$	$c_p(T_2 - T_1)$	$p(v_2 - v_1)$	$\frac{T_2}{T_1} = \frac{v_2}{v_1}$	c_p
Constant volume	$n = \infty$	$c_v(T_2 - T_1)$	0	$\frac{T_1}{T_2} = \frac{p_1}{p_2}$	c_v
Constant temperature	$n = 1$	$p_1 v_1 \log_e \frac{v_2}{v_1}$	$p_1 v_1 \log_e \frac{v_2}{v_1}$	$p_1 v_1 = p_2 v_2$	∞
Reversible adiabatic	$n = \gamma$	0	$\frac{p_1 v_1 - p_2 v_2}{\gamma - 1}$	$p_1 v_1^\gamma = p_2 v_2^\gamma$ $\frac{T_2}{T_1} = \left(\frac{v_1}{v_2} \right)^{\gamma - 1}$ $= \left(\frac{p_2}{P_1} \right)^{\frac{\gamma - 1}{\gamma}}$	0
Polytropic	$n = n$	$c_n(T_2 - T_1)$ $= c_v \left(\frac{\gamma - n}{1 - n} \right) \times (T_2 - T_1)$ $= \frac{\gamma - n}{\gamma - 1} \times \text{work done (non-flow)}$	$\frac{p_1 v_1 - p_2 v_2}{n - 1}$	$p_1 v_1^n = p_2 v_2^n$ $\frac{T_2}{T_1} = \left(\frac{v_1}{v_2} \right)^{n - 1}$ $= \left(\frac{p_2}{P_1} \right)^{\frac{n - 1}{n}}$	$c_n = c_v \left(\frac{\gamma - n}{1 - n} \right)$

Note. Equations must be used keeping dimensional consistence.

Example In an air motor cylinder the compressed air has an internal energy of 450 kJ/kg at the beginning of the expansion and an internal energy of 220 kJ/kg after expansion. If the work done by the air during the expansion is 120 kJ/kg, calculate the heat flow to and from the cylinder.

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Solution. Internal energy at beginning of the expansion,

$$u_1 = 450 \text{ kJ/kg}$$

Internal energy after expansion,

$$u_2 = 220 \text{ kJ/kg}$$

Work done by the air during expansion,

$$W = 120 \text{ kJ/kg}$$

Heat flow, Q :

Using the relation,

$$Q = (u_2 - u_1) + W$$

∴

$$Q = (220 - 450) + 120$$

$$= - 230 + 120 = - 110 \text{ kJ/kg}$$

Hence, **heat rejected by air = 110 kJ/kg. (Ans.)**

Example 0.3 kg of nitrogen gas at 100 kPa and 40°C is contained in a cylinder. The piston is moved compressing nitrogen until the pressure becomes 1 MPa and temperature becomes 160°C. The work done during the process is 30 kJ.

Calculate the heat transferred from the nitrogen to the surroundings.

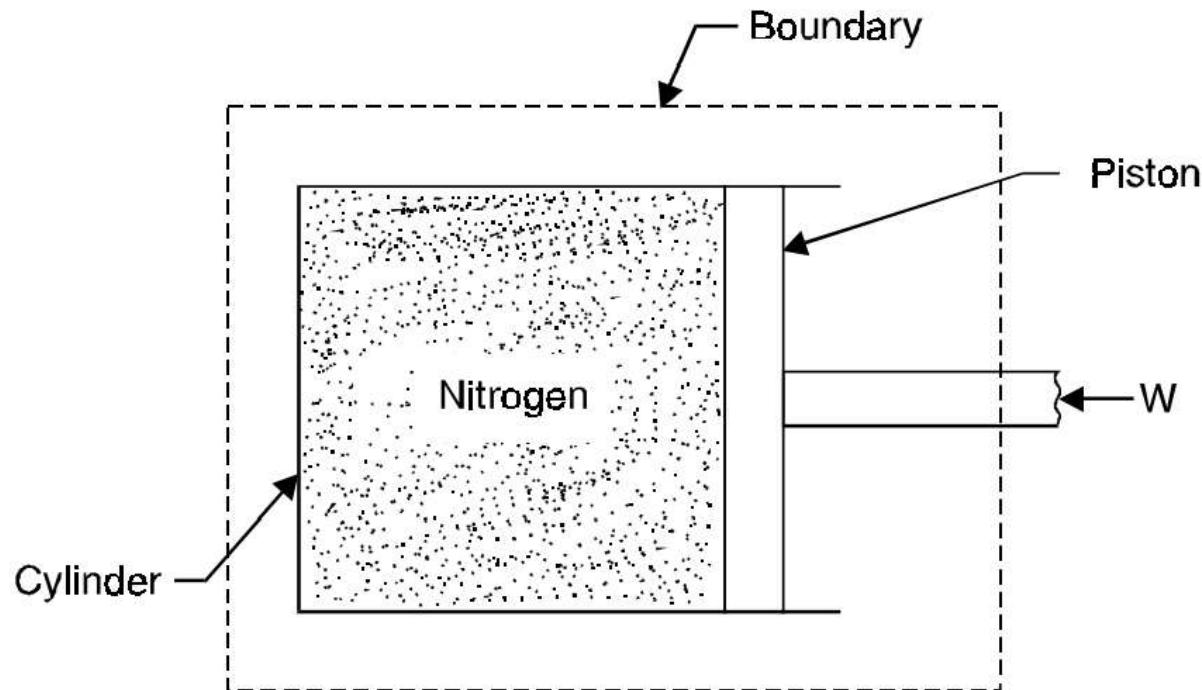
$$c_v \text{ for nitrogen} = 0.75 \text{ kJ/kg K}$$

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Calculate the heat transferred from the nitrogen to the surroundings.

$$c_v \text{ for nitrogen} = 0.75 \text{ kJ/kg K}$$

Solution. Mass of nitrogen, $m = 0.3 \text{ kg}$



Temperature before compression = 40°C or 313 K

Temperature after compression = 160°C or 433 K

The work done during the compression process, $W = -30 \text{ kJ}$

According to first law of thermodynamics,

$$\begin{aligned} Q &= \Delta U + W = (U_2 - U_1) + W \\ &= mc_v (T_2 - T_1) + W \\ &= 0.3 \times 0.75(433 - 313) - 30 = -3 \text{ kJ} \end{aligned}$$

Hence, **heat ‘rejected’ during the process = 3 kJ.** (Ans.)

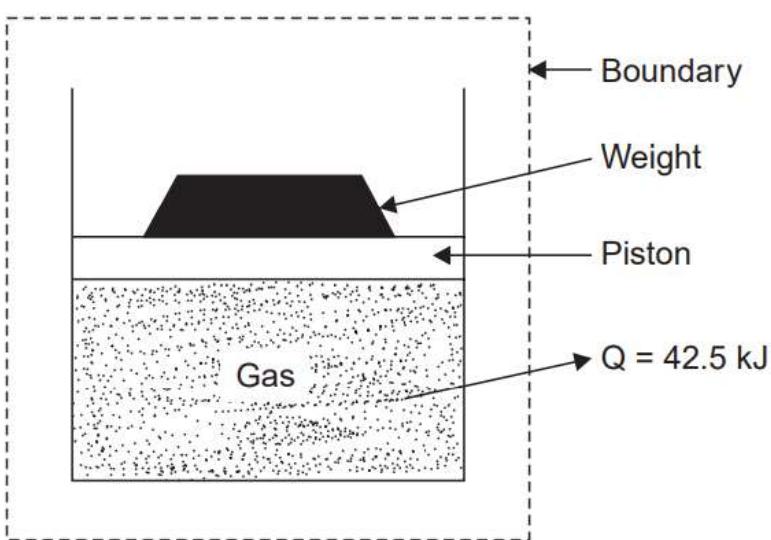
Note. Work, W has been taken –ve because it has been supplied from outside.

Example When a stationary mass of gas was compressed without friction at constant pressure its initial state of 0.4 m^3 and 0.105 MPa was found to change to final state of 0.20 m^3 and 0.105 MPa . There was a transfer of 42.5 kJ of heat from the gas during the process.

How much did the internal energy of the gas change ?

Example When a stationary mass of gas was compressed without friction at constant pressure its initial state of 0.4 m^3 and 0.105 MPa was found to change to final state of 0.20 m^3 and 0.105 MPa . There was a transfer of 42.5 kJ of heat from the gas during the process.

How much did the internal energy of the gas change ?



$$= 0.105(0.20 - 0.40) \text{ MJ} = - 21 \text{ kJ}$$

Substituting this value of W_{1-2} in equation (i), we get

$$- 42.5 = (U_2 - U_1) - 21$$

$$\therefore U_2 - U_1 = - 42.5 + 21 = - 21.5 \text{ kJ}$$

Hence 'decrease' in internal energy = 21.5 kJ . (Ans.)

Initial state

$$\text{Pressure of gas, } p_1 = 0.105 \text{ MPa}$$

$$\text{Volume of gas, } V_1 = 0.4 \text{ m}^3$$

Final state

$$\text{Pressure of gas, } p_2 = 0.105 \text{ MPa}$$

$$\text{Volume of gas, } V_2 = 0.20 \text{ m}^3$$

Process used : Constant pressure

$$\text{Heat transferred, } Q = - 42.5 \text{ kJ}$$

(-ve sign indicates that heat is rejected)

Change in internal energy, $\Delta U = U_2 - U_1$:

First law for a stationary system in a process gives

$$Q = \Delta U + W$$

or

$$Q_{1-2} = (U_2 - U_1) + W_{1-2}$$

Here

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

Example Air enters a compressor at 10^5 Pa and 25°C having volume of $1.8 \text{ m}^3/\text{kg}$ and is compressed to $5 \times 10^5 \text{ Pa}$ isothermally.

Determine : (i) Work done ;
(ii) Change in internal energy ; and
(iii) Heat transferred.

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Determine : (i) Work done ;

(ii) Change in internal energy ; and

(iii) Heat transferred.

Solution. Initial pressure of air, $p_1 = 10^5 \text{ Pa}$

Initial temperature of air, $T_1 = 25 + 273 = 298 \text{ K}$

Final pressure of air, $p_2 = 5 \times 10^5 \text{ Pa}$

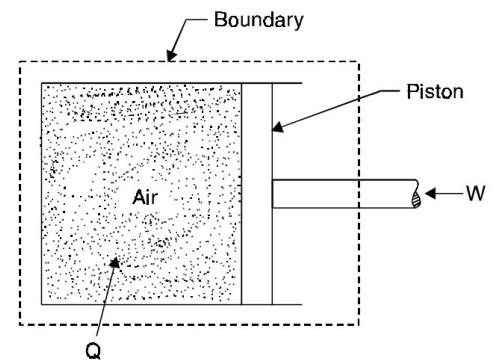
Final temperature of air, $T_2 = T_1 = 298 \text{ K}$ (isothermal process)

Since, it is a closed steady state process, we can write down the first law of thermodynamics as,

$$Q = (u_2 - u_1) + W \dots \text{per kg}$$

(i) For isothermal process :

$$W_{1-2} = \int_1^2 p \cdot dv = p_1 v_1 \log_e \left(\frac{p_1}{p_2} \right)$$



as

$$p_1v_1 = p_2v_2 \text{ for isothermal process}$$

$$\begin{aligned}\therefore W_{1-2} &= -10^5 \times 1.8 \log_e \left(\frac{1 \times 10^5}{5 \times 10^5} \right) \\ &= -2.897 \times 10^5 = -289.7 \text{ kJ/kg.}\end{aligned}$$

(- ve sign indicates that the work is supplied to the air)

∴ Work done on the air = 289.7 kJ/kg. (Ans.)

(ii) Since temperature is constant,

$$\therefore u_2 - u_1 = 0$$

∴ Change in internal energy = zero. (Ans.)

(iii) Again,

$$\begin{aligned}Q_{1-2} &= (u_2 - u_1) + W \\ &= 0 + (-289.7) = -289.7 \text{ kJ}\end{aligned}$$

(- ve sign indicates that heat is lost from the system to the surroundings)

∴ Heat rejected = 289.7 kJ/kg. (Ans.)

Example A cylinder containing the air comprises the system. Cycle is completed as follows :

(i) 82000 N-m of work is done by the piston on the air during compression stroke and 45 kJ of heat are rejected to the surroundings.

(ii) During expansion stroke 100000 N-m of work is done by the air on the piston.

Calculate the quantity of heat added to the system.

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Expansion stroke. Process 2-1 :

Solution. Refer Fig.

Compression stroke. Process 1-2 :

Work done by the piston on the air, $W_{1-2} = -82000 \text{ N-m} (= -82 \text{ kJ})$

Heat rejected to the system, $Q_{1-2} = -45 \text{ kJ}$

Now,

$$Q_{1-2} = (U_2 - U_1) + W$$

$$-45 = (U_2 - U_1) + (-82)$$

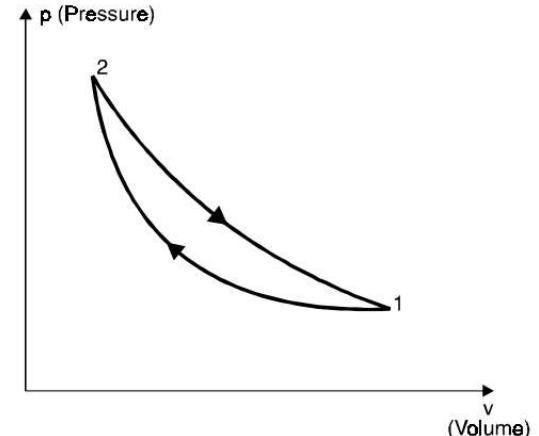
∴

$$(U_2 - U_1) = 37 \text{ kJ}$$

Work done by air on the piston, $W_{2-1} = 100000 \text{ N-m} (= 100 \text{ kJ})$

$$\begin{aligned} \text{Now, } Q_{2-1} &= (U_1 - U_2) + W \\ &= -37 + 100 \text{ kJ} = 63 \text{ kJ} \end{aligned}$$

Hence, **quantity of heat added to the system = 63 kJ. (Ans.)**



Example *0.2 m³ of air at 4 bar and 130°C is contained in a system. A reversible adiabatic expansion takes place till the pressure falls to 1.02 bar. The gas is then heated at constant pressure till enthalpy increases by 72.5 kJ. Calculate :*

(i) *The work done ;*

(ii) *The index of expansion, if the above processes are replaced by a single reversible polytropic process giving the same work between the same initial and final states.*

Take $c_p = 1 \text{ kJ/kg K}$, $c_v = 0.714 \text{ kJ/kg K}$.

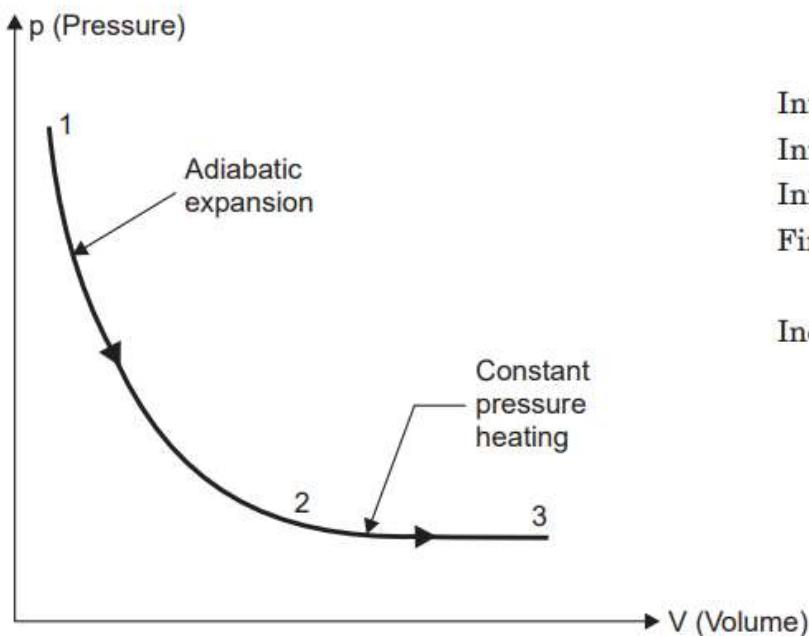
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Solution. Refer Fig.



Initial volume,	$V_1 = 0.2 \text{ m}^3$
Initial pressure,	$p_1 = 4 \text{ bar} = 4 \times 10^5 \text{ N/m}^2$
Initial temperature,	$T_1 = 130 + 273 = 403 \text{ K}$
Final pressure after adiabatic expansion,	
	$p_2 = 1.02 \text{ bar} = 1.02 \times 10^5 \text{ N/m}^2$
Increase in enthalpy during constant pressure process	
	$= 72.5 \text{ kJ.}$

(i) Work done :

Process 1-2 : Reversible adiabatic process :

$$p_1 V_1^\gamma = p_2 V_2^\gamma$$

$$V_2 = V_1 \left(\frac{p_1}{p_2} \right)^{\frac{1}{\gamma}}$$

Also

$$\gamma = \frac{c_p}{c_v} = \frac{1}{0.714} = 1.4$$

∴

$$V_2 = 0.2 \times \left(\frac{4 \times 10^5}{1.02 \times 10^5} \right)^{\frac{1}{1.4}} = 0.53 \text{ m}^3$$

Also,

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1} \right)^{\frac{\gamma-1}{\gamma}}$$

∴

$$T_2 = T_1 \left(\frac{p_2}{p_1} \right)^{\frac{\gamma-1}{\gamma}}$$

$$= 403 \left(\frac{1.02 \times 10^5}{4 \times 10^5} \right)^{\frac{1.4-1}{1.4}} = 272.7 \text{ K}$$

Mass of the gas,

$$m = \frac{p_1 V_1}{R T_1}$$

[∴ $pV = mRT$]

$$\begin{aligned} \text{where, } R &= (c_p - c_v) = (1 - 0.714) \text{ kJ/kg K} \\ &= 0.286 \text{ kJ/kg K} = 286 \text{ J/kg K or } 286 \text{ Nm/kg K} \end{aligned}$$

∴

$$m = \frac{4 \times 10^5 \times 0.2}{286 \times 403} = 0.694 \text{ kg.}$$

Process 2-3. Constant pressure :

$$Q_{2-3} = mc_p(T_3 - T_2)$$

$$72.5 = 0.694 \times 1 \times (T_3 - 272.7)$$

$$\therefore T_3 = \frac{72.5}{0.694} + 272.7 = 377 \text{ K}$$

Also,

$$\frac{V_2}{T_2} = \frac{V_3}{T_3}$$

$$\frac{0.53}{272.7} = \frac{V_3}{377}$$

$$\therefore V_3 = \frac{0.53 \times 377}{272.7} = 0.732 \text{ m}^3$$

Work done by the path 1-2-3 is given by

$$\begin{aligned} W_{1-2-3} &= W_{1-2} + W_{2-3} \\ &= \frac{p_1 V_1 - p_2 V_2}{\gamma - 1} + p_2 (V_3 - V_2) \\ &= \frac{4 \times 10^5 \times 0.2 - 1.02 \times 10^5 \times 0.53}{1.4 - 1} + 1.02 \times 10^5 (0.732 - 0.53) \\ &= \frac{10^5 (4 \times 0.2 - 1.02 \times 0.53)}{0.4} + 1.02 \times 10^5 (0.732 - 0.53) \\ &= 64850 + 20604 = 85454 \text{ Nm or J} \end{aligned}$$

Hence, **total work done** = **85454 Nm or J.** (Ans.)

(ii) **Index of expansion, n :**

If the work done by the polytropic process is the same,

$$W_{1-2-3} = W_{1-3} = \frac{p_1 V_1 - p_3 V_3}{n - 1}$$

$$85454 = \frac{4 \times 10^5 \times 0.2 - 1.02 \times 10^5 \times 0.732}{(n - 1)} = \frac{5336}{n - 1}$$

$$\begin{aligned} n &= \frac{5336}{85454} + 1 \\ n &= 1.062 \end{aligned}$$

Hence, **value of index** = **1.062.** (Ans.)

Example *0.1 m³ of an ideal gas at 300 K and 1 bar is compressed adiabatically to 8 bar. It is then cooled at constant volume and further expanded isothermally so as to reach the condition from where it started. Calculate :*

- (i) *Pressure at the end of constant volume cooling.*
- (ii) *Change in internal energy during constant volume process.*
- (iii) *Net work done and heat transferred during the cycle. Assume $c_p = 14.3 \text{ kJ/kg K}$ and $c_v = 10.2 \text{ kJ/kg K}$.*

Refer to Fig.

(i) Pressure at the end of constant volume cooling, p_3 :

$$\gamma = \frac{c_p}{c_v} = \frac{14.3}{10.2} = 1.402$$

Characteristic gas constant,

$$R = c_p - c_v = 14.3 - 10.2 = 4.1 \text{ kJ/kg K}$$

Considering process 1-2, we have :

$$p_1 V_1^\gamma = p_2 V_2^\gamma$$

$$V_2 = V_1 \times \left(\frac{p_1}{p_2} \right)^{\frac{1}{\gamma}} = 0.1 \times \left(\frac{1}{8} \right)^{\frac{1}{1.402}} = 0.0227 \text{ m}^3$$

$$\text{Also, } \frac{T_2}{T_1} = \left(\frac{p_2}{p_1} \right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{8}{1} \right)^{\frac{1.402-1}{1.402}} = 1.815$$

$$T_2 = T_1 \times 1.815 = 300 \times 1.815 = 544.5 \text{ K}$$

Considering process 3-1, we have

$$p_3 V_3 = p_1 V_1$$

$$\therefore p_3 = \frac{p_1 V_1}{V_3} = \frac{1 \times 0.1}{0.0227} = 4.4 \text{ bar. (Ans.)} \quad (\because V_3 = V_2)$$

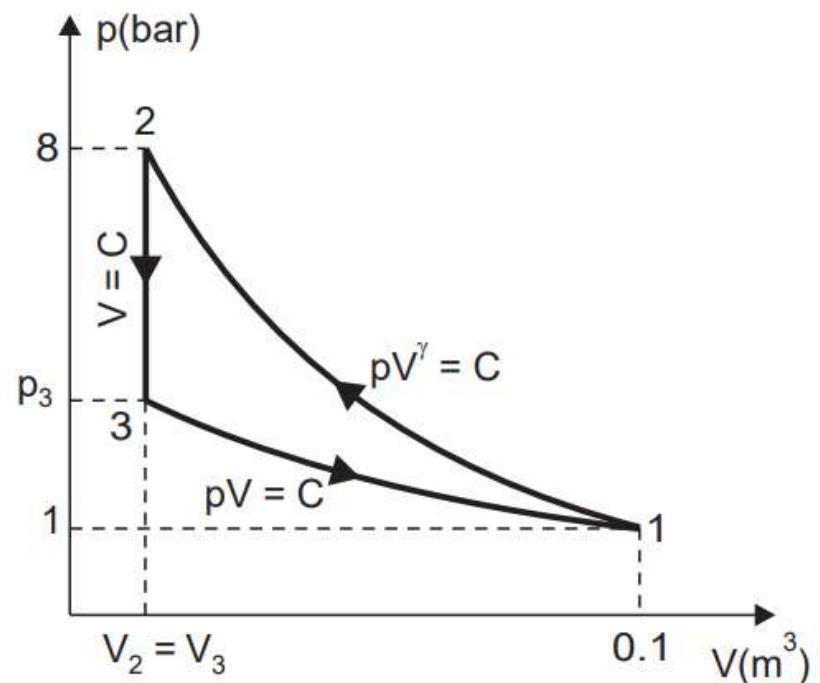


Fig. 4.24

(ii) **Change in internal energy during constant volume process, $(U_3 - U_2)$:**

Mass of gas, $m = \frac{p_1 V_1}{R T_1} = \frac{(1 \times 10^5) \times 0.1}{(4.1 \times 1000) \times 300} = 0.00813 \text{ kg}$

∴ Change in internal energy during *constant volume process 2–3*,

$$\begin{aligned} U_3 - U_2 &= mc_v(T_3 - T_2) \\ &= 0.00813 \times 10.2 (300 - 544.5) \quad (\because T_3 = T_1) \\ &= - 20.27 \text{ kJ. (Ans.)} \end{aligned}$$

(– ve sign means *decrease* in internal energy)

- During constant volume cooling process, temperature and hence internal energy is *reduced*. This *decrease in internal energy equals to heat flow to surroundings since work done is zero*.

(iii) **Net work done and heat transferred during the cycle :**

$$\begin{aligned}W_{1-2} &= \frac{p_1 V_1 - p_2 V_2}{\gamma - 1} = \frac{m R (T_1 - T_2)}{\gamma - 1} \\&= \frac{0.00813 \times 4.1 (300 - 544.5)}{1.402 - 1} = - 20.27 \text{ kJ}\end{aligned}$$

$$W_{2-3} = 0 \quad \dots \text{since volume remains constant}$$

$$\begin{aligned}W_{3-1} &= p_3 V_3 \log_e \left(\frac{V_1}{V_3} \right) = p_1 V_1 \log_e \left(\frac{p_3}{p_1} \right) \quad (\because p_3 V_3 = p_1 V_1) \\&= (1 \times 10^5) \times 0.1 \times \log_e \left(\frac{4.4}{1} \right) \\&= 14816 \text{ Nm (or J) or } 14.82 \text{ kJ}\end{aligned}$$

$$\therefore \text{Net work done} = W_{1-2} + W_{2-3} + W_{3-1} \\= (-20.27) + 0 + 14.82 = -5.45 \text{ kJ}$$

-ve sign indicates that work has been done *on the system*. (Ans.)

For a cyclic process : $\oint \delta Q = \oint \delta W$

\therefore Heat transferred during the complete cycle = - 5.45 kJ

-ve sign means heat has been *rejected i.e., lost from the system*. (Ans.)