

Monograph on Thermodynamics



Prepared by

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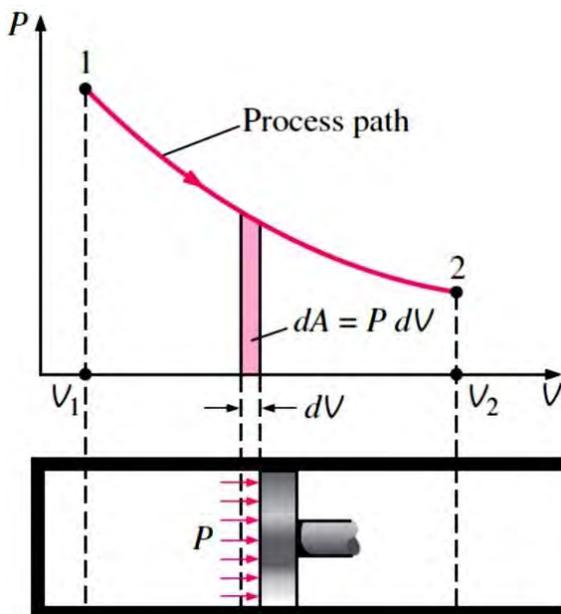
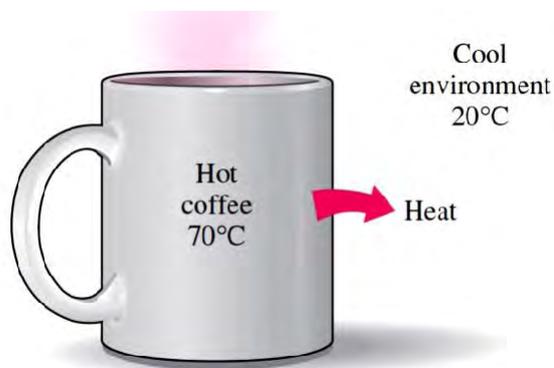
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BASIC CONCEPTS



Course Contents

- 1.1 Introduction to Engineering Thermodynamics
 - 1.2 Microscopic & Macroscopic Point of View
 - 1.3 Thermodynamic System & Control Volume
 - 1.4 Thermodynamic Properties, Processes & Cycles
 - 1.5 Thermodynamic Equilibrium
 - 1.6 Quasi-static Process
 - 1.7 Heat and Work
 - 1.8 References
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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.

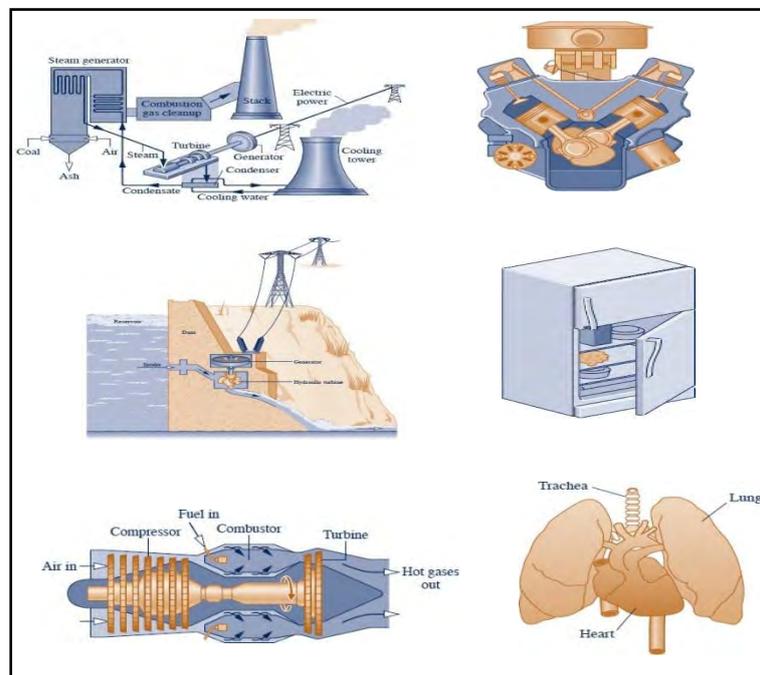


Fig. 1.1 Application areas of engineering thermodynamics

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.
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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

Types of Thermodynamic System

A. Open System

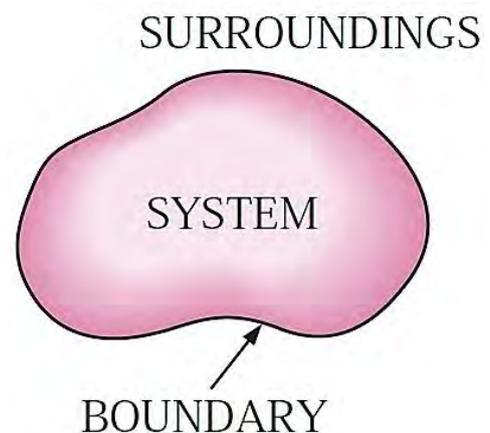
- In an open system mass and energy (in form of heat and work) both can transfer across the boundary.
- Most of the engineering devices are open system.
- **Examples:** Boiler, Turbine, Compressor, Pump, I.C. Engine, etc.

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).



System + Surrounding = Universe

Fig. 1.2 System, Surroundings and Boundary

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.

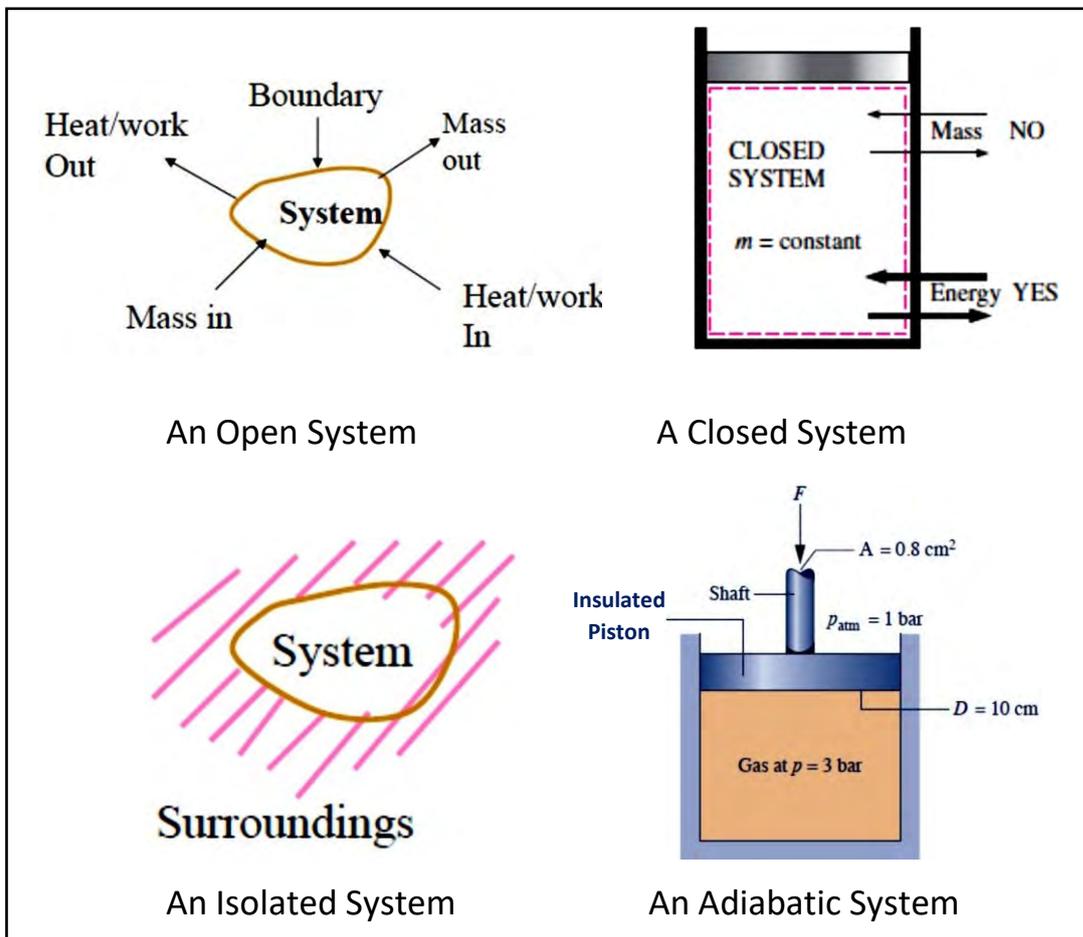


Fig. 1.3 Types of thermodynamic systems

E. Homogeneous & Heterogeneous System

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. 1.4. 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.

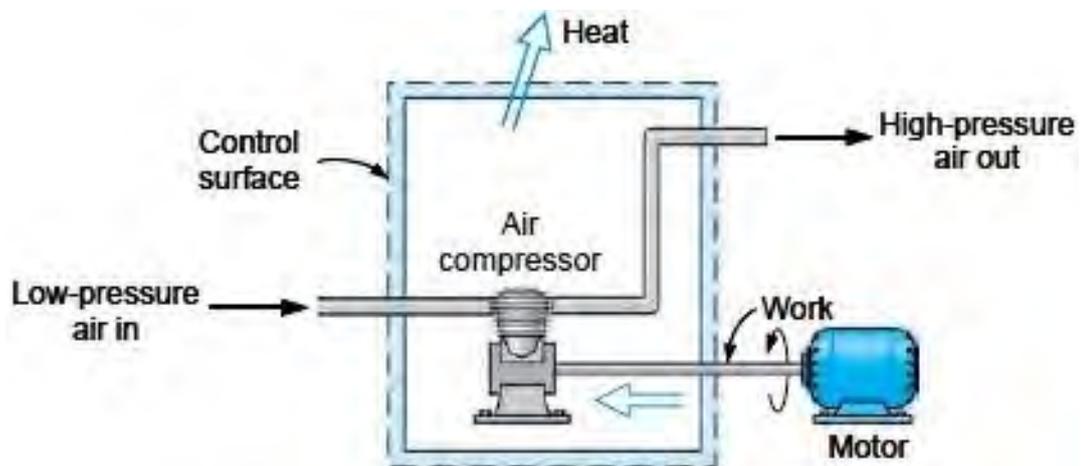


Fig. 1.4 An example of control volume

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 ($v = \frac{V}{m}$) and specific total energy ($e = \frac{E}{m}$).

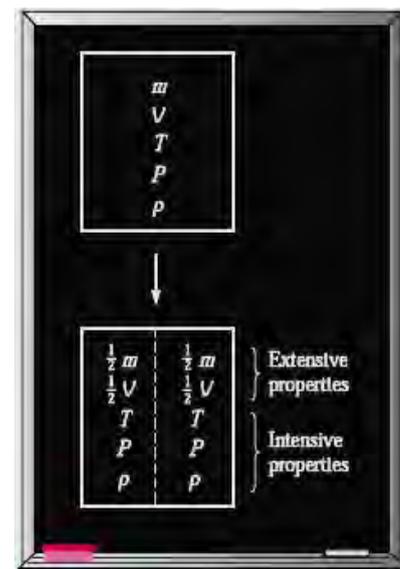


Fig. 1.5 Criterion to differentiate intensive and extensive properties

❖ 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**.

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.

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.

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. $\int_1^2 dV = V_2 - V_1$

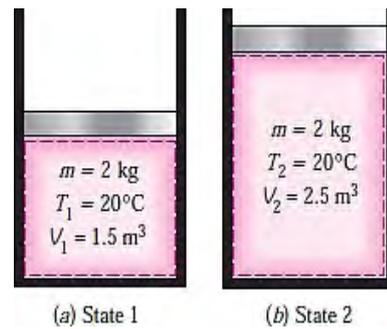


Fig. 1.6 A system at two different states

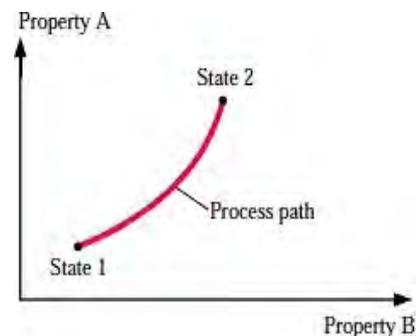


Fig. 1.7 A process between states 1 and 2 and a process path

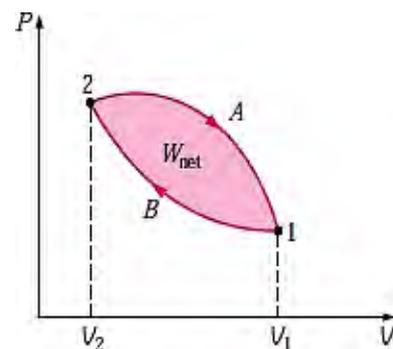


Fig. 1.8 Cycle of operations

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 .
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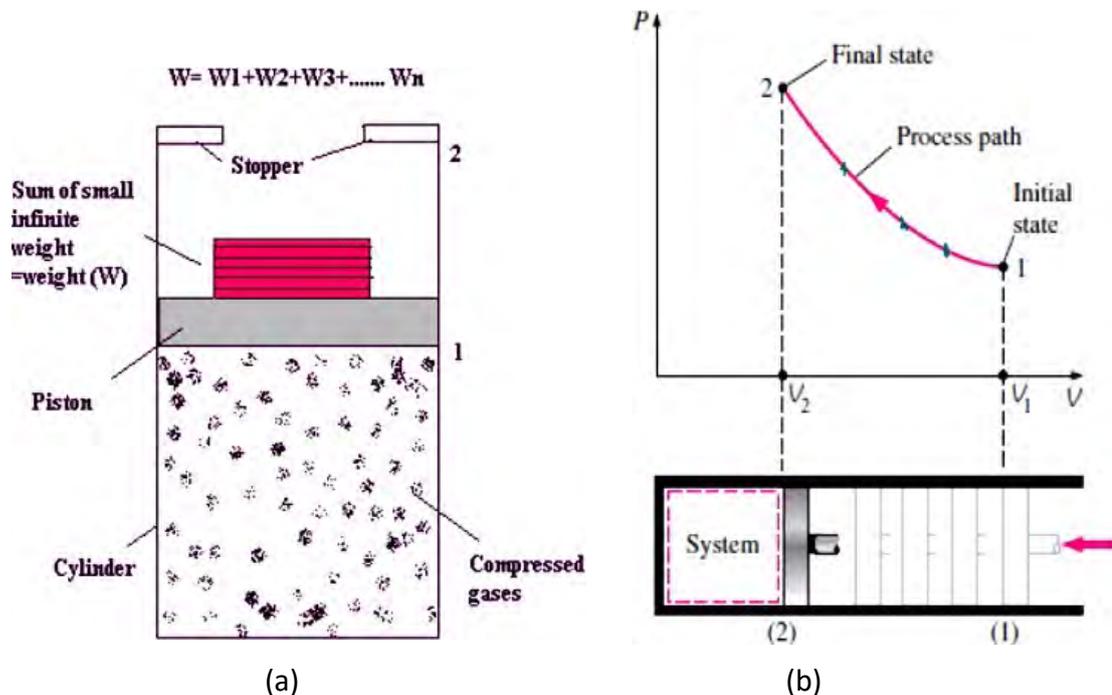


Fig. 1.9 (a) Quasi-Static Process (b) p - v diagram of a compression process

- 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 conventions 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**.

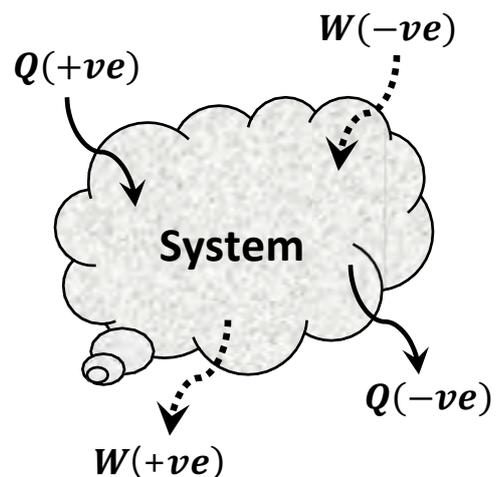


Fig. 1.10 Sign convention for heat & work

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 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 | 5. Gravitational work |
| 2. Mechanical work | 6. Acceleration work |
| 3. Moving boundary work | 7. Shaft work |
| 4. Flow 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 / $p dV$ - 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. 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,

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

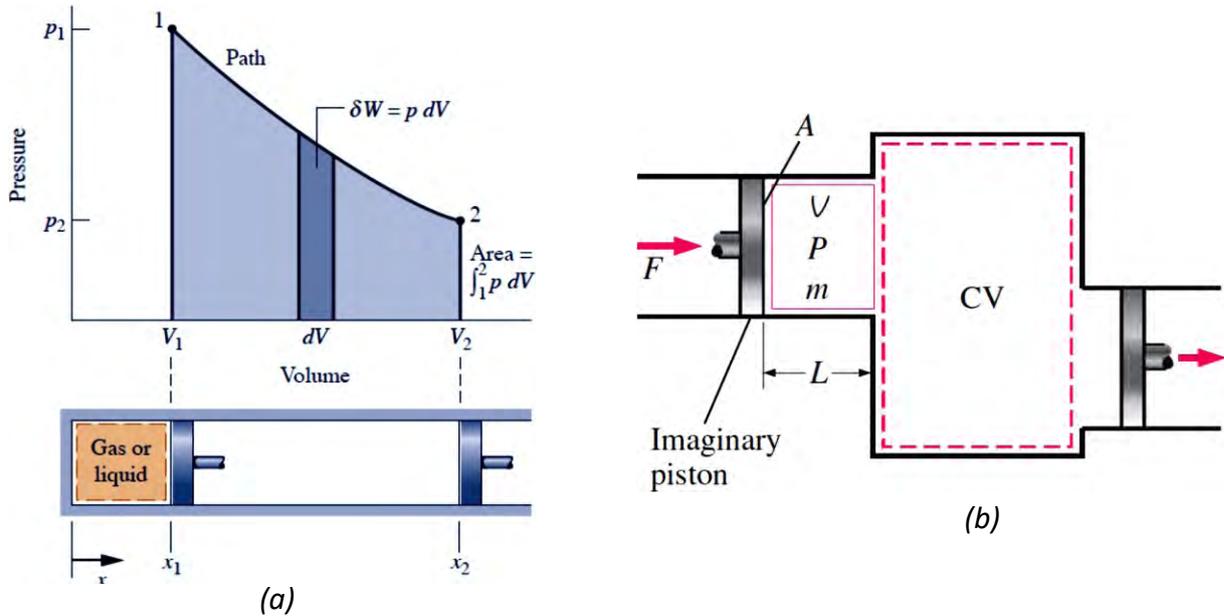


Fig. 1.11 (a) Displacement work and (b) Flow work

- 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,

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

or

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

- This work transfer during a process is equal to the area under the curve on a $p - V$ diagram as shown in Fig. 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, $W_{f2} = p_2 V_2$

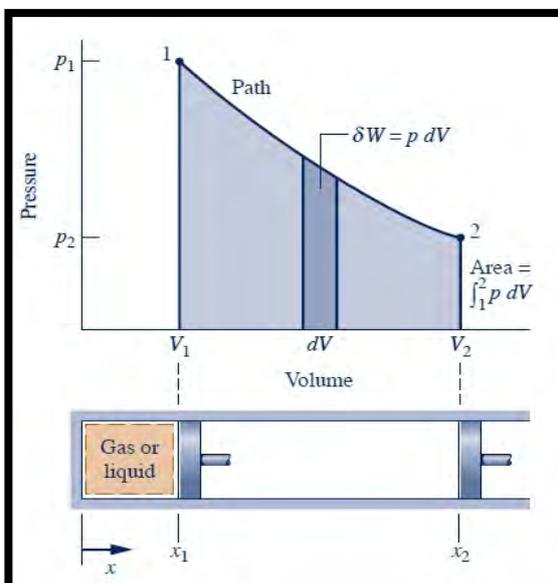
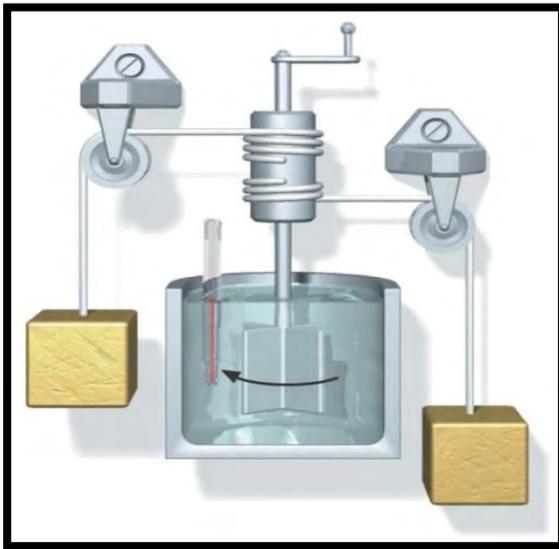
Specific Heat

- “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,

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

2

FIRST LAW OF THERMODYNAMICS



Course Contents

- 2.1 Introduction to 1st Law of Thermodynamics
- 2.2 First Law Applied to Cyclic Process – Joule's Experiment
- 2.3 First Law Applied to a Process
- 2.4 Internal Energy: A Property of the System
- 2.5 First Law Applied to Steady Flow Processes
- 2.6 SFEE Applied to Engineering Applications
- 2.7 Unsteady Flow Processes: Filling & Emptying Process
- 2.8 First Law Applied to Non Flow Processes
- 2.9 Solved Numerical
- 2.10 References

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.
- During the execution of these processes:

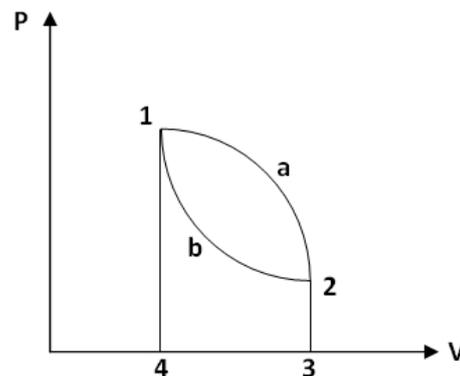


Fig. 2.1 Cyclic process

- 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).

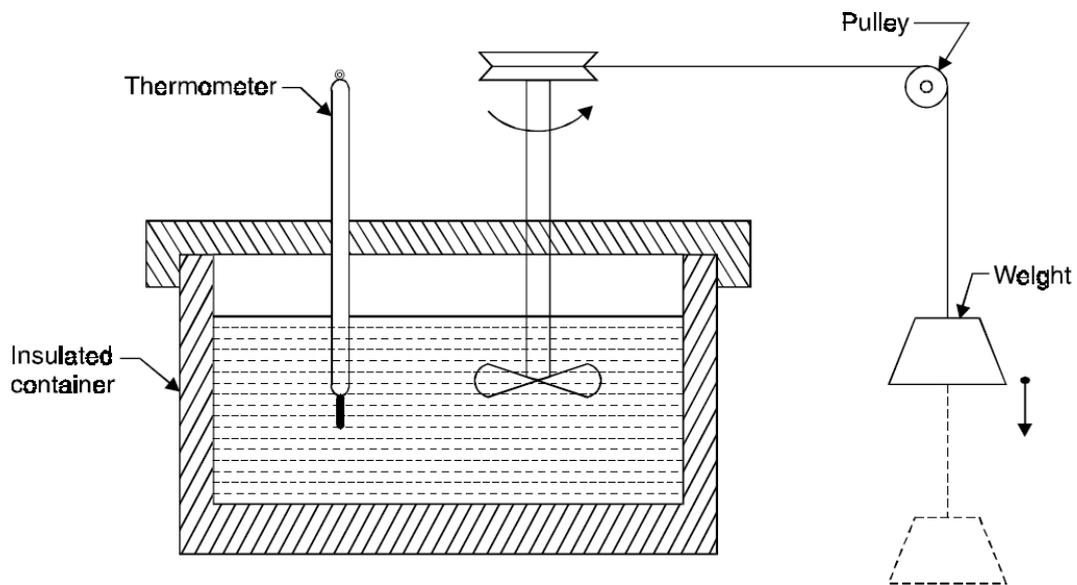


Fig. 2.2 Joule's paddle-wheel experiment

- 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,
-

$$\Delta E = Q - W \text{ --- --- --- --- --- (2.2)}$$

Where,

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

- 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.

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

- 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,

$$\delta Q - \delta W = dE \text{ --- --- --- --- --- (2.4)}$$

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

$$Q - W = 0$$

$$\therefore Q = W \text{ --- --- --- --- --- (2.5)}$$

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

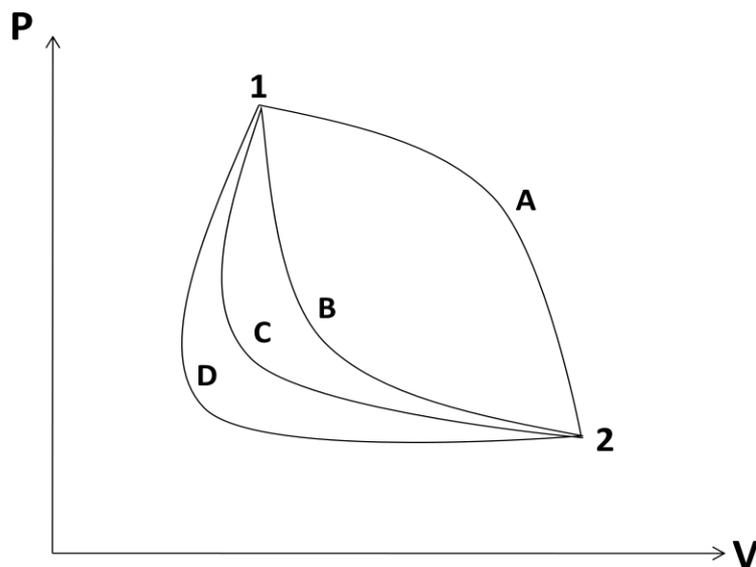


Fig. 2.3 Cyclic process with different paths

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

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

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

Similarly,

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

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

And,

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

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

Comparing equations 2.6, 2.7 and 2.8, 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 $\int^1 (\delta Q - \delta W)$

- (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 $\int^1 (\delta Q - \delta w)$ 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.

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,

$$\text{Total mass entering CV} - \text{Total mass leaving CV} = \text{Net change in mass within CV}$$

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

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

Where,

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,

$$\begin{aligned} \text{Specific volume} &= \frac{1}{\text{Density}} \\ \therefore v &= \frac{1}{\rho} \end{aligned}$$

Equation (2.9) can be expressed as,

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

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

$$Q = AC$$

For a **steady flow**,

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

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.

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

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.

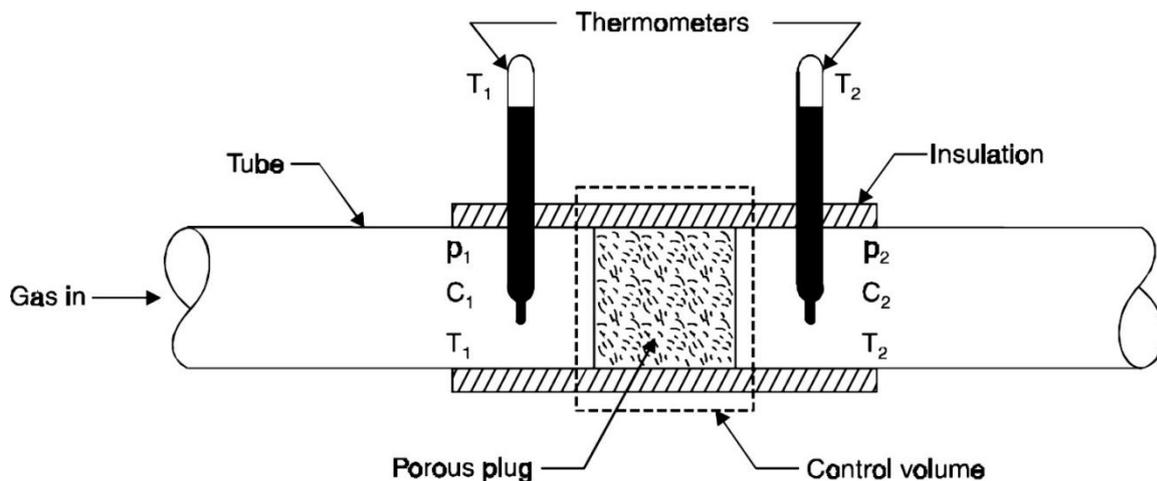
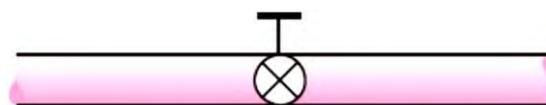


Fig. 2.12 The Joule – Thomson porous plug experiment



(a) An adjustable valve

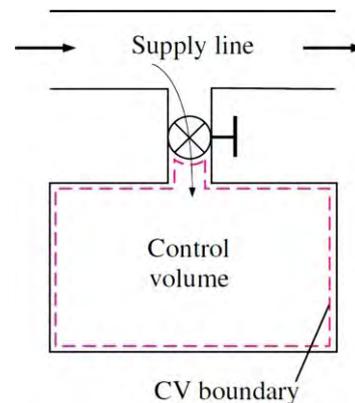


(b) A porous plug

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

2.6 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



2.7 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.

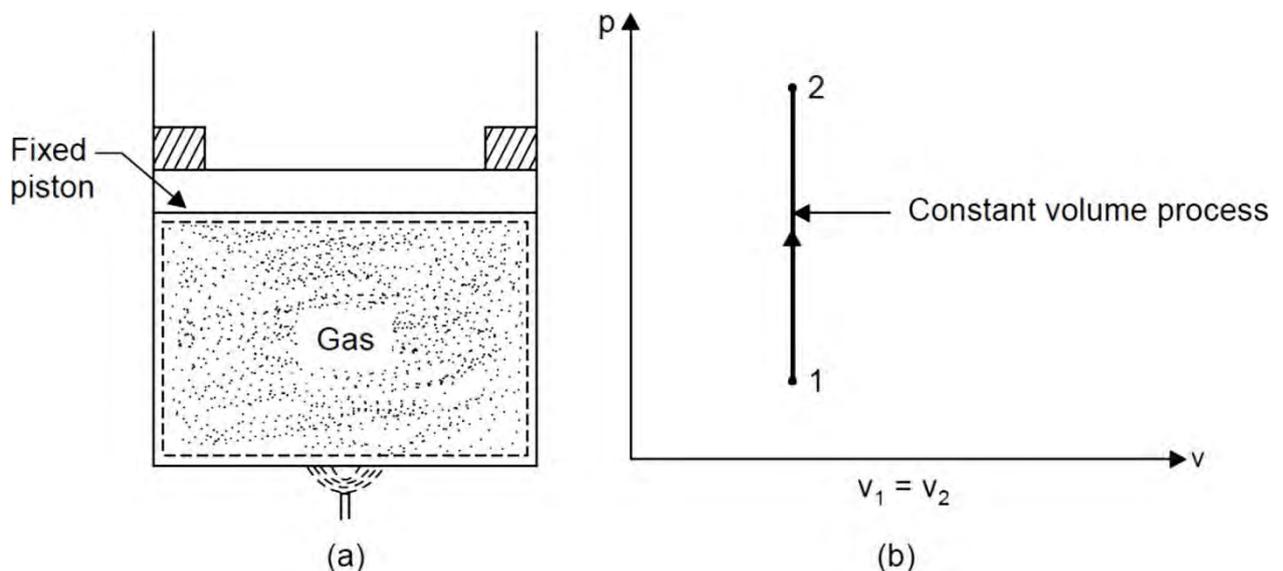


Fig. 2.15 Constant volume process (Isochoric)

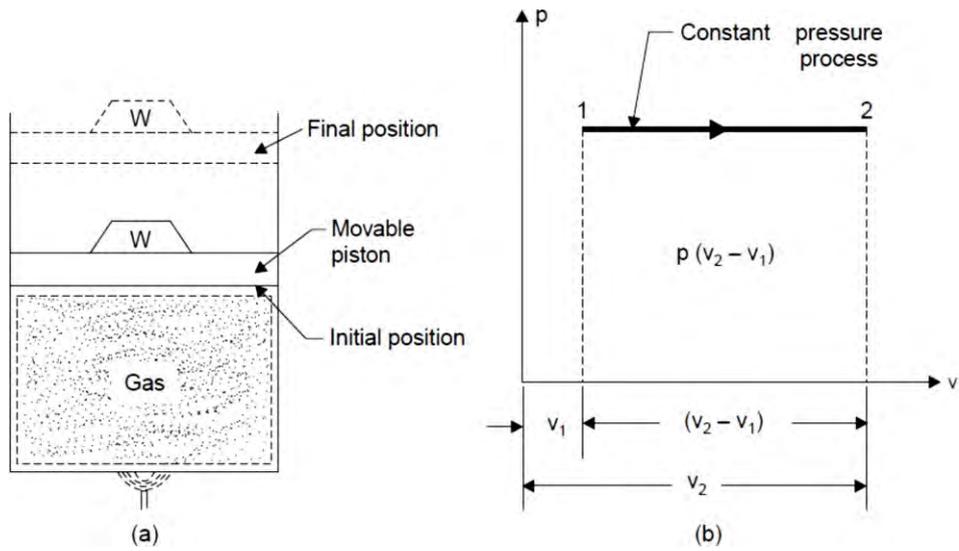


Fig. 2.16 Constant pressure process (Isobaric)

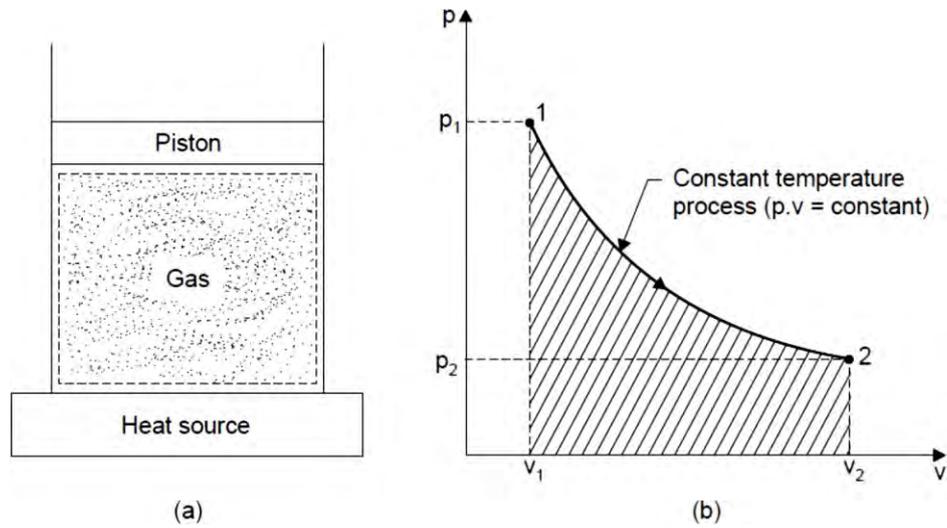


Fig. 2.17 Constant temperature process (Isothermal)

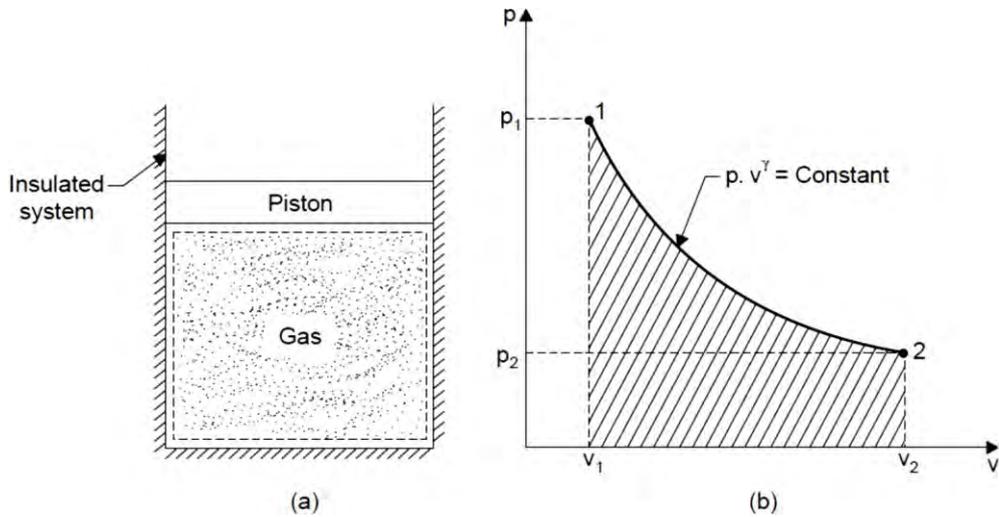


Fig. 2.18 Reversible Adiabatic Process (Isentropic process)

- 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.

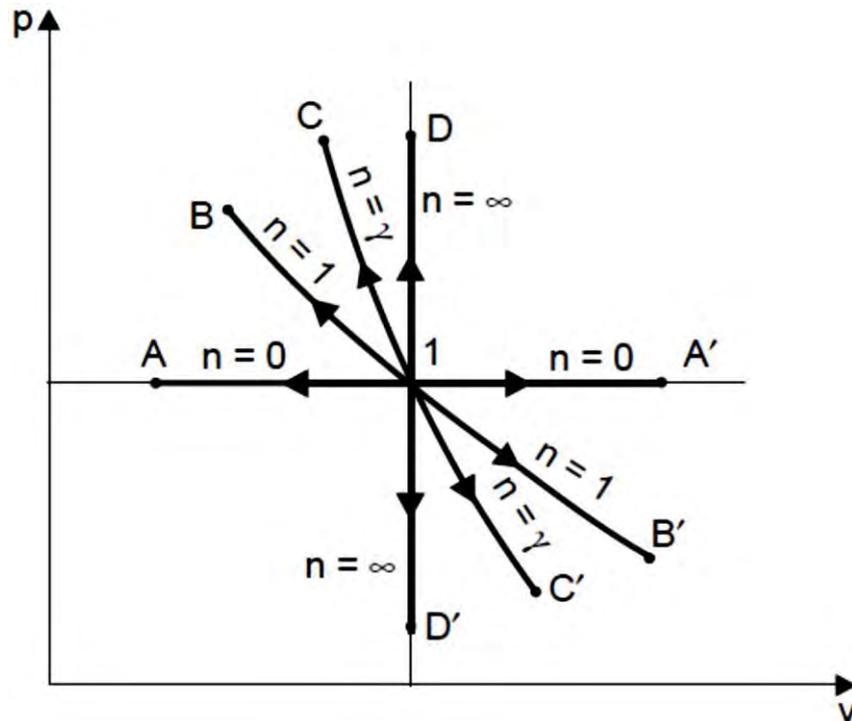


Fig. 2.19 Polytropic process for different values on index 'n'

For Air (Perfect Gas)

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

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

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

$$\gamma = 1.4$$

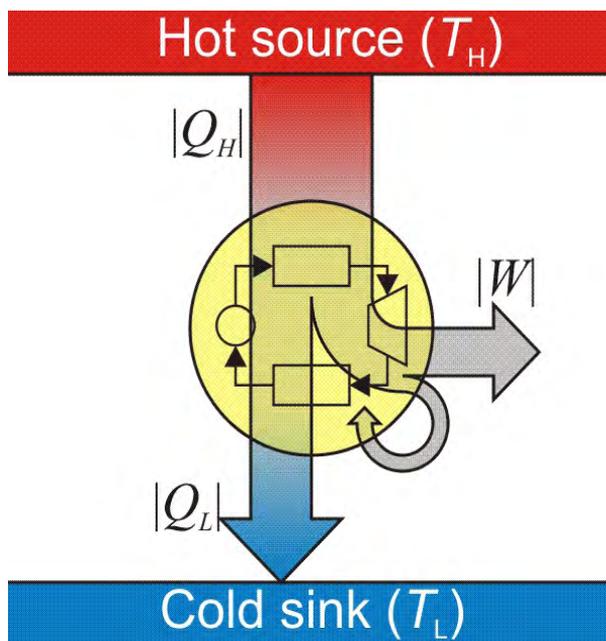
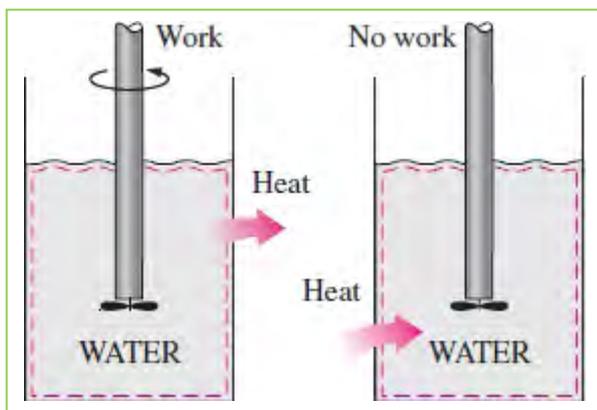
Relationship between R , C_p , C_v and γ

$$R = C_p - C_v$$

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

3

SECOND LAW OF THERMODYNAMICS



Course Contents

- 3.1 Introduction
- 3.2 Examples of First law
 - 3.2.1 Limitations of 1st Law of Thermodynamics
- 3.3 Basic Definitions
 - Thermal Reservoir
 - Heat Engine
 - Refrigerator
 - Heat pump
 - Perpetual Motion Machine
- 3.4 The Statements of Second Law of Thermodynamics
 - 3.4.1 Kelvin- Plank Statement
 - 3.4.2 Clausius Statement
- 3.5 Reversible and Irreversible processes
- 3.6 The Carnot Cycle
- 3.7 The Reversed Carnot cycle
- 3.8 The Carnot Theorem and Carnot Corollaries
- 3.9 Thermodynamic Temperature Scale

3.1 Introduction

- First law of thermodynamics deals with conservation and conversion of energy. It stipulates that when a thermodynamic process is carried out, energy is neither gained nor lost. Energy only transforms from one form into another and the energy balance is maintained. The law, however, fails to state the condition under which energy conversions are possible. The law presumes that any change of a thermodynamic state can take place in either direction.
- However, this is not true; particularly in the inter-conversion of heat and work. Processes proceed spontaneously in certain directions but not in opposite directions, even though the reversal of processes does not violate the first law.

3.2 Examples of First law

- It is common experience that a cup of hot coffee left in a cooler room eventually cools off. This process satisfies the first law of thermodynamics since the amount of energy lost by the coffee is equal to the amount gained by the surrounding air. Now let us consider the reverse process—the hot coffee getting even hotter in a cooler room as a result of heat transfer from the room air. We all know that this process never takes place. Yet, doing so would not violate the first law as long as the amount of energy lost by the air is equal to the amount gained by the coffee.



Figure 1 coffee in a cold room

- As another familiar example, consider the heating of a room by the passage of electric current through a resistor. Again, the first law says that the amount of electric energy supplied to the resistance wires be equal to the amount of energy transferred to the room air as heat. Now let us attempt to reverse this process. It will come as no surprise that transferring some heat to the wires does not cause an equivalent amount of electric energy to be generated in the wires.



Figure 2 Transferring heat to a wire will not generate electricity

-
- Consider a paddle-wheel mechanism that is operated by the fall of a mass. The paddle wheel rotates as the mass falls and stirs a fluid within an insulated container. As a result, the potential energy of the mass decreases, and the internal energy of the fluid increases in accordance with the conservation of energy principle. However, the reverse process, raising the mass by transferring heat from the fluid to the paddle wheel, does not occur in nature, although doing so would not violate the first law of thermodynamics.

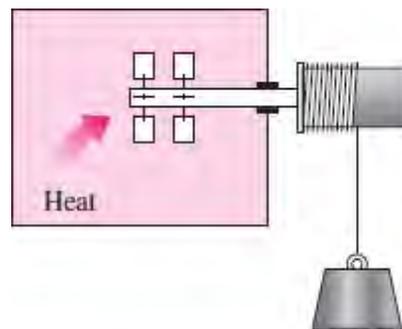


Figure 3 Transferring heat to a paddle wheel will not cause it to rotate

- Consider a running automobile vehicle stopped by applying brakes, and the process changes the kinetic energy of the vehicle in to heat and the brakes get heated up. Thus increase in internal energy of brakes in accordance with the first law. Now cooling of brakes to their initial state never puts the vehicle in to motion. Heat in the brake cannot convert to mechanical work even though that would not violate the principle of energy conversion.
- When a block slides down a rough plane, it warms. However, the reverse process where the block slides up the plane and becomes cooler is not true even though the first law will still hold good.
- Water flows from a higher level to a lower level, and reverse is not automatically possible. A mechanical energy from an external source would be required to pump the water back from the lower level to higher level.
- Fuels (coals, diesel, and petrol) burns with air to form the products of combustion. Fuels once burnt cannot be restored back to original form.
- When hydrogen and oxygen are kept in an isolated system, they produce water on chemical reaction. But the water never dissociates into hydrogen and oxygen again.
- It is clear from these above arguments that **processes proceed in a certain direction** and not in the reverse direction.



Figure 4 Processes occur in a certain direction, and not in the reverse direction

-
- A process cannot take place unless it satisfies both the first and second laws of thermodynamics.

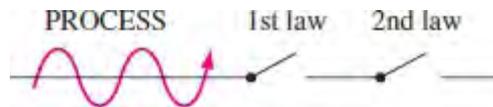


Figure 5 A processes must satisfy both the first and second laws of thermodynamics

- Therefore, it is reasonable to conclude that a process must satisfy the first law to occur. However, as explained here, satisfying the first law alone does not ensure that the process will actually take place.

3.2.1 Limitations of First Law of Thermodynamics

- First law does not help to predict whether the certain process is possible or not.
- A spontaneous process can proceed in a particular direction only, but first law does not give information about direction.
- First law not provides sufficient condition for a certain process to take place.
- First law establishes equivalence between the amount of heat used and mechanical work, but does not specify the conditions under which conversion of heat into work is possible, neither the direction in which heat transfer can take place.

3.3 Basic Definitions

3.3.1 Thermal Energy Reservoir

- “It is defined as sufficiently large system in stable equilibrium that can supply or absorb finite amount of heat without any change in its temperature.”
- A thermal reservoir is thus characterized by its temperature which remains constant.
- In practice, large bodies of water such as oceans, lakes, rivers, and atmospheric air can be considered thermal energy reservoirs.

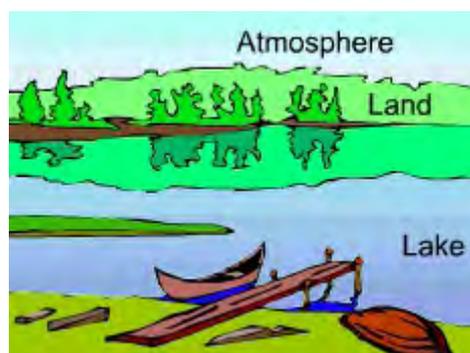


Figure 6 Thermal energy reservoirs

Heat Source

- “It is defined as the thermal reservoir which is at high temperature and supplies heat is called a heat source.” i.e. boiler furnace, combustion chamber etc.

Heat Sink

- “It is defined as the thermal reservoir which is at low temperature and to which heat is transferred is called heat sink”. i.e. atmospheric air, ocean, rivers etc.

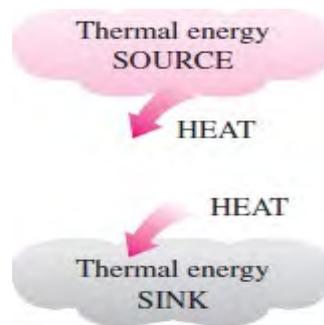


Figure 7 Heat source and Heat sink

3.3.2 Heat Engine

- “It is defined as thermodynamic device used for continuous production of work from heat when operating in a cyclic process is called heat engine”.

Characteristics of Heat Engine:

- It receives heat from a high-temperature source at temperature T_1 (furnace, nuclear reactor, solar energy etc.)
- It converts the part of this heat to work (mostly in the form of a rotating shaft).

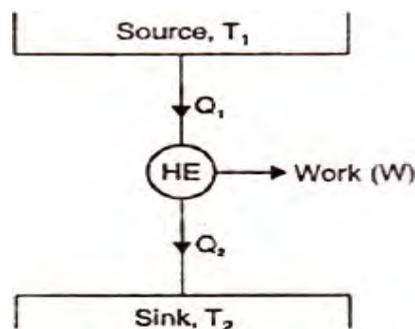


Figure 8 Heat engine

- It rejects the remaining waste heat to a low-temperature sink (the atmosphere, rivers etc.).
- It operates on complete thermodynamic cycle.

Thermal Efficiency

- “It is defined as the ratio of the desired net work output to the required heat input is called thermal efficiency.”
-

- Thus thermal efficiency of a heat engine can be expressed as,

$$\eta_{th} = \frac{\text{desired work output}}{\text{required heat input}} = \frac{W_{net}}{Q_{in}} = \frac{Q_1 - Q_2}{Q_1} = 1 - \frac{Q_2}{Q_1}$$

- Where Q_1 = Heat supplied to system, kJ
- Q_2 = Heat rejected from system, kJ
- W = Net work done by a system, kJ

3.3.3 Refrigerator

- “It is defined as the mechanical device that used for the transfer of heat from a low-temperature medium to a high-temperature medium is called refrigerator.”
- The objective of a refrigerator is to maintain the refrigerated space at a low temperature by absorbing heat from it and reject to higher-temperature medium.

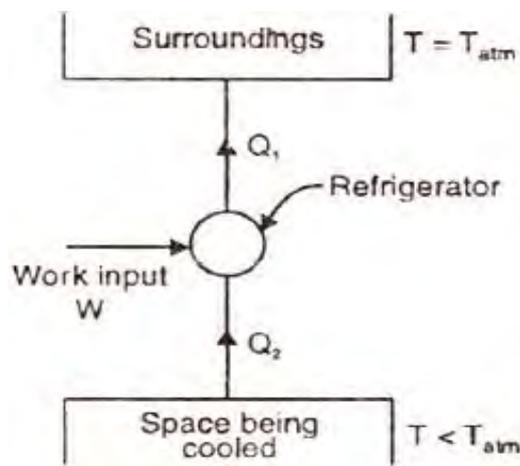


Figure 9 Refrigerator

Coefficient of Performance of Refrigerator

- “The COP of a refrigerator can be expressed as the ratio of refrigerating effect to the work input. “
- Mathematically,

$$COP_R = \frac{\text{desired output}}{\text{required input}} = \frac{\text{refrigerating effect}}{\text{work input}} = \frac{Q_2}{W_{net,in}}$$

- The conservation of energy principle for a cyclic device requires that,

$$W_{net,in} = Q_1 - Q_2$$

$$COP_R = \frac{Q_2}{Q_1 - Q_2}$$

3.3.4 Heat Pump

- “It is defined as the mechanical device that transfers heat from a low-temperature medium to a high-temperature is called heat pump.”

- The objective of heat pump is to maintain a heated space at a high temperature. This is accomplished by absorbing heat from a low-temperature source and reject to higher temperature source.

Coefficient of Performance of Heat Pump

- “The COP of a heat pump can be expressed as the ratio of heating effect to the work input”.
- Mathematically,

$$COP_{HP} = \frac{\text{desired output}}{\text{required input}} = \frac{\text{heating effect}}{\text{work input}} = \frac{Q_1}{W_{net,in}}$$

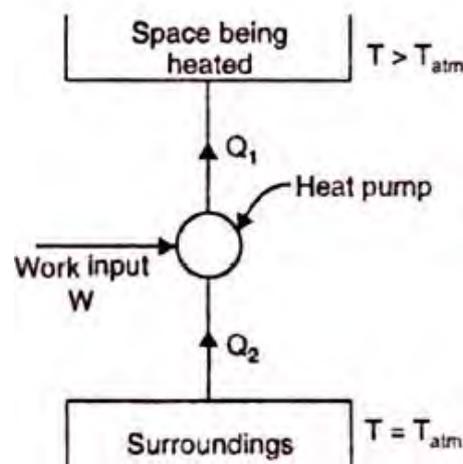


Figure 10 Heat pump

- The conservation of energy principle for a cyclic device requires that,

$$W_{net,in} = Q_1 - Q_2$$

$$COP_{HP} = \frac{Q_1}{Q_1 - Q_2}$$

3.3.5 Perpetual-Motion Machines (PMM)

- “It is defined as the device that violates either law (first or second) is called a perpetual-motion machine.”
- **PMM1:** “A device that violates the first law of thermodynamics is called a perpetual-motion machine of the first kind (PMM1).”
- **PMM2:** “A device that violates the second law of thermodynamics is called a perpetual-motion machine of the second kind (PMM2).”

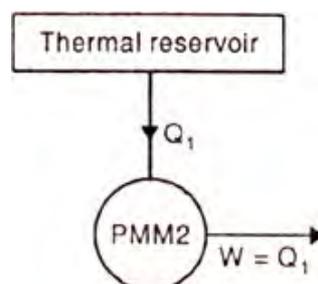


Figure 11 Perpetual motion machine of the second kind

$$\eta_{th} = \frac{W_{net}}{Q_1} = \frac{Q_1 - Q_2}{Q_1} = 1 - \frac{Q_2}{Q_1}$$

- In above equation, if $Q_2 = 0$, then $W_{net} = Q_1$ and $\eta_{th} = 100\%$. That is, if the engine exchanges heat only with one thermal reservoir, then the entire heat supplied to it gets converted into an equivalent amount of work and the efficiency becomes 100%. Such a heat engine is called a PMM2. The PMM2 is follow first law, but it violates the Kelvin-Planck statement of second law.

3.4 The Statements of Second Law of Thermodynamics

3.4.1 Kelvin-Planck Statement

- "It is impossible to construct a device that operates in thermodynamic cycle produce no effect other than work output and exchange heat with a single reservoir". (a)

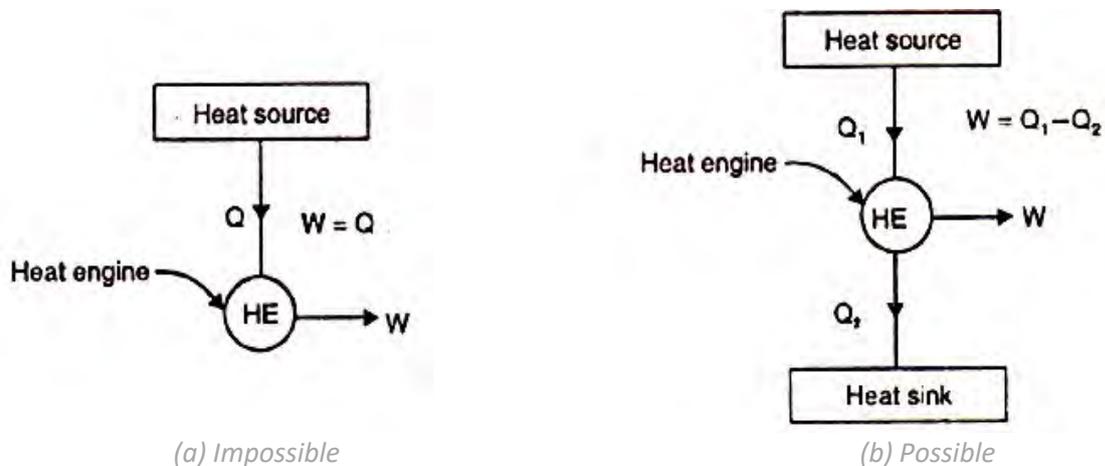


Figure 12 Schematic representation of heat engine accordance with Kelvin-Planck statement

3.4.2 Clausius Statement

- "It is impossible to construct a device that operates in a cycle and produces no effect other than the transfer of heat from a lower-temperature reservoir to a higher-temperature reservoir."

OR

- "It is impossible for any system to operate in such a way that the sole result would be an energy transfer by heat from a cooler to a hotter body."

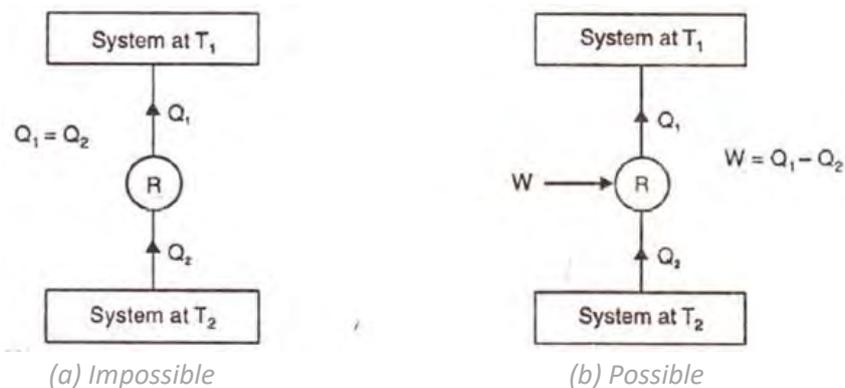


Figure 13 Schematic representation of refrigerator accordance with the Clausius statement

3.4.3 Equivalency of the Two Statements

(a) Violation of Clausius statement leading to violation of Kelvin-Planck statement.

- As shown in Fig. (a) a refrigerator R that operates in a cycle and transfers Q_2 amount of heat from low temperature reservoir at T_2 to a high temperature reservoir at T_1 without any work input. This is in violation of the Clausius statement.

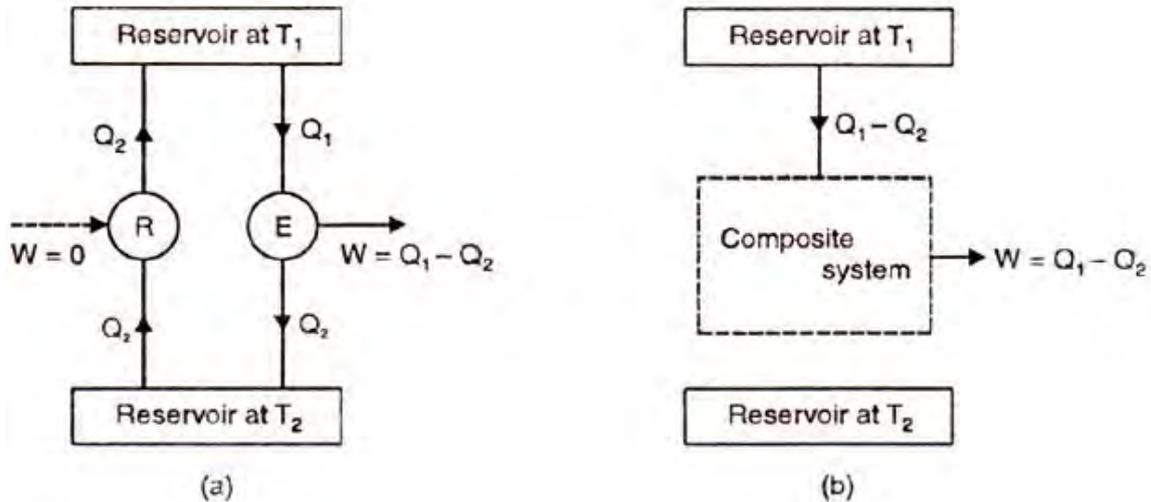


Figure 14 Proof of the violation of the Clausius statement leads to the violation of the Kelvin-Planck statement

- Along with this heat engine E , that also operates in a cycle, takes Q_1 amount of heat from the high temperature reservoir, delivers $Q_1 - Q_2$ amount of work to the surroundings and rejects the remaining Q_2 amount of heat to the low temperature reservoir.
- As shown in Fig. (b) the composite system constitutes a device that receives $Q_1 - Q_2$ amount of heat from the high temperature reservoir and converts it completely into an equivalent amount of work $W = Q_1 - Q_2$ without rejecting any heat to the low temperature reservoir. This is violation of the Kelvin-Planck statement.

(b) Violation of Kelvin-Planck statement leading to violation of Clausius statement.

- As shown in Fig. (a) an engine E which operates from a single heat reservoir at temperature T_1 . It receives Q_1 amount of heat from this reservoir and converts it completely into an equivalent amount of work $W = Q_1$ without rejecting any heat to the low temperature reservoir at T_2 . This is violation of the Kelvin-Planck statement.
- Along with this the refrigerator R which extracts Q_2 amount of heat from the low temperature reservoir, is supplied with Q_1 amount of work from an external agency (surroundings) and supplies $Q_1 + Q_2$ units of heat to the high temperature reservoir.
- As shown in Fig. (b) the work and heat interactions for the refrigerator and heat engine when coupled together. The output of the engine is utilized to drive the refrigerator.

This composite system constitutes a device which transfers heat from the low temperature reservoir to the high temperature reservoir without any work input. This is in violation of the Clausius statement. Thus violation of Kelvin-Planck statement leads to violation of Clausius statement also.

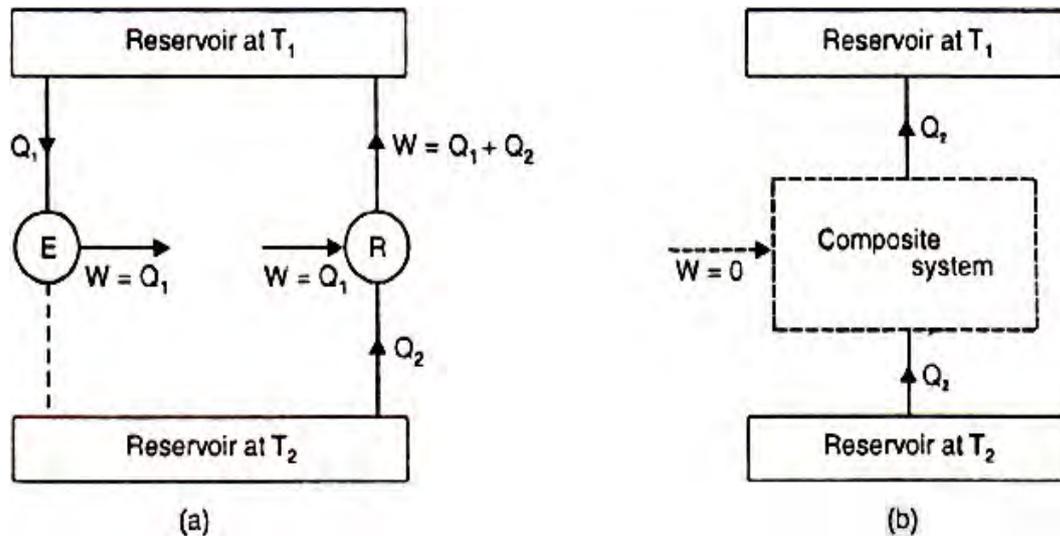


Figure 15 Proof of the violation of the Kelvin–Planck statement leads to the violation of the Clausius statement

- Therefore, the Clausius and the Kelvin–Planck statements are two equivalent expressions of the second law of thermodynamics.

3.5 Reversible and Irreversible Process

3.5.1 Reversible Process

- **Definition:** "A *reversible process* is defined as a process that can be reversed without leaving any trace on the surroundings and both the system and the surroundings are restored to their respective initial states by reversing the direction of the process".

Conditions of Reversible Process

- The process must proceed in a series of equilibrium states.
- Heat transfer should not take place with finite temperature difference.
- The process should be quasi-static and it should proceed at infinitely slow speed.
- The process should not involve friction of any kind (mechanical and intermolecular)

Salient Features

- It is quasi-static process which can be carried out in the reverse direction along the same path. It can be proceed in either direction without violating the second law of thermodynamics.
- The energy transfer as heat and work during the forward process should be identically equal to energy transfer as heat and work during the reversal of the process.
- It is possible only if the net heat and net work exchange between the system and the surroundings is zero for the combined (original and reverse) process or it leaves no trace or evidence of its occurrence in the system and surroundings.

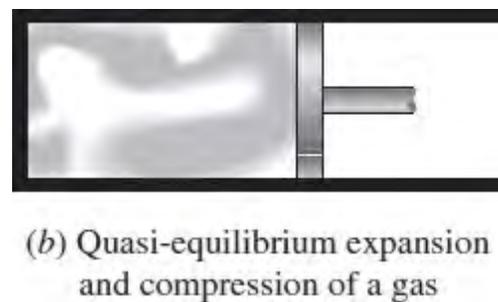
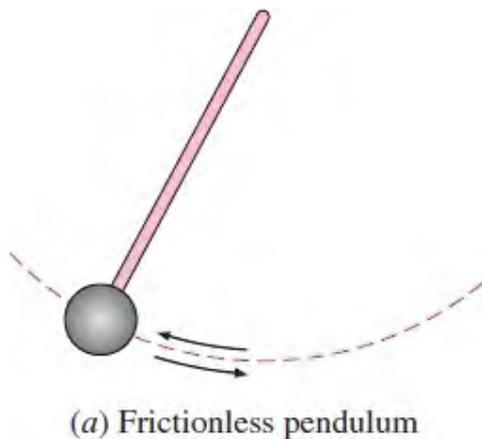
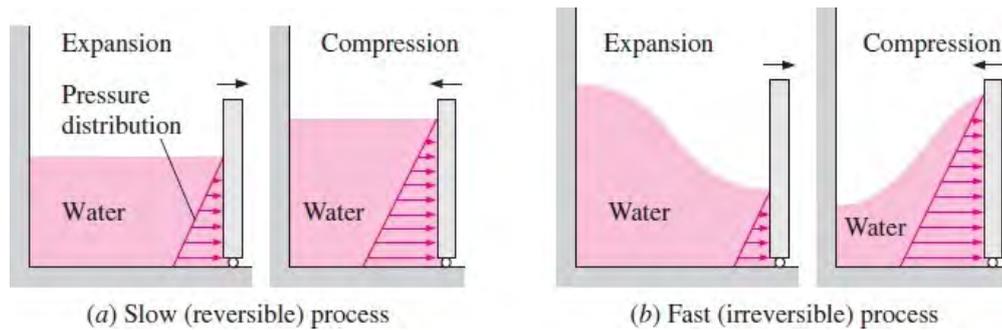


Figure 16 Reversible processes deliver the most and consume the least work

- Reversible processes can be viewed as theoretical limits for the corresponding irreversible ones.
- The more closely we approximate a reversible process, the more work delivered by a work-producing device or the less work required by a work-consuming device.
- It leads to the definition of the second law efficiency for actual processes, which is the degree of approximation to the corresponding reversible processes. This enables us to compare the performance of different devices that are designed to do the same task on the basis of their efficiencies.
- It is idealized process actually do not occur in nature.
- There should be no free or unrestricted expansion and no mixing of the fluids.
- Work done during reversible process is represented by area under process curve on p-v

diagram, and is equal to $\int_1^2 p dv$

Some Notable Examples of ideal reversible processes are:

1. Motion without friction.
2. Frictionless adiabatic and isothermal expansion or compression.
3. Restricted and controlled expansion or compression.
4. Elastic stretching of a solid.

-
5. Restrained discharge of the battery.
 6. Electric circuit with zero resistance.
 7. Polarisation, magnetisation effects and electrolysis.
 8. Condensation and boiling of liquids.

3.5.2 Irreversible Process

- **Definition:** “An *irreversible process* is defined as a process that can be reversed with permanent leaving any trace on the surroundings and both the system and the surroundings are not restored to their respective initial states by reversing the direction of the process”.
- These processes that occurred in a certain direction, once having taken place, these processes cannot reverse themselves spontaneously and restore the system to its initial state.
- *For example*, once a cup of hot coffee cools, it will not heat up by retrieving the heat it lost from the surroundings. If it could, the surroundings, as well as the system (coffee), would be restored to their original condition, and this would be a reversible process.
- It should be pointed out that a system can be restored to its initial state following a process, regardless of whether the process is reversible or irreversible. But for reversible processes, this restoration is made without leaving any net change on the surroundings, whereas for irreversible processes, the surroundings usually do some work on the system and therefore does not return to their original state.

Salient Features

1. It can be carried out in one direction.
2. It occurs at a finite rate.
3. It cannot be reversed without permanent change in surroundings.
4. The system is in never in equilibrium state at any instant during an irreversible process.

Some Notable Examples of an irreversible process are:

1. Spontaneous chemical reaction.
 2. Viscous flow, fluid flow with friction.
 3. Inelastic deformation and hysteresis effects.
 4. Electric circuit with resistance.
 5. Diffusion of gases, mixing of dissimilar gases.
 6. Heat transfer takes place with finite temperature difference.
 7. Free expansion and throttling process.
 8. Friction—sliding friction as well as friction in the flow of fluids
-

3.5.3 Irreversibilities

- **Definition:** “It is defined as the factors that cause a process to be irreversible are called irreversibilities.”

(A) Causes of Irreversibilities

- They include friction, unrestrained expansion, mixing of two fluids, and heat transfer across a finite temperature difference, electric resistance, inelastic deformation of solids, and chemical reactions. The presence of any of these effects renders a process irreversible. A reversible process involves none of these. Some of the frequently encountered irreversibilities are discussed briefly below.

1. Friction:

- When two bodies in contact are forced to move relative to each other (a piston in a cylinder, for example, as shown in Fig. a friction force that opposes the motion develops at the interface of these two bodies, and some work is needed to overcome this friction force. The energy supplied as work is eventually converted to heat during the process and is transferred to the bodies in contact, as evidenced by a temperature rise at the interface.

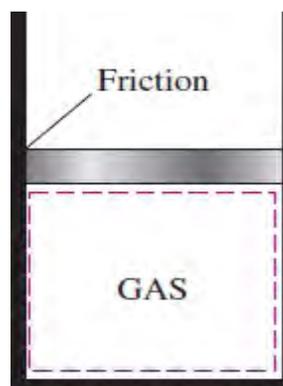


Figure 17 Friction renders a process irreversible

- When the direction of the motion is reversed, the bodies are restored to their original position, but the interface does not cool, and heat is not converted back to work. Instead, more of the work is converted to heat while overcoming the friction forces that also oppose the reverse motion. Since the system (the moving bodies) and the surroundings cannot be returned to their original states, this process is irreversible. Therefore, any process that involves friction is irreversible.

2. Unrestrained expansion:

- Unrestrained expansion of a gas separated from a vacuum by a membrane, as shown in Fig. When the membrane is ruptured, the gas fills the entire tank. The only way to restore the system to its original state is to compress it to its initial volume, while transferring heat from the gas until it reaches its initial temperature. From the conservation of energy considerations, it can easily be shown that the amount of heat transferred from the gas equals the amount of work done on the gas by the surroundings.
-

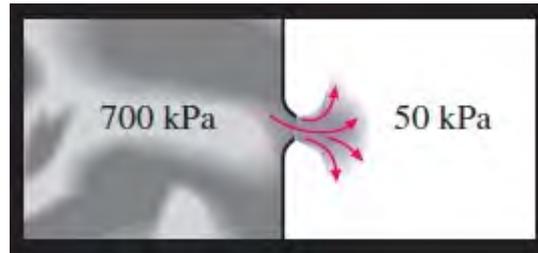


Figure 18 Unrestrained expansion of a gas makes the process Irreversible

- The restoration of the surroundings involves conversion of this heat completely to work, which would violate the second law. Therefore, unrestrained expansion of a gas is an irreversible process.

3. Heat transfer through a finite temperature difference:

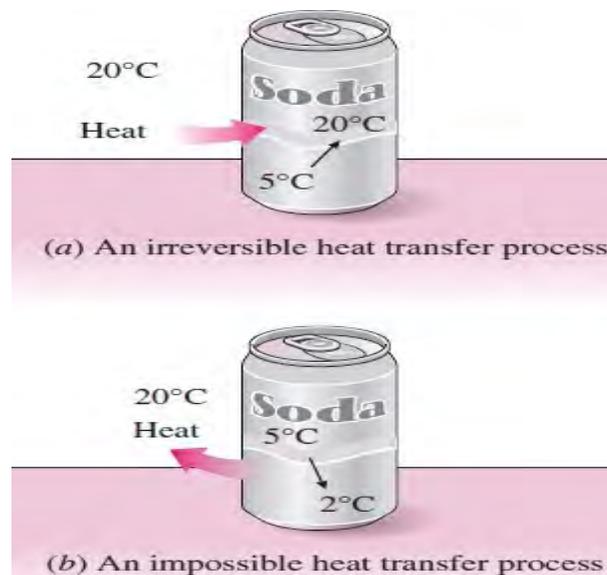


Figure 19 (a) Heat transfer through a temperature difference is irreversible, and (b) the reverse process is impossible

- Consider a can of cold soda left in a warm room Fig. Heat is transferred from the warmer room air to the cooler soda. The only way this process can be reversed and the soda restored to its original temperature is to provide refrigeration, which requires some work input. At the end of the reverse process, the soda will be restored to its initial state, but the surroundings will not be. The internal energy of the surroundings will increase by an amount equal in magnitude to the work supplied to the refrigerator. The restoration of the surroundings to the initial state can be done only by converting this excess internal energy completely to work, which is impossible to do without violating the second law.
- Since only the system, not both the system and the surroundings, can be restored to its initial condition, heat transfer through a finite temperature difference is an irreversible process.

(B) Types of Irreversibilities

- **Internally Irreversibilities:** These are associated with dissipative effects within working fluid itself.
- **Externally Irreversibilities:** These are associated with dissipative effects outside the working fluid or boundaries of the system. i.e. Mechanical friction occurring during process.

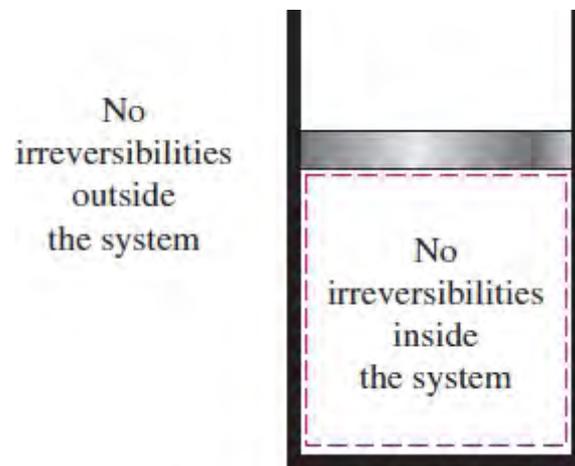


Figure 20 A reversible processes involves no internal and external irreversibilities (Totally reversible)

- As shown in Fig. Both processes are internally reversible, since both take place isothermally and both pass through exactly the same equilibrium states.
- The first process shown is externally reversible also, since heat transfer for this process takes place through an infinitesimal temperature difference dT . The second process, however, is externally irreversible, since it involves heat transfer through a finite temperature difference dT .

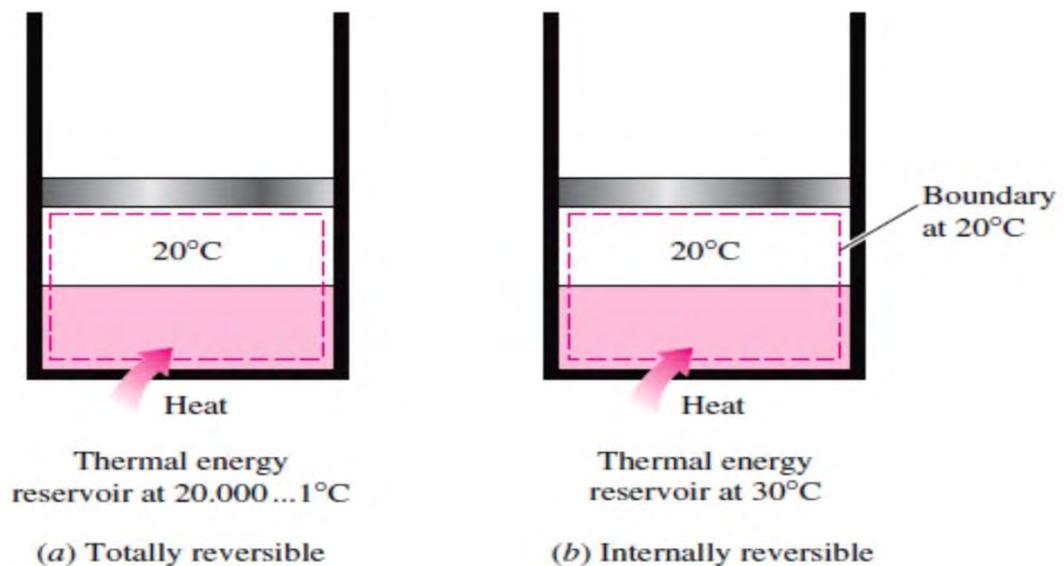


Figure 21 Totally and internally reversible heat transfer processes

- **Mechanical Irreversibilities:** These are associated with fluid friction (intermolecular friction) between the molecules and mechanical friction between the molecules and mechanical parts and friction between molecules and atmosphere.
- **Thermal Irreversibilities:** These are associated with energy transfer as heat due to a finite temperature difference between parts of system or between system and its environment.

3.6 The Carnot Cycle (Carnot Heat engine)

Assumptions for Carnot cycle

1. The piston moving in a cylinder does not develop any friction during motion.
 2. The walls of piston and cylinder are considered as perfect insulators of heat.
 3. The cylinder head is so arranged that it can be a perfect heat conductor or perfect heat insulator.
 4. The transfer of heat does not affect the temperature of source or sink.
 5. Working medium is a perfect gas and has constant specific heat.
 6. Compression and expansion are reversible.
- The Carnot cycle is composed of four reversible processes—two isothermal and two adiabatic. Consider a closed system that consists of a gas contained in an adiabatic piston–cylinder device, as shown in Fig. 3.19 the insulation of the cylinder head is such that it may be removed to bring the cylinder into contact with reservoirs to provide heat transfer.

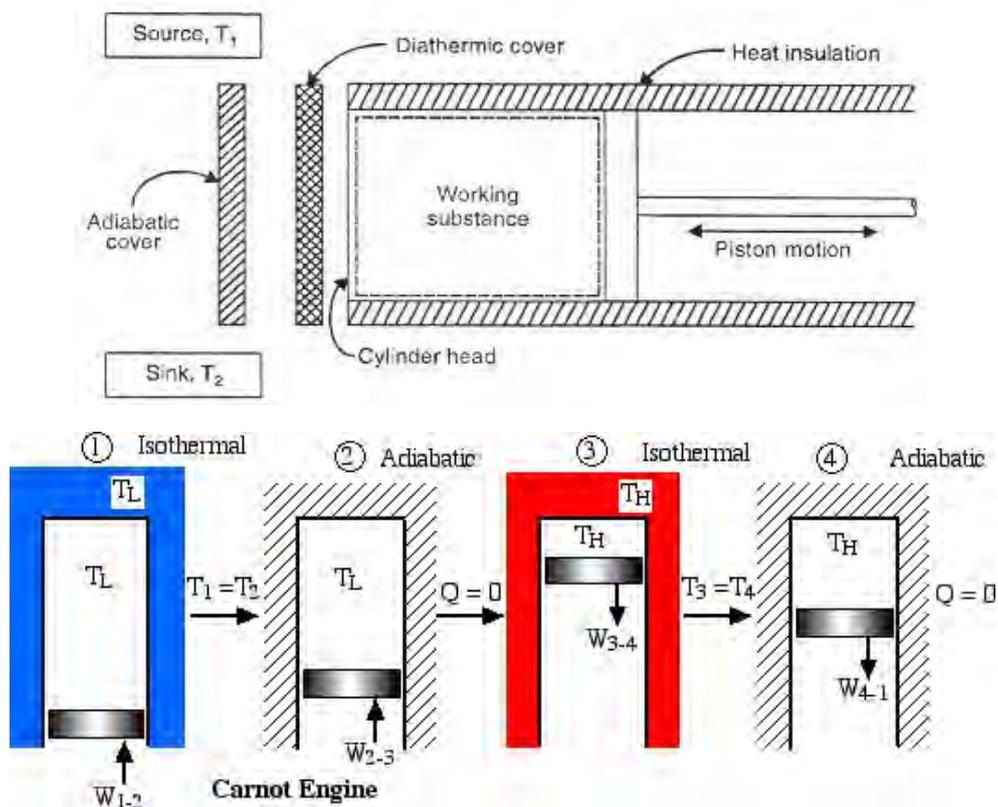


Figure 22 Carnot cycle

- *Reversible Isothermal Expansion* (process 1-2, $T_H = \text{constant}$): In this process, high temperature energy source is put contact with cylinder cover and Q_1 amount of heat is supplied while the gas expands isothermally at temperature T_H . The amount of heat transferred to the gas during this process is given by,

$$Q_1 = W_{1-2} = PV \ln \frac{V_2}{V_1} = mRT_H \ln \frac{V_2}{V_1}$$

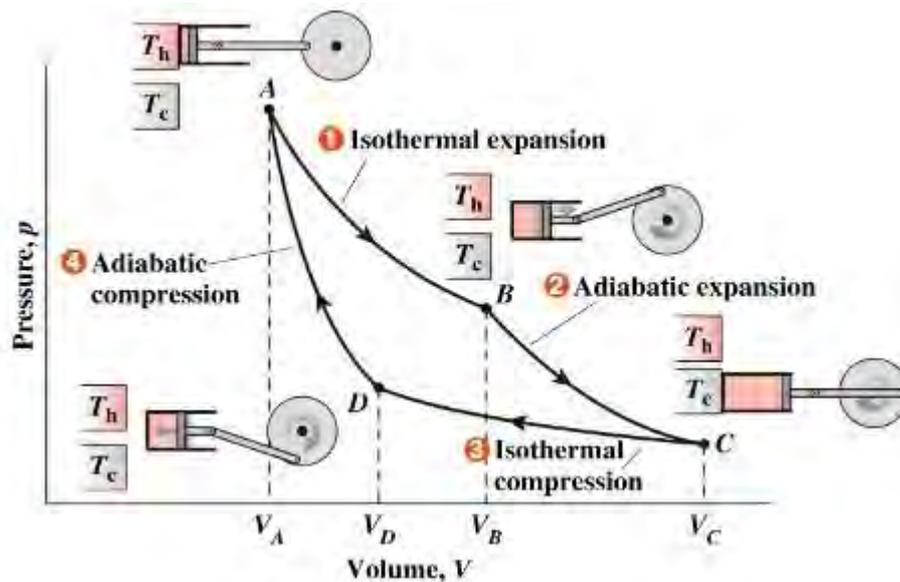


Figure 23 P-v diagram of the Carnot cycle

- *Reversible Adiabatic Expansion* (process 2-3): In this process the adiabatic cover is put contact on the cylinder head, and the gas is expanded adiabatically, thus the temperature decreases from T_H to T_L .
- *Reversible Isothermal Compression* (process 3-4, $T_L = \text{constant}$): In this process, low temperature energy sink is put contact with cylinder head cover and Q_2 amount of heat is rejected while the gas compressed isothermally at temperature T_L . The amount of total heat transferred from the gas during this process is given by,

$$Q_2 = W_{3-4} = PV \ln \frac{V_3}{V_4} = mRT_L \ln \frac{V_3}{V_4}$$

- *Reversible Adiabatic Compression* (process 4-1): In this process the adiabatic cover is put contact on the cylinder head, and the gas is compressed adiabatically, thus temperature increases from T_L to T_H and returns to its initial state 1 to complete the cycle.

- Thermal efficiency of Carnot cycle is given by,

$$\eta_{th} = \frac{W_{net}}{Q_1}$$

- As there is not heat interaction along the reversible adiabatic processes 2-3 and 4-1,

and application of first law of thermodynamics for the complete cycle gives,

$$\begin{aligned} \delta W &= \delta Q \\ W_{net} &= Q_1 - Q_2 = mRT_H \ln \frac{V_2}{V_1} - mRT_L \ln \frac{V_3}{V_4} \end{aligned}$$

- Substituting the values of W_{net} in above equation we get,

$$\begin{aligned} \eta_{th,Carnot} &= \frac{mRT_H \ln \frac{V_2}{V_1} - mRT_L \ln \frac{V_3}{V_4}}{mRT_H \ln \frac{V_2}{V_1}} \\ \eta_{th,Carnot} &= 1 - \frac{T_L \ln \frac{V_3}{V_4}}{T_H \ln \frac{V_2}{V_1}} \end{aligned}$$

- For the adiabatic expansion and compression process 2-3 and 4-1,

$$\begin{aligned} \frac{T_2}{T_3} = \frac{T_H}{T_L} = \left(\frac{V_3}{V_2} \right)^{\gamma-1} \quad \text{and} \quad \frac{T_4}{T_1} = \frac{T_H}{T_L} = \left(\frac{V_4}{V_1} \right)^{\gamma-1} \\ \frac{T_H}{T_L} = \left(\frac{V_3}{V_2} \right)^{\gamma-1} = \left(\frac{V_4}{V_1} \right)^{\gamma-1} \\ \left(\frac{V_3}{V_2} \right)^{\gamma-1} = \left(\frac{V_4}{V_1} \right)^{\gamma-1} \quad \text{or} \quad \left(\frac{V_3}{V_4} \right)^{\gamma-1} = \left(\frac{V_2}{V_1} \right)^{\gamma-1} \end{aligned}$$

- Substitute the values in above equation, we get,

$$\eta_{th,Carnot} = 1 - \frac{T_L}{T_H}$$

Conclusions from Carnot heat engine are:

1. The efficiency is independent of the working fluid and depends upon the temperature of source and sink. Being a reversible cycle, the Carnot cycle is the most efficient cycle operating between two specified temperature limits.
2. If $T_L = 0$, the engine will have an efficiency of 100%. However that means absence of heat sink which is violation of Kelvin-Planck statement of the second law.
3. The efficiency is directly proportional with the Temperature difference $T_H - T_L$ between the source and sink. Thermal efficiency increases with an increase in the average temperature at which heat is supplied to the system or with a decrease in the

average temperature at which heat is rejected from the system. If $T_H = T_L$, no work will be done and efficiency will be zero.

- Even though the Carnot cycle cannot be achieved in reality, the efficiency of actual cycles can be improved by attempting to approximate the Carnot cycle more closely.

3.7 The Reversed Carnot Cycle (Carnot Refrigerator or Carnot heat pump)

The Carnot heat-engine cycle just described is a totally reversible cycle. Therefore, all the processes that comprise it can be reversed, in which case it becomes the Carnot refrigeration cycle. Refrigerator and heat pump are *reversed heat engines*.

- **Process 1-2:** Isentropic expansion of the working fluid in the clearance space of the cylinder. The temperature falls from T_H to T_L .
- **Process 2-3:** Isothermal expansion during which heat Q_2 is absorbed at temperature T_L from the space being cooled.
- **Process 3-4:** Isothermal compression of working fluid. The temperature rises from T_L to T_H .
- **Process 4-1:** Adiabatic compression of working fluid during which heat Q_1 is rejected to a system at higher temperature.

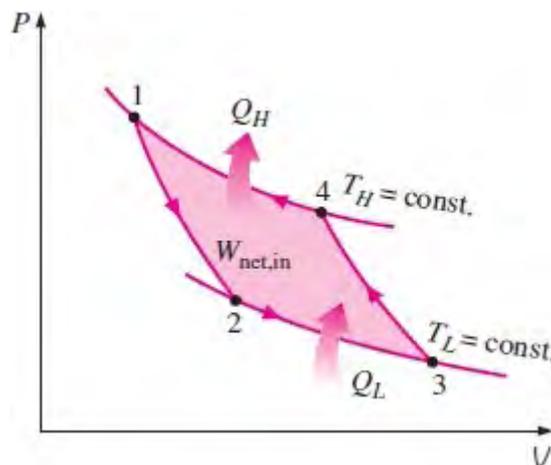


Figure 24 P-V diagram of the reversed Carnot cycle

- By using equations outlines in Carnot heat engine,
- For Carnot heat pump,

$$COP_{HP} = \frac{T_1}{T_1 - T_2}$$

- For Carnot refrigerator,

$$COP_R = \frac{T_2}{T_1 - T_2}$$

3.8 The Carnot Theorem and Carnot Corollaries

3.8.1 Carnot Theorem and Its Proof

- “The efficiency of an irreversible heat engine is always less than the efficiency of a reversible one operating between the same two reservoirs.”
- Thus if $\eta_{A(Rev)} > \eta_{B(Irev)}$

Proof of Carnot Theorem

- Consider a reversible engine E_A and an irreversible engine E_B operating between the same thermal reservoirs at temperatures T_1 and T_2 as shown in Fig. For the same quantity of heat Q withdrawn from the high temperature source, the work output from these engines is W_A and W_B respectively. As such the heat rejected is given by the reversible engine E_A is $Q - W_A$ and that from irreversible engine is $Q - W_B$.

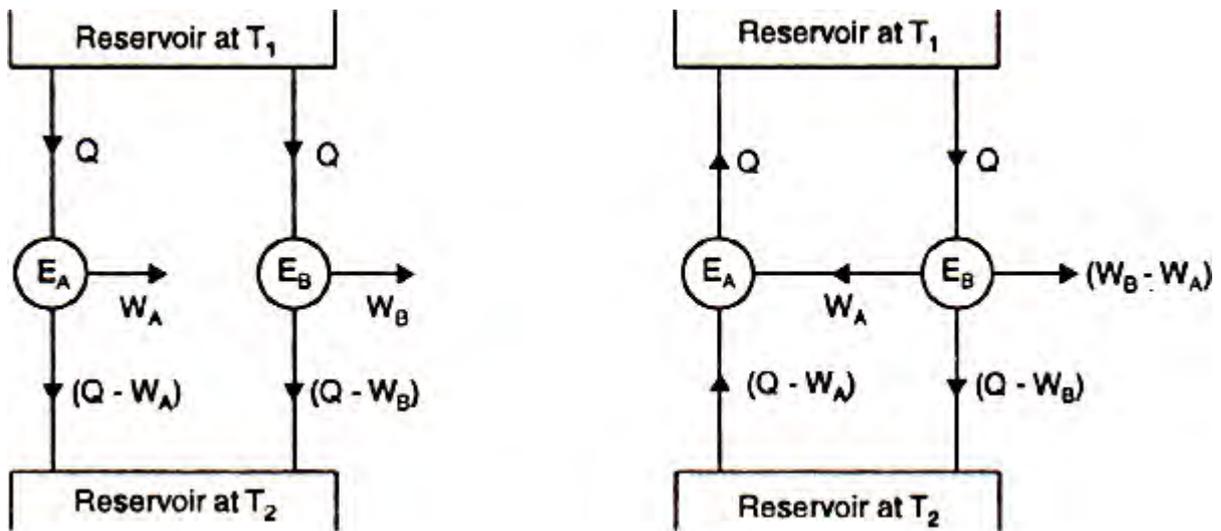


Figure 25 The proof of Carnot theorem

- Let us assume that $\eta_{B(Irev)} > \eta_{A(Rev)}$; $W_B > W_A$; $Q - W_B < Q - W_A$ (violation of Carnot theorem). Thus if irreversible engine E_B delivered $W_B - W_A$ more amount of work than the first reversible engine E_A and W_A is utilized to run reversible refrigerator R_A by reversing the reversible engine E_A then composite system as shown in Fig. is an engine that produces a net amount of work while exchanging heat with a single reservoir which is the violation of Kelvin-Planck statement (PMM-2).
- Therefore, we conclude that no irreversible heat engine can be more efficient than a reversible one operating between the same two reservoirs, thus our assumption $\eta_{B(Irev)} > \eta_{A(Rev)}$ is wrong, because $\eta_{A(Rev)} > \eta_{B(Irev)}$ is only true to satisfy Carnot theorem.

3.8.2 Carnot Corollaries

Corollary-1

- “All reversible heat engines operating between the two thermal reservoirs with fixed temperature have same efficiencies.”
- Thus $\eta_{A(Rev)} = \eta_{B(Rev)}$
- Consider a reversible engine E_A and reversible engine E_B operating between the same thermal reservoirs at temperatures T_1 and T_2 as shown in Fig. For the same quantity of heat Q withdrawn from the high temperature source, the work output from these

engines is W_A and W_B respectively. As such the heat rejected is given by the reversible engine E_A is $Q - W_A$ and that from reversible engine E_B is $Q - W_B$.

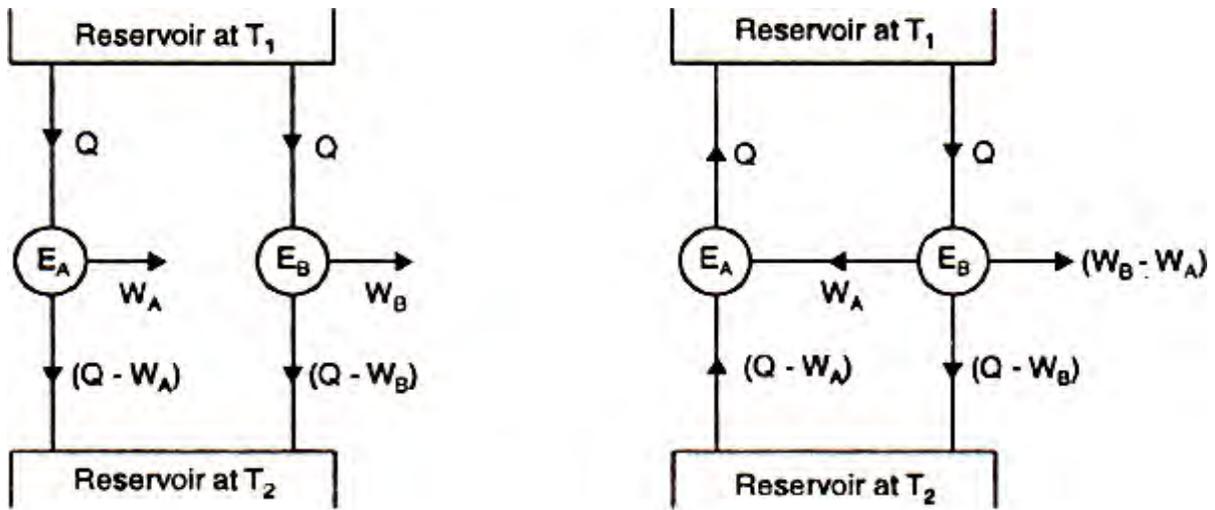


Figure 26 The proof of Carnot corollary-1

- Now let us assume that $\eta_{B(Rev)} > \eta_{A(Rev)}$; $W_B > W_A$; $Q - W_B < Q - W_A$ (violation of Carnot corollary-1). Thus reversible engine E_B delivered $(W_B - W_A)$ more amount of work than the first reversible engine E_A and W_A is utilized to run reversible refrigerator R_A by reversing the reversible engine E_A then composite system as shown in Fig. is an engine that produces a net amount of work while exchanging heat with a single reservoir which is the violation of Kelvin-Planck statement (PMM-2).
- Therefore, we conclude that no any reversible heat engine can be more efficient than other reversible heat engine when operating between the same two thermal reservoirs, thus our assumption $\eta_{B(Rev)} > \eta_{A(Rev)}$ is wrong, because $\eta_{A(Rev)} = \eta_{B(Rev)}$ is only true to satisfy Carnot corollary-1.

Corollary-2

- “The efficiency of any reversible heat engine operating between two thermal reservoirs is independent of the nature of working fluid and depends only on the temperature of thermal reservoirs.”
- as shown in Fig. The efficiency is same because both are reversible engines and work on the Carnot cycle. Efficiency depends only upon the temperature of the reservoirs. So, work is produced by engine E equal to work is required to heat pump R.
- Now assumed that, efficiency of engine E be increased by changing nature of working substance. It is as shown in fig. means that the engine E produces more work and rejects less heat to sink.

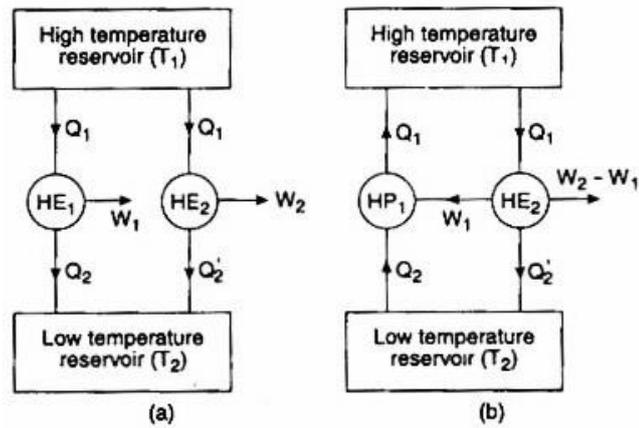
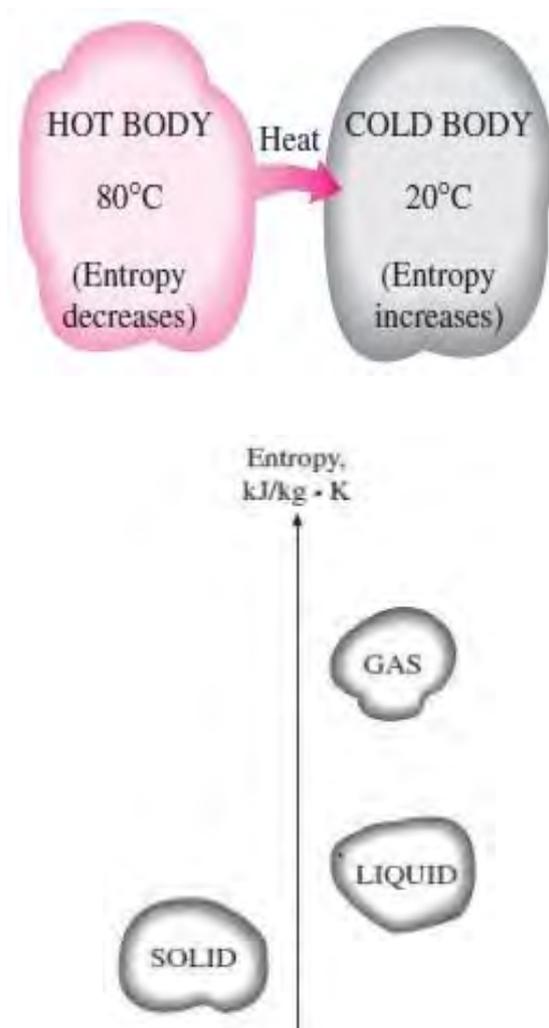


Figure 27 The proof of Carnot corollary-2

- However engine E receives Q amount of heat from source and pump R delivers same amount of heat to source. Therefore, we can eliminate high temperature source and combined system as shown in Fig. receives $W_E - W_R$ amount of heat from sink and produced same amount of work.
- This violates second law of the thermodynamics. Therefore it is concluded that efficiency does not depend on any properties of working fluid other than temperature of reservoirs.

4

ENTROPY



Course Contents

- 4.1 Introduction
- 4.2 Characteristics of entropy
- 4.3 Clausius Theorem
- 4.4 Entropy is a property
- 4.5 Clausius Inequality
- 4.6 Principle of increase of entropy
- 4.7 Applications of entropy principle
- 4.8 Change of Entropy in a Reversible Process
- 4.9 Entropy and Irreversibility
- 4.10 Entropy Changes For a Closed System
- 4.11 Third Law of Thermodynamics (Nernst Law)

4.1 Introduction

- The entropy is a thermodynamics property of a working substance and serves as a valuable tool in the second law analysis of engineering devices. We know that all heat is not equally valuable for converting into work.
- *Entropy is a function of a quantity of heat which shows the possibility of conversion of that heat into work.*
- The increase in entropy is lower when heat is added at a high temperature and the increase in entropy is higher when heat is added at a low temperature.
- The maximum entropy means, there is minimum availability for conversion into work and the minimum entropy means, there is maximum availability for conversion into work.

4.2 Characteristics of Entropy

- The characteristics of entropy in a summarised form are given below :
- Entropy is property of system.
- For reversible process between state 1 and 2, the change in entropy is given by,

$$S_2 - S_1 = \int_1^2 \left(\frac{\delta Q}{T} \right)_{\text{Rev}}$$

- The change in entropy for the system may be positive, negative or zero (depending on the heat absorption, rejection or absence)
 - Entropy is point function, independent on path of the process.
 - For a reversible process, the change in entropy for the surrounding is equal in magnitude but opposite in sign to the change in entropy for the system. so total or net change for system plus surrounding is equal to zero.
 - The increase of entropy during the process is a measure of the loss of availability of the energy of the system.
 - The entropy of a pure substance approaches zero at the absolute zero temperature.
 - From the molecular point of view, entropy can also be considered to be a measure of microscopic disorder.
 - The entropy is a measure the lack of information about a system.
 - The entropy of system is changed due to main three causes
 - a) Heat transfer - heat transfer to system increases the entropy of system, and heat transfer from system decreases the entropy of that system
 - b) Mass flow
 - c) Irreversibilities - such as friction, heat transfer due to finite temperature difference and fast expansion or compression.
-

4.3 Entropy is a Property

- Let us consider a system undergoing a reversible process from state 1 to state 2 along path A and then from state 2 to the original state 1 along path B as shown in Fig. Applying the Clausius theorem to this reversible cyclic process, we have

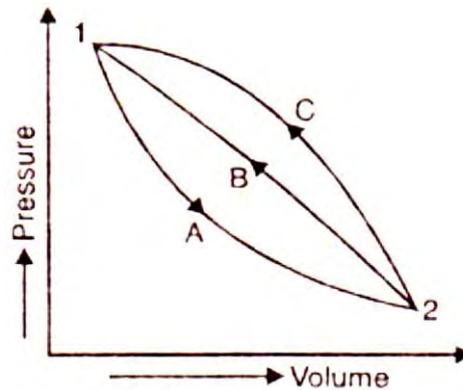


Figure 2 p-v diagram

- Hence when the system passes through the cycle 1-A-2-B-1, we have

$$\int_1^2 \frac{\delta Q}{T} + \int_2^1 \frac{\delta Q}{T} = 0$$

- Now consider another reversible cycle in which the system changes from state 1 to state 2 along path A, but returns from state 2 to the original state 1 along a different path C. For this reversible cyclic process, we have

$$\int_1^2 \frac{\delta Q}{T} + \int_2^1 \frac{\delta Q}{T} = 0$$

- From above equation we have,

–

$$\int_1^2 \frac{\delta Q}{T} = \int_2^1 \frac{\delta Q}{T}$$

- Above equation indicates that no restriction is imposed on paths, except that they must be reversible, the quantity $\frac{\delta Q}{T}$ is a function of the initial and final states of the

system and is independent of the path of the process. Hence it represents a property of the system

4.4 Applications of entropy principle

- Mixing of two fluid
- Heat transfer through a finite temperature difference
- Maximum work obtained from two finite bodies
- Minimum work required for refrigerator operates between two finite bodies
- Isothermal dissipation of work
- Adiabatic dissipation of work

4.5 Entropy and Irreversibility

- We know that change in entropy in a reversible process is equal to $\int \frac{dQ}{T}$. Let us now find the change in entropy in an irreversible process.

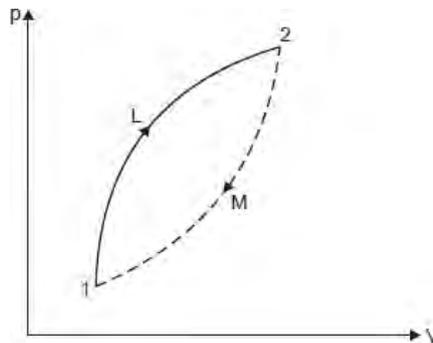


Figure 5 Entropy change for an irreversible process.

- Consider a closed system undergoing a change from state 1 to state 2 by a reversible process 1-L-2 and returns from state 2 to the initial state 1 by an irreversible process 2-M-1 as shown in Fig. on the thermodynamic coordinates, pressure and volume.
-

- Since entropy is a thermodynamic property, we can write

$$\oint dS = \int_{1(L)}^2 (dS)_R + \int_{2(M)}^1 (dS)_I = 0$$

- Now for a reversible process, from equation, we have

$$\int_{1(L)}^2 (dS)_R = \int_{1(L)}^2 \left(\frac{\delta Q}{T} \right)_R$$

- From above equation,

$$\int_{1(L)}^2 \left(\frac{\delta Q}{T} \right)_R + \int_{2(M)}^1 (dS)_I = 0$$

- Again, since in above equation the processes 1-L-2 and 2-M-1 together form an irreversible cycle, applying Clausius equality to this expression, we get

$$\oint \frac{\delta Q}{T} = \int_{1(L)}^2 \left(\frac{\delta Q}{T} \right)_R + \int_{2(M)}^1 \left(\frac{\delta Q}{T} \right)_I < 0$$

- Now subtracting above equation,

$$\int_{2(M)}^1 (dS)_I > \int_{2(M)}^1 \left(\frac{\delta Q}{T} \right)_I$$

- This for infinitesimal changes in states can be written as

$$(dS)_I > \int \left(\frac{\delta Q}{T} \right)_I$$

- Combining equation, we can write the equation in the general form as,

$$dS \geq \delta Q/T$$

- Where equality sign stands for the reversible process and inequality sign stands for the irreversible process. It may be noted here that the effect of irreversibility is always to increase the entropy of the system.

4.6 Entropy Changes For a Closed System

1) Heating of a Gas at Constant Volume Process

- Let 1 kg of gas be heated at constant volume and let the change in entropy and absolute temperature be from s_1 to s_2 and T_1 to T_2 respectively as shown in Fig.

$$\delta q = C_v dT$$

- Divided by T both the sides,

$$\frac{\delta q}{T} = C_v \frac{dT}{T}$$

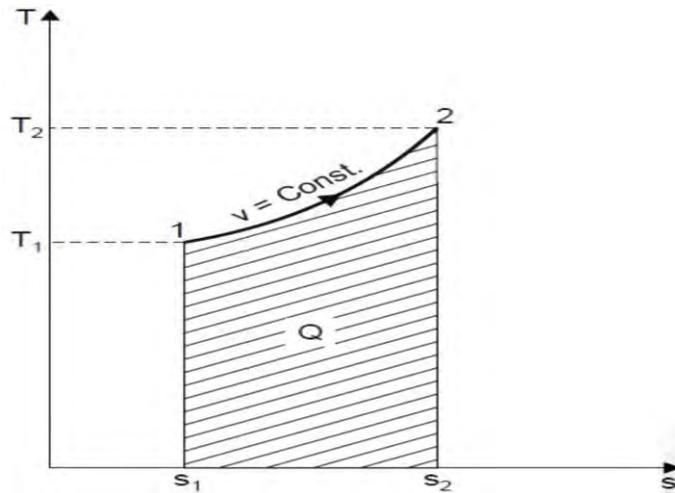


Figure 6 T-S diagram for constant volume process

- Integrating both the sides, we obtain

$$\int_1^2 ds = C_v \frac{dT}{T}$$

$$s_2 - s_1 = C_v \ln \frac{T_2}{T_1} = C_v \ln \frac{P_2}{P_1}$$

2) Heating of a Gas at Constant Pressure Process

- Let 1 kg of gas be heated at constant pressure and let the change in entropy and absolute temperature be from s_1 to s_2 and T_1 to T_2 respectively as shown in Fig.

$$\delta q = C_p dT$$

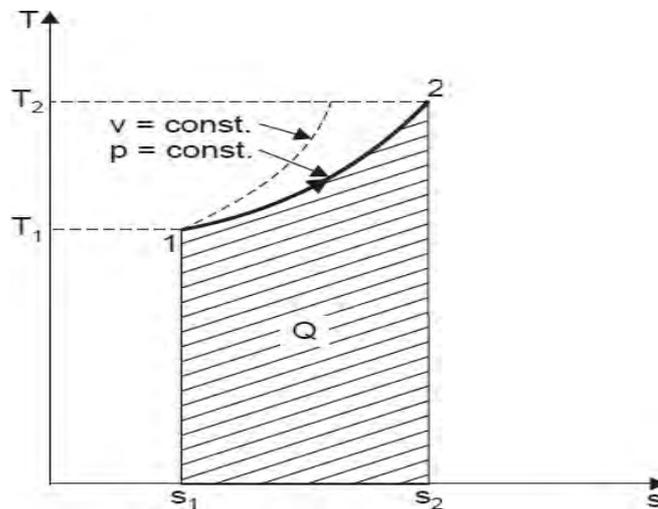


Figure 7 T-S diagram for constant pressure process

- Divided by T both the sides,

$$\frac{\delta q}{T} = C_p \frac{dT}{T}$$

- Integrating both the sides, we obtain

$$\int_1^2 ds = C_p \frac{dT}{T}$$

$$s_2 - s_1 = C_p \ln \frac{T_2}{T_1} = C_p \ln \frac{P_2}{P_1}$$

3) Heating of Gas at Isothermal Process

- An isothermal expansion 1-2 at constant temperature T is shown in Fig. Entropy changes from s_1 to s_2 when gas absorbs heat during expansion. The heat taken by the gas is given by the area under the line 1-2 which also represents the work done during expansion.

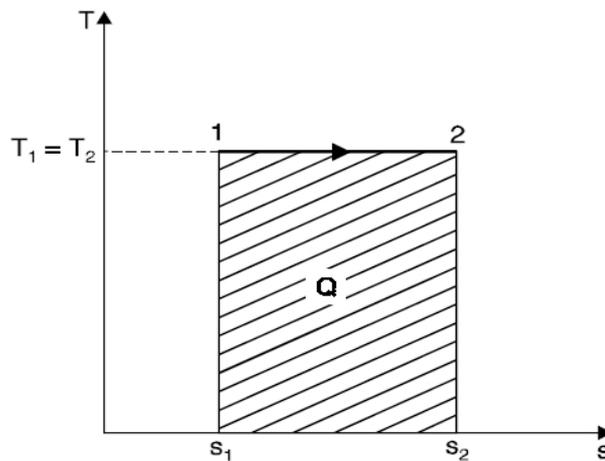


Figure 8 T-S diagram for isothermal process

- For unit mass of substance, $\delta q = du + \delta w = C_v dT + \delta w$
- If the process is reversible, $\delta w = pdv$
- Since the temperature remains constant, $du = 0$ and therefore,

$$\delta q = pdv$$

- Divided by T both the sides,

$$\frac{\delta q}{T} = \frac{pdv}{T} \text{ but } pv = RT \text{ for unit mass of the gas}$$

$$\frac{\delta q}{T} = \frac{pdv}{T}$$

$$ds = \frac{Rdv}{v}$$

- Integrating both the sides, we obtain

$$\int_1^2 ds = R \int_1^2 \frac{dv}{v}$$

$$s_2 - s_1 = R \ln \frac{v_2}{v_1} = R \ln \frac{P_1}{P_2}$$

4) Reversible Adiabatic Process (Isentropic Process)

- During an adiabatic process as heat is neither supplied nor rejected by the system,

$$\delta q = 0$$

- Divided by T both the sides then,

$$\frac{\delta q}{T} = 0$$

$$ds = 0$$

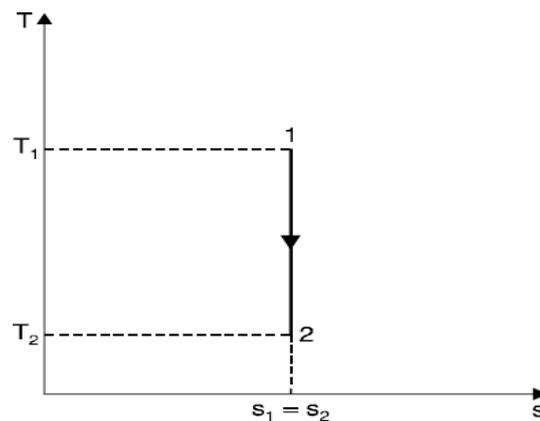


Figure 9 T-S diagram for adiabatic process

- This shows that there is no change in entropy and hence it is known as *isentropic process*. Fig. represents an adiabatic process. It is a vertical line 1-2 and therefore area under this line is nil; hence heat supplied or rejected and entropy change is zero.

5) Polytropic Process

(a) Entropy change in terms of temperature and volume:

- for unit mass of substance, $\delta q = du + \delta w = C_v dT + \delta w$

$$\delta q = C_v dT + p dv$$

- Divided by T both the sides,

$$\frac{\delta q}{T} = C_v \frac{dT}{T} + \frac{p}{T} dv \quad (pv = RT)$$

$$ds = C_v \frac{dT}{T} + \frac{R}{v} dv$$

- Integrating both the sides between initial and final states, we obtain

$$\int_1^2 ds = C_v \int_1^2 \frac{dT}{T} + R \int_1^2 \frac{dv}{v}$$

$$s_2 - s_1 = C_v \ln \frac{T_2}{T_1} + R \ln \frac{v_2}{v_1}$$

(b) Entropy change in terms of pressure and volume:

- Apply combined gas equation,

$$\frac{p_1 v_1}{T_1} = \frac{p_2 v_2}{T_2}$$

$$\frac{T_2}{T_1} = \frac{p_2 v_2}{p_1 v_1}$$

- Substitute the value of $\frac{T_2}{T_1}$ in above equation,

$$s_2 - s_1 = C_v \ln \frac{p_2 v_2}{p_1 v_1} + R \ln \frac{v_2}{v_1}$$

$$s_2 - s_1 = C_v \ln \frac{p_2}{p_1} + C_v \ln \frac{v_2}{v_1} + R \ln \frac{v_2}{v_1}$$

$$s_2 - s_1 = C_v \ln \frac{p_2}{p_1} + C_p \ln \frac{v_2}{v_1}$$

(c) Entropy change in terms of temperature and pressure:

- Apply combined gas equation,

$$\frac{p_1 v_1}{T_1} = \frac{p_2 v_2}{T_2}$$

$$\frac{v_2}{v_1} = \frac{T_2 p_1}{T_1 p_2}$$

- Substitute the value of $\frac{v_2}{v_1}$ in equation,

$$s_2 - s_1 = C_v \ln \frac{T_2}{T_1} + R \ln \frac{T_2 p_1}{T_1 p_2}$$

$$s_2 - s_1 = C_v \ln \frac{T_2}{T_1} + R \ln \frac{T_2}{T_1} + R \ln \frac{p_1}{p_2}$$

$$s_2 - s_1 = C_p \ln \frac{T_2}{T_1} + R \ln \frac{p_1}{p_2}$$

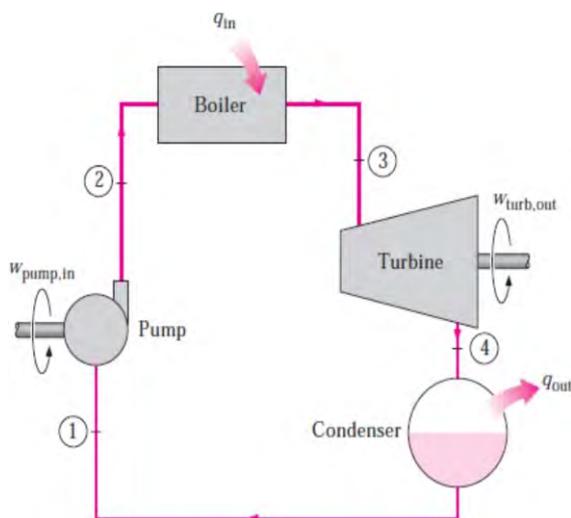
4.7 Third Law of Thermodynamics (Nernst Law)

- From a statistical point of view, entropy is a measure of molecular randomness (the uncertainty about the positions of molecules at any instant). At absolute zero temperature molecules become completely motionless. Therefore, the entropy of a pure crystalline substance at absolute zero temperature is zero since there is no uncertainty about the state of the molecules at that instant.

-
- This is third law of thermodynamics which states that
 - “The entropy of all perfect crystalline substance (solid) is zero at absolute zero temperature.’
 - If a system exists in its equilibrium crystalline state, its atoms are arranged in a pattern that represents the maximum degree of order, and if it also at absolute zero temperature, there must be a minimum of disordering thermal motion. Thus, it seems logical to assign zero absolute entropy to any system exhibiting its maximum state of order and minimum thermal motion.
 - The third law of thermodynamics provides an absolute reference point for the determination of entropy. The entropy determined relative to this reference point is called absolute entropy. Application of Third law of thermodynamics
 - (1) Provides an absolute reference point for the determination of entropy
 - (2) Explaining the behavior of solids at very low temperature.
 - (3) Measurement of action of chemical forces of the reacting substances.
 - (4) Analyzing the chemical and phase equilibrium.
-

6

VAPOR POWER CYCLES



Course Contents

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6.1 Performance Parameters of Vapor Power Cycle

a) Thermal Efficiency

Thermal efficiency is given by,

$$\eta = \frac{\text{Net work done in the cycle}}{\text{Heat supplied in the cycle}} = \frac{W_{net}}{q_1}$$

b) Work Ratio

The work ratio for a power plant is defined as ratio of the net work output of the cycle to the work developed by the turbine. It is expressed as,

$$\text{Work ratio} = \frac{W_{net}}{W_t}$$
$$\therefore \text{Work ratio} = \frac{W_t - W_p}{W_t} = 1 - \frac{W_p}{W_t}$$

A low work ratio implies large pump work. Larger the pump work, lower the work ratio.

c) Steam Rate or Specific Steam Consumption (SSC)

It is defined as the flow rate of steam per unit of power developed (kWh).

$$SSC = \frac{\text{Steam flow rate}}{\text{Power output}}$$
$$SSC = \frac{3600}{W_{net}} \cdot \frac{kg}{kWh}$$

Where, W_{net} is in kJ/kg.

d) Heat Rate

Thermal efficiency can be expressed as heat rate, which is a measure of the rate of heat input q_1 required to produce unit work output (1kW).

$$\text{Heat rate} = \frac{3600 \times q_1}{W_{net}}$$

$$\therefore \text{Heat rate} = \frac{3600}{\eta_{th}} \text{ kJ/kWh}$$

6.2 The Carnot Vapor Cycle

The Carnot cycle is the most efficient cycle operating between two specified temperature limits. The Carnot cycle is an ideal cycle for vapor power plants. However, the Carnot cycle is not a suitable model for power cycles, as there are so many practical difficulties associated with it (discussed later).

- Fig. 6.1 shows P-v, T-S, h-S and schematic diagram of the Carnot cycle when steam is used as the working substance.

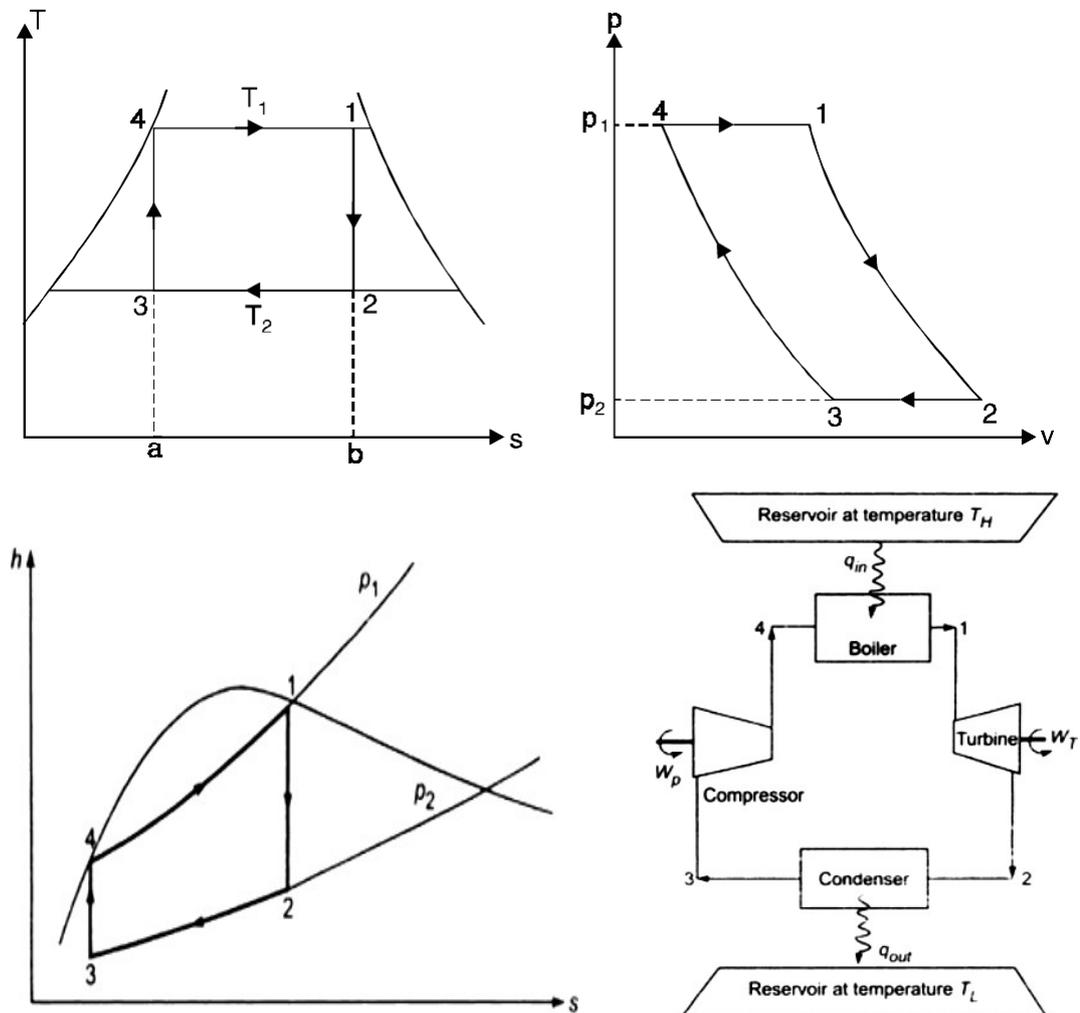


Fig. 6.1 P-v, T-S, h-S and schematic diagram of Carnot vapor cycle

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- Consider 1 kg of steam as a working substance for the analysis. The cycle is composed of two isentropic and two isothermal processes. Since the working fluid is vapor, the isothermal processes are also the constant pressure processes. These processes are discussed below:

- **Process 4 – 1: Reversible isothermal heat addition in the boiler**

Heat is supplied to the feed water (saturated water) in a boiler. Latent heat is supplied and isothermal evaporation of water takes place at constant pressure until the water gets converted into dry & saturated steam.

Heat added isothermally at temperature T_1 is given by,

$$q_1 = h_1 - h_4$$

- **Process 1 – 2: Isentropic expansion in the turbine**

The dry & saturated steam undergoes frictionless adiabatic expansion in the steam turbine and work is done by the system(+ve).

Turbine work is given by,

$$w_t = h_1 - h_2$$

- **Process 2 – 3: Controlled condensation in the condenser**

Steam leaving the turbine is condensed isothermally at constant pressure. Heat rejected isothermally at temperature T_2 is given by,

$$q_2 = h_2 - h_3$$

- **Process 3 – 4: Isentropic compression in the pump (Pumping process)**

The wet steam is compressed isentropically and it is restored to initial state point 4 and work is done on the steam(-ve).

Compressor work is given by,

$$w_c = h_4 - h_3$$

Thermal Efficiency of Carnot Vapor Cycle

- Thermal efficiency,

$$\eta = \frac{\text{Net Work}}{\text{Heat Supplied}}$$

$$\eta = \frac{w_{net}}{q_1} \text{ --- (6.1)}$$

- **Heat supplied** to the working fluid in a boiler,

$$q_1 = \text{Area under the line 4 - 1 in } T - s \text{ diagram}$$

$$q_1 = T_1 dS = T_1(S_1 - S_4)$$

As $S_1 = S_2$ and $S_3 = S_4$

$$\therefore q_1 = T_1(S_2 - S_3) \text{ --- --- --- --- --- (6.2)}$$

- **Heat rejected** during condensation process,

$q_2 = \text{Area under the line 2 - 3 in } T - s \text{ diagram}$

$$q_2 = T_2 dS = T_2(S_2 - S_3) \text{ --- --- --- --- --- (6.3)}$$

- The **net work done** of the cycle,

$$w_{net} = q_1 - q_2$$

From equation 6.2 and 6.3,

$$\begin{aligned} \therefore w_{net} &= T_1(S_2 - S_3) - T_2(S_2 - S_3) \\ \therefore w_{net} &= (S_2 - S_3)(T_1 - T_2) \quad \text{---(6.4)} \end{aligned}$$

- From equation 6.1, Thermal

efficiency,

$$\begin{aligned} \eta_{Carnot} &= \frac{(S_2 - S_3)(T_1 - T_2)}{T_1(S_2 - S_3)} \\ \therefore \eta_{Carnot} &= \frac{(T_1 - T_2)}{T_1} \\ \therefore \eta_{Carnot} &= 1 - \frac{T_2}{T_1} \quad \text{---(6.5)} \end{aligned}$$

- Equation 6.5 of Carnot vapor cycle efficiency is similar to the Carnot gas power cycle. It shows that, the efficiency of Carnot cycle is depends upon the limit of temperatures and is independent of the nature of working substance.

Practical Difficulties Associated with Carnot Vapor Power Cycle

- I. The cycle is more difficult to operate in practice with superheated steam due to the necessity of supplying the superheat at constant temperature. So maximum possible temperature is limited.
- II. In the turbine, the dry and saturated steam expands isentropically. The quality of steam decreases during expansion. The presence of high moisture content in steam will lead to erosion and wear of the turbine blades.
- III. It is difficult to control the condensation at state 3, before reaching to saturated liquid state.
- IV. It is difficult to compress a wet vapor (water + steam) isentropically, as required by the process 3-4. Because of large specific volume of vapor than liquid, the compressor size and work input will have to be large and this higher compression work will reduce the thermal efficiency of the plant.

6.3 The Rankine Cycle

- Many practical difficulties associated with the Carnot vapor cycle can be eliminated in Rankine cycle. The steam coming out of the boiler is usually in superheated state, and expands in the turbine. After expanding in the turbine, the steam is condensed completely in the condenser.
- The Rankine cycle is the ideal cycle for vapor power plants. The ideal Rankine cycle is shown schematically and on a P-v, T-s & h-s diagrams in Fig. 6.2. The liquid, vapor and wet regions are also indicated with the help of saturation curve.

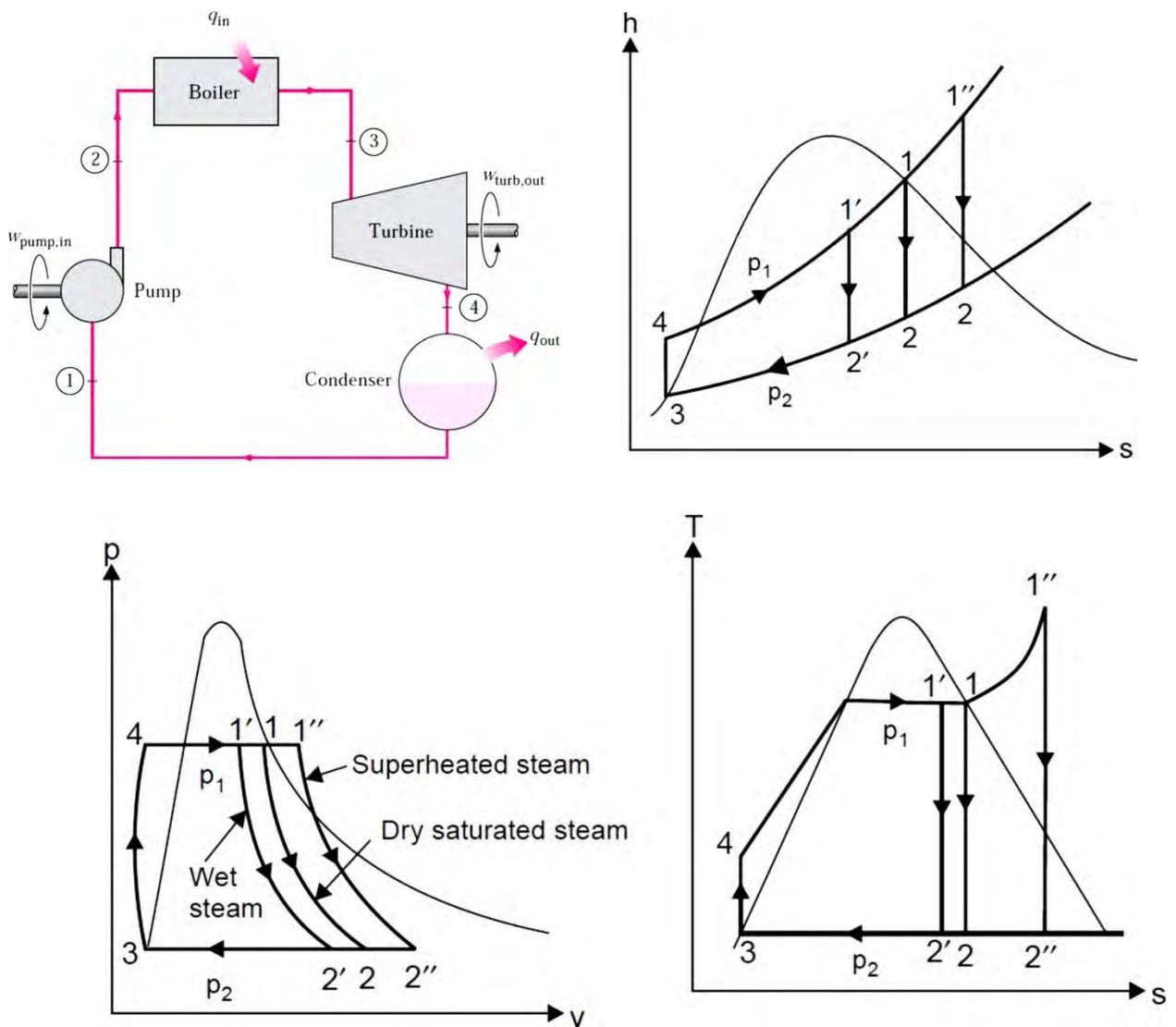


Fig. 6.2 P-v, T-S, h-S and schematic diagram of an ideal Rankine cycle

The ideal Rankine cycle consists of the following four processes:

- **Process 4 – 1: Constant pressure heat addition in the boiler**

Heat is supplied to the feed water (compressed liquid) in a boiler. Sensible heat and latent heat is supplied to the compressed liquid until the liquid gets converted into superheated steam.

Heat supplied is given by,

$$q_1 = h_1 - h_4$$

- **Process 1 – 2: Isentropic expansion in the turbine**

The superheated steam undergoes frictionless adiabatic expansion in the steam turbine and work is done by the system(+ve). Pressure of steam is reduced to condenser pressure.

Turbine work is given by,

$$w_t = h_1 - h_2$$

– **Process 2 – 3: Constant pressure heat rejection in the condenser**

Steam leaving the turbine (normally wet steam) is condensed at constant pressure in the condenser till the fluid reaches the saturated liquid state 3. Heat rejected is given by,

$$q_2 = h_2 - h_3$$

– **Process 3 – 4: Isentropic compression in the pump (Pumping process)**

The saturated liquid is compressed isentropically in the pump to the boiler pressure at the state 4 and work is done on the liquid(–ve).

Pump work is given by,

$$w_p = h_4 - h_3$$

Thermal Efficiency of Rankine Cycle

– Thermal efficiency,

$$\eta = \frac{\text{Net Work}}{\text{Heat Supplied}}$$
$$\eta = \frac{w_{net}}{q_1} \text{-----(6.6)}$$

- **Heat supplied** to the working fluid in a boiler during process 4 – 1,

$$q_1 = h_1 - h_4 \text{ --- (6.7)}$$

- **Turbine work** during process 1 – 2,

$$w_t = h_1 - h_2 \text{ --- (6.8)}$$

- **Heat rejected** during condensation process 2 – 3,

$$q_2 = h_2 - h_3 \text{ --- (6.9)}$$

- **Pump work** during process 3 – 4,

$$w_p = h_4 - h_3 \text{ --- (6.10)}$$

Where,

$h_3 = h_{f3}$ = Enthalpy of saturated liquid at condenser pressure P_2

h_4 = Enthalpy of compressed liquid at boiler pressure P_1 and can be calculated as,

$$h_4 = h_3 + w_p \text{ --- (6.11)}$$

Isentropic compression work for the flow process can be obtained as,

$$w_p = \int_{P_2}^{P_1} v_{f3} dP = v_{f3}(P_1 - P_2) \text{ --- (6.12)}$$

Where,

v_{f3} = Specific volume of liquid at condenser pressure P_2

- The **net work done** of the cycle,

$$w_{net} = w_t - w_p$$

From equation 6.8 and

6.12,

$$\therefore w_{net} = (h_1 - h_2) - v_{f3}(P_1 - P_2) \text{ --- (6.13)}$$

- From equation 6.6, 6.7 and

6.13, Thermal efficiency,

$$\eta_{Rankine} = \frac{w_{net}}{q_1} = \frac{(h_1 - h_2) - v_{f3}(P_1 - P_2)}{(h_1 - h_4)} \text{ --- (6.14)}$$

- Since feed pump work is very small compared to turbine work, w_p is usually neglected.

$$\therefore \eta_{Rankine} = \frac{(h_1 - h_2)}{(h_1 - h_4)} \text{ --- (6.15)}$$

6.4 Differences Between Carnot and Rankine Cycles

Sr. No.	Carnot Vapor Cycle	Rankine Cycle
1	It is a reversible cycle.	It is an irreversible cycle.
2	It has theoretically maximum efficiency.	It has less thermal efficiency than that of the Carnot vapor cycle.
3	Heat is added at constant temperature.	Heat is added at constant pressure.
4	Use of superheated steam is practically difficult.	It uses superheated steam and performs better.
5	Controlled condensation is required before being saturated liquid.	Complete condensation of steam takes place.
6	Mixture of water and steam exist after condensation.	Only saturated water exists after condensation.
7	It requires a large pump work to handle the two phase mixture.	It requires negligible pump work to handle the liquid water only.
8	Since it uses saturated steam, the moisture content at the end of expansion is much higher which can lead to blade erosion.	It uses superheated steam in the cycle, at the end of expansion; the quality of steam is not objectionable.
9	It is a theoretical cycle and cannot be used in practice.	Almost all thermal power plants operate on Rankine cycle.

6.5 Effect of Operating Variables on Rankine Cycle Performance

- Steam power plants are responsible for the production of most electric power in the world, and even small increases in thermal efficiency can mean large savings from the fuel requirements. Therefore, every effort is made to improve the efficiency of the cycle on which steam power plants operate.
- The basic idea behind all the modifications to increase the thermal efficiency of a power cycle is the same: **Increase the average temperature at which heat is transferred to the working fluid in the boiler, or decrease the average temperature at which heat is rejected from the working fluid in the condenser.** That is, the average fluid temperature should be as high as possible during heat addition and as low as possible during heat rejection. It can be seen from equation 6.16.

Mean Temperature of Heat Addition

- ✓ From the T-s diagram of Rankine cycle we can derive efficiency of Rankine cycle as below:

$$\eta_{Rankine} = \frac{W_{net}}{q_1} = \frac{q_1 - q_2}{q_1}$$

$$\therefore \eta_R = 1 - \frac{q_2}{q_1}$$

$$\therefore \eta_R = 1 - \frac{T_L(s_1 - s_4)}{T_m(s_1 - s_4)}$$

$$\therefore \eta_{Rankine} = 1 - \frac{T_L}{T_m} \text{----- (6.16)}$$

Where,

T_L = Temperature of heat rejection

T_m = Mean temperature of heat addition

- The effect of operating variables i.e. boiler pressure, condenser pressure and superheating are discussed below:

1) Effect of Boiler Pressure

- The effect of **increasing the boiler pressure** on the performance of Rankine cycle is illustrated on a T-s diagram in Fig. 6.3.
- By increasing the boiler pressure, the mean temperature of heat addition increases, and thus raises the thermal efficiency of the cycle.

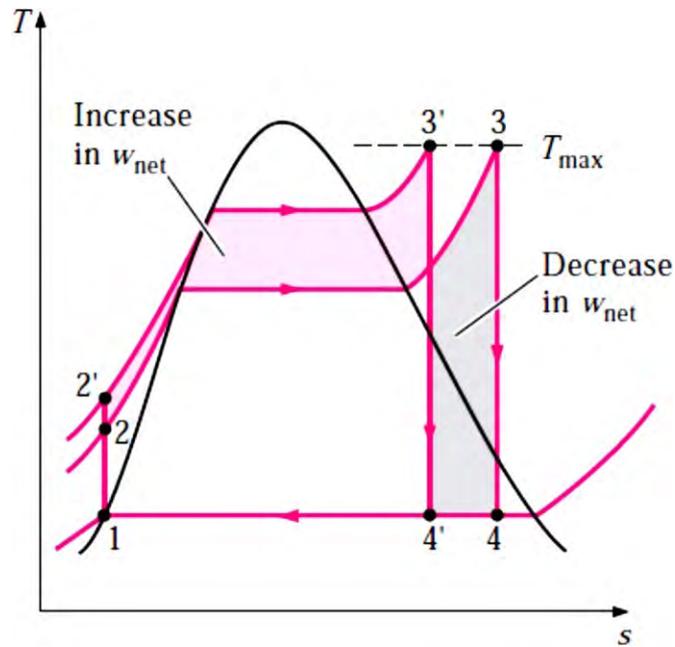


Fig. 6.3 Effect of boiler pressure on Rankine cycle performance

- Notice that for a fixed turbine inlet temperature and condenser pressure, the cycle shifts to the left and the moisture content of steam at the turbine exit increases. This undesirable side effect can be corrected, however, by reheating the steam (discussed later).
- The net work done by the cycle remains almost same, thus, the Rankine cycle efficiency increases, with an increase in maximum pressure or boiler pressure.

2) Effect of Condenser Pressure

- The effect of lowering the condenser pressure on the Rankine cycle efficiency is illustrated on a T-s diagram in Fig. 6.4.

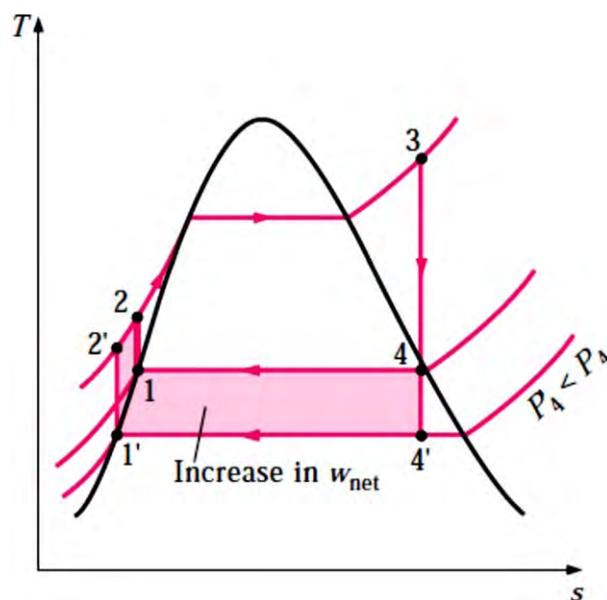


Fig. 6.4 Effect of condenser pressure on the Rankine cycle performance

- The steam enters the condenser as a saturated mixture of vapor and moisture at the saturation temperature corresponding to the pressure inside the condenser. **If this condenser pressure lowered**, the saturation temperature of exhausted steam is decreases, and thus, the amount of heat rejection in the condenser also decreases, which will increase the efficiency of Rankine cycle.
- For comparison purposes, the turbine inlet state is maintained the same. The colored area on this diagram represents the increase in net work output as a result of lowering the condenser pressure from P_4 to P'_4 . The heat input requirements also increase (represented by the area under curve 2 to 2'), but this increase is very small. Thus the overall effect of lowering the condenser pressure is an increase in the thermal efficiency of the cycle.
- However there are limitations to this method. These are
 - Lowering the condenser pressure causes an increase in moisture content of the steam leaving the turbine. It is an unfavorable effect and may lead to turbine blade erosion.
 - To maintain the high vacuum, the air extraction pump will run continuously and its work input will increase, thus reducing the useful work.

3) Effect of Superheating

- The effect of superheating on the performance of Rankine cycle is illustrated on a T-s diagram in Fig. 6.5.

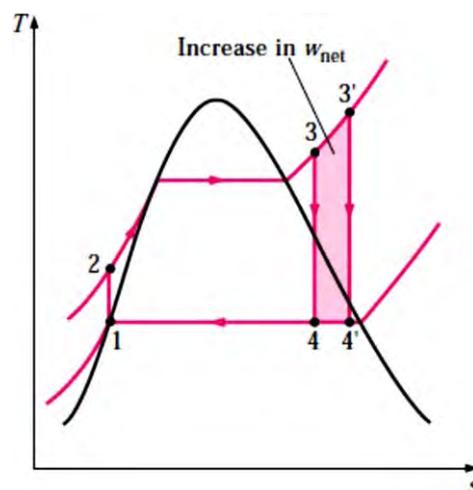


Fig. 6.5 Effect of superheating on Rankine cycle performance

- The colored area on this diagram represents the increase in the net work. The total area under the process curve 3-3' represents the increase in the heat input. Thus both the net work and heat input increase as a result of superheating the steam to a higher temperature.
- The overall effect is an increase in thermal efficiency, however, since the average temperature at which heat added is increases.

-
- Superheating the steam to higher temperatures has another very desirable effect: It decreases the moisture content of the steam at the turbine exit, as can be seen from the T-s diagram.
 - However the metallurgical considerations restrict the superheating of steam to a very high temperature.

Quick Review:

- *We can conclude that the efficiency of Rankine cycle can be increases by lowering the condenser pressure, by increasing the boiler pressure and by superheating the steam.*
- *The quality of steam leaving the turbine decreases by lowering the condenser pressure and by increasing the boiler pressure, while it improves by superheating.*

6.6 Reheat Rankine Cycle

- Increasing the boiler pressure increases the thermal efficiency of the Rankine cycle, but it also increases the moisture content of the steam to unacceptable levels. This side effect can be corrected by reheating the steam.
 - Reheating is a practical solution to the excessive moisture problem in turbines, and it is commonly used in modern steam power plants.
 - Reheating is to be done by allowing the steam to expand in the turbine in two or more stages and reheat it in between. In other words, modify the simple ideal Rankine cycle with a reheat process.
 - Due to reheating, the work output of the turbine increases, thus improving the thermal efficiency.
 - The T-s diagram of the ideal reheat Rankine cycle and the schematic of the power plant operating on this cycle are shown in Fig. 6.6.
 - The ideal reheat Rankine cycle differs from the simple ideal Rankine cycle in that the expansion process takes place in two stages. In the first stage (the high pressure turbine), steam is expanded isentropically to an intermediate pressure and sent back to the boiler where it is reheated at constant pressure, usually to the inlet temperature of the first turbine stage. Steam then expands isentropically in the second stage (low-pressure turbine) to the condenser pressure.
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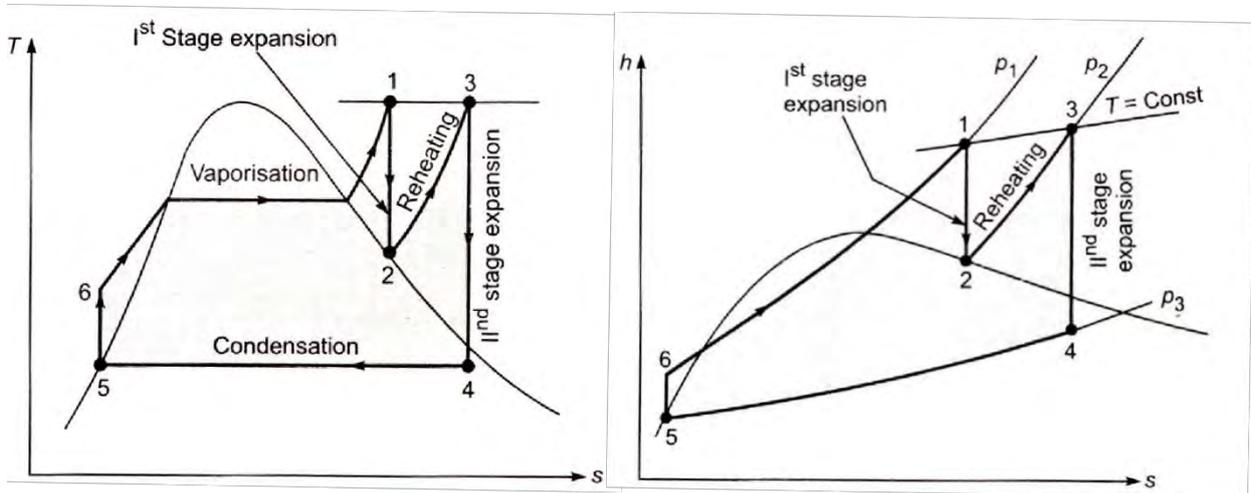
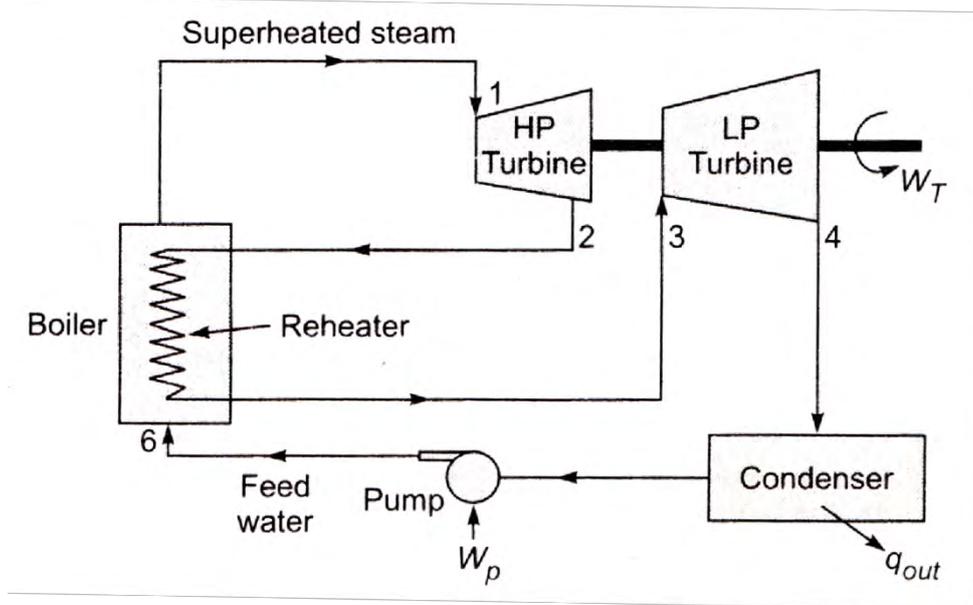


Fig. 6.6 Schematic, T - s and h - s diagram of Reheat Rankine cycle

- **Turbine work** per unit mass of steam,

$$w_t = \text{WD in the HP turbine} + \text{WD in the LP turbine}$$

$$w_t = (h_1 - h_2) + (h_3 - h_4)$$

- **Pump work** per unit mass of steam,

$$w_p = (h_6 - h_5)$$

- **Net work done** per unit mass of steam,

$$w_{net} = w_t - w_p$$

$$\therefore w_{net} = (h_1 - h_2) + (h_3 - h_4) - (h_6 - h_5)$$

- **Heat supplied** per unit mass of steam,

$$q_s = \text{Heat supplied in boiler} + \text{Heat supplied in reheater}$$

$$\therefore q_s = (h_1 - h_6) + (h_3 - h_2)$$

-
- Reheat cycle efficiency,

$$\eta_{reheat} = \frac{\text{Net work done}}{\text{Heat supplied}}$$

$$\therefore \eta_{reheat} = \frac{W_{net}}{q_s}$$

$$\therefore \eta_{reheat} = \frac{(h_1 - h_2) + (h_3 - h_4) - (h_6 - h_5)}{(h_1 - h_6) + (h_3 - h_2)} \text{-----(6.17)}$$

-
- The reheat cycle reduces the moisture content at low pressure turbine and accordingly the erosion and corrosion problems in the turbine are eliminated.
 - It is evident from the T-s diagram that there is very less gain in the thermal efficiency by reheating the steam. However, the mean temperature of heat addition can be increased by including the number of expansion and reheating processes. Thus, the thermal efficiency of the cycle would further increase.

Advantages of Reheating:

- a) There is an increased output of the turbine.
- b) Erosion and corrosion problems in the steam turbine are eliminated/avoided.
- c) There is an improvement in the thermal efficiency of the turbines.
- d) Final dryness fraction of steam is improved.
- e) There is an increase in the nozzle and blade efficiencies.

Disadvantages of Reheating:

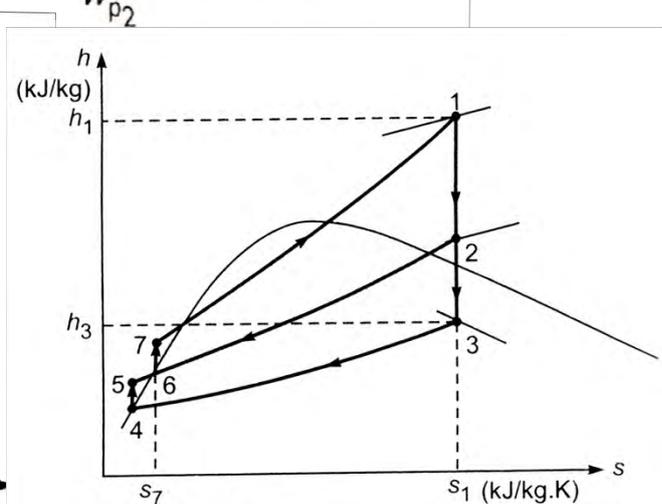
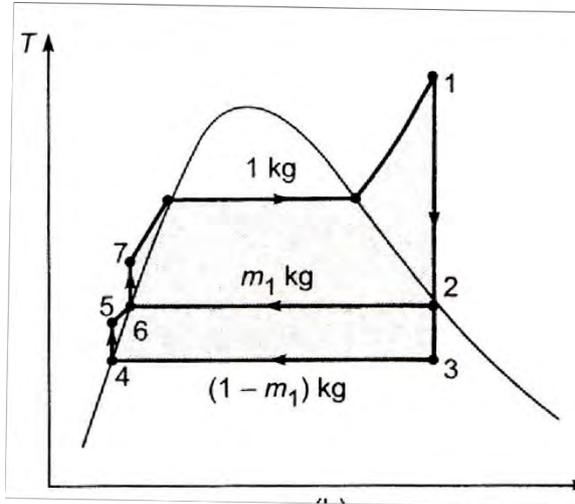
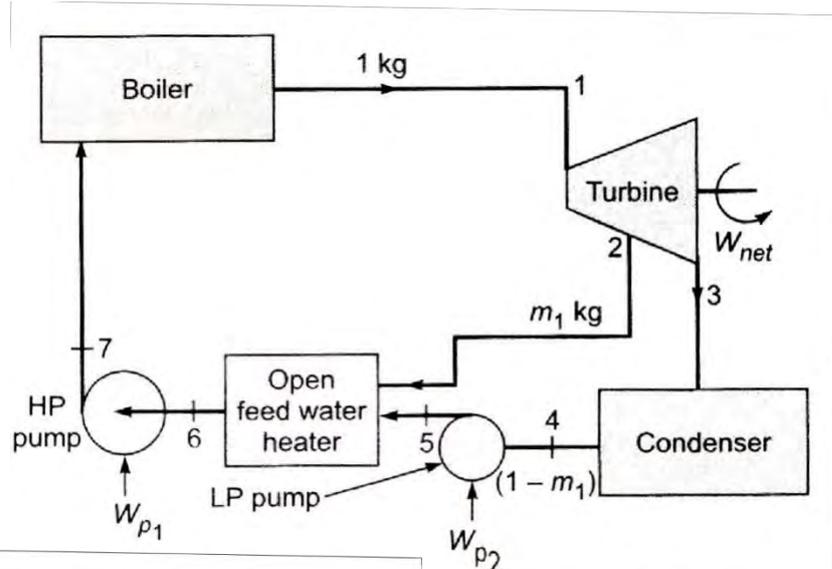
- a) Reheating requires more maintenance.
- b) The increase in thermal efficiency is not appreciable in comparison to the expenditure incurred in reheating.

6.7 Regenerative Rankine Cycle (With Open Feed-Water Heater)

- In a simple Rankine cycle, a significant amount of heat is added for sensible heating of compressed liquid coming out of the pump. The mean temperature at which sensible heat added is much lower than the source temperature.
 - The mean temperature of heat addition in the Rankine cycle can be improved by decreasing the amount of heat supplied at lower temperatures and it is to be done by preheating the feed water before it enters the boiler.

 - For preheating, part of the steam is extracted at some intermediate stage during expansion in the turbine, which is also known as “bleeding” and it is mixed with feed water coming from the condenser. The rest of the steam expands in the turbine to the condenser pressure.
 - The device where the feed water is heated by regeneration is called a regenerator, or a feed water heater (FWH).
 - Fig. 6.7 shows the schematic. T-s and h-s diagram of a Regenerative Rankine cycle employing open feed water heater.
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- Let, 1 kg of steam be leaving the boiler and entering the turbine. m_1 kg of steam per kg is extracted at the state 2 from the turbine at intermediate pressure p_2 . $(1 - m_1)$ kg of steam per kg flow through the remaining part of the turbine during expansion from 2-3, condensation from 3-4 and pumping from 4-5.
- $(1 - m_1)$ kg of steam enters in open feed water heater and mixed with m_1 kg of steam extracted from the turbine at the state 2.
- After mixing the mass of saturated liquid becomes 1 kg at the state 6 and it is pumped to boiler pressure at the state 7.



- **Thermal efficiency** of the regenerative cycle,

$$\eta_{reg} = \frac{\text{Net work}}{\text{Heat supplied}}$$

$$\therefore \eta_{reg} = \frac{w_t - w_p}{q_s}$$

Advantages of Regenerative cycle over Simple Rankine cycle:

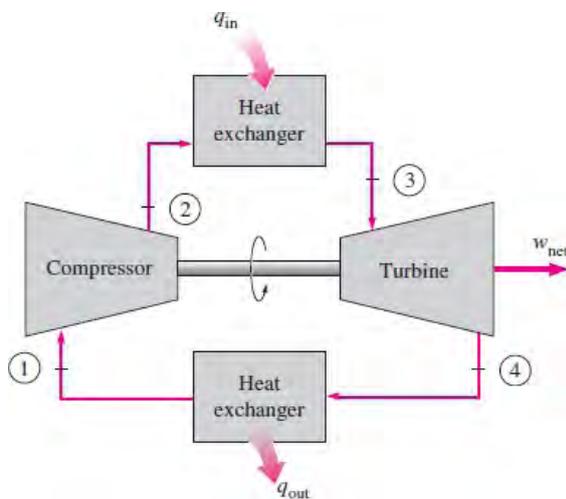
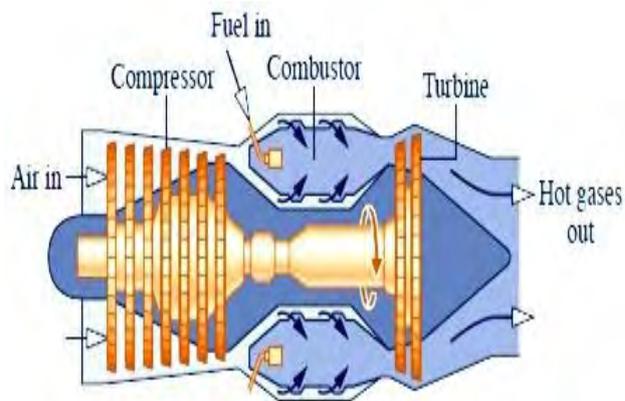
- a) It raises the temperature of feed water to saturation temperature, and thus the amount of heat addition in the boiler reduces.
- b) With an infinite number of heaters, the heating process in the boiler tends to become reversible.
- c) The thermal stresses set up in the boiler are minimized. This is due to the fact that temperature ranges in the boiler are reduced.
- d) The thermal efficiency is improved because the average temperature of heat addition to the cycle is increased.
- e) The blade height is less due to the reduced amount of steam passed through the low pressure stages.
- f) A small size condenser is required.

Disadvantages of Regeneration:

- a) The plant becomes more complicated and less flexible.
 - b) Because of addition of heaters greater maintenance is required.
 - c) For given power a large capacity boiler is required.
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7

GAS POWER CYCLES



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- 7.7 Comparison of Otto Diesel & Dual Cycle
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- 7.10 Methods for Improvement of Thermal Efficiency of Open Cycle Gas Turbine Plant
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7.1 Terminology Used in Gas Power Cycles

- a) **Cycle:** "A Cycle is defined as a repeated series of operations occurring in a certain order."
- b) **Air standard cycle:** "The thermodynamics cycle with air as the working fluid is called an air standard cycle."
- c) **Compression ratio (r):**

$$r = \frac{\text{Total cylinder volume}}{\text{Clearance volume}}$$

$$r = \frac{V_c + V_s}{V_c} \text{ --- (7.1)}$$

- Higher the compression ratio better will be the performance of an engine.

- d) **Piston Speed:** "The distance travelled by the piston in one minute is called piston speed."

$$\text{Piston Speed} = \frac{2LN}{60} \frac{m}{sec} \text{ --- (7.2)}$$

- e) **Mechanical Efficiency:** It is defined as the ratio of the brake power and the indicated power. Mechanical efficiency is indicator of losses due to friction.

$$\eta_{mech} = \frac{B. P.}{I. P.} \text{ --- (7.3)}$$

- f) **Thermal Efficiency:** "It is the ratio of work done to heat supplied by fuel."

$$\eta_{th} = \frac{\text{Work output}}{\text{Heat input}} = \frac{Q_1 - Q_2}{Q_1} \text{ --- (7.4)}$$

Where,

Q_1 = Heat addition

Q_2 = Heat rejection

[Assuming no friction & heat losses, so $W = Q_1 - Q_2$]

- i. **Indicated thermal efficiency** = Indicated Power/ Heat supplied by fuel

$$\eta_{ith} = \frac{I. P.}{m_f \times CV} \text{ --- (7.5)}$$

Where, m_f = mass of fuel supplied, Kg/sec and CV = calorific value of fuel, J/kg

ii. Brake thermal efficiency = Brake Power/ Heat supplied by fuel

$$\eta_{bth} = \frac{B. P.}{m_f \times CV} \text{-----(7.6)}$$

g) **Air standard efficiency:** The efficiency of engine using air as the working medium is known as an “Air standard efficiency” or “Ideal efficiency”.

- The actual efficiency of a cycle is always less than the air standard efficiency of that cycle under ideal conditions.
- This is taken into account by introducing a new term “Relative efficiency”.

$$\eta_{\text{relative}} = \frac{\text{Actual thermal efficiency}}{\text{Air standard efficiency}} \text{ --- (7.8)}$$

- The analysis of all air standard cycles is based upon the following assumptions.

Assumptions:

1. The gas in the engine cylinder is a perfect gas i.e. it obeys the gas laws and has constant specific heat.
2. The compression and expansion processes are adiabatic and they take place without internal friction i.e. these processes are isentropic.
3. No chemical reaction takes place in the cylinder. Heat is supplied or rejected by bringing a hot body or a cold body in contact with cylinder at appropriate points during the process.
4. The engine operates in a closed cycle. The cylinder is filled with constant amount of working medium and the same fluid is used repeatedly.

The approach and concept of ideal air cycle helps to.....

1. Indicate the ultimate performance i.e. to determine the maximum ideal efficiency of a specific thermodynamics cycle.
2. Study qualitatively the influence of different variables on the performance of an actual engine.
3. Evaluate one engine relative to another.

7.2 Mean Effective Pressure

- The pressure variation versus volume inside the cylinder of a reciprocating engine is plotted with the help of an engine indicator. The resulting contour is closed one and is referred to as indicator diagram as shown in Fig. 7.1.
-

- The area enclosed by the contour is a measure of the work output per cycle from the engine.

- **Mean effective pressure** is defined as the average pressure acting on the piston which will produce the same output as is done by the varying pressure during a cycle.

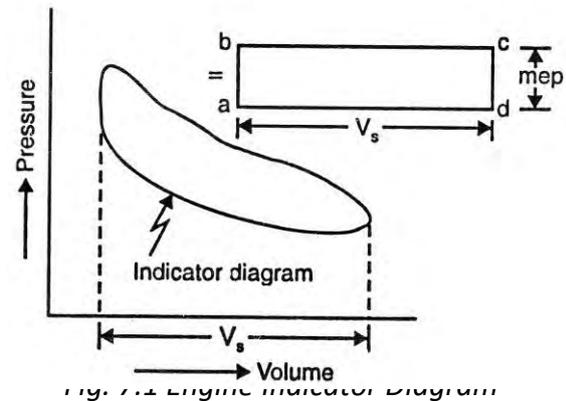


Fig. 7.2 Engine Indicator Diagram

- Therefore
Area of indicator loop = Area of rectangle abcd

- The height of the rectangle than represents the mean effective pressure.

$$mep = \frac{\text{work done per cycle}}{\text{swept volume}}$$

$$= \frac{\text{Area of indicator loop}}{\text{length of loop}} \text{ --- (7.9)}$$

Unit: bar or KN/m²

- Mean effective pressure is used as a parameter to compare the performance of reciprocating engines of equal size.
- An engine that has a large volume of mep will deliver more net work and will thus perform better.

7.3 The Carnot Gas Power Cycle

- A Carnot cycle is a hypothetical cycle consisting four different processes: two reversible isothermal processes and two reversible adiabatic (isentropic) processes.
- According to Carnot theorem ***“No cycle can be more efficient than a reversible cycle operating between the same temperature limits.”***

Assumptions made in the working of the Carnot cycle

- Working fluid is a perfect gas.
- Piston cylinder arrangement is weightless and does not produce friction during motion.
- The walls of cylinder and piston are considered as perfectly insulated.
- Compression and expansion are reversible.
- The transfer of heat does not change the temperature of sources or sink.

- Fig. 7.2 shows essential elements for a Carnot cycle, P-v and T-S diagrams.

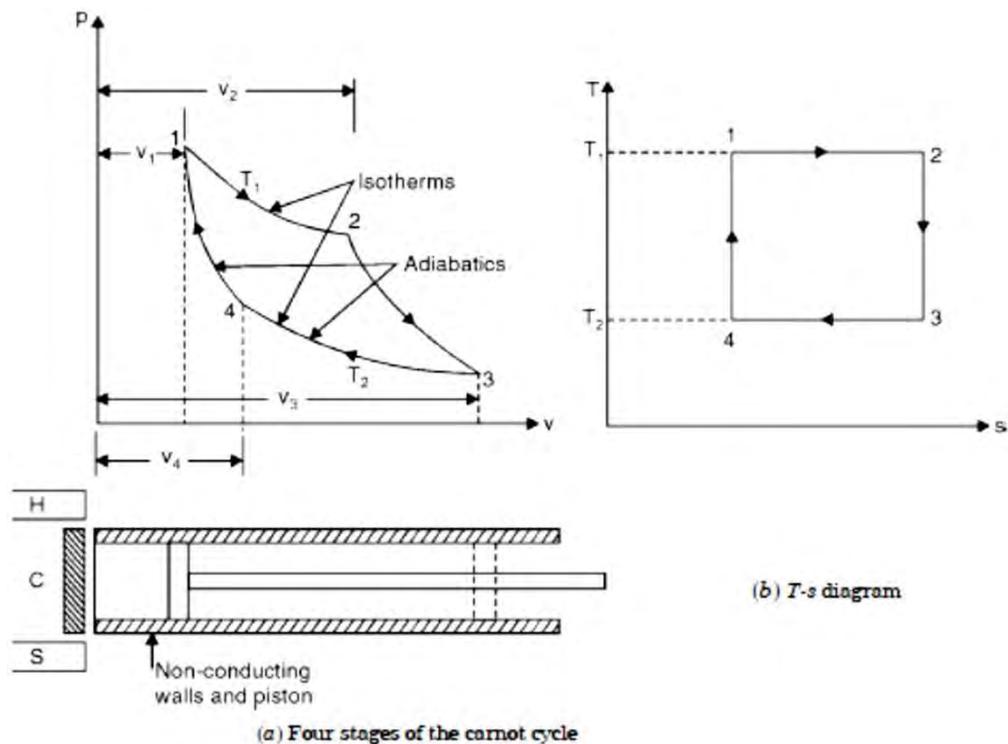


Fig. 7.2 P-v, T-S and schematic diagram of Carnot gas power cycle

- This cycle has the highest possible efficiency and it consists four simple operations as below:
 - Isothermal Expansion (1 – 2)
 - Isentropic Expansion (2 – 3)
 - Isothermal Compression (3 – 4)
 - Isentropic Compression (4 – 1)

Limitations of Carnot Gas Cycle:

- ✓ The Carnot cycle is hypothetical.
- ✓ The thermal efficiency of Carnot cycle depends upon absolute temperature of heat source T_1 and heat sink T_2 only, and independent of the working substance.
- ✓ Practically it is not possible to neglect friction between piston and cylinder. It can be minimized but cannot be eliminated.
- ✓ It is impossible to construct cylinder walls which are perfect insulator. Some amount of heat will always be transferred. Hence perfect adiabatic process cannot be achieved.
- ✓ The isothermal and adiabatic processes take place during the same stroke. Therefore the piston has to move very slowly for isothermal process and it has to move very fast during remaining stroke for adiabatic process which is practically not possible.

-
- ✓ The output obtained per cycle is very small. This work may not be able to overcome the friction of the reciprocating parts.

7.4 The Otto Cycle OR Constant Volume Cycle (Isochoric)

- The cycle was successfully applied by a German scientist Nicolous A. Otto to produce a successful 4 – stroke cycle engine in 1876.

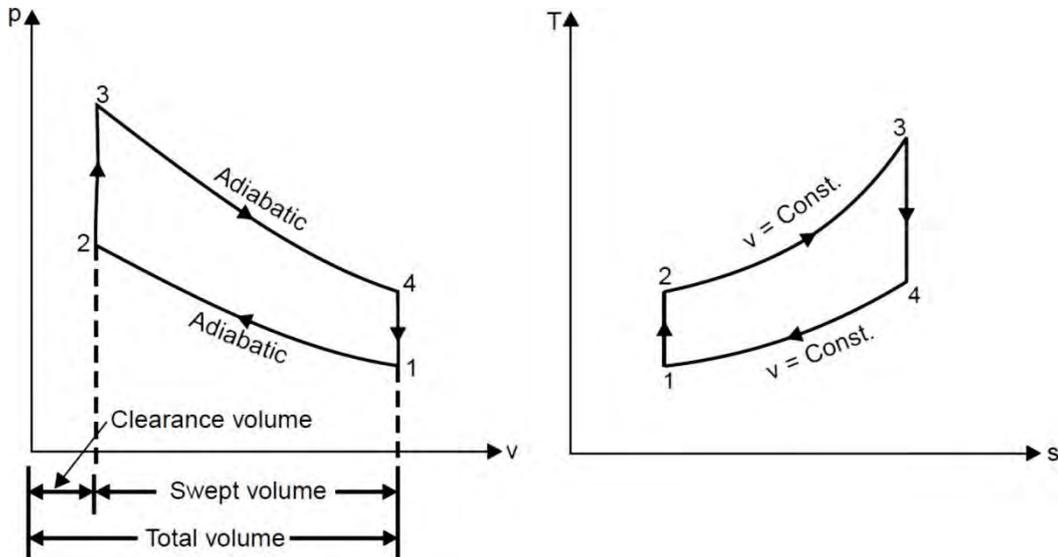


Fig. 7.3 p-V and T-s diagrams of Otto cycle

- The thermodynamic cycle is operated with isochoric (constant volume) heat addition and consists of two adiabatic processes and two constant volume changes.
- Fig. 7.3 shows the Otto cycle plotted on $p - V$ and $T - s$ diagram.

Adiabatic Compression Process (1 – 2):

- At pt. 1 cylinder is full of air with volume V_1 , pressure P_1 and temp. T_1 .
- Piston moves from BDC to TDC and an ideal gas (air) is compressed isentropically to state point 2 through compression ratio,

$$r = \frac{V_1}{V_2}$$

Constant Volume Heat Addition Process (2 – 3):

Heat is added at constant volume from an external heat source.

The pressure rises and the ratio $r_p = \frac{P_3}{P_2}$ is called expansion ratio or pressure ratio.

Adiabatic Expansion Process (3 – 4):

- The increased high pressure exerts a greater amount of force on the piston and pushes it towards the BDC.
- Expansion of working fluid takes place isentropically and work done by the system.
- The volume ratio $\frac{V_4}{V_3}$ is called isentropic expansion ratio.

Constant Volume Heat Rejection Process (4 – 1):

- Heat is rejected to the external sink at constant volume. This process is so controlled that ultimately the working fluid comes to its initial state 1 and the cycle is repeated.
- Many petrol and gas engines work on a cycle which is a slight modification of the Otto cycle.
- This cycle is called constant volume cycle because the heat is supplied to air at constant volume.

Thermal Efficiency of an Otto Cycle:

- Consider a unit mass of air undergoing a cyclic change.
- **Heat supplied** during the process 2 – 3,

$$q_1 = C_V(T_3 - T_2)$$

- **Heat rejected** during process 4 – 1 ,

$$q_2 = C_V(T_4 - T_1)$$

- **Work done,**

$$\therefore W = q_1 - q_2$$

$$\therefore W = C_V (T_3 - T_2) - C_V(T_4 - T_1)$$

Thermal efficiency,

$$\begin{aligned} \eta &= \frac{\text{Work done}}{\text{Heat supplied}} = \frac{W}{q_1} \\ &= \frac{C_V (T_3 - T_2) - C_V(T_4 - T_1)}{C_V (T_3 - T_2)} \\ &= 1 - \frac{(T_4 - T_1)}{(T_3 - T_2)} \text{---(7.13)} \end{aligned}$$

For Adiabatic compression process (1 – 2),

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

$$\therefore T_2 = T_1 r^{\gamma-1} \text{---(7.14)}$$

For Isentropic expansion process (3 – 4),

$$\frac{T_4}{T_3} = \left(\frac{V_3}{V_4}\right)^{\gamma-1}$$

$$\therefore T_3 = T_4 \left(\frac{V_4}{V_3}\right)^{\gamma-1}$$

$$\therefore T_3 = T_4 \left(\frac{V_1}{V_2}\right)^{\gamma-1} (\because V_1 = V_4, V_2 = V_3)$$

$$\therefore T_3 = T_4 (r)^{\gamma-1} \text{---(7.15)}$$

- From equation 7.13, 7.14 & 7.15, we get,

$$\eta_{otto} = 1 - \frac{(T_4 - T_1)}{T_4 r^{\gamma-1} - T_1 r^{\gamma-1}}$$

$$\therefore \eta_{otto} = 1 - \frac{(T_4 - T_1)}{r^{\gamma-1}(T_4 - T_1)}$$

$$\therefore \eta_{otto} = 1 - \frac{1}{r^{\gamma-1}} \text{---(7.16)}$$

Expression 7.16 is known as the air standard efficiency of the Otto cycle.

- It is clear from the above expression that efficiency increases with the increase in the value of r (as γ is constant).
- We can have maximum efficiency by increasing r to a considerable extent, but due to practical difficulties its value is limited to 8.

- In actual engines working on Otto cycle, the compression ratio varies from 5 to 8 depending upon the quality of fuel.
- At compression ratios higher than this, the temperature after combustion becomes high and that may lead to spontaneous and uncontrolled combustion of fuel in the cylinder.
- The phenomenon of uncontrolled combustion in petrol engine is called **detonation** and it leads to poor engine efficiency and in structural damage of engine parts.
- Fig. 7.4 shows the variation of air standard efficiency of Otto cycle with compression ratio.

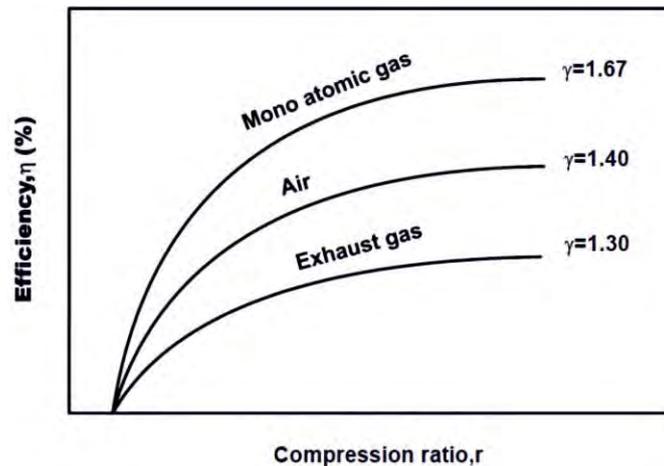


Fig. 7.4 Variation of Otto cycle efficiency with compression ratio

Mean Effective Pressure:

Net work done per unit mass of air,

$$W_{net} = C_V (T_3 - T_2) - C_V(T_4 - T_1) \text{ --- (7.17)}$$

Swept volume,

$$\begin{aligned} \text{Swept volume} &= V_1 - V_2 = V_1 \left(1 - \frac{V_2}{V_1}\right) = \frac{RT_1}{P_1} \left(1 - \frac{1}{r}\right) \\ &= \frac{RT_1}{P_1 r} (r - 1) \text{ --- (7.18)} \end{aligned}$$

Mean effective pressure,

$$\begin{aligned} mep &= \frac{\text{Work done per cycle}}{\text{swept volume}} \\ &= \frac{C_V (T_3 - T_2) - C_V(T_4 - T_1)}{\frac{RT_1}{P_1 r} (r - 1)} \\ &= \frac{C_V}{R} \frac{P_1 r}{(r - 1)} \left[\frac{(T_3 - T_2) - (T_4 - T_1)}{T_1} \right] \text{ --- (7.19)} \end{aligned}$$

For process 1 – 2,

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

$$T_2 = T_1 r^{\gamma-1}$$

Process 2 – 3,

$$\frac{T_3}{T_2} = \frac{P_3}{P_2} \quad (\because V_2 = V_3)$$

$$\therefore T_3 = T_2 \alpha \quad (\alpha = \text{explosion pressure ratio})$$

$$\therefore T_3 = T_1 \alpha r^{\gamma-1}$$

Process 3 – 4,

$$T_4 = T_3 \left(\frac{V_3}{V_4} \right)^{\gamma-1}$$

$$\therefore T_4 = T_1 \alpha r^{\gamma-1} \left(\frac{V_2}{V_1} \right)^{\gamma-1}$$

$$\therefore T_4 = T_1 \alpha r^{\gamma-1} \times \frac{1}{r^{\gamma-1}}$$

$$\therefore T_4 = T_1 \cdot \alpha$$

Substituting all these temperature values in equation 7.19, We get,

$$mep = \frac{C_V}{R} \frac{P_1 r}{(r-1)} \left[\frac{(T_1 \alpha r^{\gamma-1} - T_1 r^{\gamma-1}) - (T_1 \alpha - T_1)}{T_1} \right]$$

$$\therefore mep = \frac{C_V}{R} \frac{P_1 r}{(r-1)} \left[\frac{T_1 r^{\gamma-1}(\alpha - 1) - T_1(\alpha - 1)}{T_1} \right]$$

$$\therefore mep = \frac{C_V}{R} \frac{P_1 r}{(r-1)} [(r^{\gamma-1} - 1)(\alpha - 1)]$$

$$\therefore mep = \frac{P_1 r}{(r-1)(\gamma-1)} [(r^{\gamma-1} - 1)(\alpha - 1)] \text{ --- (7.20)}$$

Condition for Maximum Work:

- For unit mass of air,

$$W = q_1 - q_2$$

$$\therefore W = C_V (T_3 - T_2) - C_V (T_4 - T_1)$$

$$\therefore \frac{W}{C_V} = T_3 - T_2 - T_4 + T_1 \text{ --- (7.21)}$$

We know that,

$$T_2 = T_1 r^{\gamma-1}$$

$$T_4 = T_3 \frac{1}{r^{\gamma-1}} = T_3 \frac{T_1}{T_2} \quad (\because r^{\gamma-1} = \frac{T_2}{T_1})$$

So

$$\frac{W}{C_V} = T_3 - T_2 - \frac{T_3 T_1}{T_2} + T_1 \text{ --- (7.22)}$$

- The intermediate temperature T_2 for maximum work output can be obtained by differentiating the above equation with respect to T_2 & setting the derivatives equal to zero.

$$\therefore \frac{1}{C_V} \frac{dW}{dT_2} = -1 + \frac{T_1 T_3}{T_2^2} = 0 \quad (\text{for max work})$$

$$\therefore T_2^2 = T_1 T_3$$

$$\therefore T_2 = \sqrt{T_1 T_3} \text{ --- (7. 23)}$$

- Similarly for temperature T_4

$$\frac{W}{C_V} = T_3 - \frac{T_1 \cdot T_3}{T_4} - T_4 + T_1$$

$$\therefore \frac{1}{C_V} \frac{dW}{dT_4} = \frac{T_1 T_3}{T_4^2} - 1 = 0 \quad (\text{for max work})$$

$$\therefore T_4 = \sqrt{T_1 T_3} \text{ --- (7. 24)}$$

- Thus for maximum work,

$$T_2 = T_4 = \sqrt{T_1 T_3} \text{ --- (7. 25)}$$

i.e. the intermediate temperature T_2 & T_4 must be equal for maximum work.

Maximum work,

$$W_{max} = C_V(T_3 - T_2 - T_4 + T_1)$$

$$\therefore W_{max} = C_V(T_3 - \sqrt{T_1 T_3} - \sqrt{T_1 T_3} + T_1)$$

$$\therefore W_{max} = C_V(T_3 + T_1 - 2\sqrt{T_1 T_3}) \text{ --- (7. 26)}$$

7.5 The Diesel Cycle OR Constant Pressure Cycle (Isobaric)

- This cycle was discovered by a German engineer Dr. Rudolph Diesel. Diesel cycle is also known as **constant pressure heat addition cycle**.

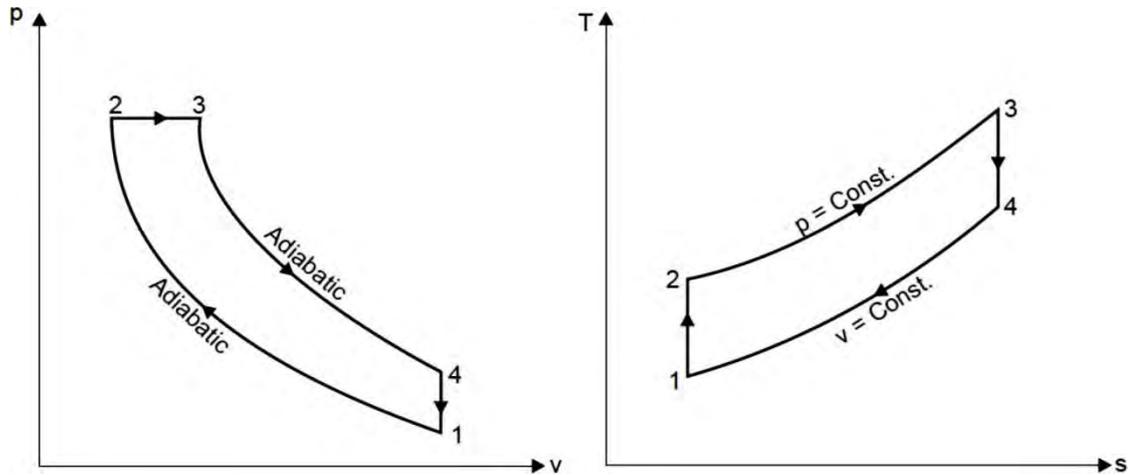


Fig. 7.5 p-V and T-s diagrams of Diesel cycle

Adiabatic Compression Process (1 – 2):

Isentropic (Reversible adiabatic) compression with $= \frac{V_1}{V_2}$.

Constant Pressure Heat Addition Process (2 – 3):

- The heat supply is stopped at point 3 which is called the cut – off point and the volume ratio $\rho = \frac{V_3}{V_2}$ is called **cut off ratio** or Isobaric expansion ratio.

Adiabatic Expansion Process (3 – 4):

- Isentropic expansion of air $\frac{V_4}{V_3}$ = isentropic expansion ratio.

Constant Volume Heat Rejection Process (4 – 1):

- In this process heat is rejected at constant volume.

This thermodynamics cycle is called constant pressure cycle because heat is supplied to the air at constant pressure.

Thermal Efficiency for Diesel Cycle:

- Consider unit mass of air.
- **Heat supplied** during process 2 – 3,

$$q_1 = C_P(T_3 - T_2)$$

- **Heat rejected** during process 4 – 1,

$$q_2 = C_V(T_4 - T_1)$$

Work done,

$$W = q_1 - q_2$$

$$W = C_P(T_3 - T_2) - C_V(T_4 - T_1)$$

Thermal efficiency,

$$\eta = \frac{\text{Work done}}{\text{Heat supplied}}$$

$$\therefore \eta = \frac{C_P(T_3 - T_2) - C_V(T_4 - T_1)}{C_P(T_3 - T_2)}$$

$$\therefore \eta = 1 - \frac{C_V(T_4 - T_1)}{C_P(T_3 - T_2)}$$

$$\therefore \eta = 1 - \frac{1(T_4 - T_1)}{\gamma(T_3 - T_2)} \text{-----(7.27)}$$

For adiabatic compression process (1 – 2),

$$r = \frac{V_1}{V_2} \text{-----(a)}$$

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

$$P_2 = P_1 r^\gamma \text{-----(b)}$$

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

For constant pressure heat addition process (2 – 3)

$$P_3 = P_2 = P_1 r^\gamma \text{-----(d)}$$

$$\rho = \frac{V_3}{V_2} \text{ (Cutoff ratio) -----(e)}$$

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

$$= T_2 \rho$$

$$\therefore T_3 = T_1 r^{\gamma-1} \rho \text{-----(f)}$$

For adiabatic expansion process (3 – 4),

$$P_4 = P_3(V_3/V_4)^\gamma = P_3(V_3/V_1)^\gamma$$

$$\therefore T_4 = \frac{T_1 r^{\gamma-1} \rho \rho^{\gamma-1}}{r^{\gamma-1}}$$

$$\therefore T_4 = T_1 \rho^\gamma \text{------(h)}$$

From equation 7.27,

$$\eta = 1 - \frac{1 (T_4 - T_1)}{\gamma (T_3 - T_2)}$$

$$\therefore \eta = 1 - \frac{1 (T_1 \rho^\gamma - T_1)}{\gamma (T_1 r^{\gamma-1} \rho - T_1 r^{\gamma-1})}$$

$$\therefore \eta = 1 - \frac{1 (\rho^\gamma - 1)}{\gamma (r^{\gamma-1} \rho - r^{\gamma-1})}$$

$$\therefore \eta = 1 - \frac{1 (\rho^\gamma - 1)}{r^{\gamma-1} [\frac{\gamma(\rho - 1)}{\gamma(\rho - 1)}]} \text{------(7. 28)}$$

Apparently the efficiency of diesel cycle depends upon the compression ratio (r) and cutoff ratio (ρ) and hence upon the quantity of heat supplied.

Fig. 7.6 shows the air standard efficiency of diesel cycle for various cut off ratio.

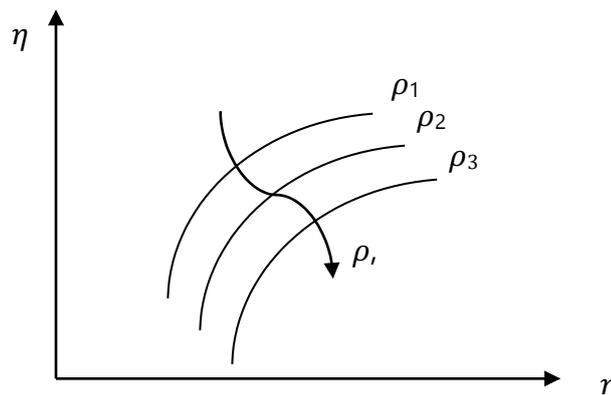


Fig. 7.6 Efficiency of Diesel cycle for various cut-off ratio

Further,

$$K = \frac{\rho^\gamma - 1}{\gamma(\rho - 1)}$$

reveals that with an increase in the cut – off ratio (ρ) the value of factor K increases.

That implies that for a diesel engine at constant compression ratio, the efficiency would increase with decrease in ρ and in the limit $\rho \rightarrow 1$, the efficiency would become

$$1 - \frac{1}{r^{\gamma-1}}$$

- Since the factor $K = \frac{\rho^\gamma - 1}{\gamma(\rho - 1)}$ is always greater than unity, the Diesel cycle is always less efficient than a corresponding Otto cycle having the same compression ratio.

- However Diesel engine operates on much higher compression ratio (14 to 18) compared to those for S.I. Engines operating on Otto cycle.
- High compression ratios for Diesel engines are must not only for high efficiency but also to prevent diesel knock; a phenomenon which leads to uncontrolled and rapid combustion in diesel engines.

Mean Effective Pressure:

- **Net work done** per unit mass of air,

$$W_{net} = C_p (T_3 - T_2) - C_v(T_4 - T_1) \text{ --- (7.29)}$$

- **Swept volume,**

$$\begin{aligned} \text{Swept volume} &= V_1 - V_2 = V_1 \left(1 - \frac{V_2}{V_1}\right) = \frac{RT_1}{P_1} \left(1 - \frac{1}{r}\right) \\ &= \frac{RT_1}{P_1 r} (r - 1) \text{ --- (7.30)} \end{aligned}$$

Mean effective pressure,

$$\begin{aligned} mep &= \frac{\text{Work done per cycle}}{\text{swept volume}} \\ \therefore mep &= \frac{C_p (T_3 - T_2) - C_v(T_4 - T_1)}{\frac{RT_1}{P_1 r} (r - 1)} \\ \therefore mep &= \frac{C_v}{R} \frac{P_1 r}{(r - 1)} \left[\frac{\gamma(T_3 - T_2) - (T_4 - T_1)}{T_1} \right] \text{ --- (7.31)} \end{aligned}$$

- From equation (c), (f) and (h),

$$T_2 = T_1 r^{\gamma-1}$$

$$T_3 = T_1 r^{\gamma-1} \rho$$

$$T_4 = T_1 \rho^\gamma$$

$$\begin{aligned} \therefore mep &= \frac{C_v}{R} \frac{P_1 r}{(r - 1)} \left[\frac{\gamma(T_1 r^{\gamma-1} \rho - T_1 r^{\gamma-1}) - (T_1 \rho^\gamma - T_1)}{T_1} \right] \\ \therefore mep &= \frac{P_1 r}{(\gamma - 1)(r - 1)} [\gamma r^{\gamma-1} (\rho - 1) - (\rho^\gamma - 1)] \text{ --- (7.32)} \end{aligned}$$

7.6 The Dual Combustion Cycle OR The Limited Pressure Cycle

- This is a cycle in which the addition of heat is partly at constant volume and partly at constant pressure.

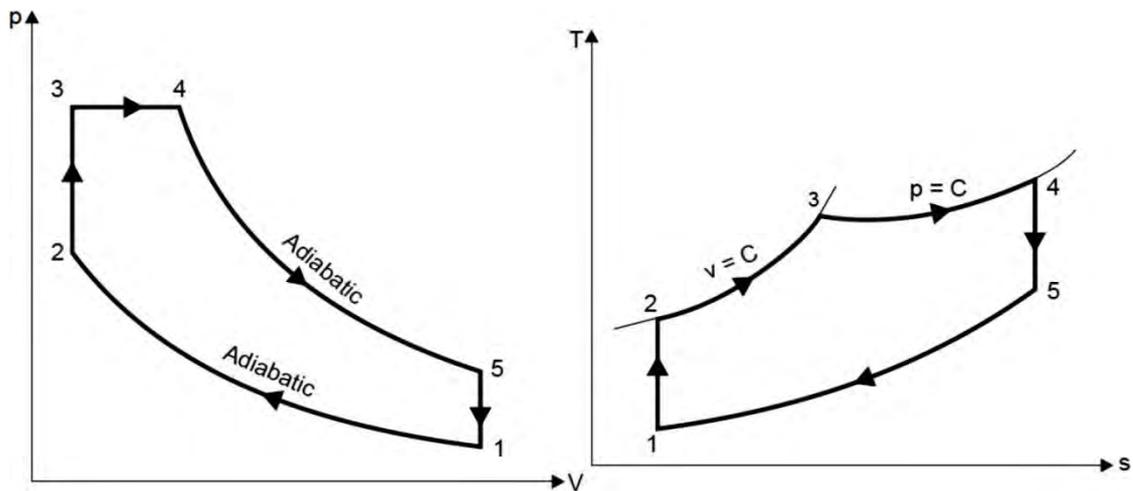


Fig. 7.7 p-V and T-s diagrams of Diesel cycle

Adiabatic Compression Process (1 – 2):

- Isentropic (Reversible adiabatic) compression with $= \frac{V_1}{V_2}$.

Constant Volume Heat Addition Process (2 – 3):

- The heat is supplied at constant volume with explosion ratio or pressure ratio $\alpha = \frac{P_3}{P_2}$.

Constant Pressure Heat Addition Process (3 – 4):

- The heat supply is stopped at point 4 which is called the cut – off point and the volume ratio $\rho = \frac{V_4}{V_3}$ is called **cut off ratio**.

Adiabatic Expansion Process (4 – 5):

- Isentropic expansion of air with $\frac{V_5}{V_4}$ = isentropic expansion ratio.

Constant Volume Heat Rejection Process (5 – 1):

- In this process heat is rejected at constant volume.

The high speed Diesel engines work on a cycle which is slight modification of the Dual cycle.

Thermal Efficiency for Dual Cycle:

- Consider unit mass of air undergoing the cyclic change.

-
- **Heat supplied,**

$$q_1 = q_{2-3} + q_{3-4}$$

$$q_1 = C_V(T_3 - T_2) + C_P(T_4 - T_3)$$

- **Heat rejected** during process 5 – 1,

$$q_2 = C_V(T_5 - T_1)$$

-
- **Work done,**

$$W = q_1 - q_2$$

$$W = C_V(T_3 - T_2) + C_P(T_4 - T_3) - C_V(T_5 - T_1)$$

- **Thermal efficiency,**

$$\eta = \frac{\text{Work done}}{\text{Heat supplied}}$$

$$\therefore \eta = 1 - \frac{(\rho^\gamma \alpha - 1)}{[r^{\gamma-1} \{(\alpha - 1)\alpha + \gamma\alpha(\rho - 1)\}]}$$

$$\therefore \eta = 1 - \frac{1}{r^{\gamma-1}} \left[\frac{(\alpha \rho^\gamma - 1)}{(\alpha - 1) + \gamma\alpha(\rho - 1)} \right] \text{---(7.34)}$$

- It can be seen from the equation 7.34 that the thermal efficiency of a Dual cycle can be increased by supplying a greater portion of heat at constant volume (high value of α) and smaller portion at constant pressure (low value of ρ).
- In the actual high speed Diesel engines operating on this cycle, it is achieved by early fuel injection and an early cut-off.
- It is to be noted that Otto and Diesel cycles are special cases of the Dual cycle.
- If $\rho = 1$ ($V_3 = V_4$)

Hence, there is no addition of heat at constant pressure. Consequently the entire heat is supplied at constant volume and the cycle becomes the Otto cycle.

By substituting $\rho = 1$ in equation 7.34, we get,

$$\eta = 1 - \frac{1}{r^{(\gamma-1)}} = \text{Efficiency of Otto cycle}$$

- Similarly if $\alpha = 1$, the heat addition is only at constant pressure and cycle becomes Diesel cycle.

By substituting $\alpha = 1$ in equation 7.34, we get,

$$\eta = 1 - \frac{1}{r^{\gamma-1}} \left[\frac{(\rho^\gamma - 1)}{\gamma(\rho - 1)} \right] = \text{Efficiency of Diesel cycle}$$

Mean Effective Pressure:

$$\therefore mep = \frac{P_1 r}{(\gamma - 1)(r - 1)} [(\alpha - 1)r^{\gamma-1} + \gamma \alpha r^{\gamma-1}(\rho - 1) - (\alpha \rho^\gamma - 1)]$$

----- (7.37)

7.7 Comparison of Otto, Diesel and Dual Cycles

- Following are the important variable factors which are used as a basis for comparison of the cycles:
 - Compression ratio
 - Maximum pressure
 - Heat supplied
 - Heat rejected
 - Net work.

A. For the Same Compression Ratio and the Same Heat Input

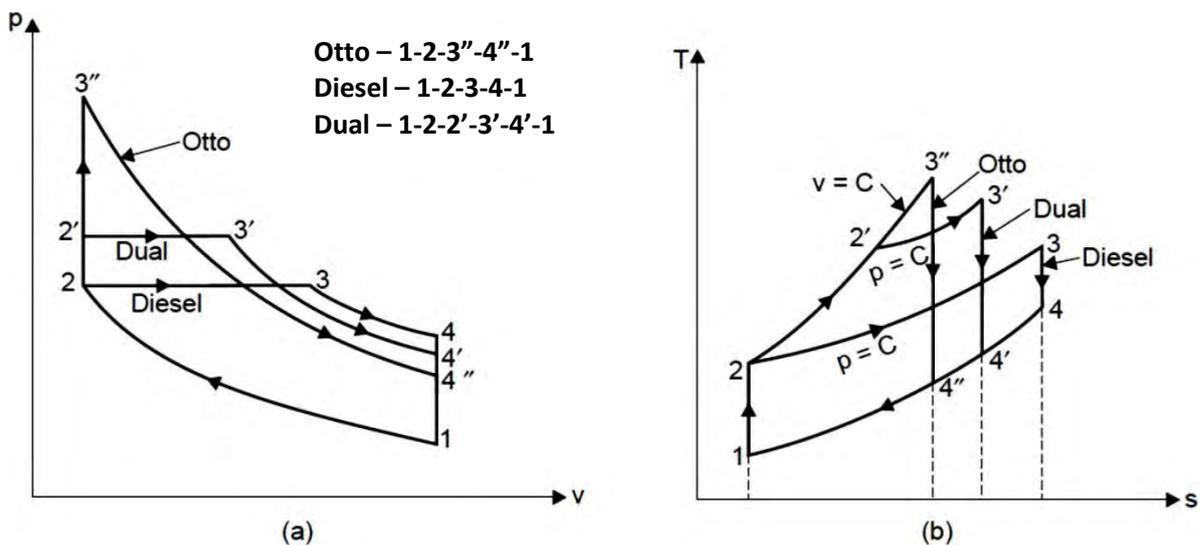


Fig. 7.8 (a) P-V diagram and (b) T-S diagram

- We know that,

$$\eta = 1 - \frac{\text{Heat Rejected}}{\text{Heat Supplied}} = 1 - \frac{q_2}{q_1} \text{----- (7.38)}$$

- The quantity of heat rejected from each cycle is represented by the appropriate area under the line 4 – 1 on the T – S diagram.
- From equation 7.38; it is clear that the cycle which has the least heat rejected will have the highest efficiency.

$$\therefore \eta_{\text{Otto}} > \eta_{\text{Dual}} > \eta_{\text{Diesel}}$$

B. Same Maximum Pressure and Temperature

- When pressure is the limiting factor in engine design, it becomes necessary to compare the air standard cycles on the basis of same maximum pressure & temperature.

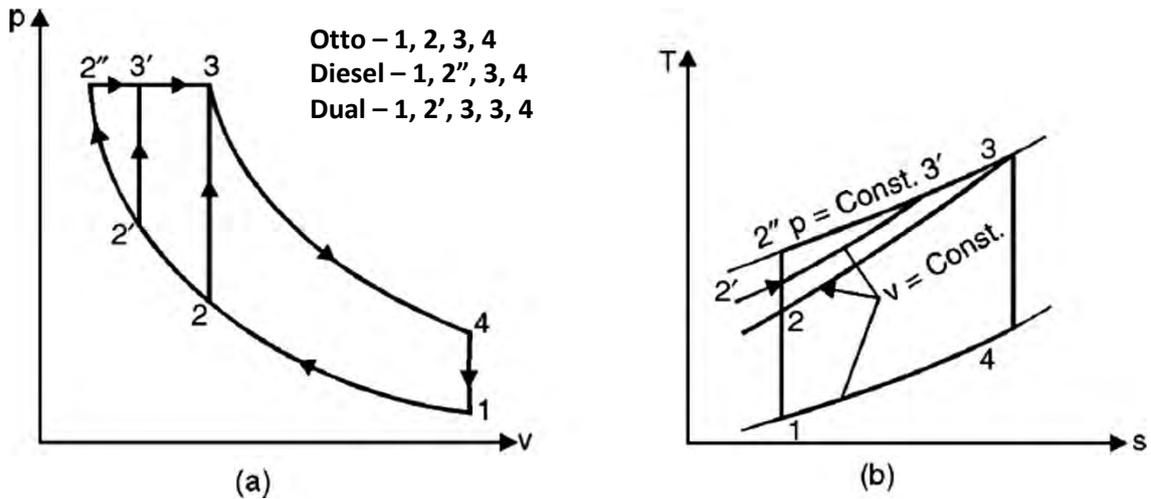


Fig. 7.9 (a) P-V diagram and (b) T-S diagram

- Here the Otto cycle must be limited to low compression ratio to fulfill the condition that point 3 (same maximum pressure & temperature) is to be a common state for all the three cycles.
- From Fig. 7.9 it is clear that the heat rejected is same for all the three cycles. Hence with the same heat rejected, the cycle with greater heat addition is more efficient.
- We know that,

$$\eta = 1 - \frac{\text{Heat Rejected}}{\text{Heat Supplied}} = 1 - \frac{q_2}{q_1} \text{----- (7.39)}$$

- From Fig. 7.9,

$$\therefore \eta_{\text{Diesel}} > \eta_{\text{Dual}} > \eta_{\text{Otto}}$$

C. For Constant Maximum Pressure and Heat Input

- Fig. 7.10 shows the Otto and Diesel cycles on P-V and T-S diagrams for constant maximum pressure and heat input respectively.

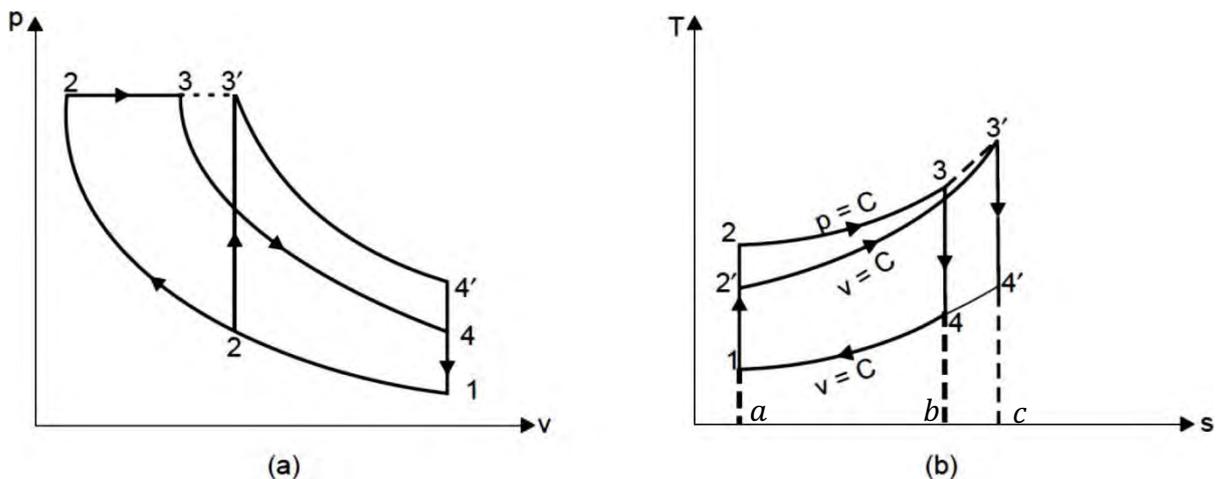


Fig. 7.10 (a) P-V diagram and (b) T-S diagram

- For the constant maximum pressure, points 3 and 3' must lie on the constant pressure line.
- Also for the same heat input the areas $a - 2 - 3 - b$ and $a - 2' - 3' - c$ on the T-S plot must be equal.
- Now,

$$\eta = 1 - \frac{\text{Heat Rejected}}{\text{Heat Supplied}} = 1 - \frac{q_2}{q_1} \text{---(7.40)}$$

- Hence for the same amount of heat supplied the cycle with less heat rejected has a higher value of thermal efficiency.
- From Fig. 7.10,

$$\therefore \eta_{\text{Diesel}} > \eta_{\text{Dual}} > \eta_{\text{Otto}}$$

7.8 The Brayton Cycle OR The Joule Cycle

- The Brayton cycle is a constant pressure cycle for a perfect gas. It is also called Joule cycle.
- It is a theoretical cycle on which constant pressure gas turbine works.

The various operations are as follows:

- **Isentropic Compression (1 – 2):**

The air is compressed isentropically from the lower pressure p_1 to the upper pressure p_2 , the temperature rising from T_1 to T_2 . No heat flow occurs.

- **Constant Pressure Heat Addition (2 – 3):**

The compressed air is passed through a heat exchanger, where heat is externally supplied to it at constant pressure. Heat flows into the system increasing the volume from V_2 to V_3 and temperature from T_2 to T_3 whilst the pressure remains constant at p_2 .

- **Isentropic Expansion (3 – 4):**

Isentropic expansion of high pressure & high temperature air takes place in the turbine during which the work is done by the system. The air is expanded isentropically from p_2 to p_1 , the temperature falling from T_3 to T_4 . No heat flow occurs.

- **Constant Pressure Heat Rejection (4 – 1):**

The air at state point 4 is passed through a heat exchanger and heat is rejected at constant pressure. The volume decreases from V_4 to V_1 and the temperature from T_4 to T_1 whilst the pressure remains constant at p_1 .

- The closed Brayton cycle is shown in the Fig. 7.11 (a) and it is represented on p-v and T-s diagrams as shown in Figs. 7.11 (b) and (c) respectively.

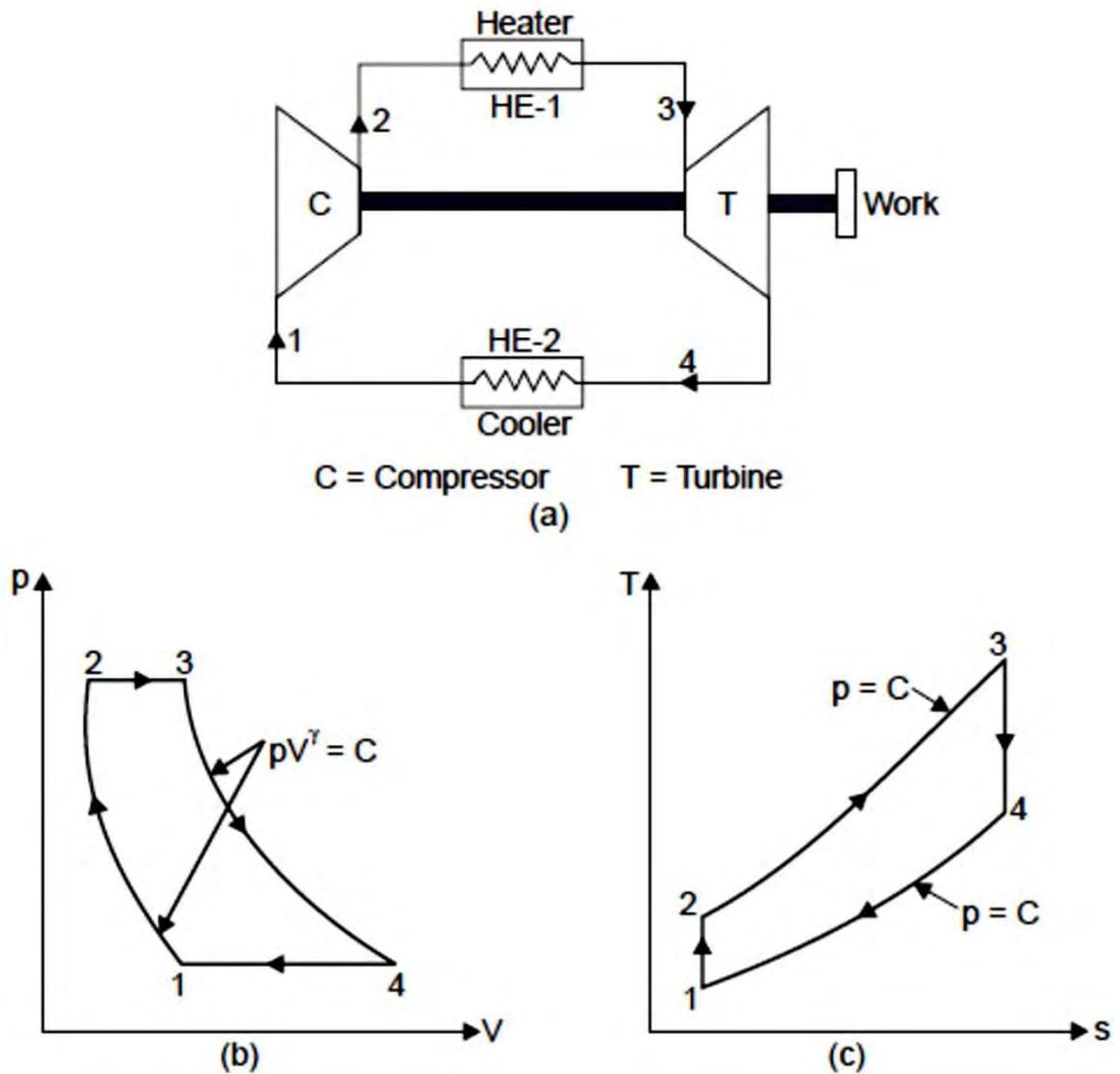


Fig. 7.11 The P-v, T-s and Schematic diagram of Brayton cycle

Thermal Efficiency for Closed Brayton Cycle:

- For unit mass of air,
- **Heat supplied** during process 2 – 3,

$$q_1 = C_P(T_3 - T_2)$$

- **Heat rejected** during process 4 – 1,

$$q_2 = C_P(T_4 - T_1)$$

- **Work done,**

$$W = q_1 - q_2$$

$$\therefore W = C_p(T_3 - T_2) - C_p(T_4 - T_1)$$

- Thermal efficiency,

$$\eta = \frac{\text{Work done}}{\text{Heat supplied}}$$

$$\therefore \eta = \frac{C_p(T_3 - T_2) - C_p(T_4 - T_1)}{C_p(T_3 - T_2)}$$

$$\therefore \eta = 1 - \frac{(T_4 - T_1)}{(T_3 - T_2)} \text{ --- (7.41)}$$

- Take pressure ratio,

$$r_p = \frac{P_2}{P_1} = \frac{P_3}{P_4} \text{ --- (7.41a)}$$

- For isentropic compression process (1 – 2),

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} = (r_p)^{\frac{\gamma-1}{\gamma}} \text{ --- (7.41b)}$$

- For isentropic expansion process (3 – 4),

$$\frac{T_3}{T_4} = \left(\frac{P_3}{P_4}\right)^{\frac{\gamma-1}{\gamma}} = (r_p)^{\frac{\gamma-1}{\gamma}} \text{ --- (7.41c)}$$

- Thus from equation (7.41b) and (7.41c),

$$\frac{T_2}{T_1} = \frac{T_3}{T_4}$$

$$\therefore \frac{T_4}{T_1} = \frac{T_3}{T_2} \text{ --- (7.41d)}$$

- From equation 7.41,

$$\eta = 1 - \frac{(T_4 - T_1)}{(T_3 - T_2)}$$

$$\therefore \eta = 1 - \frac{T_1 \left(\frac{T_4}{T_1} - 1\right)}{T_2 \left(\frac{T_3}{T_2} - 1\right)} = 1 - \frac{T_1 \left(\frac{T_3}{T_2} - 1\right)}{T_2 \left(\frac{T_3}{T_2} - 1\right)} \quad (\because \text{equation (7.41d)})$$

$$\therefore \eta = 1 - \frac{T_1}{T_2}$$

$$\therefore \eta = 1 - \left(\frac{P_1}{P_2}\right)^{\frac{\gamma-1}{\gamma}}$$

$$\therefore \eta = 1 - \left(\frac{1}{r_p}\right)^{\frac{r-1}{\gamma}} \text{-----}(7.42)$$

- Thermal efficiency of Brayton cycle is function of pressure ratio. Efficiency increases with pressure ratio as shown in Fig. 7.12.

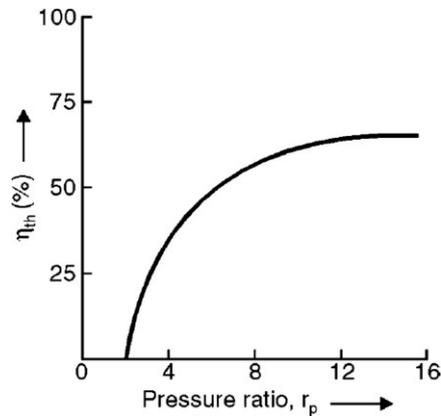


Fig. 7.12 Effect of pressure ratio on the efficiency of Brayton cycle

- The curve tends to become flat at higher pressure ratios, which implies that though the efficiency is increasing, the rate of increase starts diminishing at higher pressures.

7.9 The Open Cycle Gas Turbine OR Actual Brayton Cycle:

- The fundamental gas turbine unit is one operating on the open cycle. In Open cycle gas turbine, the products of combustion coming out from the turbine are exhausted to the atmosphere as they cannot be used any more. The working fluids (air and fuel) must be replaced continuously as they are exhausted into the atmosphere.
- In practice, it is not possible to achieve either isentropic compression or isentropic expansion because of internal friction, turbulence and leakage.
- If pressure drop is neglected in combustion chamber, the actual Brayton cycle on T-S diagram is shown by process 1-2'-3-4' in Fig. 7.13.

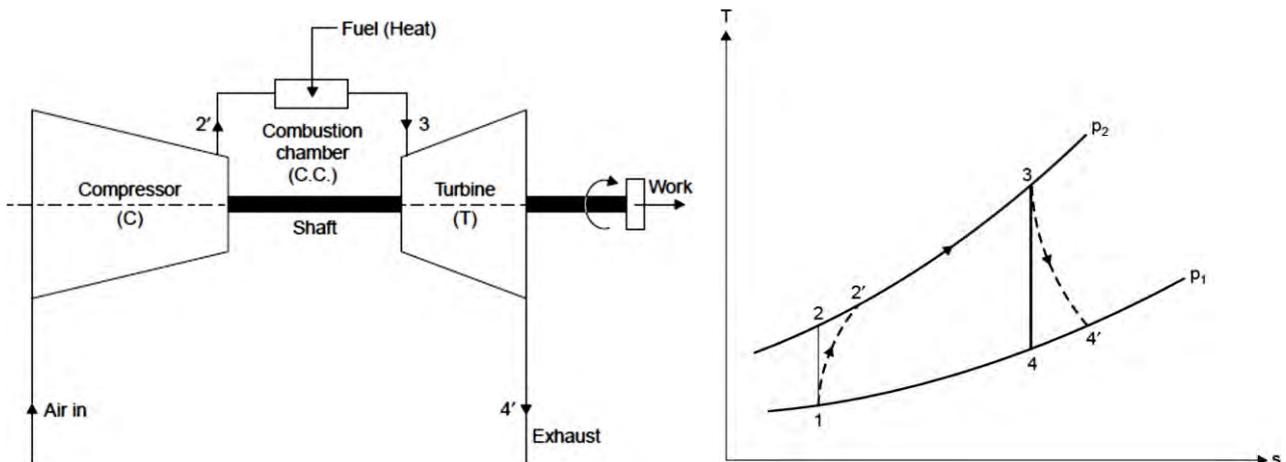


Fig. 7.13 Schematic and T-S diagram of an actual Brayton cycle

- In actual cycle, the temperatures at the end of compression and at the end of expansion are higher than in an ideal case for the same pressure ratio.

7.10 Methods for Improvement of Thermal Efficiency of Open Cycle Gas Turbine Plant

- The following methods are employed to increase the specific output and thermal efficiency of the plant: 1) Intercooling 2) Reheating and 3) Regeneration.

1. Intercooling

- A compressor in a gas turbine cycle utilizes the major percentage of power developed by the gas turbine. The work required by the compressor can be reduced by compressing the air in two stages and incorporating an intercooler between the two as shown in Fig. 7.14.

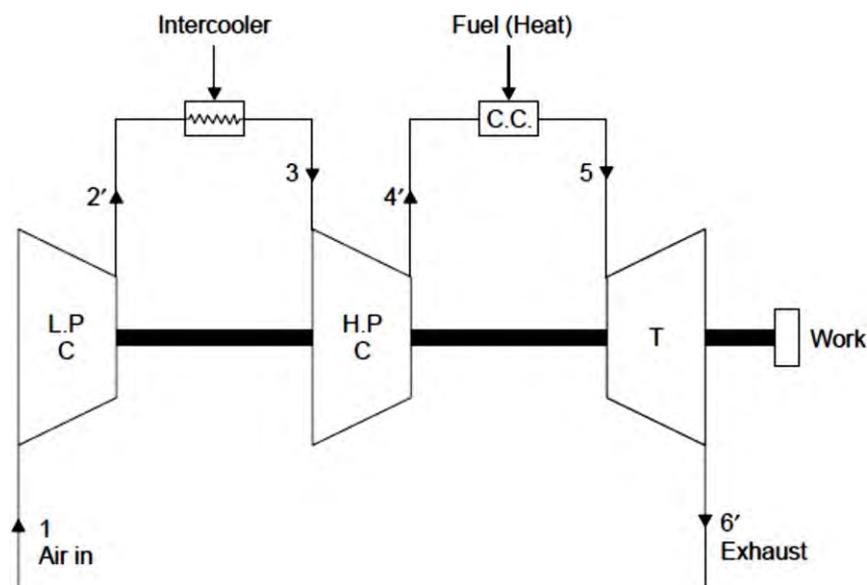


Fig. 7.14 Open cycle gas turbine plant with intercooler

2. Reheating

- The output of a gas turbine can be improved by expanding the gases in two stages with a reheater between the two as shown in Fig. 7.16.
- By reheating or adding heat to the gases after they have passed through the turbine stage, a further increase in work done is obtained.
- In reheating, the gas temperature, which has dropped due to expansion, is brought back to approximately the initial temperature for the expansion in the next stage.

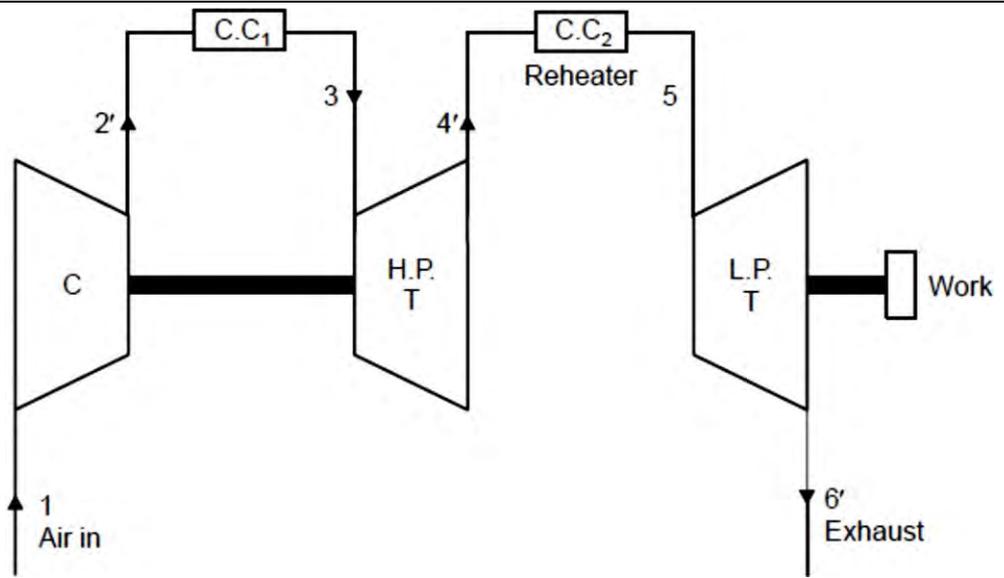


Fig. 7.16 Open cycle gas turbine plant with reheat

3. Regeneration

- The temperature of exhaust gases leaving the turbine of a gas turbine engine is considerably higher than the temperature of air delivered by the compressor.
- Therefore, high pressure air leaving the compressor can be heated by hot exhaust gases, thereby reducing the mass of fuel supplied in the combustion chamber. Hence the thermal efficiency can be increased.
- The heat exchanger used to transfer the heat from exhaust gases to compressed air is known as regenerator.
- The net work is not affected by the addition of the recuperator or regeneration to the cycle, only the heat required to be supplied in the combustion chamber is decreased which gives the gain in thermal efficiency.

- The corresponding schematic and T-s diagram is shown in Fig. 7.18 & 7.19 respectively. The actual processes take place as follows :

1-2'-----Compression in compressor

2'-3 ---- Heat addition into the compressed air during its passage through the heat exchanger

3-4-----Heat addition in the combustion chamber

4-5'-----Expansion in turbine

5'-6-----Heat rejection in heat exchanger to the compressed air

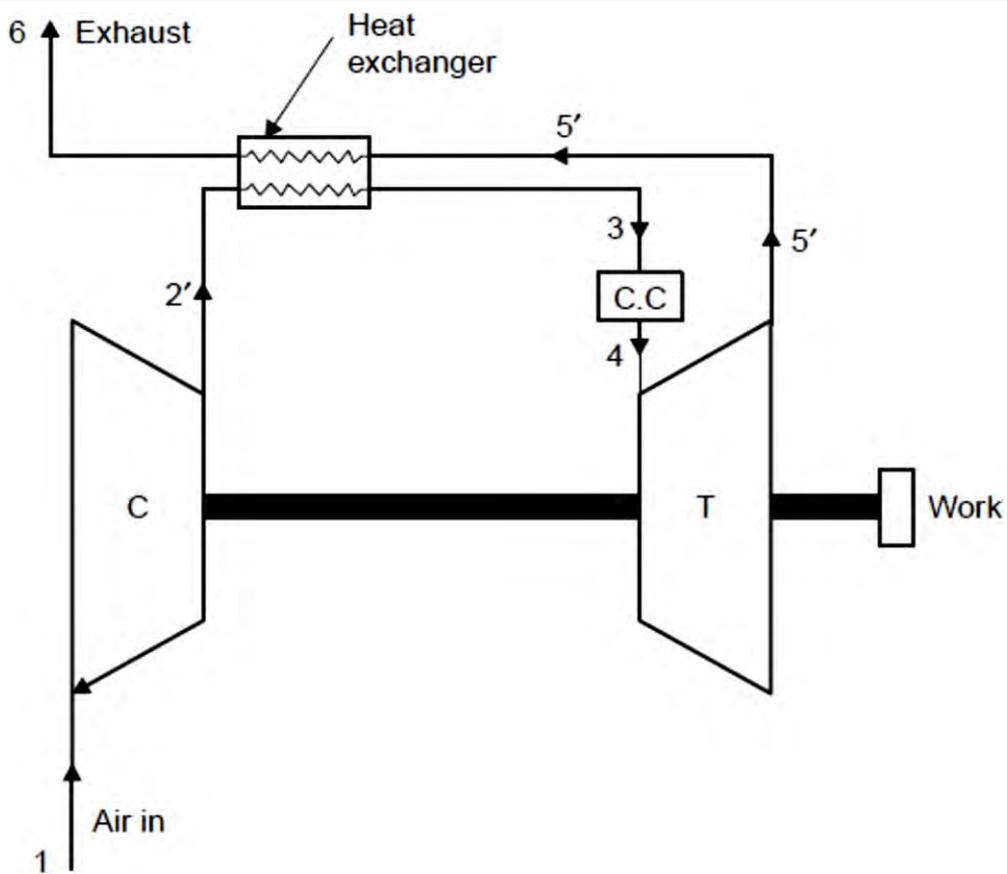


Fig. 7.18 Open cycle gas turbine plant with regeneration

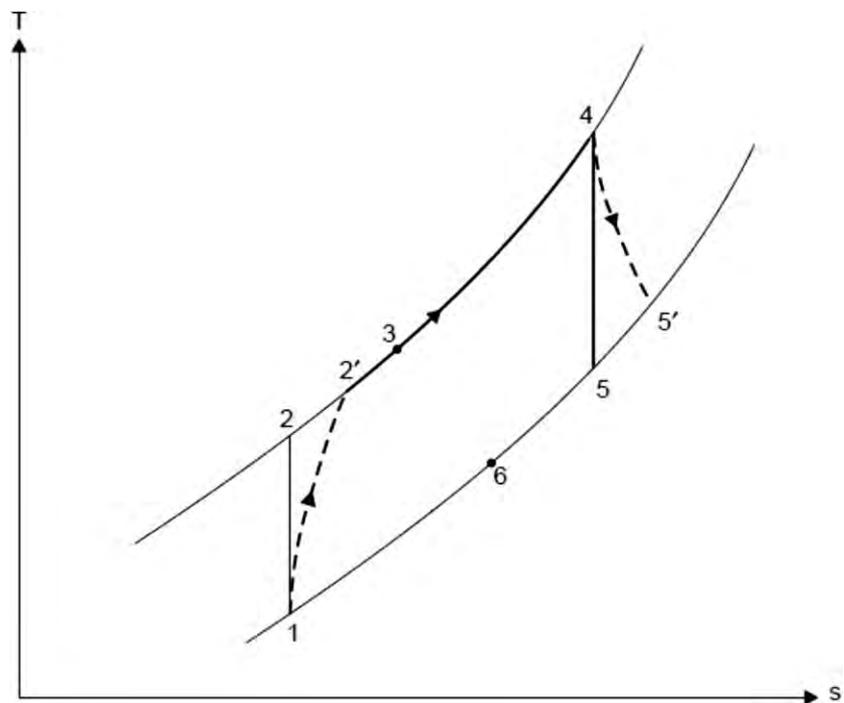


Fig. 7.19 T-s diagram of open cycle gas turbine with regeneration