ENGINEERING THERMODYNAMICS

UNIT I

Introductory Concepts.

Definition of THERMODYNAMICS:

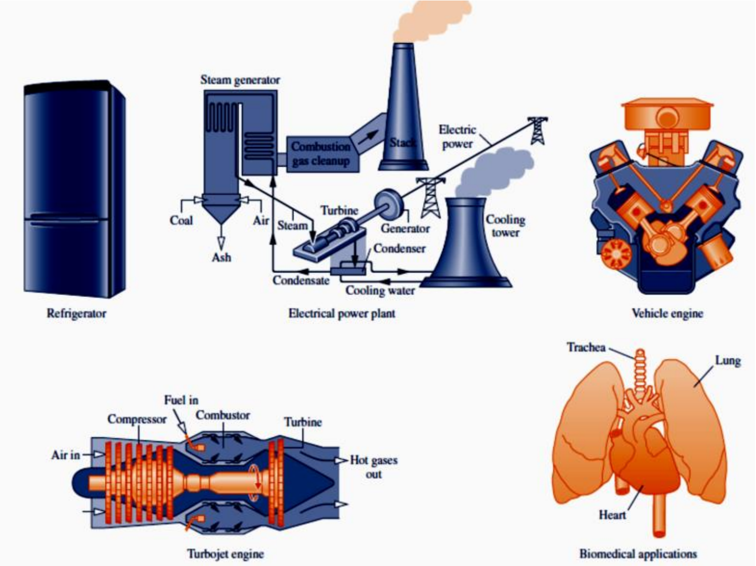
- Thermodynamics is the science that includes the study of energy transformations and of the relationships among the physical properties of the substances which are affected by these transformations.

- The term 'Thermodynamics' was first used in a publication by Lord Kelvin in 1849. The first thermodynamics textbook was written in 1859 by William Rankine, a professor at the University of Glasgow.

- **Scope of Thermodynamics**

Although aspects of thermodynamics have been studied since ancient times, the formal study of thermodynamics began in the early nineteenth century through consideration of the capacity of hot objects to produce work. Today the scope is much larger. Thermodynamics now provides essential concepts and methods for addressing critical twenty-first-century issues, such as using fossil fuels more effectively, fostering renewable energy technologies, and developing more fuel-efficient means of transportation. Also critical are the related issues of greenhouse gas emissions and air and water pollution. Thermodynamics is both a branch of science and an engineering specialty. Engineers are generally interested in studying systems and how they interact with their surroundings. To facilitate this, thermodynamics has been extended to the study of systems through which matter flows, including bioengineering and biomedical systems.

Areas of Application of Engineering Thermodynamics



1. Aircraft and rocket propulsion,
2. Alternative energy systems
3. Fuel cells
4. Geothermal systems
5. Wind turbines
6. Automobile engines
7. Bioengineering applications
8. Biomedical applications
9. Combustion systems
10. Compressors, pumps
11. Steam and gas turbines
12. Power production
13. Propulsion
14. Magneto hydrodynamic (MHD) converters
15. Ocean thermal, wave, and tidal power generation
16. Solar-activated heating, cooling, and power generation
17. Thermoelectric and thermionic devices
18. Cooling of electronic equipment
19. Cryogenic systems, gas separation, and liquefaction

20. Fossil and nuclear-fuelled power stations
21. Heating, ventilating, and air-conditioning systems
22. Absorption refrigeration and heat pumps
23. Vapour-compression refrigeration and heat pumps

Thermodynamic Properties and energy relationships can be studied by two methods.
(i) Classical Thermodynamics
(ii) Statistical Thermodynamics

i. **Classical and statistical Thermodynamics:** It Involve studies which are undertaken without recourse to the nature of the Individual Particles which make up a substance and to their reactions. This is macroscopic view towards matter, and it requires no hypothesis about the detailed structure of matter on the atomic scale.

For **example**, the pressure of a gas in a container is the result of momentum transfer between the molecules and the walls of the container. However, one does not need to know the behaviour of the gas particles to determine the pressure in the container. It would be sufficient to attach a pressure gage to the container.

classical thermodynamics allows important aspects of system behaviour to be evaluated from observations of the overall system. It provides a direct and easy way to the solution of engineering problems.

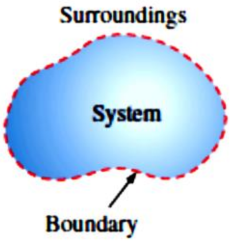
ii. **Statistical Thermodynamics:** It is based on the statistical behaviour of large groups of Individual particles. This is microscopic view point of matter.

The statistical thermodynamics or microscopic approach to thermodynamics, is concerned directly with the structure of matter. The objective of statistical thermodynamics is to characterize by statistical means the average behaviour of the particles making up a system of interest and relate this information to the observed macroscopic behaviour of the system.

For applications involving lasers, plasmas, high speed gas flows, chemical kinetics, very low temperatures (cryogenics), and others, the methods of statistical thermodynamics are essential.

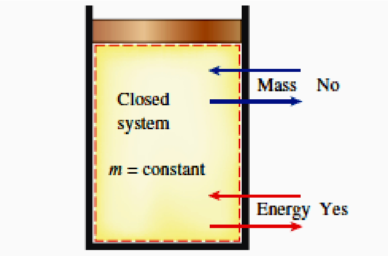
System: A thermodynamic system is a Three dimensional region of space or an amount of matter, bounded by an arbitrary surface.

Everything external to the system is considered to be part of the system’s **surroundings**. The system is distinguished from its surroundings by a specified b**oundary**, which may be at rest or in motion.

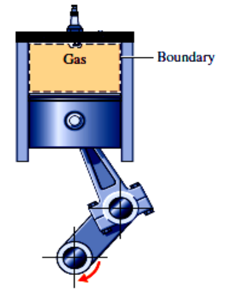


Systems may be considered to be *closed* or *open*, depending on whether a fixed mass or a fixed volume in space is chosen for study. A **closed system** (also known as a **control mass** or just *system* when the context makes it clear) consists of a fixed amount of mass, and no mass can cross its boundary. That is, no mass can enter or leave a closed system, as shown in fig. However energy may cross the system boundary.

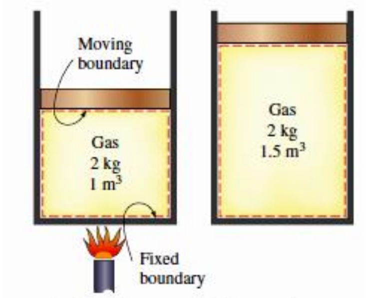
Examples:



Mass cannot cross the boundaries of a closed system, but energy can.



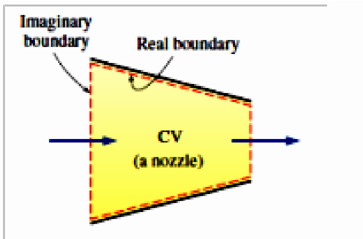
Closed system: A gas in a piston–cylinder assembly.



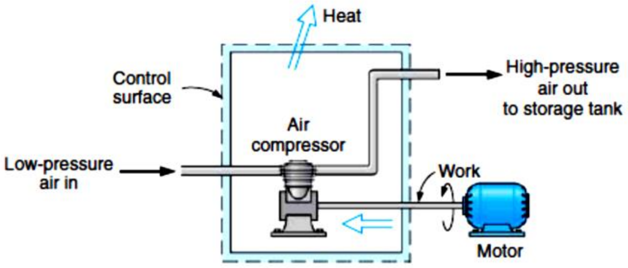
A closed system with a moving boundary.

An **open system**, or a **control volume**, as it is often called, is a properly selected region in space. It usually encloses a device that involves mass flow such as a compressor, turbine, or nozzle. Flow through these devices is best studied by selecting the region within the device as the control volume. Both mass and energy can cross the boundary of a control volume. The boundaries of a control volume are called a *control surface,* and they can be real or imaginary.

A large number of engineering problems involve mass flow in and out of a system and, therefore, are modelled as *control volumes.*
Example: A water heater, a car radiator, a turbine, and a compressor all involve mass flow and should be analyzed as control volumes (open systems) instead of as control masses (closed systems).



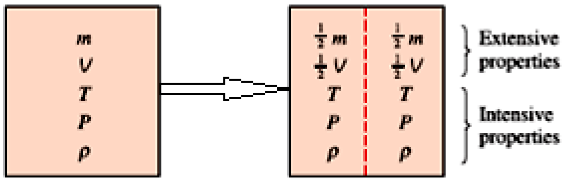
A control volume (CV) with real and imaginary boundaries



- **Properties:** The state or physical condition of the system can be described by some parameters called as Properties. Properties are the coordinates to describe the state of the system. Every property has a fixed value at a particular state.
  Some familiar properties are pressure P, temperature T, volume V, and mass m. The list can be extended to include less familiar ones such as viscosity, thermal conductivity, modulus of elasticity, thermal expansion coefficient, electric resistivity, and even velocity and elevation.

- Properties are considered to be either *intensive* or *extensive*.
- **Intensive properties** are those that are independent of the Size or Extent or mass of a system, such as temperature, pressure, and density.
- **Extensive properties** are those whose values depend on the size—or extent—of the system. Total mass, total volume, and total momentum are some examples of extensive properties. 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. Each part will have the same

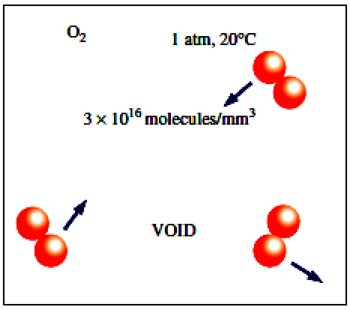
value of intensive properties as the original system, but half the value of the extensive properties.



Criterion to differentiate intensive and extensive properties.

- Extensive properties per unit mass are called **specific properties**. Some examples of specific properties are specific volume ($v = V/m$) and specific total energy ($e = E/m$).
- **Continuum:** Matter is made up of atoms that are widely spaced in the gas phase. Yet it is very convenient to disregard the atomic nature of a substance and view it as a continuous, homogeneous matter with no holes, that is, a **continuum**.
- The continuum idealization allows us to treat properties as point functions and to assume the properties vary continually in space with no jump discontinuities. This idealization is valid as long as the size of the system we deal with is large relative to the space between the molecules.

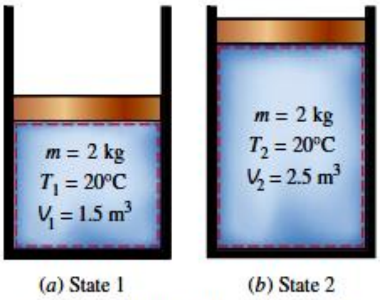
- To have a sense of the distance involved at the molecular level, consider a container filled with oxygen at atmospheric conditions. The diameter of the oxygen molecule is about
- 3×10^{-10} m and its mass is 5.3×10^{-26} kg. Also, the *mean free path* of oxygen at 1 atm pressure and 20°C is 6.3×10^{28} m. That is, an oxygen molecule travels, on average, a distance of $6.3 \text{ X } 10^{28}$ m (about 200 times of its diameter) before it collides with another molecule.
- Also, there are about $3 \text{ X } 10^{16}$ molecules of oxygen in the tiny volume of 1 mm^3 at 1 atm pressure and 20°C. The continuum model is applicable as long as the characteristic length of the system (such as its diameter) is much larger than the mean free path of the molecules.
- At very high vacuums or very high elevations, the mean free path may become large (for example, it is about 0.1 m for atmospheric air at an elevation of 100 km). For such cases the **rarefied gas flow theory** should be used, and the impact of individual molecules should be considered. In this text we will limit our consideration to substances that can be modelled as a continuum.



Despite the relatively large gaps between molecules, a gas can usually be treated as a continuum because of the very large number of molecules even in an extremely small volume.

- **State:** The state of a system is the condition of the system described by the values of its properties.
- **Equilibrium:** If the Properties are invariant with respect to time then that state is called as an Equilibrium state.

Consider a system not undergoing any change. At this point, all the properties can be measured or calculated throughout the entire system, which gives us a set of properties that completely describes the condition, or the **state**, 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. In the below figure shows a system at two different states.



(*a*) State 1 (*b*) State 2

A system at two different states.

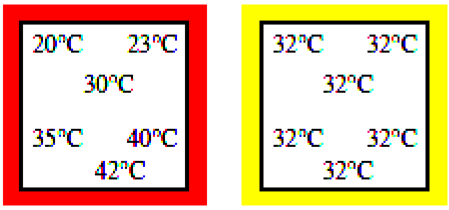
There are many types of equilibrium, and a system is not in **thermodynamic equilibrium** unless the conditions of all the relevant types of equilibrium are satisfied. For example,

iii. a system is in **thermal equilibrium** if the temperature is the same throughout the entire system, as shown in Fig. That is, the system involves no temperature differential, which is the driving force for heat flow.

iv. **Mechanical equilibrium** is related to pressure, and a system is in mechanical equilibrium if there is no change in pressure at any point of the system with time. However, the pressure may vary within the system with elevation as a result of gravitational effects.

v. Finally, a system is in **chemical equilibrium** if its chemical composition does not change with time, that is, no chemical reactions occur. A system will not be in equilibrium unless all the relevant equilibrium criteria are satisfied.

If all the above equilibrium are satisfied then the system is said to be in Thermodynamic Equilibrium.



(*a*) Before (*b*) After

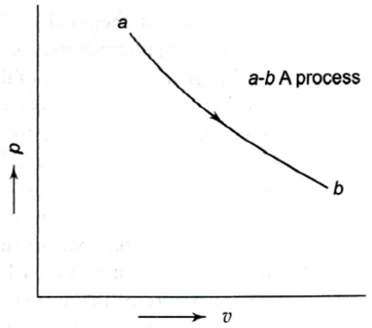
A closed system reaching thermal equilibrium.

State Postulate:

- The state of a simple compressible system is completely specified by two independent, intensive properties.

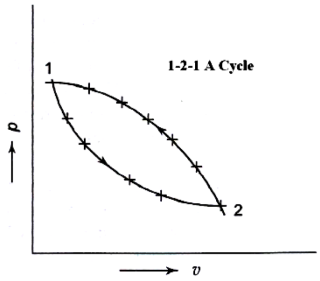
Processes and cycles:

- 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.

If the process proceeds in such a way that if the final state is same as initial state then a **CYCLE** is said to be completed.



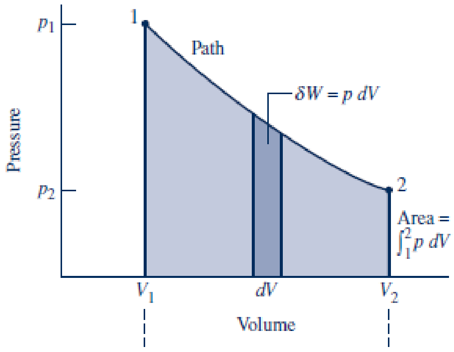
- **Quasi static Process**

  When a process proceeds in such a manner that the system remains infinitesimally close to an equilibrium state at all times, it is called a **quasi-static**, or **quasi-equilibrium**, **process**.

- **Expansion or Compression Work in Quasi-Equilibrium Processes**

A Quasi Equilibrium process is one in which the departure from thermodynamic equilibrium is at most infinitesimal. All states through which the system passes in a quasi equilibrium process may be considered equilibrium states. Because non equilibrium effects are inevitably present during actual processes, systems of engineering interest can at best approach, but never realize, a quasi equilibrium process.

Imagine that one of the masses is removed, allowing the piston to move upward as the gas expands slightly. During such an expansion, the state of the gas would depart only slightly from equilibrium. The system would eventually come to a new equilibrium state, where the pressure and all other intensive properties would again be uniform in value. Moreover, were the mass replaced, the gas would be restored to its initial state, while again the departure from equilibrium would be slight. If several of the masses were removed one after another, the gas would pass through a sequence of equilibrium states without ever being far from equilibrium. In the limit as the increments of mass are made vanishingly small, the gas would undergo a quasi equilibrium expansion process. A quasi equilibrium compression can be visualized with similar considerations.



Work of a quasiequilibrium expansion or compression process.

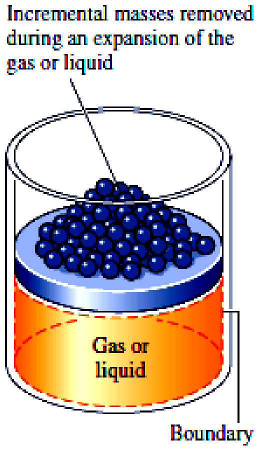


Illustration of a quasiequilibrium expansion or compression.

TEMPERATURE AND THE ZEROTH LAW OF THERMODYNAMICS

Temperature is rooted in the notion of the “hotness” or “coldness” of objects. We use our sense of touch to distinguish hot objects from cold objects and to arrange objects in their order of “hotness,” deciding that 1 is hotter than 2, 2 hotter than 3, and so on. But however sensitive human touch may be, we are unable to gauge this quality precisely.

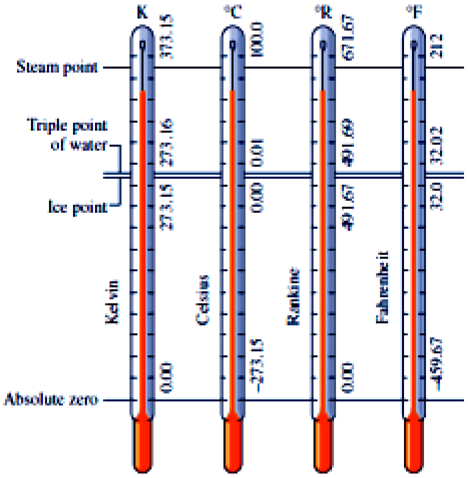
To illustrate this, consider two copper blocks, and suppose that our senses tell us that one is warmer than the other. If the blocks were brought into contact and isolated from their surroundings, they would interact in a way that can be described as a **thermal (heat) interaction**. During this interaction, it would be observed that the volume of the warmer block decreases somewhat with time, while the volume of the colder block increases with time. Eventually, no further changes in volume would be observed, and the blocks would feel equally warm. Similarly, we would be able to observe that the electrical resistance of the warmer block decreases with time and that of the colder block increases with time; eventually the electrical resistances would become constant also. When all changes in such observable properties cease, the interaction is at an end. The two blocks are then in **thermal equilibrium**. Considerations such as these lead us to infer that the blocks have a physical property that determines whether they will be in thermal equilibrium. This property is called **temperature**, and we postulate that when the two blocks are in thermal equilibrium, their temperatures are equal.

Zeroth Law of Thermodynamics:

- when two objects are in thermal equilibrium with a third object, they are in thermal equilibrium with one another.
- If we want to know if two objects are at the same temperature, it is not necessary to bring them into contact and see whether their observable properties change with time, as described previously. It is necessary only to see if they are individually in thermal equilibrium with a third object. The third object is usually a *thermometer*.
- Any object with at least one measurable property that changes as its temperature changes can be used as a thermometer. Such a property is called a **thermometric property**. The particular substance that exhibits changes in the thermometric property is known as a *thermometric substance*.

Temperature scales:

- The temperature scales used in the SI and in the English system today are the **Celsius scale** and the **Fahrenheit scale** respectively**.** On the Celsius scale, the ice and steam points were originally assigned the values of 0 and 100°C, respectively. The corresponding values on the Fahrenheit scale are 32 and 212°F. These are often referred to as *two-point scales* since temperature values are assigned at two different points.
- In thermodynamics, it is very desirable to have a temperature scale that is independent of the properties of any substance or substances. Such a temperature scale is called a **thermodynamic temperature scale**, which is developed later in conjunction with the second law of thermodynamics.
- The thermodynamic temperature scale in the SI is the **Kelvin scale**, named after Lord Kelvin (1824–1907). The temperature unit on this scale is the **kelvin**, which is designated by K. The lowest temperature on the Kelvin scale is absolute zero, or 0 K.
- The thermodynamic temperature scale in the English system is the **Rankine scale**, named after William Rankine (1820–1872). The temperature unit on this scale is the **rankine**, which is designated by R.
- The relationship of the Kelvin, Rankine, Celsius, and Fahrenheit scales is shown in Fig. together with values for temperature at three fixed points: the triple point, ice point, and steam point.
- By international agreement, temperature scales are defined by the numerical value assigned to the easily reproducible **triple point** of water: the state of equilibrium among steam, ice and liquid water. The temperature at this standard fixed point is defined as 273.16 Kelvins, abbreviated as 273.16 K.



Comparison of temperature scales.

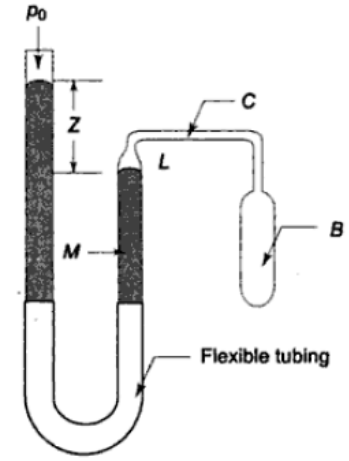
- The relationship between centigrade scale and Kelvin scale is $T(^0C)= T(K) -273.15$.
- The relationship between fahrenheit scale and Rankine scale is $T(^0F)= T(R) -459.67$.
- The relationship between fahrenheit scale and centigrade scale is $T(^0F)= 1.8T(^0C) +32$

Constant volume Gas thermometer:

- A small amount of gas is enclosed in bulb B which is in communication via the capillary tube C with one limb of the mercury manometer M. The other limb of mercury manometer is open to the atmosphere and can be moved vertically to adjust the mercury levels so that mercury just touches the Lip L of the capillary. The pressure in the bulb is used as a thermometric property and is given by

$$p = p_o + \rho_m Z g.$$

where p_o is the atmospheric pressure and ρ_m is the density of mercury.



Constant volume gas thermometer

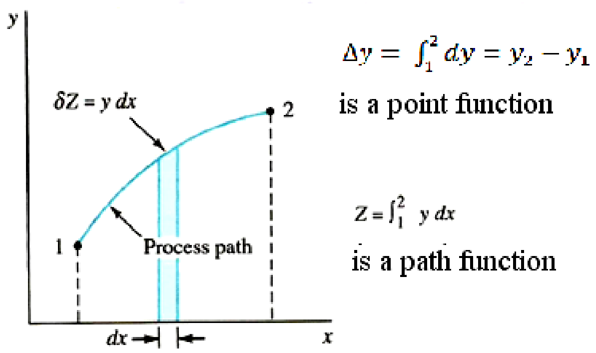
when the bulb is brought in contact with the system whose temperature is to be measured, the bulb, in course of time, comes in thermal equilibrium with the system. The gas in the bulb expands, on being heated, pushing the mercury downwards. The flexible limb of the manometer is then adjusted so that the mercury again touches the lip L. The difference in the mercury levels Z is recorded and the pressure p of the gas in the bulb is estimated. since the volume of the trapped gas remains constant, from the ideal gas equation

$$\Delta T = \frac{V}{R}\Delta P$$

i.e temperature increase is proportional to pressure increase.

Point and Path functions:

- Thermodynamic quantities can be divided into two categories: point or state functions and path or process functions.



- All properties are state functions, since the change in the value of a property depends solely on the property values at the initial and final states, and not on the path of the process.
- A property change for a process with given end states 1 and 2 is described mathematically by the exact differential *dy*, such that

$$\Delta y = \int_1^2 dy$$

- Quantities whose values depend on the path of the process are called process or path functions.
- Path functions are inexact differentials and hence

$$Z_{12} \neq \int_1^2 dz$$

The two major process functions in thermodynamic studies are work and heat.

Density, Specific Volume, and Specific Gravity:

- The density ρ is defined as the mass per unit volume:

$\rho = \frac{mass}{volume} = \frac{m}{v}$,its unit is kg per m^3

- The specific volume v is defined as volume per unit mass:

$v = \frac{volume}{mass} = \frac{V}{m}$, its unit is m^3 per kg

- The specific gravity of a substance is the ratio of its density to that of water at a specified temperature, such as 4 or 20^oC and one atmosphere:

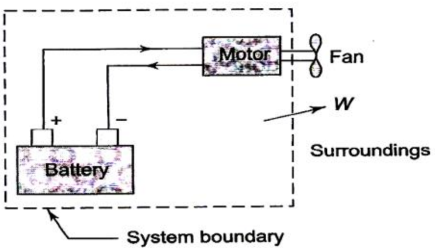
$$Sp.gr = \frac{\rho}{\rho_{water}} \text{ it has no units}$$

- The density of water at 4^oC is close to 1.00 g/cm^3 (kg/L), 1000 kg/m^3, while that of liquid mercury is close to 13.6 g/cm^3, 13600 kg/m^3.
- The specific weight *w* of a substance is the weight per unit volume:

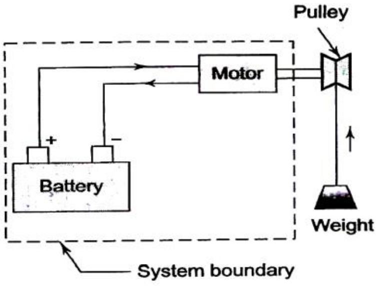
$w = \frac{weight}{volume} = \frac{W}{V}$, its unit is N per m^3

Thermodynamic work

- Work is said to be done by a system if the sole effect on things external to the system can be reduced to the raising of a weight.



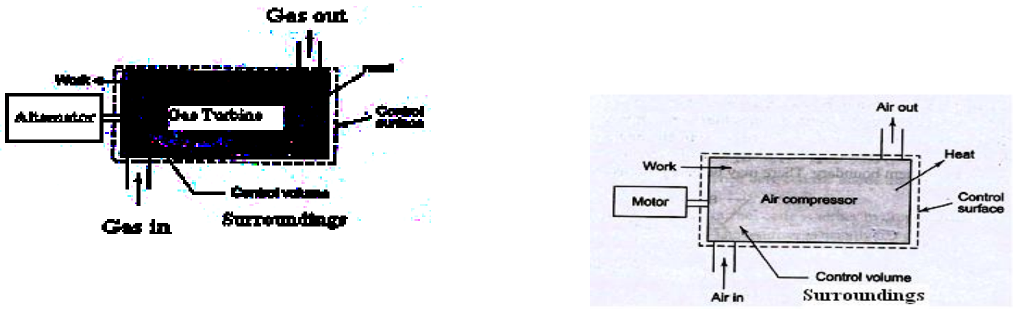
Battery-motor System driving a fan



Work transfer from a System

Sign Convention:

- When work is done by a system it is arbitrarily taken to be positive, and when work is done on a system, it is taken to be negative.



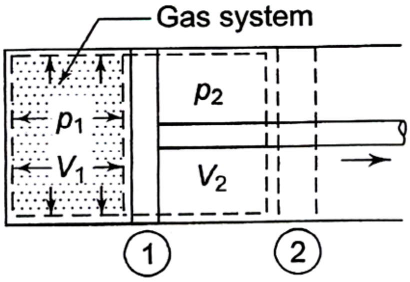
(a) W is positive (b) W is negative

Work interaction between a System and the Surroundings

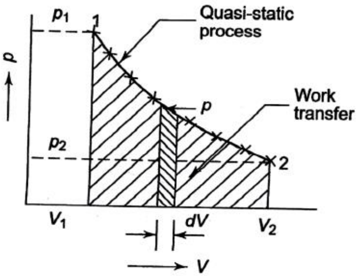
- The symbol W is used for work transfer. The unit of work is N.m or Joule.
- The rate at which the work is done by, or upon, the system is known as power. The unit of power is J/s or Watt.

Displacement work or pdV Work:

- Consider expansion of gas in a piston-cylinder assembly as shown in fig. 1.13.
- The expansion of the gas by outward movement of the piston can be represented on p-V diagram as given in Fig.1.14.



pdV work



Quasi-static pdV work

- The shaded area represents work done due to small movement of the piston and the total work done by the gas during expansion process is

$$W_{1-2} = \int_1^2 pdV$$

- The integral $\int_1^2 pdV$ can be evaluated, only if we know the relation between p and V or the path of the process.
- The area under the curve 1-2 represents the work done during the process 1-2.

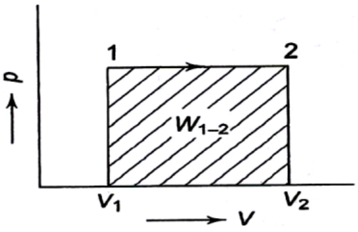
pdV-work in Various Quasi-Static Processes:

- Constant pressure process (isobaric or isopiestic process)

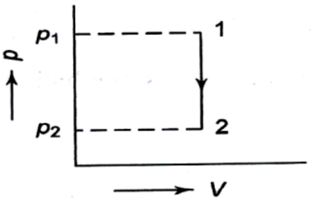
$$W_{1-2} = \int_1^2 pdV = p(V_2 - V_1)$$

- Constant volume process (isochoric process)

$$2W_{1-2} = \int_1^2 pdV = 0$$



Constant Pressure Process



Constant Volume Process

- Process in which pV = C

$$W_{1-2} = \int_{V1}^{V2} pdV = p_1v_1ln\frac{V_2}{V_1} = p_1v_1ln\frac{P_1}{P_2}$$

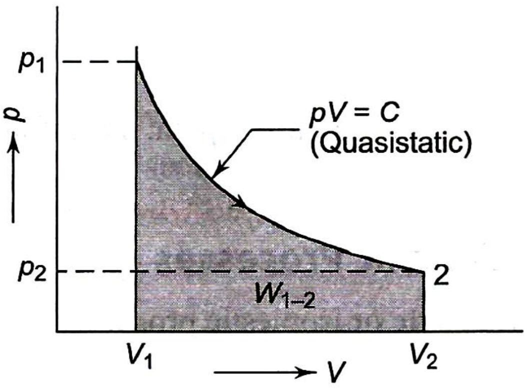
- Process in which pV^n=C, where n is a constant

$$p_1{v_1}^n = p_2{v_2}^n$$

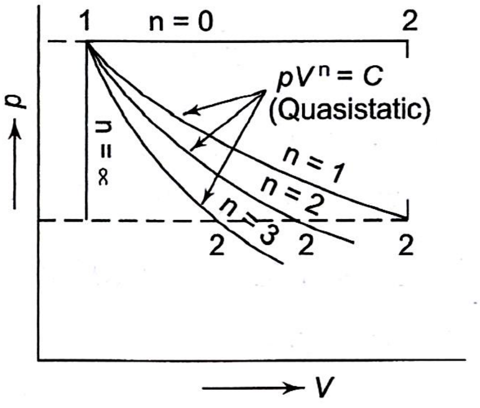
$$p = \frac{p_1{v_1}^n}{v^n}$$

$$W_{1-2} = \int_{V_1}^{V_2}\frac{C}{v^n}dv = C\left|\frac{V_2^{1-n}}{1-n} - \frac{V_1^{1-n}}{1-n}\right| = p_2{v_2}^n * \frac{V_2^{1-n}}{1-n} - p_1{v_1}^n * \frac{V_1^{1-n}}{1-n}$$

$$\therefore W_{1-2} = \frac{p_2v_2 - p_1v_1}{n-1}$$



Process in which pV=Constant



Profess in which pV^n=Constant

Similarly, for process in which pv^{γ}=C

$$W_{1-2} = \frac{p_2v_2 - p_1v_1}{\gamma - 1}$$

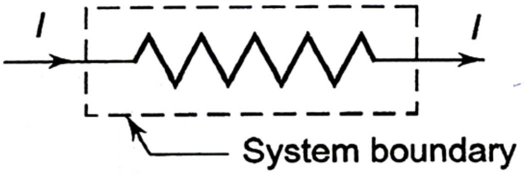
Other Types of Work Transfer

Electrical Work:

- When a current flows through a resistor, taken as a system, there is work transfer into the system.
- It is a thermodynamic work because the current can drive a motor, the motor can drive a pulley and the pulley can raise a weight.
- The current flow, *I*, in amperes, is given as

$I = \frac{dc}{dt}$ where C is the charge in coulombs and t is time in seconds.

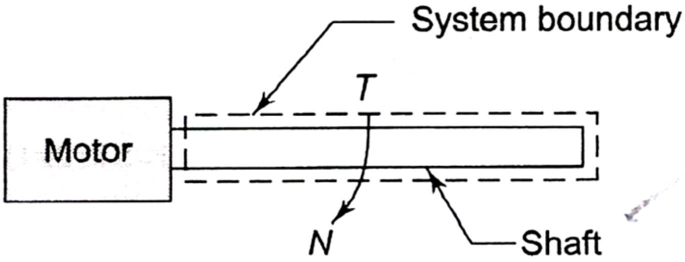
- If E is the voltage potential, the work, $dW = E.dc = EIdt$
- $W = E.dc = \int_{t_1}^{t_2} EIdt$



Electrical Work

Shaft Work:

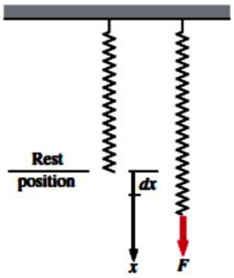
- When a shaft rotated by a motor, taken as a system, there is work transfer into the system.



Shaft work

- This is a form of thermodynamic work because the shaft can rotate a pulley which can raise a weight.
- If T is the torque applied to the shaft and $d\theta$ is the angular displacement of the shaft, the shaft work is $W = \int_1^2 Td\theta$

Spring Work:



- It is common knowledge that when a force is applied on a spring, the length of the spring changes.
- When the length of the spring changes by a differential amount *dx* under the influence of a force *F*, the work done is

$$dW_{spring} = F\,dx$$

- The displacement x is proportional to the force applied

$$F = kx \qquad \text{(kN)}$$

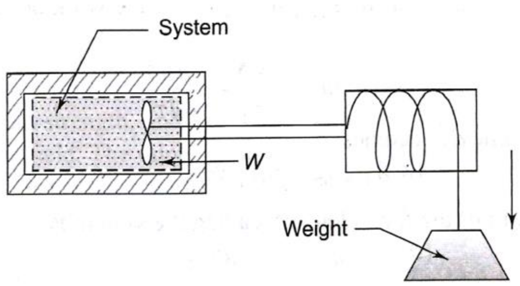
- where k is the spring constant and has the unit kN/m. The displacement *x* is measured from the undisturbed position of the spring (that is, *x* = 0 when F = 0).
- Work done = F.distance

For Infinitesimal extension (dx) of spring work is $\delta w = F.dx$

$$\text{Total } work = \int_1^2 Fdx = \int_1^2 kxdx = k\left[\frac{x_2^2}{2} - \frac{x_1^2}{2}\right] \qquad \text{(kJ)}$$

where x_1 and x_2 are the initial and the final displacements of the spring, respectively, measured from the undisturbed position of the spring.

Paddle-wheel work or Stirring Work:



- The paddle-wheel turns when the weight is lowered.
- The paddle-wheel stirs fluid system and hence, there is work transfer into the fluid system.
- Since the volume of the system remains constant, $\int_1^2 \text{pdV} = 0$
- If m is the mass of the weight lowered through a distance dz and T is the torque transmitted by the shaft in rotating through an angle dθ , the differential work transfer to the fluid is given by

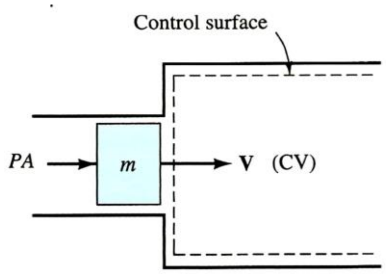
  $$\text{dW} = \text{mgdz} = Td\theta \quad = W = \int_1^2 mgdz = \int_1^2 Td\theta = 0$$

- The total work transfer is

  $$mg\Delta z = T\Delta\theta$$

Flow Work:

- The flow work is significant only in a flow process or an open system.
- When mass *m* enters or leaves a control volume, work is required to push the fluid into or out of the system. This term is referred to as flow work.
- A mass *m* in region *A* (Fig. 1.21) initially resides just outside a control surface.



Flow work at a Control Surface

- The normal force exerted at the control surface of area *A* is simply the pressure times the area, or *PA*.
- Thus the rate of flow work $\dot{W}_{flow}$ is given by

  $\dot{W}_{flow} = pAV,$ where V is the velocity of fluid mass *m*.

  Since *m* = AV/v, therefore $\dot{W}_{flow} = pmv.$ Where *v* is the specific volume.

- The flow work per unit mass is pv.

Work done in Stretching a Wire:

- Let us consider a wire as the system.
- If the length of the wire is changed from L to L + dL, the infinitestimal amount of work that is done is equal to dW = - F dL, where F is the tension in the wire.

- The minus sign is used because a positive value of dL means an expansion of the wire, for which work must be done on the wire, i.e., negative work.

- For a finite change of length.

$$W = -\int_1^2 Fdl$$

- If we limit the problem to within the elastic limit, where E is the modulus of elasticity, τ is the stress, ε is the strain, and A is the cross-sectional area, then

$$F = \tau A = E\epsilon A, since\ E = \frac{\tau}{\varepsilon}$$

and $= \frac{dl}{L}$.

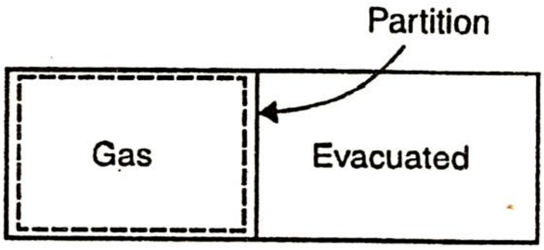
$$dw = -FdL = -E\epsilon ALd\varepsilon$$

$$\therefore W = -A\varepsilon L \int_1^2 \epsilon d\epsilon = -\frac{AEL}{2(\epsilon_2^2 - \varepsilon_1^2)}$$

Unrestrained or Free Expansion:

- The expansion of gas against a vacuum is called free expansion; essentially it is expansion which is not restrained by an opposing force.

- Let us consider a gas separated from the vacuum by a partition. Let the partition be removed. The gas rushes to fill the entire volume.



Unrestrained Expansion

- Though this free expansion process involves a change of volume yet the work transfer is zero since the vacuum does not offer any resistance to the expansion process.

- Free expansion process is a totally irreversible process for which work transfer is zero even though $\int$ pdv is not zero.

Heat Transfer:

- Heat is defined as the form of energy that is transferred across a boundary by virtue of temperature difference. The temperature difference is the 'potential' or 'force' and heat transfer is the 'flux'.

- Heat flow into a system is taken to be positive, and heat flow out of a system is taken as negative. The symbol Q is used for heat transfer.

- Like work transfer, heat transfer is a path function and is an inexact differential.

- A process in which no heat crosses the boundary of the system is called an adiabatic process.

- Thus, an adiabatic process is one in which there is only work interaction between the system and its surroundings.

- A wall which is impermeable to the flow of heat is an adiabatic wall, whereas a wall which permits the flow of heat is a diathermic wall.

Specific Heat:

- The specific heat of a substance is defined as the amount of heat required to raise a unit mass of the substance through a unit rise in temperature. The symbol *c* will be used for specific heat.

$$C = \frac{Q}{m\Delta T} \qquad \text{J/kg K.}$$

- For gases, if the process is at constant pressure, it is c_p, and if the process is at constant volume, it is c_v.

- For solids and liquids, however, $c_p=c_v=c$, as they are incompressible.

Latent Heat:

- The latent heat is the amount of heat transfer required to cause a phase change in unit mass of a substance at a constant pressure and temperature.

- There are three phases in which matter can exist; solid, liquid, and vapour or gas.

- The latent heat of fusion (L_{fu}) is the amount of heat transferred to melt unit mass of solid into liquid, or to freeze unit mass of liquid to solid.

- The latent heat of vaporization (L_{vap}) is the quantity of heat required to vaporise unit mass of liquid into vapour or condense unit mass of vapour into liquid.

- The latent heat of sublimation (L_{sub}) is the amount of heat transferred to convert unit mass of solid to vapour or vice versa.

- L_{fu} is not much affected by pressure, whereas L_{vap} is highly sensitive to pressure.

Comparison of Heat and Work:

Similarities:

- Both heat and work are path function; they are not properties of the system and their differentials are not exact.

- They represent energy crossing the system boundary; and hence they are a boundary phenomenon.

- Both represent transient phenomenon; these energy interactions occur only when a system undergoes change of state. They exist as stored energy before or after the interaction.

- Concepts of heat and work are associated not with a ‘store’ but with a ‘transfer across boundary’.

Dissimilarities:

- There cannot be work transfer in a stable system. No such restriction exists for heat interaction.

- Heat is energy interaction due to temperature difference only; work is by reasons other than temperature difference.

- Heat is a low grade energy whereas work is a high grade energy.

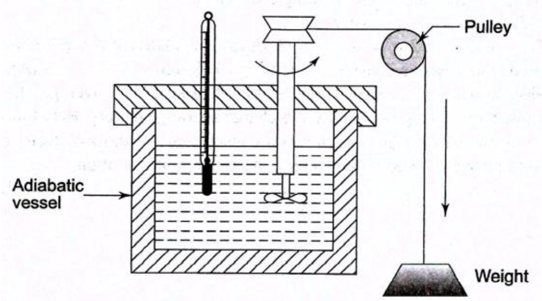
EENGINEERING THERMODYNAMICS

Unit – II

Learning Material

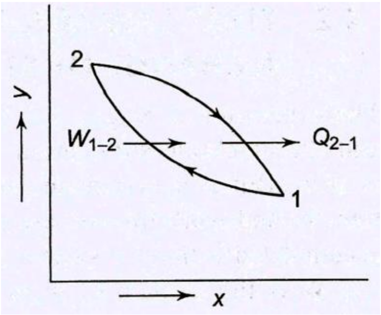
The first Law of Thermodynamics for a Control Mass Undergoing a Cycle - Joule's Experiment

- Consider a closed system consisting of known mass of water, m, contained in an adiabatic vessel having a thermometer and a paddle wheel, as shown in fig.2.3.



Adiabatic Work

- Let a certain amount of work W_{1-2} be done upon the system by the paddle wheel. The quantity of work can be measured by the fall of weight which drives the paddle wheel through a pulley.
- Let the system is initially at temperature T_1, the same as that of atmosphere, and after work transfer let the temperature rise to T_2. The pressure is always 1 atm.
- The process 1-2 undergone by the system is shown in fig. in generalized thermodynamic coordinates, X, Y.



Adiabatic Work Transfer W_{1-2} Followed by Heat Transfer Q_{2-1}

- Let the insulation now be removed. The system and the surroundings interact by heat transfer till the system returns to the original temperature T_1, attaining the condition of thermal equilibrium with the atmosphere.
- The amount of heat transfer Q_{2-1} from the system during this process, 2-1, shown in fig. can be estimated from $Q_{2-1} = m\, c_p\, (T_2 – T_1)$.
- The system thus executes a cycle, which consists of definite amount of work input W_{1-2} to the system followed by the transfer of an amount of heat Q_{2-1} from the system.

- It has been found that this W_{1-2} is always proportional to the heat Q_{2-1}, and the constant of proportionality is called the Joule's equivalent or the mechanical equivalent of heat.
- In the simple example given here, there are only to energy transfer quantities as the system performs a thermodynamic cycle. If the cycle involves many more heat and work quantities, the same result will be found. Expressed algebraically.

$$\left(\sum W\right)_{cycle} = \left(\sum Q\right)_{cycle}$$

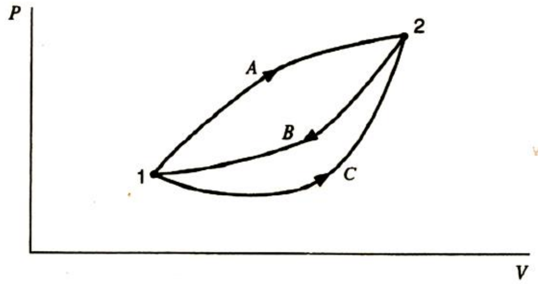
- This is also expressed in the form

$$\oint dW = J \oint dQ$$

- Where the symbol $\oint$ denotes the cyclic integral for the closed path. This is the first law for a closed system undergoing a cycle. It is accepted as a general law of nature. Since no violation of it has ever been demonstrated.
- *The first law of thermodynamics states that during any cycle a system (Control mass) undergoes, the cyclic integral of the heat is equal to the cyclic integral of the work.*

The First Law of Thermodynamics for a Change in State of a Control Mass

- Consider a system that undergoes a cycle in which it changes from state 1 to state 2 by process A and returns from state 2 to state 1 by process B. This cycle is shown in Fig. on a pressure – volume diagram.



Demonstration of the Existence of Thermodynamic Property E

- From the first law of thermodynamics

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

- Considering the two separate processes, we have $\int_1^2 \delta Q_A + \int_2^1 \delta Q_B = \int_1^2 \delta W_A + \int_2^1 \delta W_B$
- Now consider another cycle in which the control mass changes from state 1 to state 2 by process C and returns to state 1 by process B, as before. For this cycle we can write $\int_1^2 \delta Q_C + \int_2^1 \delta Q_B = \int_1^2 \delta W_C + \int_2^1 \delta W_B$

  Subtracting the second of these equations from the first, we obtain $\int_1^2 \delta Q_A - \int_1^2 \delta Q_C = \int_1^2 \delta W_A - \int_1^2 \delta W_C$

  or by rearranging, $\int_1^2 (\delta Q - \delta W)_A = \int_1^2 (\delta Q - \delta W)_C$

- Since A and C represent arbitrary processes between states 1 and 2, the quantity $(\delta Q - \delta W)$ is the same for all processes between states 1 and 2. Therefore, $(\delta Q - \delta W)$ depends only on the initial and final states and not on the path followed between the two states. We conclude that this is a point function, and therefore it is the differential of a property of the mass. This property is the energy of the mass and is given the symbol E. Thus we can write dE = $\delta Q - \delta W$
- Because E is property, its derivative is written dE. When equation is integrated from an initial state 1 to a final state 2, we have $E_2 - E_1 = Q_{1-2} - W_{1-2}$
- Where E_1 and E_2 are the initial and final values of the energy E of the control mass, Q_{1-2} is the heat transferred to the control mass during the process from state 1 to state 2, and W_{1-2} is the work done by the control mass during the process.
- The physical significance of the property E is that it represents all the energy of the system in the given state. This energy might be present in a variety of forms, such as the kinetic or potential energy of the system as a whole with respect to the chosen coordinate frame, energy associated with the motion and position of the molecules, energy associated with the structure of the atom, chemical energy present in a storage battery, energy present in a charged condenser, or any of a number of other forms.
- E = Internal energy + kinetic energy + potential energy (or)
- E = U + KE + PE
- $dE = dU + d(KE) + d(PE) = \delta Q - \delta W$
- In words this equation states that as a control mass undergoes a change of state, energy may cross the boundary as either heat or work, and each may be positive or negative. The net change in the energy of the system will be exactly equal to the net energy that crosses the boundary of the system. The energy of the system may change in any or three ways – by a change in internal energy, in kinetic energy, or in potential energy.
- The kinetic energy is expressed as $KE = \frac{1}{2}mV^2$, where V is the velocity of the system as a whole.
- The potential energy is expressed as $PE = mgZ$, where Z is the altitude of the center of gravity of the system as a whole from the datum line.

- Therefore, the fist law thermodynamics for a change of state of the system is expressed as

$$U_2 - U_1 + \frac{m(V_2^2 - V_1^1)}{2} + mg(Z_2 - Z_1) = Q_{1-2} - W_{1-2}$$

- *The net change of the energy of the control mass during a process is always equal to the net transfer of energy across the boundary as heat and work.*

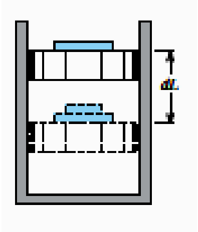
Internal Energy – A thermodynamic Property

- Internal energy is an extensive property because it depends on the mass of the system. Similarly, kinetic and potential energies are extensive properties.

- The symbol *U* designates the internal energy of a given mass of substance.
- The internal energy per unit mass, u, is the intensive property of the system.

The Thermodynamic Property Enthalpy

- Let us consider a control mass undergoing a quasi-equilibrium constant-pressure process, as shown in fig.



Constant-Pressure Quasi-equilibrium Process

- Assume that there are no changes in kinetic or potential energy and that the only work done during the process is that associated with the boundary (piston) movement. Taking the gas as control mass and applying the first law as

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

- The work done can be calculated from the relation $W_{1-2} = \int_1^2 PdV$
- Since the pressure is constant, $W_{1-2} = P\int_1^2 dV = P(V_2 - V_1)$
- Therefore, $Q_{1-2} = U_2 - U_1 + P_2V_2 - P_1V_1$

  $= (U_2 + P_2V_2) - (U_1+P_1V_1)$

- We find that, in this very restricted case, the heat transfer during the process is given in terms of the change in the quantity (U + PV) between the initial and final states.
- Because all these quantities are thermodynamic properties, that is, functions only of the state of the system, their combination must also have these same characteristics. Therefore, we find it convenient to define a new extensive property, the enthalpy, H = U + PV or, per unit mass, h = u + pv
- The heat transfer in a constant-pressure quasi-equilibrium process is equal to the change in enthalpy, which includes both the change in internal energy and the work for this particular process.

The First Law as a Rate Equation

- $\frac{dU}{dt} + \frac{d(KE)}{dt} + \frac{d(PE)}{dt} = \dot{Q} - \dot{W}$
- In the absence of kinetic and potential energies, $\frac{dE}{dt} = \dot{Q} - \dot{W}$

Energy of an isolated system

- An isolated system is one in which there is no interaction of the system with the surroundings.
- For an isolated system dQ = 0, dW=0. Hence, application first law of thermodynamics gives dE = 0. Therefore, E = constant.

- The energy of an isolated system is always constant.

Perpetual Motion Machine of the First Kind – PMM1

- There can be no machine which would continuously supply mechanical work without some other form of energy disappearing simultaneously. Such a fictitious machine is called a perpetual motion machine of the first kind, or in brief, PMM1. A PMM1 is thus impossible.

The Constant-Volume and Constant-Pressure Specific Heats

- The specific heat at constant volume is defined as the amount of heat required to raise the temperature of 1 kg substance by 1 degree when volume is maintained constant $C_v = \frac{1}{m}\left(\frac{\delta Q}{\delta T}\right)_v$.
- Constant volume, for which the work term (P dV) is zero, so that the specific heat at constant volume can also be expressed as $C_v = \frac{1}{m}\left(\frac{\delta Q}{\delta T}\right)_v = \frac{1}{m}\left(\frac{\partial U}{\partial T}\right)_v = \left(\frac{\partial u}{\partial T}\right)_v$
- The specific heat at constant pressure is defined as the amount of heat required to raise the temperature of 1 kg substance by 1 degree when pressure is maintained constant $C_p = \frac{1}{m}\left(\frac{\delta Q}{\delta T}\right)_p$
- Constant pressure, for which the work term can be integrated and the resulting PV terms at the initial and final states can be associated with the internal energy terms, thereby leading to the conclusion that the heat transfer can be expressed in terms of the enthalpy change. The corresponding specific heat at constant pressure can be expressed as $C_p = \frac{1}{m}\left(\frac{\delta Q}{\delta T}\right)_p = \frac{1}{m}\left(\frac{\partial H}{\partial T}\right)_p = \left(\frac{\partial h}{\partial T}\right)_p$

Relationship between Specific Heats and Gas Constant

- The enthalpy, h = u + pv.

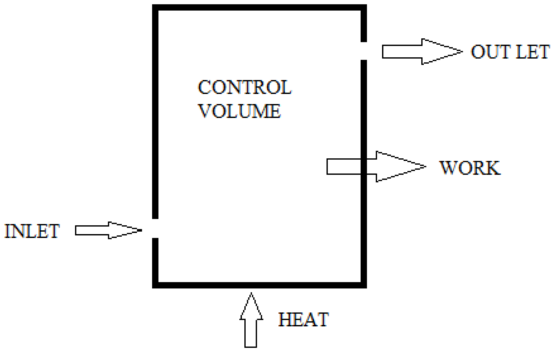
  = u + RT
- dh = du + RdT

  Therefore, $\frac{dh}{dT} = \frac{du}{dT} + R$

  $$c_p = c_v + R; \quad c_p - c_v = R$$

First-Law Analysis for a Control Volume

- For an open system, mass as well as heat and work can cross the control surface, and the mass in the control volume can change with time.



Flow Process and Control Volume

- Applying the law of conservation of mass to the control volume with several possible flows as

$$\frac{dm_{C.V.}}{dt} = \sum \dot{m}_i - \sum \dot{m}_e$$

- The extension of the first law of thermodynamics becomes

$$\frac{dE_{C.V.}}{dt} = \dot{Q}_{C.V.} - \dot{W}_{C.V.} + \dot{m}_i(e_i + p_i v_i) - \dot{m}_e(e_e + p_e v_e)$$

$$= \dot{Q}_{C.V.} - \dot{W}_{C.V.} + \dot{m}_i\left(h_i + \frac{1}{2}V_i^2 + gZ_i\right) - \dot{m}_e\left(h_e + \frac{1}{2}V_e^2 + gZ_e\right)$$

- For a control volume with several entering and leaving mass flow rates,

$$\frac{dE_{C.V.}}{dt} = \dot{Q}_{C.V.} - \dot{W}_{C.V.} + \sum \dot{m}_i\left(h_i + \frac{1}{2}V_i^2 + gZ_i\right) - \sum \dot{m}_e\left(h_e + \frac{1}{2}V_e^2 + gZ_e\right)$$

The steady-State Process

- The control volume does not move relative to the coordinate frame.
- The state of the mass at each point in the control volume does not vary with time.
- As for the mass that flows across the control surface, the mass flux and the state of this mass at each discrete area of flow on the control surface do not vary with time.
- The rates at which heat and work cross the control surface remain constant.
- Therefore, $\frac{dm_{C.V.}}{dt} = 0$ and also $\frac{dE_{C.V.}}{dt} = 0$
- The first-law for a control volume under steady-state with several entering and leaving mass flow rates is expressed as

$$\dot{Q}_{C.V.} + \sum \dot{m}_i\left(h_i + \frac{V_i^2}{2} + gZ_i\right) = \sum \dot{m}_e\left(h_e + \frac{V_e^2}{2} + gZ_e\right) + \dot{W}_{C.V.}$$

- Many of the engineering applications of the steady-state model involve only on flow stream entering and leaving the control volume. For this type of process, we can write

$$\dot{Q}_{C.V.} + \dot{m}\left(h_i + \frac{V_i^2}{2} + gZ_i\right) = \dot{m}\left(h_e + \frac{V_e^2}{2} + gZ_e\right) + \dot{W}_{C.V.}$$

  Rearranging this equation, we have

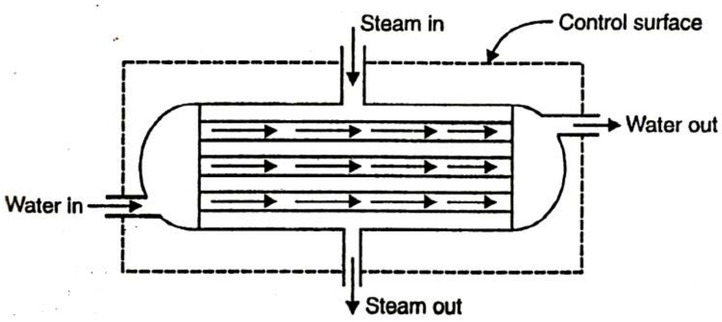
$$q + h_i + \frac{V_i^2}{2} + gZ_i = h_e + \frac{V_e^2}{2} + gZ_e + w$$

  Where, *q* and *w* are heat and work interactions per unit mass flow rate.

Examples of Steady-State Processes

a) Heat Exchanger

- A heat exchanger is device in which heat transferred from one fluid to another. One such example is the steam condenser, where steam condenses outside the tubes and cooling water flows through the tubes, as shown in figure 2.5.



Schematic Diagram of a Steam Condenser

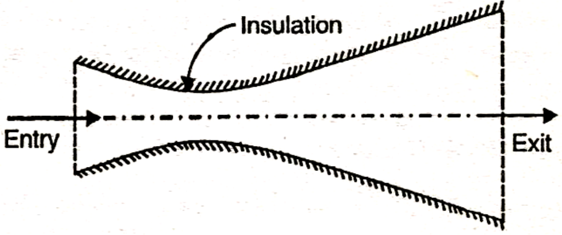
- The flow through a heat exchanger is characterized by
  - (a) the Heat exchange process tends to occur at constant pressure and frictional pressure drop in the tubes is neglected.
  - (b) there is no means for doing any work (shaft work, electrical work, etc.) and
  - (c) changes in kinetic and potential energies are negligibly small.
  - (d) no external heat interaction.
- Using the subscripts 's' for steam and 'w' for water and applying the steady flow energy equation for the heat exchanger, we get

$$\dot{m}_s(h_i)_s + \dot{m}_w(h_i)_w = \dot{m}_s(h_e)_s + \dot{m}_w(h_e)_w \qquad \text{or}$$

$$\dot{m}_s(h_i - h_e)_s = \dot{m}_w(h_e - h_i)_w$$

b) Nozzle and diffuser

- A nozzle is a steady-state device whose purpose is to create high velocity fluid stream at the expense of the fluid pressure.
- A diffuser is a steady-state device whose purpose is to raise the pressure of the fluid at the expense of fluid velocity.



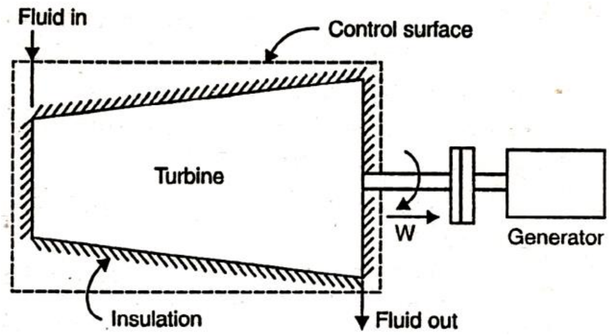
Schematic Diagram of a Nozzle

- The flow through a nozzle is characterized by the following features:
  - (a) There is no means to do any work
  - (b) There is little or no change in potential energy.
  - (c) There is usually little or no heat transfer. An exception is the large nozzle on a liquid-propellant rocket.
- With these assumptions, the steady flow energy equation for the case of nozzle or diffuser becomes

$$h_i + \frac{V_i^2}{2} = h_e + \frac{V_e^2}{2}$$

c) Steam or Gas Turbine

- A turbine is a rotary steady-state machine whose purpose is to produce shaft work at the expense of the pressure of the working fluid. Two general classes of turbines are steam turbines and gas turbines.



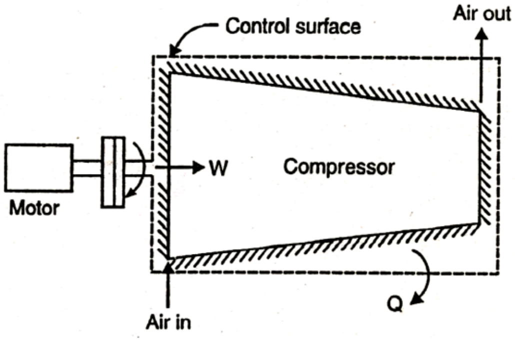
Schematic Diagram of a Turbine

- The characteristic features of flow through a steam or gas turbine are:
  a) There is little or no change in potential energy.
  b) There is usually little or no heat transfer.
  c) There is little or no change in kinetic energy.
- With these assumptions, the steady flow energy equation for the case of turbine becomes

$$\dot{m}h_i = \dot{m}h_e + \dot{W}_{shaft}$$

d) Rotary Compressor

- The purpose of the steady state compressor is to increase the pressure of a fluid by putting in shaft work. The most common is a rotary type compressor (either axial flow or radial / centrifugal flow).



Schematic Diagram of a Rotary Compressor

- The characteristic features of flow through a rotary compressor are
  a) Shaft work is done on the system and the fluid is compressed; *W* is negative.
  b) Heat is lost to the surroundings; *Q* is negative
  c) There is little or no change in potential energy.
- With these assumptions, the steady flow energy equation may be written as

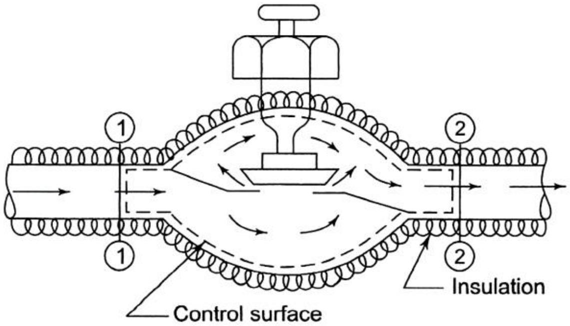
$$\dot{m}(h_i + \frac{V_i^2}{2}) - \dot{Q} = \dot{m}(h_e + \frac{V_e^2}{2}) - \dot{W}_{shaft}$$

If the velocity changes are neglected and the flow process is treated as adiabatic (Q=0), then

$$\dot{W}_{shaft} = \dot{m}(h_e - h_i)$$

e) Throttling Device

- When a fluid flows through a restricted passage, like a partially opened wall, an orifice, or a porous plug, there is an appreciable drop in pressure, and the flow is said to be throttled. Figure 2.8 shows the process of throttling by a partially opened valve on a fluid following in an insulated pipe.



Flow through a Valve

- The flow through a throttling device is characterized by the following features:
  a) There is no means to do any work.
  b) There is little or no change in potential energy.
  c) There is usually little or no heat transfer.
- With these assumptions, the steady flow energy equation may be written as

$$(h_i + \frac{V_i^2}{2}) = (h_e + \frac{V_e^2}{2})$$

- Often the velocities in throttling are so low that the kinetic energy terms are also negligible. So

$$h_i = h_e$$

- Therefore, throttling process is an isenthalpic process for which enthalpy remains constant.

Engineering Thermodynamics

Unit – III

Learning Material

Limitations of First Law of Thermodynamics

- First law fixes the exchange rate between heat and work, and places no restrictions on the direction of change.
- Processes proceed spontaneously in certain directions, but the reverse is not automatically attainable even though the reversal of the processes does not violate the first law.
- First law provides a necessary but not a sufficient condition for a process to occur, and
- There does exist some directional law which would tell whether a particular process occurs or not. Answer is provided by the second law of thermodynamics.

Thermal Reservoir

- A thermal (heat) reservoir is that part of environment which can exchange heat energy with a system. It has sufficiently large heat capacity and its temperature is not affected by the quantity of heat transferred to or from it.
- A thermal reservoir is thus characterized by its temperature which remains constant.
- The reservoir which is at high temperature and supplies heat is known as heat source. Examples are a boiler furnace, a combustion chamber and a nuclear reactor, etc.
- The reservoir which is at low temperature and to which heat is transferred is called the heat sink. Atmospheric air, ocean and river etc. constitute the heat sink.

Heat Engine

- A heat engine may be defined as a device that operates in a thermodynamic cycle and does a certain amount of net positive work through the transfer of heat from a high-temperature body to a low-temperature body
- The internal combustion engine and the gas turbine are examples of such devices.
- Another example of a heat engine is the thermoelectric power generation device.

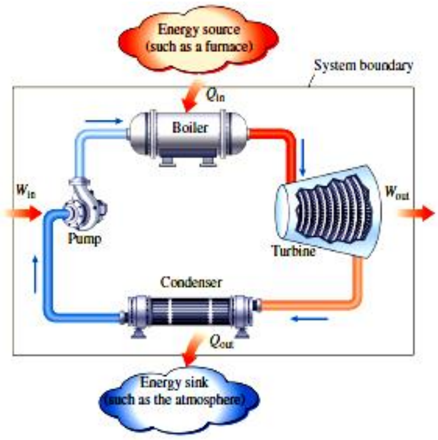


Fig. 3.1: A Simple Steam Power Cycle

- Thermal efficiency is defined as the ratio of net work output to heat input

$$\eta_{thermal} = \frac{Network\ output}{Heat\ input} = \frac{W_{net}}{Q_H} = \frac{Q_H - Q_L}{Q_H}$$

- Typical values for the thermal efficiency of real engines are about 35-50% for large power plant, 30-35% for gasoline engines, and 35-40% for diesel engines.

Refrigerator or Heat Pump

- A refrigerator or heat pump may be define as a device that operates in a thermodynamic cycle and transfer heat from a low-temperature space or body to a high-temperature space or body by receiving work energy as input.
- The purpose of the refrigerator is to maintain the space at a temperature lower than the surroundings by extracting heat from it.

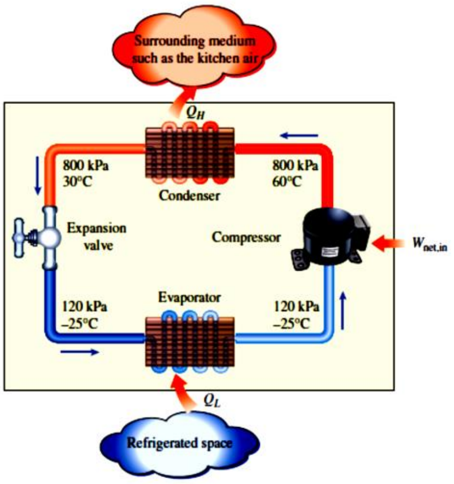


Fig. 3.2: A Simple Refrigeration Cycle

- The purpose of the heat pump is to maintain the space at a temperature higher than the surroundings by supplying heat to it.
- The “efficiency” of a refrigerator or heat pump is expressed in terms of the coefficient of performance, which we designate as COP.
- The coefficient of performance is defined as the ratio of desired effect to the work input.
- For a refrigerator, the desired effect is the amount of heat extracted from a low temperature space, Q_L. Thus, the COP of a refrigerator is

$$(COP)_R = \frac{Q_L}{W}$$

- For a heat pump, the desired effect is the amount of heat supplied to a high temperature space, Q_H. Thus, the COP of a heat pump is

$$(COP)_{HP} = \frac{Q_H}{W}$$

- The relationship between COP of heat pump and COP of refrigerator is derived as

$$(COP)_{HP} = \frac{Q_H}{W} = \frac{Q_L + W}{W} = 1 + \frac{Q_L}{W} = 1 + (COP)_R$$

The Second Law of Thermodynamics

- **The Kelvin-Planck statement**: It is impossible to construct a device that will operate in a cycle and produce no effect other than the raising of a weight and the exchange of heat with a single reservoir.

- This statement ties in with our discussion of the heat engine. It states that it is impossible to construct a heat engine that operates in a cycle, receives a given amount of heat from a high-temperature body, and does an equal amount of work. The only alternative is that some heat must be transferred from the working fluid to a low-temperature body.
- This implies that it is impossible to build a heat engine that has thermal efficiency of 100%
- **The 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 cooler body to a hotter body.
- This statement is related to the refrigerator or heat pump. It states that it is impossible to construct a refrigerator that operates without input of work. This also implies that the coefficient of performance is always less than infinity.

Perpetual-Motion Machine of Second Kind

- A perpetual-motion machine of the second kind would extract heat from a source and then convert this heat completely into other forms of energy, thus violating the second law.

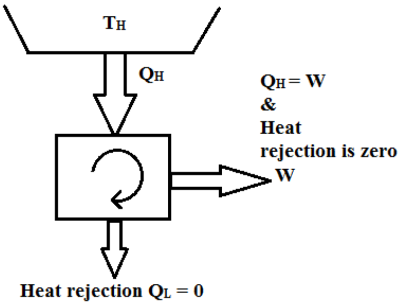


Fig. 3.3: Perpetual-Motion Machine of Second Kind

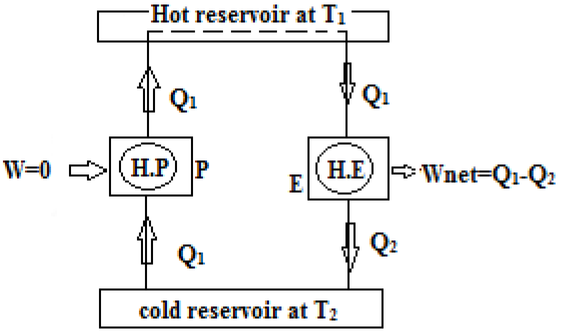
- Perpetual-motion machine of second kind has 100% thermal efficiency.

Equivalence of Kelvin Planck and Classius statement

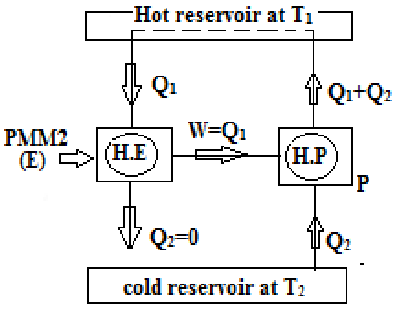
At first Kelvin-Planck's and classius statements may appear to be unconnected, but it can easily be shown that they are virtually two parallel statements of the second law and are equivalent in all respects.

The equivalence of the two statements will be proved if it can be shown that the violation of one statement implies the violation of the second, and vice versa.

1. Let us first consider a cyclic heat pump P which transfers heat from a low temperature reservoir (T_2) to a high temperature reservoir (T_1) with no other effect, i.e., with no expenditure of work, ***violating classius statement***. Let us assume a cyclic heat engine E operating between the same thermal reservoirs, producing W_{net} in one cycle. The rate of working of the engine is such that it draws an amount of heat Q_1 from the hot reservoir equal to that discharged by the heat pump. Then the hot reservoir may be eliminated and the heat Q_1 discharged by the heat pump is fed to the heat engine. So we see that the heat pump P and the heat engine E acting together constitute a heat engine operating in cycles and producing net work while exchanging heat only with one body at a single fixed temperature (T_2). This violates Kelvin-Planck Statement.



Violation of the classius statement

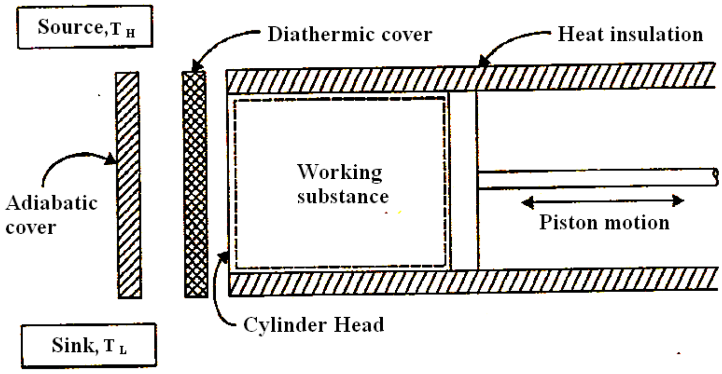


Violation of Kelvin-Planck statement

2. Let us now consider a perpetual motion machine of second kind (E) which produces net work in a cycle by exchanging heat with only one thermal reservoir (at T_1) and thus violates the Kelvin-planck statement. Let us assume a cyclic heat pump (P) extracting heat Q_2 from a low temperature reservoir at T_2 and discharging heat to a high temperature reservoir at T_1 with the expenditure of work W equal to what the PMM2 delivers in a complete cycle. So E and P together constitute a heat pump working in cycles and producing the sole effect of transferring heat from a lower to a higher temperature body, thus violating the classius statement.

Carnot Cycle and Carnot Heat Engine

A Carnot cycle is a hypothetical cycle consisting of four distinct processes: two reversible isothermal processes and two reversible adiabatic processes. The cycle was proposed in 1824 by a young French engineer, Sadi Carnot.



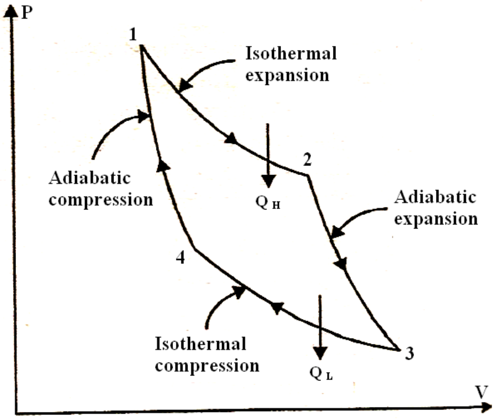


Fig. 3.4a: Essential Elements of a Heat Engine working on Carnot Cycle

Fig. 3.4b: Carnot Heat Engine Cycle on P-V plot

The sequence of operation for the different processes constituting a Carnot Cycle is:

Isothermal expansion (1 – 2): The heat is supplied to the working fluid at constant temperature T_H. This is achieved by bringing the heat source in good thermal contact with the cylinder head through diathermic cover. The gas expands isothermally from state point 1 to state point 2.

The heat supplied equals the work done which is represented by area under the curve 1-2 on pressure-volume plot and is given by

$$Q_H = W_{1-2} = p_a V_1 log_e \frac{V_2}{V_1} = m\,R\,T_1 log_e \frac{V_2}{V_1}$$

Adiabatic Expansion (2-3): At the end of isothermal expansion (state point 2), the heat source is replaced by adiabatic cover. The expansion continues adiabatically and reversibly up to state point 3. Work is done by the working fluid at the expense of internal energy and its temperature falls to T_L at state point 3.

Isothermal Compression (3-4): After state point 3, the piston starts moving inwards and the working fluid is compressed isothermally at temperature T_L. The constant temperature T_L is maintained by removing the adiabatic cover and bringing the heat sink in contact with the cylinder head. The compression continues up to state point 4.

The working fluid loses heat to the sink and its amount equals the work done on the working fluid. This work is represented by area under the curve 3 - 4 and its amount is given by.

$$Q_L = W_{3-4} = p_3 V_3 log_e \frac{V_3}{V_4} = m\,R\,T_3 log_e \frac{V_3}{V_4}$$

Adiabatic Compression (4 – 1): At the end of isothermal compression (state point 4), the heat sink is removed and is replaced by adiabatic cover. The compression now proceeds adiabatically and reversibly till the working fluid returns back to its initial state point 1. Work is done on the working fluid, the internal energy increases and temperature is raised to T_H.

Since all the processes that constitute a Carnot cycle are reversible, the Carnot cycle is referred to as a reversible cycle. The thermal efficiency of Carnot heat engine is given by

$$\eta = \frac{net\ work\ output}{heat\ input} = \frac{W_{net}}{Q_H}$$

There are no heat interactions along the reversible adiabatic processes 2 – 3 and 4 – 1, and application of the first law of thermodynamics for the complete cycle gives.

$$\oint \delta W = \oint \delta Q \qquad \text{or}$$

$$W_{net} = Q_H - Q_L = mRT_1 log_e \frac{V_2}{V_1} - mRT_3 log_e \frac{V_3}{V_4}$$

Therefore, $$\eta = \frac{mRT_1 log_e \frac{V_2}{V_1} - mRT_3 log_e \frac{V_3}{V_4}}{mRT_1 log_e \frac{V_2}{V_1}} = 1 - \frac{T_3}{T_1} X \frac{log_e \frac{V_3}{V_4}}{log_e \frac{V_2}{V_1}}$$

For the adiabatic expansion processes 2 – 3 and 4 – 1,

$$\frac{T_2}{T_3} = \left(\frac{V_3}{V_2}\right)^{\gamma-1} and\ \frac{T_1}{T_4} = \left(\frac{V_4}{V_1}\right)^{\gamma-1}$$

Since $T_1 = T_2 = T_H$ and $T_3 = T_4 = T_L$, we have $\frac{V_3}{V_2} = \frac{V_4}{V_1}$ or $\frac{V_3}{V_4} = \frac{V_2}{V_1}$

Substituting the above relation 3.10 in the equation 3.9, we get

$$\eta = 1 - \frac{T_3}{T_1} = 1 - \frac{T_L}{T_H} = \frac{T_H - T_L}{T_H}$$

Following conclusions can be made with respect to efficiency of a Carnot engine:

(1) The efficiency is independent of the working fluid and depends upon the temperatures of source and sink.

(2) The efficiency is directly proportional to temperature difference (T_1 – T_2) between the source and the sink.

(3) Higher the temperature difference between source and sink, the higher will be the efficiency.

(4) The efficiency increases with an increase in temperature of source and a decrease in temperature of sink.

(5) If $T_1 = T_2$, no work will be done and efficiency will be zero.

Metallurgical considerations and the high cost of temperature resisting materials limit the higher temperature T_1. The lower temperature T_2 is limited by atmospheric or sink conditions.

Reversed Heat Engine (Carnot Heat Pump or Refrigerator)

Refrigerators and heat pumps are reversed heat engines.

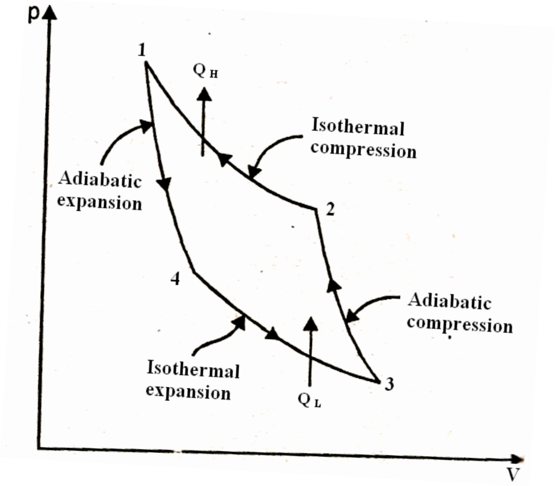


Fig. 3.5: Carnot Heat Pump or Refrigerator Cycle on P-V plot

Fig. 3.5 shows the P – V plot of a Carnot heat pump (i.e. reversed Carnot heat engine). The sequence of operation is:

1 – 4: Isentropic (reversible adiabatic) expansion of working fluid in the clearance space of the cylinder. The temperature falls from T_1 and T_2.

4 – 3: Isothermal expansion during which heat Q_L is absorbed at temperature T_2 from the space being cooled.

3 – 2: Isentropic compression of working fluid. The temperature rises from T_2 to T_1.

3 – 1: Isothermal compression of working fluid during which heat Q_H is rejected to a system at higher temperature.

As outlined above i.e. in the case of heat engine,

$$Q_H = mRT_1 log_e \frac{V_2}{V_1}; \;\; Q_L = mRT_3 log_e \frac{V_3}{V_4}$$

Also $\frac{V_3}{V_4} = \frac{V_2}{V_1}$, $T_1 = T_2 = T_H$ and $T_3 = T_4 = T_L$

Therefore, for a heat pump

$$(COP)_{\text{Heat pump}} = \frac{Q_H}{Q_H - Q_L}$$

$$= \frac{mRT_1 log_e \frac{V_2}{V_1}}{mRT_1 log_e \frac{V_2}{V_1} - mRT_3 log_e \frac{V_3}{V_4}} = \frac{T_1}{T_1 - T_3} = \frac{T_H}{T_H - T_L}$$

For a refrigerator,

$$(COP)_{\text{Refrigerator}} = \frac{Q_L}{Q_H - Q_L}$$

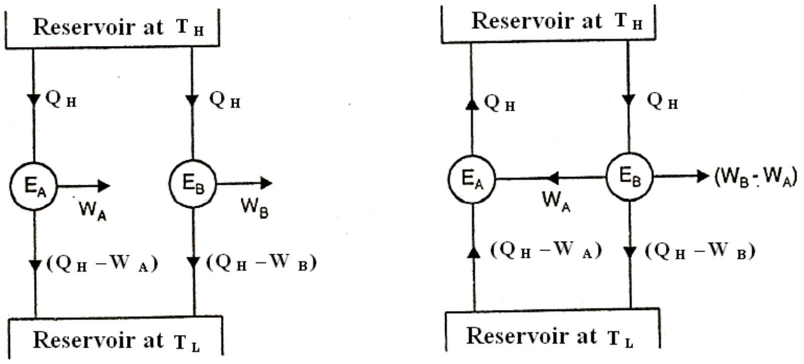
$$= \frac{mRT_3 log_e \frac{V_3}{V_4}}{mRT_1 log_e \frac{V_2}{V_1} - mRT_3 log_e \frac{V_3}{V_4}} = \frac{T_3}{T_1 - T_3} = \frac{T_L}{T_H - T_L}$$

Carnot Theorem

No heat engine operating in a cycle between two given thermal reservoirs, with fixed temperatures, can be more efficient than a reversible engine (Carnot Engine) operating between the same thermal reservoirs.

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_H and T_L. For the same quantity of heat Q_H withdrawn from the high temperature source, the work output from these engines is W_A and W_B respectively. As such the heat given off by the reversible engine is $(Q_H – W_A)$ and that from irreversible engine is $(Q_H – W_B)$.



(a) (b)

Fig. 3.6: Proof of Carnot Theorem

Let it be presumed that the irreversible engine E_B is more efficient than the reversible engine E_A. Then $\frac{W_B}{Q_H} > \frac{W_A}{Q_H}; W_B > W_A \; and \; (Q_H - W_A) > (Q_H - W_B) i.e.,$ work output from irreversible engine is more than that from reversible engine.

Let the reversible engine E_A now be made to operate as a refrigerator or heat pump; the irreversible engine continues to operate as an engine.

Since engine E_A is reversible, the magnitudes of heat and work interactions will remain the same but their direction will be reversed. The work required to drive the refrigerator can be withdrawn from the irreversible engine by having a direct coupling between the two. Fig (b) shows the work and heat interactions for the composite system constituted by the reversible engine (now operating as refrigerator) and the irreversible engine. The net effect is

- No net interaction with the high temperature heat reservoir. It supplies and recovers back the same amount of heat.
- The composite system withdraws $(Q_H – W_A) – (Q_H – W_B) = (W_B – W_A)$ units of heat from the low temperature reservoir and converts that into equivalent amount of work output.

The combination thus constitutes a perpetual motion of the second kind in violation of the second law. Obviously the assumption that the irreversible engine is more efficient than the reversible engine is wrong. Hence, an irreversible engine cannot have efficiency higher than that from a reversible engine operating between the same thermal reservoirs.

Corollaries of Carnot’s Theorem:

Corollary 1: All reversible engines operating between the two given thermal reservoirs, with fixed temperature, have the same efficiency.

Corollary 2: The efficiency of any reversible heat engine operating between two reservoirs is independent of the nature of working fluid and depends only on the temperature of the reservoirs.

The Thermodynamic Temperature Scale

- The concept of thermodynamic temperature scale may be developed with the help of figure 3.7, which shows three reservoirs and three engines that operate on the Carnot cycle.

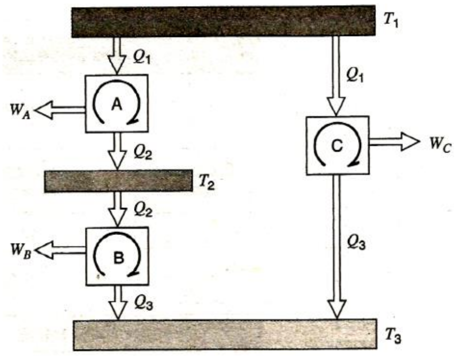


Fig. 3.7: Arrangement of heat engines to demonstrate the Thermodynamic Temperature scale

- T_1 is the highest temperature, T_3 is the lowest temperature, and T_2 is an intermediate temperature, and the engines operate between the various reservoirs as indicated. Q_1 is the same for both A and C and, since we are dealing with reversible cycles, Q_3 is the same for B and C. Since the efficiency of a Carnot cycle is a function only of the temperature, we can write

$$\eta_{thermal} = 1 - \frac{Q_L}{Q_H} = 1 - \frac{T_L}{T_H} = 1 - \psi(T_L, T_H)$$

Where ψ designates a functional relation. Let us apply this functional relation to the three Carnot Cycles shown in figure 3.7.

$$\frac{Q_1}{Q_2} = 1 - \psi(T_{1,}T_2); \quad \frac{Q_2}{Q_3} = 1 - \psi(T_{2,}T_3); \quad \frac{Q_1}{Q_3} = 1 - \psi(T_{1,}T_3)$$

Since $\frac{Q_1}{Q_3} = \frac{Q_1 Q_2}{Q_2 Q_3}$

It follows that $\psi(T_1, T_3) = \psi(T_1, T_2) \times \psi(T_2, T_3)$

Note that the left side is a function of T_1 and T_3 (and not of T_2), and therefore the right side of this equation must also be a function of T_1 and T_3 (and not of T_2). From this fact we can conclude that the form of the function ψ must be such that

$$\psi(T_1, T_2) = \frac{f(T_1)}{f(T_2)}; \quad \psi(T_2, T_3) = \frac{f(T_2)}{f(T_3)}$$

For in this way $f(T_2)$ will cancel from the product of $\psi(T_{1,}T_2) \times \psi(T_2, T_3)$. Therefore, we conclude that $\frac{Q_1}{Q_3} = \psi(T_1, T_3) = \frac{f(T_1)}{f(T_3)}$

In general terms, $\frac{Q_H}{Q_L} = \frac{f(T_H)}{f(T_L)}$

Suppose we had a heat engine operating on the Carnot cycle that received heat at the temperature of the steam point and rejected heat at the temperature of the ice point. The efficiency of such an engine could be measured to be 26.8%,

$$\eta_{th} = 1 - \frac{T_L}{T_H} = 1 - \frac{T_{ice\ point}}{T_{steam\ point}} = 0.2680$$

$$\frac{T_{ice\ point}}{T_{steam\ point}} = 0.7320$$

This gives us one equation concerning the two unknowns T_H and T_L. The second equation comes from the difference between the steam point and ice point.

$$T_{\text{steam point}} - T_{\text{ice points}} = 100$$

Solving these two equations simultaneously, we find

$$T_{\text{steam point}} = 373.15\text{ K} \quad \text{and} \quad T_{\text{ice point}} = 273.15\text{ K}$$

It follows that, $T(^oC) + 273.15 = T(K)$

The Inequality of Clausius

- The inequality of Clausius is expressed as $\oint \frac{\delta Q}{T} \leq 0$.
- The inequality of Clausius is a corollary or a consequence of the second law of thermodynamics. It will be demonstrated to be valid for all possible cycles, including both reversible and irreversible heat engines and refrigerators.

Consider first a reversible (Carnot) heat engine cycle operating between reservoirs at temperatures T_H and T_L, as shown in Fig. 3.8. For this cycle, the cyclic integral of the heat transfer, $\oint \delta Q$, is greater than zero.

$$\oint \delta Q = Q_H - Q_L > 0$$

Since T_H and T_L are constant, from the definition of the absolute temperature scale and from the fact this is a reversible cycle, it follows that

$$\oint \frac{\delta Q}{T} = \frac{Q_H}{T_H} - \frac{Q_L}{T_L} = 0$$

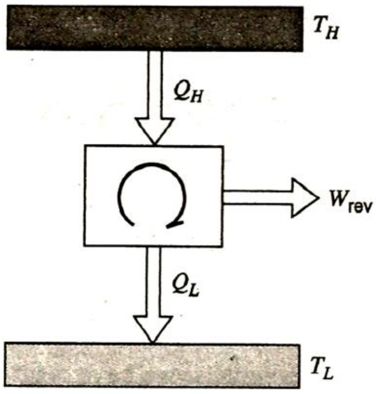


Fig. 3.8: Reversible heat engine cycle for demonstration of the inequality of Clausius

If $\oint \delta Q$, the cyclic integral of δQ, approaches zero (by making T_H approach T_L) and the cycle remains reversible, the cyclic integral of $\delta Q/T$ remains zero. Thus, we conclude that for all reversible heat engine cycles

$$\oint \frac{\delta Q}{T} = 0$$

Now consider an irreversible cyclic het engine operating between the same T_H and T_L as the reversible engine of Fig. 8.1 and receiving the same quantity of heat Q_H. Comparing the irreversible cycle with the reversible one, we conclude from the second law that

$$W_{irr} < W_{rev}$$

Since $Q_H - Q_L = W$ for both the reversible and irreversible cycles, we conclude that

$(Q_H - Q_L)_{irr} < (Q_H - Q_L)_{rev}$ and therefore, $(Q_L)_{irr} > (Q_L)_{rev}$

Consequently, for the irreversible cyclic engine,

$$\oint \delta Q = (Q_H - Q_L)_{irr} > 0$$

$$\oint \frac{\delta Q}{T} = \frac{Q_H}{T_H} - \frac{(Q_L)_{irr}}{T_L} < 0$$

Thus, we conclude that for all irreversible heat engine cycles

$$\oint \frac{\delta Q}{T} < 0$$

Therefore, in general, for any heat engine or refrigerator $\oint \frac{\delta Q}{T} \leq 0$

The Significance of the inequality of Clausius may be illustrated by considering the simple steam power plant cycle shown in Fig.3.9.

Heat is transferred in two places, the boiler and the condenser. Therefore,

$$\oint \frac{\delta Q}{T} = \int \left(\frac{\delta Q}{T}\right)_{boiler} + \int \left(\frac{\delta Q}{T}\right)_{condenser}$$

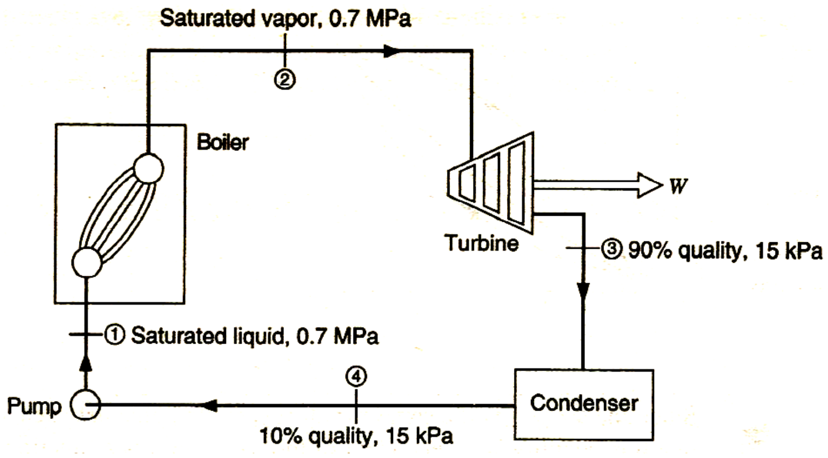


Fig.3.9: A simple Steam Power Plant that demonstrates the Inequality of Clausius

Since the temperature remains constant in both the boiler and condenser, this may be integrated as follows:

$$\oint \frac{\delta Q}{T} = \frac{1}{T_1}\int_1^2 \delta Q + \frac{1}{T_3}\int_3^4 \delta Q = \frac{Q_{12}}{T_1} + \frac{Q_{34}}{T_3}$$

Let us consider a 1 kg mass as the working fluid. We have then

$$q_{12} = h_2 - h_1 = 2066.3\ kJ/kg, \quad T_1 = 164.97^oC$$

$$q_{34} = h_4 - h_3 = 463.4 - 2361.8 = -1898.4\ kJ/kg, \quad T_3 = 53.97^oC$$

Therefore,

$$\oint \frac{\delta Q}{T} = \frac{2066.3}{164.97 + 273.15} - \frac{1898.4}{53.97 + 273.15} = -1.087\ kJ/kg - K$$

Thus, this cycle satisfies the inequality of Clausius, which is equivalent to saying that it does not violate the second law of thermodynamics.

Entropy – A Property of a System

By applying Eq.3.28 and Fig. 3.10 we can demonstrate that the second law of thermodynamics leads to a property of a system that we call entropy.

- *Entropy is a measure of molecular disorderliness of a substance.*

Let a closed system undergo a reversible process from state 1 to state 2 along a path A, and let the cycle be completed along path B, which is also reversible.

Because this is a reversible cycle, we can write

$$\oint \frac{\delta Q}{T} = \int_1^2 \left(\frac{\delta Q}{T}\right)_A + \int_2^1 \left(\frac{\delta Q}{T}\right)_B = 0$$

Now consider another reversible cycle, which proceeds first along path C and is then completed along path B. For this cycle we can write

$$\oint \frac{\delta Q}{T} = \int_1^2 \left(\frac{\delta Q}{T}\right)_C + \int_2^1 \left(\frac{\delta Q}{T}\right)_B = 0$$

Subtracting the equation 3.30 from the equation 3.29, we get

$$\int_1^2 \left(\frac{\delta Q}{T}\right)_A = \int_1^2 \left(\frac{\delta Q}{T}\right)_C$$

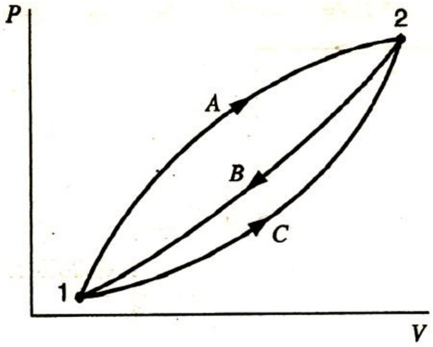


Fig. 3.10: Two reversible cycles demonstrating the fact that entropy is a property of a substance

Since the $\int \delta Q$/T is the same for all reversible paths between states 1 and 2, we conclude that this quantity is independent of the path and it is a function of the end states only; it is therefore a property. This property is called entropy and is designated by ‘S’. It follows that entropy may be defined as a property of a substance in accordance with the relation.

$$dS = \left(\frac{\delta Q}{T}\right)_{rev} \qquad \textbf{(Equation 3.32)}$$

- Entropy is an extensive property, and the entropy per unit mass is designated by ‘s’. The change in the entropy of a system as it undergoes a change of state may be found by integrating Eq.3.32. Thus,

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

- To perform this integration, we must know the relation between T and Q.
- Since entropy is a property, the change in the entropy of a substance in going from one state to another is the same for all processes, both reversible and irreversible, between these two states.
- Equation 3.33 enables us to calculate changes of entropy, but it tells us nothing about absolute values of entropy.
- From the third law of thermodynamics, which is based on observations of low-temperature chemical reactions, it is concluded that the entropy of all pure substances (in the appropriate structural form) can be assigned the absolute value of zero at the absolute zero of temperature.
- It also follows from the subject of statistical thermodynamics that all pure substances in the (hypothetical) ideal-gas state at absolute zero temperature have zero entropy.

Entropy Change of a control mass during a Reversible Process

The entropy change during a reversible process 1 – 2 is given by

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

The relationship between δQ and T can be obtained from the thermodynamics property relations.

The Thermodynamic Property Relations

The two important thermodynamic property relations for a compressible substance can be derived from the first law of thermodynamics.

$$\delta Q = dU + \delta W$$

For a reversible process of simple compressible substance, we can write

$$\delta Q = TdS \text{ and } \delta W = PdV$$

Substituting these relations into the first law equation, we get

$$TdS = dU + PdV$$

Since enthalpy is defined as $= U + PV$, on differentiation we get

$$dH = dU + PdV + VdP$$

$$= \delta Q + VdP$$

$$= TdS + VdP \qquad \text{or}$$

$$TdS = dH - VdP$$

These equations can also be written for a unit mass,

$$TdS = du + Pdv$$

$$TdS = dh - vdP$$

Entropy Change of a Control Mass during an Irreversible Process

Consider a control mass that undergoes the cycles shown in fig. 3.11.

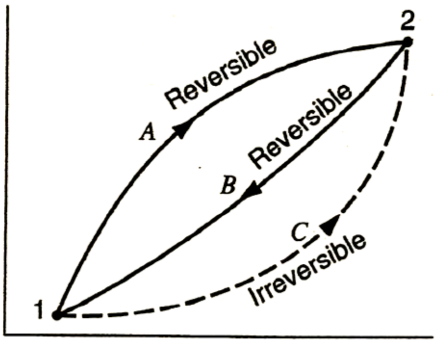


Fig. 3.11: Entropy Change of a Control Mass during an irreversible process

Since the cycle made up of the reversible processes A and B is a reversible cycle, we can write

$$\oint \frac{\delta Q}{T} = \int_1^2 \left(\frac{\delta Q}{T}\right)_A + \int_2^1 \left(\frac{\delta Q}{T}\right)_B = 0$$

The cycle made of the irreversible process C and the reversible process B is an irreversible cycle. Therefore, for this cycle the inequality of Clausius may be applied as

$$\oint \frac{\delta Q}{T} = \int_1^2 \left(\frac{\delta Q}{T}\right)_C + \int_2^1 \left(\frac{\delta Q}{T}\right)_{\boldsymbol{B}} < 0$$

Subtracting the equation 3.34 from the equation 3.33 and rearranging, we have

$$\int_1^2 \left(\frac{\delta Q}{T}\right)_A > \int_1^2 \left(\frac{\delta Q}{T}\right)_C$$

Since path A is reversible, and since entropy is a property,

$$\int_1^2 \left(\frac{\delta Q}{T}\right)_A = \int_1^2 dS_A = \int_1^2 dS_C$$

Therefore,

$$\int_1^2 dS_C > \int_1^2 \left(\frac{\delta Q}{T}\right)_C$$

As path C was arbitrary, the general result is

$$dS \geq \frac{\delta Q}{T}$$

or

$$S_2 - S_1 \geq \int_1^2 \frac{\delta Q}{T}$$

In these equations the equality holds for a reversible process and the inequality for an irreversible process.

- Thus, If an amount of heat δQ is transferred to a control mass at temperature T in a reversible process, the change of entropy is given by the relation.

$$dS = \left(\frac{\delta Q}{T}\right)_{rev}$$

- If any irreversible effects occur while the amount of heat δQ is transferred to the control mass at temperature T, however, the change of entropy will be greater than that of the reversible process. We would then write

$$dS > \left(\frac{\delta Q}{T}\right)_{irr}$$

Entropy Generation

The conclusion from the previous consideration is that the entropy change for an irreversible process is larger than the change in a reversible process for the same δQ and T. This can be written out in a common form as an equality

$$dS = \frac{\delta Q}{T} + \delta S_{gen}$$

Provided the last term is positive,

$$\delta S_{gen} \geq 0$$

The amount of entropy, δS_{gen}, is the entropy generation in the process due to irreversibilities occurring inside the system.

- This internal generation can be caused by the processes such as friction, unrestrained expansions, and the internal transfer of energy (redistribution) over a finite temperature difference.
- In addition to this internal entropy generation, external irreversibilities are possible by heat transfer over finite temperature differences as the δQ is transferred from a reservoir or by the mechanical transfer of work.
- We can generate but not destroy entropy. This is in contrast to energy which we can neither generate nor destroy.

- Since $\delta Q = 0$ for an adiabatic process, and the increase in entropy is always associated with the irreversibilities.
- The presence of irreversibilities will cause the actual work to be smaller than the reversible work. This means less work out in an expansion process and more work input in a compression process.

Principles of the increase of Entropy

Consider the process shown in Fig. 3.12 in which a quantity of heat δQ is transferred from the surroundings at temperature T_0 to the control mass at temperature T. Let the work done during this process be δW.

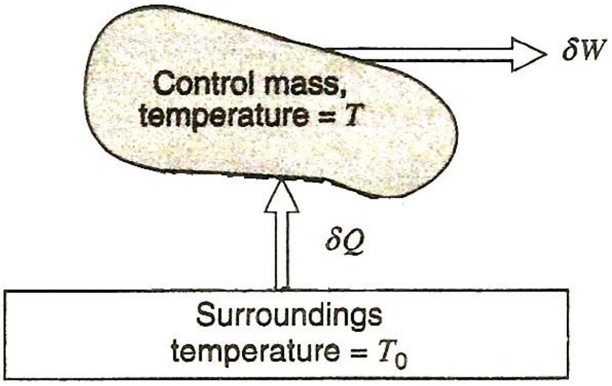


Fig. 3.12: Entropy Change for the Control Mass Plus Surroundings

For this process we can apply equation 3.38 to the control mass and write

$$\delta S_{c.m.} \geq \frac{\delta Q}{T}$$

For the surroundings at T_0, δQ is negative, and we assume a reversible heat extraction so

$$\delta S_{surr} = \frac{-\delta Q}{T_0}$$

The total net change of entropy is therefore

$$\delta S_{net} = dS_{c.m.} + dS_{surr} \geq \frac{\delta Q}{T} - \frac{\delta Q}{T_0}$$

$$\geq \delta Q \left(\frac{1}{T} - \frac{1}{T_0}\right)$$

If T > T_0, the heat transfer is from the control mass to the surroundings, and both δQ and the quantity {(1/T) – (1/T_0)} are negative, thus yielding the same result.

$$dS_{net} = dS_{c.m.} + dS_{surr} \geq 0$$

The net entropy change could also be termed the total entropy generation:

$$dS_{net} = dS_{c.m.} + dS_{surr} = \sum \delta W_{gen} \geq 0$$

where the equality holds for reversible processes and the inequality for irreversible processes.

- This is a very important equation, not only for thermodynamics but also for philosophical thought. This equation is referred to as the principle of the increase of entropy.
- The great significance is that the only processes that can take place are those in which the net change in entropy of the control mass plus its surroundings increases (or in the limit, remain constant). The reverse process, in which both the control mass and surroundings are returned to their original state, can never be made to occur.

- Thus, the principle of the increase of entropy can be considered a quantitative general statement of the second law and applies to the combustion of fuel in our automobile engines, the cooling of our coffee, and the processes that take place in our body.

Entropy Change of a Solid or Liquid

Writing the first thermodynamic property relation,

$$Tds = du + Pdv$$

Since change in specific volume for a solid or liquid is very small,

$$ds \approx \frac{du}{T} \approx c\frac{dT}{T}$$

For many processes involving a solid or liquid, we may assume that the specific heat remains constant, in which case equation 3.47 can be integrated. The result is

$$s_2 - s_1 = c\ in\ \frac{T_2}{T_1}$$

Where, C is the specific heat in J/kg -K.

Entropy Change of an Ideal Gas

Writing the first thermodynamic property relation,

$$Tds = du + Pdv$$

For an ideal gas, du = C_v dT and $\frac{P}{T} = \frac{R}{V}$

Therefore, ds = $c_v \frac{dT}{T} + R\frac{dv}{V}$

Upon integration, we have

$$s_2 - s_1 = \int_1^2 c_v \frac{dT}{T} + R\ ln\ \frac{v_2}{v_1}$$

Where, c_v is the specific heat at constant volume in J/kg –K.

Similarly,

$$Tds = dh - vdP$$

For an ideal gas, dh = c_p dT and $\frac{v}{T} = \frac{R}{P}$

Therefore, ds = $c_p \frac{dT}{T} - R\frac{dP}{P}$

Upon integration, we have

$$s_2 - s_1 = \int_1^2 c_p \frac{dT}{T} - R\ ln\ \frac{P_2}{P_1}$$

Where, c_p is the specific heat at constant pressure in J/kg –K.

Entropy as a Rate Equation

$$\frac{dS}{\delta t} = \frac{1}{T}\frac{\delta Q}{\delta t} + \frac{\delta S_{gen}}{\delta t}$$

High and Low Grade Energy

High Grade Energy: High Grade Energy is the energy that can be completely transformed into shaft work without any loss and hence is fully utilizable. Examples are mechanical and electric work, water, wind and ideal power; kinetic energy of jets; animal and manual power.

Low Grade Energy: Low Grade Energy is the energy of which only a certain portion can be converted into mechanical work. Examples are heat or thermal energy; heat from nuclear fission or fusion; heat from combustion of fuels such as coal, wood, oil, etc.

Available and Unavailable Energy

- The portion of thermal energy input to a cyclic heat engine which gets converted into mechanical work is referred to as available energy.
- The portion of thermal energy which is not utilizable and is rejected to the sink (surroundings) is called unavailable energy.
- The terms exergy and anergy are synonymous with available energy and unavailable energy, respectively. Thus Energy = exergy+anergy.

The following two cases arise when considering available and unavailable portions of heat energy

Case 1: Heat is withdrawn at constant temperature

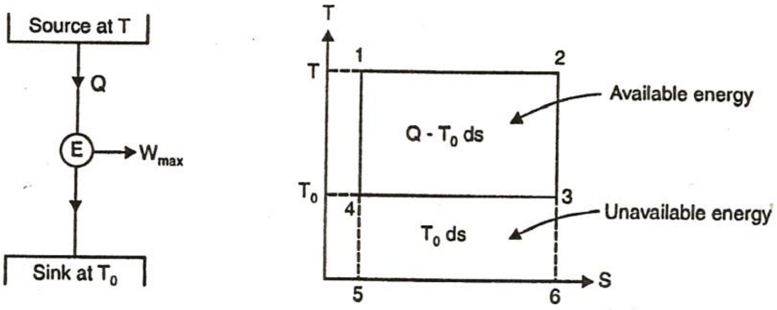


Fig. 3.13: Available and Unavailable Energy: Heat Withdrawn from an Infinite Reservoir

Fig.3.13 represents a reversible engine that operates between a constant temperature reservoir at temperature T and a sink at temperature T_0. Corresponding to heat Q supplied by the reservoir, the available work W_{max} is given by

$$\eta = \frac{W_{max}}{Q} = \frac{T-T_0}{T}$$

Therefore,

W_{max} = Available energy = $Q\left[\frac{T-T_0}{T}\right] = Q\left[1-\frac{T_0}{T}\right] = Q - T_0\frac{Q}{T} = Q - T_0\,ds$

Unavailable energy = $T_0\,ds$

Where ds represents the change of entropy of the system during the process of heat supply Q.

Case 2: Heat is withdrawn at varying temperature.

In case of a finite reservoir, the temperature changes as heat is withdrawn from it (Fig. 3.14), and as such the supply of heat to the engine is at varying temperature. The analysis is then made by breaking the process into a series of infinitesimal Carnot cycles each supplying δQ of heat at the temperature T (different for each cycle) and rejecting heat at the constant temperature T_0. Maximum amount of work (available energy) then equals

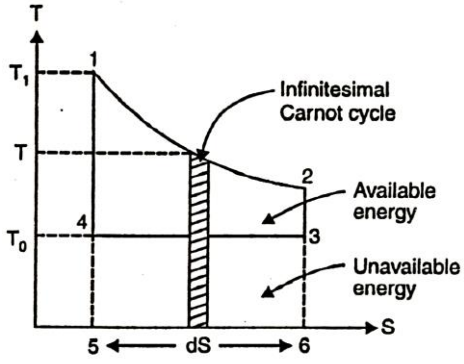


Fig. 3.14: Available and Unavailable Energy: Heat Supply at varying Temperature

$$W_{max} = \int \left[1 - \frac{T_0}{T}\right] \delta Q$$

$$= \int \delta Q - \int T_0 \frac{\delta Q}{T}$$

$$= \int \delta Q - T_0 \int \frac{\delta Q}{T} = Q - T_0\, ds$$

It is to be seen that expressions for both the available and unavailable parts are identical in the two cases.

Loss of Available Energy due to Heat Transfer through a Finite Temperature Difference

Consider a certain quantity of heat Q transferred from a system at constant temperature T_1 to another system at constant temperature T_2 ($T_1 > T_2$) as shown in Fig. 3.15.

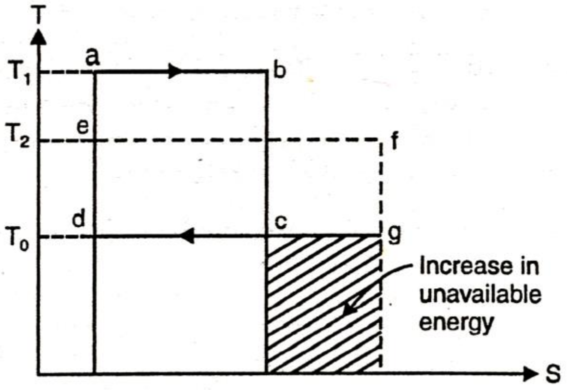


Fig. 3.15: Decrease in Available Energy due to Heat Transfer through a Finite Temperature Difference

Before heat is transferred, the energy Q is available at T_1 and the ambient temperature is T_0.

Therefore, Initial available energy, $(AE)_1 = Q\left[1 - \frac{T_0}{T_1}\right]$

After heat transfer, the energy Q is available at T_2 and again the ambient temperature is T_0. Therefore, Final available energy, $(AE)_2 = Q\left[1 - \frac{T_0}{T_2}\right]$

Change in available energy = $(AE)_1 - (AE)_2 = Q\left[1 - \frac{T_0}{T_1}\right] - Q\left[1 - \frac{T_0}{T_2}\right]$

$$= T_0\left[\frac{-Q}{T_1} + \frac{Q}{T_2}\right] = T_0(dS_1 + dS_2) = T_0(dS)_{net}$$

Where $dS_1 = -\frac{Q}{T_1}$, $dS_2 = \frac{Q}{T_2}$ and $(dS)_{net}$ is the net change in the entropy of the combination to the two interacting systems. This net entropy change is called the entropy change of universe or entropy production.

Since the heat transfer has been through a finite temperature difference, the process is irreversible, i.e., $(dS)_{net} > 0$ and hence there is loss or decrease of available energy.

The above aspects lead us to conclude that:

- Whenever heat is transferred through a finite temperature difference, there is always a loss of available energy.
- Greater the temperature difference ($T_1 - T_2$), the more net increase in entropy and, therefore, more is the loss of available energy.
- The available energy of a system at a higher temperature is more than at a lower temperature, and decreases progressively as the temperature falls.

- The concept of available energy provides a useful measure of the quality of energy. Energy is said to be degraded each time it flows through a finite temperature difference. The second law may, therefore, be referred to as law of degradation of energy.

Availability

- The work potential of a system relative to its dead state, which exchanges heat solely with the environment, is called the *availability* of the system at that state.
- When a system and its environment are in equilibrium with each other, the system is said to be in its dead state.
- Specifically, a system in a dead state is in thermal and mechanical equilibrium with the environment at T_0 and P_0.
- The numerical values of (T_0, P_0) recommended for the dead state are those of the standard atmosphere, namely, 298.15 K and 1.01325 bars (1 atm).

Availability of Non-flow or Closed System

Consider a piston-cylinder arrangement (closed system) in which the fluid at P_1, V_1, T_1, expands reversibly to the environmental state with parameters P_0, V_0, T_0. The following energy (work and het) interactions take place:

- The fluid expands and expansion work W_{exp} is obtained. From the principle of energy conservation, $\delta Q = \delta W + dU, we\ get : -Q = W_{exp} + (U_0 - U_1)$

  The heat interaction is negative as it leaves the system.

  Therefore $W_{exp} = (U_1 - U_0) - Q$

- The heat Q rejected by the piston-cylinder assembly may be made to run a reversible heat engine. The output from the reversible engine equals

  $W_{eng} = Q\left[1 - \frac{T_0}{T_1}\right] = Q - T_0(S_1 - S_0)$ **(Equ.3.60)**

The sum total of expansion work W_{exp} and the engine work W_{eng} gives maximum work obtainable from the arrangement.

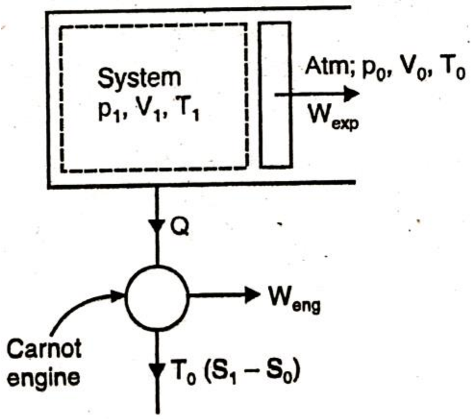


Fig. 3.16: Availability of a Non-Flow System

$$W_{max} = [(U_1 - U_0) - Q] + [Q - T_0(S_1 - S_0)]$$
$$= (U_1 - U_0) - T_0(S_1 - S_0)$$

The piston moving outwards has to spend a work in pushing the atmosphere against its own pressure. This work, which may be called as the surrounding work is simply dissipated, and as such is not useful. It is given by

$$W_{surr} = P_0(V_0 - V_1)$$

The energy available for work transfer less the work absorbed in moving the environment is called the useful work or net work.

Therefore, Maximum available useful work or net work,

$$(W_{useful})_{max} = W_{max} - W_{surr}$$
$$= (U_1 – U_0) – T_0(S_1 – S_0) – P_0(V_0 – V_1)$$
$$= (U_1 + P_0V_1 – T_0S_1) – (U_0 + P_0V_0 – T_0S_0)$$
$$= A_1 – A_0$$

Where $A = (U+P_0V – T_0S)$ is known as non-flow availability function. It is a composite property of the system and surroundings as it consists of three extensive properties of the system (U, V and S) and two intensive properties of the surroundings (P_0 and T_0).

When the system undergoes a change from state 1 to state 2 without reaching the dead state, then

$$(W_{useful})_{max} = W_{net} = (A_1 – A_0) – (A_2 – A_0) = A_1 – A_2$$

Availability of Steady Flow System

Consider a steady flow system and let it be assumed that the following fluid has the following properties and characteristics:

Internal energy U, specific volume V, specific enthalpy H, pressure P, velocity C and location Z.

The properties of the fluid would change when flowing through the system. Let subscript 1 indicate the properties of the system at inlet and subscript 0 be used to designate the fluid parameters at outlet corresponding to dead state. Further let Q units of heat be rejected by the system and let the system deliver W_{shaft} units of work.

$$U_1 + P_1V_1 + \frac{C_1^2}{2} + gZ_1 - Q = U_0 + P_0V_0 + \frac{C_0^2}{2} + gZ_0 + W_{shaft}$$

Neglecting potential and kinetic energy changes,

$$U_1 + P_1V_1 – Q = U_0 + P_0V_0 + W_{shaft}$$
$$H_1 – Q + H_0 + W_{shaft}$$

Therefore, Shaft work $W_{shaft} = (H_1 – H_0) – Q$

The heat Q rejected by the system may be made to run a reversible heat engine. The output from this engine equals

$W_{eng} = Q\left[1 - \frac{T_0}{T_1}\right] = Q - T_0(S_1 - S_0)$ **(Equation 3.67)**

Therefore, Maximum available useful work or net work

$W_{net} = W_s + W_{eng} = (H_1 – H_0) – Q + Q – T_0(S_1 – S_0)$

$= (H_1 – T_0 S_1) – (H_0 – T_0 S_0)$

$= B_1 – B_0$ **(Equation 3.68)**

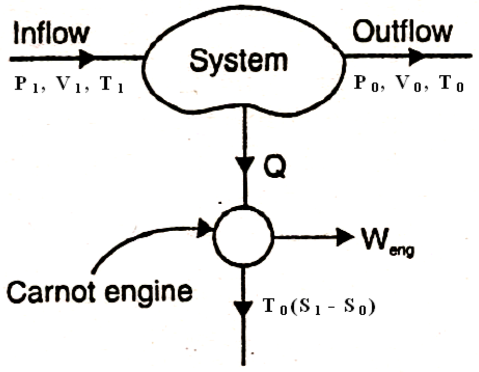


Fig. 3.17: Availability of a Steady flow System

Where $B = (H – T_0S)$ is known as the steady flow availability function. It is composite property of system and surroundings involving two extensive properties H and S of the system and one intensive property T_0 of the surroundings.

When the system changes from state 1 to some intermediate state 2, the change in steady flow availability function is given by

$$dB = (B_1 - B_0) - (B_2 - B_0) = B_1 - B_2$$

Helmholtz and Gibb's Functions

For a non-flow process, the maximum work output from the system when $T_1 = T_2 = T_0$, is given by

$$W_{max} = (U_1 - T_1S_1) - (U_2 - T_2S_2) = A_1 - A_2$$

- The term (U – TS) is called the Helmholtz function and is defined as the difference between the internal energy and the product of temperature and entropy.
- The maximum work of the process is equal to the decrease in Helmholtz function of the system.

In the case of flow process, the maximum work output from the system when $T_1 = T_2 = T_0$ and neglecting kinetic and potential energies, is given by

$$\begin{aligned} W_{max} &= (U_1 + P_1V_1 - T_1S_1) - (U_2 + P_2V_2 - T_2S_2) \\ &= (H_1 - T_1S_1) - (H_2 - T_2 S_2) = G_1 - G_2 \end{aligned}$$

- The term (H – TS) is called Gibb's function and is defined as the difference between enthalpy and product of temperature and entropy.
- The changes of both Helmholtz and Gibb's functions are called free energy i.e., energy that is free to be converted into work. Further, both the Helmholtz and Gibb's functions establish a criterion for thermodynamic equilibrium. At equilibrium, these functions are at their minimum values.

Maxwell Relations

The Maxwell relations can be derived from the different forms of the thermodynamic property relations discussed earlier such as

$du = Tds - Pdv$; $dh = Tds + vdP$;

$A = U - TS$ (or) $a = u - Ts$ and $G = H - TS$ (or) $g = h - Ts$

These relations are exact differentials and are of the general form $dz = M\,dx + N\,dy$.

For exact differentials, we have

$$\left(\frac{\partial M}{\partial y}\right)_x = \left(\frac{\partial N}{\partial x}\right)_y.$$

Therefore using this relationship we can derive the following equations:

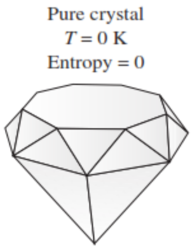
$$\left(\frac{\partial T}{\partial v}\right)_s = -\left(\frac{\partial P}{\partial s}\right)_v \quad ; \quad \left(\frac{\partial T}{\partial P}\right)_s = -\left(\frac{\partial v}{\partial s}\right)_P$$

$$\left(\frac{\partial P}{\partial T}\right)_v = -\left(\frac{\partial s}{\partial v}\right)_T \quad ; \quad \left(\frac{\partial v}{\partial T}\right)_P = -\left(\frac{\partial s}{\partial P}\right)_T$$

These four equations are known as the Maxwell Relations for a simple compressible fluid.

Third Law of Thermodynamics (Nernst Law)

At absolute zero temperature, the entropy of all homogeneous crystalline (condensed) substances in a state of equilibrium becomes zero. the molecules of a substance in solid phase continually oscillate, creating an uncertainty about their position. These oscillations, however, fade as the temperature is decreased, and the molecules supposedly become motionless at absolute zero. This represents a state of ultimate molecular order (and minimum energy). 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 statement is known as the **third law of thermodynamics**. The third law of thermodynamics provides an absolute reference point for the determination of entropy. The entropy determined relative to this point is called **absolute entropy**, and it is extremely useful in the thermodynamic analysis of chemical reactions. Notice that the entropy of a substance that is not pure crystalline (such as a solid solution) is not zero at absolute zero temperature. This is because more than one molecular configuration exists for such substances, which introduces some uncertainty about the microscopic state of the substance.



ENGINEERING THERMODYNAMICS

Unit – VI

Objectives:

- To introduce the students to gas power cycles, vapour power cycles and refrigeration cycles

Syllabus:

Gas power cycles: Otto, diesel, dual combustion cycles, description and representation on P-v and T-s diagram, thermal efficiency, mean effective pressure on air standard basis- comparison of cycles, Brayton cycle

Vapour power cycles: Simple Rankine cycle, Refrigeration cycles: Bell Coleman cycle, vapour compression refrigeration system- performance evaluation.

Outcomes:

Students will be able to

- Evaluate thermal efficiency of Otto, diesel, dual cycle and Brayton cycle and they can represent on P-v and T-s diagrams
- Compare various gas power cycles
- Understand vapour power cycles
- Understand refrigeration cycles
- Evaluate performance of refrigeration cycles

- **Air-Standard Assumptions**

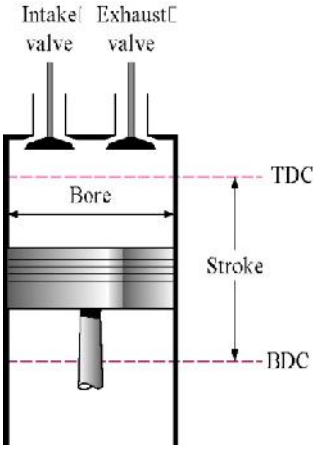
In our study of gas power cycles, we assume the working fluid is air, and the air undergoes a thermodynamic cycle even though the working fluid in the actual power system does not undergo a cycle.

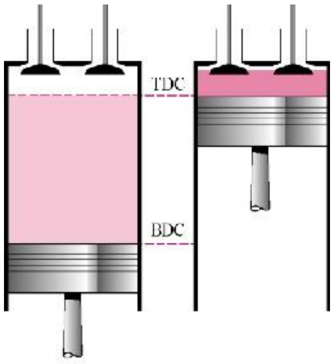
To simplify the analysis, we approximate the cycles with the following assumptions:

- The air continuously circulates in a closed loop and always behaves as an ideal gas.
- All the processes that make up the cycle are internally reversible.
- The combustion process is replaced by a heat-addition process from an external source.
- A heat rejection process that restores the working fluid to its initial state replaces the exhaust process.
- The cold-air-standard assumptions apply when the working fluid is air and has constant specific heat evaluated at room temperature (25^{o}C or 77^{o}F).

- **Terminology for Reciprocating Devices**

The following is some terminology we need to understand for reciprocating engines—typically piston-cylinder devices. Let's look at the following figures for the definitions of top dead center (TDC), bottom dead center (BDC), stroke, bore, intake valve, exhaust valve, clearance volume, displacement volume, compression ratio, and mean effective pressure.





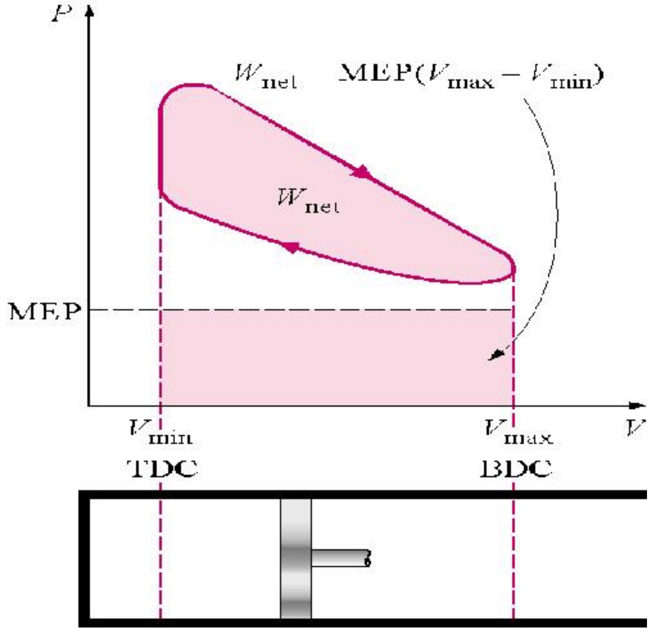
(a) Displacement volume
(b) Clearance volume

- The compression ratio *r* of an engine is the ratio of the maximum volume to the minimum volume formed in the cylinder.

$$r = \frac{V\max}{V\min} = \frac{V_{BDC}}{V_{TDC}}$$

- The mean effective pressure **(MEP)** is a fictitious pressure that, if it operated on the piston during the entire power stroke, would produce the same amount of net work as that produced during the actual cycle.

$$MEP = \frac{W_{net}}{V_{\max} - V_{\min}} = \frac{w_{net}}{v_{\max} - v_{\min}}$$

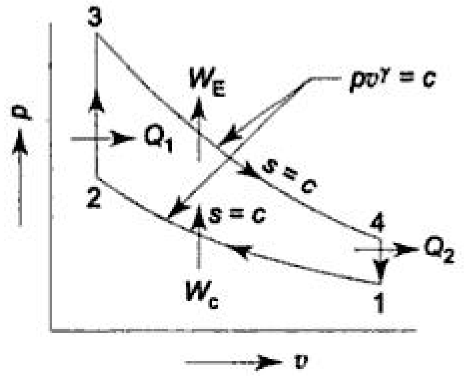


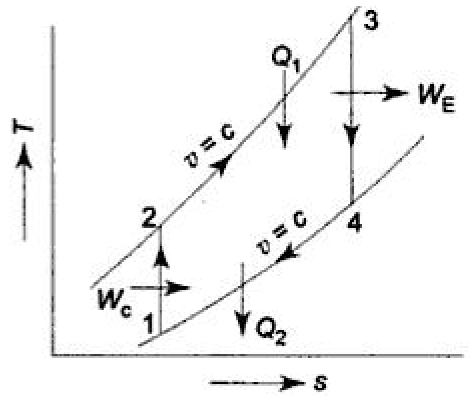
- **Otto Cycle (Constant Volume Cycle):**

This ideal heat engine cycle was proposed in 1862 by Bean de Rochas. In 1876 Dr. Otto designed an engine to operate on this cycle. The Otto engine immediately became so successful from a commercial stand point, that its name was affixed to the cycle used by it.

The ideal p - v and T-s diagrams of this cycle are shown in fig. In working out the air-standard efficiency of the cycle, the following assumptions are made:

(i) The working fluid (working substance) in the engine cylinder is air, and it behaves as a perfect gas, i.e., it obeys the gas laws and has constant specific heats.
(ii) The air is compressed adiabatically (without friction) according to law $pv^{\gamma} = C$
(iii) The heat is supplied to the air at constant volume by bringing a hot body in contact with the end of the engine cylinder.
(iv) The air expands in the engine cylinder adiabatically (without friction) during the expansion stroke.
(v) The heat is rejected from the air at constant volume by bringing a cold body in contact with the end of the engine cylinder.





Process 1→ 2 Isentropic compression
Process 2 → 3 Constant volume heat addition
Process 3 → 4 Isentropic expansion
Process 4 → 1 Constant volume heat rejection

Consider one kilogram of air in the engine cylinder at point (1). This air is compressed adiabatically to point (2), at which condition the hot body is placed in contact with the end of the cylinder. Heat is now supplied at constant volume, and temperature and pressure rise; this operation is represented by (2-3). The hot body is then removed and the air expands adiabatically to point (4). During this process, work is done on the piston. At point (4), the cold body is placed at the end of the cylinder. Heat is now rejected at constant volume, resulting in drop of temperature and pressure. This operation is represented by (4-1). The cold body is then removed after the air is brought to its original state (condition). The cycle is thus completed. The cycle consists of two constant volume processes and two reversible adiabatic processes. The heat is supplied during constant volume process (2-3) and rejected during constant volume process (4-1). There is no exchange of heat during the two reversible adiabatic processes (1-2) and (3-4).

The performance is often measured in terms of the cycle efficiency.

$$\eta_{th} = \frac{W_{net}}{Q_{in}}$$

Thermal Efficiency of the Otto cycle

$$\eta_{th} = \frac{W_{net}}{Q_{in}} = \frac{Q_{net}}{Q_{in}} = \frac{Q_{in} - Q_{out}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}}$$

Now to find Q_{in} and Q_{out}.

Apply first law closed system, V = constant.

Heat supplied during constant volume operation (2-3), Heat rejected during constant volume operation (4-1) is

$$q_{in} = u_3 - u_2 = c_v(T_3 - T_2)$$
$$q_{out} = u_4 - u_1 = c_v(T_4 - T_1)$$

$$Q_{net,23} = \Delta U_{23}$$
$$Q_{net,23} = Q_{in} = mC_v(T_3 - T_2)$$

$$Q_{net,41} = \Delta U_{41}$$
$$Q_{net,41} = -Q_{out} = mC_v(T_1 - T_4)$$
$$Q_{out} = -mC_v(T_1 - T_4) = mC_v(T_4 - T_1)$$

The thermal efficiency becomes

$$\eta_{th,Otto} = 1 - \frac{Q_{out}}{Q_{in}}$$
$$= 1 - \frac{mC_v(T_4 - T_1)}{mC_v(T_3 - T_2)}$$

$$\eta_{th,Otto} = 1 - \frac{(T_4 - T_1)}{(T_3 - T_2)}$$
$$= 1 - \frac{T_1(T_4 / T_1 - 1)}{T_2(T_3 / T_2 - 1)}$$

Recall processes 1-2 and 3-4 are isentropic, so

$$\frac{T_1}{T_2} = \left(\frac{v_2}{v_1}\right)^{\gamma - 1} = \left(\frac{v_3}{v_4}\right)^{\gamma - 1} = \frac{T_4}{T_3}$$

Since $V_3 = V_2$ and $V_4 = V_1$

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

The Otto cycle efficiency becomes

$$\eta_{th,Otto} = 1 - \frac{T_1}{T_2}$$

Since process 1-2 is isentropic,

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

Where the compression ratio is

$$r = \frac{v_{\max}}{v_{\min}} = \frac{v_1}{v_2}$$

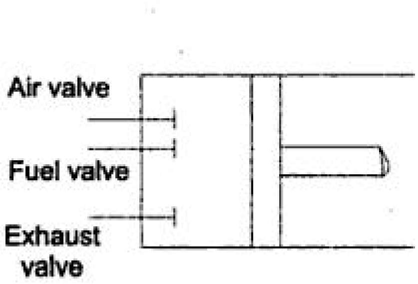
$$\eta_{th,\,Otto} = 1 - \frac{1}{r^{k-1}}$$

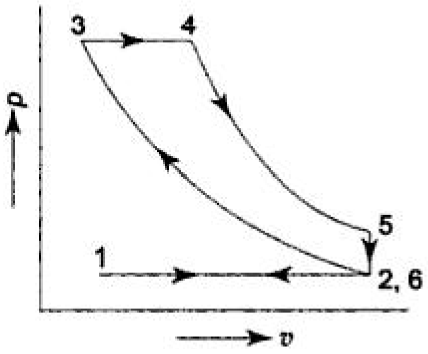
- **Air-Standard Diesel Cycle (or constant pressure cycle):**

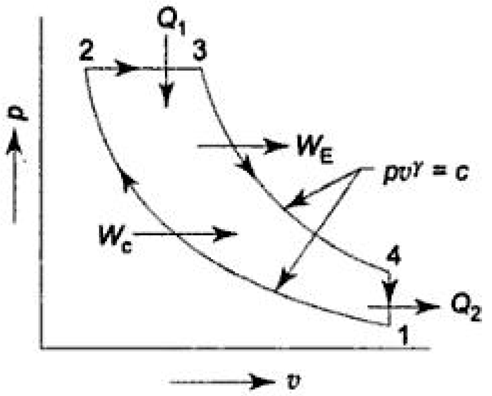
The air-standard Diesel cycle is the ideal cycle that approximates the Diesel combustion engine

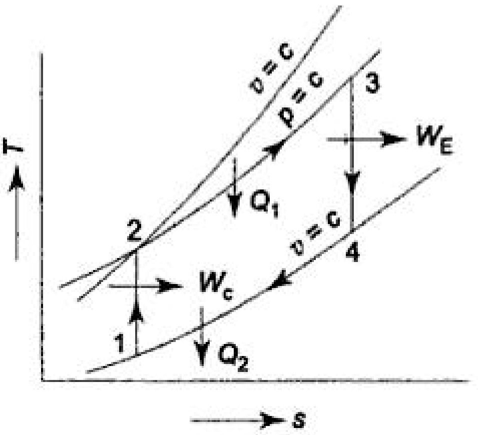
Process	Description
1-2	isentropic compression
2-3	Constant pressure heat addition
3-4	isentropic expansion
4-1	Constant volume heat rejection

The *P*-*v* and *T*-*s* diagrams are









$$Heat\ supplied = Q_1 = Q_{2-3} = mc_p(T_3 - T_2)$$

$$Heat\ \text{Rejected} = \text{Q}_2 = Q_{4-1} = mc_v(T_4 - T_1)$$

$$\text{Effieciency} = \eta = 1 - \frac{Q_2}{Q_1} = 1 - \frac{mc_v(T_4 - T_1)}{mc_p(T_3 - T_2)} = 1 - \frac{(T_4 - T_1)}{\gamma(T_3 - T_2)}$$

The efficiency may be expressed terms of any two of the following.

$$Compression\ Ratio = r_k = \frac{v_1}{v_2}$$

$$Expansion\ Ratio = r_e = \frac{v_4}{v_3}$$

$$Cut-off\ \ ratio = r_c = \frac{v_3}{v_2}$$

$$r_k = r_e . r_c$$

Process 3-4

$$\frac{T_4}{T_3} = \left(\frac{v_3}{v_4}\right)^{\gamma-1} = \frac{1}{r_e^{\gamma-1}}$$

$$T_4 = T_3\left(\frac{v_3}{v_4}\right)^{\gamma-1} = T_3\frac{r_e^{\gamma-1}}{r_k^{\gamma-1}}$$

Process 2-3

$$\frac{T_2}{T_3} = \frac{p_2 v_2}{p_3 v_3} = \frac{v_2}{v_3} = \frac{1}{r_e}$$

$$T_2 = T_3\frac{1}{r_e}$$

Process 1-2

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

$$T_1 = T_2 \frac{1}{r_k^{\gamma-1}} = \frac{T_3}{r_c} \frac{1}{r_k^{\gamma-1}}$$

By subsisting T1,T2 and T4 in the expression of efficiency

$$\eta = 1 - \frac{T_3 \frac{r_c^{\gamma-1}}{r_k^{\gamma-1}} - \frac{T_3}{r_c} \frac{1}{r_k^{\gamma-1}}}{\gamma\left(T_3 - T_3 \frac{1}{r_c}\right)}$$

$$\eta_{diesel} = 1 - \frac{1}{\gamma} \frac{1}{r_c^{\gamma-1}} . \frac{r_c^{\gamma-1}}{r_c - 1}$$

- **Dual Cycle (mixed cycle/ limited pressure cycle):**

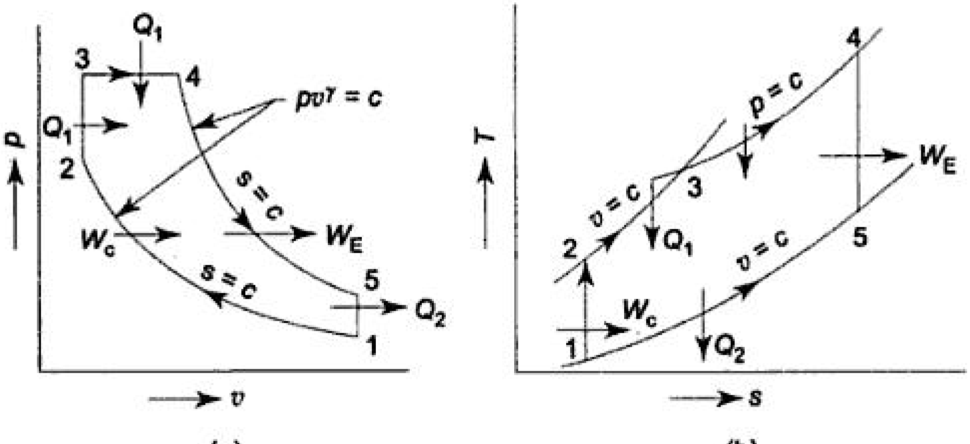
Process 1 → 2 Isentropic compression

Process 2 → 3Constant volume heat addition

Process 3 → 4 Constant pressure heat addition

Process 4 → 5 Isentropic expansion

Process 5→ 1 Constant volume heat rejection



(a) (b)

Thermal Efficiency:

where $r_c = {}^{v_3}\!/_{v_{2.5}}$ and $\sim\; = {}^{P_3}\!/_{P_2}$

Note, the Otto cycle (r_c=1) and the Diesel cycle (a=1) are special cases:

$$¦_{Otto} = 1 - \frac{1}{r^{k-1}} \qquad ¦_{\substack{Diesel \\ const\ c_V}} = 1 - \frac{1}{r^{k-1}}\left[\frac{1}{k}\cdot\frac{\left(r_c^k - 1\right)}{\left(r_c - 1\right)}\right]$$

The use of the Dual cycle requires information about either:

i) The fractions of constant volume and constant pressure heat addition (common assumption is to equally split the heat addition), or

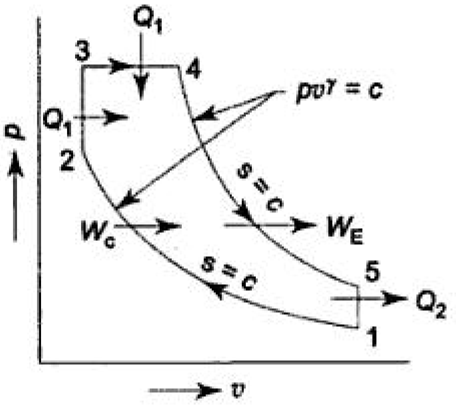
ii) Maximum pressure P_3.

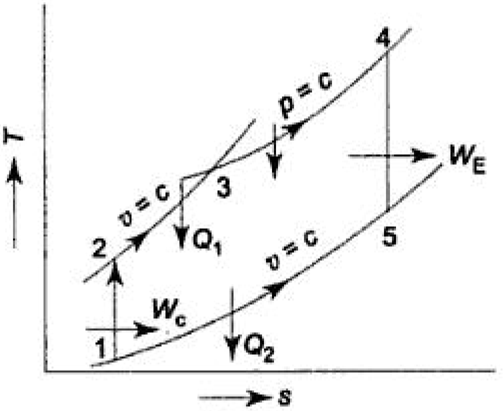
$$Q_1 = mc_v(T_3 - T_2) + mc_p\left(T_4 - T_3\right)$$
$$Q2 = mc_v(T_5 - T_1)$$

Here Q_1 -= heat input

Q_2 =Out put

$$¦ = 1 - \frac{Q_2}{Q_1} = 1 - \frac{mc_v(T_5 - T_1)}{mc_v(T_3 - T_2) + mc_p\left(T_4 - T_3\right)} = 1 - \frac{T_5 - T_1}{(T_3 - T_2) + ¥\left(T_4 - T_3\right)}$$





$$Compression\ Ratio = r_k = \frac{v_1}{v_2}$$

$$Expansion\ Ratio = r_e = \frac{v_4}{v_3}$$

$$cons\tan t - volume - pressure - ratio = r_p = \frac{p_3}{p_2}$$

$$r_k = r_c . r_e$$

$$r_e = \frac{r_k}{r_e}$$

$$process 3-4$$

$$r_c = \frac{v_4}{v_3} = \frac{T_4 p_3}{p_4 T_3} = \frac{T_4}{T_3}$$

$$T_3 = \frac{T_4}{r_c}$$

$$\Pr ocess 2-3$$

$$\frac{p_2 v_2}{T_2} = \frac{p_3 v_3}{T_3}$$

$$T_2 = T_3 \frac{p_2}{p_3} = \frac{T_4}{r_p r_c}$$

$$process - 1 - 2$$

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

$$T_1 = \frac{T_4}{r_p . r_c . r_k^{\text{¥}-1}}$$

Process 4-5

$$T_1 = \frac{T_4}{r_p . r_c . r_k^{\text{¥}-1}}$$

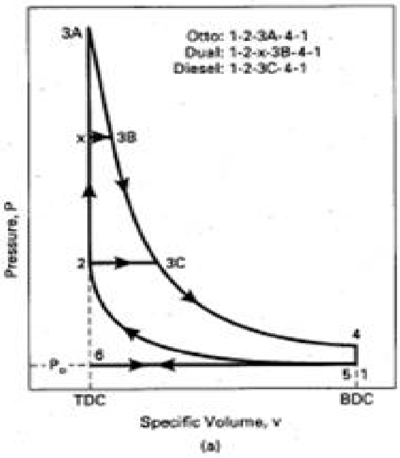
$$\frac{T_5}{T_4} = \left(\frac{v_4}{v_5} \right)^{\text{¥}-1} = \frac{1}{r_e^{\text{¥}-1}}$$

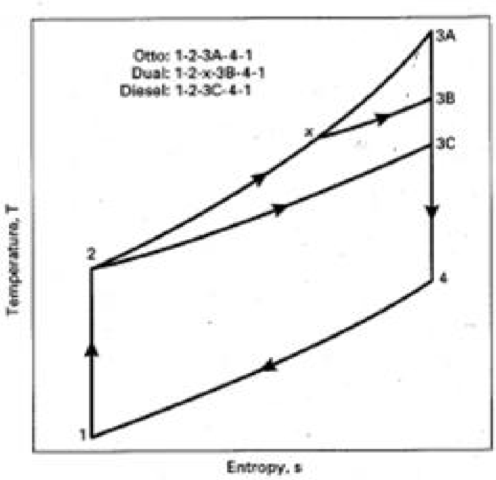
$$T_5 = T_4 \frac{r_c^{\text{¥}-1}}{r_k^{\text{¥}-1}}$$

SubtitlingT1, T2,T3 and T4values

$$\eta_{dual} = 1 - \frac{T_4 \dfrac{r_c^{\gamma-1}}{r_k^{\gamma-1}} - \dfrac{T_4}{r_p . r_c . r_k^{\gamma-1}}}{\left(\dfrac{T_4}{r_c} - \dfrac{T_4}{r_p r_c}\right) + \gamma\left(T_4 - \dfrac{T_4}{r_c}\right)} = 1 - \frac{1}{r_k^{\gamma-1}} \frac{r_p r_c^{\gamma-1}}{r_p - 1 + \gamma r_p \left(r_c - 1\right)}$$

- **Comparison of cycles:**
  - For the same inlet conditions P_1, V_1 and the same compression ratio P_2/P_1:

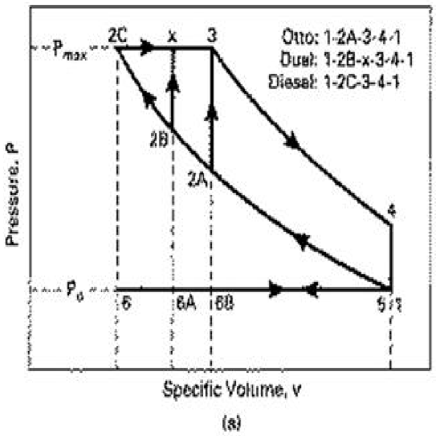


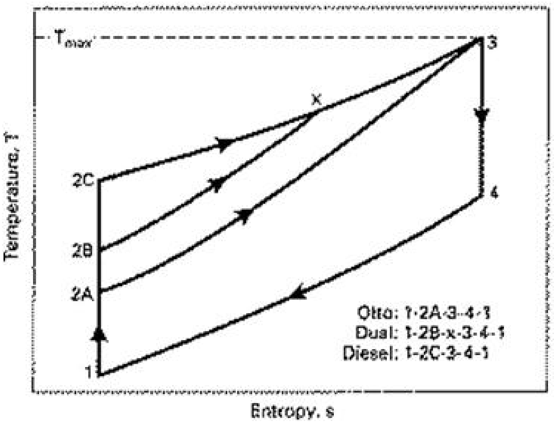


For the same initial conditions P_1, V_1 and the same compression ratio:

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

  - For the same inlet conditions P_1, V_1 and the same peak pressure P_3:





For the same initial conditions P_1, V_1 and the same peak pressure P_3

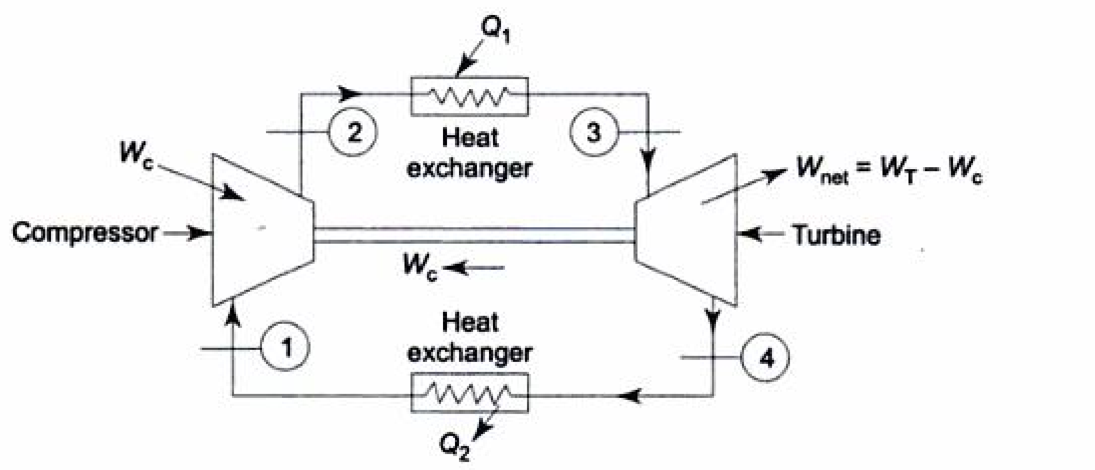
(Actual design limitation in engines):

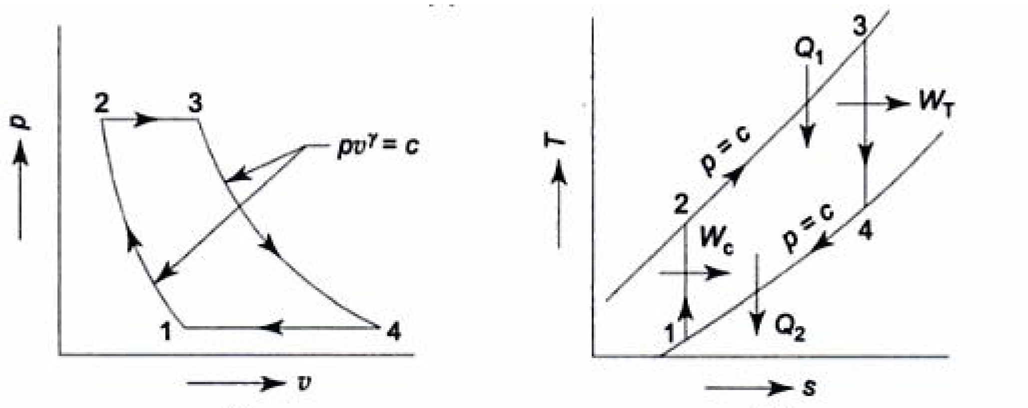
$$\eta_{Diesel} > \eta_{Dual} > \eta_{otto}$$

- **Brayton Cycle (or Joule cycle)**

The Brayton cycle is the air-standard ideal cycle approximation for the gas-turbine engine. This cycle differs from the Otto and Diesel cycles in that the processes making the cycle occur in open systems or control volumes. Therefore, an open system, steady-flow analysis is used to determine the heat transfer and work for the cycle.

We assume the working fluid is air and the specific heats are constant and will consider the cold-air-standard cycle.





(b) (c)

The closed cycle gas-turbine engine

The *T*-*s* and *P*-*v* diagrams for the

Closed Brayton Cycle

Process	Description
1-2	Isentropic compression (in a compressor)
2-3	Constant pressure heat addition
3-4	Isentropic expansion (in a turbine)
4-1	Constant pressure heat rejection

Thermal efficiency of the Brayton cycle

$$\boxed{\eta_{th,\ Brayton} = \frac{W_{net}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}}}$$

Now to find Q_{in} and Q_{out}.

Apply the conservation of energy to process 2-3 for P = constant (no work), steady-flow, and neglect changes in kinetic and potential energies.

$$\begin{aligned}\dot{E}_{in} &= \dot{E}_{out}\\ \dot{m}_2 h_2 + \dot{Q}_{in} &= \dot{m}_3 h_3\end{aligned}$$

The conservation of mass gives

$$\begin{aligned}\dot{m}_{in} &= \dot{m}_{out}\\ \dot{m}_2 &= \dot{m}_3 = \dot{m}\end{aligned}$$

For constant specific heats, the heat added per unit mass flow is

$$\begin{aligned}\dot{Q}_{in} &= \dot{m}(h_3 - h_2)\\ \dot{Q}_{in} &= \dot{m}C_p(T_3 - T_2)\\ q_{in} &= \frac{\dot{Q}_{in}}{\dot{m}} = C_p(T_3 - T_2)\end{aligned}$$

The conservation of energy for process 4-1 yields for constant specific heats

$$\boxed{\begin{aligned}\dot{Q}_{out} &= \dot{m}(h_4 - h_1)\\ \dot{Q}_{out} &= \dot{m}C_p(T_4 - T_1)\end{aligned}}$$

$$q_{out} = \frac{\dot{Q}_{out}}{\dot{m}} = C_p(T_4 - T_1)$$

The thermal efficiency becomes

$$\eta_{th,\ Brayton} = 1 - \frac{\dot{Q}_{out}}{\dot{Q}_{in}} = 1 - \frac{q_{out}}{q_{in}}$$
$$= 1 - \frac{C_p(T_4 - T_1)}{C_p(T_3 - T_2)}$$

$$\boxed{\eta_{th,\ Brayton} = 1 - \frac{(T_4 - T_1)}{(T_3 - T_2)}}$$
$$= 1 - \frac{T_1(T_4 / T_1 - 1)}{T_2(T_3 / T_2 - 1)}$$

Recall processes 1-2 and 3-4 are isentropic, so

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}}$$
$$\frac{T_3}{T_4} = \left(\frac{p_3}{p_4}\right)^{\frac{\gamma-1}{\gamma}}$$

Since $P_3 = P_2$ and $P_4 = P_1$,

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

The Brayton cycle efficiency becomes

$$\eta_{th,\ Brayton} = 1 - \frac{T_1}{T_2}$$

Since process 1-2 is isentropic,

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

Where the pressure ratio is $r_p = P_2/P_1$ and

$$\boxed{\eta_{th,\ Brayton} = 1 - \frac{1}{r_p^{(\gamma-1)/\gamma}}}$$

SIMPLE RANKINE CYCLE

Rankine Cycle: The simplest way of overcoming the inherent practical difficulties of the Carnot cycle without deviating too much from it is to keep the processes 1-2 and 2-3 of the latter unchanged and to continue the process 3-4 in the condenser until all the vapour has been converted into liquid water. Water is then pumped into the boiler upto the pressure corresponding to the state 1 and the cycle is completed. Such a cycle is known as the Rankine cycle. This theoretical cycle is free of all the practical limitations of the Carnot cycle.

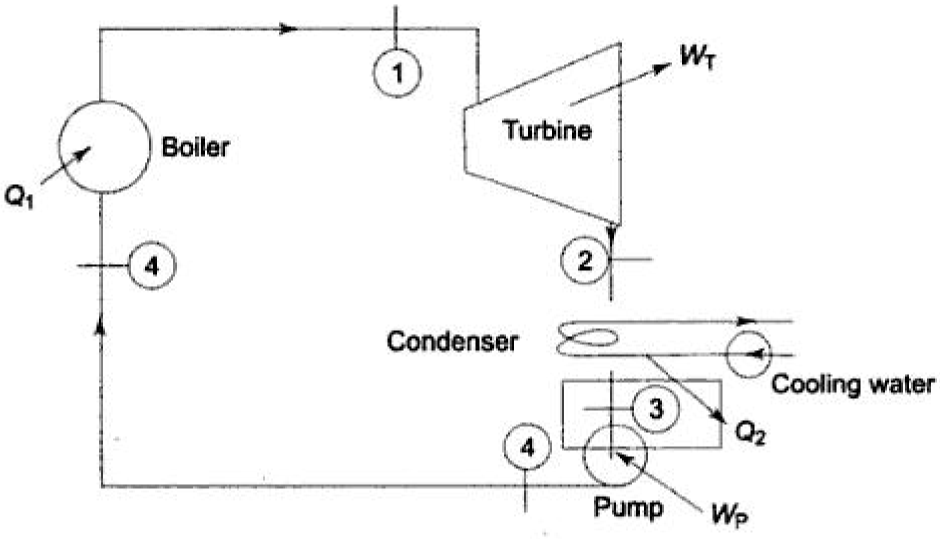


Figure (a) shows the schematic diagram for a simple steam power cycle which works on the principle of a Rankine cycle.

The Rankine cycle comprises the following processes.

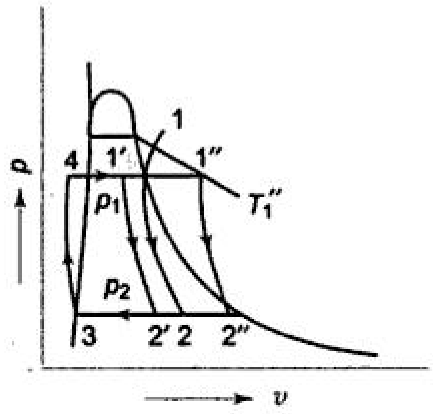
Process 1-2: Constant pressure heat transfer process in the boiler

Process 2-3: Reversible adiabatic expansion process in the steam turbine

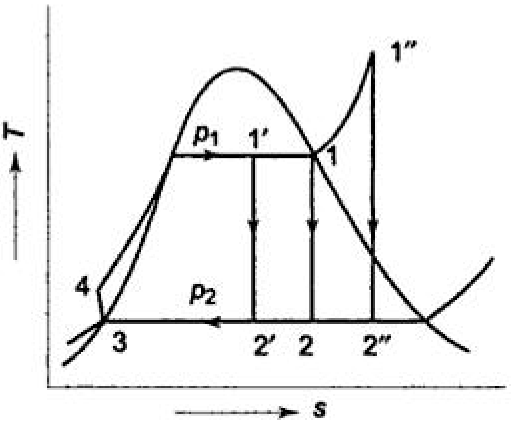
Process 3-4: Constant pressure heat transfer process in the condenser and

Process 4-1: Reversible adiabatic compression process in the pump.

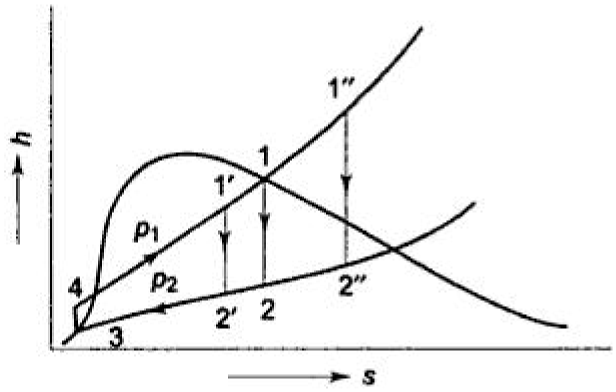
Figure (b) represents the T-S diagram of the cycle.



(a)



(b)



The numbers on the plots correspond to the numbers on the schematic diagram. For any given pressure, the steam approaching the turbine may be dry saturated (state 2), wet (state 2^1) or superheated (state 2^{11}), but the fluid approaching the pump is, in each case, saturated liquid (state 4). Steam expands reversibly and adiabatically in the turbine from state 2 to state 3 (or 2^1 to 3^1 or 2^{11} to 3^{11}), the steam leaving the turbine condenses to water in the condenser reversibly at constant pressure from state 3 (or 3^1, or 3^{11}) to state 4. Also, the water is heated in the boiler to form steam reversibly at constant pressure from state 1 to state 2 (or 2^1 or 2^{11})

Applying SFEE to each of the processes on the basis of unit mass of fluid and neglecting changes in KE & PE, the work and heat quantities can be evaluated

For 1kg of fluid, the SFEE for the boiler as the CV, gives,

$h_4 + Q_1 = h_1$ i.e., $Q_1 = h_1 - h_4$ --- (1)

SFEE to turbine, $h_1 = W_T + h_2$ i.e., $W_T = h_1 - h_2$ --- (2)

SFEE to condenser, $h_2 = Q_2 + h_3$ i.e., $Q_L = h_2 - h_3$ --- (3)

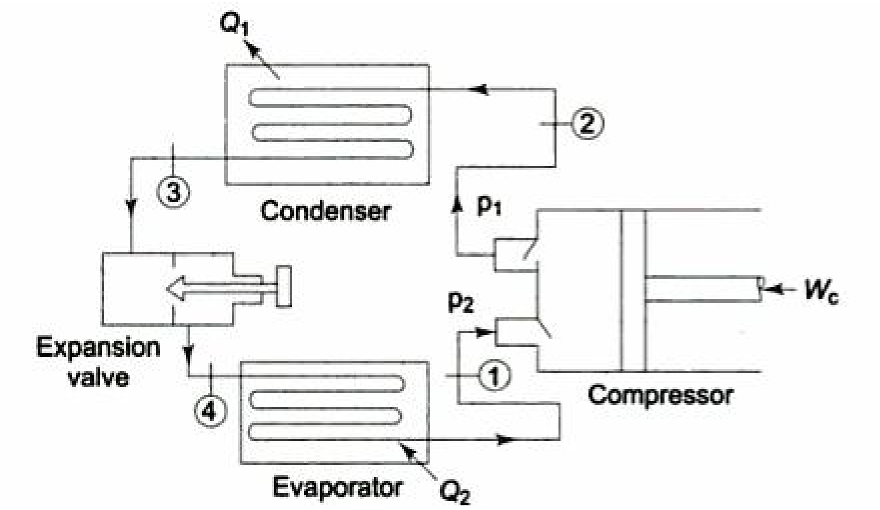
SFEE to pump, $h_3 + W_P = h_4$ i.e., $W_P = h_4 - h_3$ --- (4)

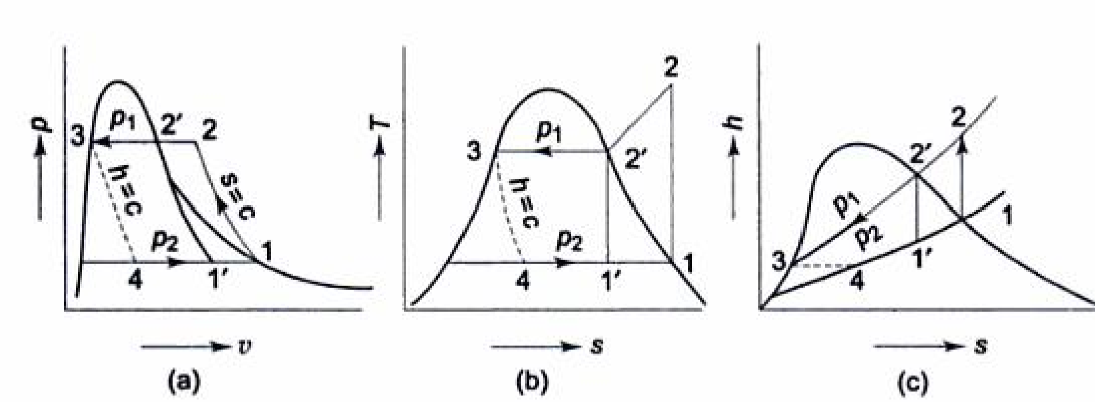
The efficiency of Rankine cycle is $\eta = \frac{W_{net}}{Q_1}$

The efficiency of Rankine cycle is $\boxed{\eta = \frac{W_{net}}{Q_1} = \frac{W_T - W_p}{Q_1} = \frac{(h_1 - h_2) - (h_4 - h_3)}{h_1 - h_4}}$

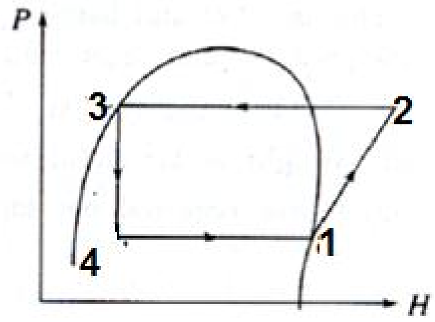
VAPOUR COMPRESSION REFRIGERATION SYSTEM

In vapour compression system, the refrigerants used are ammonia, carbon dioxide, freons etc. the refrigerants alternately undergoes condensation and evaporation during the cycle. When refrigerant enters the evaporator it will be in liquid state and by absorbing latent heat it become vapours. Thus the C.O.P of this system is always much higher that air refrigeration systems.

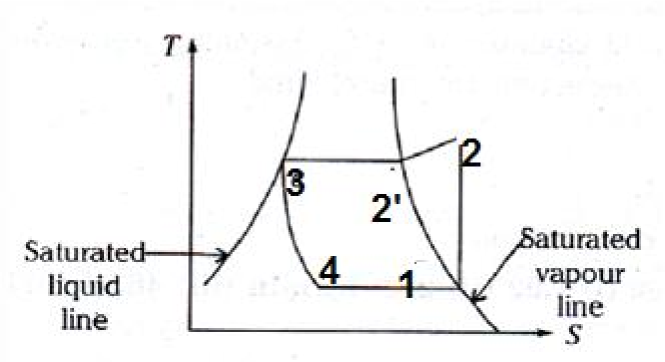




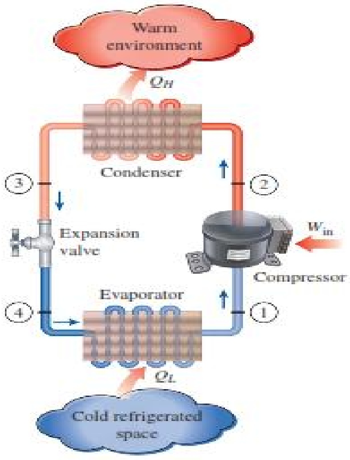
VAPOUR COMPRESSION REFRIGERATION SYSTEM



P-V Diagramv



T-S Diagram



The various processes are

Process 1-2 .

The vapour refrigerant entering the compressor is compressed to high pressure and temperature in a isentropic manner.

Process 2-3.

This high pressure and high temperature vapour then enters a condenser where the temperature of the vapour first drops to saturation temperature and subsequently the vapour refrigerants condenses to liquid state.

- **Process 3-4.**

This liquid refrigerant is collected in the liquid storage tank and later on it is expanded to low pressure and temperature by passing it through the throttle valve. At point d we have low temperature liquid refrigerant wuitn small amount of vapour.

- **Process 4-1**.

This low temperature liquid then enters the evaporator where it absorbs heat from the space to be cooled namely the refrigerator and become vapour.

Compressor work Wc = h_2-h_1 kJ/kg

Condenser work = h_2-h_3 kJ/kg

Expansion value = h_3=h_4 kJ/kg

h_{f2}= h_{f1}+(x_4 h_{fg4})

$$x_4 = \frac{\left(hf_2 - hf_1\right)}{hfg_4}$$

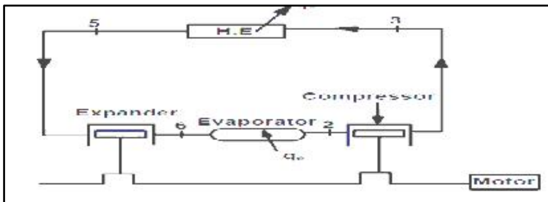
Evaporator $Q_2 = h_4 - h_1$ kJ/kg

Refrigerant effect is amount of heat removed from the surrounding per unit mass flow rate of refrigerant

Coefficient of performance $\boxed{cop = \frac{Q_2}{w_c} = \frac{h_1 - h_4}{h_2 - h_1}}$

Air Refrigeration System And Bell-Coleman Cycle Or Reversed Brayton Cycle

The components of the air refrigeration system are shown in Fig.(a). In this system, air is taken into the compressor from atmosphere and compressed. The hot compressed air is cooled in heat exchanger upto the atmospheric temperature (in ideal conditions). The cooled air is then expanded in an expander. The temperature of the air coming out from the expander is below the atmospheric temperature due to isentropic expansion. The low temperature air coming out from the expander enters into the evaporator and absorbs the heat. The cycle is repeated again. The working of air refrigeration cycle is represented on p-v and T-s diagrams in Fig.(b) and (c).



bell coleman refrigeration cycle

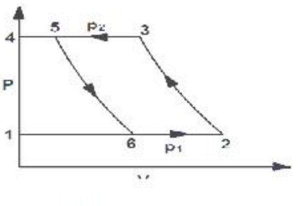


Fig b. P V Diagram

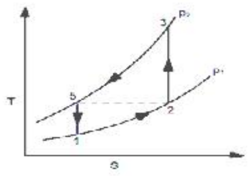


fig . C. T S Diagramm

Process 1-2 represents the suction of air into the compressor.

Process 2-3 represents the isentropic compression of air by the compressor.

Process 3-5 represents the discharge of high pressure air from the compressor into the heat exchanger. The reduction in volume of air from v3 to v5 is due to the cooling of air in the heat exchanger. Process 5-6 represents the isentropic expansion of air in the expander.

Process 6-2 represents the absorption of heat from the evaporator at constant pressure

Assumptions:

1) The compression and expansion processes are reversible adiabatic processes.

2) There is a perfect inter-cooling in the heat exchanger.

3) There are no pressure losses in the system.

$$cop = \frac{Net\ refrigeration\ effect}{Net\ work\ supplied}$$

Net refrigeration effect

Net work supplied

Work done per kg of air for the isentropic compression process 2-3 is given by,

$$W_c = C_p(T_3 - T_2) \ \text{kJ/kg K}$$

Work developed per kg of air for the isentropic expansion process 5-6 is given by,

$$W_E = C_p(T_5 - T_6) \ \text{kJ/kg K}$$

Net work required $W_{net} = (W_C - W_E) = (C_p(T_3 - T_2)) - (C_p(T_5 - T_6))$ kJ/kg K

Net refrigerating effect per kg of air is given by,

$R_{net} = C_p (T_2 - T_6)$ kJ/kg K

$$cop = \frac{c_p\left(T_2 - T_6\right)}{c_p(T_3 - T_2) - \left(T_5 - T_6\right)}$$

For perfect inter-cooling, the required condition is $T_5 = T_2$

$$\boxed{cop = \frac{c_p\left(T_2 - T_6\right)}{c_p(T_3 - T_2) - \left(T_2 - T_6\right)}}$$

$$\frac{T_3}{T_2} = \frac{p_1}{p_2}^{\frac{¥-1}{¥}} \rightarrow \qquad \frac{T_5}{T_6} = \frac{p_2}{p_1}^{\frac{¥-1}{¥}} \qquad \frac{T_3}{T_2} = \frac{T_5}{T_6} \qquad \frac{T_6}{T_5} = \frac{T_2}{T_3}$$

or $T_5 = T_2$

Performance of The system $\boxed{cop = \frac{T_2}{T_3 - T_2}}$