# INSTITUTE OF AERONAUTICAL ENGINEERING

**(Autonomous)**

Dundigal, Hyderabad -500 043

## AERONAUTICAL ENGINEERING

## COURSE LECTURE NOTES

| | |
|---|---|
| **Course Name** | **ENGINEERING THERMODYNAMICS** |
| **Course Code** | **AAEB02** |
| **Programme** | B.Tech |
| **Semester** | III |
| **Course Coordinator** | Mr. R.Sabarivihar, Assistant Professor, AE |
| **Course Faculty** | Mr. R.Sabarivihar, Assistant Professor, AE<br>Mrs. M.Sravani, Assistant Professor, AE |

## COURSE OBJECTIVES:

| **The course should enable the students to:** | |
|---|---|
| I | Understand the laws of thermodynamics and determine thermodynamic properties, gas laws. |
| II | Apply knowledge of pure substances, mixtures, usage of steam tables and Mollier chart, psychrometric charts. |
| III | Understand the direction law and concept of increase in entropy of universe. |
| IV | Understand the working of ideal air standard, vapour cycles and evaluate their performance in open systems like steam power plants, internal combustion engines, gas turbines and refrigeration systems. |
| V | Understand the basic concepts of heat transfer and working and types of heat exchangers. |

## COURSE LEARNING OUTCOMES (CLOs):

| **S. No** | **Description** |
|---|---|
| AAEB02.01 | Understand the basic terms and terminologies of thermodynamics along with different view point of thermodynamic systems. |
| AAEB02.02 | Get knowledge about concept of temperature and explain zeroth law of thermodynamics and also about quality of temperature. |
| AAEB02.03 | Explain about first law of thermodynamics and its various corollaries along with Joules experiment. |
| AAEB02.04 | Understand the limitations of first law of thermodynamics. |
| AAEB02.05 | Explain about thermal reservoir, heat pump, heat engine and parameters of performance. |
| AAEB02.06 | Explain second law of thermodynamics, Kelvin planck and Clausius statement of it. |
| AAEB02.07 | Understand the Kelvin planck and Clausius equivalence, corollaries and understand about perpetual motion machine one. |
| AAEB02.08 | Understand the term entropy, its principle and how it influences the availability and irreversibility of thermodynamic potentials. |

| S. No | Description |
|---|---|
| AAEB02.09 | Understand pure substances and phase diagrams and about terms triple point and critical point. |
| AAEB02.10 | Understand how properties like wet bulb temperature, dry bulb temperature, dew bulb temperature help in building mollier chart and psychrometric chart. |
| AAEB02.11 | Determine the equilibrium states of a wide range of systems, ranging from mixtures of gases, liquids, solids and pure condensed phases that can each include multiple components. |
| AAEB02.12 | Introduction to concepts of power and refrigeration cycles. Their efficiency and coefficients of performance. |
| AAEB02.13 | Ability to use modern engineering tools, software and equipment to analyze energy transfer in required air-condition application. |
| AAEB02.14 | Explore the use of modern engineering tools, software and equipment to prepare for competitive exams, higher studies etc. |
| AAEB02.15 | Understand about working of heat exchangers and different types of heat exchangers. |
| AAEB02.16 | Understand the working of gas compressors and air compressors and different types of air compressors. |

**SYLLABUS:**

| Module -I | BASIC CONCEPTS AND FIRST LAW OF THERMODYNAMICS |
|---|---|
| Basic concepts: System, control volume, surrounding, boundaries, universe, types of systems, macroscopic and microscopic viewpoints, concept of continuum, thermodynamic equilibrium, state, property, process, cycle, reversibility, quasi static process, irreversible process, causes of irreversibility, various flow and non flow processes ,energy in state and in transition, types-work and heat, point and path function, Zeroth law of thermodynamics, concept of quality of temperature, Principles of thermometry, reference points, constant volume gas thermometer, ideal gas scale, PMMI Joule's experiments, first law of thermodynamics, corollaries first law applied to a process, applied to a flow system, steady flow energy equation. | |
| **Module -II** | **SECOND LAW OF THERMODYNAMICS** |
| Limitations of the first law: thermal reservoir, heat engine, heat pump, parameters of performance, second Law of thermodynamics, Kelvin Planck and Clausius statements and their equivalence, Corollaries, PMM of second kind, Carnot's principle, Carnot cycle and its specialties, thermodynamic scale of temperature, Clausius inequality, Entropy, principle of Entropy increase, availability and irreversibility, thermodynamic potentials, Gibbs and Helmholtz functions, Maxwell relations, Third Law of thermodynamics. | |
| **Module -III** | **PURE SUBSTANCES AND MIXTURES OF PERFECT GASES** |
| Pure substances: Phase transformations, T-S and H-S diagrams, P-V-T surfaces, triple point at critical state properties during change of phase, dryness fraction, Mollier charts, psychometric properties, dry bulb temperature, wet bulb temperature, dew point temperature, thermodynamic wet bulb temperature, specific humidity, relative humidity, saturated air, vapour pressure, degree of saturation, adiabatic saturation, Carrier's equation, Psychometric chart. | |
| **Module -IV** | **POWER CYCLES** |
| Power cycles: Otto, Diesel, Dual combustion cycles, description and representation on P-V and T-S diagram, thermal efficiency, mean effective pressures on air standard basis, comparison of cycles, | |

| introduction to Brayton cycle and Bell Coleman cycle. | |
|---|---|
| **Module-V** | **ELEMENTS OF HEAT TRANSFER AND GAS COMPRESSORS** |
| Basic concepts of Heat Transfer: Conduction, Convection and Radiation, Heat Exchangers, Types of Heat Exchangers. Basic concepts of: Gas Compressors, Air Compressors, Single-Stage Reciprocating Air Compressor, Multi-Stage Compression, Volumetric Efficiency, Air Motors, Rotary Compressors | |
| **Text Books:** | |
| 1. P. K. Nag, “Engineering Thermodynamics”, Tata McGraw Hill Publishers, 5th Edition, 2013.<br>2. Yunus Cengel, Michael A. Boles, “Thermodynamics-An Engineering Approach”, Tata McGraw Hill publishers, 8th Edition, 2014. | |
| **Reference Books:** | |
| 1. J. B. Jones, R. E. Dugan, “Engineering Thermodynamics”, Prentice Hall of India Learning.<br>2. Y. V. C. Rao, “An Introduction to Thermodynamics”, Universities Press.<br>3. K. Ramakrishna, “Engineering Thermodynamics”, Anuradha Publishers.<br>4. J.P Holman, “Thermodynamics” Tata McGraw Hill Publishers. | |

# Module I

## Basic concepts and first law of thermodynamics

Thermodynamics is the branch of physics that deals with heat and temperature, and their relation to energy, work, radiation, and properties of matter. The behavior of these quantities is governed by the four laws of thermodynamics which convey a quantitative description using measurable macroscopic physical quantities, but may be explained in terms of microscopic constituents by statistical mechanics. Thermodynamics applies to a wide variety of topics in science and engineering, especially physical chemistry, chemical engineering and mechanical engineering, but also in fields as complex as meteorology.

### 1.1 Macroscopic Approach:

In this approach a certain quantity of matter is considered without taking into account the events occurring at molecular level. In other words this approach to thermodynamics is concerned with gross or overall behavior. This is known as classical thermodynamics. The analysis of macroscopic system requires simple mathematical formula. The values of the properties of the system are their average values. For examples consider a sample of gas in a closed container. The pressure of the gas is the average value of the pressure exerted by millions of individual molecules.

### 1.2 Microscopic Approach:

The approach considers that the system is made up of a very large number of discrete particles known as molecules. These molecules have different velocities are energies. The values of these energies are constantly changing with time. This approach to thermodynamics, which is concerned directly with the structure of the matter, is known as statistical thermodynamics. The behavior of the system is found by using statistical methods, as the number of molecules is very large. So advanced statistical and mathematical methods are needed to explain the changes in the system. The properties like velocity, momentum, impulse, kinetic energy and instruments cannot easily measure force of impact etc. that describe the molecule. Large numbers of variables are needed to describe a system. So the approach is complicated.

Thermodynamic system (or simply ‘system’) is a definite macroscopic region or space in the universe, in which one or more thermodynamic processes take place. Everything external to a thermodynamic system is called surroundings.

System and surroundings are separated by a definite border called boundary. System, surroundings and boundary constitute the universe.

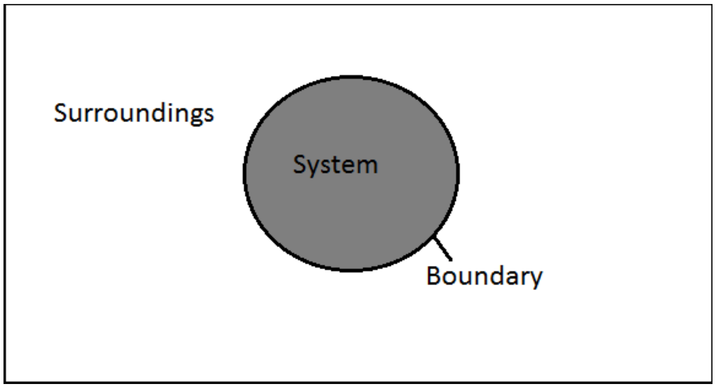


Fig .1.1 System, surroundings and boundary

### 1.3 Types of Thermodynamic System:

Thermodynamic systems can be broadly classified into three types. They are:

Open System

Closed System

Isolated System

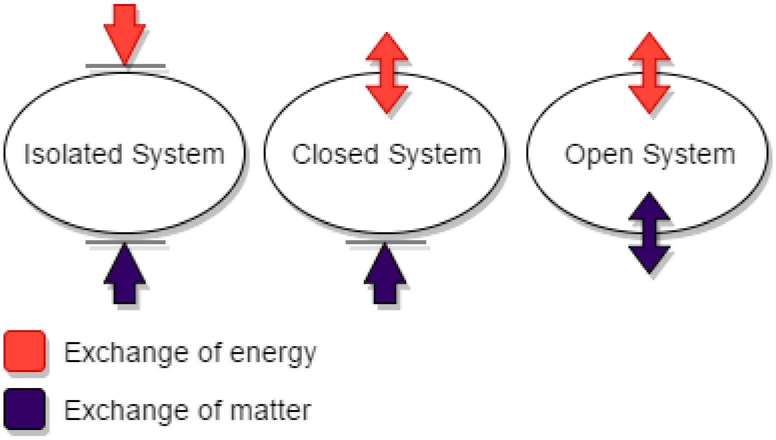


Fig .1.2 Types of energy

### 1.3.1. Open System:

An open system is a thermodynamic system which allows both mass and energy to flow in and out of it, across its boundary. The image below illustrates open system. Example: Water heated in an open container – Here, heat is the energy transferred, water is the mass transferred and container is the thermodynamic system. Both heat and water can pass in and out of the container.

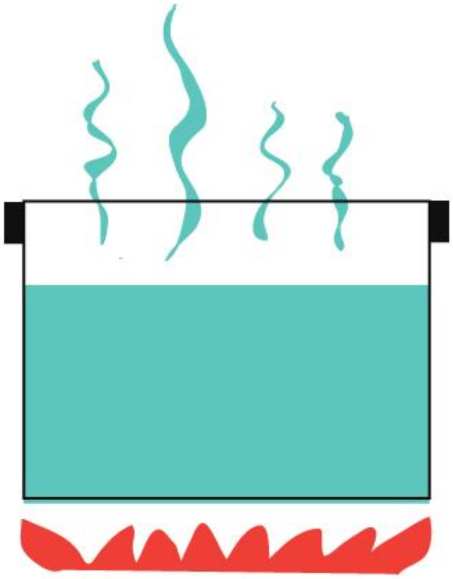


Fig .1.3 Example of open system

**1.3.2. Closed System:**

A closed system allows only energy (heat and work) to pass in and out of it. It does not allow mass transfer across its boundary. Example: Water heated in a closed vessel – Here only heat energy can pass in and out of the vessel

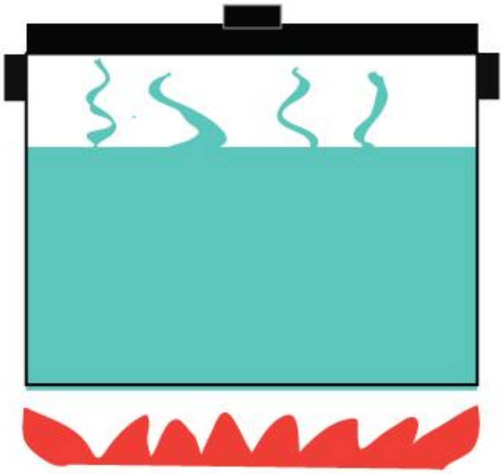


Fig .1.4 Example of closed system

### 1.3.3. Isolated System:

An isolated system does not interact with its surroundings. It does not allow both mass and energy transfer across its boundary. It is more restrictive. In reality, complete isolated systems do not exist. However, some systems behave like an isolated system for a finite period of time. A thermoflask is an isolated system

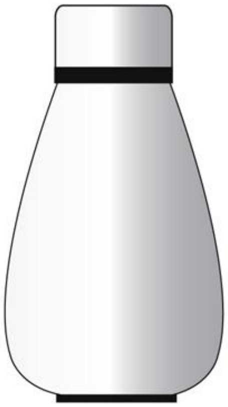


Fig .1.5 Example of isolated system

## 1.4 Thermodynamic process

Defined by change in a system, a thermodynamic process is a passage of a thermodynamic system from an initial to a final state of thermodynamic equilibrium. The initial and final states are the defining elements of the process. The actual course of the process is not the primary concern, and often is ignored. A state of thermodynamic equilibrium endures unchangingly unless it is interrupted by a thermodynamic operation that initiates a thermodynamic process. The equilibrium states are each respectively fully specified by a suitable set of thermodynamic state variables, that depend only on the current state of the system, not the path taken by the processes that produce that state. In general, during the actual course of a thermodynamic process, the system passes through physical states which are not describable as thermodynamic states, because they are far from internal thermodynamic equilibrium. Such a process may therefore be admitted for non-equilibrium thermodynamics, but not be admitted for equilibrium thermodynamics, which primarily aims to describe the continuous passage along the path, at definite rates of progress.

Though not so in general, it is, however, possible, that a process may take place slowly or smoothly enough to allow its description to be usefully approximated by a continuous path of equilibrium thermodynamic states. Then it may be approximately described by a process function that does depend on the path. Such a process may be idealized as a "quasi-static" process, which is infinitely slow, and which is really a theoretical exercise in differential geometry, as opposed to an actually possible physical process; in this idealized case, the calculation may be exact, though the process does not actually occur in nature. Such idealized processes are useful in the theory of thermodynamics.

**1.5 Thermodynamic processes:** Classical thermodynamics considers three main kinds of thermodynamic process: change in a system, cycles in a system, and flow processes.

Defined by change in a system, a thermodynamic process is a passage of a thermodynamic system from an initial to a final state of thermodynamic equilibrium. The initial and final states are the defining elements of the process. The actual course of the process is not the primary concern, and thus often is ignored. This is the customary default meaning of the term 'thermodynamic process'. In general, during the actual course of a thermodynamic process, the system passes through physical states which are not describable as thermodynamic states, because they are far from internal thermodynamic equilibrium. Such processes are useful for thermodynamic theory.

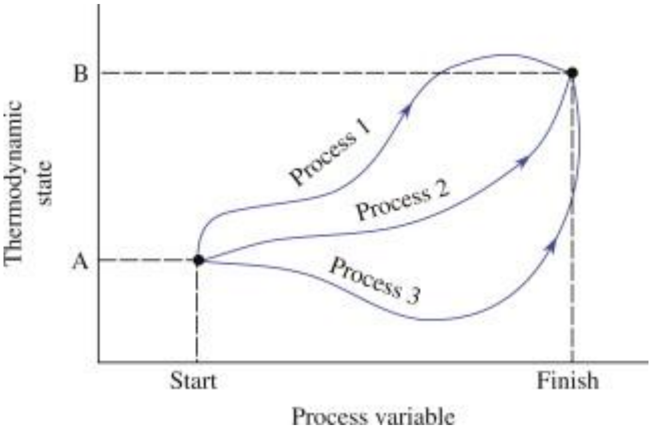


Fig .1.6 Thermodynamic processes

Defined by a cycle of transfers into and out of a system, a cyclic process is described by the quantities transferred in the several stages of the cycle, which recur unchangingly. The descriptions of the staged states of the system are not the primary concern. Cyclic processes were important conceptual devices in the early days of thermo dynamical investigation, while the concept of the thermodynamic state variable was being developed.

Defined by flows through a system, a flow process is a steady state of flows into and out of a vessel with definite wall properties. The internal state of the vessel contents is not the primary concern. The quantities of primary concern describe the states of the inflow and the outflow materials, and, on the side, the transfers of heat, work, and kinetic and potential energies for the vessel. Flow processes are of interest in engineering

**1.5.1 Cyclic process**

Defined by a cycle of transfers into and out of a system, a cyclic process is described by the quantities transferred in the several stages of the cycle. The descriptions of the staged states of the system may be of little or even no interest. A cycle is a sequence of a small number of thermodynamic processes that indefinitely often repeatedly returns the system to its original state. For this, the staged states themselves are not necessarily described, because it is the transfers that are of interest. It is reasoned that if the cycle can be repeated indefinitely often, then it can be assumed that the states are recurrently unchanged. The condition of the system during the several staged processes may be of even less interest than is the precise nature of the recurrent states. If, however, the several staged processes are idealized and quasi-static, then the cycle is described by a path through a continuous progression of equilibrium states.

### 1.5.2 Flow process

Defined by flows through a system, a flow process is a steady state of flow into and out of a vessel with definite wall properties. The internal state of the vessel contents is not the primary concern. The quantities of primary concern describe the states of the inflow and the outflow materials, and, on the side, the transfers of heat, work, and kinetic and potential energies for the vessel. The states of the inflow and outflow materials consist of their internal states, and of their kinetic and potential energies as whole bodies. Very often, the quantities that describe the internal states of the input and output materials are estimated on the assumption that they are bodies in their own states of internal thermodynamic equilibrium. Because rapid reactions are permitted, the thermodynamic treatment may be approximate, not exact.

**1.6 Homogeneous system** is defined as the one whose chemical composition and physical properties are the same in all parts of the system, or change continuously from one point to another. A homogeneous system can be exemplified by imagining a column of atmospheric air, which is a mixture of a number of gases, mainly nitrogen and oxygen. In a system of this kind, acted upon by the force of gravity, both the composition of the system and its physical properties will continuously change from one point to another.

**1.7 heterogeneous system** is denned as one consisting of two or more homogeneous bodies. The homogeneous bodies of a heterogeneous system are referred to as phases. Each phase is separated from other phases by interfaces, or boundaries, and in passing over such a boundary the chemical composition of the substance or its physical properties abruptly change. This phase boundary must not be regarded as a mathematical surface but as a thin layer separating the phases, a layer where the properties of one phase pass, or turn, rapidly into the properties of the other phase.

### 1.8 Thermodynamic equilibrium:

State and Equilibrium At a given state, all the properties of a system have fixed values. Thus, if the value of even one property changes, the state will change to different one. In an equilibrium state, there are no unbalanced potentials (or driving forces) within the system. A system in equilibrium experiences no changes when it is isolated from its surroundings.

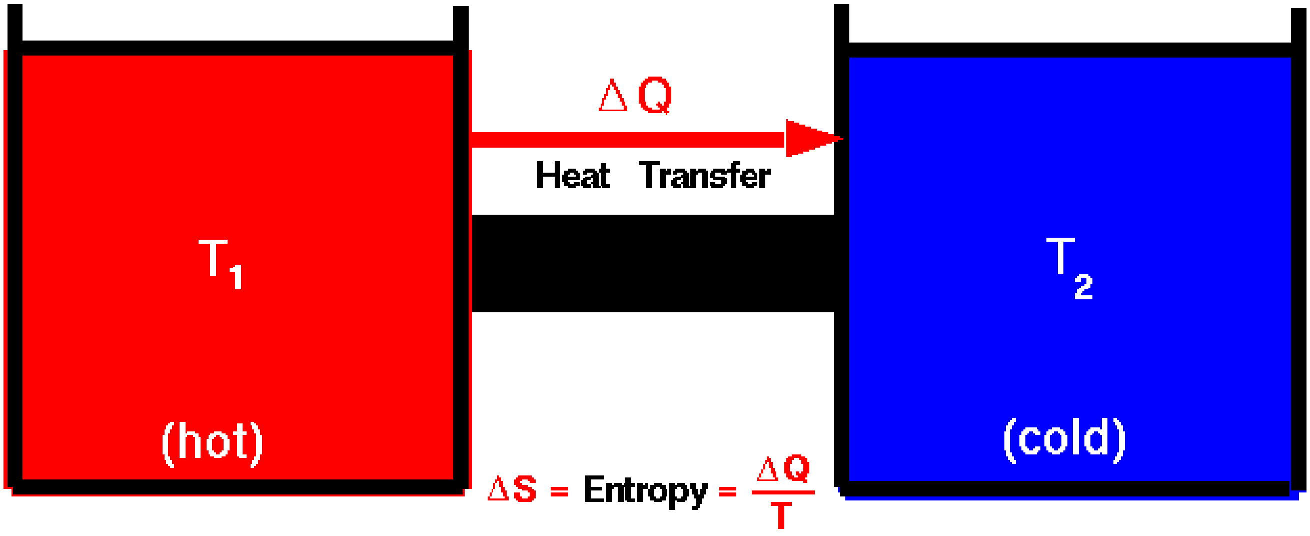


Fig .1.7 Entropy

**1.8.1 Thermal equilibrium:** when the temperature is the same throughout the entire system.

**1.8.2 Mechanical equilibrium:** when there is no change in pressure at any point of the system. However, the pressure may vary within the system due to gravitational effects.

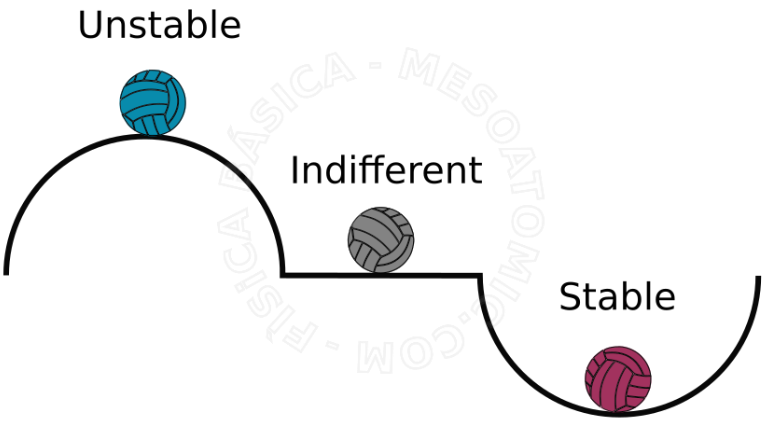


Fig .1.8 Types of equillibrium

**1.8.3 Phase equilibrium:** in a two phase system, when the mass of each phase reaches an equilibrium level.

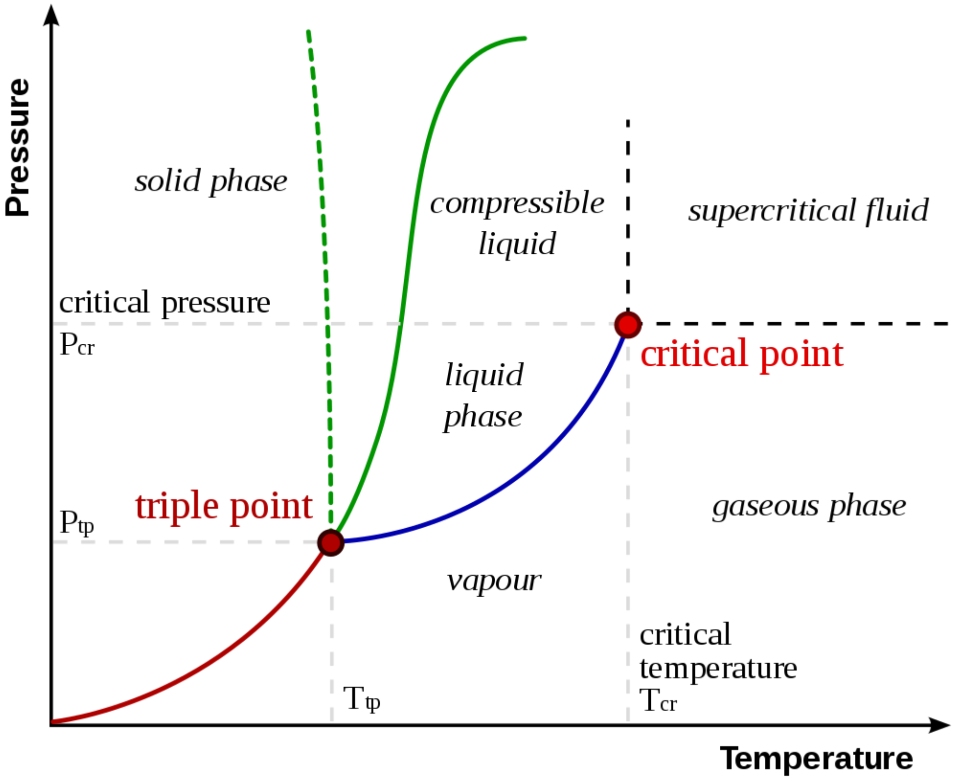


Fig .1.9 Phases of substance

**1.8.4 Chemical equilibrium:** when the chemical composition of a system does not change with time, i.e., no chemical reactions occur.

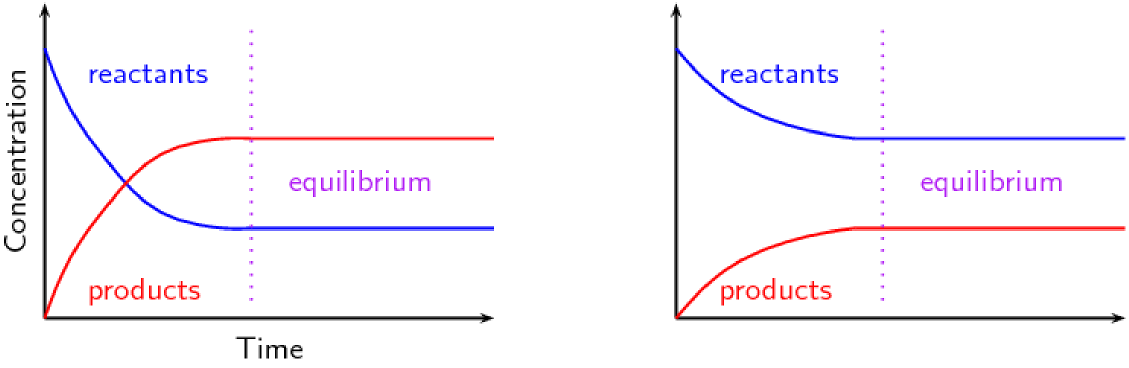


Fig .1.10 Chemical equillirium

## 1.9 Causes of irreversibility:

There are basically two reasons of irreversibility of a thermodynamic process:

1. Lack of thermodynamic equilibrium during the process
2. Involvement of dissipative effect during the process

The second cause of irreversibility of a process i.e. involvement of dissipative effect during the process Involvement of dissipative effect during the process will also be a cause of irreversibility of a process. There are following various types of dissipative effect during a process:

1. Mechanical friction.
2. Magnetic hysteresis.
3. Electrical resistance.
4. Viscosity or fluid viscosity.

Therefore if there is no involvement of dissipative effect during a process and there is no lack of thermodynamic equilibrium then process will be considered as reversible process but we must note it here that each and every natural process will have involvement of dissipative effect and lack of thermodynamic equilibrium.

## 1.10 Zeroth law of thermodynamics:

The zeroth law of thermodynamics states that if two thermodynamic systems are each in thermal equilibrium with a third one, then they are in thermal equilibrium with each other. Accordingly, thermal equilibrium between systems is a transitive relation.

Two systems are said to be in the relation of thermal equilibrium if they are linked by a wall permeable only to heat and they do not change over time. As a convenience of language, systems are sometimes also said to be in a relation of thermal equilibrium if they are not linked so as to be able to transfer heat to each other, but would still not do so (even) if they were connected by a wall permeable only to heat.

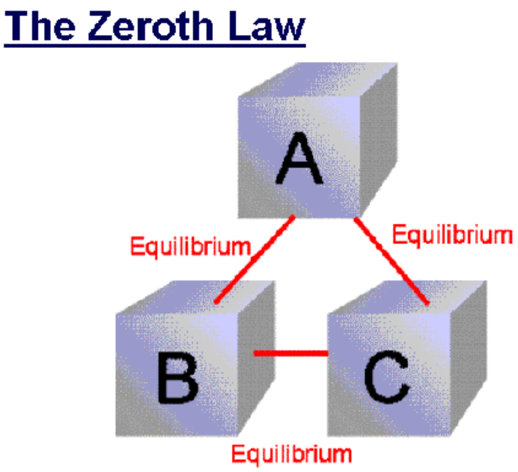


Fig .1.11 Zeroth Law

The physical meaning is expressed by Maxwell in the words: "All heat is of the same kind". Another statement of the law is "All diathermal walls are equivalent".

**1.11 Principles of thermometry:**

Any property of a material which changes with temperature can be used to indicate or measure temperature. For example, the expansion of solids, liquids and gases are all used to make thermometers.

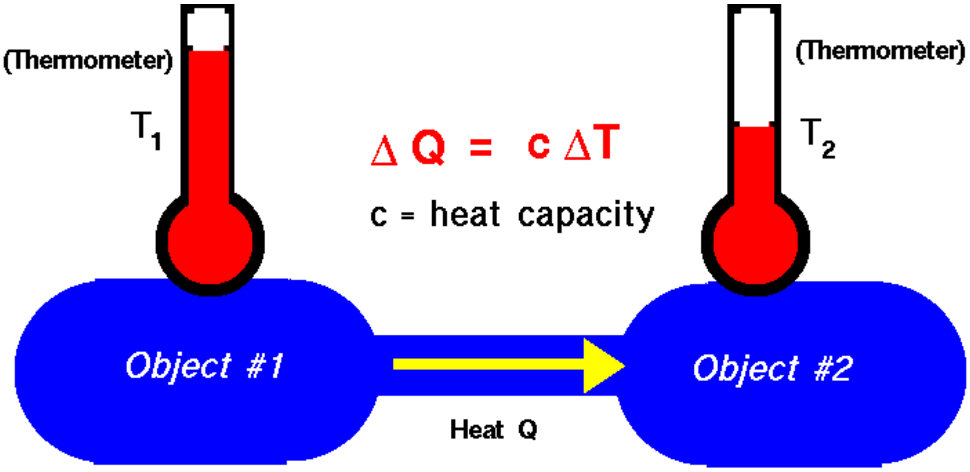


Fig .1.12 Heat transfer

**1.11.1 Upper and Lower Fixed Points**

To set a temperature scale on a thermometer we chose two easily obtainable temperatures, the temperature at melting point and at the boiling point, these two temperatures and called the lower and upper fixed point. On the Celsius scale the lower fixed point is the temperature of melting pure ice, also known as the ice point. The ice point is fixed at $0^{o}$ C. The upper fixed point is the temperature of the steam just above boiling water and is known as the steam point. The steam point is $100^{o}$ C. We can then divide the temperature range between the two fixed points into number of equal parts called degrees.

Absolute zero is the lowest temperature possible, it is -273 oC or 0 K (kelvin). On the Kelvin scale or the absolute scale, one division is called the Kelvin and is exactly equal to one division or degree on the Celsius scale. Therefore the following holds true

Absolute zero: 0 K or $-273^{o}$ C
Ice point : 273 K or $0^{o}$C
Steam point : 373 K or $+373^{o}$C

To convert degree Celcius to Kelvin, use the following equation: Kelvin = degree celcius + 273

$$^{\circ}F = 1.8^{\circ}C + 32 \qquad K = {}^{\circ}C + 273.15 \qquad \Delta^{\circ}C = 1.8\Delta^{\circ}F$$

$$^{\circ}C = \frac{^{\circ}F - 32}{1.8} \qquad ^{\circ}R = {}^{\circ}F + 460 \qquad \Delta K = 1.8\Delta^{\circ}R$$

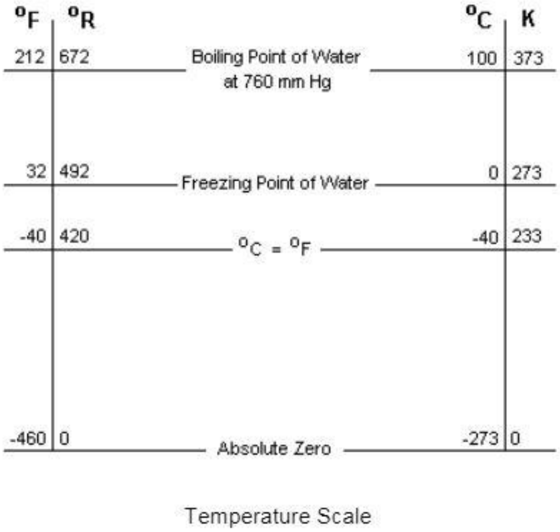


Fig .1.13 Temperature scales

### 1.12 Types of Thermometers

#### 1.12.1 Thermocouple

If two different metals are joined in an electric circuit and one wire junction is cold and the other is hot, a small electric current is generated in the circuit. The current increases as the temperature difference between the two junctions increases. So if one junction is kept at a fixed temperature such as 0 $^{o}$C, the other junction can be used as a small probe to measure temperatures greater than 0 $^{o}$C.

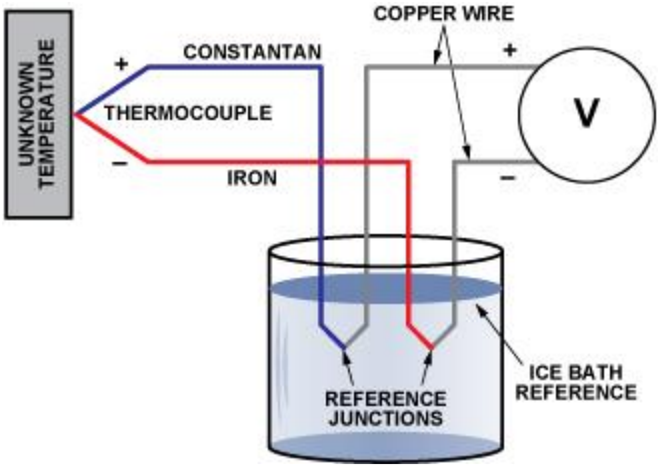


Fig .1.15 Thermocouple

The main advantages of the thermocouple thermometers are:

The wire junction can be very small and needs very little heat to warm it up. This means that it responds very quickly to temperature changes and that it can be used in very small or precise locations.

The output of the thermometer is an electrical signal which can be used to operate electrical equipment capable of giving warning of sudden temperature changes or of keeping continuous records of temperatures.

By choosing particular pairs of metal temperatures of up about 1500oC can be measured.

### 1.12.2 Liquid in glass thermometer

The mercury in glass or alcohol in glass thermometer use the cubical expansion of a liquid to measure the temperature.

Design features the liquid is contained in a thin-walled glass bulb to help conduction of heat through the glass to the liquidthe amount of liquid is small if a quick response is needed; because a small quantity takes less time to warm up.The fine tube should be uniform to give even expansion along itMaking the tube finer increases the sensitivity of the thermometer.

The space above the liquid is evacuated during manufacture to prevent a high pressure of the trapped air when the liquid expands a lot.

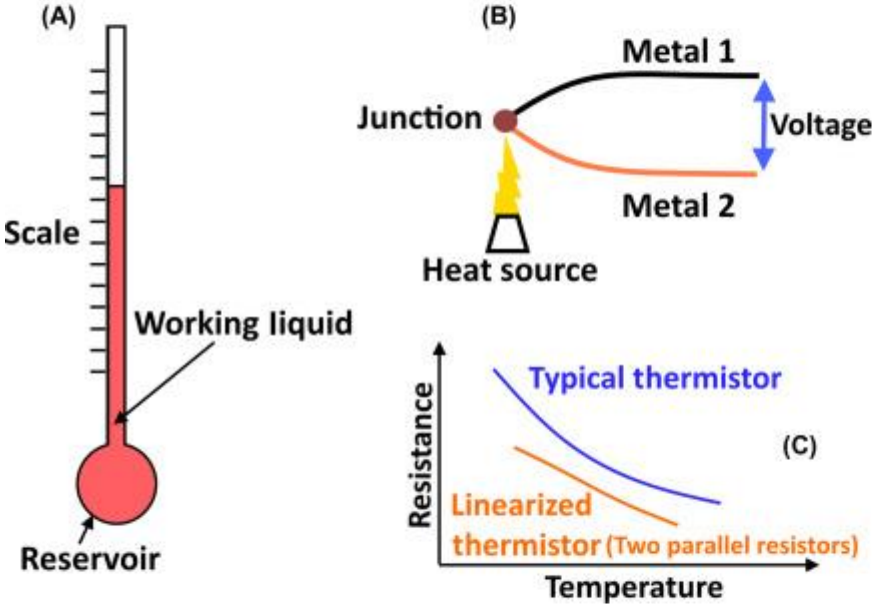


Fig .1.16 Thermometer

The maximum ranges of liquid in glass thermometers depend on the choice of liquid. Mercury is suitable for most purposes but alcohol can be used at a lower temperature before it freezes.

Mercury thermometers are fairly cheap, very easy to use and are portable, but they cannot be used to record temperatures automatically or electrically.

Clinical thermometers have a constriction just above the bulb so that it prevents the mercury in the stem from flowing back into the bulb before a reading is taken. They have a shorter range (35 $^{o}$C - 42 $^{o}$C) compared to a laboratory thermometer (which may range from -10 $^{o}$C to 110 $^{o}$C) because it is not necessary to have a thermometer to measure a human temperature of 80 $^{o}$C.

### 1.12.3 Joules Experiment:

James P. Joule placed known amounts of water, oil, and mercury in an insulated container and agitated the fluid with a rotating stirrer. The amounts of work done on the fluid by the stirrer were accurately measured, and the temperature changes of the fluid were carefully noted. He found for each fluid that a fixed amount of work was required per unit mass for every degree of temperature rise caused by the stirring, and that the original temperature of the fluid could be restored by the transfer of heat through simple contact with a cooler object. In this experiment you can conclude there is a relationship between heat and work or in other word heat is a form of energy.

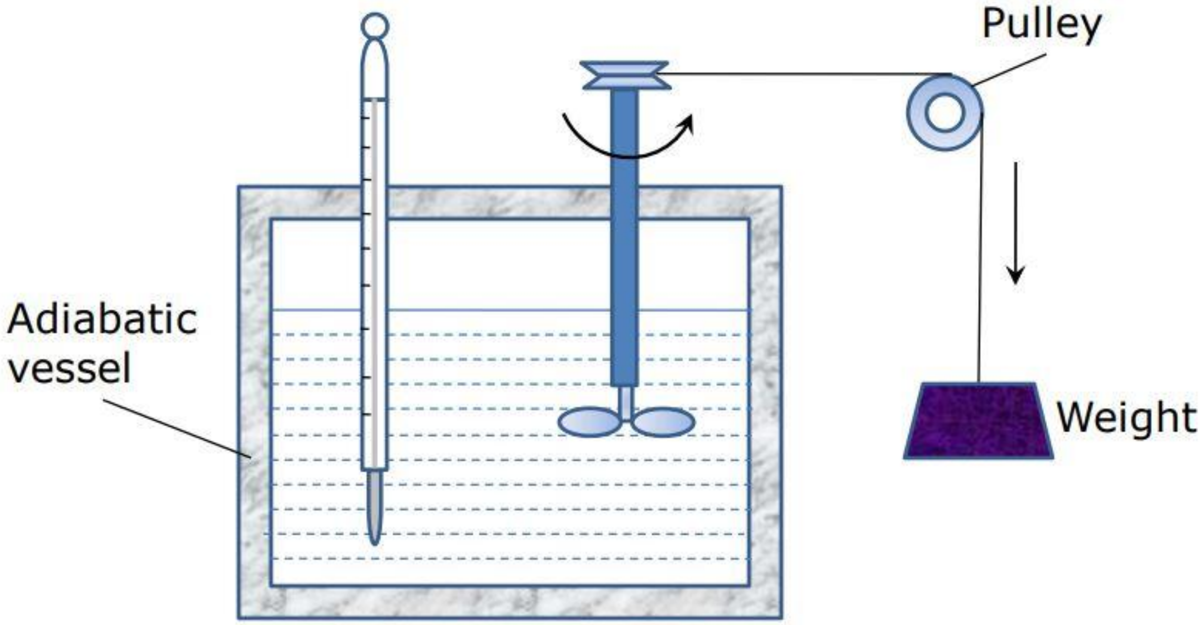


Fig. 1.17 Joules experiment

If the cycle involves many more heat and work quantities, the same result will be found. Expressed algebraically.

$$(\Sigma W)_{\text{cycle}} = J\,(\Sigma Q)_{\text{cycle}}$$

If *J* is the Joules equivalent. This is also expressed in the form

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

**1.13 Constant volume gas thermometer:**

Thermometers are working examples of the zeroth law of thermodynamics. The significance of constant volume gas thermometers is that they are used to calibrate other thermometers.

**1.13.1 Construction**

A constant volume gas thermometer is composed of a bulb filled with a fixed amount of a dilute gas that is attached to a mercury manometer. A manometer is a device used to measure pressure.

The mercury manometer has a column partially filled with mercury that is connected to a flexible tube that has another partially filled column of mercury, called a reservoir, attached to the other end. The height of the mercury in the first column is set to a reference point or pressure P that it must stay at, while the mercury in the reservoir is allowed to move up and down in relation to a scale or ruler. From the Law of Gay-Lussac, we know that when the temperature of an ideal gas increases, that there is a corresponding increase in pressure. Conversely, when the temperature decreases, so does the pressure. Constant volume gas thermometers operate on the same principle, with the restrictions that the gas is at low pressure and the temperature of it is well above that of liquefaction.

### 1.13.2 Operation

The gas bulb is inserted into a bath or place we wish to find the temperature of, such as water. When the temperature increases or decreases, the volume also increases or decreases as well as the pressure, as we have seen in Charles' Law and the aforementioned Gay-Lussac's Law. The pressure of the mercury also changes such that it begins to move up or down and thus away from the reference point.

To stop this movement, which will also stop the gas from expanding, the reservoir at the other end is physically lifted up or down, and the ensuing new pressure at this height is measured. The difference between the reference and reservoir heights gives the final pressure P, which is then used to calculate the temperature.

### 1.14 First Law of Thermodynamics

The first law of thermodynamics states that the energy cannot be created nor destroyed it can only be changed from one form to another. Another name for this law is the law of conservation of energy. This means that the total energy of a system plus its surroundings is constant and does not change. Energy can, however, be transferred in or out of the system and to or from the surroundings through work or heat.

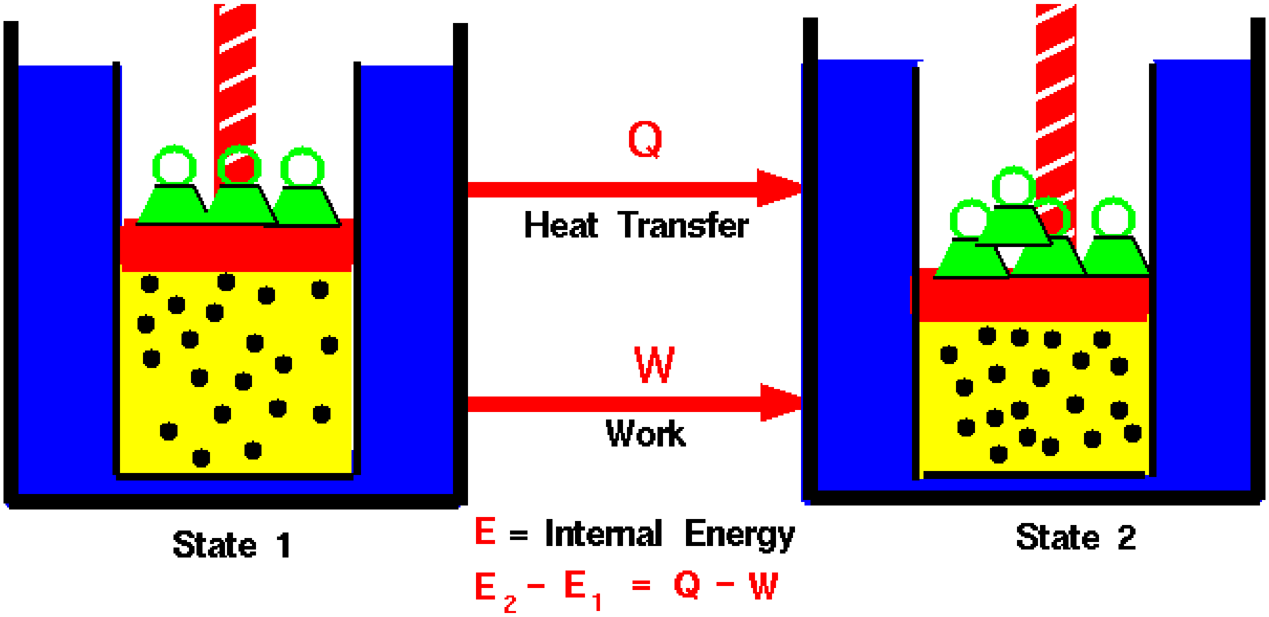


Fig .1.18 Internal energy

### 1.14.1 Conservation of Energy

Energy may be defined as the capacity to do work or to cause heat to flow. In the system term, energy may be defined as the property of a system that changes by an amount equal to the work or heat transferred across the system boundary. The total amount of energy that a system contains cannot be determined. We are accustomed therefore to measuring energy above some arbitrary datum. Energy is scalar quantity with no direction relative to the frame of reference. It can exist in different forms, in principle, all forms of energy are mutually convertible. There is a transfer or flow of energy when a change in form takes place.

First Corollary of the First Law

The first corollary of the first law of thermodynamics is the application of the conservation of energy to a closed system.

Final Energy – Initial Energy = Energy added to the system.

$E2 - E1 = Q + (-W)$

Where heat has been added (+Q) and work has been done to the system (-W)

$(PE2 + KE2 + U2) - (PE1 + KE1 + U1) = Q + (-W)$

The work described in the systems the work non-flow

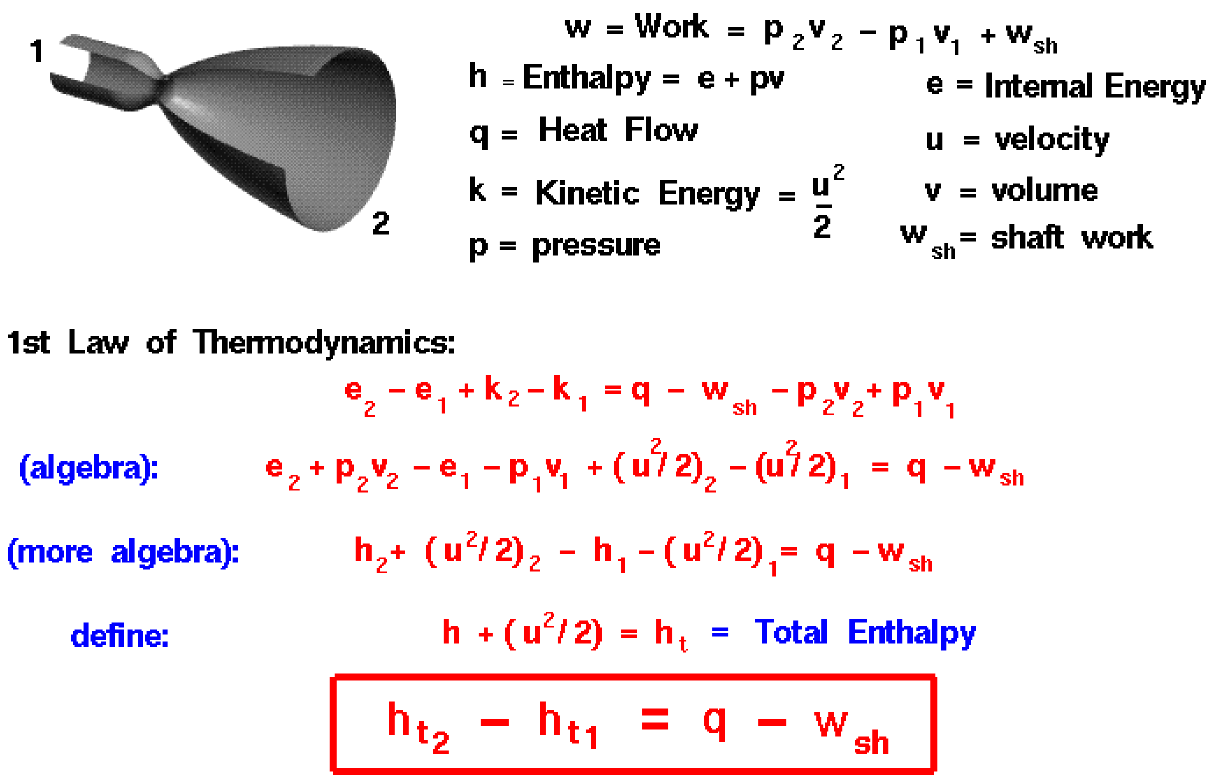
$Q = \Delta PE + \Delta KE + \Delta U + W_{NF}$

Since additional mass is not allowed to enter and leave the system

$\Delta PE = \Delta KE = 0,$

$Q = \Delta U + W_{NF}$

$\partial Q = dU + \partial W_{NF}$ (Non-Flow Energy Equation)



$w$ = Work = $p_2 v_2 - p_1 v_1 + w_{sh}$

$h$ = Enthalpy = $e + pv$

$e$ = Internal Energy

$q$ = Heat Flow

$u$ = velocity

$k$ = Kinetic Energy = $\frac{u^2}{2}$

$v$ = volume

$p$ = pressure

$w_{sh}$ = shaft work

1st Law of Thermodynamics:

$$e_2 - e_1 + k_2 - k_1 = q - w_{sh} - p_2 v_2 + p_1 v_1$$

(algebra): $e_2 + p_2 v_2 - e_1 - p_1 v_1 + (u^2/2)_2 - (u^2/2)_1 = q - w_{sh}$

(more algebra): $h_2 + (u^2/2)_2 - h_1 - (u^2/2)_1 = q - w_{sh}$

define: $h + (u^2/2) = h_t$ = Total Enthalpy

$$\boxed{h_{t_2} - h_{t_1} = q - w_{sh}}$$

Fig .1.19 Thrust equation

**Second Corollary of the First Law**

The second corollary of the first law of thermodynamics is the application of the conservation of energy to the open system.

E2 – E1 = Q + (-W)

(PE2 + KE2 + U2 + Wf2) - (PE1 + KE1 + U1 + $W_{f1}$) = Q + (-W)

the work describe in this system is the work steady flow

(PE2 + KE2 + H2) - (PE1 + KE1 + H1) = Q – $W_{SF}$

Q = ΔPE + ΔKE + ΔH + $W_{SF}$

(Steady Flow Energy Equation)

If ΔPE = ΔKE is negligible

$Q = \Delta H + W_{SF}$

$\partial Q = dH + \partial W_{SF}$

Combining the NFEE and SFEE,

$\partial Q = dU + \partial W_{NF} = dH + \partial W_{SF}$

$\Delta H = \Delta U + \Delta(PV)\ (\partial U + \partial(PV)) + \partial W_{SF} = \partial U + \partial W_{NF}$
$\partial U + P\partial V + V\partial P + \partial W_{SF} = \partial U + \partial W_{NF}$

$P\partial V + V\partial P + \partial W_{SF} = \partial W_{NF}$

$$W_{SF} = -\int_{P_1}^{P_2} VdP$$

**1.15 corollaries first law applied to a process**

Work done in any adiabatic ($Q = 0$) process is a function of state. We can write the first law, setting the heat transfer term equal to zero, as

$$\Delta U = \cancelto{0}{Q} - W.$$

Since $\Delta U$ depends only on the state change, now $W$ can be found as a function of the state change.

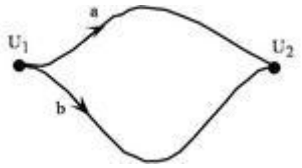


Figure 1.20 The change in energy between two states is not path dependent.

For a cyclic process heat and work transfers are numerically equal

Figure 1.21 Since energy is a function of state only, any process that returns a system to its original state leaves its energy unchanged.

therefore

$U_{final} = U_{initial}$

$\triangle U = 0$

And

$Q = W$

Since no power cycle can have a thermal efficiency of 100%, it is of interest to investigate the maximum theoretical efficiency. The maximum theoretical efficiency for systems undergoing power cycles while communicating thermally with two thermal reservoirs at different temperatures is evaluated with reference to the following two corollaries of the second law, called the Carnot corollaries.

1. The thermal efficiency of an irreversible power cycle is always less than the thermal efficiency of a reversible power cycle when each operates between the same two thermal reservoirs.
2. All reversible power cycles operating between the same two thermal reservoirs have the same thermal efficiency.

A cycle is considered reversible when there are no irreversibilities within the system as it undergoes the cycle and heat transfers between the system and reservoirs occur reversibly.

The idea underlying the first Carnot corollary is in agreement with expectations stemming from the discussion of the second law thus far. Namely, the presence of irreversibilities during the execution of a cycle is expected to exact a penalty: If two systems operating between the same reservoirs each receive the same amount of energy QH and one executes a reversible cycle while the other executes an irreversible cycle, it is in accord with intuition that the net work developed by the irreversible cycle will be less, and thus the irreversible cycle has the smaller thermal efficiency.

The second Carnot corollary refers only to reversible cycles. All processes of a reversible cycle are perfectly executed. Accordingly, if two reversible cycles operating between the same reservoirs each receive the same amount of energy QH but one could produce more work than the other, it could only be as a result of more advantageous selections for the substance making up the system (it is conceivable that, say, air might be better than water vapor) or the series of processes making up the cycle (nonflow processes might be preferable to flow processes). This corollary denies both possibilities and indicates that the cycles must have the same efficiency whatever the choices for the working substance or the series of processes.

## MODULE- II

## SECOND LAW OF THERMODYNAMICS

### 2.1 THE LIMITATIONS OF FIRST LAW

- It does not tells us about direction in which heat flows when they are in contact
- It does not tell about the final temperature of two bodies when they are in direct contact.
- It does not tell about the entropy of system.

### 2.2 THERMAL ENERGY RESERVOIR

A thermal energy reservoir is a hypothetical body that can supply or absorb finite amounts of heat without undergoing any change in temperature (large bodies of water, atmospheric air, and two-phase systems Any physical body whose thermal energy capacity is large relative to the amount of energy it supplies or absorbs can be modeled as a reservoir (e.g. the air in a room) A reservoir that supplies energy in the form of heat is called a source, and one that absorbs energy in the form of heat is called a sink

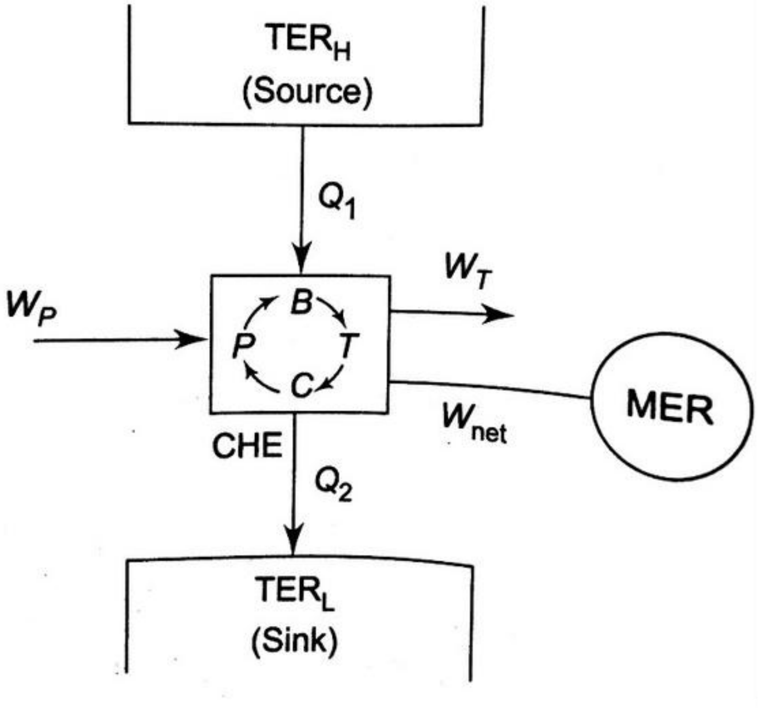


Fig .2.1 TER

## 2.3 HEAT ENGINES

1. They receive heat from a high temperature source (solar energy, oil furnace, nuclear reactor, etc.)

2. They convert part of this heat to work (usually in the form of a rotating shaft)

3. They reject the remaining waste heat to a low-temperature sink (the atmosphere, rivers, etc.)

4. They operate on a cycle

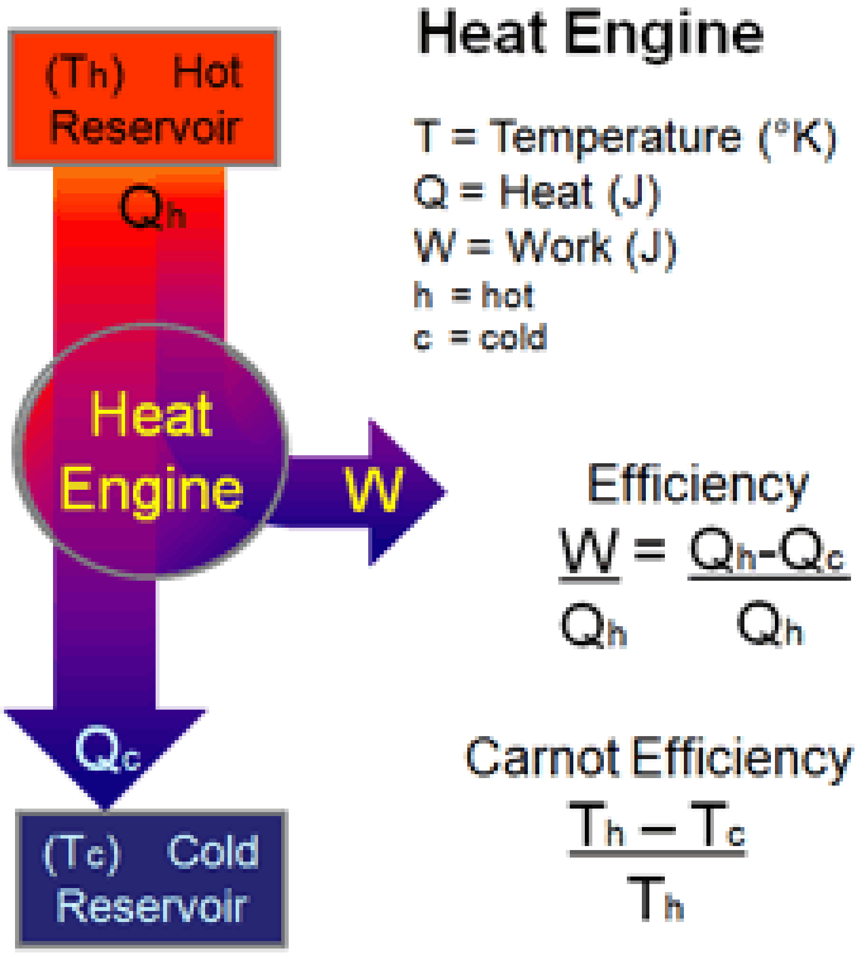


Fig .2.2 Heat engine

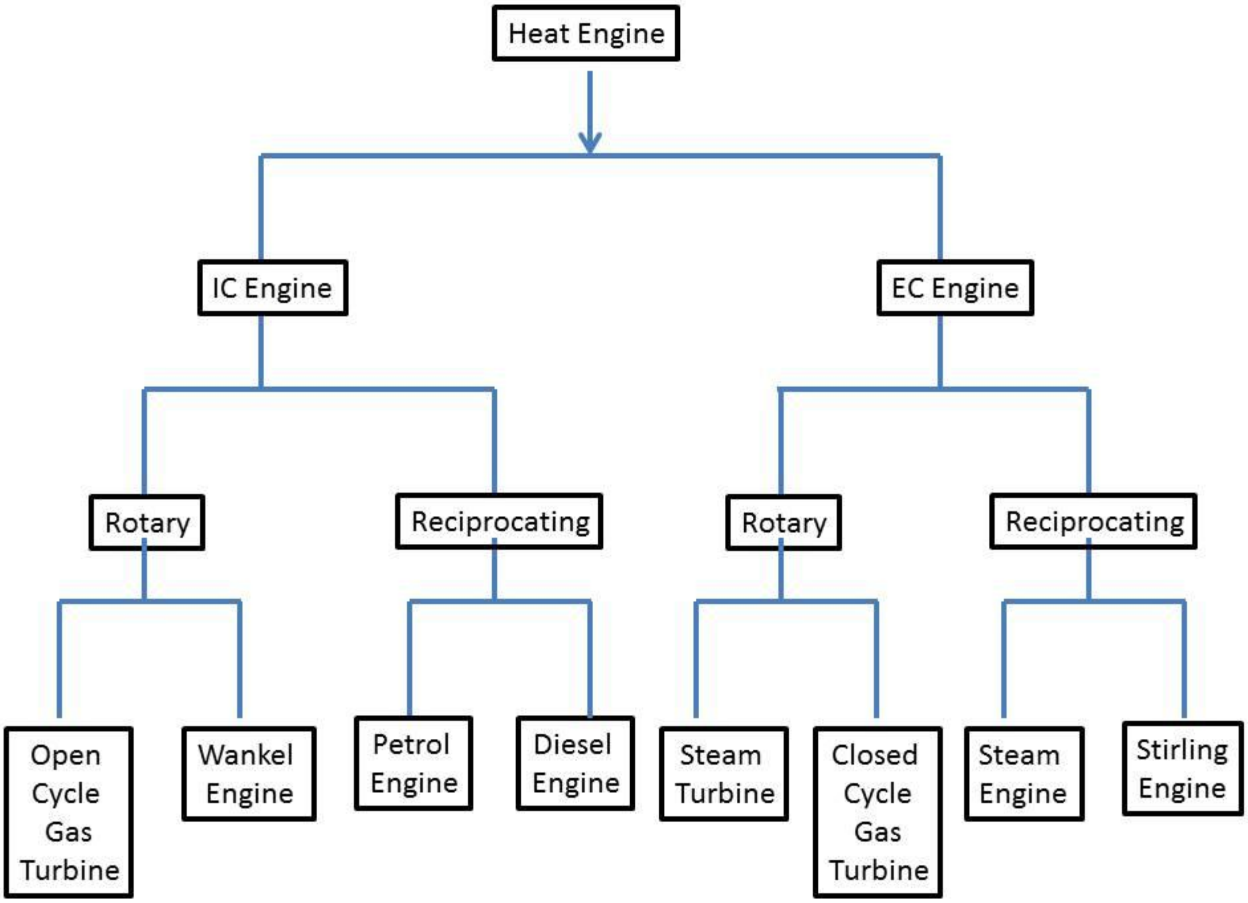


Fig .2.3 Heat engine examples

## 2.4 HEAT PUMP

A **heat pump** is a device that transfers heat energy from a source of heat to what is called a heat sink. Heat pumps move energy in the opposite direction of spontaneous heat transfer, by absorbing heat from a cold space and releasing it to a warmer one. A heat pump uses external power to accomplish the work of transferring energy from the heat source to the heat sink. The most common design of a heat pump involves four main components – a condenser, an expansion valve, an evaporator and a compressor. The heat transfer medium circulated through these components is called refrigerant.

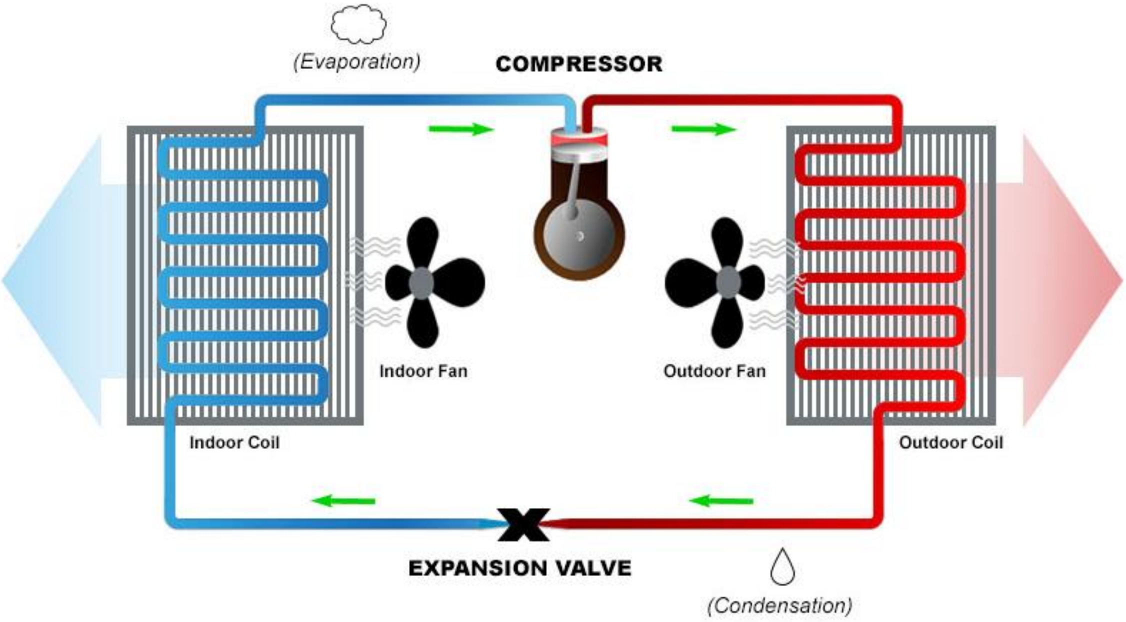


Fig .2.4 Heat pump

For cycles of this type, Qin is the energy transferred by heat into the system undergoing the cycle from the cold body, and $Q_{out}$ is the energy discharged by heat transfer from the system to the hot body. To accomplish these energy transfers requires a net work input, $w_{cycle}$ . The quantities $Q_{in}$, $Q_{out}$ , and $w_{cycle}$ are related by the energy balance, which for refrigeration and heat pump cycles takes the form

$$w_{cycle} = Q_{out} - Q_{in}$$

Since $w_{cycle}$ is positive in this equation, it follows that $Q_{out}$ is greater than $Q_{in}$ .

Although we have treated them as the same to this point, refrigeration and heat pump cycles actually have different objectives. The objective of a refrigeration cycle is to cool a refrigerated space or to maintain the temperature within a dwelling or other building below that of the surroundings. The objective of a heat pump is to maintain the temperature within a dwelling or other building above that of the surroundings or to provide heating for certain industrial processes that occur at elevated temperatures. Since refrigeration and heat pump cycles have different objectives, their performance parameters, called coefficients of performance, are defined differently. These coefficients of performance are considered next.

### 2.4.1 Refrigeration Cycles

The performance of refrigeration cycles can be described as the ratio of the amount of energy received by the system undergoing the cycle from the cold body, Qin, to the net work into the system to accomplish this effect, Wcycle. Thus, the coefficient of performance, β, is

$\beta = \frac{Q_{in}}{Q_{out} - Q_{in}}$(Refrigeration Cycles)

For a household refrigerator, Qout is discharged to the space in which the refrigerator is located. Wcycle is usually provided in the form of electricity to run the motor that drives the refrigerator

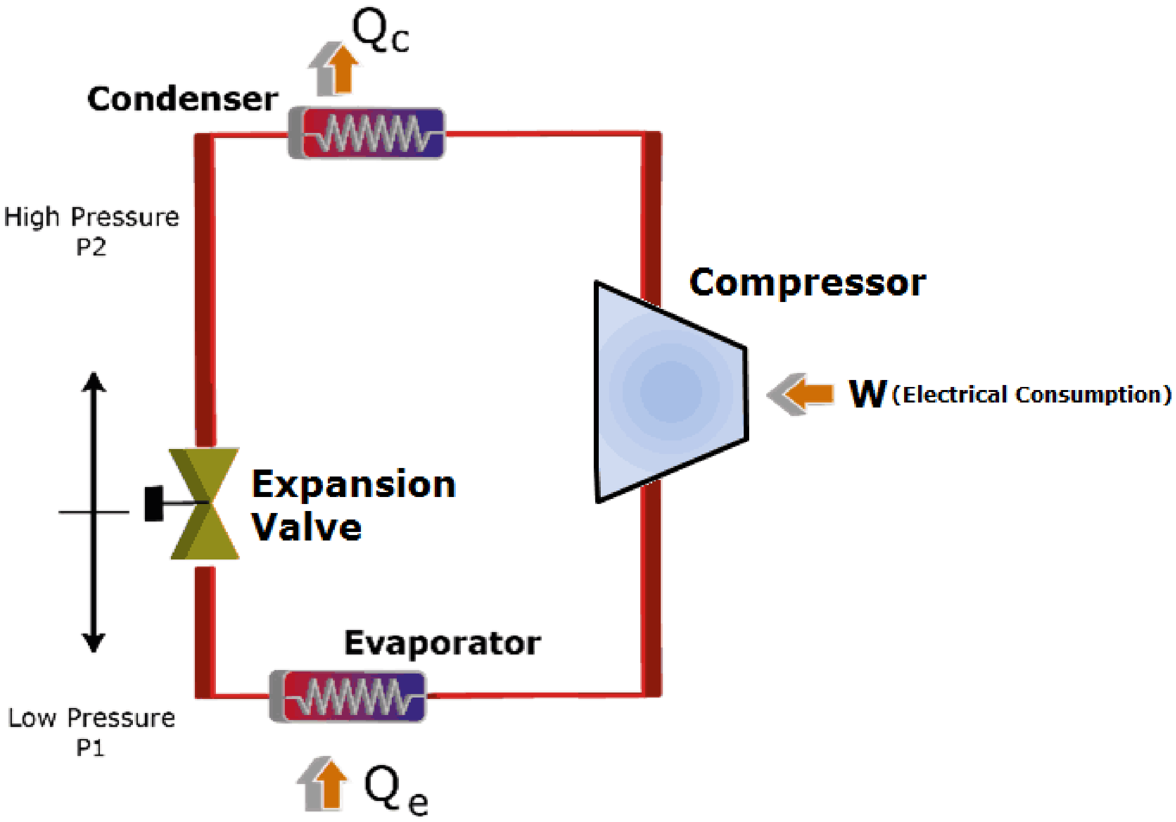


Fig .2.5 Compressor

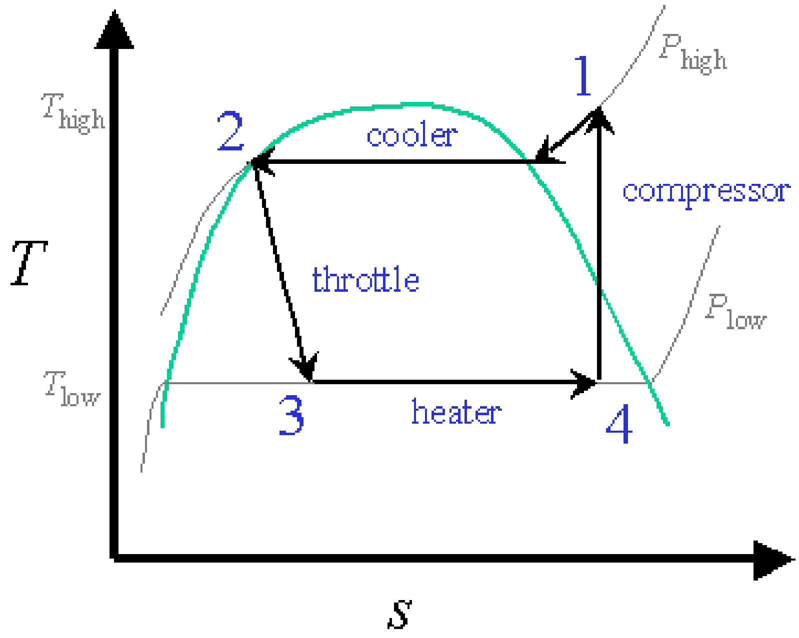


Fig .2.6 T-S Diagram of compressor

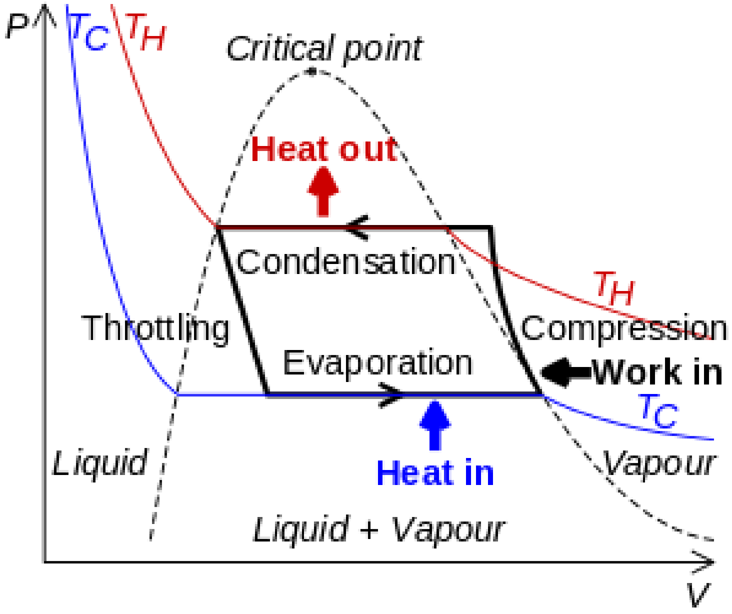


Fig .2.7 P-V Diagram of compressor

### 2.4.2 Heat Pump Cycles

The performance of heat pumps can be described as the ratio of the amount of energy discharged from the system undergoing the cycle to the hot body, Qout, to the net work into the system to accomplish this effect, $W_{cycle}$ . Thus, the coefficient of performance, $\Upsilon$ is

$$\Upsilon = \frac{Q_{out}}{W_{cycle}} \text{(Heat Pump Cycles)}$$

An alternative expression for this coefficient of performance is obtained as

$$\Upsilon = \frac{Q_{out}}{W_{cycle}} \text{(Heat Pump Cycles)}$$

From this equation it can be seen that the value of g is never less than unity. For residential heat pumps, the energy quantity Qin is normally drawn from the surrounding atmosphere, the ground, or a nearby body of water. $W_{cycle}$ is usually provided by electricity.

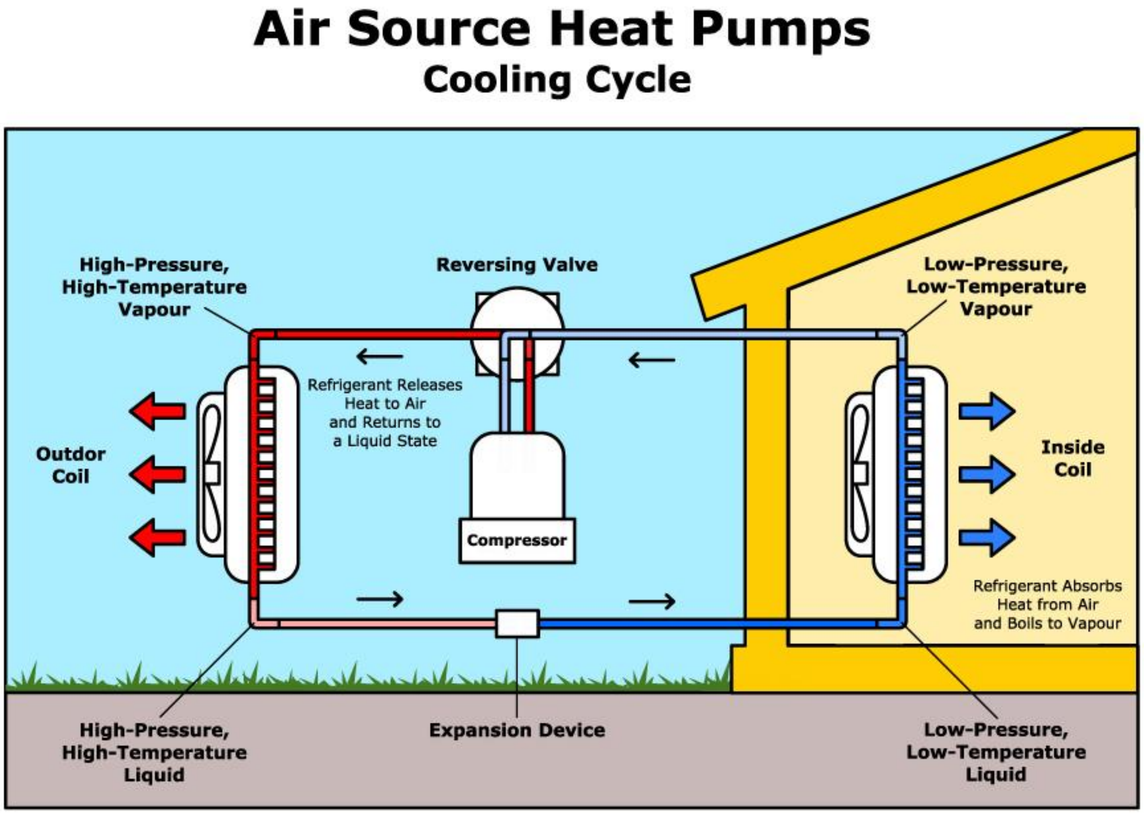


Fig .2.7 Air source heat pumps

The coefficients of performance b and g are defined as ratios of the desired heat transfer effect to the cost in terms of work to accomplish that effect. Based on the definitions, it is desirable thermodynamically that these coefficients have values that are as large as possible. However, coefficients of performance must satisfy restrictions imposed by the second law of thermodynamics.

## 2.5 KELVIN-PLANK STATEMENT

It is impossible for any device that operates on a cycle to receive heat from a single reservoir and produce a net amount of work. No heat engine can have a thermal efficiency of 100 percent. This limitation applies to both the idealized and the actual heat engines.

Before giving the Kelvin–Planck statement of the second law, the concept of a thermal reservoir is introduced. A thermal reservoir, or simply a reservoir, is a special kind of system that always remains at constant temperature even though energy is added or removed by heat transfer. A reservoir is an idealization of course, but such a system can be approximated in a number of ways—by the earth's atmosphere, large bodies of water (lakes, oceans), a large block of copper, and a system consisting of two phases at a specified pressure (while the ratio of the masses of the two phases changes as the system is heated or cooled at constant pressure, the temperature remains constant as long as both phases coexist). Extensive properties of a thermal reservoir such as internal energy can change in interactions with other systems even though the reservoir temperature remains constant.

Having introduced the thermal reservoir concept, we give the Kelvin–Planck statement of the second law:

It is impossible for any system to operate in a thermodynamic cycle and deliver a net amount of energy by work to its surroundings while receiving energy by heat transfer from a single thermal reservoir.

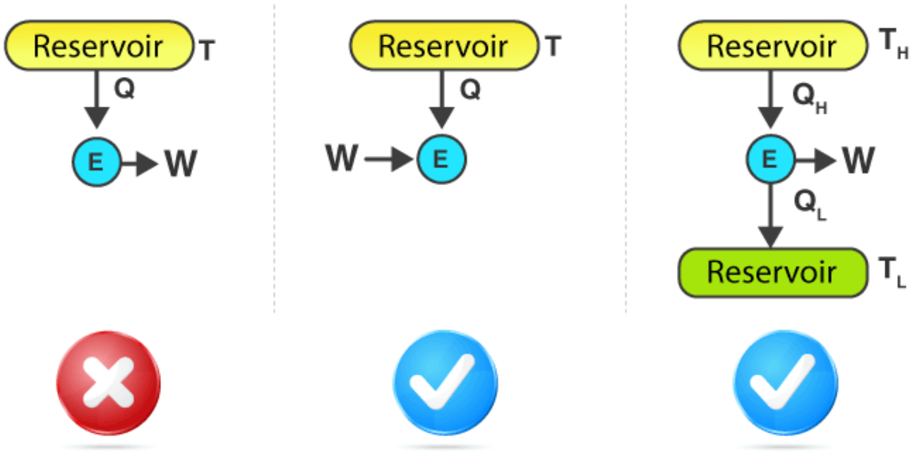


Fig .2.8 Clausius in equality

The Kelvin–Planck statement does not rule out the possibility of a system developing a net amount of work from a heat transfer drawn from a single reservoir. It only denies this possibility if the system undergoes a thermodynamic cycle. The Kelvin–Planck statement can be expressed analytically. To develop this, let us study a system undergoing a cycle while exchanging energy by heat transfer with a single reservoir.

The Kelvin–Planck statement can be expressed analytically. To develop this, let us study a system undergoing a cycle while exchanging energy by heat transfer with a single reservoir, as shown by the adjacent figure. The first and second laws each impose constraints: c A constraint is imposed by the first law on the net work and heat transfer between the system and its surroundings. According to the cycle energy balance

$$w_{cycle} = Q_{cycle}$$

In words, the net work done by (or on) the system undergoing a cycle equals the net heat transfer to (or from) the system. Although the cycle energy balance allows the net work $w_{cycle}$ to be positive or negative, the second law imposes a constraint, as considered next.

According to the Kelvin–Planck statement, a system undergoing a cycle while communicating thermally with a single reservoir cannot deliver a net amount of work to its surroundings: The net work of the cycle cannot be positive. However, the Kelvin–Planck statement does not rule out the possibility that there is a net work transfer of energy to the system during the cycle or that the net work is zero. Thus, the analytical form of the Kelvin–Planck statement is

$$w_{cycle} \leq 0$$

where the words single reservoir are added to emphasize that the system communicates thermally only with a single reservoir as it executes the cycle. we associate the “less than” and “equal to” with the presence and absence of internal irreversibilities, respectively. The concept of irreversibilities is considered

The equivalence of the Clausius and Kelvin–Planck statements can be demonstrated by showing that the violation of each statement implies the violation of the other.

Associating Signs with the Kelvin–Planck Statement Consider a system that undergoes a cycle while exchanging energy by heat transfer with a single reservoir, Work is delivered to, or received from, the pulley–mass assembly located in the surroundings. A flywheel, spring, or some other device also can perform the same function. The pulley–mass assembly, flywheel, or other device to which work is delivered, or from which it is received, is idealized as free of irreversibility’s. The thermal reservoir is also assumed free of irreversibility's. To demonstrate the correspondence of the "equal to" with the absence of irreversibility's, consider a cycle operating for which the equality applies. At the conclusion of one cycle.

The system would necessarily be returned to its initial state. Since $w_{cycle}$ there would be no net change in the elevation of the mass used to store energy in the surroundings.. Thus, the system and all elements of its surroundings would be exactly restored to their respective initial conditions. By definition, such a cycle is reversible. Accordingly, there can be no irreversibility's present within the system or its surroundings. It is left as an exercise to show the converse: If the cycle occurs reversibly, the equality applies (see end-of-chapter Problem. Since a cycle is reversible or irreversible and we have linked the equality with reversible cycles, we conclude the inequality corresponds to the presence of internal irreversibility's. Moreover, the inequality can be interpreted as follows: Net work done on the system per cycle is converted by action of internal irreversibility's to internal energy that is discharged by heat transfer to the thermal reservoir in an amount equal to net work.

## 2.6 CLAUSIUS STATEMENT

It is impossible to construct a device that operates in a cycle and produces no effect other than the transfer of heat from a lower temperature body to a higher-temperature body .Clausius and the Kelvin-Planck statements are two equivalent expressions of the second law of thermodynamics

:It is impossible for any system to operate in such a way that the sole result would be an energy transfer by heat from a cooler to a hotter body. The Clausius statement does not rule out the possibility of transferring energy by heat from a cooler body to a hotter body, for this is exactly what refrigerators and heat pumps accomplish. However, as the words "sole result" in the statement suggest, when a heat transfer from a cooler body to a hotter body occurs, there must be other effects within the system accomplishing the heat transfer, its surroundings, or both. If the system operates in a thermodynamic cycle, its initial state is restored after each cycle, so the only place that must be examined for such other effects is its surroundings.

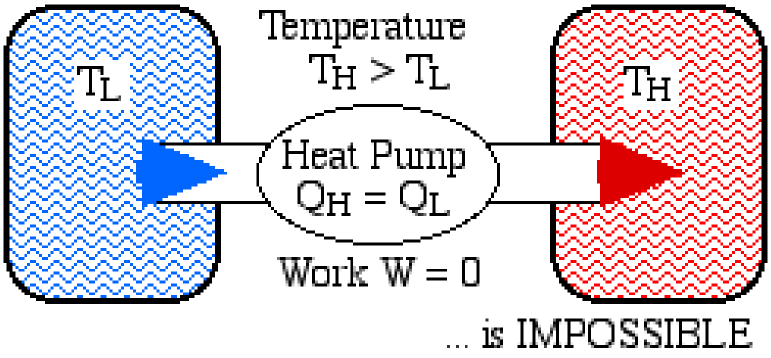


Fig .2.9 Clausius statement

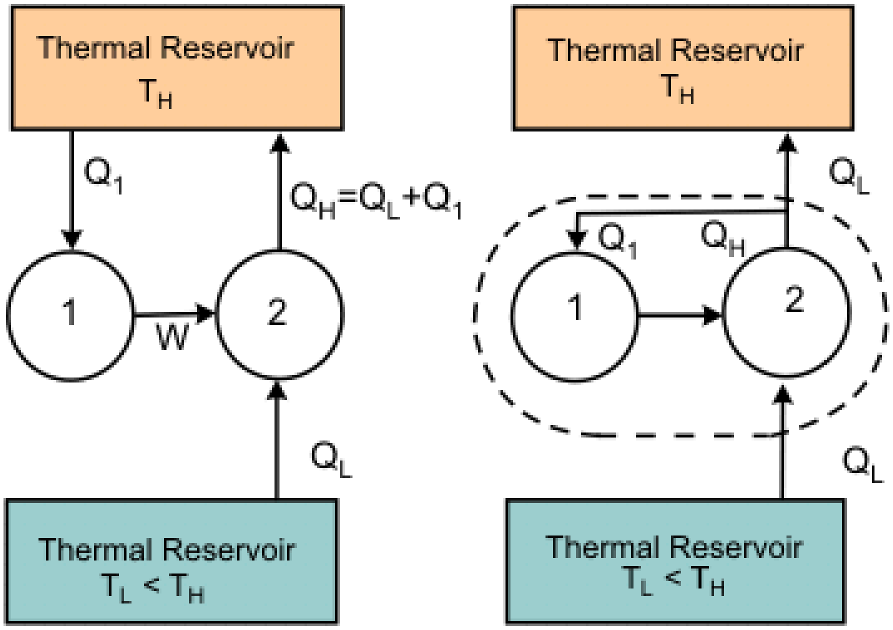


Fig .2.10 Clausius statement

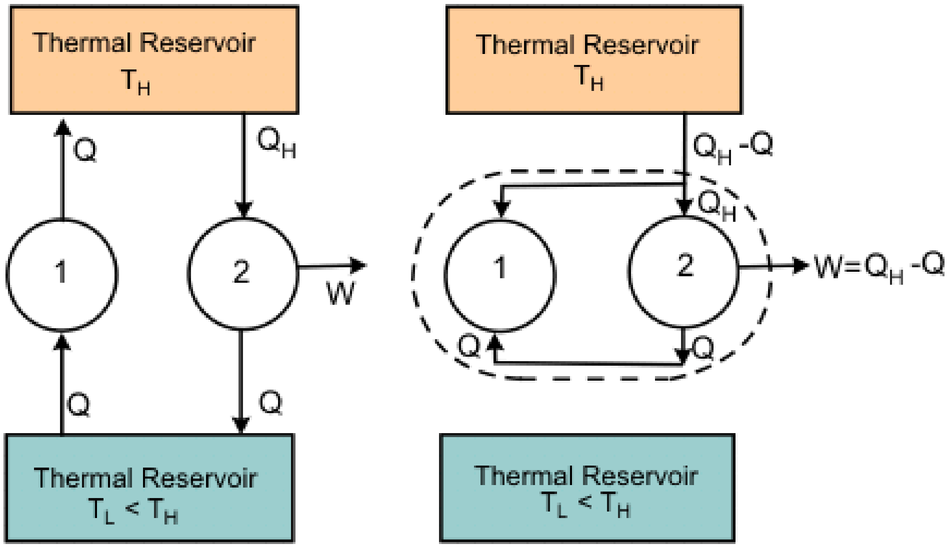


Fig .2.11 Clausisus statement with work done

For example-cooling of food is most commonly accomplished by refrigerators driven by electric motors requiring power from their surroundings to operate. The Clausius statement implies it is impossible to construct a refrigeration cycle that operates without a power input.

## 2.7 EQUIVALENCE OF THE TWO STATEMENTS

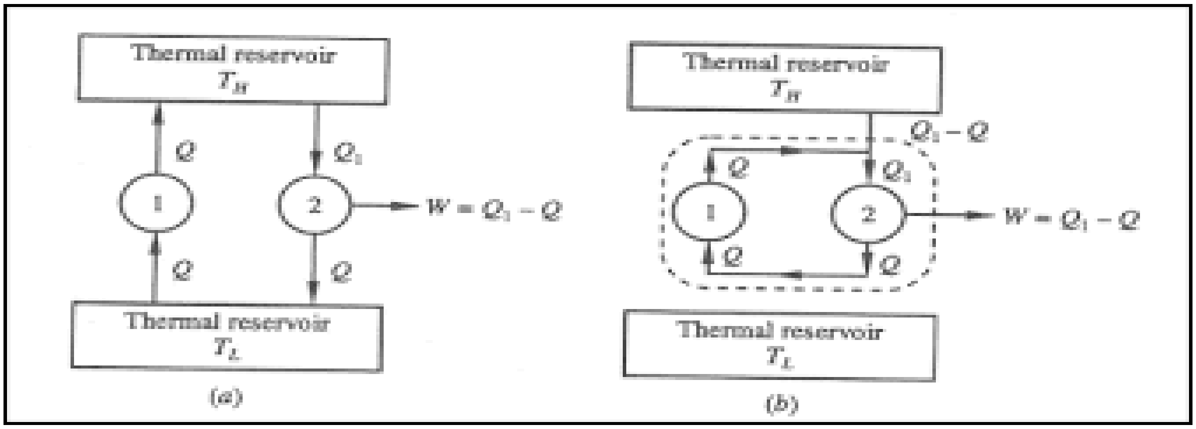


Fig 2.12 Violation of the Kelvin-Planck statement results in the violation of the Clausius statement.

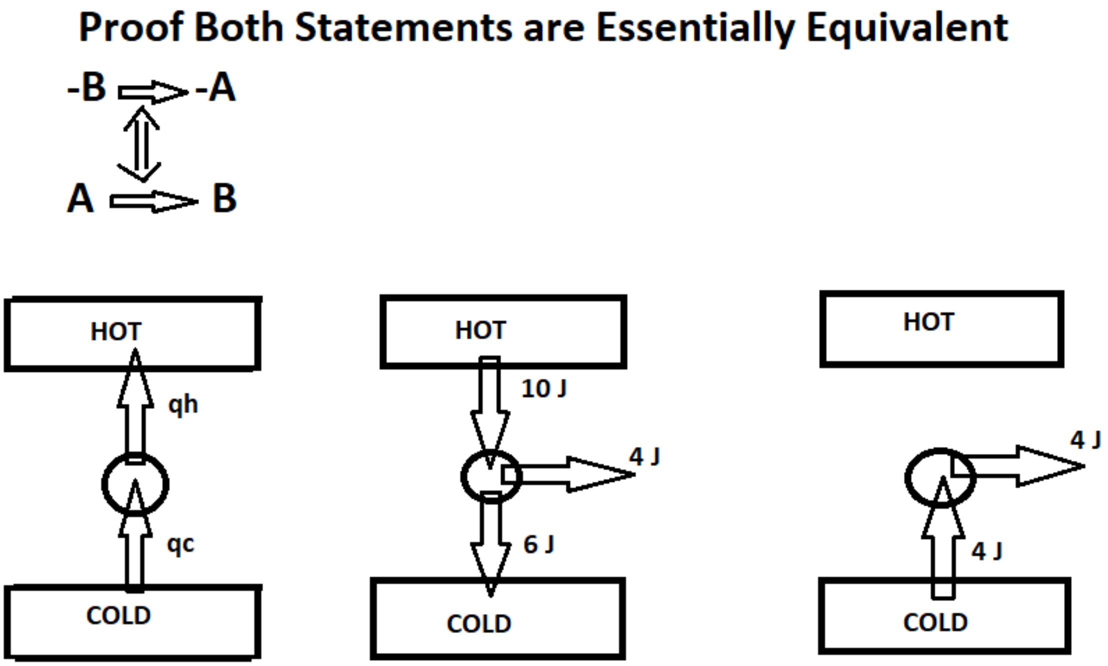


Fig .2.13 Proof of Clausius inequality

## 2.8 PERPETUAL-MOTION MACHINES (PMM)

Any device which violates first law or second law of thermodynamics is called a perpetual motion machine (PMM). These devices operate under the principle of sustained or perpetual motion. That is, the machine will continuously perform same function repeatedly without stopping.

PMM-1: Perpetual motion machines of first class does work without intake of energy, thus violate the first law of thermodynamics.

PMM-2: Perpetual motion machines of second class is an engine without any heat rejection or a refrigerator without work input, thus violate second law of thermodynamics.

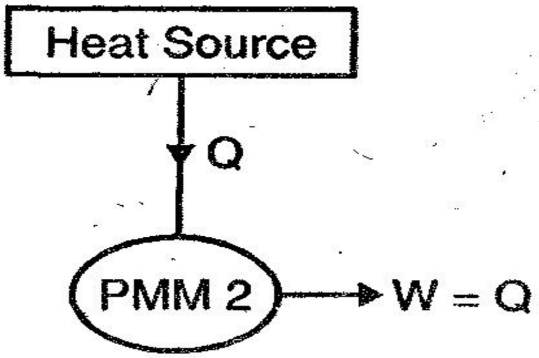


Fig .2.14 PMM 1 Example

Fig 2.15 perpetual-motion machine of the second kind (PMM2)

## 2.9 THE CARNOT PRINCIPLES

1. The efficiency of an irreversible heat engine is always less than the efficiency of a reversible one operating between the same two reservoirs.

2. The efficiencies of all reversible heat engines operating between the same two reservoirs are the same

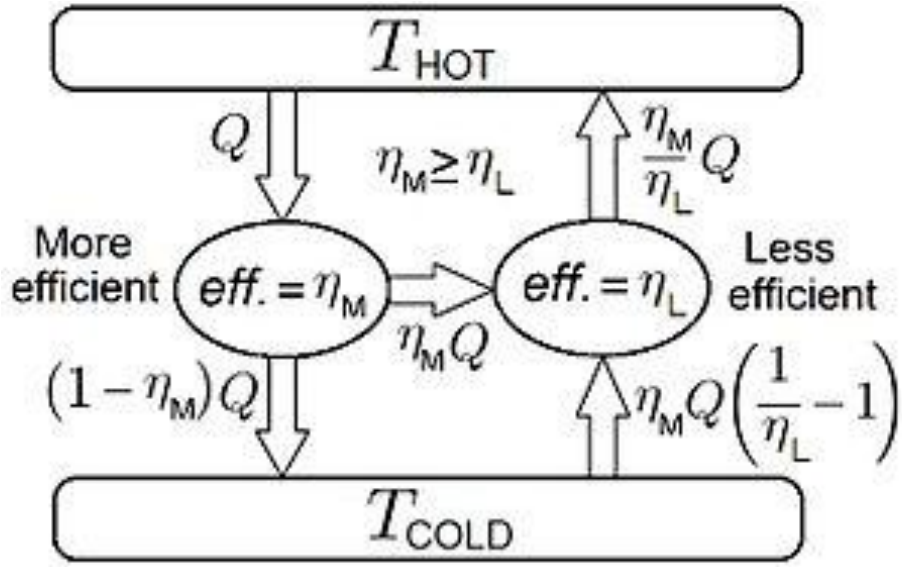


Fig .2.16 Carnot principle

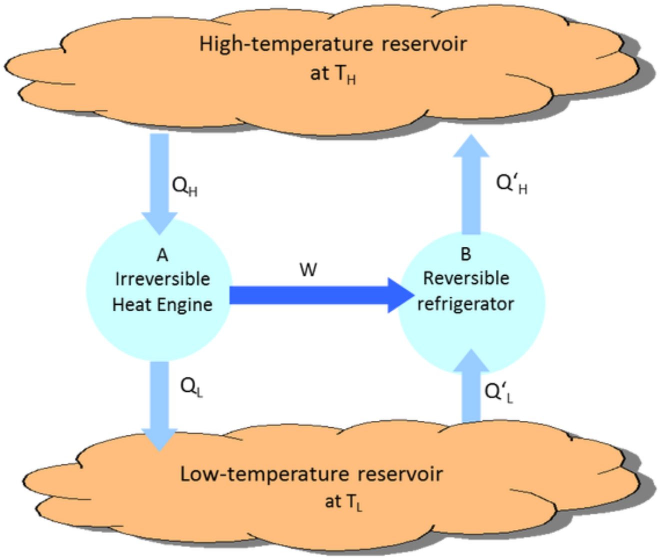


Fig .2.17 Reversible and irreversible processes

## 2.10 THE CARNOT CYCLE

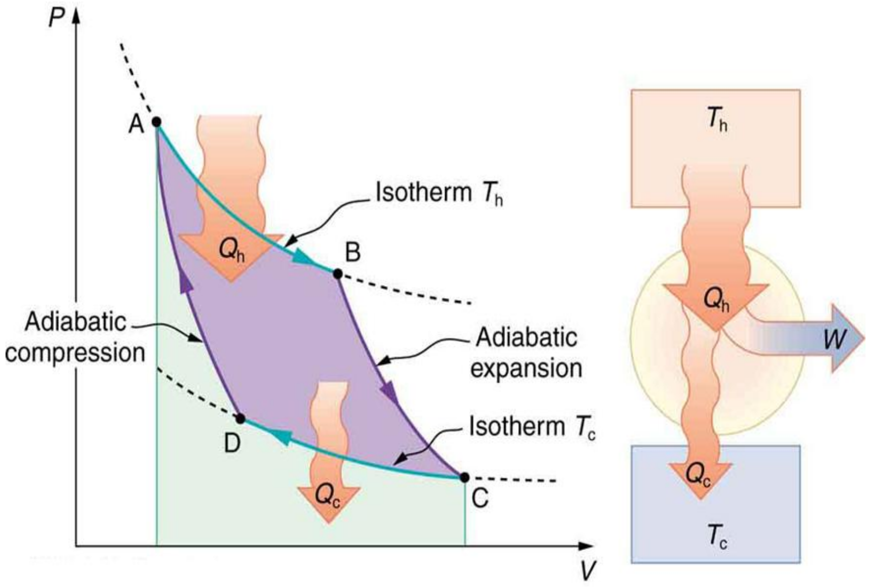


Fig 2.18 PV diagram for a Carnot cycle

PV diagram for a Carnot cycle, employing only reversible isothermal and adiabatic processes. Heat transfer occurs into the working substance during the isothermal path AB, which takes place at constant temperature. Heat transfer occurs out of the working substance during the isothermal path CD, which takes place at constant temperature. The net work output equals the area inside the path ABCDA. Also shown is a schematic of a Carnot engine operating between hot and cold reservoirs at temperatures and any heat engine using reversible processes and operating between these two temperatures will have the same maximum efficiency as the Carnot engine.

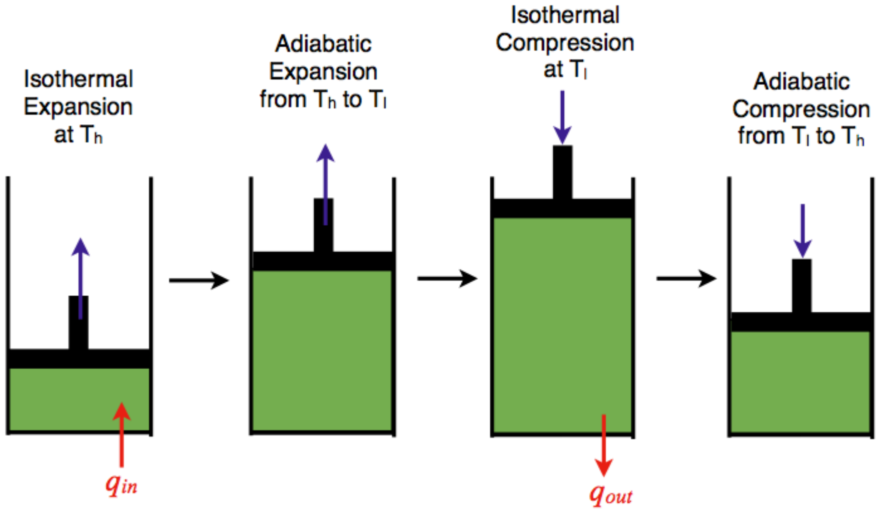
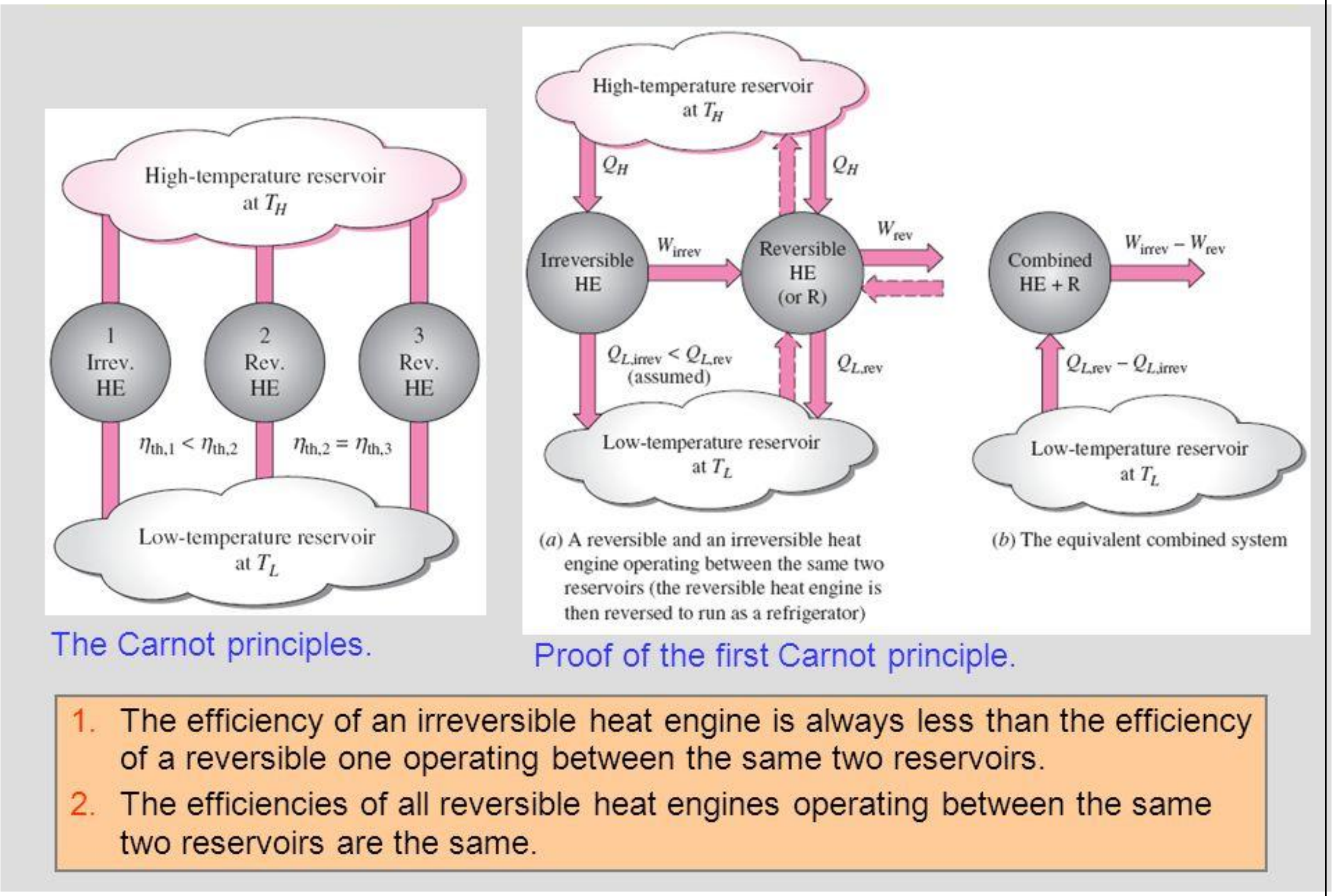


Fig .2.19 Types of processes



(*a*) A reversible and an irreversible heat engine operating between the same two reservoirs (the reversible heat engine is then reversed to run as a refrigerator)

(*b*) The equivalent combined system

The Carnot principles.

Proof of the first Carnot principle.

1. The efficiency of an irreversible heat engine is always less than the efficiency of a reversible one operating between the same two reservoirs.
2. The efficiencies of all reversible heat engines operating between the same two reservoirs are the same.

Fig .2.20 Carnot cycles

## 2.11 THERMODYNAMIC SCALE OF TEMPERATURE

To define a temperature scale that does not depend on the thermometric property of a substance, Carnot principle can be used since the Carnot engine efficiency does not depend on the working fluid. It depends on the temperatures of the reservoirs between which it operates.

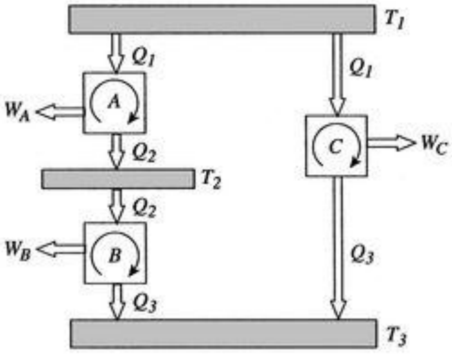


Fig .2.21 Scales of temperature

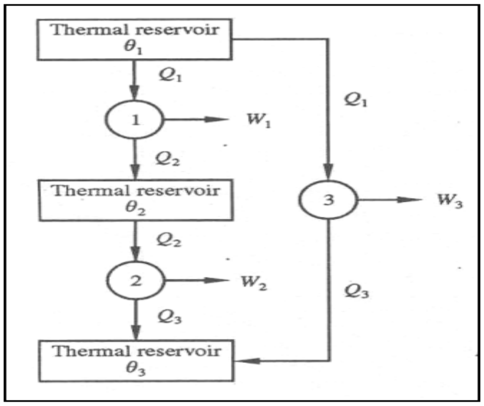


Fig 2.22 Thermodynamic scale of temperature

Consider the operation of three reversible engines 1, 2 and 3. The engine 1 absorbs energy $Q_1$ as heat from the reservoir at $T_1$, does work $W_1$ and rejects energy $Q_2$ as heat to the reservoir at $T_2$.

Let the engine 2 absorb energy $Q_2$ as heat from the reservoir at $T_2$ and does work $W_2$ and rejects energy $Q_3$ as heat to the reservoir at $T_3$.

The third reversible engine 3, absorbs energy $Q_1$as heat from the reservoir at $T_1$, does work $W_3$ and rejects energy $Q_3$ as heat to the reservoir at $T_3$.

$h_1 = W_1 / Q_1 = 1- Q_2/Q_1 = f(T_1,T_2)$or, $Q_1/Q_2 = F(T_1,T_2)$
$h_2 = 1- Q_3/Q_2 = f(T_2,T_3)$or, $T_2/T_3 = F(T_2,T_3)$
$h_3 = 1- Q_3/Q_1 = f(T_1,T_3)$
$T_1/T_3 = F(T_1,T_3)$

Then , $Q_1/Q_2 = (Q_1/Q_3)/(Q_2/Q_3)$Or, $F(T_1,T_2) = F(T_1,T_3) /F(T_2,T_3)$
Since $T_3$ does not appear on the left side, on the RHS also $T_3$ should cancel out. This is possible if the function F can be written as
$F(T_1, T_2) = f(T_1)\ y\ (T_2)$

$f(T_1)\ y\ (T_2) = \{f(T_1)\ y\ (T_3)\} / \{f(T_2)\ y\ (T_3)\}$

Therefore, $y\ (T_2) = 1 / f(T_2)$
Hence, $Q_1 / Q_2 = F(T_1,T_2) = f(T_1)/ f(T_2)$
Now, there are several functional relations that will satisfy this equation. For the thermodynamic scale of temperature, Kelvin selected the relation

$Q_1/Q_2 = T_1/T_2$

That is, the ratio of energy absorbed to the energy rejected as heat by a reversible engine is equal to the ratio of the temperatures of the source and the sink.

## 2.12 CLAUSIUS INEQUALITY

A given cycle may be subdivided by drawing a family of reversible, adiabatic lines. Every two adjacent adiabatic lines may be joined by two reversible isotherms.

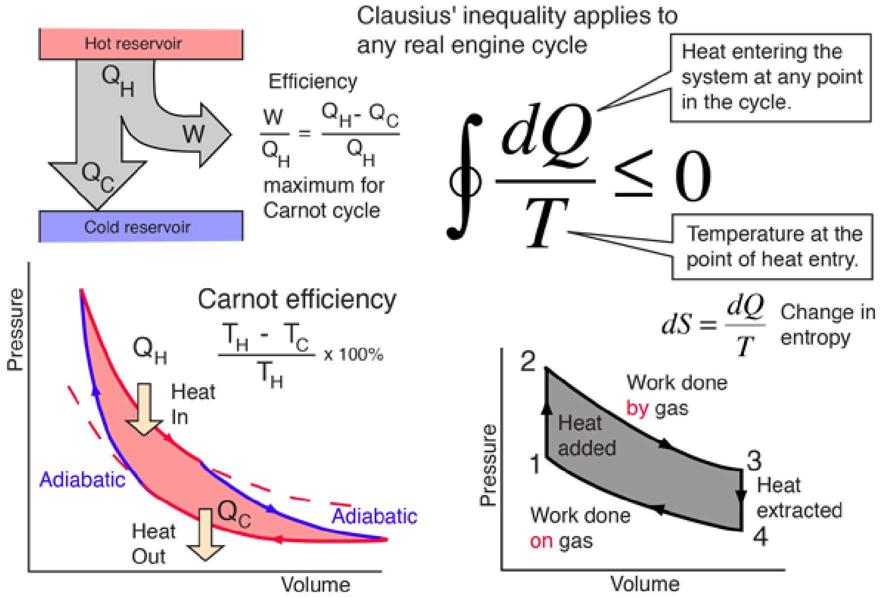


Fig .2.23 Clausius inequality

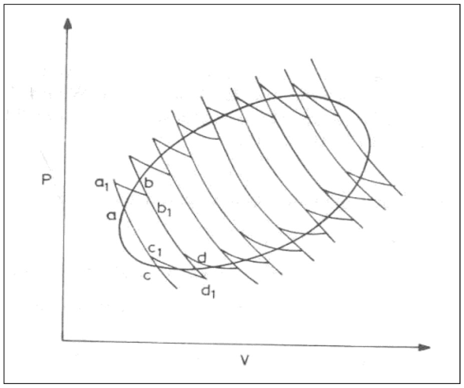


Fig 2.24 clausius inequality chart

The heat interaction along the reversible path is equal to the heat interaction along the reversible isothermal path.

The work interaction along the reversible path is equal to the work interaction along the reversible adiabatic and the reversible isothermal path.

That is,

$Q_{a-b}=Q_{a1-b1}$ and $Q_{c-d}=Q_{c1-d1}$

a1-b1-d1-c1 is a Carnot cycle.

The original reversible cycle thus is a split into a family of Carnot cycles. For every Carnot cycle

$$\oint dQ/T = 0$$

Therefore for the given reversible cycle,

$$\oint dQ/T = 0$$

If the original cycle is irreversible

$$\oint dQ/T < 0$$

so the generalized observation is

$$\oint dQ/T \leq 0$$

Whenever a system undergoes a cyclic change, however complex the cycle may be( as long as it involves heat and work interactions), the algebraic sum of all the heat interactions divided by the absolute temperature at which heat interactions are taking place considered over the entire cycle is less than or equal to zero (for a reversible cycle).

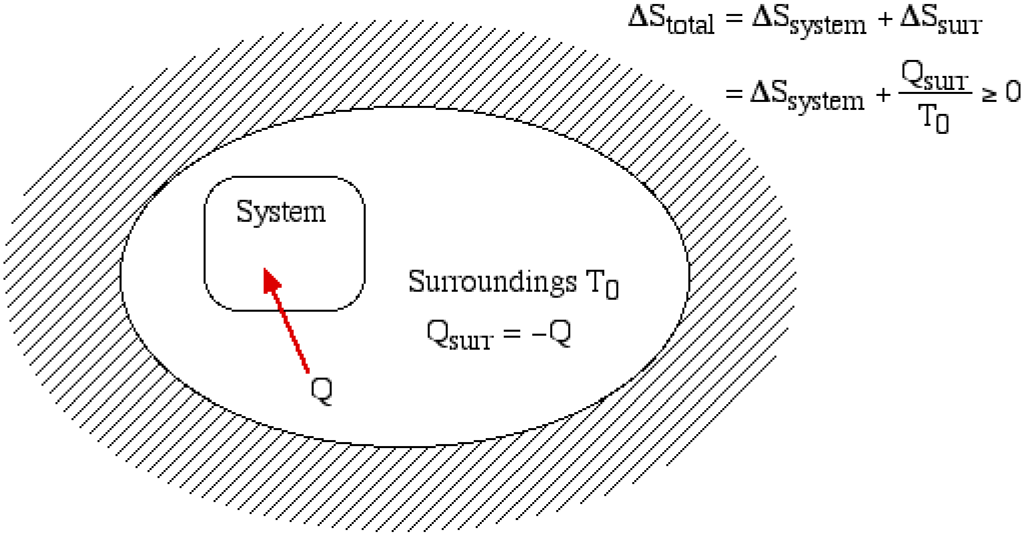
## 2.13 ENTROPY

In statistical mechanics, entropy is an extensive property of a thermodynamic system. It is closely related to the number Ω of microscopic configurations (known as microstates) that are consistent with the macroscopic quantities that characterize the system (such as its volume, pressure and temperature). Under the assumption that each microstate is equally probable, the entropy is the natural logarithm of the number of microstates, multiplied by the Boltzmann constant $k_B$. Formally (assuming equiprobable microstates)

There is yet another way of expressing the second law of thermodynamics. This version relates to a concept called entropy. By examining it, we shall see that the directions associated with the second law—heat transfer from hot to cold, for example—are related to the tendency in nature for systems to become disordered and for less energy to be available for use as work. The entropy of a system can in fact be shown to be a measure of its disorder and of the unavailability of energy to do work.

## 2.14 PRINCIPLE OF ENTROPY INCREASE

The entropy of various parts of the system may change, but the total change is zero. Furthermore, the system does not affect the entropy of its surroundings, since heat transfer between them does not occur. Thus the reversible process changes neither the total entropy of the system nor the entropy of its surroundings. Sometimes this is stated as follows: *Reversible processes do not affect the total entropy of the universe.* Real processes are not reversible, though, and they do change total entropy. We can, however, use hypothetical reversible processes to determine the value of entropy in real, irreversible processes. The following example illustrates this point.



Entropy generated $S_{gen}$:

$$\boxed{S_{gen} = \Delta S_{total} = \Delta S_{system} + \frac{Q_{surr}}{T_0} \geq 0} \quad (Q_{surr} = -Q)$$

Dividing by m: $\boxed{s_{gen} = \Delta s_{system} + \frac{q_{surr}}{T_0} \geq 0}$

Fig .2.25 Total entropy change

It is reasonable that entropy increases for heat transfer from hot to cold. Since the change in entropy , there is a larger change at lower temperatures. The decrease in entropy of the hot object is therefore less than the increase in entropy of the cold object, producing an overall increase, just as in the previous example.

This result is very general:*There is an increase in entropy for any system undergoing an irreversible process.*With respect to entropy, there are only two possibilities: entropy is constant for a reversible process, and it increases for an irreversible process. There is a fourth version of the second law of thermodynamics stated in terms of entropy:*The total entropy of a system either increases or remains constant in any process; it never decreases.*

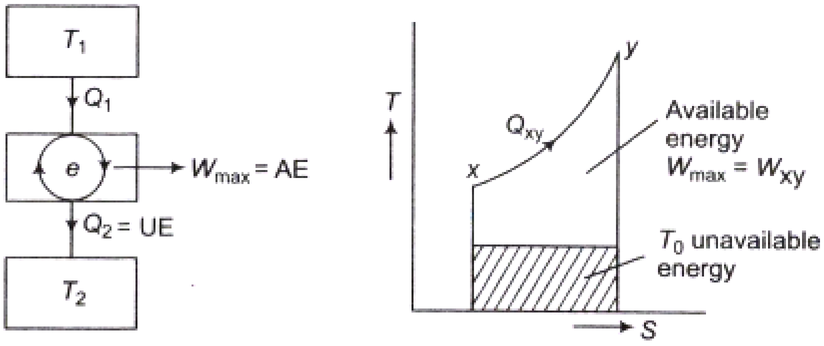
## 2.15 AVAILABILITY AND IRREVERSIBILITY

You are already familiar with the basic second law concepts of a heat engine. In particular, the heat engine draws heat from a source at TH, converts some of this heat into useful work, and discards the rest to an environment at TC . The second law placed a limit on the thermal efficiency of the heat engine; the maximum efficiency corresponding to a reversible cycle for which

ηrev = 1 – TL/ TH and the maximum work that could be obtained from the heat source would be

$\dot{W}$ revHE = $\dot{Q}$ H ηrev = $\dot{Q}$ H ( 1 − TL /TH )

The maximum work $\dot{W}$ revHE can be viewed as the available work or, alternatively, the useful work potential, of the source $\dot{Q}$ H. It represents the theoretical maximum work that could be derived from the source, and would be obtained if all processes in the heat engine were completely reversible. The available work (or availability), in this case, depends both on the temperature of the heat source and the temperature of the environment.



Availability and unavailability of energy

Fig .2.26 Availability and unavailability

What we want to do here is extend (or generalize) the concept of availability beyond an application to heat engines. As in the past, we will deal separately with closed and open systems in developing availability concepts. With regard to closed systems, an availability analysis seeks to quantify the work potential (i.e., availability) of system at a specified initial state. To derive work from this system, the system would need to undergo a process to a final state. The final state, in our availability analysis, will always correspond to the environment conditions (often called the dead state) and characterized by properties T0, P0, s0, . . ..

An availability analysis applied to an open system typically attempts to derive the maximum work potential of a work producing/consuming device such as a turbine or compressor. As is the case with the closed system, the availability will depend on the environment conditions.

## 2.16 GIBBS AND HELMHOLTZ FUNCTIONS

One of the confusing things about thermodynamics is the number of energy functions in use. We've already met the internal (kinetic) energy U and the enthalpy, defined as

$H \equiv U + PV$ ……. (1)

The enthalpy is the total energy required to create the system from nothing, in which the environment at constant pressure P must be pushed back to create the volume V in which the new system is to be stored. Thus the enthalpy is effectively the energy of the system in constant pressure environments. The Helmholtz free energy F (other sources call it A) is defined as

$F \equiv U - TS$ …….. (2)

Schroeder's description of this definition is rather vague, since he claims that F is the work required to create a system out of nothing, if the system is in contact with a thermal reservoir so that its temperature is held constant at T. This arises because for isothermal, reversible processes, the entropy absorbed from a thermal reservoir is $S = Q/T$, so $TS = Q$ is the contribution of the reservoir to the total energy U; thus the difference $U - TS$ must be the work required to produce the system.

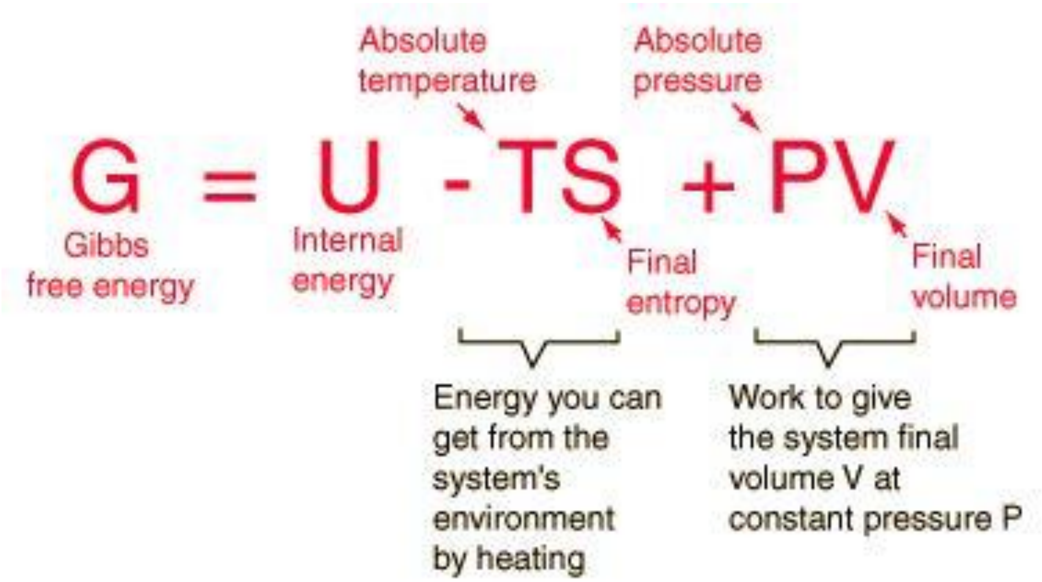


Fig .2.27 Gibbs energy

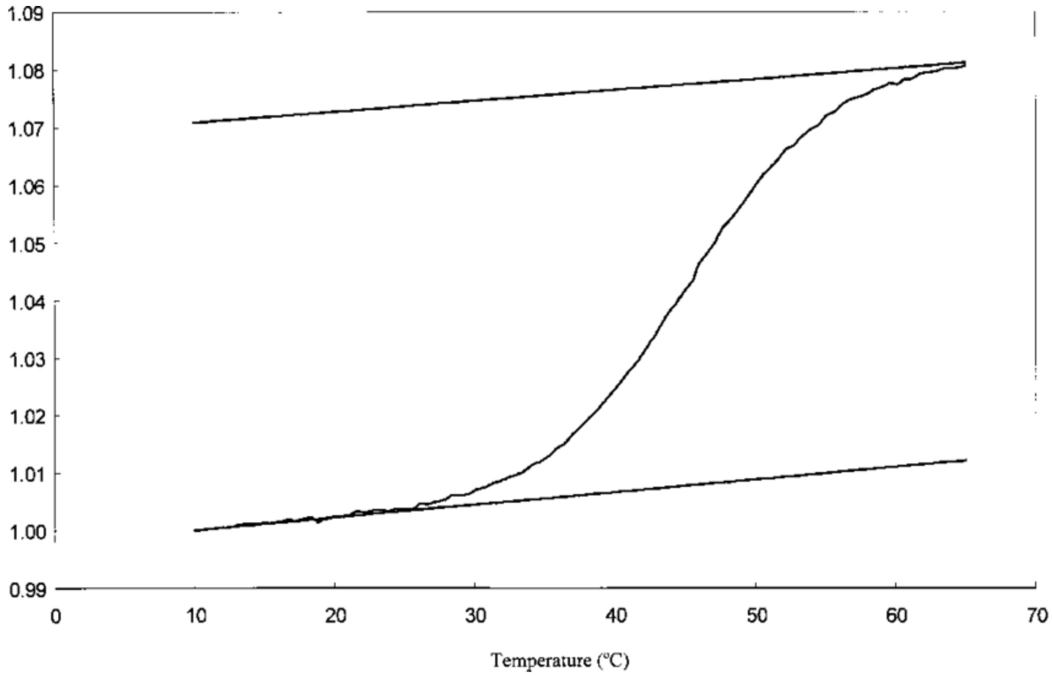


Fig .2.28 T-S Diagram

However, in the definition of enthalpy, the total energy of a system created at constant pressure is the sum of U and the work P V required to make room for the system by pushing back the atmosphere. Thus it would seem that U excludes the work P V required to make room for the system.

Other sites on the web point out that F is actually the work required to create the system at constant temperature and constant volume. That is, space has already been cleared for the system, which is then placed in contact with the reservoir so it can absorb the heat T S. Any extra energy required to top up the total energy to the value U must then be provided by doing work (for example, electrical work, which doesn't change the volume) on the system. The Gibbs free energy is then defined as the Helmholtz free energy plus the work P V required to make room for the system at constant pressure:

$G \equiv F + PV = U - TS + PV$ ……….. (3)

The four energies U, H, F and G are known as thermodynamic potentials. As an example, we'll look at one mole of argon gas at room temperature (298 K) and atmospheric pressure (1 bar ≈ 105 Pa). We've already worked out U, S and V for this system:

$U = 3739$ J ……… (4)

$S = 155$ J K−1 ………… (5)

$V = 0.025\ m^3$ …….(6)

The other potentials are

H = U +P V = 3739+0.025×105 = 6239 J ……….(7)

F = U −T S = 3739−298×155 = −4.2×104 J …………(8)

G = F +P V = −4.2×104 +0.025×105 = −4×104 J ………(9)

Since in practice, only differences in energy are measured, the fact that F and G are negative shouldn't worry us.

## 2.17 MAXWELL RELATIONS

Maxwell's relations are a set of equations in thermodynamics which are derivable from the symmetry of second derivatives and from the definitions of the thermodynamic potentials. These relations are named for the nineteenth-century physicist James Clerk Maxwell.

The structure of Maxwell relations is a statement of equality among the second derivatives for continuous functions. It follows directly from the fact that the order of differentiation of an analytic function of two variables is irrelevant (Schwarz theorem). In the case of Maxwell relations the function considered is a thermodynamic potential and $x_i$ and $x_j$ are two different natural variables for that potential

$$\left(\frac{\partial T}{\partial v}\right)_s = -\left(\frac{\partial P}{\partial s}\right)_v \text{ [From equation } du = Tds - Pdv]$$

$$\left(\frac{\partial T}{\partial P}\right)_s = \left(\frac{\partial v}{\partial s}\right)_P \text{ [From equation } dh = Tds + vdP]$$

$$\left(\frac{\partial P}{\partial T}\right)_v = \left(\frac{\partial s}{\partial v}\right)_T \text{ [From equation } da = -Pdv - sdT]$$

$$\left(\frac{\partial v}{\partial T}\right)_P = -\left(\frac{\partial s}{\partial P}\right)_T \text{ [From equation } dg = vdP - sdT]$$

## 2.18 THIRD LAW OF THERMODYNAMICS

The Third law of thermodynamics is sometimes stated as follows, regarding the properties of closed systems in thermodynamic equilibrium:

The Entropy of a system approaches a constant value as its temperature approaches absolute zero.

This constant value cannot depend on any other parameters characterizing the closed system, such as pressure or applied magnetic field. At absolute zero (zero kelvin) the system must be in a state with the minimum possible energy.

Entropy is related to the number of accessible microstates, and there is typically one unique state (called the ground state) with minimum energy.[1] In such a case, the entropy at absolute zero will be exactly zero. If the system does not have a well-defined order (if its order is glassy, for example), then there may remain some finite entropy as the system is brought to very low temperatures, either because the system becomes locked into a configuration with non-minimal energy or because the minimum energy state is non-unique. The constant value is called the residual entropy of the system.

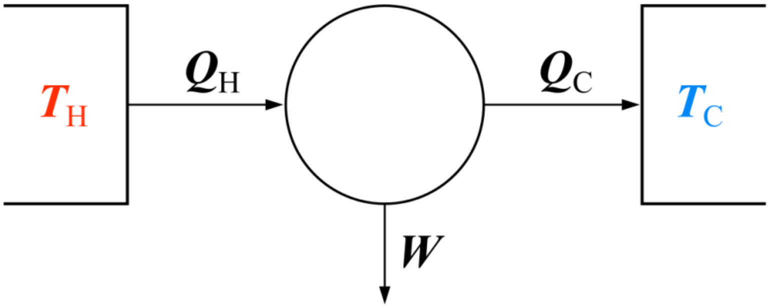


Fig .2.29 Third law of thermodynamics

The entropy is essentially a state-function meaning the inherent value of different atoms, molecules, and other configurations of particles including subatomic or atomic material is defined by entropy, which can be discovered near 0 K. The Nernst–Simon statement of the third law of thermodynamics concerns thermodynamic processes at a fixed, low temperature

The entropy change associated with any condensed system undergoing a reversible isothermal process approaches zero as the temperature at which it is performed approaches 0 K.

Here a condensed system refers to liquids and solids. A classical formulation by Nernst (actually a consequence of the Third Law) is:

It is impossible for any process, no matter how idealized, to reduce the entropy of a system to its absolute-zero value in a finite number of operations.[

There also exists a formulation of the Third Law which approaches the subject by postulating a specific energy behavior:

If the composite of two thermodynamic systems constitutes an isolated system, then any energy exchange in any form between those two systems is bounded.

# MODULE-III

# PURE SUBSTANCES AND MIXTURES OF PERFECT GASES

## 3.1 PURE SUBSTANCE

A substance that has a fixed chemical composition throughout is called a pure substance such as water, air, and nitrogen. A pure substance does not have to be of a single element or compound. A mixture of two or more phases of a pure substance is still a pure substance as long as the chemical composition of all phases is the same.

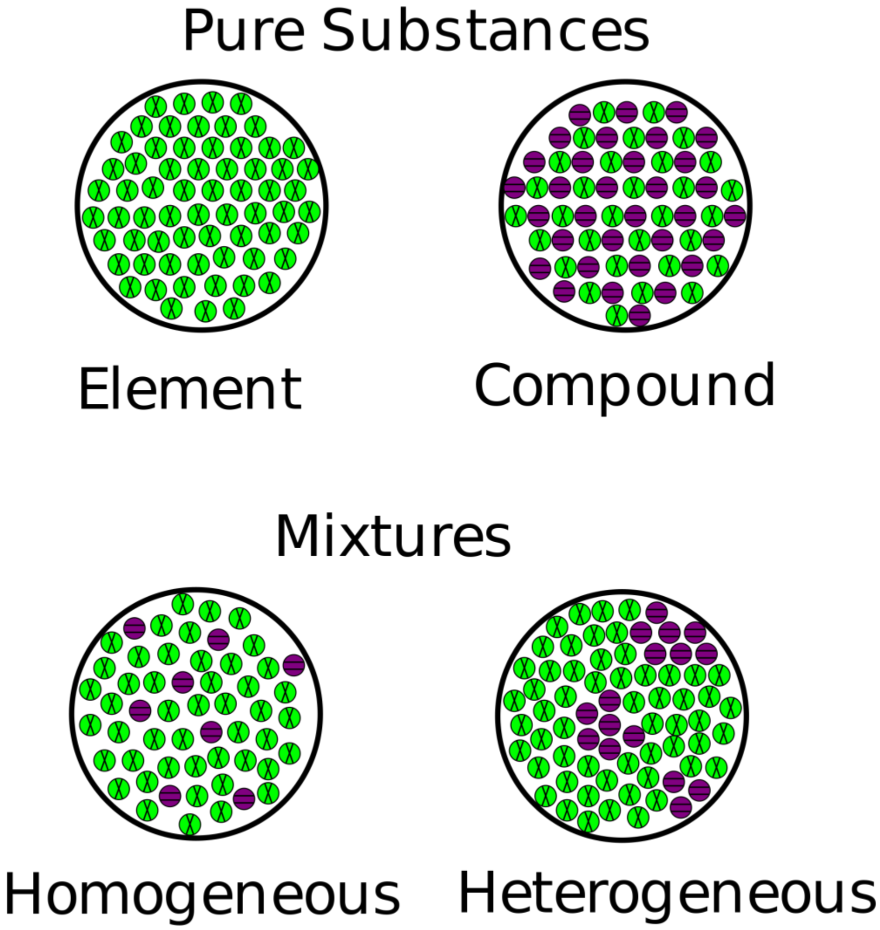


Fig .3.1 Types of substances

### 3.1.1 PHASES OF A PURE SUBSTANCE

A pure substance may exist in different phases. There are three principal phases solid, liquid, and gas. A phase: is defined as having a distinct molecular arrangement that is homogenous throughout and separated from others (if any) by easily identifiable boundary surfaces. A substance may have several phases within a principal phase, each with a different molecular structure. For example, carbon may exist as graphite or diamond in the solid phase, and ice may exist in seven different phases at high pressure. Molecular bonds are the strongest in solids and the weakest in gases. Solid: the molecules are arranged in a three-dimensional pattern (lattice) throughout the solid. The molecules cannot move relative to each other; however, they continually oscillate about their equilibrium position. Liquid: the molecular spacing in liquid phase is not much different from that of the solid phase (generally slightly higher), except the molecules are no longer at fixed positions relative to each other. Gas: the molecules are far apart from each other, and a molecular order does not exist. Gas molecules move randomly, and continually collide with each other and the walls of the container they are in. Molecules in the gas phase are at a considerably higher energy level than they are in liquids or solid phases.

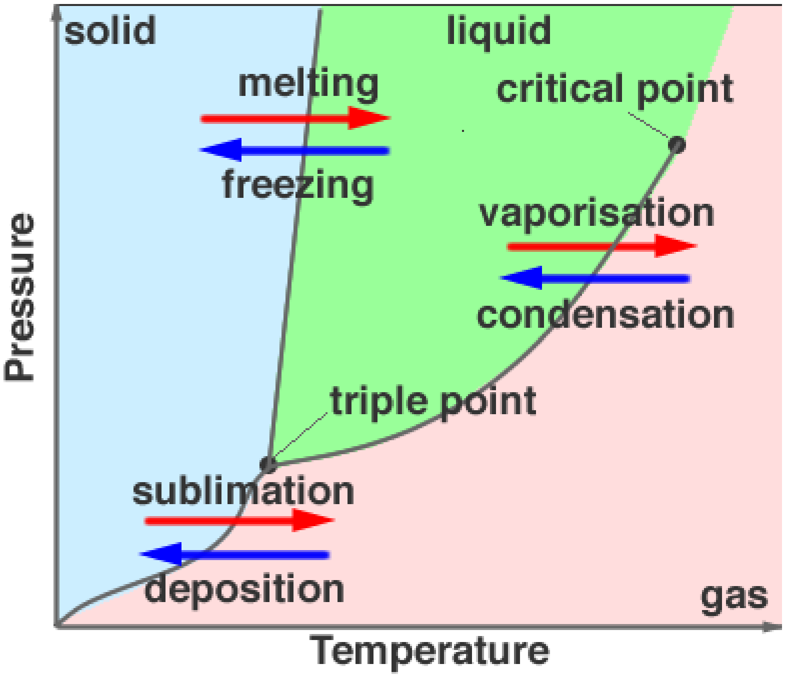


Fig .3.2 Phase diagram

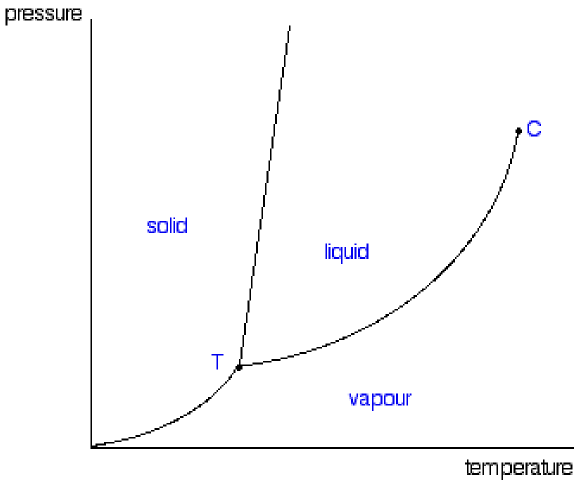


Fig .3.3 Triple point

### 3.2 T-S AND H-S DIAGRAMS

A T-s diagram is the type of diagram most frequently used to analyze energy transfer system cycles. ... By the definition of entropy, the heat transferred to or from a system equals the area under the T-s curve of the process.

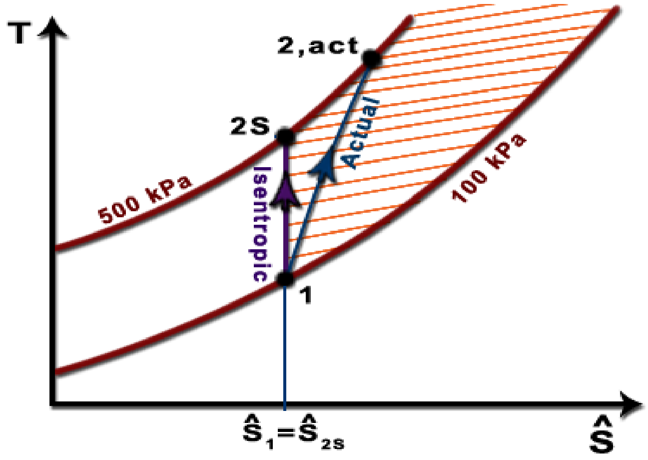


Fig.3.4 Mollier (t-s) diagram

The Mollier diagram is used only when quality is greater than 50% and for superheated steam.

For any state, at least two properties should be known to determine the other unknown properties of steam at that state.

**Accessible States**

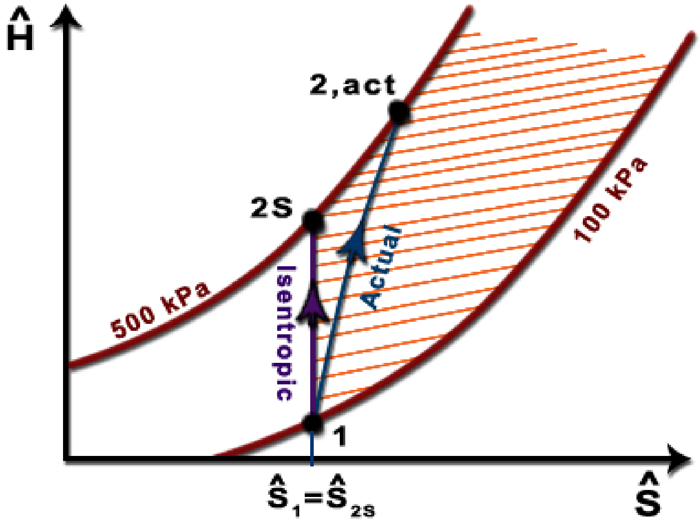


Fig.3.5 Mollier or Enthalpy-Entropy (h-s) diagram

## 3.3 P-V-T SURFACES

As we know very well that equation of state for an ideal gas deals with the relationship between pressure, volume and temperature. If we will plot above mentioned variables along x, y and z axis then we will have one surface which will indicate the equation of state i.e. PV=RT

And this surface will be termed as P-V-T surface in thermodynamics. Following figure displayed here indicates the P-V-T surface for an ideal gas.

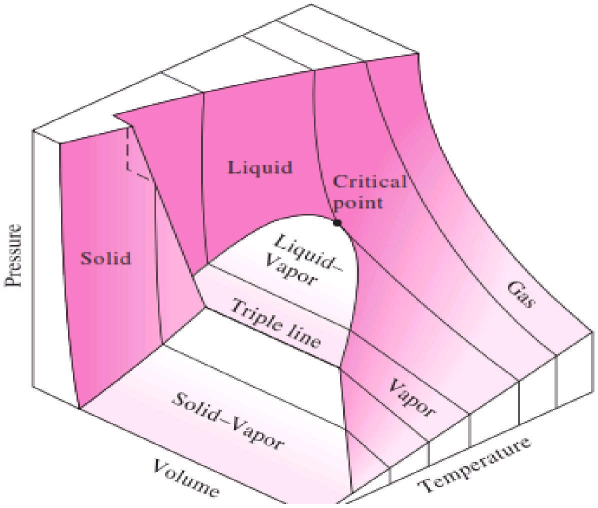


Fig 3.6 P-V-T surface in thermodynamics

Over this P-V-T surface, each point will indicate equilibrium state and each line will indicate the process.

P-V-T surface indicate lots of information at one glance, but practically in thermal engineering it will be quite easy to work with two dimensional diagram such as P-T, V-T and P-V diagrams.

## 3.4 TRIPLE POINT AT CRITICAL STATE PROPERTIES DURING CHANGE OF PHASE

For simplicity and clarity, the generic notion of *critical point* is best introduced by discussing a specific example, the liquid-vapor critical point. This was the first critical point to be discovered, and it is still the best known and most studied one.

The figure to the right shows the schematic PT diagramof a *pure substance* (as opposed to mixtures, which have additional state variables and richer phase diagrams, discussed below). The commonly known phases *solid, liquid* and *vapor* are separated by phase boundaries, i.e. pressure-temperature combinations where two phases can coexist. At the triple point, all three phases can coexist. However, the liquid-vapor boundary terminates in an endpoint at some *critical temperature* $T_c$ and *critical pressure* $p_c$. This is the *critical point*.

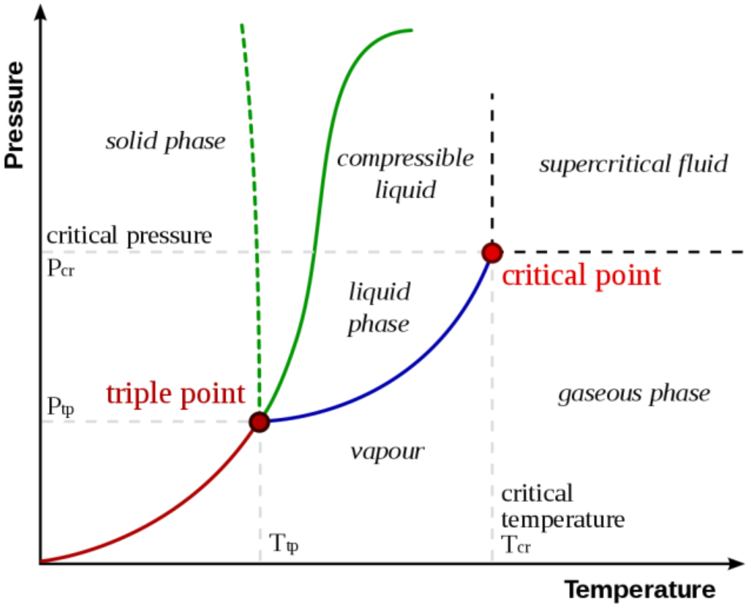


Fig 3.7 triple point at critical state properties during change of phase

In water, the critical point occurs at around 647 K (374 °Cor 705 °F) and 22.064 MPa (3200 psia or 218 atm).

In the *vicinity* of the critical point, the physical properties of the liquid and the vapor change dramatically, with both phases becoming ever more similar. For instance, liquid water under normal conditions is nearly incompressible, has a low thermal expansion coefficient, has a high dielectric constant, and is an excellent solvent for electrolytes. Near the critical point, all these properties change into the exact opposite: water becomes compressible, expandable, a poor dielectric, a bad solvent for electrolytes, and prefers to mix with nonpolar gases and organic molecules.

*At* the critical point, only one phase exists. The heat of vaporization is zero. There is a stationary inflection point in the constant-temperature line (*critical isotherm*) on a PV diagram. This means that at the critical point:

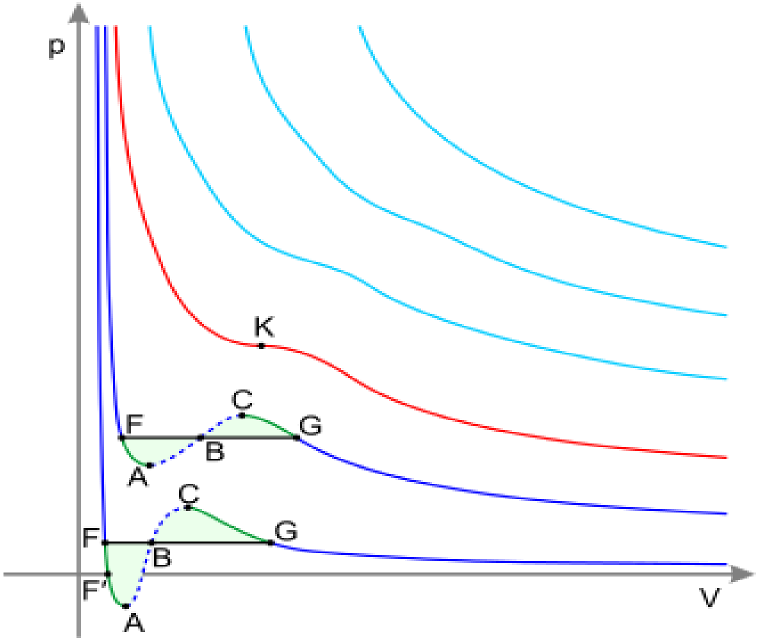


Fig 3.8 The *critical isotherm* with the critical point K

*Above* the critical point there exists a state of matter that is continuously connected with (can be transformed without phase transition into) both the liquid and the gaseous state. It is called supercritical fluid. The common textbook knowledge that all distinction between liquid and vapor disappears beyond the critical point has been challenged by Fisher and Widom who identified a p,T-line that separates states with different asymptotic statistical properties (Fisher-Widom line).

### 3.5 DRYNESS FRACTION

This handout assumes the student is familiar with Steam Tables and the terms found therein. If required, please review Steam Tables before continuing. The heavy solid line in the above chart represents the transformation of 1 kg of water at 0˚C and atmospheric pressure into steam, with the addition of heat. From 0˚C to 100˚C, energy is added to the water in the form of sensible heat. This causes an increase in temperature while its state remains the same. This energy is referred to in steam tables as “hf”. The change from 1 kg of water at 0˚C into 1 kg of water at 100˚C requires the addition of 419.04 kJ of energy. Therefore, at atmospheric pressure: hf = 419.04 kJ/kg Thesaturati on temperature of water at atmospheric pressure is 100˚C. The addition of more heat will not cause a temperature change but will, instead, cause a change of state.

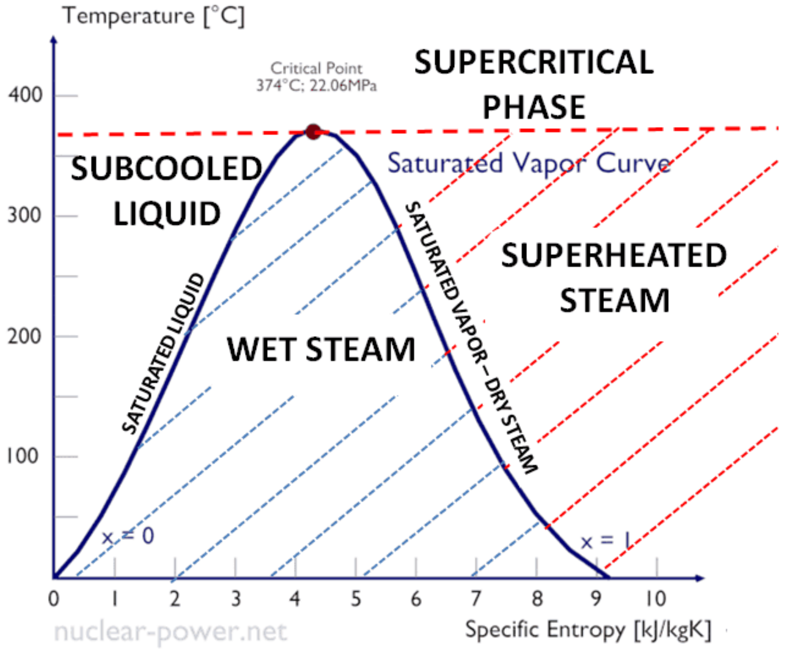


Fig .3.9 Specific entropy

In this case, evaporation into steam at 100˚C. The change from 1 kg of water at 100˚C into dry saturated steam at 100˚C requires the addition of 2257.0 kJ of energy. Therefore, at atmospheric pressure: hfg = 2257.0 kJ/kg. Referring to the diagram, you will notice that hg = hf + hfg If not all of hfg is added to the water, then not all of the water can change into steam. If, say, 50% of hfg is added then only 50% of the water will be changed into steam and the steam will be referred to as 50% dry. This is known as the “dryness fraction” of the steam. Expanding on this, then, it can be seen that the total enthalpy content of steam of a certain dryness fraction, and made from water at 0˚C, can be found out by totaling hf and that portion of hfg which has been added (hfg multiplied by the dryness fraction). If the steam is 100% dry, then the entire amount of hfg has been added and the dryness fraction of the steam would be 100% or 1. Putting this into a formula we get: total enthalpy = hf + (dryness fraction) x (hfg) Using this formula and the information found in Steam Tables, one can determine the dryness fraction of steam at any pressure or temperature.

## 3.6 MOLLIER CHARTS

Mollier diagram is named after Richard Mollier (1863-1935), a German professor who pioneered experimental research on thermodynamics associated with water, steam and water-vapor mixture. Mollier diagram is a graphical representation of a functional relationship between enthalpy, entropy, temperature, pressure and quality of steam. Mollier is often referred to as Enthalpy – Entropy Diagram or Enthalpy – Entropy Chart. The enthalpyentropy charts in Appendix B are Mollier Diagrams. They used commonly in the design and analysis associated with power plants, steam turbines, compressors, and refrigeration systems. Mollier diagram is available in two basic versions: The SI/Metric Unit version and the US/Imperial Unit version. Figure 2.1 depicts the SI/Metric version of the Mollier diagram. The US and SI versions of the Mollier diagram are included in Appendix B. The abscissa (horizontal or x-axis in a Cartesian coordinate system) and ordinate (vertical or y-axis in a Cartesian coordinate system) scales represent entropy and enthalpy, respectively. Therefore, Mollier diagram is also referred to as the Enthalpy-Entropy Chart.

The constant pressure and constant temperature lines in the Mollier diagram are referred to as isobars and isotherms, respectively. In addition, the graph includes lines representing constant steam quality, “x,” in the bottom half of the diagram. The bold line, spanning from left to right, in the lower half of Mollier diagram is the saturation line. The saturation line, labeled as x = 1, represents the set of points on Mollier diagram where the steam is 100% vapor. All points above the saturation line are in the superheated steam realm. All points below the saturation line represent a mixture of liquid and 16 vapor phases. The concept of quality is explained and illustrated in Segment 3. A comparison of the Mollier diagram and the psychrometric chart reveals convincing similarity between these two versatile and commonly applied thermodynamics tools. Some schools of thought explain the process of transformation of the Mollier diagram to the psychrometric chart on the basis of geometric manipulation. This relationship between Mollier diagram and the psychrometric chart is apparent from the fact that both involve critical thermodynamic properties such as enthalpy, temperature, sensible heat, latent heat and quality.

A comparison of the Mollier diagram and the steam tables also reveals a marked similarity and equivalence between the two. This equivalence is illustrated through Example 3.6 in Segment 3. The reader would be better prepared to appreciate the illustration of the relationship between the Mollier diagram and the steam tables after gaining a clear comprehension of the saturated and superheated steam tables in Segment 3. Example 3.6 demonstrates the interchangeability of the Mollier diagram and the Superheated Steam Tables as equivalent tools in deriving the enthalpy values associated with the change in the temperature of superheated steam. This equivalence between Mollier diagram and the steam tables is further reinforced by the fact that both involve critical thermodynamic properties of steam such as enthalpy, entropy, temperature and pressure. Application of Mollier Diagram A common application of Mollier diagram involves determination of an unknown parameter among the key Mollier diagram parameters such as, enthalpy, entropy, temperature pressure and quality. Typical applications of Mollier diagram are illustrated through the example problems that follow.

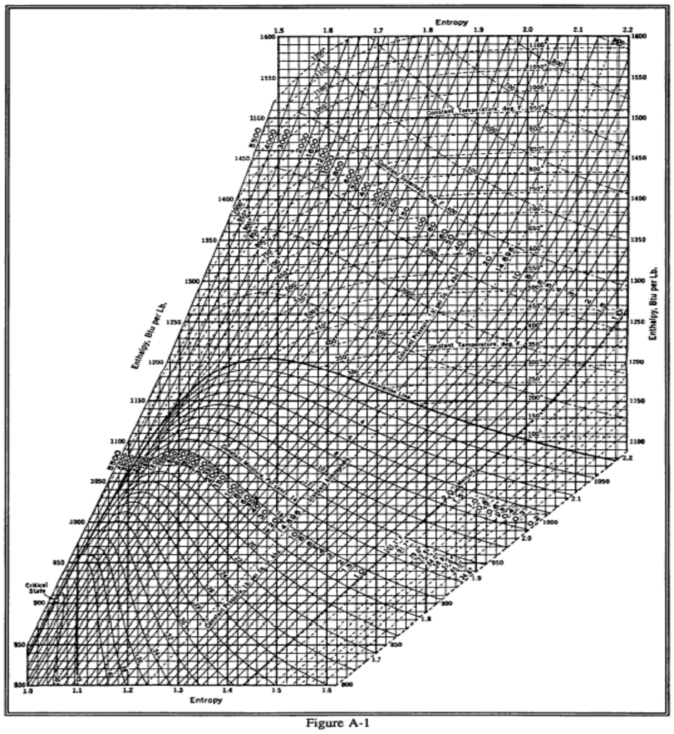


Fig .3.10 Mollier chart

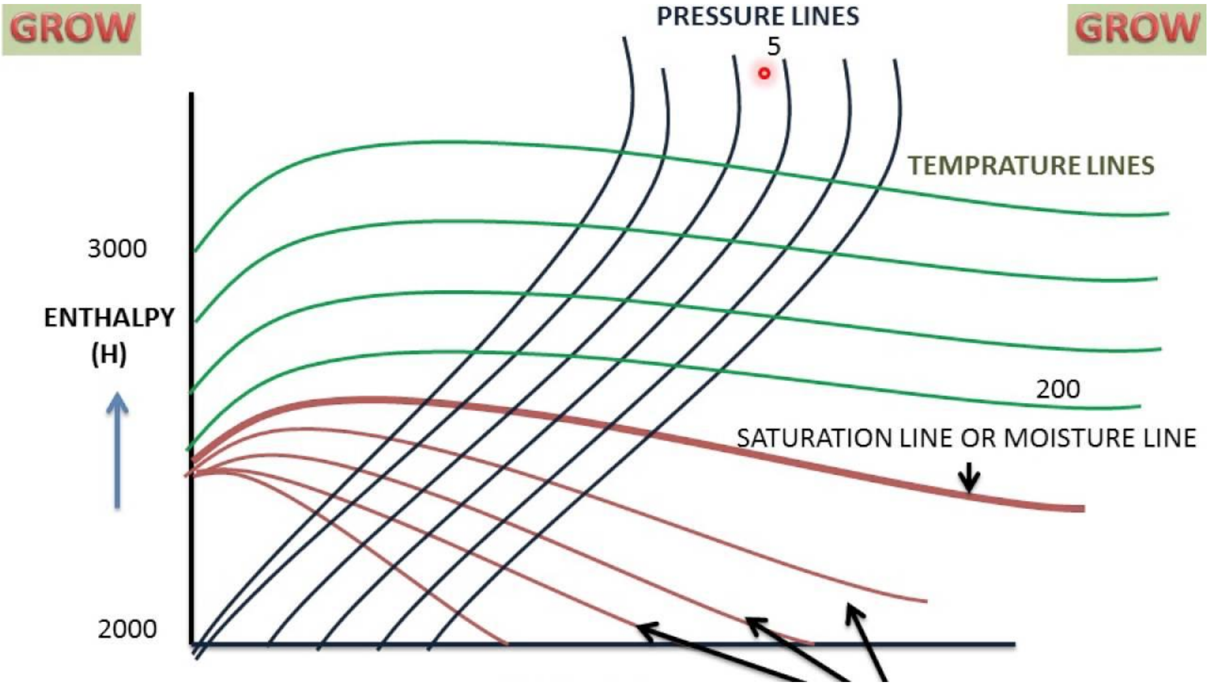


Figure 3.11 – Mollier Diagram, SI/Metric Units

## 3.7 PSYCHOMETRIC PROPERTIES

Here is a differentiation of reliability and validity as applied to the preparation of research instruments.
One of the most difficult parts in research writing is when the instrument's psychometric properties are scrutinized or questioned by your panel of examiners. Psychometric properties may sound new to you, but they are not actually new.

In simple words, psychometric properties refer to the reliability and validity of the instrument. So, what is the difference between the two?

Reliability refers to the consistency while validity refers to the test results' accuracy. An instrument should accurately and dependably measure what it ought to measure. Its reliability can help you have a valid assessment; its validity can make you confident in making a prediction.

## 3.8 INSTRUMENT'S RELIABILITY

How can you say that your instrument is reliable? Although there are many types of reliability tests, what is more usually looked at is the internal consistency of the test. When presenting the results of your research, your panel of examiners might look for the results of the Cronbach's alpha or the Kuder-Richardson Formula 20 computations. If you cannot do the analysis by yourself, you may ask a statistician to help you process and analyze data using a reliable statistical software application.

But if your intention is to determine the inter-correlations of the items in the instrument and if these items measure the same ***construct***, Cronbach's alpha is suggested. According to David Kingsbury, a construct is the behavior or outcome a researcher seeks to measure in the study. This is often revealed by the independent variable.

When the inter-correlations of the items increase, the Cronbach's alpha generally increases as well. The table below shows the range of values of Cronbach's alpha and the corresponding descriptions on internal consistency.

## 3.9 INSTRUMENT'S VALIDITY

There are many types of validity measures. One of the most commonly used is the construct validity. Thus, the *construct* or the independent variable must be accurately defined.

To illustrate, if the independent variable is the school principals' leadership style, the sub-scales of that construct are the types of leadership style such as authoritative, delegative and participative.

The construct validity would determine if the items being used in the instrument have good validity measures using factor analysis and each sub-scale has a good inter-item correlation using Bivariate Correlation. The items are considered good if the p-value is less than 0.05.

## 3.10 THERMODYNAMIC METHOD OF MEASURING HUMIDITY

It is the only method used in mines. The instruments used are called hygrometers or psychrometers. These instruments have a pair of thermometers, one of them having its bulb covered with wet muslin cloth. The thermometer with wet bulb muslin cloth on its bulb records wet-bulb temperature and the other one records dry-bulb temperature. These two temperatures along with barometric pressure is used in calculating humidity. Let us understand the three terms separately.

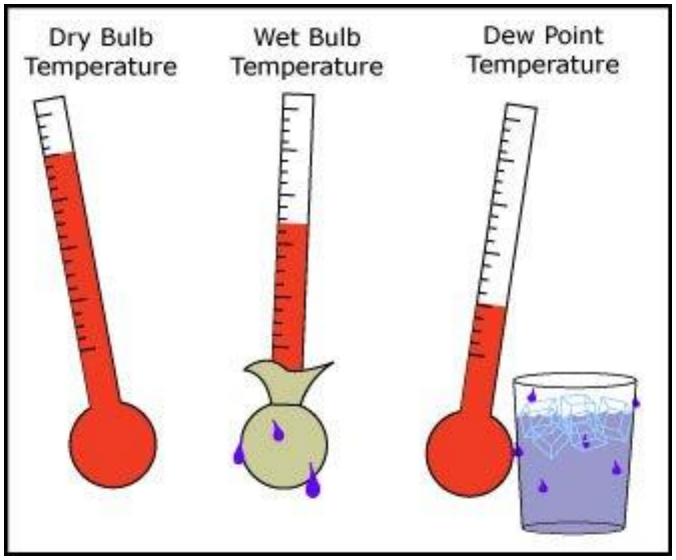


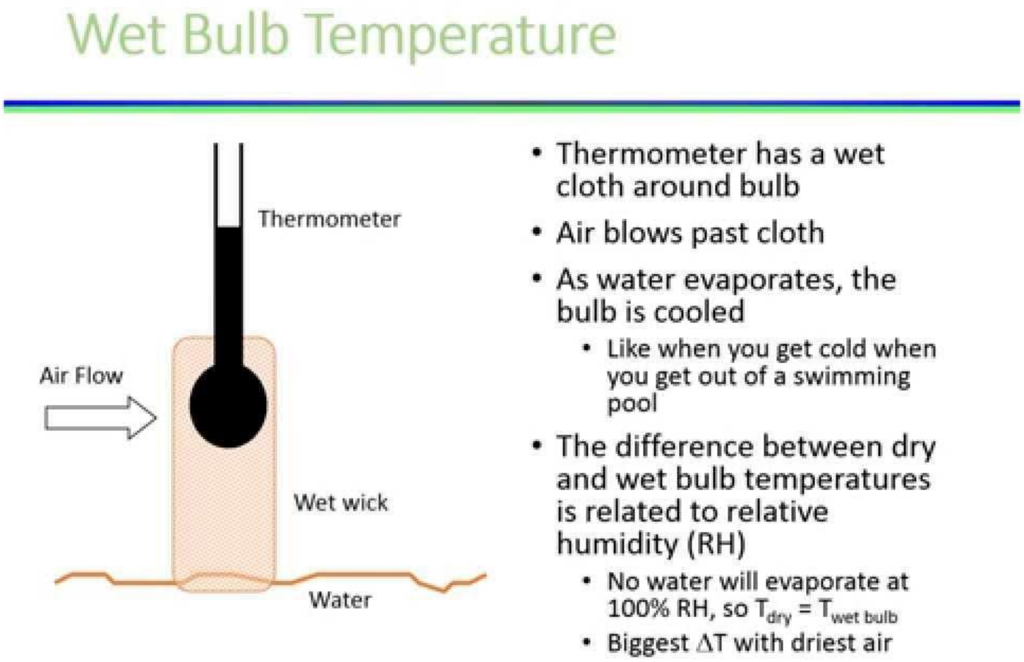
Fig .3.12 Types of temperatures

## 3.11 DRY-BULB TEMPERATURE

It is the temperature recorded by using a conventional thermometer. The thermometer without muslin cloth in the psychrometer records dry-bulb temperature. It just reads the ordinary temperature of the air and is a measure of sensible heat content of the air. Its unit is °F or °C or kelvin (K).

## 3.12 WET-BULB TEMPERATURE

It is recorded by thermometer having wet muslin cloth on its bulb. The temperature recorded is in general lower than dry-bulb temperature because of cooling effect of the evaporating water of wet muslin cloth. They are equal only when air is in saturation and no net evaporation of water from wet muslin cloth takes place. Wetbulb temperature can never be higher than dry-bulb temperature. From the definition point of view, it is defined as the temperature at which water vapour evaporating into the air can bring down the air in saturation adiabatically at that temperature. It is a measure of the evaporating capacity of the air. Its unit is °F or °C or kelvin (K).



Wet Bulb Temperature

- Thermometer has a wet cloth around bulb
- Air blows past cloth
- As water evaporates, the bulb is cooled
  - Like when you get cold when you get out of a swimming pool
- The difference between dry and wet bulb temperatures is related to relative humidity (RH)
  - No water will evaporate at 100% RH, so $T_{dry} = T_{wet\ bulb}$
  - Biggest ΔT with driest air

Fig .3.13 Wet bulb temperature

### 3.13 CONCEPT OF WET-BULB TEMPERATURE

The water molecules in the wet muslin cloth take up energy from the neighboring molecules and evaporate into the air. The evaporating molecules leave the thermometer surface with reduced energy. This causes depression in the temperature near the thermometer bulb. Thus, lower temperature is recorded. Thus, a difference between the temperature at the bulb and the atmosphere exists. This causes flow of heat from the air through convection. Initially this flow of heat from air to bulb with wet muslin cloth is slower than the rate of heat loss from the bulb with wet muslin due to evaporation. But, a stage comes when the rate of heat loss and rate of heat gained in the two opposite processes equal. At this point, no further depression in temperature of wet-bulb is observed. At equilibrium, the temperature of thermometer with wet muslin cloth on its bulb is taken as wet-bulb temperature.

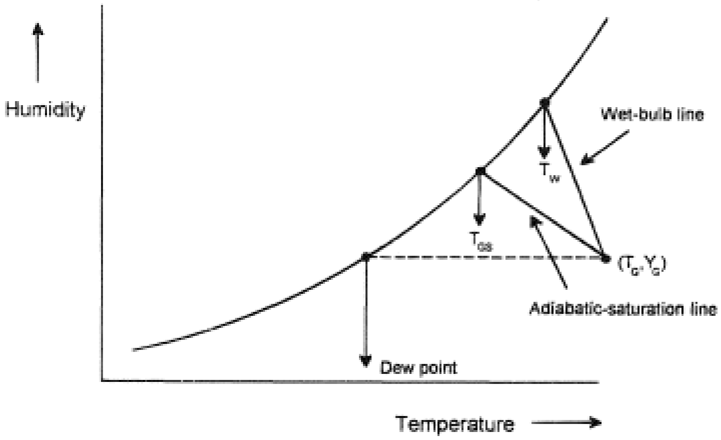


Fig .3.14 Temperature and humidity

### 3.14 DEW POINT TEMPERATURE

It is defined as the temperature at which air attains saturation and a further addition of water vapour leads to dew formation because of condensation of water vapour. It is rarely used to indicate the moisture content of the air/atmosphere. The temperature recorded in this case is dry bulb temperature. But let me tell that at dew point, dry bulb and wet bulb temperature are same [as per equation (2) in Lecture 1 and Lecture 2]. What can be inferred from the above sentences are as follow: - At saturation point e and esw are same. - Relative humidity of the air is 100%. - Specific humidity = 0.622esw/(Pb –esw) kg/kg dry air - Dry bulb temperature and wet bulb temperature are same. - Dew point suggests that if further moisture is added to the atmosphere, it will condense into mist/dew. This indicates that both evaporation and condensation process are taking place at equal rate. Thus, there cannot be any net evaporation in the system.

### 3.15 THERMODYNAMIC WET BULB TEMPERATURE

The thermodynamic wet-bulb temperature is the temperature a volume of air would have if cooled adiabaticallyto saturation by evaporation of water into it, all latent heat being supplied by the volume of air.

The temperature of an air sample that has passed over a large surface of the liquid water in an insulated channel is called the thermodynamic wet-bulb temperature—the air has become saturated by passing through a constant-pressure, ideal, adiabatic saturation chamber.

Meteorologists and others may use the term "isobaric wet-bulb temperature" to refer to the "thermodynamic wet-bulb temperature". It is also called the "adiabatic saturation temperature", though it should be pointed out that meteorologists also use "adiabatic saturation temperature" to mean "temperature at the saturation level", i.e. the temperature the parcel would achieve if it expanded adiabatically until saturated.

## 3.16 THERMODYNAMIC WET-BULB TEMPERATURE IS PLOTTED ON A PSYCHOMETRIC CHART.

The thermodynamic wet-bulb temperature is a thermodynamic property of a mixture of air and water vapour. The value indicated by a simple wet-bulb thermometer often provides an adequate approximation of the thermodynamic wet-bulb temperature.

For an accurate wet-bulb thermometer, "the wet-bulb temperature and the adiabatic saturation temperature are approximately equal for air-water vapor mixtures at atmospheric temperature and pressure. This is not necessarily true at temperatures and pressures that deviate significantly from ordinary atmospheric conditions, or for other gas–vapor mixtures."[4]

## 3.17 RELATIVE HUMIDITY

It is defined as the ratio of vapour pressure at a temperature to the saturation vapour pressure at that dry bulb temperature. It should be kept in mind that for calculating relative humidity, saturation vapour pressure is taken at dry bulb temperature and not at wet bulb temperature. Numerically it can be expressed as:

$Relativehumidity = eesd \times 100\%$ …….(3.1)

Using equation $e = esw - 0.000644\ Pb\ (td - tw)\ kPa$ …………………..(3.2)

and

$es = 610.6\ ex(\ 17.27{*}t\ 237.3{+}t\ )\mathrm{Pa}$ …………………….(3.3)

described in Lecture – 1, equation (1)

can be written as:

$Relativehumidity = (esw - 0.000644\ Pb\ (td - tw)\ kPa0)/(0.6106\ exp\ (\ 17.27{*}td\ 237.3{+}td\ ))kPa \times 100\ \%$

We can see that, relative humidity is unit less. It is represented in percentage.

## 3.18 SPECIFIC HUMIDITY

It is defined as the mass of water vapour present in kg per kg of dry air. Mathematically it is expressed as follow.

$Specifichumidity$ = 0.622 $ePb - ekgkgdryair$ …..(3.4)

Where, e = Vapour pressure or Partial pressure due to water vapour (kPa)

Pb = barometric pressure (kPa)

### 3.19 DEGREE OF SATURATION

It is stated as the ratio of weight of water vapour in air at given conditions to the weight of the water vapour in air at saturation, keeping temperature constant. It is Page 5 of 9 also called saturation ratio or percentage humidity. Mathematically, it can be expressed as

Degree of saturation= 0.622( $/Pb - e$ )/(0.622 $esd\ /Pb - esd$ )× 100% = ($e/\ Pb - e$)/( $esd/\ Pb - esd$) × 100% ..(6)

Where,

e = Vapour pressure or Partial pressure due to water vapour (kPa)

Pb = Barometric pressure (kPa )

esd = Saturation vapour pressure at wet bulb temperature (kPa)

We can see that e and esd are very small compared to Pb , so we can neglect them and equation (6) becomes equal to equation (3). From this, we can take degree of saturation approximately equal to relative humidity, but numerically they are not similar.

Of all the humidity terminology discussed, specific humidity is most widely used.

Now, let us discuss some of the very conceptual points.

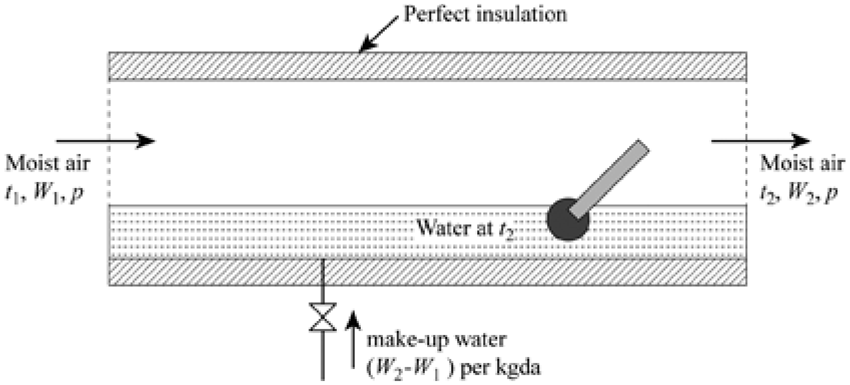
- Water vapour is not a chemical constituent of air. It is like an impurity to air like dust, smog, etc.

- Instead of saying air is saturated, it is better to say that space is saturated. Actually it is the space which becomes saturated, and not air. It means that even if we evacuate a system and fill it with water vapour, the system can hold the same amount of water vapour that air of the same volume can hold at that temperature. But, conventionally we call it as air is saturated.

### 3.20 ADIABATIC SATURATION

Adiabatic saturation temperature refers to a temperature at which water converts into air by the process of evaporation adiabatically. The device used for this type of process is known as adiabatic saturator.

The adiabatic saturator device is shown below in Figure .



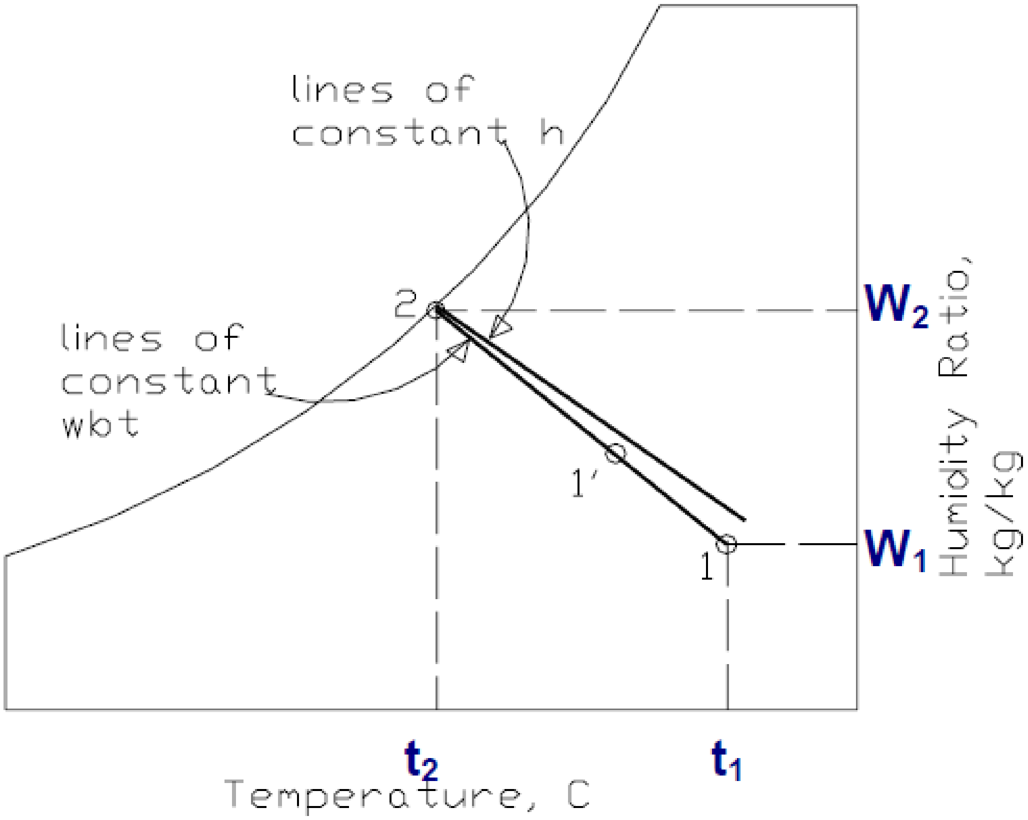


Fig 3.15 Adiabatic saturation

As seen in Figure (1), moist air is entering into the saturator device duct from the left and exiting at the right. When air comes in contact with water, heat and mass transformation takes place. For a perfect equilibrium condition, the duct should be long so that air can be fully saturated. To proceed with the procedure, make-up water must be given to adjust for the measure of water dissipated into the air.

The temperature of the make-up water is controlled with the goal that it is the same as that in the channel. After the adiabatic saturator has accomplished an equilibrium state condition, the temperature demonstrated by the thermometer drenched in the water is the thermodynamic wet-bulb temperature.

The wet bulb temperature is measured by the thermometer. Here the bulb of the thermometer is wrapped in a wet cloth. When air passes through it heat will be extracted and cloth absorbs some moisture which results into the reduction of temperature of air. The wet bulb temperature is the lowest temperature and is always equal to or less than the dry point temperature, but always greater than dew point temperature.

## 3.21 CARRIER'S EQUATION

When DBT and WBT are given, for calculating the partial pressure of water vapour in air many equations have been proposed of which Dr. Carriers equation is most widely used.
Where,

$$p_v = (p_g) - \frac{(p-p_g)-(t_{db}-t_{wb})1.8}{2800-1.3(1.8t_{db})+32} \qquad (3.5)$$

$(p_g)_{wb}$ = saturation pressure at wet bulb temperature.
$p_v$ = partial pressure of water vapour
$p_g$ = partial pressure of saturated vapour
p = total pressure of moist air
$t_{db}$ = dry bulb temperature, $^0$C
$t_{wb}$ = wet bulb temperature, $^0$C

## 3.22 PSYCHOMETRIC CHART.

A Psychometric chart graphically represents the thermodynamic properties of moist air. Standard psychometric charts are bounded by the dry-bulb temperature line (abscissa) and the vapor pressure or humidity ratio (ordinate). The Left Hand Side of the psychometric chart is bounded by the saturation line. Figure 27.2 shows the schematic of a psychometric chart. Psychometrics charts are readily available for standard barometric pressure of 101.325 kPa at sea level and for normal temperatures (0-50o C). ASHRAE has also developed psychometrics charts for other temperatures and barometric pressures (for low temperatures: -40 to 10o C, high temperatures 10 to 120o C and very high temperatures 100 to 120o C)

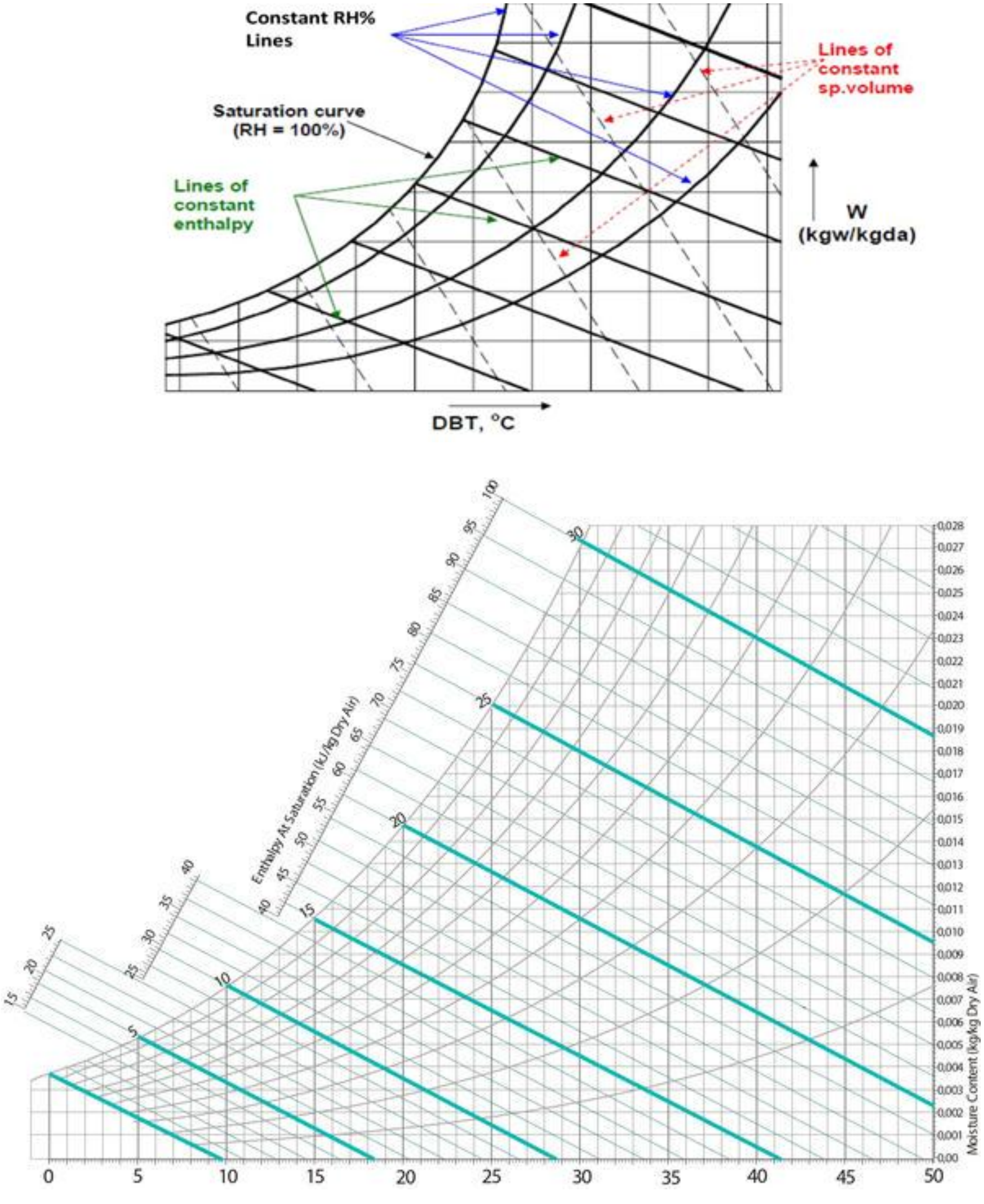


Fig 3.16 Psychometric chart graphically represents the thermodynamic properties of moist air

Psychrometer is an instrument to measure the wet-bulb and dry-bulb temperature of an air-water vapour mixture. This instrument uses the principle of adiabatic saturation. The specific humidity and relative humidity of air-water vapour mixture can be determined with knowledge of dry-bulb and wet-bulb temperatures figure 36.1

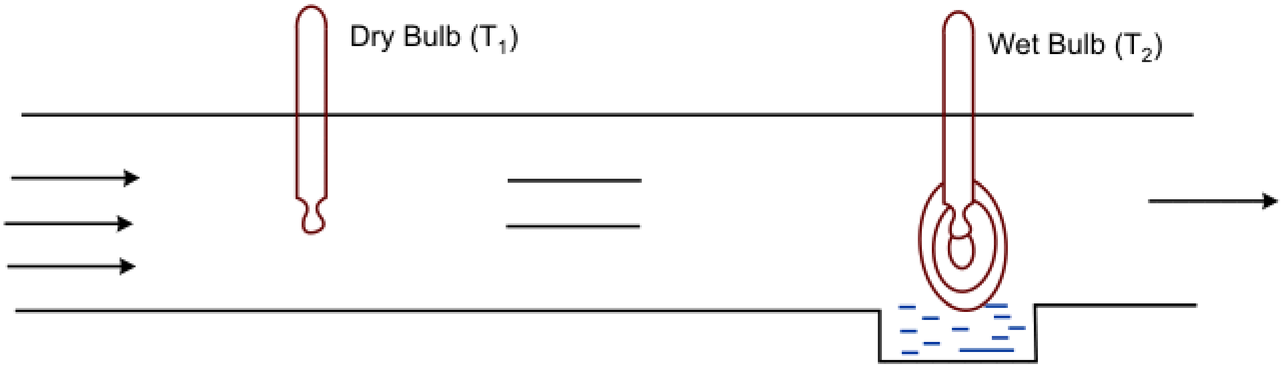


Fig3.17 Dry-Bulb Temperature

- The dry-bulb temperature is the temperature of the incoming mixture.
- The wet-bulb temperature is the temperature of the saturated air-water vapour mixture.
- For air-water vapour mixtures, the wet- bulb temperature is found to be approximately equal to the adiabatic Saturation temperature (AST).
- If $T_1$ and $T_2$ are known, $SH_1$ & $RH_1$ can be found out.
- The enthalpy of air-water vapour mixture is expressed as

$$h^* = ha + (SH)hw \tag{3.5.1}$$

where $hw$ is the enthalpy of the accompanying water vapour, and $SH = w = \dot{m}_w / \dot{m}_a$

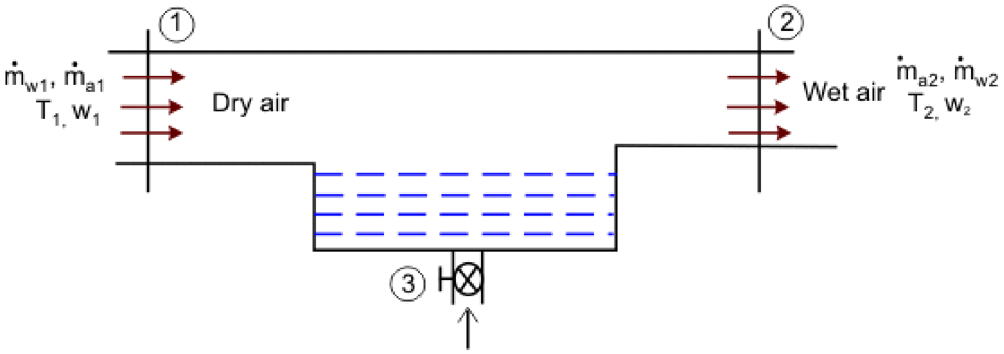


Fig3.18 Air-Water Vapour Mixture

## 3.23 Adiabatic Saturation

Specific humidity or the relative humidity of an air – water vapour mixture can be measured in principle with the help of a device called the adiabatic saturator (see figure35.2).

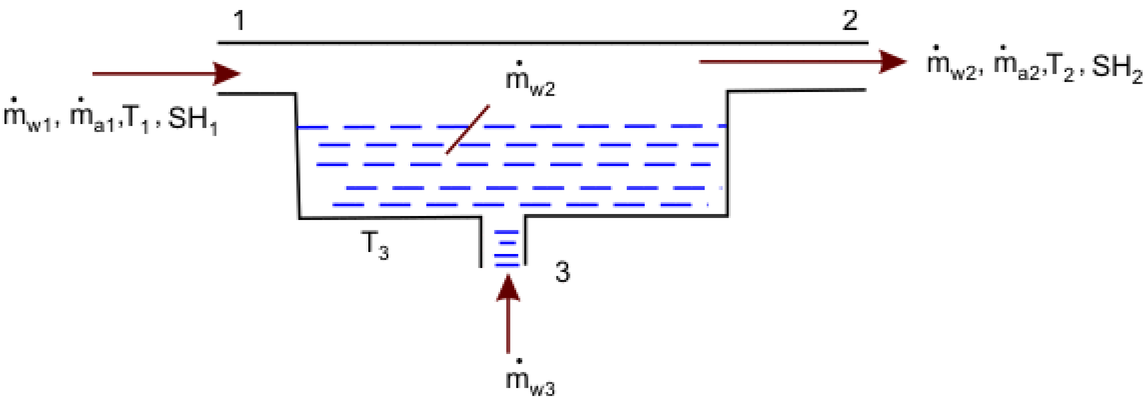


Fig 3.19 Adiabatic Saturation

The air – water vapour mixture flows steadily into the device. The SH or $w$ of the incoming mixture has to be determined.

The air – water vapour mixture leaves the adiabatic saturator as saturated mixture. Let the device be insulated so that there is no energy loss.

Since the unsaturated air – water vapour mixture is sweeping over a layer of liquid water, some water evaporates. The energy needed for the evaporation comes from the air mixture. Hence, the air – water vapour mixture leaves the adiabatic saturator at a temperature lower than that of the entering air. As the air leaving the adiabatic saturator is in equilibrium with the liquid water, the temperature of the liquid water is equal to the temperature of the saturated air – water vapour mixture.

Mass balance for air

$$\dot{m}_{a1} = \dot{m}_{a2} \qquad (3.6)$$

Mass balance for water

$$\dot{m}_{w1} + \dot{m}_{w3} = \dot{m}_{w2} \qquad (3.7)$$

Energy balance

$$\dot{m}_{a1}h_{a1}+\dot{m}_{w1}h_{w1}+\dot{m}_{w3}h_{w3}=\dot{m}_{a2}h_{a2}+\dot{m}_{w2}h_{w2} \qquad (3.8)$$

Dividing (35.17) by $\dot{m}_{a1}\left(=\dot{m}_{a2}\right)$

$$\frac{\dot{m}_{w1}}{\dot{m}_{a1}}+\frac{\dot{m}_{w3}}{\dot{m}_{a1}}=\frac{\dot{m}_{w2}}{\dot{m}_{a2}}$$

$$SH_1+\frac{\dot{m}_{w3}}{\dot{m}_{a1}}=SH_2$$

$$\dot{m}_{w3}=\dot{m}_{a1}\left(SH_2-SH_1\right) \qquad (3.9)$$

Dividing (35.18) by $\dot{m}_{a1}$

$$h_{a1}+SH_1h_{w1}+\left(SH_2-SH_1\right)h_{w3}=h_{a2}+SH_2h_{w2}$$

or

$$SH_1=\frac{\left(h_{a2}-h_{a1}\right)+SH_2\left(h_{w2}-h_{w3}\right)}{\left(h_{w1}-h_{w3}\right)}=w_1 \qquad (3.10)$$

The quantity

$$\left(h_{a2}-h_{a1}\right)$$

$$=c_p\left(T_2-T_1\right)$$

Another term, $\left(h_{w2}-h_{w3}\right)$ has to be estimated properly.

Here $h_{w2}$ refer to the enthalpy of saturated water vapour at temperature $T_2$ and $h_{w3}$ refers to the enthalpy of the saturated liquid at temperature $T_3$ or $T_2$ $\left(T_2=T_3\right.$ ) water pool temperature at steady state is same as $T_2$ )

Therefore

$$\left(h_{w2} - h_{w3}\right) = \left(h_{fg}\right)_2 \tag{3.11}$$

$h_{w1} = h_{g1} =$ enthalpy of the saturated water vapour at state 1

$h_{w3} = h_{f3} =$ enthalpy of the saturated liquid water at temperature $T_3$ or $T_2$, $= h_{f2}$

$T_2$ does not depend on the temp at which the liquid water enters the device (make-up water temperature)

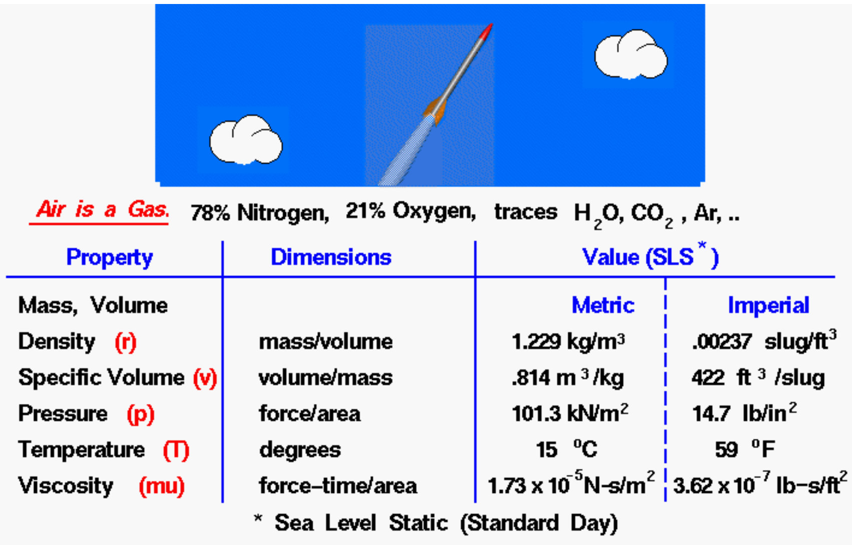
The adiabatic saturation temperature $T_2$ depends only on the conditions $T_1, SH_1$ of the entering fluid.

Finally

$$SH = w_1 = \frac{c_p\left(T_2 - T_1\right) + w_2 h_{fg2}}{h_{g1} - h_{f2}} \tag{3.12}$$

### 3.24 Properties of Atmospheric Air

Dry air is a mechanical mixture of the following gases: Oxygen, nitrogen, carbon dioxide, hydrogen, argon, neon, krypton, helium, ozone, and xenon. Dry air is considered to consist of 21% oxygen and 79% nitrogen by volume. It consists of 23% oxygen, and 77% nitrogen by mass.



Air is a Gas. 78% Nitrogen, 21% Oxygen, traces $H_2O$, $CO_2$, Ar, ..

| Property | Dimensions | Value (SLS*) | |
|---|---|---|---|
| Mass, Volume | | Metric | Imperial |
| Density (r) | mass/volume | 1.229 kg/m³ | .00237 slug/ft³ |
| Specific Volume (v) | volume/mass | .814 m³/kg | 422 ft³/slug |
| Pressure (p) | force/area | 101.3 kN/m² | 14.7 lb/in² |
| Temperature (T) | degrees | 15 °C | 59 °F |
| Viscosity (mu) | force–time/area | $1.73 \times 10^{-5}$ N-s/m² | $3.62 \times 10^{-7}$ lb–s/ft² |

* Sea Level Static (Standard Day)

Fig .3.20 Gas properties

Water vapour in varying amount is diffused through it. If Pa and Pware the partial pressures of dry air and water vapour respectively, then by Dalton's law of partial pressure

$$Pa + Pw = P \qquad (3.13)$$

Where P is the atmospheric pressure

### 3.25 Mole – fraction of dry air,

$$Y_a = \frac{P_a}{P} = P_a \qquad (3.14)$$

$P_m$ is considered to be 1 atm

### 3.26 Mole – fraction of water vapour,

$$Y_w = \frac{P_w}{P} = P_w \qquad (3.15)$$

Since $P_w$ is very small, the saturation temperature of water vapour at $P_w$ is less than the atmospheric temperature $T_{atm}$. So the water vapour in air exists in the superheated state, and the air is said to be unsaturated.

If the air- water vapour mixture which is initially not saturated is cooled at constant pressure, the partial pressure of water vapour in the mixture remains constant till it is equal to the saturation pressure of water. Further cooling result in condensation of water vapour. The temperature at which the vapour condenses when the air-water vapour mixture is cooled at constant pressure, is called Dew Point (Figure 35.1)

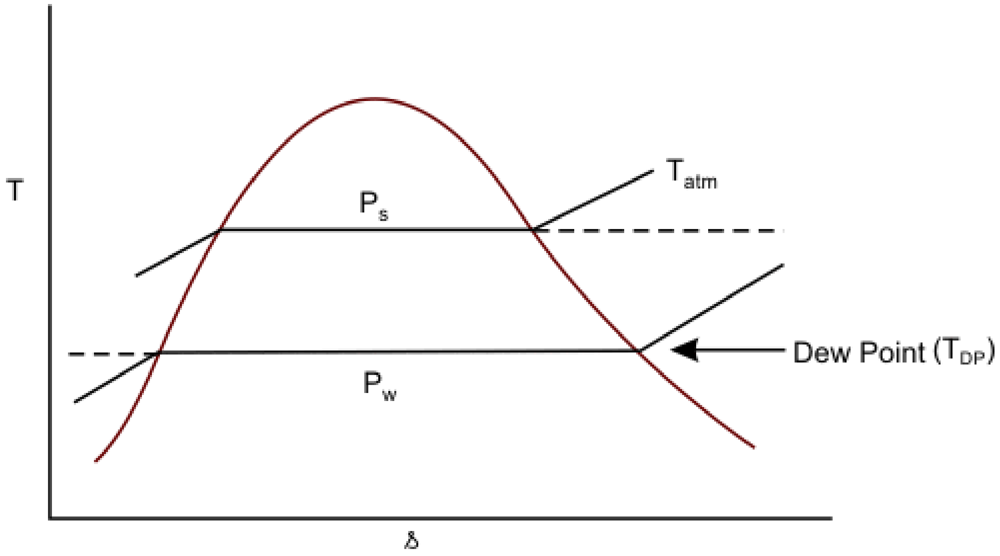


Fig 3.21 Mole – fraction of water vapour

### 3.27 Relative Humidity (RH)

Relative humidity is defined as the ratio of partial pressure of water vapour, $P_w$, in a mixture to the saturation pressure, $P_s$ of pure water at the temperature of the mixture

$$RH = \frac{P_w}{P_s} = \phi \tag{3.16}$$

If water is injected into unsaturated air in a container, water will evaporate, which will increase the moisture content of the air. and $P_w$ will increase. This will continue till the air becomes saturated at that temperature and there will be no more evaporation of water. For saturated air, relative humidity is 100%. Assuming water vapour as an ideal gas,

$$P_w V = m_w R_{H_2O} T = N_W \bar{R} T \tag{3.17}$$

$$P_s V = m_s R_{H_2O} T = N_s \bar{R} T \tag{3.18}$$

And V is the volume and T the temperature of air, the subscripts W and s indicating the unsaturated and saturated states of air respectively.

$$\boxed{RH = \frac{P_w}{P_s} = \frac{m_w}{m_s}} = \phi \tag{3.19}$$

RH= mass of water vapour in a given volume of air at temperature T / mass of water vapour when the same volume of air is saturated at temperature T

$$= \frac{N_w}{N_s} = \frac{Y_w}{Y_s} \tag{3.20}$$

### 3.28 Specific Humidity or Humidity Ratio

SH is defined as the **mass of water vapour** per unit **mass of dry air** in a mixture of air and water vapour.

If $m_a$ = mass of dry air, $m_w$ = mass of water vapour

$$SH = \frac{m_w}{m_a} = w \tag{3.21}$$

Also we know that

$$P_w = m_w R_w T \text{ and } P_a V = m_a R_a T \tag{3.22}$$

$$SH = \frac{m_w}{m_a} = \frac{P_w}{P_a} . \frac{R_a}{R_w} = w \tag{3.23}$$

or,

$$SH = \frac{P_w}{P_a} . \frac{8.3143/28.96}{8.3143/18} = 0.622 \frac{P_w}{P_a} = w \tag{3.24}$$

Or

$$\boxed{SH = 0.622\frac{P_w}{(P - P_w)} = w} \tag{3.25}$$

Where P is the atmosperic pressure

Relative humidity,

$$RH = \phi = \frac{P_w}{P_s} \tag{3.26}$$

$$w = 0.622\frac{P_w}{P_s}.\frac{P_s}{P_a} = 0.622\phi\frac{P_s}{P_a}$$

Or

$$w = 0.622\phi\frac{P_s}{P - P_w} = 0.622\phi\frac{P_s}{P - \phi P_s}$$

Or

$$\phi = \frac{w}{0.622}.\frac{P_a}{P_s} \tag{3.27}$$

If a mixture of air and superheated (or unsaturated) water vapour is cooled at constant pressure, the partial pressure of each constituent remains constant until the water vapour reaches its saturated state. Further cooling causes condensation. The temperature at which water vapour starts condensing is called the dew point temperature $T_{DP}$ of the mixture. it is equal to the saturation temperature at the partial pressure, $P_w$ of the water vapour in mixture..

# Module-IV

# POWER CYCLES

## 4.1 INTRODUCTION

Our study of gas power cycles will involve the study of those heat engines in which the working fluid remains in the gaseous state throughout the cycle.

We often study the ideal cycle in which internal irreversibility's and complexities (the actual intake of air and fuel, the actual combustion process, and the exhaust of products of combustion among others) are removed.

We will be concerned with how the major parameters of the cycle affect the performance of heat engines. The performance is often measured in terms of the cycle efficiency.

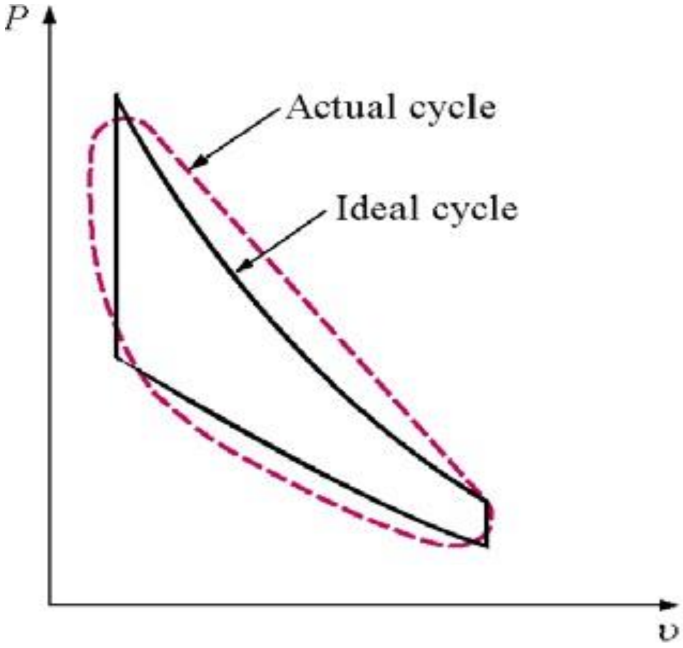


Fig 4.1 plot between actual cycle and ideal cycle

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

The use of Eq results in an expression for the thermal efficiency of a system undergoing a reversible power cycle while operating between thermal reservoirs at temperatures which is known as the Carnot efficiency. As temperatures on the Rankine scale differ from Kelvin temperatures only by the factor 1.8, the T's in Eq. 5.9 may be on either scale of temperature. Recalling the two Carnot corollaries, it should be evident that the efficiency given by Eq. 4.2 is the thermal efficiency of all reversible power cycles operating between two reservoirs at temperatures TH and TC, and the maximum efficiency any power cycle can have while operating between the two reservoirs. By inspection, the value of the Carnot efficiency increases as TH increases and/or TC decreases. Equation 4.1 is presented graphically in Fig. 4.1. T

he temperature TC used in constructing the figure is 298 K in recognition that actual power cycles ultimately discharge energy by heat transfer at about the temperature of the local atmosphere or cooling water drawn from a nearby river or lake. Note that the possibility of increasing the thermal efficiency by reducing TC below that of the environment isnot practical, for maintaining TC lower than the ambient temperature would require a refrigerator that would have to be supplied work to operate. Figure 4.1 shows that the thermal efficiency increases with TH. Referring to segment a–b of the curve, where TH and h are relatively low, we see that h increases rapidly as TH increases, showing that in this range even a small increase in TH can have a large effect on efficiency. Though these conclusions, drawn as they are from Eq. 4.2 apply strictly only to systems undergoing reversible cycles, they are qualitatively correct for actual power cycles. The thermal efficiencies of actual cycles are observed to increase as the average temperature at which energy is added by heat transfer increases and/or the average temperature at which energy is discharged by heat transfer decreases. However, maximizing the thermal efficiency of a power cycle may not be the only objective. In practice, other considerations such as cost may be overriding. Conventional power-producing cycles have thermal efficiencies ranging up to about 40%. This value may seem low, but the comparison should be made with an appropriate limiting value and not 100%.

## 4.2 MEAN EFFECTIVE PRESSURES ON AIR STANDARD BASIS

The air standard cycles-In what are known as air standard cycles, or ideal cycles, the constant volume, constant pressure and adiabatic processes are put together to form theoretical engine cycles which we can show on the *p*/*V* diagram. The actual *p*/*V* diagram is different from what is possible in practice, because, for instance, we assume that the gas is air throughout the cycle when in fact it may be combustion gas. We also assume that valves can open and close simultaneously and that expansion and compressions are adiabatic.

Air standard cycles are reference cycles which give an approximation to the performance of internal combustion engines.

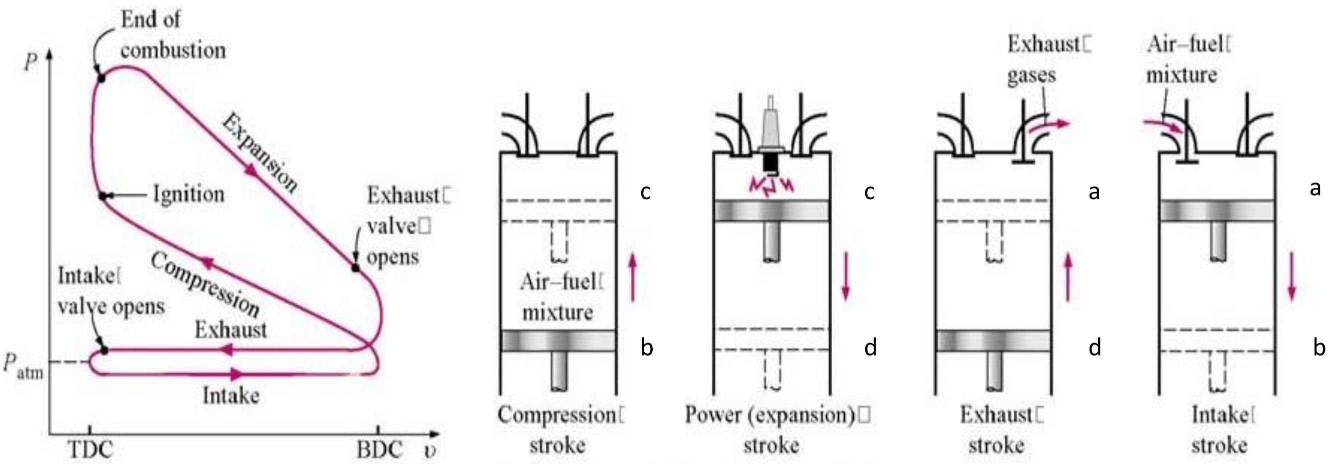
Constant volume (Otto) cycle

This is the basis of the petrol engine cycle.

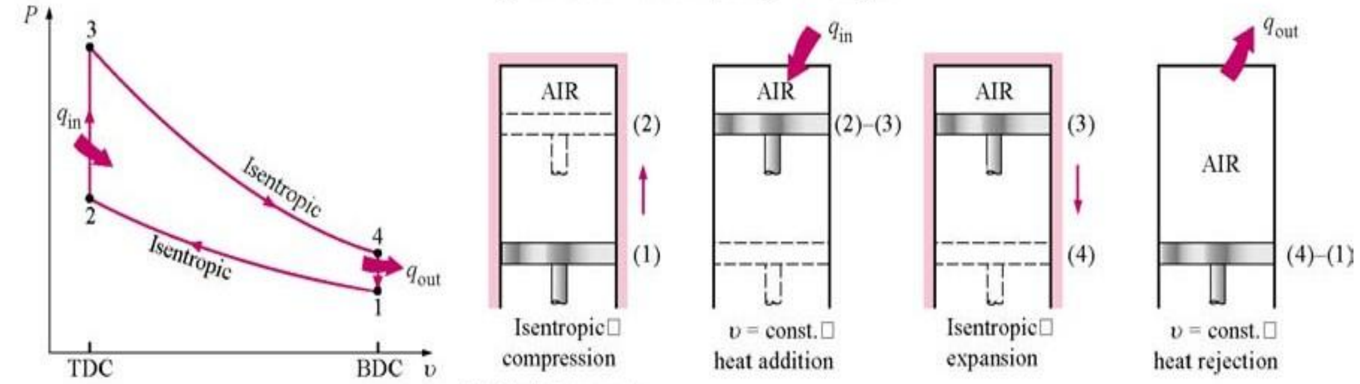
Figure -shows the cycle, made up of an adiabatic compression, 1–2 (piston rises to compress the air in the cylinder), heat energy added at constant volume, 2–3 (the fuel burns), adiabatic expansion, 3–4 (the hot gases drive the piston down the cylinder), and heat energy rejected at constant volume, 4–1 (exhaust).

### 4.3 OTTO CYCLE: THE IDEAL CYCLE FOR SPARK-IGNITION ENGINES

1. Consider the automotive spark-ignition power cycle.
2. Processes Intake stroke
3. Compression stroke Power (expansion)
4. stroke Exhaust stroke



(a) Actual four-stroke spark-ignition engine



(b) Ideal Otto cycle

Fig 4.1 Otto cycle

Fig 4.2 The ideal cycle for spark-ignition engines

Often the ignition and combustion process begins before the completion of the compression stroke. The number of crank angle degrees before the piston reaches TDC on the number one piston at which the spark occurs is called the engine timing. What are the compression ratio and timing of your engine in your car, truck, ormotorcycle?

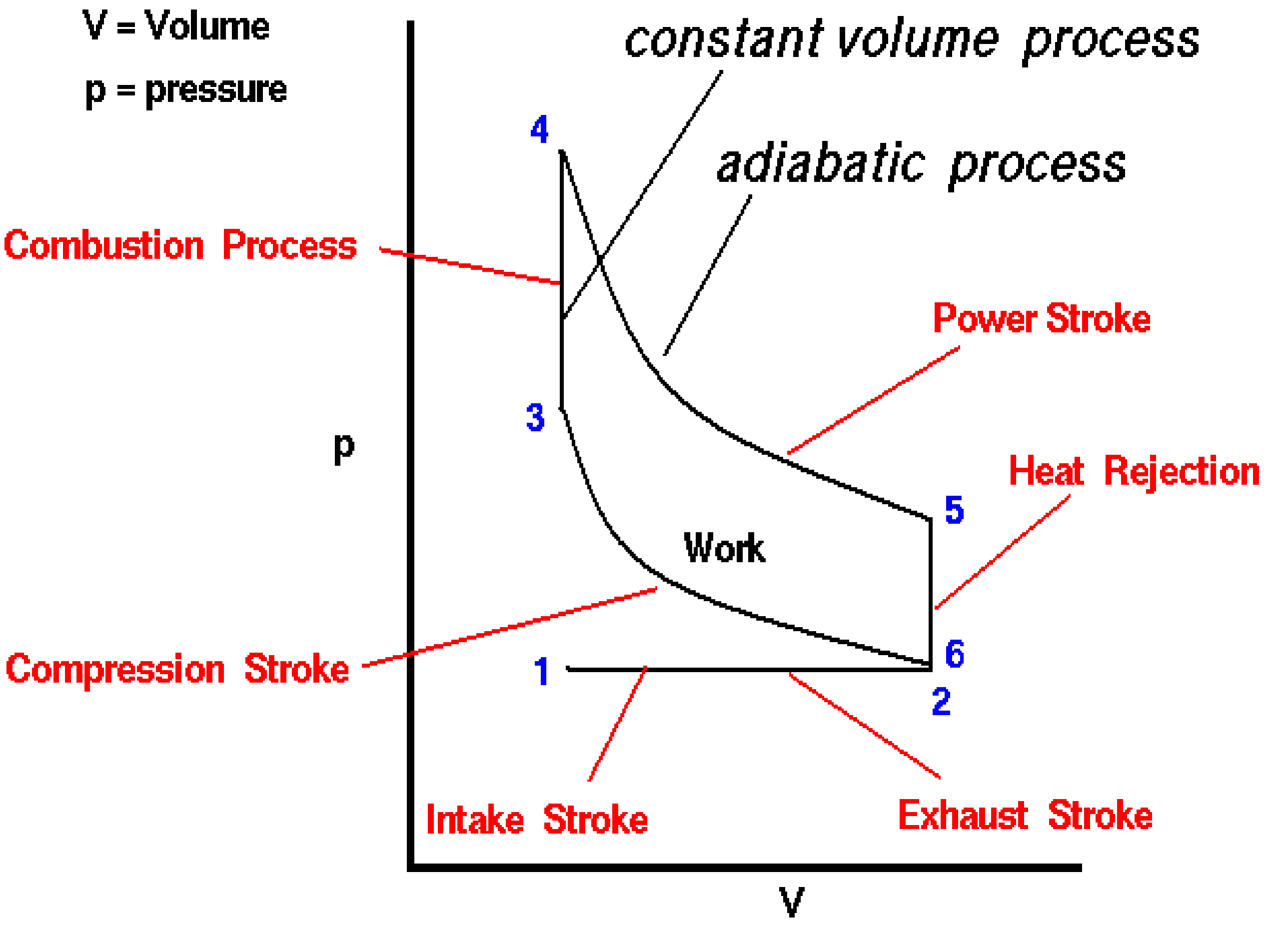


Fig 4.2 P-V Diagram

**4.3.1 The air-standard Otto cycle** is the ideal cycle that approximates the spark- ignition combustion engine.

| Process | Description |
|---|---|
| 1-2 | Isentropiccompression |
| 2-3 | Constant volume heataddition |
| 3-4 | Isentropicexpansion |

4-1 Constant volume heat rejection The *P*-*v* and *T*-*s* diagramsare

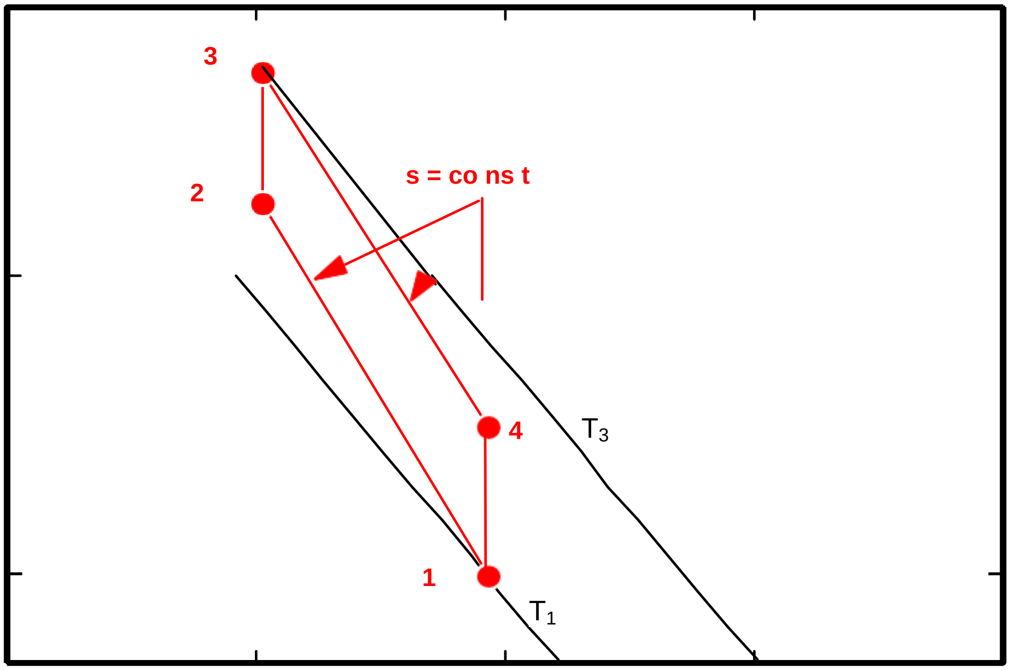


Fig 4.3 Air OttoCycleP -v Diagram

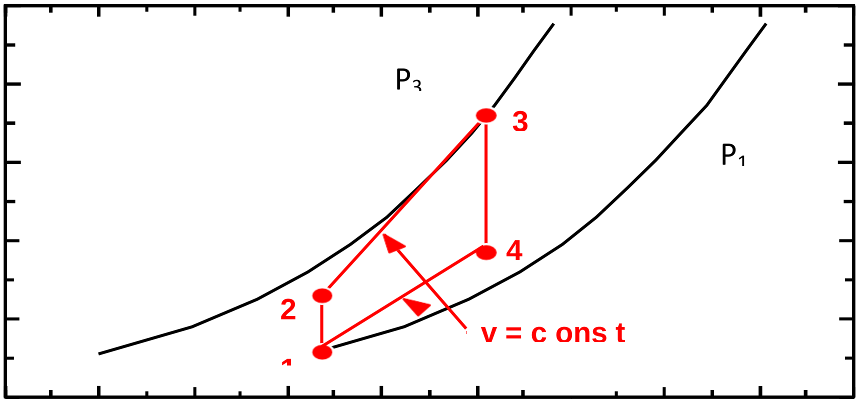


Fig 4.4 Air Otto Cycle T- s Diagram

## AIR STANDARD DUAL CYCLE

Figures 4.5 (a) and (b) shows the working principles of a Dual cycle. In the dual cycle, the energy addition is accomplished in two stages: Part of the energy is added at constant volume and part of the energy is added at constant pressure. The remaining processes are similar to those of the Otto cycle and the Diesel cycle. The efficiency of the cycle can be estimated in the following way

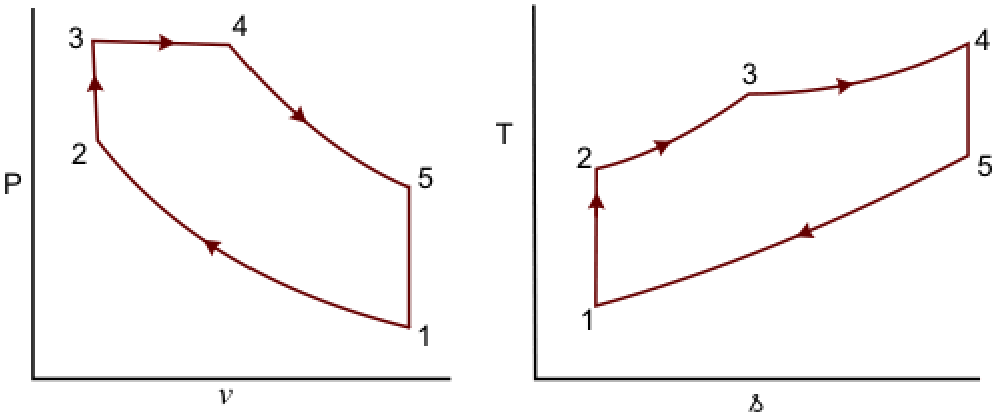


Figure 4.5 (a) P-V Diagram and (b) T –S Diagram

Energy added

$$q_1 = c_v(T_3 - T_2) + c_p(T_4 - T_3) \tag{4.1}$$

Energy rejected

$$q_2 = c_v(T_5 - T_1) \tag{4.2}$$

$$\eta = 1 - \frac{c_v(T_5 - T_1)}{c_v(T_3 - T_2) + c_p(T_4 - T_3)} \tag{4.3}$$

or

$$\eta = 1 - \frac{(T_5 - T_1)}{(T_3 - T_2) + \gamma(T_4 - T_3)} \tag{4.4}$$

The efficiency of the cycle can be expressed in terms of the following ratios

Compression ratio, $r_0 = \frac{V_1}{V_2}$ (4.5)

Cut-off ratio, $r_c = \frac{V_4}{V_3}$ (4.6)

Expansion ratio, $r_e = \frac{V_5}{V_4}$ (4.7)

Constant volume pressure ratio, $r_{vp} = \frac{p_3}{p_2}$ (4.8)

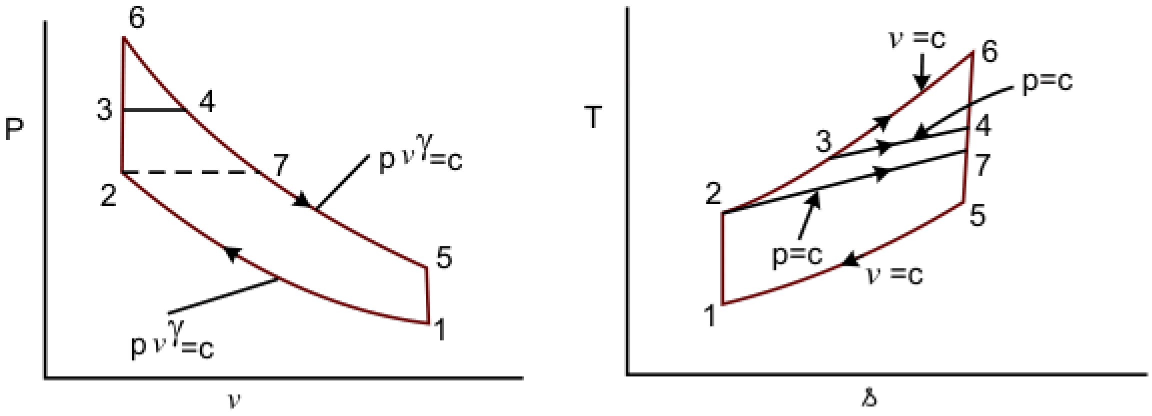
$$\eta_{Dual} = 1 - \frac{1}{(r_0)^{\gamma-1}} \frac{r_{vp}(r_c)^{\gamma} - 1}{(r_{vp} - 1) + \gamma r_{vp}(r_c - 1)} \tag{4.9}$$

If $r_c = 1,\ \eta_{\mathrm{Dual}} \rightarrow \eta_{\mathrm{Otto}}$

If $r_{vp} = 1,\ \eta_{\mathrm{Dual}} \rightarrow \eta_{\mathrm{Diesel}}$

Comparison of Otto, Diesel & Dual Cycles

For same compression ratio and heat rejection (Figures 4.6 (a) and (b))



(a)

(b)

Figure 4.6 (a) P –V and (b) T-S

**1-6-4-5 Otto cycle**

**1-7-4-5 diesel cycle**

**1-2-3-4-5 Dual cycle**

For the same $Q_2$ , the higher the $Q_1$ , the higher is the cycle efficiency

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

for the same maximum pressure and temperature (figures 4.7 (a) and (b))

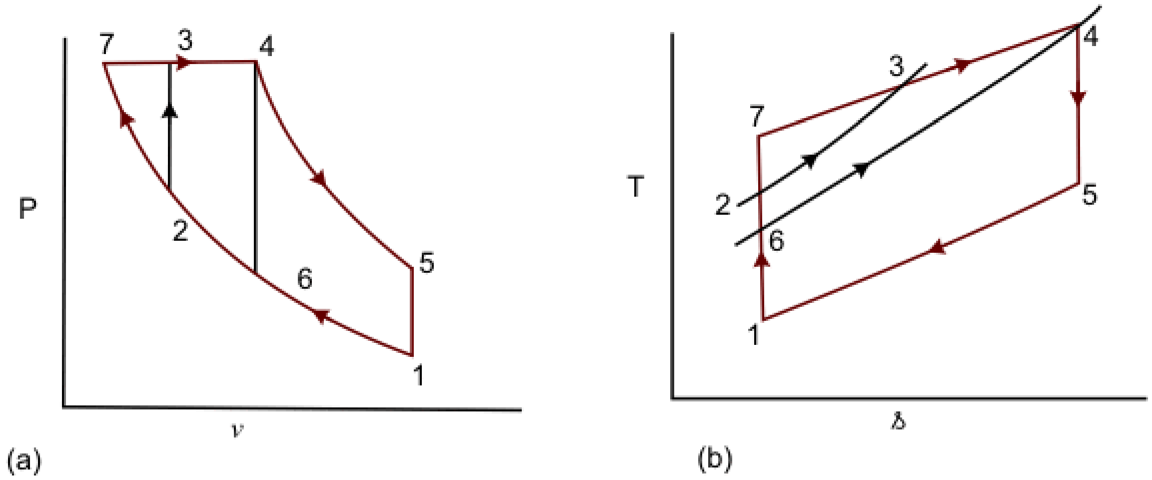


Figure 4.7 (a) T-S  and (b) P-V

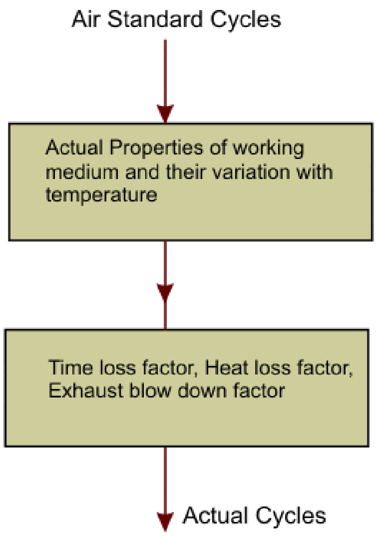
**1-6-4-5 Otto cycle**

**1-7-4-5 diesel cycle**

**1-2-3-4-5 Dual cycle**

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

The actual cycles are modifications on the Air Standard cycles in the following manner:



## 4.8 Air Standard Brayton Cycle

Gas turbines function based on Brayton cycles..

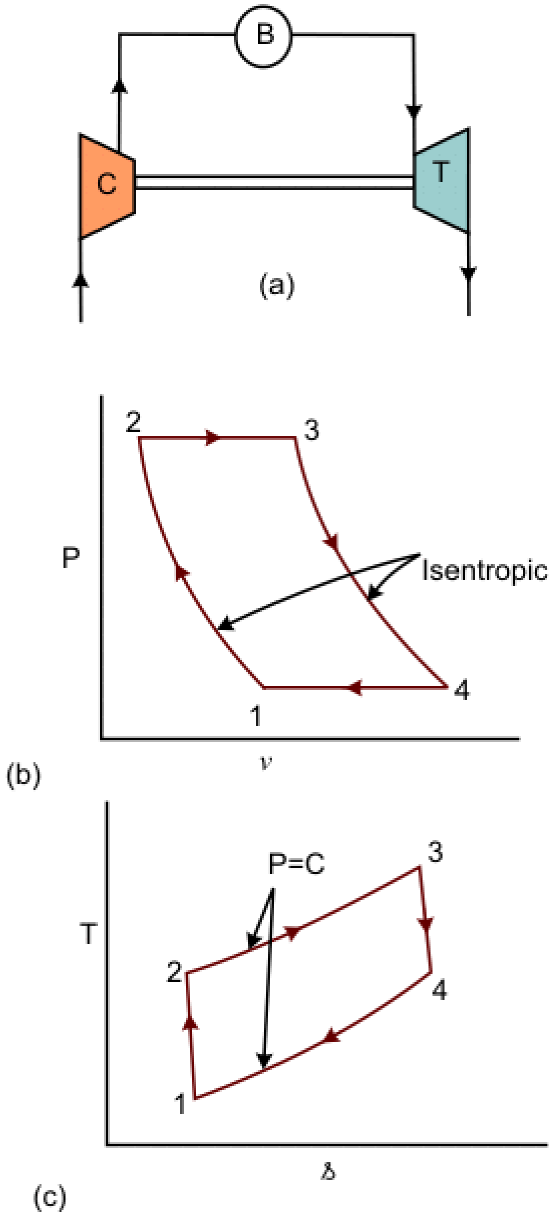


figure 4.9 (a) (b) and (c) air standard brayton cycle

The air-standard Brayton cycle consists of

$$q_1 = c_p \left(T_3 - T_2\right) \qquad (4.10)$$

$$q_2 = c_p \left(T_4 - T_1\right) \qquad (4.11)$$

$$\eta = 1 - \frac{T_4 - T_1}{T_3 - T_2} \tag{4.12}$$

$$\eta = 1 - \frac{T_1\left(T_4/T_1 - 1\right)}{T_2\left(T_3/T_2 - 1\right)} \tag{4.13}$$

$r_p = \frac{p_2}{p_1}$ is the pressure ratio (4.14)

$$\left[\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}}\right] \tag{4.15}$$

and

$$\frac{p_3}{p_4} = \frac{p_2}{p_1} \quad \text{or} \quad \frac{T_3}{T_4} = \frac{T_2}{T_1} \tag{4.16}$$

or,

$$\frac{T_3}{T_2} = \frac{T_4}{T_1} \tag{4.17}$$

so,

$$\eta = 1 - \frac{T_1}{T_2} \tag{4.17}$$

or

$$\eta = 1 - \frac{1}{\left(r_p\right)^{\frac{\gamma-1}{\gamma}}} \tag{4.18}$$

he variation of $\eta$ as a function of $r_p$ is shown in Figure 4.9

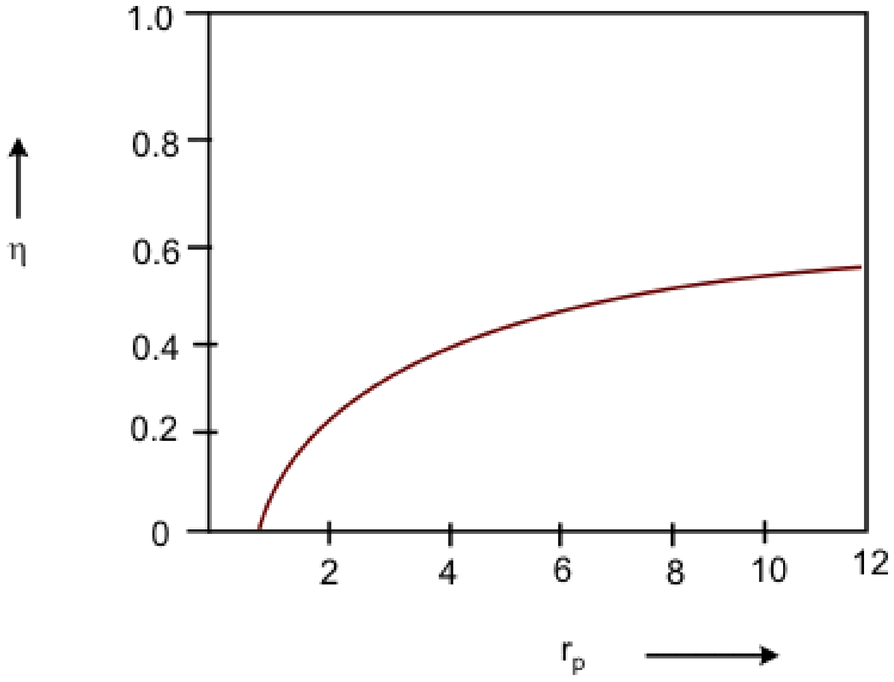


fig 4.10 air standard brayton cycle

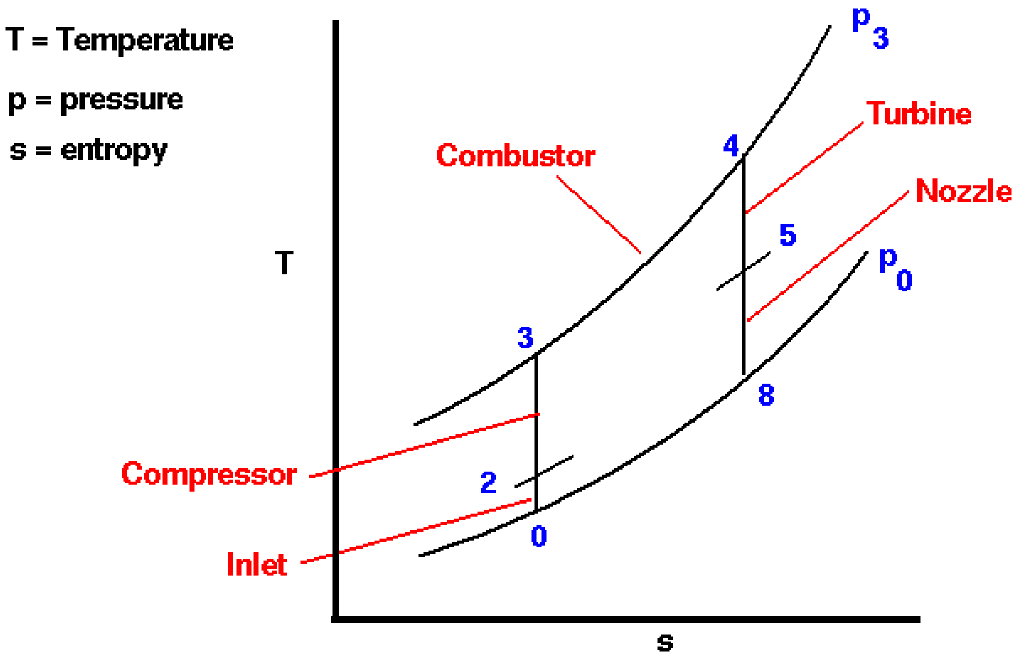


fig 4.11 T-S

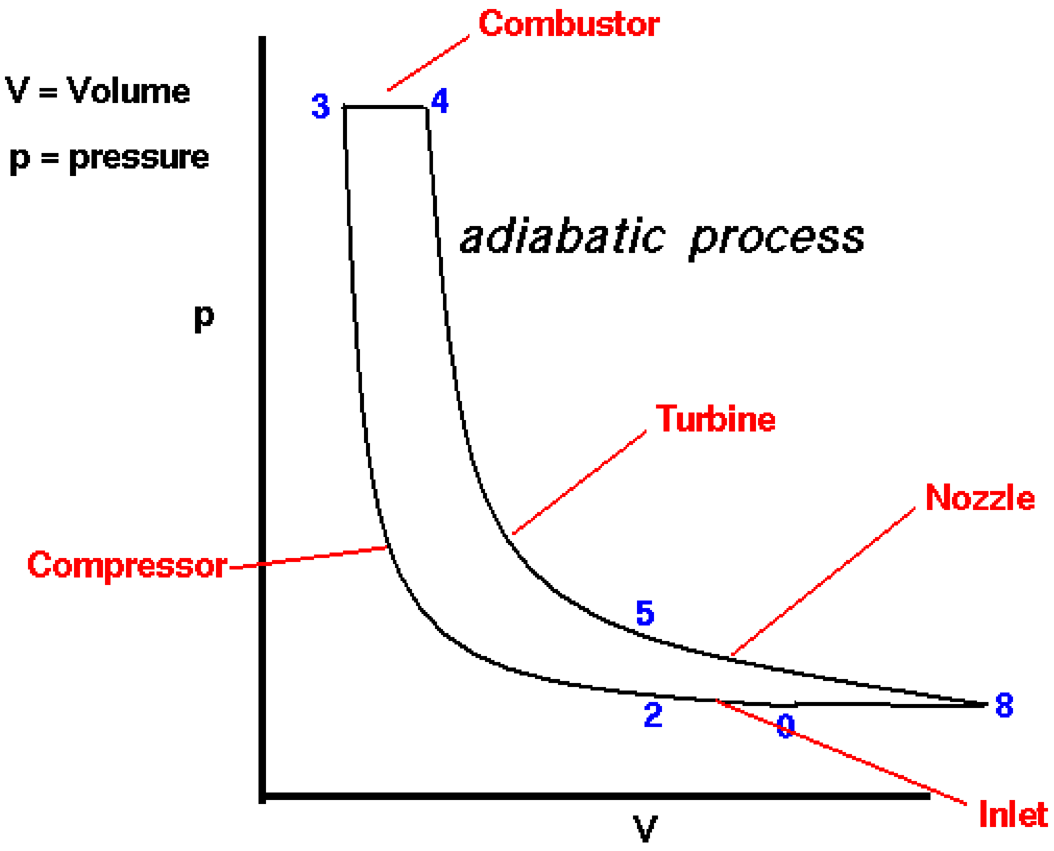


fig 4.12 P-V

$$W_{net} = W_T - W_C = (h_3 - h_4) - (h_2 - h_1) \tag{4.19}$$

$$W_{net} = c_p (T_3 - T_4) - c_p (T_2 - T_1) \tag{4.20}$$

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}, \quad \frac{T_3}{T_4} = \left(\frac{P_3}{P_4}\right)^{\frac{\gamma-1}{\gamma}}$$

But

$$\frac{P_2}{P_1} = \frac{P_3}{P_4} = r_p \quad \& \quad \frac{T_2}{T_1} = \frac{T_3}{T_4}$$

$$W_{\text{net}} = c_p T_3 \left(1 - \frac{T_4}{T_3}\right) - c_p T_1 \left(\frac{T_2}{T_1} - 1\right)$$

or

$$W_{\text{net}} = c_p T_3 \left[1 - \frac{1}{\left(r_p\right)^{\frac{\gamma-1}{\gamma}}}\right] - c_p T_1 \left[\left(r_p\right)^{\frac{\gamma-1}{\gamma}} - 1\right] \tag{4.21}$$

The optimum pressure ratio is obtained by differentiating W wrtr$_p$ holding T$_1$ and T$_3$ constant, and setting the expression equal to zero.

This gives

$$\left(r_p\right) optimum = \left(\frac{T_3}{T_1}\right)^{\frac{\gamma}{2(\gamma-1)}}$$

- **Derivation:**

$$\frac{dW_{\text{net}}}{d_{rp}} = 0 = \left\{- c_p T_3 \left(- \frac{r-1}{\gamma}\right) r_p^{\frac{-(\gamma-1)}{\gamma}-1}\right\} - \left\{ c_p T_1 \left(\frac{r-1}{\gamma}\right) r_p^{\frac{(\gamma-1)}{\gamma}-1}\right\}$$

or $$T_3 \left(r_p\right)^{\frac{-(2\gamma-1)}{\gamma}} = T_1 \left(r_p\right)^{-\frac{1}{\gamma}}$$

or $$\left(r_p\right)^{\frac{-2\gamma+1+1}{\gamma}} = \frac{T_1}{T_3}$$

or $$\left(r_p\right)^{\frac{-2(\gamma-1)}{\gamma}} = \frac{T_1}{T_3}$$

or $$\frac{1}{\left(r_p\right)^{\frac{2-\gamma}{\gamma}}} = \frac{T_1}{T_3}$$

or $$\frac{1}{(r_p)^{\frac{2-\gamma}{\gamma}}} = \frac{T_1}{T_3}$$

finally, $$r_p = \left(\frac{T_3}{T_1}\right)^{\frac{\gamma}{2(\gamma-1)}}$$

### 4.3.2 P-V AND T-S DIAGRAMS OF OTTO CYCLE:

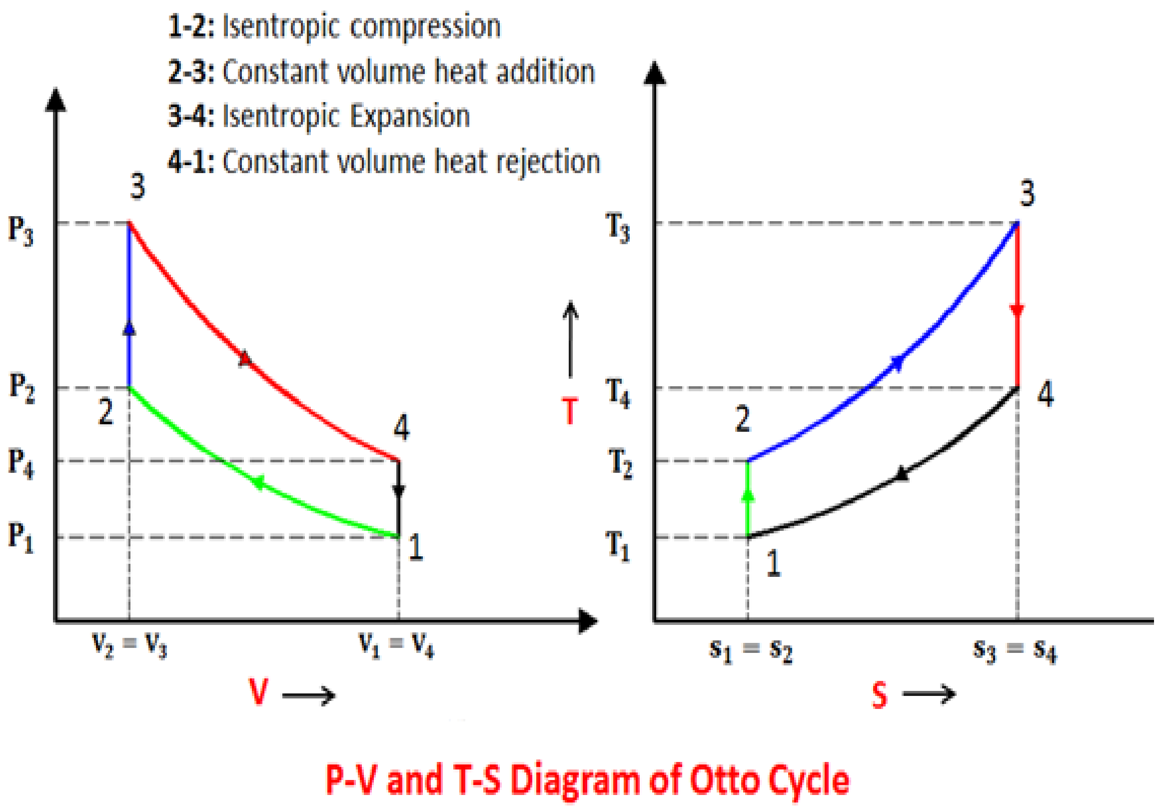


Fig 4.13 P-V Diagram and T-s Diagram

### 4.3.3 Processes in Otto Cycle:

As stated earlier, Otto cycle consists of four processes. They are as follows:

Process 1-2: Isentropic compression

In this process, the piston moves from bottom dead centre (BDC) to top dead centre (TDC) position. Air undergoes reversible adiabatic (isentropic) compression. We know that compression is a process in which volume decreases and pressure increases. Hence, in this process, volume of air decreases from $V_1$ to $V_2$ and pressure increases from $p_1$ to $p_2$. Temperature increases from $T_1$ to $T_2$. As this an isentropic process, entropy remains constant (i.e., $s_1=s_2$). Refer p-V and T-s diagrams for better understanding.

Process 2-3: Constant Volume Heat Addition:

Process 2-3 is isochoric (constant volume) heat addition process. Here, piston remains at top dead centre for a moment. Heat is added at constant volume ($V_2 = V_3$) from an external heat source. Temperature increases from $T_2$ to $T_3$, pressure increases from $p_2$ to $p_3$ and entropy increases from $s_2$ to $s_3$. (See p-V and T-s diagrams above).

Process 3-4: Isentropic expansion

In this process, air undergoes isentropic (reversible adiabatic) expansion. The piston is pushed from top dead centre (TDC) to bottom dead centre (BDC) position. Here, pressure decreases fro $p_3$ to $p_4$, volume rises from $v_3$ to $v_4$, temperature falls from $T_3$ to $T_4$ and entropy remains constant ($s_3=s_4$). (Refer p-V and T-s diagrams above).

Process 4-1: Constant Volume Heat Rejection

The piston rests at BDC for a moment and heat is rejected at constant volume ($V_4=V_1$). In this process, pressure falls from $p_4$ to $p_1$, temperature decreases from $T_4$ to $T_1$ and entropy falls from $s_4$ to $s_1$. (See diagram above).
In process 4-1,

Heat Rejected = $mC_v(T_4 – T_1)$

Thermal efficiency (air-standard efficiency) of Otto Cycle,

$$\eta_{th} = \frac{\text{Heat Supplied - Heat Rejected}}{\text{Heat Supplied}}$$

$$\eta_{th} = \frac{mC_v\left(T_3 - T_2\right) - mC_v\left(T_4 - T_1\right)}{mC_v\left(T_3 - T_2\right)}$$

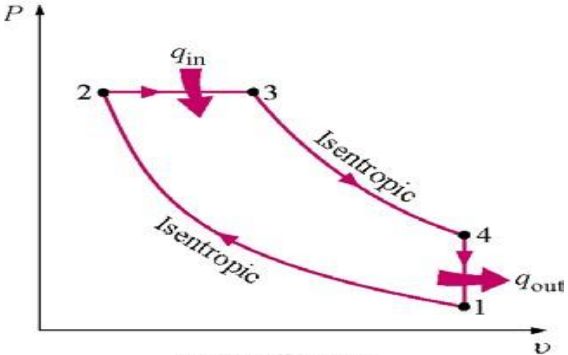
$$\eta_{th} = 1 - \frac{\left(T_4 - T_1\right)}{\left(T_3 - T_2\right)} = \eta_{Otto}$$

The complete derivation of air-standard efficiency of Otto cycle can be found here and the complete derivation of mean effective pressure (m.e.p) of Otto Cycle can be found here.

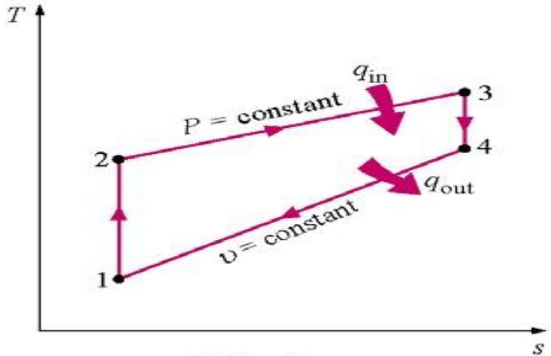
## 4.4 DIESEL CYCLE

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

| **Process** | **Description** |
|---|---|
| 1-2 | Isentropiccompression |
| 2-3 | Constant pressure heataddition |
| 3-4 | Isentropicexpansion |
| 4-1 | Constant volume heat rejection The *P-v* and *T-s* diagramsare |



(a) *P*-υdiagram



(b) *T*-*s* diagram

Fig 4.14 *P-v* and *T-s* diagrams

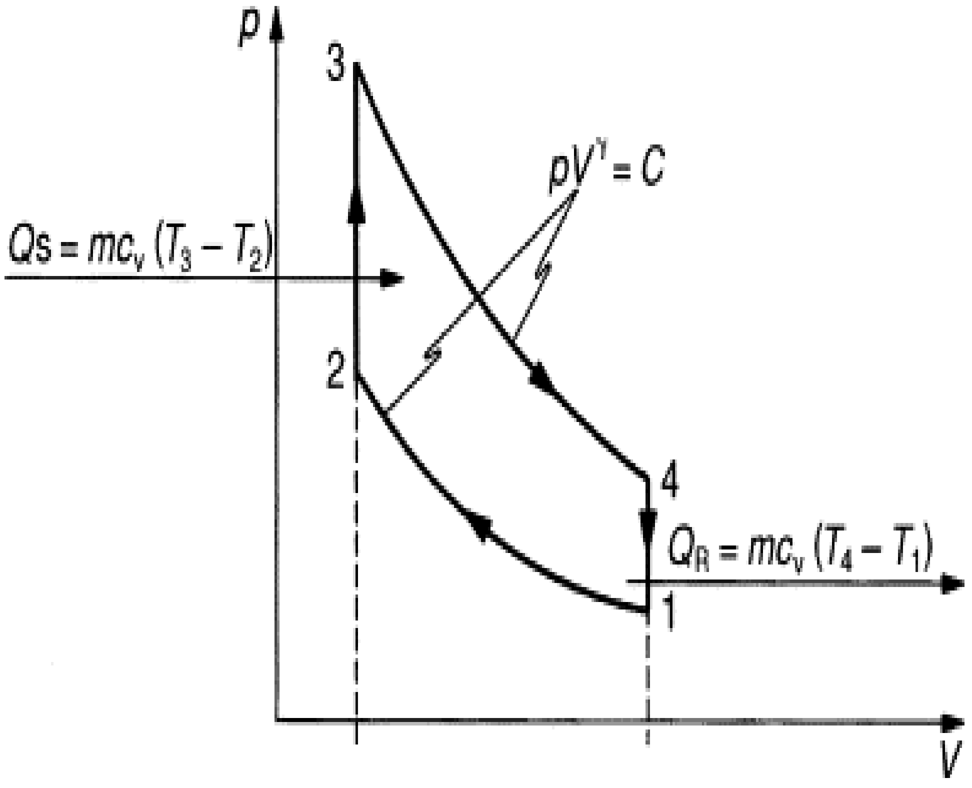


Fig 4.15 Performance of internal combustion engines

### 4.5 COMPARISON OF OTTO, DIESEL AND DUAL CYCLES:

The important variable factors which are used as the basis for comparison of the cycles are compression ratio, peak pressure, heat addition, heat rejection and the net work. In order to compare the performance of the Otto, Diesel and Dual combustion cycles, some of the variable factors must be fixed. In this section, a comparison of these three cycles is made for the same compression ratio, same heat addition, constant maximum pressure and temperature, same heat rejection and net work output. This analysis will show which cycle is more efficient for a given set of operating conditions.

#### 4.5.1 Same Compression Ratio and Heat Addition:

The Otto cycle 1-2-3-4-1, the Diesel cycle 1-2-3'-4'-1 and the Dual cycle 1-2-2”-3”-4”-1 are shown in p-V and T-θ diagram in Fig.4.7.1 (a) and (b) respectively for the same compression ratio and heatinput

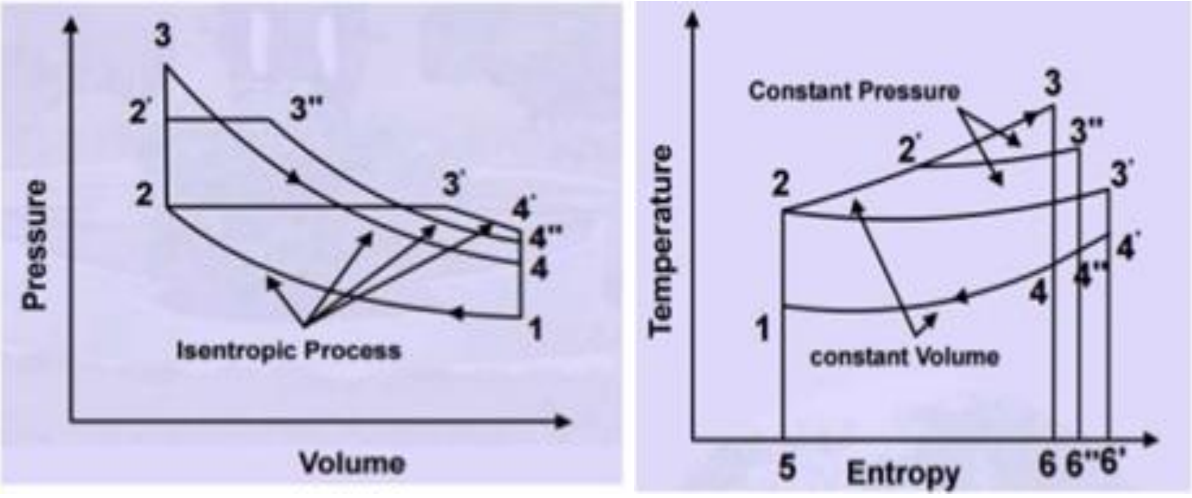


Fig.4.16 Same compression ratio and heat addition

From the T-s diagram, it can be seen that Area 5-2-3-6 = Area 5-2-3'-6’ = Area 5-2-2''- 3''-6'' as this area represents the heat input which is the same for all cycles. All the cycles start from the same initial state point 1 and the air is compressed from state 1 to 2 as the compression ratio is same. It is seen from the T-s diagram for the same heat input, the heat rejection in Otto cycle (area 5-1-4-6) is minimum and heat rejection in Diesel cycle (5-1-4'-6') is maximum.. Consequently, Otto cycle has the highest work output and efficiency. Diesel cycle has the least efficiency and Dual cycle having the efficiency between the two. One more observation can be made i.e., Otto cycle allows the working medium to expand more whereas Diesel cycle is least in this respect. The reason is heat is added before expansion in the case of Otto cycle and the last portion of heat supplied to the fluid has a relatively short expansion in case of the Diesel cycle.

## 4.6 DESCRIPTION AND REPRESENTATION ON P-V AND T-S DIAGRAM

Otto cycle is a gas power cycle that is used in spark-ignition internal combustion engines (modern petrol engines). This cycle was introduced by Dr. Nikolaus August Otto, a German Engineer.

An Otto cycle consists of four processes:

1. Two isentropic (reversible adiabatic) processes
2. Two isochoric (constant volume) processes

These processes can be easily understood if we understand p-V (Pressure-Volume) and T-s (Temperature-Entropy) diagrams of Otto cycle.

## 4.7 BRAYTON 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.

*Q*in

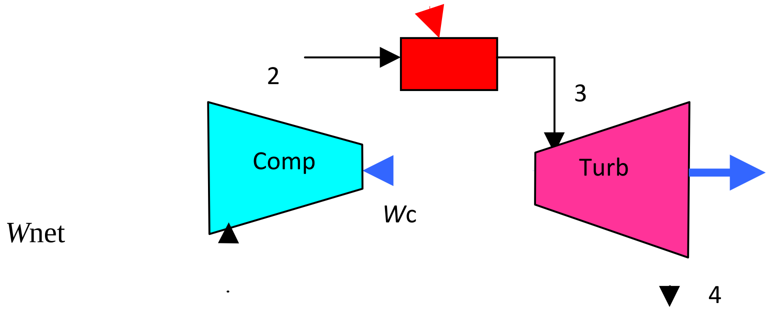
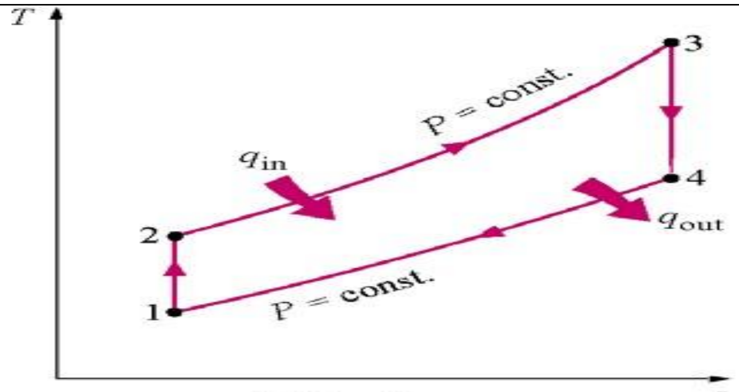


Fig 4.17Brayton cycle

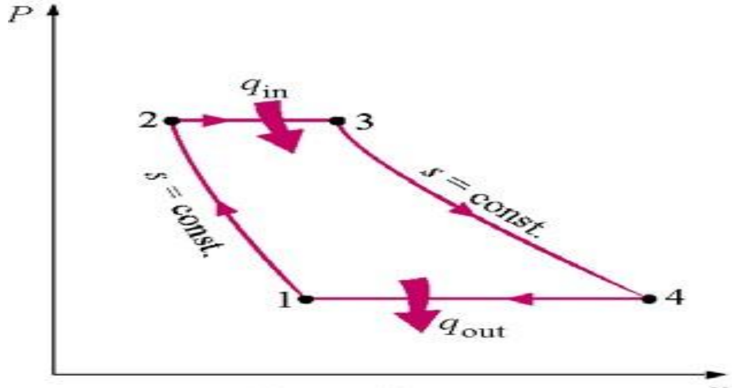
**The closed cycle gas-turbine engine**

| Process | Description |
|---|---|
| 1-2 | Isentropic compression (in a compressor) 2-3 Constant pressure heataddition |
| 3-4 | Isentropic expansion (in aturbine) |
| 4-1 | Constant pressure heat rejection |

The*T-s* and *P-v* diagramsare



(a) *T-s* diagram



(b) *P-v* diagram

Fig 4.18 *T-s* and *P-v* diagrams

### 4.8 COMPARISON OF THE OTTO, DIESEL AND DUAL CYCLES

Various factors as the basis for comparison of cycles

1. Compression ratio, peak pressure, heat addition, heat rejection and the net work output.
2. In order to compare the performance of cycles some of the variable factors must be fixed.
3. Comparison is made to analyze which cycle is most efficient for a given set of operating condition

### 4.8.1 Comparison of the Otto, Diesel and Dual Cycles

Various factors as the basis for comparison of cycles

1. Compression ratio, peak pressure, heat addition, heat rejection and the net work output.
2. In order to compare the performance of cycles some of the variable factors must be fixed.
3. Comparison is made to analyze which cycle is most efficient for a given set of operating condition

### 4.8.2 Comparison of the Otto, Diesel and Dual Cycles

Various factors as the basis for comparison of cycles

1. Compression ratio, peak pressure, heat addition, heat rejection and the net work output.

2. In order to compare the performance of cycles some of the variable factors must be fixed.
3. Comparison is made to analyze which cycle is most efficient for a given set of operating conditions

## 4.9 BELL COLEMAN CYCLE.

Air refrigeration system is the oldest refrigeration method. Initially it was developed by a scientist called Bell-Coleman. The aim of this study is to know the refrigeration effect using both Bell-Coleman cycle using air as the refrigerant and finding its COP because air is available free of cost and abundantly in nature. Bell-Coleman cycle air refrigeration can be used in aircrafts and ships to produce refrigeration effect in them. Air refrigeration system generally uses air as medium, whereas other refrigeration systems use refrigerants (Freon's, ammonia etc.,) as medium. Since air is used as refrigerant is safe and it won't do any harm and no damage to atmosphere. By using other refrigerants like CFC's damage to atmosphere such as ozone layer depletion takes place. In this study compressed air is selected as the refrigerant and it is produced by compressor. It need electric power to produce Compression of air. This system produces low COP because of which it has become obsolete. Other refrigeration systems have high COP but have severe impact on atmosphere. Moreover these refrigerants are too expensive and there is a handling difficult of these refrigerants. This study gives the working of components of Bell-Coleman cycle by using air as refrigerant and knowing the coefficient of performance (cooling effect)for future development and application. This study gives the scope of replacing conventional refrigeration systems with air refrigeration system.

Refrigerants

In the vapour compression refrigeration system, the working fluid undergoes a phase change during the cycle. There are a few other requirements. The first requirement is that the pressure at which the refrigerant enters the compressor should be slightly higher than the atmospheric pressure to make sure that no air leaks in. It is also necessary that the boiling point of the refrigerant should be lower then the temperature at which the evaporator is to be maintained. The refrigerant is compressed to a pressure of approximately 1 MPa where its saturation temperature is greater than the surrounding temperature so that energy can be rejected to the surroundings. During the energy rejection process the refrigerant undergoes a phase change from vapour to liquid. Hence the refrigerant's critical pressure should be high. The refrigerant should be non-toxic and non flammable. In view of this the commonly used refrigerant are Ammonia and Freons. Generally Freons are methane-based hydrocarbons where hydrogen atoms are replaced by chlorine or fluorine atoms. These are denoted by a number of two digits, where the first digit minus one is the number of hydrogen atoms and the second digit indicates the number of fluorine atoms, while the other atoms are chlorine.

$R-12 \rightarrow CCl_2F_2 -$ dichloro – difluoro methane

$R-22 \rightarrow CHCl_2F_2 -$ monochloro –difluorpmethan

Absorption Refrigeration System

The vapour absorption system is shown in Figure 31.4.

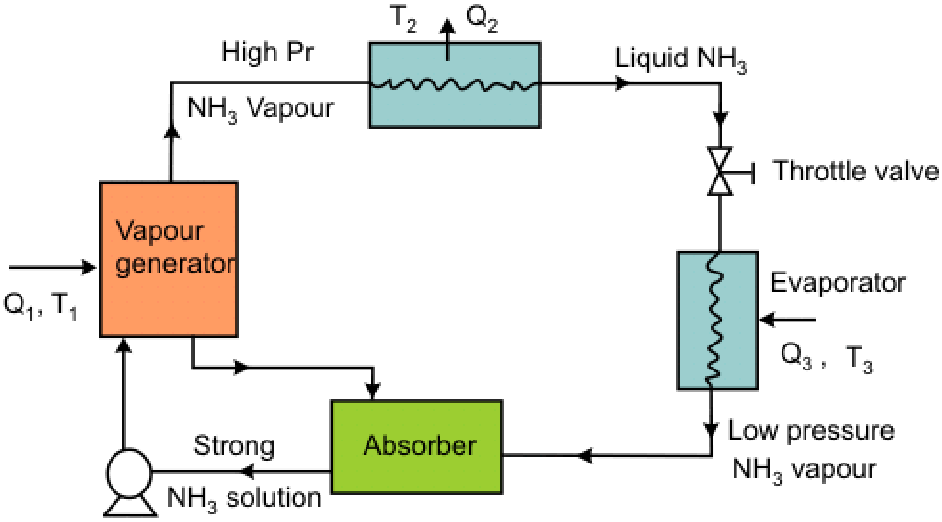


Figure 4.19 Absorption Refrigeration System

In the absorption refrigeration system, refrigeration effect is produced mainly by the use of energy as heat. In such a system, the refrigerant is usually dissolved in a liquid. A concentrated solution of ammonia is boiled in a vapour generator producing ammonia vapour at high pressure. The high pressure ammonia vapour is fed to a condenser where it is condensed to liquid ammonia by rejecting energy as heat to the surroundings. Then, the liquid ammonia is throttled through a valve to a low pressure. During throttling, ammonia is partially vapourized and its temperature decreases.

This low temperature ammonia is fed to an evaporator where it is vapourized removing energy from the evaporator. Then this low-pressure ammonia vapour is absorbed in the weak solution of ammonia. The resulting strong ammonia solution is pumped back to the vapour generator and the cycle is completed. The COP of the absorption system can be evaluated by considering it as a combination of a heat pump and a heat engine (Figure 31.5).

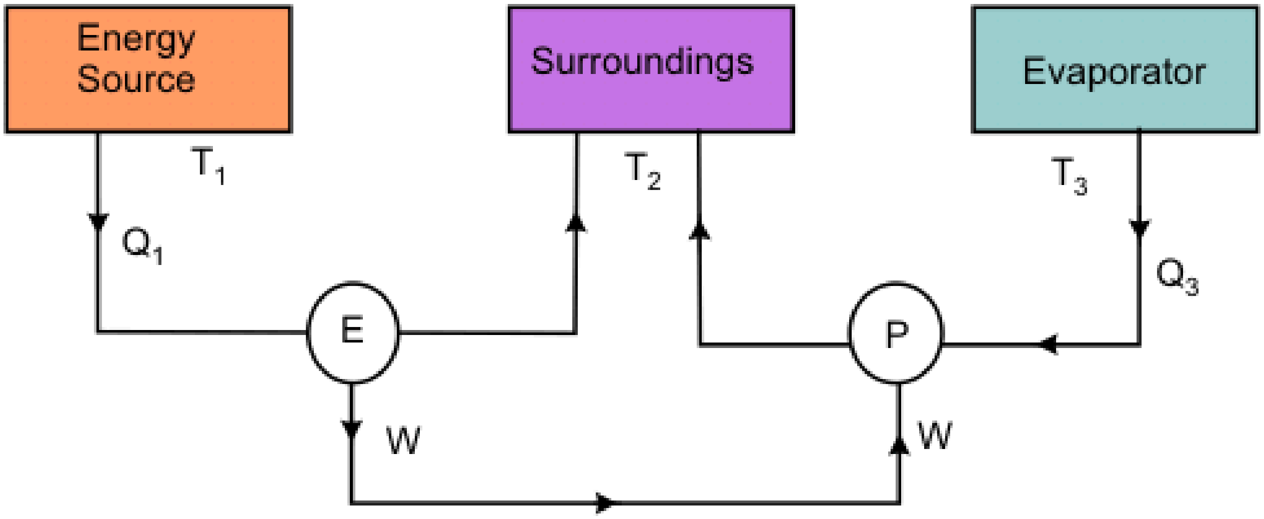


Figure 4.20 Absorption Refrigeration System

Heat Engine

$$W = \frac{Q_1(T_1 - T_2)}{T_1} \tag{4.22}$$

Heat Pump

$$\frac{Q_3}{W} = \frac{T_3}{T_2 - T_3} \tag{4.23}$$

Or

$$W = \frac{Q_3(T_2 - T_3)}{T_3} \tag{4.23}$$

now,

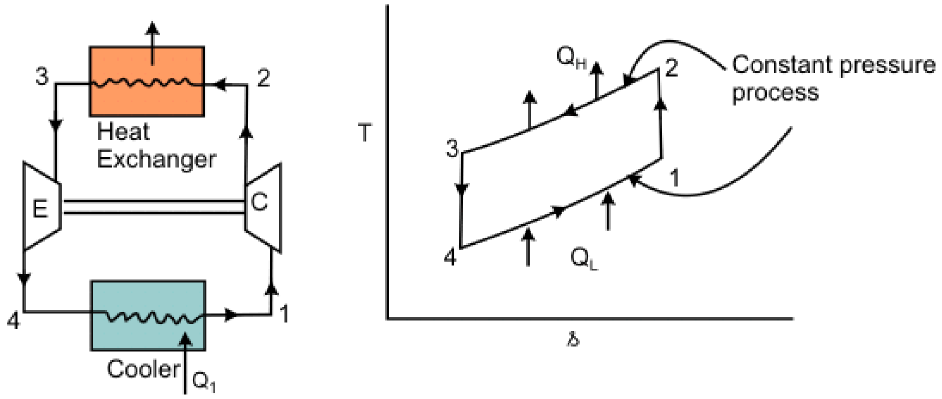
$$\frac{Q_1(T_1 - T_2)}{T_1} = \frac{Q_3(T_2 - T_3)}{T_3} \tag{4.24}$$

or,

$$\frac{Q_3}{Q_1} = \frac{T_3\left(T_1 - T_2\right)}{T_1\left(T_2 - T_3\right)} \tag{4.25}$$

**Gas Refrigeration Cycle:**

In this refrigeration system the working fluid is Air. The system is used for aircraft cabin cooling. The working of a gas refrigeration cycle is shown in Figures 31.6 (a) and (b).



(a)

(b)

Figures 4.21 (a) and (b)

The atmospheric air at state 1 is compressed isentropically to state 2. The compressed air is cooled at constant pressure to state 3 by exchanging heat with the surroundings. Then the air is expanded isentropically to state 4. Because of adiabatic expansion, the temperature of the gas is reduced. The cooled air takes up heat from the cabin to reach state 1. The work obtained during the expansion process can be utilized to run the compressor

The compressor work:

$$W_c = h_2 - h_1 = c_p\left(T_2 - T_1\right) \tag{4.26}$$

The expander work:

$$W_e = h_3 - h_4 = c_p\left(T_3 - T_4\right) \quad (4.27)$$

The net work required:

$$W_{\text{net}} = c_p\,(T_2 - T_1 - T_3 + T_4) \quad (4.28)$$

What is the work required to be supplied

$$\text{COP} = \frac{Q_L}{W_{\text{net}}} = \frac{c_p(T_1 - T_4)}{c_p(T_2 - T_1 - T_3 + T_4)} \quad (4.29)$$

or

$$\text{COP} = \frac{(T_1 - T_4)}{(T_2 - T_1 - T_3 + T_4)} \quad (4.30)$$

# MODULE V

## ELEMENTS OF HEAT TRANSFER AND GAS COMPRESSORS

### 5.1 INTRODUCTION

Energy balances by first law have been made in a variety of physical situations. say, in a feedwater heater or a cooling coil. However, no indication has beengiven regarding the size of the heat exchanger for heating or cooling of a fluid. If we consider steel block heated in a furnace. to be allowed to cool in room air,we can estimate the amount of heat lost by the block in cooling by energy balance.But how long the cooling process will take place cannot be answered bythermodynamics.

It is the science of heat transfer which is concerned with theestimation of the rate at which heat is transferred, the duration of heating orcooling for a certain heat duty with the surface area required to accomplish thatheatduty.

There are three modes in which heat may be transferred:

(a) conduction
(b) convection
(c) radiation.

Conduction refers to the transfer ofheat between two bodies or two pans of thesame body through molecules which are more or less stationary. In liquids andgases conduction results from the transport of energy by molecular motion nearthe wall and in solids it takes place by a combination of lattice vibration and electron transport. In general, good electrical conductors are also good thermalconductors.

Convection heat transfer occurs because of the motion of a fluid past a heatedsurface-the faster the motion, the greater the heat transfer.Radiation heat transfer is the result of electromagnetic radiation emitted by asurface because of the temperature of the surface.

### 5.2 Conduction Heat Transfer:

Fourier's law of heat conduction states that the rate of heat flux is linearly proportional to the temperature gradient. For one dimensional or unidirectionalheat conduction,

or

$q \alpha dt/dx$

$q = - K dt/dx$

where q is the rate of heat flux in $W/m^2$,dt/dx is the temperature gradient inx-direction, and K is the constant of proportionality which is a property ofthe material through which heat isbeing conducted and is known asthermal conductivity

### 5.3 Heat Conduction through a Cylinder

Let us assume that the inside and outside surfaces of the cylinder aremaintainedattemperatures$t_1$ and$t_2$ respectively, and $t_1$ isgreaterthan$t_2$. We willalso assume that heat is flowing, under steady state, only in the radial direction,and there is no heat conduction along the length or the periphery of the cylinder.The rate of heat transfer through the thin cylinder of thickness dr is given by

$Q = -KA\ dt/dr$

$= - K 2 \pi rL\ dt/dr$

### 5.4 Heat Exchangers

A heat exchanger is a device in which heat is transferred between two movingfluids.Heat exchangers may be parallel flow. Counter flow or cross flow, dependingupon the direction of the motion of the two fluids. If both the fluids move in thesame direction, it is a parallel flow heat exchanger. If the fluids flow in theopposite directions, it is a counter flow heat exchanger. If they flow normal toeach other it is a cross flow beat exchange.

#### 5.4.1 Shell and tube heat exchanger

Shell and tube heat exchangers consist of a series of tubes which contain fluid that must be either heated or cooled. A second fluid runs over the tubes that are being heated or cooled so that it can either provide the heat or absorb the heat required. A set of tubes is called the tube bundle and can be made up of several types of tubes: plain, longitudinally finned, etc. Shell and tube heat exchangers are typically used for high-pressure applications (with pressures greater than 30 bar and temperatures greater than 260 °C). This is because the shell and tube heat exchangers are robust due to their shape. Several thermal design features must be considered when designing the tubes in the shell and tube heat exchangers

#### 5.4.2 Plate heat exchangers

Another type of heat exchanger is the plate heat exchanger. These exchangers are composed of many thin, slightly separated plates that have very large surface areas and small fluid flow passages for heat transfer. Advances in gasket and brazing technology have made the plate-type heat exchanger increasingly practical. In HVAC applications, large heat exchangers of this type are called plate-and-frame; when used in open loops, these heat exchangers are normally of the gasket type to allow periodic disassembly, cleaning, and inspection. There are many types of permanently bonded plate heat exchangers, such as dip-brazed, vacuum-brazed, and welded plate varieties, and they are often specified for closed-loop applications such as refrigeration. Plate heat exchangers also differ in the types of plates that are used, and in the configurations of those plates. Some plates may be stamped with "chevron", dimpled, or other patterns, where others may have machined fins and/or grooves.

### 5.4.3 Plate and shell heat exchanger

A third type of heat exchanger is a plate and shell heat exchanger, which combines plate heat exchanger with shell and tube heat exchanger technologies. The heart of the heat exchanger contains a fully welded circular plate pack made by pressing and cutting round plates and welding them together. Nozzles carry flow in and out of the plate pack (the 'Plate side' flow path). The fully welded plate pack is assembled into an outer shell that creates a second flow path ( the 'Shell side'). Plate and shell technology offers high heat transfer, high pressure, high operating temperature, using and close approach temperature. In particular, it does completely without gaskets, which provides security against leakage at high pressures and temperatures.

## 5.5 THERMAL CONDUCTIVITY,K

As noted previously, thermal conductivity is a thermodynamic property of a material. From the State Postulate given in thermodynamics, it may be recalled that thermodynamic properties of pure substances are functions of two independent thermodynamic intensive properties, say temperature and pressure. Thermal conductivity of real gases is largely independent of pressure and may be considered a function of temperature alone. For solids and liquids, properties are largely independent of pressure and depend on temperature alone.

$k = k(T)$

| Material | Thermal Conductivity, W/m K |
|---|---|
| Copper | 401 |
| Silver | 429 |
| Gold | 317 |
| Aluminum | 237 |

| | |
|---|---|
| Steel | 60.5 |
| Limestone | 2.15 |
| Bakelite | 1.4 |
| Water | 0.613 |
| Air | 0.0263 |

Table 1 gives the values of thermal conductivity for a variety of materials.

Letustrytogainaninsightintothebasicconceptofthermalconductivityforvariousmaterials.The fundamental concept comes from the molecular or atomic scale activities. Molecules/atoms of various materials gain energy through different mechanisms. Gases, in which molecules are free to move with a mean free path sufficiently large compared to their diameters, possess energy in the form of kinetic energy of the molecules. Energy is gained or lost through collisions/interactions of gasmolecules.

Solids, on the other hand, have atoms/molecules which are more closely packed which cannot move as freely as in gases. Hence, they cannot effectively transfer energy through these same mechanisms.Instead,solidsmayexhibitenergythroughvibrationorrotationofthenucleus.Hence, the energy transfer is typically through latticevibrations.

Another important mechanism in which materials maintain energy is by shifting electrons into higher orbital rings. In the case of electrical conductors the electrons are weakly bonded to the molecule and can drift from one molecule to another, transporting their energy in the process. Hence, flow of electrons, which is commonly observed in metals, is an effective transport mechanism, resulting in a correlation that materials which are excellent electrical conductors are usually excellent thermal conductors.

## 5.6 BASIC CONCEPTS OF: GAS COMPRESSORS

A compressor is a mechanical device that increases the pressure of a gasby reducing its volume. An air compressor is a specific type of gas compressor.

Compressors are similar to pumps: both increase the pressure on a fluidand both can transport the fluid through a pipe. As gases are compressible, the compressor also reduces the volume of a gas. Liquids are relatively incompressible; while some can be compressed, the main action of a pump is to pressurize and transport liquids.

## 5.7 AIR COMPRESSORS

Air compressors collect and store air in a pressurized tank, and use pistons andvalves to achieve the appropriate pressure levels within an air storage tank thatis attached to the motorized unit. There are a few different types of pistoncompressors that can deliver even air pressures to the user.Automotive compressors are combustion engine compressors that use the up-and-down stroke of the piston to allow air in and pressurize the air within thestorage tank. Other piston compressors utilize a diaphragm, oil-free piston. These pull air in, and pressurize it by not allowing air to escape during thecollection period. These are the most common types of air compressors that are used today byskilled workers and craftsmen. Before the day of motorized engines, aircompressors were not what they are today. "unable to store pressurized air.

### 5.7.1 SINGLE-STAGE RECIPROCATING AIR COMPRESSOR

The sectional view of an air cooled, single-stage, single-acting reciprocating air compressor is shown in fig. 11-1. Both intake (suction) and discharge (delivery) valves are disc type and are automatic in their action. They are opened and closed by difference in the air pressure acting on their two sides. When the pressures are equal on their two sides, they are kept closed by light springs. During the outward or suction stroke, the pressure in the cylinder falls below the atmospheric pressure as a result of which the intake valve opens and air is drawn from the atmosphere into the cylinder. During the inward or compression stroke, as a result of the piston action the pressure of the air in the cylinder gradually increases and reaches a value sufficiently above the receiver pressure. The high pressure of air, thus produced, overcomes the resistance of the spring on the discharge valve and causes the valve to open and discharge takes place from the cylinder to the receiver. The receiver is a simple vessel which acts as a storage tank. The compressor is driven by some form of prime mover (electric motor or engine). When the compressor is to be started against tank (receiver) pressure, the prime mover will have to supply very high starting torque. To avoid this, hand unloaded is used for releasing pressure from the compressor cylinder when the compressor is stopped.

### 5.7.2 MULTI-STAGE COMPRESSION

In this method, the compression of air is carried out in two or more stages in separate cylinders. The pressure of the air is increased in each stage. It is a common practice to provide intercoolers between the cylinders of multi-stage compressor, for the purpose of cooling the compressed air to atmospheric (intake) temperature before entering the succeeding (next) stage. It is this cooling between the cylinders that keeps the compression very near to isothermal .

### 5.7.3 TWO-STAGE AIR COMPRESSOR

A two-stage air compressor with water jacketed cylinders and intercooler The suction in the L.P. cylinder ends at 1 and the air is drawn in the cylinder at pressure pi. The air is then compressed polytropically to 2’. The L.P. cylinder then discharges (delivers) the air along line 2-p2 to the intercooler where air is cooled at constant pressure pa to the original (intake) temperature corresponding to point 1 by the circulating cold water. When air is cooled in the intercooler to intake temperature corresponding to point 1, the cooling is perfect. The air in cooling at constant pressure suffers a reduction of volume from 2'-p2 to p2- 2.

The cooled air is then drawn into the H.P. cylinder along line p2- 2 for the second stage compression, where it is compressed polytropically to the final pressure P3 along line 2-3, and then delivered to the receiver (not shown) at constant pressure P3 along line 3-p3. In the combined ideal indicator diagram is shown for the low pressure and high pressure cylinders of a single-acting, two-stage air compressor with perfect-intercooling.

The low pressure cylinder diagram is shown as pr-1-2’-p2, and high pressure cylinder diagram as p2-2—3-p3. The reduction of work required due to intercooling is shown by the shaded are 2-3-3’-2’. When cooling is perfect, i.e., when air is cooled to intake temperature in the intercooler (Ti = T2), the point 2 will lie on the isothermal line 1 - 3". It may be noted that each stage will increase the pressure of air while the intake temperature Ti (corresponding to point 1) is maintained same at the end. The isothermal line during the process has been approximated as shown by the diagram, and the shaded area 2-3-3’-2’ shows the saving of work as a result of this approximated isothermal.

## 5.8 VOLUMETRIC EFFICIENCY

Volumetric efficiency of an air compressor is the ratio of the adual volume of the free air at standard atmospheric conditions discharged in one delivery stroke, to the volume swept by the piston during the stroke. The standard atmospheric conditions (S.T.P.) is actually taken as pressure of 760 mm Hg (1 01325 bar) and temperature 15‘C in this connection. Thus, . Volume of free air delivered per stroke .

$$\text{Volumetric efficiency} = \frac{\text{Volume of free air delivered per stroke}}{\text{Volume swept by piston per str oke}}$$

The value of volumetric efficiency varies between 70 to 85 per cent according to the type of compressor. The volumetric efficiency decreases as the dearance volume increases. Other factors that lower the volumetric efficiency are : - Valve leakage, specially at the inlet valve, - Obstruction at inlet valves, - Piston ring leakage, which allows air to pass from one side of the cylinder to the other, - Heating of air by contact with hot cylinder walls, and Very high speed of rotation. With the decrease of volumetric efficiency, the capacity (quantity of free air delivered) of the compressor decreases.

### 5.8.1 EFFECT OF CLEARANCE ON VOLUMETRIC EFFICIENCY

The clearance space is provided in an actual compressor to safeguard the piston from striking the cylinder head or cylinder cover. The events taking place in a reciprocating compressor with clearance are the same as those taking place in a compressor without clearance. All the air compressed in the cylinder at the end of the compression stroke will not be discharged from it but some air will be left in the clearance space at the end of the delivery stroke 2-3 .The high pressure air, thus, left in the clearance space will re-expand along the curve 3-4 to the suction pressure (pr) before the suction valve can open and the suction starts again. The volume of air drawn into the cylinder without clearance is equal to the displacement volume corresponding to full stroke vs. However with clearance, the volume of fresh air drawn into the cylinder is only va corresponding to stroke 4-1. Thus, the effect of clearance in a compressor is to decrease the amount of fresh air that can be drawn into the cylinder during the suction stroke. Therefore, there is a considerable reduction in the volumetric efficiency of the compressor due to clearance. In practice the clearance volume is limited to, two or three per cent of the displacement or swept volume (va) of the piston.

## 5.9 RECIPROCATING COMPRESSED AIR MOTOR

Air motor is in effect a reversed air compressor. The compressed air to be used in an air motor is taken from the compressor reservoir (receiver). The most common form of compressed air motor is the cylinder and double-acting piston type. The air is admitted into the motor cylinder through a mechanically operated inlet valve and drives the piston forward but after a portion of the stroke of the piston has been performed, the air supply is cut-off and the stroke is completed under decreasing pressure as the air expands in the cylinder. After the expansion stroke is completed, the air which has done the work is allowed to escape into atmospheric through a mechanically operated discharge valve. The return stroke is performed by compressed air acting on the other side of the piston. A motor of this type works like a reciprocating double-acting steam engine.

The important application of air motor is the use in mines where use of electric motor is dangerous. There will be a fall in the pressure of air due to friction in the pipe, the fall being greater, the greater the distance of the air motor from the compressor reservoir (receiver).

## 5.10 ROTARY AIR COMPRESSORS

Depending on their pressure ratio, $r_p = \frac{P_2}{P_1}$, rotary air compressors may be classified Pi as follows :

Fans ( rp = 1 to 1.1 ) - The main purpose of a fan is to move air or to circulate air through the ducts of an air conditioning system and to supply low-pressure air blast. As the fluid passing through the unit does not suffer appreciable change in density, it can be treated as incompressible like water. Principally, fans are axial-flow compressors without casing around the impeller periphery.

Blowers ( rp =1-1 to 4 ) and compressors ( rp> 3 ) - If compressibility effect is considerable, it is to be taken into account while designing the unit and the unit is known as blower or a compressor proper depending on the pressure ratio. Blower may be positive displacement rotary compressor (Root’s blower, lysholm, vane type, screw type, etc.) or non-positive displacement rotary compressor (centrifugal compressor).

The purposes of a blower is to furnish forced draught to furnaces, besemer convertors, cupolas, etc. The purpose of compressor (centrifugal or axial flow) 'is to supply compressed air in large quantity, such as in gas turbine plants.

## 5.11 NON-POSITIVE DISPLACEMENT ROTARY OR STEADY FLOW COMPRESSORS

Centrifugal and axial flow compressors come under this heading. In all forms of turbo-machinery, whether expanders (called turbines or centrifugal and axial flow compressors), work changes are effected by means of velocity changes instead of by displacement changes of a boundary, such as with a piston. If the air enters at the centre axially and flows radially outward towards the circumference, the compressor is known as centrifugal compressor. On the other hand if the air flows parallel to the shaft, it is called axial flow compressor.