

ELECTRIC ENERGY GENERATION, UTILIZATION AND CONSERVATION NOTES

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING (SYLLABUS)

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UNIT I ELECTRIC DRIVES AND TRACTION **9**
Fundamentals of electric drive - choice of an electric motor - application of motors for particular services - traction motors - characteristic features of traction motor – systems of railway electrification - electric braking - train movement and energy consumption - traction motor control - track equipment and collection gear.

UNIT II ILLUMINATION **9**
Introduction - definition and meaning of terms used in illumination engineering - classification of light sources - incandescent lamps, sodium vapour lamps, mercury vapour lamps, fluorescent lamps – design of illumination systems - indoor lighting schemes - factory lighting halls - outdoor lighting schemes - flood lighting – street lighting - energy saving lamps, LED.

UNIT III HEATING AND WELDING **9**
Introduction - advantages of electric heating – modes of heat transfer - methods of electric heating - resistance heating - arc furnaces - induction heating – dielectric heating - electric welding – types - resistance welding - arc welding - power supply for arc welding - radiation welding.

UNIT IV SOLAR RADIATION AND SOLAR ENERGY COLLECTORS **9**
Introduction - solar constant - solar radiation at the Earth's surface - solar radiation geometry – estimation of average solar radiation - physical principles of the conversion of solar radiation into heat – flat-plate collectors - transmissivity of cover system - energy balance equation and collector efficiency - concentrating collector – advantages and disadvantages of concentrating collectors - performance analysis of a cylindrical - parabolic concentrating collector – Feeding Invertors.

UNIT V WIND ENERGY **9**
Introduction - basic principles of wind energy conversion - site selection considerations - basic components of a WECS (Wind Energy Conversion System) - Classification of WECS - types of wind Turbines - analysis of aerodynamic forces acting on the blade - performances of wind.

TOTAL: 45 PERIODS

TEXT BOOKS:
1. N.V. Suryanarayana, "Utilisation of Electric Power", Wiley Eastern Limited, New Age International Limited,1993.
2. J.B.Gupta, "Utilisation Electric power and Electric Traction", S.K.Kataria and Sons, 2000.
3. G.D.Rai, "Non-Conventional Energy Sources", Khanna Publications Ltd., New Delhi, 1997. AULibrary.com

REFERENCES:
1. R.K.Rajput, Utilisation of Electric Power, Laxmi publications Private Limited.,2007.
2. H.Partab, Art and Science of Utilisation of Electrical Energy", Dhanpat Rai and Co., New Delhi, 2004.
3. C.L.Wadhwa, "Generation, Distribution and Utilisation of Electrical Energy", New Age International Pvt.Ltd.,

SUBJECT IN – CHARGE **HOD**

UNIT I
ELECTRIC DRIVES AND TRACTION

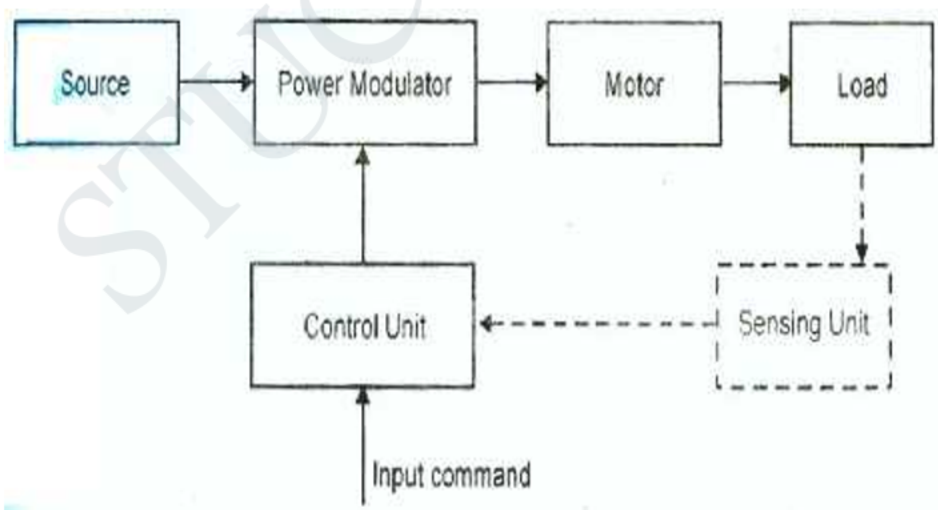
Fundamentals of electric drive - choice of an electric motor - application of motors for particular services - traction motors - characteristic features of traction motor – systems of railway electrification - electric braking - train movement and energy consumption - traction motor control - track equipment and collection gear

FUNDAMENTALS OF ELECTRIC DRIVE

- System employed for motion control are called driver and drives employing Electric Motors Are Electrical Drives.
- Electric drives are characterized by the nature of speed torque characteristics such as constant torque drives or constant hp drives. These are sometimes characterized by the type of motor used.
- Electrical drives which employs solid state derives thyristors for their control operations are termed as solid state drives.
- Solid state drives are used in steel rolling mill, Paper mills, Printing machines, cranes and lifts, fan drives, Aircraft power supplies, etc.

COMPONENTS OF ELECTRICAL DRIVES:

The block diagram of an electrical drives is shown below.



LOAD:

- Load is usually machinery designed to accomplish a given task.
- Fans, Pumps, Robots, Washing machines, Machine tools, Trains and drills.
- Usually load requirements can be specified in terms of speed and torque demands.

MOTOR:

- A motor having speed-torque characteristics and capabilities compatible to the load requirements is chosen most commonly used motor are

=>**Dc motor**: Shunt motor, Series motor, Compound motor and permanent magnet motors.
=>**Ac motors**: Induction motor and synchronous motors
=>**Special m/c**: Brushless Dc motor, Stepper motors and switching reluctance motors are also used.

POWER MODULATOR:

- Power modulator performs one or more of the following four functions:

=>Modulates flow of power from the source to the motor in such a manner that motor is imparted by the speed torque characteristics required by the load.
=>During transient operations such as starting braking and speed reversal it restricts source and motor current within permissible values excessive current drawn from the source may overload it or may course a voltage clip.
=>Converts electrical energy of the source in the form suitable to the motor.
=>Selects the mode of operation of the motor in motoring or braking.

CONTROL UNIT:

- Control unit has built in control for power modulation it usually operates at much lower voltage and power.
- In addition to operate the power modulator as desired it may also generate commands for the protection of power modulation and motor.
- Input command signal adjusts the operating point of the drive and forms an input to the control unit.
- Sensing of certain drive parameter such as motor current and speed may be required either for protection or for closed loop operation.

ADVANTAGES OF ELECTRICAL DRIVES:

- They hove flexible control characteristics the steady start and dynamic characteristics of electrical of electrical drives can be shaped to satisfy load requirements.
- Control gear required for speed control starting and braking is usually simple and easy to operate.
- They are available in wide range of torque of torque speed and power.
- Electric motor have high efficiency low or no load losses and considerable short time overloading capability compared to other prime movers they have longer life lower noise lower maintenance requirements andcleaner operation.
- They are adaptable to almost any operating conditions such as explosive and radioactive environments submerged in liquids, critical mountings, and so on.
- Do not pollute the environment.
- In operate in all the 4 quadrants of speed torque plane with considerable scaring of energy during braking.
- Unlike other prime movers there is no need to refuel or warm up the motor
- They can be started instantly and can immediately be fully loaded.
- They are powered by electrical energy which has a number of advantages over other forms of energy.

CHOICE OF AN ELECTRIC MOTOR

There are certain factor that governs or influences, the selection choice electrical drives. They are:

Availability of Electrical Supply

The electric drive is a drive system with electrical motor as a prime mover. The selection of electrical drive is based on the availability of electrical supply. There are three-types electrical supplies, namely AC supply, DC supply, and Rectified DC supply. If AC supply is available. Then AC drive is selected motor. An AC drive consists of AC motor as a drive motor .If DC supply is available, then DC drive is selected .DC drive consist of DC motor as a drive motor. Hence nature of electrical supply available governs selection of electric drive.

Nature of Operation characteristics of Electric drive motors

The electric drive motor has different types of operating characteristics such as

1) Starting characteristics

2) Running characteristics

3) Speed control characteristics

4) Braking characteristics

For example the running characteristic of electric drive motor shows how the motor behaves where it is loaded .In some cases if the load is increased , the speed of the motor is drastically reduced .so such motors are not selected for constant speed applications.

Economic Consideration

The electrical motor is selected based on two economic considerations, namely

1. Initial cost:

The initial cost is nothing out capital cost. This is the cost occurred during purchase and erection.

2. Running cost:

This is the cost running the electric drive. Ex: Maintenance cost , Fuel cost etc..

Type of the Drive system

Type of the Drive system available also governs the choice of electric motor. There are three types of drive system namely Group drive, Individual diver and Multi motor drive. Assume that at any particular location, different small loads are available. Since the loads are separate unit, it can be driven by single large motor (group drive) So here a DC motor or an AC motor is selected with huge HP rating.

Types of Load

The type of load available , also governs the selection of electric drive . Generally the loads are classified based on the Torque characteristics .Torque is the twisting force required to drive (rotate) the load ,based on the Torque characteristics loads are classified as follows.

1. Load requiring constant Torque with speed

2. Load requiring increasing Torque with speed

3. Load requiring high starting Torque (high inertia load)

Assume that load cannot with high inertia available .This high inertia loads cannot be accelerated or deaccelerated quickly .They require high starting Torque. Therefore motor with high starting torque such as DC series or 3 (There Phase) Slip ring induction motor is selected .Thus type of load influence the choice of electric motor.

Mechanical considerations

i) Type of enclosure

ii) Type of bearings

iii) Type of Transmission devices

EnvironmentalConsiderations

I. Noise pollution

II. Environmental Pollution

Load – With standing Capability of motors

The size and rating required for the drive motor influence the selection of the electric drive motor. The size of the motor describes load- withstanding capability .when the motor is loaded, the line current drawn by the motor increases. As a result losses increases and more heat is developed .If the heat is hot dissipated then insulation in the motor fails leading to complete breakdown of the motor. Here duty cycle of the load and the Torque requirement are important factors in deciding size and rating of the motor.

Different Types Of Loading Of Drives: While selecting a motor it is necessary to consider the variation of load torque with speed and time. This is related to the torque rating of the motor i.e. how much and what type of torque motor can produce safely. The variation of load torque with speed basically decides the type of motor to be selected. While the variation of load torque with time decides the rating of the motor to be selected. Such a factor which influences the selection of rating of motor based on the load variation with time is called load variation factor. One cycle of variation of load is called a duty cycle. The different types of load variations with and corresponding examples of load are given below:

i) Continuous or constant loads:In this type load occurs for a long time under the same conditions.e.g., fan type loads, paper making machines etc.

ii) Continuous variable loads : The load is variable over a period of time but occurs repetitively for a longer duration. e.g., metal cutting lathes, conveyers etc.

iii) Pulsating loads: A torque which exhibits a combination of constant load torque superimposed by pulsations. e.g., reciprocating pumps, compressors, all loads having crank shaft.

iv) Impact loads: These are peak loads occur at regular intervals of time. e.g., rolling mills, presses, sharing machines, forging hammers. Motors for such loads are provided with heavy fly wheels.

v)Short time intermittent loads : The load appears periodically identical duty cycles, each consisting of a period of applications of load and one or rest. e.g., all forms of cranes, hoists, elevators.

vi) Short time loads : A constant load appears on the drive and the system rests for the remaining period of cycle. e.g. motor- generator sets for charging batteries, household equipment.

1.3 APPLICATION OF MOTOR FOR PARTICULAR SERVICE

Type	Advantages	Disadvantages	Typical application	Typical drive, output
Self-commutated motors				
Brushed DC	Simple speed control Low initial cost	Maintenance (brushes) Medium lifespan Costly commutator and brushes	Steel mills Paper making machines Treadmill exercisers Automotive accessories	Rectifier, linear transistor(s) or DC chopper controller.[77]
Brushless DC motor (BLDC) or (BLDM)	Long lifespan Low maintenance High efficiency	Higher initial cost Requires EC controller with closed-loop control	Rigid ("hard") disk drives CD/DVD players Electric vehicles RC Vehicles UAVs	Synchronous; single-phase or three-phase with PM rotor and trapezoidal stator winding; VFD typically VS PWM inver ter type.[73][77][78]
Switched reluctance motor (SRM)	Long lifespan Low maintenance High efficiency No permanent magnets Low cost Simple construction	Mechanical resonanc e possible High iron losses Not possible: * Open or vector control * Parallel operation Requires EC controller[75]	Appliances Electric Vehicles Textile mills Aircraft applications	PWM and various other drive types, which tend to be used in very specialized / OEM applications.[75][79]
Universal motor	High starting torque, compact, high speed.	Maintenance (brushes) Shorter lifespan Usually acoustically noisy Only small ratings are economical	Handheld power tools, blenders, vacuum cleaners, insulation blowers	Variable single phase AC, half-wave or full-wave phase-angle control with triac(s); closed-loop control optional.[77]

AC asynchronous motors				
AC polyphase squirrel-cage or wound-rotor induction motor (SCIM) or (WRIM)	Self-starting Low cost Robust Reliable Ratings to 1+ MW Standardized types.	High starting current Lower efficiency due to need for magnetization.	Fixed-speed, traditionally, SCIM the world's workhorse especially in low performance applications of all types Variable-speed, traditionally, low-performance variable-torque pumps, fans, blowers and compressors. Variable-speed, increasingly, other high-performance constant-torque and constant-power	Fixed-speed, low performance applications of all types. Variable-speed, traditionally, WRIM drives or fixed-speed V/Hz-controlled VSDs. Variable-speed, increasingly, vector-controlled VSDs displacing DC, WRIM and single-phase AC induction motor drives.
AC SCIM split-phase capacitor-start	High power high starting torque	Speed slightly below synchronous Starting switch or relay required	Appliances Stationary Power Tools	Fixed or variable single-phase AC, variable speed being derived, typically, by full-wave phase-angle control with triac(s); closed-loop control optional.[77]
AC SCIM split-phase capacitor-run	Moderate power High starting torque No starting switch Comparatively long life	Speed slightly below synchronous Slightly more costly	Industrial blowers Industrial machinery	
AC SCIM split-phase, auxiliary start winding	Moderate power Low starting torque	Speed slightly below synchronous Starting switch or relay required	Appliances Stationary power tools	
AC induction shaded	Low cost Long life	Speed slightly below synchronous Low starting torque	Fans, appliances, record players	

-pole motor		Small ratings low efficiency		
AC synchronous motors				
Wound-rotor synchronous motor (WRSM)	Synchronous speed Inherently more efficient induction motor, low power factor	More costly	Industrial motors	Fixed or variable speed, three-phase; VFD typically six-step CS load-commutated inverter type or VS PWM inverter type.[77][78]
Hysteresis motor	Accurate speed control Low noise No vibration High starting torque	Very low efficiency	Clocks, timers, sound producing or recording equipment, hard drive, capstan drive	Single-phase AC, two-phase capacitor-start, capacitor run motor[80][81]
Synchronous reluctance motor (SyRM)	Equivalent to SCIM except more robust, more efficient, runs cooler, smaller footprint Competes with PM synchronous motor without demagnetization issues	Requires a controller Not widely available High cost	Appliances Electric vehicles Textile mills Aircraft applications	VFD can be standard DTC type or VS inverter PWM type.[82]
Specialty motors				
Pancake or axial rotor motors	Compact design Simple speed control	Medium cost Medium lifespan	Office Equip Fans/Pumps, fast industrial and military servos	Drives can typically be brushed or brushless DC type.[73]
Stepper motor	Precision positioning High holding torque	Some can be costly Require a controller	Positioning in printers and floppy disc drives; industrial machine tools	Not a VFD. Stepper position is determined by pulse counting.[83][84]

1.4. TRACTION MOTORS

- The dc series motor possess a high starting torque and variable speed characteristics therefore it is very much used in traction application.
- It is more robust capable of withstanding very severe mechanical shock and take more overload.
- Ventilation for the motor should be carefully designed ,to avoid surface which attract dust,dirt,grit,from track or road.
- The field frame is of cast steel and usually of box type, with opening at each end bored and recessed to provide the armature bearing which are fastened securely by steel bolts screwed into it.
- Locomotive motors are axle mounted and wherever the HP exceeds 400 they are placed on the

locomotive frame.

- The maximum speed and output of the motor decides the choice of mounting.

In earlier days, DC motor is suited for traction because of the high-starting torque and having the capability of handling overloads. In addition to the above characteristics, the speed control of the DC motor is very complicated through semiconductor switches. So that, the motor must be designed for high base speed initially by reducing the number of turns in the field winding. But this will decrease the torque developed per ampere at the time of staring. And regenerative braking is also complicated in DC series motor; so that, the separately excited motors can be preferred over the series motor because their speed control is possible through semi-controlled converters.

1.4.1 DC series motor

- From the construction and operating characteristics of the DC series motor, it is widely suitable for traction purpose. Following features of series motor make it suitable for traction.
- DC series motor is having high-starting torque and having the capability of handling overloads that is essential for traction drives.
- These motors are having simple and robust construction.
- The speed control of the series motor is easy by series parallel control.
- Sparkless commutation is possible, because the increase in armature current increases the load torque and decreases the speed so that the emf induced in the coils undergoing commutation.
- Series motor flux is proportional to armature current and torque. But armature current is independent of voltage fluctuations. Hence, the motor is unaffected by the variations in supply voltage.

1.4.2 shunt motor

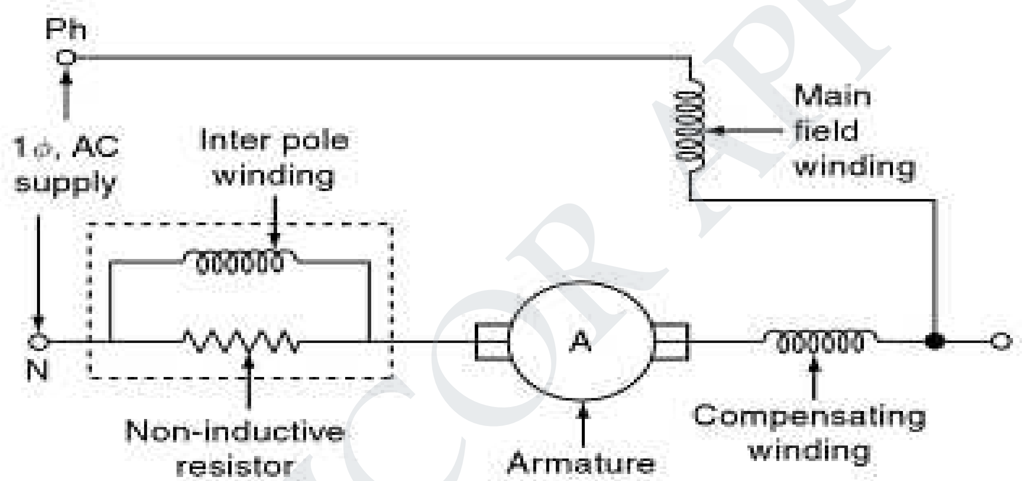
- From the characteristics of DC shunt motor, it is not suitable for traction purpose, due to the following reasons:
- DC shunt motor is a constant speed motor but for traction purpose, the speed of the motor should vary with service conditions.
- In case of DC shunt motor, the power output is independent of speed and is proportional to torque. In case of DC series motor, the power output is proportional to So that, for a given load torque, the shunt motor has to draw more power from the supply than series motor.
- For shunt motor, the torque developed is proportional to armature current ($T \propto I_a$). So for a given load torque motor has to draw more current from the supply.
- The flux developed by shunt motor is proportional to shunt field current and hence supply voltage.

- But the torque developed is proportional to φ_{sh} and I_a. Hence, the torque developed by the shunt motor is affected by small variations in supply voltage.

1 . 4 . 3 AC series motor

- Practically, AC series motor is best suited for the traction purpose due to high-starting torque When DC series motor is fed from AC supply, it works but not satisfactorily due to some of the following reasons:
- If DC series motor is fed from AC supply, both the field and the armature currents reverse for every half cycle. Hence, unidirectional torque is developed at double frequency.
- Alternating flux developed by the field winding causes excessive eddy current loss, which will cause the heating of the motor. Hence, the operating efficiency of the motor will decrease.
- Field winding inductance will result abnormal voltage drop and low power factor that leads to the poor performance of the motor.

- Induced emf and currents flowing through the armature coils undergoing commutation will cause sparking at the brushes and commutator segments.



1.4.4Three-phase induction motor

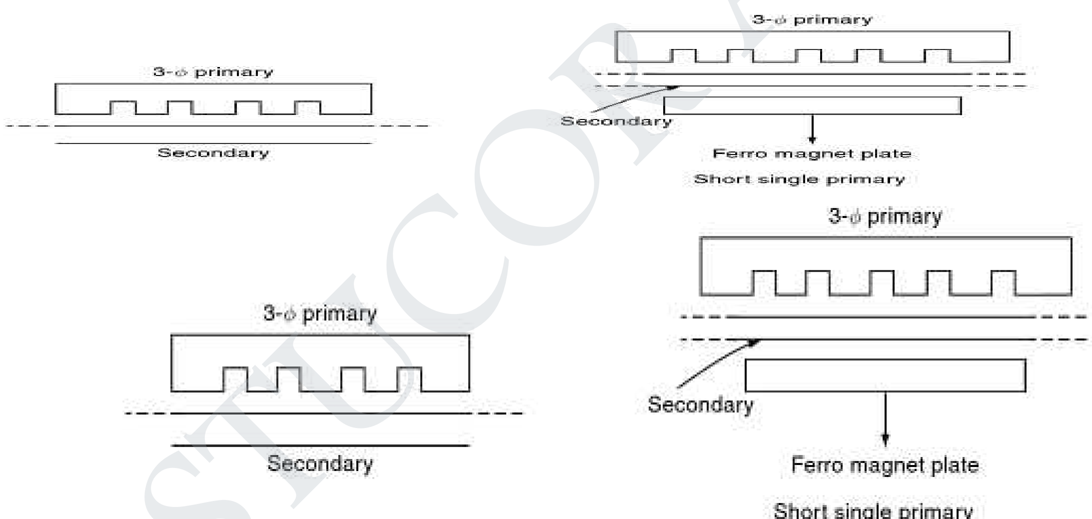
- The three-phase induction motors are generally preferred for traction purpose due to the following advantages.
- Simple and robust construction.
- Trouble-free operation.
- The absence of commutator.
- Less maintenance.
- Simple and automatic regeneration.
- High efficiency.
- Three-phase induction motors also suffer from the following drawbacks.
- Low-starting torque.
- High-starting current and complicated speed control system.
- It is difficult to employ three-phase induction motor for a multiple-unit system used for propelling a heavy train.
- Three-phase induction motor draws less current when the motor is started at low frequencies.

When a three-phase induction motor is used, the cost of overhead distribution system increases and it consists of two overhead conductors and track rail for the third phase to feed power to locomotive, which is a complicated overhead structure and if any person comes in contact with the third rail, it may cause danger to him or her.

1.4.5 Linear induction motor

- It is a special type of induction motor that gives linear motion instead of rotational motion, as in the case of a conventional motor.
- In case of linear induction motor, both the movement of field and the movement of the conductors are linear.
- A linear induction motor consists of 3-φ distributed field winding placed in slots, and secondary is nothing but a conducting plate made up of either copper or aluminum
- The field system may be either single primary or double primary system. In single primary system, a ferro magnetic plate is placed on the other side of the copper plate; it is necessary to provide low reluctance path for the magnetic flux. When primary is excited by 3-φ AC supply, according to mutual induction, the induced currents are flowing through secondary and ferro magnetic plate.

- Now, the ferro magnetic plate energized and attracted toward the primary causes to unequal air gap between primary and secondary. This drawback can be overcome by double primary system. In this system, two primaries are placed on both the sides of secondary, which will be shorter in length compared to the other depending upon the use of the motor.



1.4.6 Synchronous Motor

- The synchronous motor is one type of AC motor working based upon the principle of magnetic lacking. It is a constant speed motor running from no-load to full load. The construction of the synchronous motor is similar to the AC generator; armature winding is excited by giving three- phase AC supply and field winding is excited by giving DC supply. The synchronous motor can be operated at leading and lagging power factors by varying field excitation.
- The synchronous motor can be widely used various applications because of constant speed from no-load to full load.

- High efficiency.
- Low-initial cost.
- Power factor improvement of three-phase AC industrial circuits.

1.5 CHARACTERISTIC FEATURES OF TRACTION MOTOR

Electrical features:

- High starting speed
- Simple speed control
- Series speed torque characteristics
- It should be suitable for dynamic or regenerative braking
- Even when the supply voltage fluctuate commutations should be good

- **High-starting torque**

A traction motor must have high-starting torque, which is required to start the motor on load during the starting conditions in urban and suburban services.

- **Speed control**

The speed control of the traction motor must be simple and easy. This is necessary for the frequent starting and stopping of the motor in traction purpose.

- **Dynamic and regenerative braking**

Traction motors should be able to provide easy simple rheostatic and regenerative braking subjected to higher voltages so that system must have the capability of withstanding voltage fluctuations.

- **Temperature**

The traction motor should have the capability of withstanding high temperatures during transient conditions.

- **Overload capacity**

The traction motor should have the capability of handling excessive overloads. No single motor can have all the electrical operating features required for traction.

Mechanical features

- Due to the high speed of the train the motor should be robust and should withstand continuous vibration
- Weight should be minimum and over all dimension should be small
- As they are to be placed beneath the locomotive or motor coach they should be protected from dirt and dampness

No single motor fulfils the above needs the DC series and compound motors are found to be suitable for DC.
AC series motor is found to be suitable for single and induction motors for three phase system.

1.6. SYSTEMS OF RAILWAY ELECTRIFICATION

In this system of traction, the electric motors employed for getting necessary propelling torque should be selected in such a way that they should be able to operate on DC supply. Examples for such vehicles operating based on DC system are tramways and trolley buses. Usually, DC series motors are preferred for tramways and trolley buses even though DC compound motors are available where regenerative braking is desired. The operating voltages of vehicles for DC track electrification system are 600, 750, 1,500, and 3,000 V. Direct current at 600–750 V is universally employed for tramways in the urban areas and for many suburban and main line railways, 1,500–3,000 V is used.

1.6.1. 1-φ AC system

In this system of track electrification, usually AC series motors are used for getting the necessary propelling power. The distribution network employed for such traction systems is normally 15–25 kV at reduced frequency of 163⅔ Hz or 25 Hz. The main reason of operating at reduced frequencies is AC series motors that are more efficient and show better performance at low frequency. These high voltages are stepped down to suitable low voltage of 300–400 V by means of step-down transformer. Low frequency can be obtained from normal supply frequency with the help of frequency converter. Low-frequency operation of overhead transmission line reduces the line reactance

1.6.2. 3-φ AC system

In this system of track electrification, 3-φ induction motors are employed for getting the necessary propelling power. The operating voltage of induction motors is normally 3,000–3,600-V AC at either normal supply frequency or 16⅔-Hz frequency.

Usually 3-φ induction motors are preferable because they have simple and robust construction, high operating efficiency, provision of regenerative braking without placing any additional equipment, and better performance at both normal and seduced frequencies. In addition to the above advantages, the induction motors suffer from some drawbacks; they are low-starting torque, high-starting current, and the absence of speed control. The main disadvantage of such track electrification system is high cost of overhead distribution structure. This distribution system consists of two overhead wires and track rail for the third phase and receives power either directly from the generating station or through transformer substation.

1.6.3 Composite system

As the above track electrification system have their own merits and demerits, 1-φ AC system is preferable in the view of distribution cost and distribution voltage can be stepped up to high voltage with the use of transformers, which reduces the transmission losses. Whereas in DC system, DC series motors have most desirable features and for 3-φ system, 3-φ induction motor has the advantage of automatic regenerative braking. So, it is necessary to combine the advantages of the DC/AC and 3-φ/1-φ systems. The above cause leads to the evolution of composite system.

Composite systems are of two types.

Single-phase to DC system.

Single-phase to three-phase system or kando system.

Single-phase to DC system

In this system, the advantages of both 1-φ and DC systems are combined to get high voltage for distribution in order to reduce the losses that can be achieved with 1-φ distribution networks, and DC series motor is employed for producing the necessary propelling torque. Finally, 1-φ AC distribution network results minimum cost with high transmission efficiency and DC series motor is ideally

suited for traction purpose. Normal operating voltage employed of distribution is 25 kV at normal frequency of 50 Hz. This track electrification is employed in India.

1.7 ELECTRIC BRAKING

Electric braking

In this method of braking, the kinetic energy of the moving parts that is motor is converted into electrical energy which is consumed in a resistance as heat or alternatively it is returned to the supply source. Electric braking is superior to the friction braking as it is fast and cheap since there is no cost of maintenance of the brake shoes or lining. During braking operation a motor has to function as a generator. The motor can be held at stand still. In other words the electric braking cannot hold the motor at rest. Thus it becomes essential to provide mechanical brakes in addition to electric braking.

Various types of electrical braking are:

a) Plugging

b) Rheostatic braking

c) Regenerative braking

1.7.1 Plugging

This is a simple method of electric braking and consists in reversing the connections of the armature of the motor so as to reverse its direction of rotation which will oppose the original direction of rotation of the motor and will bring it to zero speed when mechanical brakes can be applied.

At the end of the braking period the supply to the motor is automatically cut off. This method of braking can be applied to the following motors.

1) DC motors
2) Induction motors
3) Synchronous motors

DC motors:

To reverse a DC motors, it is necessary to reverse the connections of the armature while the connections of the field are kept the same. The direction of m.m.f remains the same even during braking periods.

Series motors:

The arrangements of connection before and after the braking are shown in fig.

Shunt motors:

The arrangements of connections before and after braking for shunt motor are shown in fig. Total voltage of V+ E_b is available across the armature terminals which causes a current Ito flow around the circuit. When E_b = V then the voltage across the armature is 2V and at the time of braking twice the normal voltage is applied to the resistance in series with the armature at this time in order to limit the current. While the motor is being braked, the current is still being

drawn from the supply. This method requires energy from the supply for its action and not only the kinetic energy of the motor is being wasted, but this energy is also being dissipated. Speed and braking torque

Electric braking to torque

$T_B \alpha \Phi I$ ------------------------------- (1)

$T_B = K \Phi I$ ----------------------------- (2)

Where K is a constant

Current = V+ E_b / R ------------------------ (3)

$E_b = K_1 N \Phi$ --------------------- (4)

Where V is applied voltage

E_b is back emf of the motor.

R is the resistance of the motor

N is the speed

K_1 is a constant

Substitute the value of E_b from equation (4) in (3)

Current $I = (V + K_1 N \Phi)/ R$ -------------------- (5) In view of equations (2) and (5)

$T_B = K \Phi[(V + K_1 N \Phi)/ R] = K \Phi V/ R + KK_1 N \Phi_2/ R$

$= K_2 \Phi + K_3 \Phi_2 N$ ------------- (6)

Where $K_2 = KV/ R$ -------------------- (7)

And $K_3 = KK_1/R$ --------------------- (8) Apply the results obtained to the series motor, where

$\Phi \propto$ armature current (I_a) ------------------- (9)

Then electric braking in series motor,

$= K_4 I_a + K_5 I_{a2}$ -------------------- (10)

In the case of shunt motor since flux is constant, so

Electric braking torque TB $= K_6 + K_7 N$ ------------------- (11)

Wherever there is a load on the machine the load will also exert braking torque due to it and then the total braking torque (T)

T = Electric braking torque + Load torque ------------- (12)

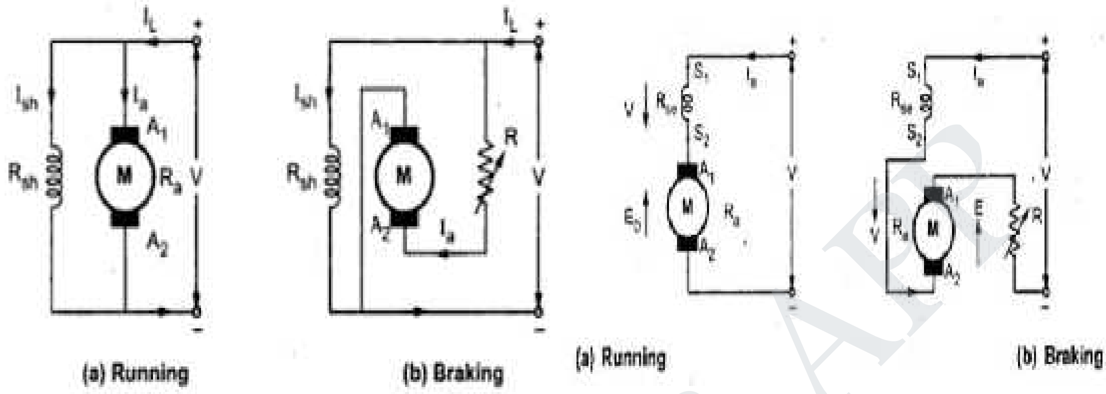


Fig:1 Plugging of DC Shunt and Series Motor

Induction motors

In the case of induction motor its speed can be reversed by inter changing any of the two stator phases which reverses the direction of rotation of motor field. Actually at the time of braking when the induction motor is running at near synchronous speed. The point Q represents the torque at the instant of plugging one can notice that the torque increases gradually as one approaches the stand still speed. Different values of rotor resistance give rise to different shapes of speed torque curve in order to give any desired braking effect. The rotor current I_2 can be calculated during the braking period from the following relation and is plotted as shown.

$I_2 = SE_2 / \sqrt{[R_{e2} + (SX_2)2]}$ ------------------- (13)

Where E_2 is the e.m.f. induced in rotor at standstill

R_2 is the rotor resistance

X_2 is the standstill reactance of the rotor and

S_2 is the percentage slip

Synchronous motors

Plugging can be applied to the synchronous motors, with the only difference that the field on the rotor will be rotating in opposite direction to that of the rotating field on the stator with the synchronous speed and the relative velocity between the two will be twice the synchronous speed.This will meant that there is one synchronous motor torque but the same will be produced by the induction in the starting winding. Since most of the motors are equipped with starting winding, a synchronous motor provides satisfactory braking.

1.7.2 Rheostatic braking

In this method of braking, the motor is disconnected from the supply and run as generator driven by the remaining kinetic energy of the equipment that is the energy stored in motor and load which are to be braked.

The following drives can be braked by the rheostatic method:

i. DC motor, ii. Induction motor, iii. Synchronous motor.

Dc motors:

Shunt motor

In this type of motor, the armature is simply disconnected from the supply and is connected to as resistance in series with it, the field; winding remains connect to the supply as Fig. The braking can be adjusted suitably by varying the resistance in the armature circuit. In the case of failure of the supply, there is no braking torque because of absence of the field.

Series motor

In this case of the connections are made as shown is fig during braking operation. The motor after disconnection from the supply in made to run as a DC series generator. Resistance inserted in the circuit must be less than the critical resistance otherwise the generator will not be self exciting. When the series motor is disconnected from the supply the direction of the armature current is reversed.

Braking torque and speed

Electric braking torque is given by equation (3)

Braking current = E_b / R ---------------------------------- (14)

Hence braking current of equation (14) and (4)

= $K_1\Phi N/R$ ------------------------------------ (15)

Substitute the value of braking current is equation (1)

Electric braking torque = $KK_1\Phi_2 N/R = K_2\Phi_2 N$ ------------------------- (16)

Where $K_2 = KK_1/R$ -------------------------------- (17)

In the case of a series motor the flux dependent upon the armature current

= $K_3 I_{a2} N$ ------------------------------- (18)

While in the case of shunt motor since flux is constant

Electric braking torque = K_4N ------------------------------- (19)

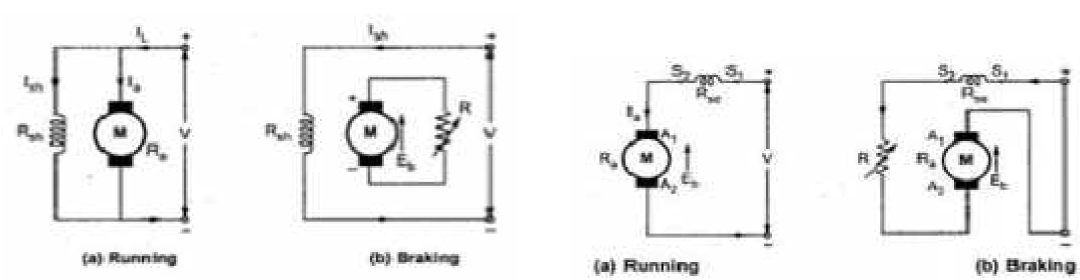


Fig:2 Rheostatic Braking of DC Shunt and Series Motor

Induction motor

In this case the stator is disconnected from the supply and is connected to DC supply which excites the windings thereby producing a DC field. The rotor is short-circuited across through resistance in each phase. When the short circuited rotor moves it outs the steady flux produced in the air gap due to DC current flowing in the stator produced in the air gap due to DC current flowing in the stator and an e.m.f is induced in the rotor conductors.

The satisfactory application of this method is applicable only to the phase wound inductor motor where external resistance can be inserted in each phase.

Synchronous motors

Rheostatic braking in the synchronous motors is similar to the rheostatic braking in induction motors. In this case the stator is shorted across resistance in star or delta and the machine works like an alternator supplying the current to the resistance, there by dissipating in kinetic energy in the form of losses in the resistances.

1.7.3 Regenerative braking

In this type of braking the motor is not disconnected from the supply but remains connected to it and its feeds back the braking energy or its kinetic energy to the supply system. This method is better than the first and second methods of braking since no energy is wasted and rather it is supplied back to the system. This method is applicable to following motors:

- D.C motors ,• Induction motors

D.C motors: Shunt motor

In a DC machine where energy will be taken from the supply or delivered to it depends upon the induced emf, if it in less than the line voltage the machine will operate as motor and if it is more than the line voltage, the machine will operate as generator.

The e.m.f induced in turn depends upon the speed and excitation that is when the field current or the speed is increased the induced e.m.f exceeds the line voltage and the energy will be field into the system. This will quickly decrease the speed of the motor and will bring it to rest.

Series motor

In this case, complications arise due to fact that the reversal of the current in the armature would cause a reversal of polarity of the series field and hence back emf would be reversed.

Induction motor

In the case of induction motors, the regenerative braking is inherent, since an induction motor act as a generator when running at speeds above synchronous speeds and it feeds power back to the supply system. No extra auxiliaries are needed for this purpose. This method is however very seldom used for braking but its application is very useful to lifts.

1.9.TRACTION MOTOR CONTROL

Traction motor control

The traction motor control is required for stating without drawing excessive current from the supply for providing smooth acceleration without sudden shock, to avoid damage to couplings and inconvenience to the passengers and for speed control depending upon the type of service.

i)D.C.Series motor control

1.9.1 Armature resistance control

▪The current drawn by d.c. motor is given by where V is ~~the~~ supply voltage, the back and R is the total armature circuit resistance.

- At start, therefore, an external resistance in series with the armature should be connected in order to limit the starting current as value of armature resistance is usually quite small.

•A suitable value of starting resistance is connected so that the starting current does not exceed a certain maximum value of

•As the motor accelerates, back is built up and current starts decreasing from its maximum value. When certain minimum value of current is reached, the resistances are cut off.

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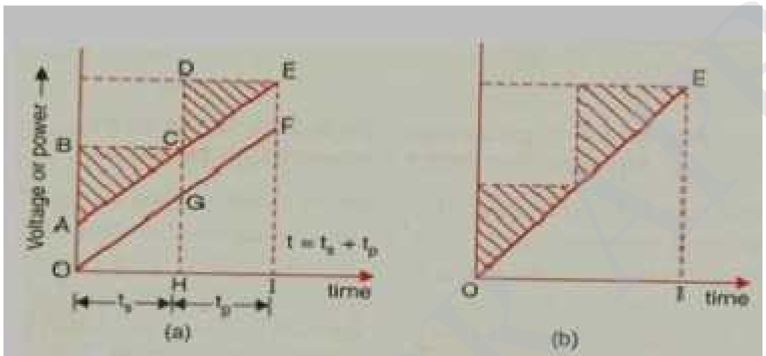


Energy Diagram. Series Parallel Operation

If voltage drop across the armature resistance is neglected, energy wasted in starting resistance is given by the shaded area of figure.

1.9.2 Series Parallel Control

•This method of control assumes that at least tow motors are being used which are connected in series at start for low speed and in parallel for full speed running. Hence, the name series –parallel control.

•With two motors, therefore, half the supply voltage is applied across each motor and they will run to approximately half the rated speed at which they are switched in parallel and full voltage is applied to each motor when they run finally at their rated speed.

•Normally, in order to limit the starting current to suitable values, external resistances are connected in series at starting and are cut out gradually with the motors in the series connection and are reintroduced when the motors are switched into parallel and again gradually they are cut out.

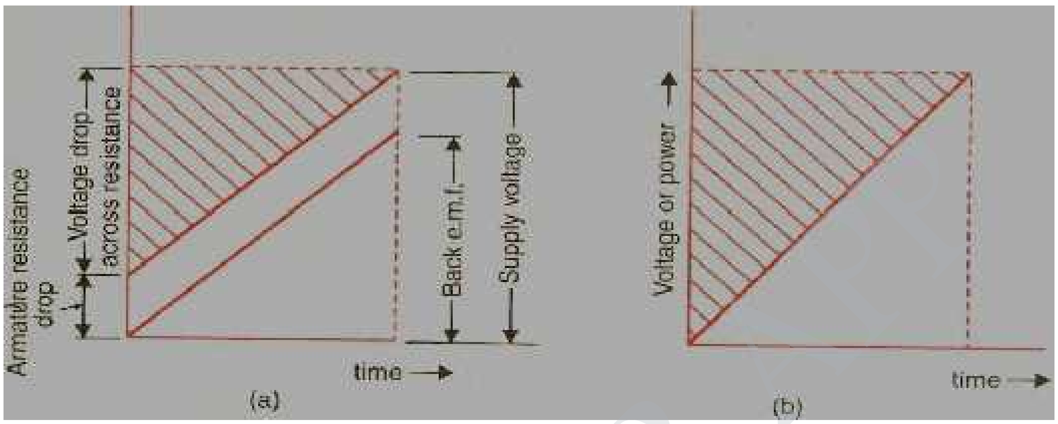
•Between OH the two motors are connected in series and at H, half of the voltage is applied across each motor when the resistance is cut out completely.

•At this instant GH is the back developed across each motor and GC is the armature drop. Upto time the energy wasted per motor is given by the hatched area ABC.

•At point H and beyond i.e., the motors are switched in parallel with the suitable amount of resistance reintroduced and the acceleration continues till time when the total resistance is again cut off.

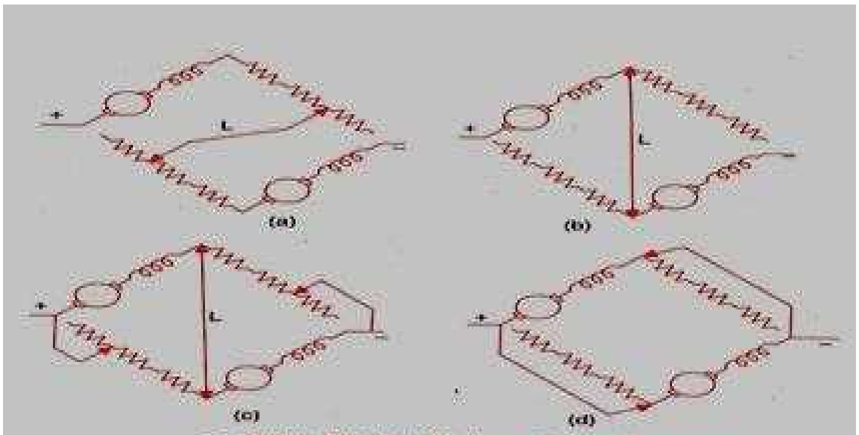
•The ordinate IF represents the back developed by each motor and FE the armature drop of each motor.

•The area CDE represents the energy loss per motor during the period again assuming armature drop to be negligible, the duration of starting for series and parallel operation will be identical.



Shunt transition:

Since during the torque developed by the motor is reduced suddenly, the vehicle experiences a sudden jerk and causes inconvenience to the passengers, this method is normally employed for light vehicles like trams etc.



Series Parallel Starting—Bridge Transition

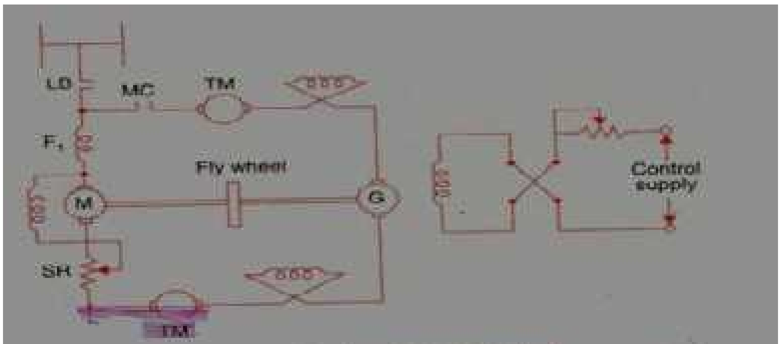
The advantage of the bridge transition method is that during transition, the motors are always connected to the supply and as the resistances are so adjusted that the value of current remains same, the torque does not change and hence uniform acceleration is obtained without causing inconvenience to the passengesrs. This method is used for railway traction.

1.9.3 Speed control by field weakening

The armature voltage control is used whenever speeds lower than normal speeds are required, and field control is used when speeds more than normal are required. In case of traction motors, due to certain design difficulties, field control is usually limited to one or two tappings so that an increase of 15 to 30 in speed is made possible. Since the speed is inversely proportional to the flux, by weakening the filed, the speed is increased. For weakening the field either a diverter is provided or the field is tapped. A combination of both the filed and voltage control provides sufficient flexibility in the operation of traction motors.

1.94 Buck and Boost method

The armatures of both the traction motors and the motor generator set are connected in series and across the supply. When the generator voltage equals the supply voltage and is in opposition to it, the main contractor (MC) is closed.



Buck and Boost Method

•Under this condition, there is no voltage across the traction motors and hence their speed is zero.

•If now the generator voltage is reduced, voltage across traction motors starts increasing and their speed rises.

•When generator voltage is zero, full supply voltage appears across the motors i.e., each motor receives one half of the supply voltage.

•If the polarity of the generated equals supply voltage, each traction motor will receive voltage equal to supply voltage.

•Thus by adjusting the generator excitation the equivalent supply voltage can be reduced or boosted up. Following are the advantages of this method:

It is possible to obtain any operating speed of traction motors, whereas in case of resistance controllers only a few speeds are possible.

In case of temporary interruption in the supply, the K.E. of the fly wheel can be utilized in generating energy from the MG set and fed to the traction motors.

There is no energy loss in the starting resistance of the traction motors. However, loss does take place in the starting resistance of motor generator set.

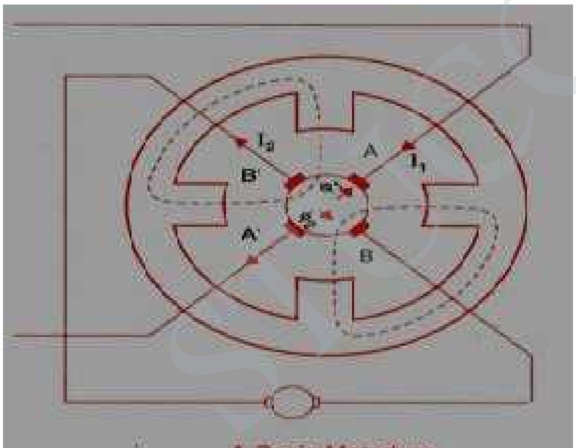
1.9.5 Metadyne Control

- Machines with more than two brush sets per pair of poles are called metadynes.

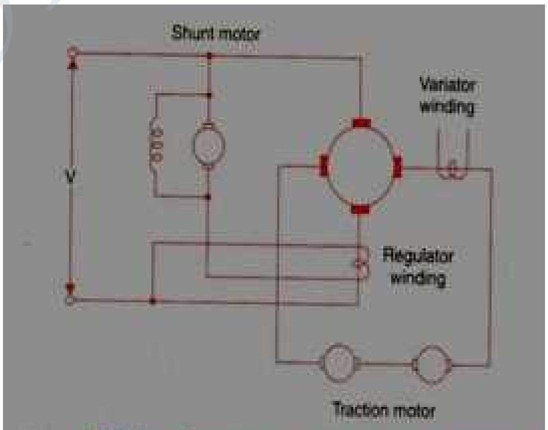
•It is a device which converts power at constant voltage and variable current into one with constant current variable voltage.

•The main advantage of Metadyne control is that the loss is much lower than in case of resistance starting method

•current throughout the starting periods can be maintained constant hence uniform tractive effort is developed which avoids jerky movement of train which otherwise exists in resistance striating methods where the current varies between a certain maximum and minimum value whenever the notch position is changed.



A Basic Metadyne



Metadyne Converter alongwith its Control components

•Suppose the output from the converter is more than its input, therefore, the speed of the converter goes down. With this the speed of the shunt motor also goes down and the back developed decreases.

•For the same supply voltage the armature current, therefore, increases and hence the current through the regulator winding increases which will have more demagnetizing effect along AA.

•In order to have same value of flux the current drawn by the converter, therefore, increases. Hence input to the converter increases and balance between output and input is restored and the metadyne again runs at a constant speed by shunt motor.

1.10. TRACK EQUIPMENT AND COLLECTION GEAR.

There are mainly two systems for locomotives, tramways or trolley buses.

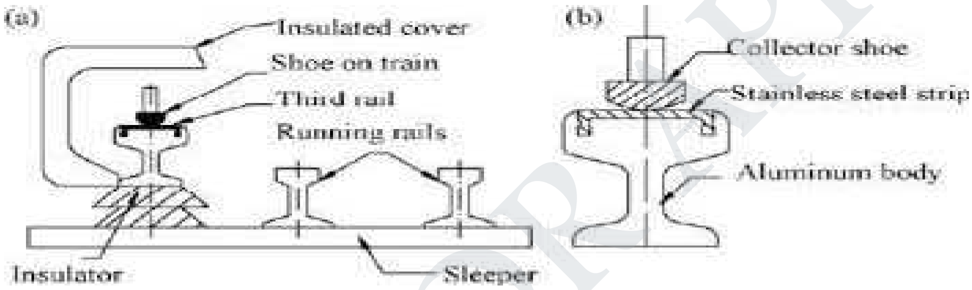
a. Conductor rail system. b. Overhead system.

1.10.1 Conductor Rail System:

It is employed at 600V for suburban services since it is cheaper, inspection and maintenance easier. The current is supplied to the electrically operated vehicle. The insulated return rail is elimination to electrolytic action due to currents on other public services buried in the cicinity of railway tunnels. A special steel alloy (iron 99.63%, carbon 0.05%, manganese 0.2%, phosphorus 0.05%, silicon 0.02% and sulphur 0.05%) is used.

It has a resistance of about the conductor rail is not fixed rigidly to the insulators in order to take care of the contraction and expansion of rails.

The current can be collected at about 300 to 500A. At least two shoes must be provided on each side to avoid discontinuity in the current flow and for voltage 1200V.



1.10.2 Overhead System:

This system is adopted when the trains are to be supplied at high voltage of 1500V or above. This system is used for ac railways and also used with dc tramways, trolley buses and locomotives operating at voltages 1500V and above with return conductor. Three types of current collectors are commonly used.

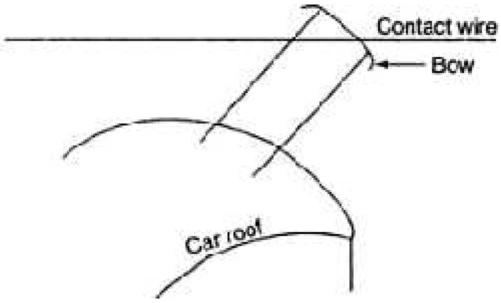
a) Trolley Collector:

It is employed with tramways and trolley buses. It consists of a grooved gun metal wheel or grooved slider shoe with carbon insert carried at the end of a long pole. The other end of this pole is hinged to a swiveling base fixed to the roof of the vehicle. The necessary upward pressure for the pole and current collector is achieved by springs. As two trolley wires are required for a trolley bus, a separate trolley collector is provided for each wire.

b) Bow Collector:

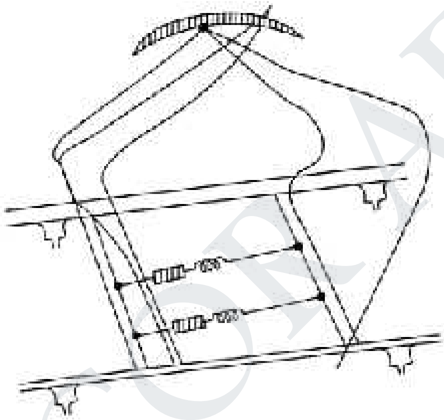
The low collector consists of light metal strip or low 0.6 or 0.9 m wide pressing against the trolley wire and attached to a framework mounted on the roof of vehicle. Collection

strip is made of soft material such as copper, aluminum or carbon that it should wear instead of trolley wire as it is easy to replace worn out collection strip than trolley wire.



c) <u>Pantograph Collector:</u>

The pantograph is employed in railways for collection of current where the operating speed is as high as 100 or 130 kmph and current to be collected are as large as 2000 or 3000A. pantograph are mounted on the roof of the vehicles and usually carry a sliding shoe for
contact with the overhead trolley wire. The contact shoes are usually about 1.2m long.



There may be a single shoe or two shoes on each pantograph. Materials used for pantograph is oftern steel with wearing plates of copper or bronze inserted. The pressure varies from 5 to 15kg.

UNIT II
ILLUMINATION

Introduction - definition and meaning of terms used in illumination engineering - classification of light sources - incandescent lamps, sodium vapour lamps, mercury vapour lamps, fluorescent lamps – design of illumination systems - indoor lighting schemes - factory lighting halls - outdoor lighting schemes - flood lighting – street lighting - energy saving lamps, LED.

2.1 INTRODUCTION

Illumination differs from light very much, through generally these terms are used more or less synonymously. Strictly speaking light is the cause and illumination is the result of that light on surfaces on which it falls. Thus the illumination makes the surface look more or less bright with a certain colour and it is this brightness and colour which the eyes sets and interperts as something useful, or pleasant or otherwise.

Light may be produced by passing electric current through filaments as in the incandescent lamps, through arcs between carbon or metal rods, or through suitable gases as in neon and other light is due to fluorescence excited by radiation arising from the passage of electric current through mercury vapour.

Some bodies reflect light in some measure, and when illuminated from an original source they become secondary sources of light.

A good example is the moon, which illuminate the earth by means of the reflected light originating in the sun.

Lamp $\rightarrow$ Lamp is equipment, which produces light.

Light $\rightarrow$ Lighting is an essential service of human for the day to day activity

Light is in the form radiant energy.

Illumination $\rightarrow$ Light is a cause of illumination is the result of light falling on the surface. Illumination makes a surface to be visible. It is differ from lights.

2.2 DEFINITION AND MEANING OF TERMS USED IN ILLUMINATION:

1) Light:

It is defined as the radiant energy from a hot body which produces the visual sensation upon the human eye.

It is usually denoted by Q, expressed in lumen – hours and is analogous to, watt – hours.

2) Luminous flux

It is defined as the total quantity of light energy emitted per second from a luminous body. It is represented by symbol 'F' or 'ϕ' and is measured in lumens.

The conception of luminous flux helps us to specify the output and efficiency of a given light source.

$$\phi = \frac{Q}{t}$$ where Q → light energy (or) radiant energy

3) Luminous Intensity

Luminous Intensity in any given direction is the luminous flux emitted by the source per unit solid angle, measured in the direction in which the intensity is required.

It is denoted by symbol I and is measured in candela (or) lumens per steradian.

$$I = \frac{\phi}{\omega}$$ Unit is $\frac{\text{lumens}}{\text{steradian}}$ (or) candela

4) Lumen:

The lumen is the unit of luminous flux.

It is defined as the amount of luminous flux emitted by a source of one candle power in a unit solid angle.

(ie) Lumens = Candle power × Solid angle

$$\text{Lumens} = CP \times \omega$$

Total lumens emitted by a source of one candle power is 4π lumens.

5) Candle Power (CP):

It is defined as the number of limens emitted by that source per unit solid angle in a given directions.

It is denoted by CP.

(i.e.,) $$CP = \frac{\text{Lumens}}{\text{Solid angle}}$$

6) Illumination:

When the light falls upon any surface, the phenomenon is called the illumination. It is defined as the number of lumens, falling on the surface, per unit area.

It is denoted by symbol 'E' and is measured in lumens/m^2 (or) lux (or) metre - candle.

If a flux of 'F' lumens falls on a surface of area 'A', then the illumination of the surface is given by,

$\frac{F}{A}$, Unit is $E = \frac{\text{Lumens}}{m^2}$ (or) lux

$$E = \frac{F}{\text{Area}} = \frac{\text{Lumens}}{A} = \frac{CP \times \omega}{A} = \frac{CP}{r^2} \times \frac{A}{A} = \frac{CP}{r^2}$$

7) Lux (or) Metre Candle

It is the of illumination and is defined as the luminous flux falling per square metre on the surface, which is every where perpendicular to the rays light from a source of 1 CP and one metre away from it.

8) Foot - Candle:

It is also the unit of illumination and is defined as the luminous flux falling per sqaure foot on the surface which is every perpendicular to the rays of light from a source of 1 CP and one foot away from it.

(i.e.,) 1 Food-candle = 1 lumen/ft^2

$$= \frac{1\text{Lumens}}{\left(\frac{1m}{3.28}\right)^2}$$

1 Foot - candle = 10.76 metre - candle or lux

9) Candela:

It is the unit of luminous intensity.

It is defined as $\frac{1}{60}^{th}$ of the luminous intensity per cm^2 of a black body radiator at the temperature of solidification of platinum.

10) Mean Horizontal Candle Power (MHCP)

It is defined as the mean of candle powers in all directions in the horizontal plane containing the source of light.

11) Mean Spherical Candle Power (MSCP)

It is defined as the mean of candle powers in all directions and in all planes from the source of light.

12) Mean Hemi - Spherical Candle Power (MHSCP)

It is defined as the mean of candle powers in all directions above or below the horizontal plane passing through the source of light.

13) Reduction Factor:

Reduction factor of a source of light is defined as the ratio of its mean spherical candle power to its mean horizontal candle power.

(ie) Reduction factor = $\frac{MSCP}{MHCP}$

14) Lamp efficiency:

It is defined as the ratio of the luminous flux to the power input. It is expressed in lumens per watt.

15) Brightness (or) Luminance

Brightness (or) Luminance is defined as the luminous intensity per unit projected area of either a surface source of light or a reflecting surface and is denoted by 'L'.

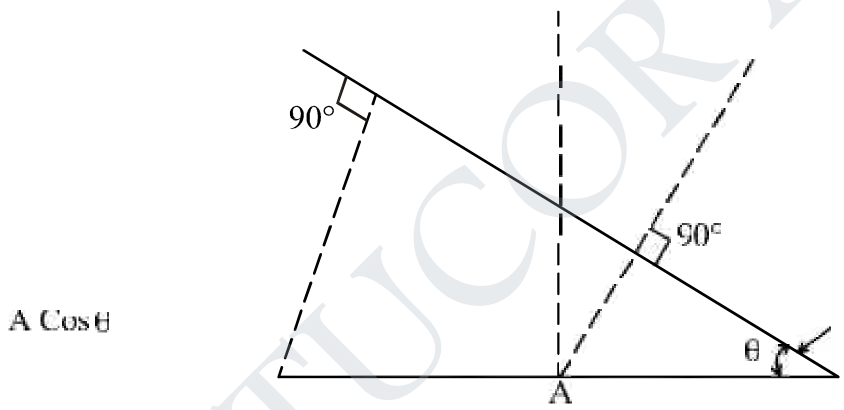


Fig. 2.1 Brightness (or) Luminance

As shown in Fig. 2.1, if a surface of area 'A' has an effective luminous intensity of 'I' candelas in a direction θ to the normal, then the luminance (brightness) of that surface is

$$L = \frac{1}{A\cos\theta} \text{ candle/m}^2 \text{ or 'nits'}$$

(i.e.,) nit is defined as candle per square metre. Bigger unit of luminance is 'stilb' which is defined as candle per square centimetre.

Lambert is also the unit of brightness which is lumens/cm^2. Foot lamberts is lumens/ft^2.

nit $\rightarrow$ candela/m^2
stilb $\rightarrow$ candela/cm^2
Lambert $\rightarrow$ lumens/cm^2
Foot - Lamberts $\rightarrow$ Lumens/ft^2

16) Glare:

Glare may be difined as the brightness within the field of vision of such a character as to cause annoyance, discomfort, interference with vision or eye - fatique.

eg: Motor car head lights.

17) Space Height ratio:

It is defined as the ratio of horizontal distance between adjacent lamps and height of their mountings.

$$\text{Space height ratio} = \frac{\text{Horizontal distance between two adjacent Lamps}}{\text{Mounting height of lamps above working plane}}$$

18) Utillisation Factor (or) Co-efficient of Utillisation:

It is defined as the ratio of total lumens reaching working plane to total lumens given out by the lamp.

$$\text{Utillisation factor} = \frac{\text{Total lumens reaching the working plane}}{\text{Total lumens given out by the lamp}}$$

19) Maintenance factor:

It is defined as the ratio of illumination under normal working conditions to the illumination when the things are perfectly clean.

$$\text{Maintenance factor} = \frac{\text{Illumination normal working condition}}{\text{Illumination when everything is perfectly clean}}$$

20) Beam factor:

The ratio of limens in the beam of projector to the lumens given out by lamps is called beam factor. Its value varies from 0.3 to 0.6.

This factor takes into account the absorption of light by reflector and front glass of the projector lamp.

21) Waste light factor:

Whenever a surface illuminated by a number of sources of light, there is always a certain amount of waste of light on account of overlapping and falling of light outside the edges of the surface.

The effect is taken into account by multiplying the theoretical value of lumens required by 1.2 for rectangular areas and 1.5 for irregular areas and object such as statue, monuments etc.

22) Reflection factor:

When a ray of light impinges on a surface it is reflected from the surface at an angle of incidence, as shown in Fig. 2.2.

Normal

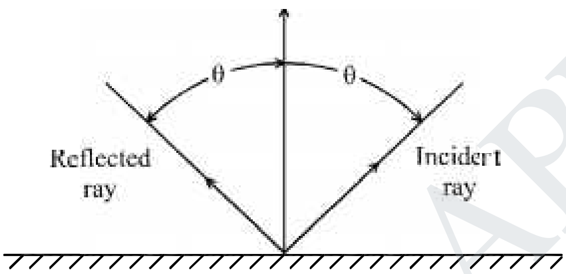


Fig. 2.2 Waste light factor

A certain portion of incident light is absorbed by the surface. The ratio of reflected light to the incident light is called the reflection factor. It is always less than unity.

23) Plane Angle:

When two straight lines lying in the same plane meet at a point there will be angle between there converging lines at the meeting point. This angle is termed as plane angle. $\angle AOB$ is the plane angle as shown in Fig. 2.3.

Fire

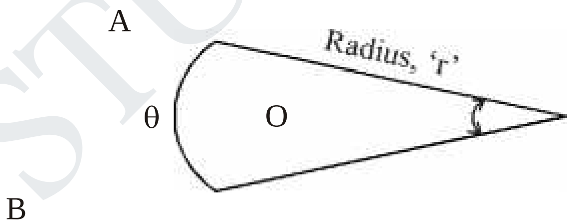


Fig. 2.3 Plane angle

A plane angle is subtended at a point and is enclosed by two straight lines lying in the same plane.

✓ A plane angle is expressed in degrees (or) θ (or) 'radians'.

A radian is the angle subtended by an arc of a circle whose length equals the radius of the circle.

$$\theta = \frac{\text{Arc}}{\text{Radius}} \text{ in radians, i.e., } \boxed{\theta = \frac{AB}{OA}}$$

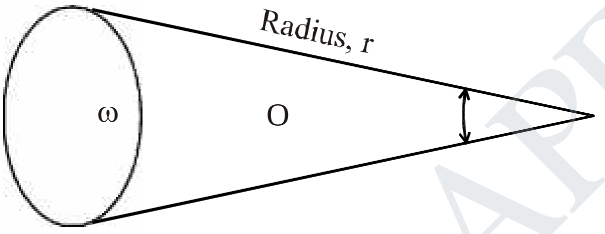
The largest angle subtended at a point is 2 π radians.

24) Solid angle:

Solid angle is the angle generated by the surface passing through the point in space and the periphery of the area.

A

Area 'A'



B *Fig. 2.4 Solid angle*

Fig. 2.4 shows solid angle denoted by ' ω ' and expressed in 'steradians'

It is given by the ratio of the area of the surface to the square of the distance between the area and the point.

$$\text{(ie)} \quad \omega = \frac{\text{Area}}{(\text{Radius})^2}$$

$$\boxed{\omega = \frac{A}{r^2}}$$

Note:

The largest solid angle subtended at a points is that due to a sphere at its centre. If 'r' is the radius of any sphere, its surface area is $4\pi r^2$

$\therefore$ Solid angle subtended at its centre by its surface, $\omega = \frac{4\pi r^2}{r^2}$

$$\omega = 4\pi$$

$$\boxed{\omega = 4\pi \text{ steradians.}}$$

2.2.1 Relationship between Plane and Solid Angle

Consider a curved surface of a spherical segment of height 'H' and radius 'r'

Surface area of a segment = $2\pi r H$

From the Fig. 2.5,

H = OC – OB

$$= r - r\cos\frac{\alpha}{2} = r\left[1 - \cos\frac{\alpha}{2}\right]$$

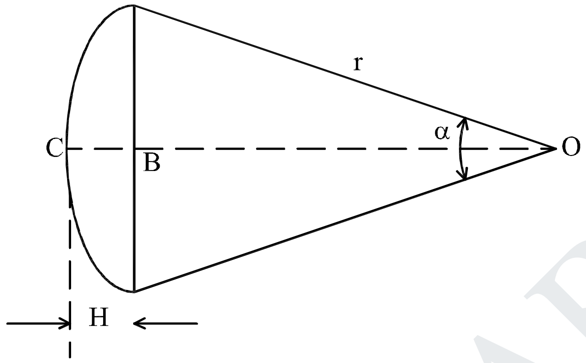


Fig. 2.5 Sectional view for solid angle

Surface area of the surface under consideration

$$= 2\pi r \times r\left[1 - \cos\frac{\alpha}{2}\right]$$

$$= 2\pi r^2\left[1 - \cos\frac{\alpha}{2}\right]$$

$\therefore$ Solid angle, $\omega = \dfrac{\text{Surface area}}{r^2}$

$$= \frac{2\pi r^2\left[1 - \cos\frac{\alpha}{2}\right]}{r^2}$$

$$\boxed{\omega = 2\pi\left[1 - \cos\frac{\alpha}{2}\right]}$$

Thus the solid angle subtended at a point can be determined directly from the above relation knowing the plane angle substended by its section.

2.3 LAWS OF ILLUMINATION

There are two laws of Illumination. They are, (i)

Law of inverse squares, and

(ii) Lambert's consine law.

2.3.1 Law of Inverse Squares

If a source light which emits lights equally in all directions be placed at the centre of a hollow sphere, the light will fall uniformly on the inner surface of the sphere, that is to say, each square mm of the surface will receive the same amount of light. If the sphere be replaced by one of the larger radius, the same total amount of light is spread over a larger area proportional to the square of the radius. The amount which falls upon any square *mm* of such a surface will, i.e., diminish as the radius increases, and will be inversely proportional to the square of the distance.

A similar relation holds if we have to deal with a beam of light in the form of a cone or pyramid, as shown in Fig. 2.6. If we consider parallel surfaces which cut the pyramid at different distances from the source, the areas of these surfaces are proportional to the square of these distances and, therefore, the amount of light which falls on one unit of the area of these surfaces, is inversely proportional to the square of the distance from the source.

This relationship is referred to as the "Law of inverse squares".

Mathematically it can be proved as follows,

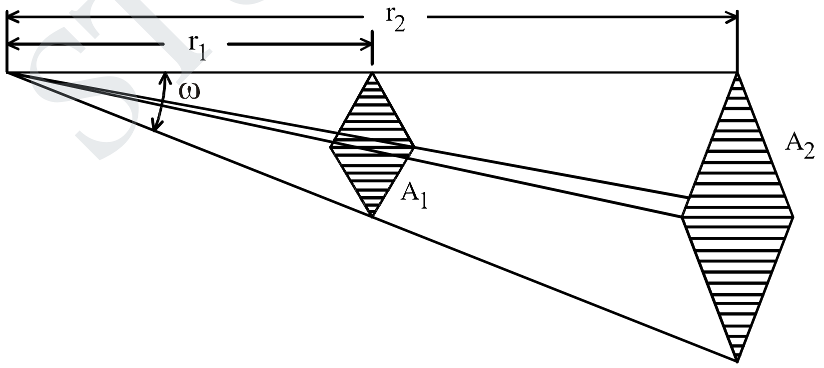


Fig. 2.6 Law of inverse squares

Let us consider surface area A_1 and surface area A_2 at distances r_1 and r_2 respt from the point source 'S' of luminous intensity 'I' and normal to the rays as shown in Fig. 2.6.

Let the solid angle subtended be 'ω' steradians

Luminous flux radiated per steradians $I = \frac{F}{\omega}$

Total luminous flux radiated, F = I ω lumens.

Illumination on the surface of Area A_1 is

$E_1 = \frac{I\omega}{A_1}$ lumens/units area.

and Area $A_1 = \omega r_1^2$

∴ Illumination on the surface of Area A_1.

$E_1 = \frac{I\omega}{\omega r_1^2}$

$$E_1 = \frac{I}{r_1^2} \text{ lumens/unit area.}$$

Similarly, Illumination on the surface of Area A_2,

$E_2 = \frac{I\omega}{A_2}$

$= \frac{I\omega}{\omega r_2^2}$

$$E_2 = \frac{I}{r_2^2} \text{ lumens/unit area}$$

Hence the illumination of a surface is inversely proportional to the square of the distance between the surface and the light source provided that distance between the surface and the source is sufficiently large so that source can be regarded as a point source.

Illumination at a point is inversely proportional to the square of its distance from the point source and directly proportional to the Luminous Intensity (CP) of the source of light in that direction.

2.3.2 Lambert's Cosine Law

This law states that Illumination 'E' any point on a surface is directly proportional to the consine of the angle between the normal at that point and the line of flux".

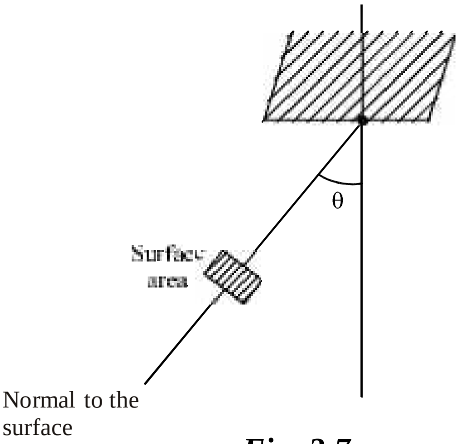


Fig. 2.7

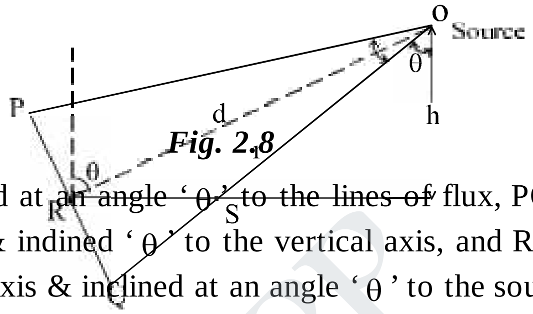


Fig. 2.8

Let us assume that the surface is indined at an angle ‘θ’ to the lines of flux, PQ = The surface area normal to the source & indined ‘θ’ to the vertical axis, and RS = The surface area normal to the vertical axis & inclined at an angle ‘θ’ to the source ‘O’.

From Fig. 2.7

PQ = RS cos θ

∴ The Illumination of the surface PQ is given by,

$$E_{PQ} = \frac{\text{Flux}}{\text{Area of PQ}} = \frac{I\omega}{\text{Area of PQ}} \qquad \therefore \omega = \frac{A}{r^2}$$

$$= \frac{I}{\text{Area of PQ}} \times \frac{\text{Area of PQ}}{d^2}$$

$$E_{PQ} = \frac{I}{d^2} \qquad \dots (1)$$

∴ The Illumination of the surface RS is given by,

$$E_{RS} = \frac{\text{Flux}}{\text{Area of RS}}$$

From Fig. 2.8, Area of RS $= \frac{PQ}{\cos\theta}$

$$= \frac{\text{Flux}}{\frac{PQ}{\cos\theta}}$$

$$E_{RS} = \frac{I}{d^2}\cos\theta \qquad \dots (2)$$

$$E_{RS} = \frac{I}{\left(\frac{h}{\cos\theta}\right)^2}\cos\theta \qquad \text{W.K.T,} \quad \cos\theta = \frac{h}{d}, \quad d = \frac{h}{\cos\theta}$$

$$E_{RS} = \frac{I}{h^2}\cos^3\theta \text{ cosine cube law} \qquad \ldots (3)$$

$$\therefore E_{RS} = \frac{I}{d^2}\cos\theta \text{ (or)}$$

$$\therefore E_{RS} = \frac{I}{h^2}\cos^3\theta$$

Where,

d $\rightarrow$ Distance between the source and surface in metre, h $\rightarrow$ Height of source from the surface in metre,

I $\rightarrow$ luminous intensity in candela.

The Equ. (3) is called as "Cosine Cube" law. It states That the, "Illumination at any point on a surface is depend on the cube of cosine of the angle between line of flux and normal at that point".

2.3.3 Problems

Problem 1:

The flux emitted by a lamp in all direction is 1,000 lumens. Calculate its MSCP.

☺ ***Solution:***

Total luminous flux emitted, F = 1000 lumens,

MSCP of the Lamp $= \frac{F}{4\pi} = \frac{1000}{4\pi} = 80$

Problem 2:

A 250 V lamp has a toal flux of 3000 lumen and takes a current of 0.8A. Calculate (i) lumens per watt and (ii) MSCP per watt

☺ ***Solution:***

Wattage of Lamp = V × I = 250 × 0.8 = 200 Watts

Output of Lamp, F = 3000 lumens

MSCP of the lamp $= \frac{F}{4\pi} = \frac{3000}{4\pi} = 240$

(i) Lumens per watt (Efficiency of the lamp) $= \frac{\text{Output lamp in lumens}}{\text{Wattage of lamp in watts}}$

$= \frac{3000}{200} = 15$ lumens/watt

(ii) MSCP per watt $= \frac{\text{MSCP of the lamp}}{\text{Wattage of lamp}} = \frac{240}{200} = 1.2$

Problem 3:

A 200 V lamp takes a current of 1.2 A, it produces a total flux of 2860 lumens. Calculate (i) MSCP of the lamp, (ii) Efficiency of the lamp.

☺ ***Solution:***

Wattage of Lamp = V × I = 200 × 1.2 = 240 Watts

Output of Lamp, F = 2860 lumens

(i) MSCP of the lamp $= \frac{F}{4\pi} = \frac{2860}{4\pi} = 227.71$

(ii) Efficiency of the lamp $= \frac{\text{Output lamp in lumens}}{\text{Wattage of lamp in watts}}$

$= \frac{2860}{240} = 11.9$ lumens/watts

Problem 4:

A 0.4 metre diameter diffusing sphere of opal glass (20% absorption) encloses an incandescent lamp with a luminous flux of 4850 lumens.Calculate the average luminance of the sphere.

☺ ***Solution:***

Flux by the globe, F = (1 – 0.2) × 4850 = 0.8 × 4850

= 3880 lumens

Surface area of the globe = $4\pi r^2$

$= 4\pi (0.2)^2 = 0.16\pi \text{ m}^2$

Average luminance sphere $= \frac{\text{Flux emitted}}{\text{Surface area}} = \frac{3880}{0.16\pi}$

= 7720 lumens/m^2

Problem 5:

A filament lamp of 500 W is suspended at a height of 5 metres above working plane and given uniform illumination over an area of 8 m diameter. Assume efficiency of reflector as 60%. Determine the illumination on the working plane. Efficiency of lamp is 0.9 watt per candle power.

☺ ***Solution:***

Candle power of lamp $= \frac{500}{0.9} = 555.6$ CP

Luminous output of Lamp $= 4\pi \times 555.6$ lumes

Flux emitted by reflector of lamp = Efficiency of Reflector × Total luminous output

$= 0.6 \times 4\pi \times 55.6$

$= 1333.3\pi$ lumens.

Area of the working plane $= \frac{\pi(8)^2}{4} = 16\pi\ m^2$

Illumination on the working plane $= \frac{1333.3\pi}{16\pi} = 83.33$ lumens/m^2

2.3.4 POLAR CURVE

✓ The Luminous flux emitted by a source can be determined from the Intensity Distribution Curve

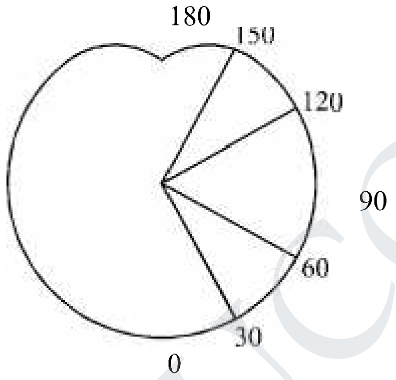
✓ The Luminous Intensity (CP) of any practical lamp is not uniform in all directions due to its unsymmetrical shapes.

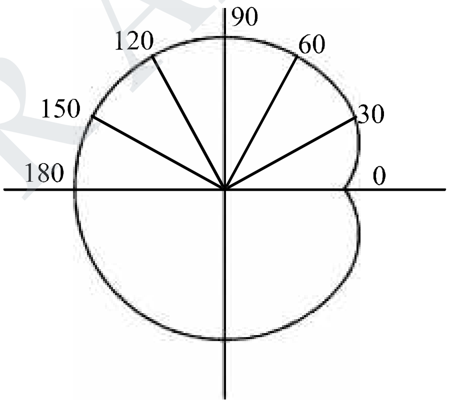
✓ The distribution of light is given by "Polar Curve"

✓ A radial ordinate pointing in any particular direction on a polar curve represents the luminous intensity of the source when viewed from that direction.

✓ If the luminous intensity is measured in a horizontal plane a vertical axis and a curve is plotted between candle power and the angular position & horizontal polar curve is obtained by vise versa, vertical polar curve gives the relationship of candle power in vertical plane passing through the lamp at various angles.

Typical vertical and horizontal polar curves for a filament lamp are shown in Fig. 2.27.





(a) Verical polar curve ***(b) Horizontal polar curve***

Fig. 2.27 Polar Curve

The Rousseau's Diagram:

The Rousseau diagram is a geometric means by which the sine function is given by,

$$F = 2\pi \int_{\theta_1}^{\theta_2} \sin\theta \, d\theta$$

The total flux emitted is given when θ varies from 0 to π radians.

$$F = \int_0^\pi I_o \sin\theta \, d\theta$$

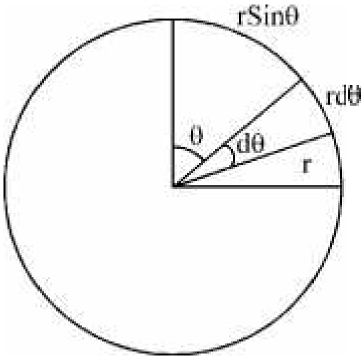


Fig. 2.28 Flux distribution with respect to '¯'

✓ Can be graphically portrayed together with the intensity I which is a function of θ as shown in Fig. 2.28.

✓ The above diagram gives an area proportional to the flux emitted by the source and from it the total flux total flux and zonal flux.

✓ The Rousseau diagram is constructed as follows,

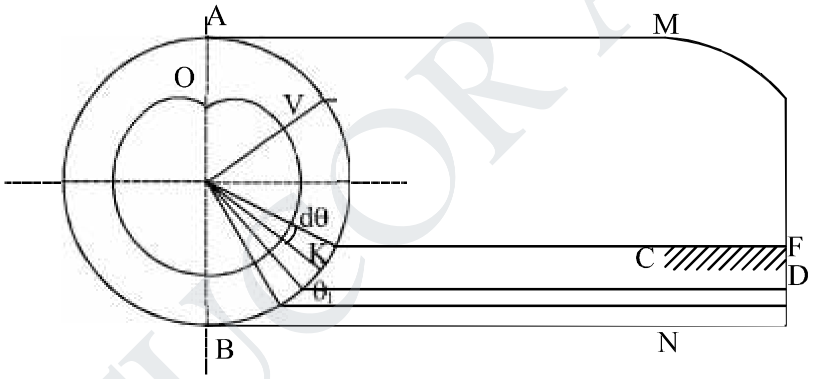


Fig. 2.29 Rousseau construction

✓ The polar curve of the given source is enclosed in a circle of radius '*r*' as shown in Fig. 2.29.

✓ Draw a line MN parallel to the vertical axis of the polar curve at a suitable distance.

✓ The circle is divided into angular zones and the and the intercepts of the zonal limits and the circle is projected horizontally cutting the line MN at right angles.

✓ The intensity value related to each radial line of the polar curve is plotted along the corresponding horizontal line, the line MN being used as base line.

Eg: CD is made equal to OK.

✓ Sufficient number of intensity values are plotted so that a smooth curve can be drawn.

✓ It can now be proved that the area of the Rousseau diagram is directly proportional to the flux emitted.

Luminous Efficacy:

✓ Luminous efficacy expresses the relative effectiveness of one Watt of radiant power producing luminous flux.

✓ By definition, one watt of homogeneous radiation at 0.554 micron wavelength yields 621 lumens and the luminous efficacy of this radiation is 621 lumens/watt.

✓ Luminous efficacy of the incandescent lamp never exceeds 25 lumens/watt.

Luminous efficacy form the radiation of a fire fly is approximately 560 lumens/ watt.

✓ It may be noted here that the quantity luminous efficacy has sometimes been called as luminous efficiency.

2.3.5 PHOTOMETRY

✓ Except for the measurement of luminance of sources, measurements by visual comparisons have been replaced by photocell because these cells give more accurate and faster measurements.

✓ If certain precautions are observed the measurements by photocells is not only more accurate they are consistent as well.

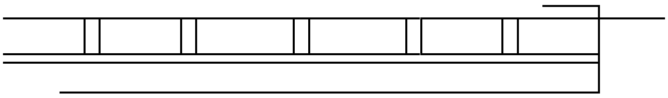
✓ The two types of photocells used for photometry measurements are

(i) Photovoltaic cells

(ii) Photo – emissive cells.

Photovoltaic cells

The construction of a photovoltaic cell, also known as the barriers layer or rectified cell is shown Fig. 2.30.



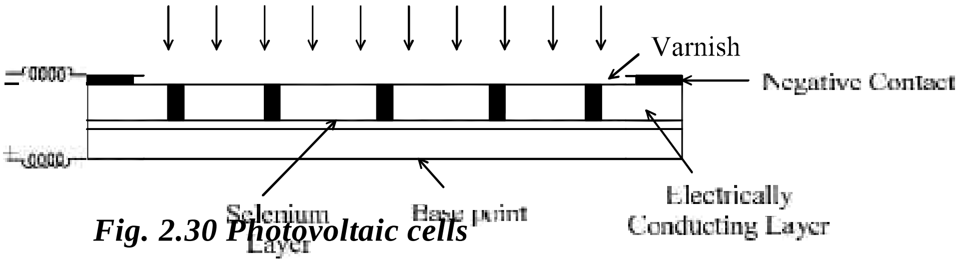


Fig. 2.30 Photovoltaic cells

- ✓ It consists of a base plate made of either steel or aluminum and carries a layer of metallic selenium which is light sensitive.
- ✓ An electrically conducting layer of cadmium oxide is applied by spattering over the selenium layer.
- ✓ Layer is sufficiently thin to allow light to reach the selenium and is electrically continuous as it acts as the negative pole.
- ✓ Base plate form the positive contact.
- ✓ The front surface of the cell is protected by a transparent varnish.
- ✓ When light falls on the upper surface of the selenium, electrons are released from the surface which maintain a flow of current through the external circuit connected between the +ve and the –ve contacts.
- ✓ Current output of the photocell should be proportional to the illumination achieved by keeping the external resistance at a low value.
- ✓ Smaller the size of the cell belter a linear relation is obtained between the current and illumination. Because for such a cell, the resistance of the electrically conducting film is at a minimum. Also, since the I is small, the voltage drop will be low.

Limitations of photocell:

If the light is incident at angles of 60^o or above the layer tends to reflect significant amount of light which therefore does not reach the selenium layer. Thus the reading is less than what it should be according to cosine law of illumination. Some compensation for this error can be made be using a matt lacquer.

- ✓ A better method is to omit the lacquer and cover the cell with hemispherical dome of transparent plastic.
- ✓ Care should be taken that whole of the cell is illuminated otherwise incorrect readings may result.

Equivalent circuit of cell:

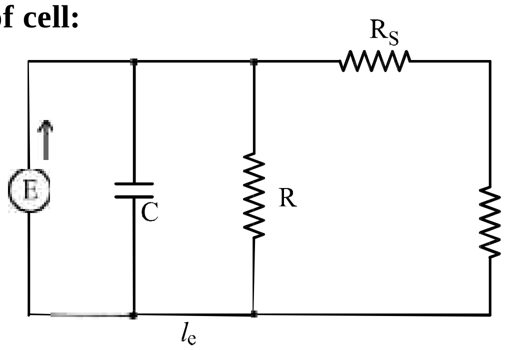


Fig. 2.31 Equivalent circuit of photovoltaic cell

✓ Fig. 2.31 shows the equivalent circuit of photovoltaic cell. Here 'E' perfect photovoltaic generator which generates (produces) a current proportional to the illumination, R_S the series resistance, C_A is the effective capacitance and R_L is the resistance of the external circuit.

✓ The temperature dependence and non linearity error are attributed to the variation of R with temperature and illumination.

✓ These effects reduced by making the effect of R_S and R_L as small as possible, so that R is short circuited.

✓ For more accurate work a circuit presenting zero resistance to the photocell should used.

Campbell – Freeth circuit

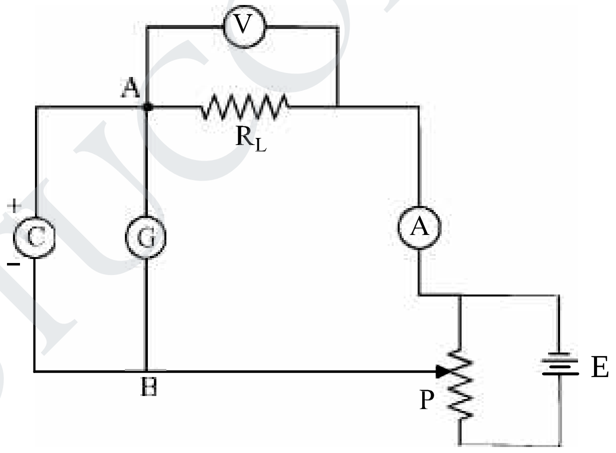


Fig. 2.32 Campbell – freeth circuit

The basic circuit due to Campbell – freeth is shown in Fig. 2.32 for this purpose.

Balance is obtained by adjusting the photometer P (ie) point A and B across which galvanometer G is connected, are at the potential which is equivalent to saying that A & B are short circuited & hence the resistance R in Fig. 2.32, is S.C which is the requirement for obtaining linear relation between illumination of the current as no current is not diverted through R.

Photoemissive cell

When greates precision in terms of linearity & stability is required it is better to use photoemissive cell rather than photovoltaic cell.

The photoemissive cell has the anode made of a cylindrical wire mesh with cathode placed in its axis as shown in Fig. 2.33.

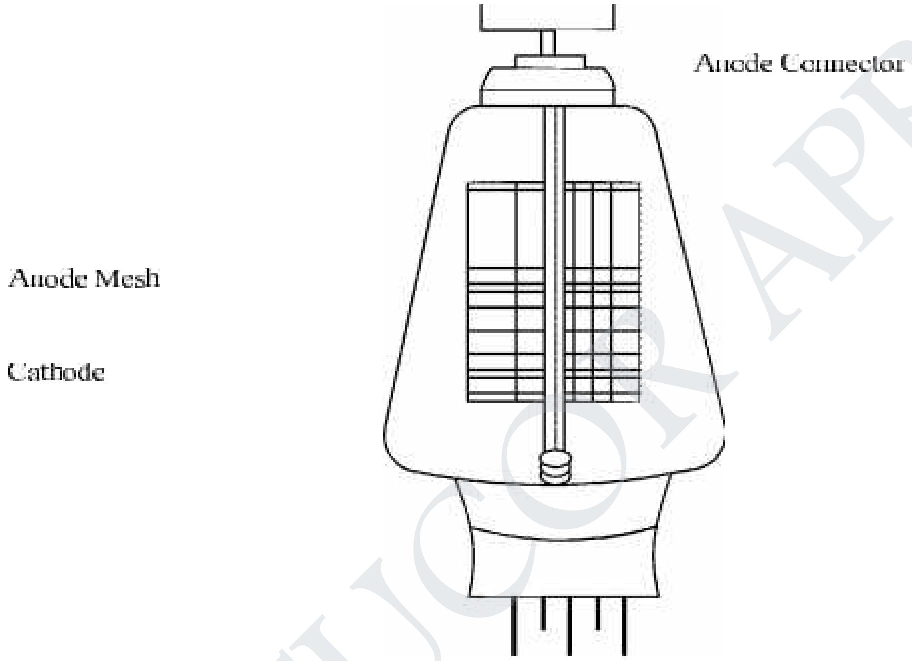


Fig. 2.33 A vacuum type photoemissive cell

Electrons are emitted from the cathode when light falls on it. Anode is 30 to 50 V at higher potential as compared to the cathode.

The spectral response of the cell is matched with the eye by using a suitable solution of cupric chloride and potassium dichromate to correct respectively the blue and red ends of the response.

DISTRIBUTION PHOTOMETRY

It helps in finding out the variation of luminous intensity around a light fitting so that polar curves for the fitting can be obtained and also the performance of the fitting is studied.

For proper distribution photometry, it is important,

(i) Only that which is to be measured should be allowed to reach the photocell

(ii) Optical path is made sufficiency long for inverse square law.

(iii) Since the flux of some source like fluorescent tubes depends upon the temperature of the surroundings, the temperature of the test area should be kept stable.

A very simple distribution photometer is shown in Fig. 2.34.

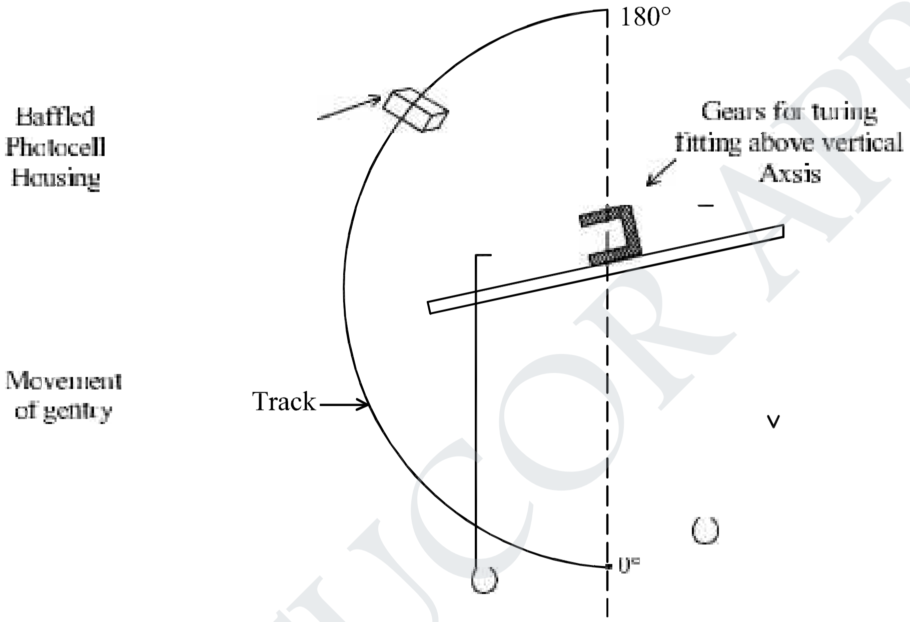


Fig. 2.34 Track distribution photometry

✓ The photocell fitting moves around the fitting on a semicircular track and its position is controlled by means of a flexible cable.

✓ A complete series of curves at different angles of azimuth can be obtained by rotating the fitting about a vertical axis.

✓ The mounting of the fitting on the apparatus is facilitated by mounting a gear system on the gentry which turns the fitting so that it can be brought down to easy access.

2.4 CLASSIFICATION OF LIGHT SOURCE

Introduction

According to principle of operation the light sources may be grouped as follows.

- Arc Lamps
- High Temperature Lamps
- Gaseous discharge Lamps
- Fluorescent type Lamps.

1. Arc lamps

Electric discharge through air provides intense light. This principle is utilized in arc lamps.

2. High temperature lamps

Oil and gas and incandescent filament type lamps, which emit when heated to high temperature.

3. Gaseous Discharge lamps

Under certain conditions, it is possible to pass electric current through a gas or metal vapour, which is accompained by visible radiations. Sodium and mercury vapours lamps operate on this principle.

4. Fluorescent type lamps:

Certain materials, when exposed to ultra violet rays, transform the absorbed energy into radiations of longer wavelength lying within the visible. This principle is employed in fluorescent lamps.

Types of lamps.

1. Arc lamps

a) Carbon arc lamp b)

Flame arc lamp

c) Magnetic arc lamp

2. Filament lamps or incandescent lamps

a) Halogen lamp b)

Cold lamp

3. Filament Discharge lamps

a) Sodium vapour discharge lamp

b) High pressure mercury vapour discharge lamp c)

Neon lamp and Neon tube lamp

4. Fluorescent lamps.

a) Mercury Iodide lamp b) Neon lamp

c) Neon tube d) Fluorescent tube

Some few important types of lamps & its construction are discussed below.

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2.4.1 INCANDESCENT LAMP

The electrical light source which works on the principle of incandescent phenomenon is called **Incandescent Lamp**. In other words, the lamp works due to glowing of the filament caused by electric current through it, is called **incandescent lamp**.

How do Incandescent Lamps Work?

When an object is made hot, the atoms inside the object become thermally excited. If the object is not melt the outer orbit electrons of the atoms jump to higher energy level due to the supplied energy. The electrons on these higher energy levels are not stable they again fall back to lower energy levels. During falling from higher to lower energy levels, the electrons release their extra energy in a form of photons. These photons then emitted from the surface of the object in the form of electromagnetic radiation. This radiation will have different wavelengths. A portion of the wavelengths is in the visible range of wavelengths, and a significant portion of wavelengths are in inferred range.

The electromagnetic wave with wavelengths within the range of inferred is heat energy and the electromagnetic wave with wavelengths within visible range is light energy. Incandescent means producing visible light by heating an object. An incandescent lamp works in the same principle. The simplest form of the artificial source of light using electricity is an incandescent lamp. Here we use electric current to flow through a thin and fine filament to produce visible light. The current rises the temperature of the filament to such extent that it becomes luminous.

Working Principle and Construction of Incandescent Lamp

The filament is attached across two lead wires. One lead wire is connected to the foot contact and other is terminated on the metalic base of the bulb. Both of the lead wires pass through glass support mounted at the lower middle of the bulb. Two support wires also attached to glass support, are used to support filament at its middle portion. The foot contact is isolated from metalic base by insulation materials.

The entire system is encapsulated by a colored or phasphare coated or transparent glass bulb. The glass bulb may be filled with insert gases or it is kept vacuum depending upon rating of the incandescent lamp. The filament of **incandescent lamps** is air-tightly evacuated with a glass bulb of suitable shape and size. This glass bulb is used to isolate the filament from surrounding air to prevent oxidation of filament and to minimize convention current surround the filament hence to keep the temperature of the filament high. The glass bulb is either kept vacuum or filled with inert gases like argon with a small percentage of nitrogen at low pressure. Inert gases are used to minimize the evaporation of filament during service of the lamps. But due to convection flow of inert gas inside the bulb, there will be greater chances of losing the heat of filament during operation. Again vacuum is a great insulation of heat, but it accelerates the evaporation of filament during operation. In the case of gas-filled incandescent lamps, 85 % of argon mixed with 15 % of nitrogen is used. Occasionally krypton can be used to reduce filament evaporation because the molecular weight of krypton gas is quite higher. But it costs greater. At about 80 % of atmospheric pressure, the gasses are filled into the bulb. Gas is filled in the bulb with the rating more than 40 W. But for less than 40 W bulb; there is no gas used.

The various parts of an incandescent lamp are shown below.

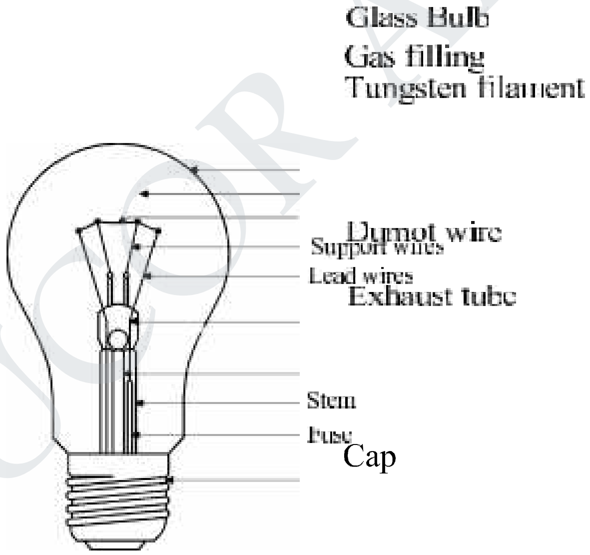


Fig. 2.52 Incandescent Lamp

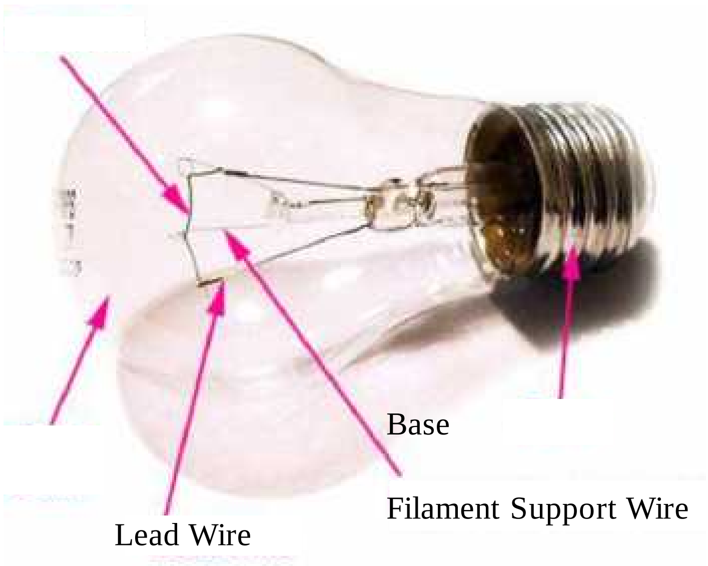


Fig. 2. Incandescent Lamp

Availability of the Incandescent Bulbs in the Market

There are various attractive shapes and sizes of the bulbs available in the market. PS30 lamps have a pear shape, T12 bulb is tubular with diameter 1.5 inch, R40 bulb is with reflector bulb envelope with a diameter of 5 inches. Based on availability of wattage the bulbs are common in the market with 25, 40, 60, 75, 100, 150 and 200 W etc. We can follow the Table 2.5 to get important data about the **incandescent lamp**.

Table 2.5 Important data related to Incandescent Lamp

Watts	Filament Temperature (K)	Initial Lumens	Initial Lumen/Watt	Life (H)	Uncoiled filament length (cm)	Filament Diameter (μ m)	% lumen Depreciation
25	2560	235	9.4	2500	56.4	30.5	79
40	2740	455	11.4	1500	38.1	33	88
60	2770	870	14.5	1000	53.3	45.7	93
75	2840	1.190	15.9	750	54.9	53.3	92
100	2860	1.750	17.5	750	57.9	63.5	91
200	2890	3.710	18.5	750	63.5	96.5	85
300	2920	5.820	19.4	1000	76.2	129.5	86
500	3000	10.850	21.7	1000	87.4	180.3	89

2.4.2 HIGH PRESSURE SODIUM LAMPS OR (HPS LAMPS)

It is very difficult to get any material which is free from corrosion in presence of sodium vapour in high temperature and pressure. This was the main difficulty of producing **high pressure sodium lamp shown Fig. 2.55**. In 1959, the development of polycrystalline alumina (PCA) opened a new path to introduce the high pressure sodium vapor Lamp. As this material is very rarely affected by high pressure and temperature sodium vapour. The first lamp with 400 W, 42000 initial lumens and 6000 hour life first came in the market in 1965. But afterward some improvements made this lamp with 50000 initial lumens with 24000 hours at 10 hours per start. We can get a lamp that has 2.4 times lumens output of its mercury counterpart with same rated life span.

Diagram of High Pressure Sodium Lamp

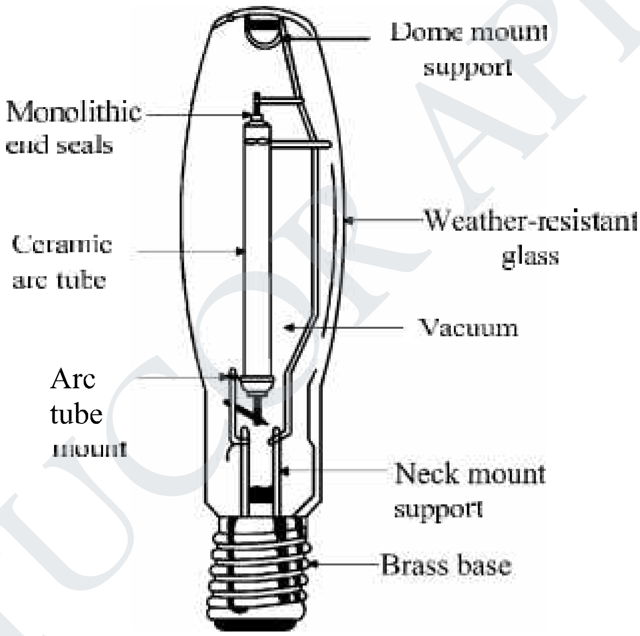


Fig. 2.55 High Pressure Sodium Lamp

It has an inner PCA arc tube that is filled with xenon gas. This xenon gas is used for starting purpose of the lamp as ionization potential of xenon gas is lowest among all other inert gases used for this purpose. In addition to xenon gas sodium mercury amalgam is present in this arc tube, too.

In each end, back wound and coated tungsten electrodes are mounted. To seal the tube monolithic seal is used instead of niobium end cap. The arc tube is inserted into a heat resistant outer bulb. It is supported by an end clamp that is floating. This end clamp permits the entire structure to expand contract without distorting. The space between the tube and the bulb is a vacuum space. This vacuum space is needed to insulate heat from the arc tube. Because it is necessary to keep the arc tube at required temperature to sustain arc during normal operation.

High pressure sodium lamp has very small diameter (3/8 inch). So there is no enough space to provide any starting electrode in the arc tube. So higher voltage is required to initiate arc. A ballast with ignitor is used for this purpose. High voltage is fed to the lamp from the ballast by using the phenomenon of superimposing a low energy high voltage pulse. Generally a typical pulse has a peak voltage of 2500 V and it has durability for only 1 microsecond only. This high voltage pulse makes the xenon gas ionized sufficiently. Then it initiates and maintains the xenon arc. The initial arc has sky blue color. Amalgam used in the reservoir formed inside the arc tube. It is in the back of one of the electrodes. It is normally vaporized during lamp operation. As the xenon arc has started temperature of arc tube is increased which first vaporizes mercury and the lamp start glowing with bluish white color. This color represents the effect of the xenon and mercury mixture at excitation. Gradually the temperature again rises, and sodium becomes vaporized lastly and becomes excited, a low pressure monochromatic yellow sodium spectrum results. During the period of sodium spectral line becomes at 589 nm.

2.4.3 MERCURY VAPOUR LAMP

In case of fluorescent lamp the **mercury vapour** pressure is maintained at lower level such that 60% of the total input energy gets converted into 253.7 nm single line as shown in Fig. 2.56. Again transition of the electrons requires least amount of input energy from a colliding electron. As pressure increases the chance of multiple collisions gets increased. A schematic diagram of mercury lamp is shown below. This lamp is containing an inner quartz arc tube and outer borosilicate glass envelope. The quartz tube is able to withstand arc temperature 1300°K, whereas the outer tube withstands only 700°K.

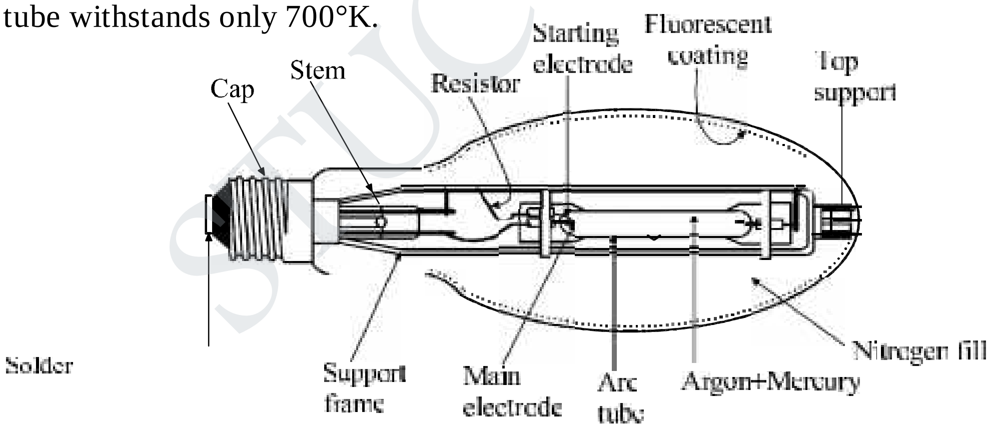


Fig. 2.56 Mercury Vapour Lamp

Between two tubes nitrogen gas is used to be filled to provide thermal insulation. This insulation is for to protect the metal parts from oxidation due to higher arc temperature. The arc tube contains the mercury and argon gas. Its operational function is same as the fluorescent lamp.

Two main electrodes and a starting electrode are inside the arc tube. Each main electrode holds a tungsten rod and upon which a double layer of coiled tungsten wire is wound. Basically the electrodes are dipped into a mixture of thorium, calcium and barium carbonates. They are heated to convert these compounds into oxides after dipping. Thus they get thermally and chemically stable to produce electrons. The electrodes are connected through a quartz tube by molybdenum foil leads. Just

when the main supply voltage is applied to the mercury lamp, this voltage comes across the starting electrode and the adjacent main electrode (bottom electrode) as well as across two main electrodes (bottom and top electrodes). As the gap between starting electrode and bottom main electrode is small the voltage gradient is high in this gap. Because of this high voltage gradient across the stating electrode and the adjacent main electrode (bottom) a local argon arc is created, but the current gets limited by using a starting resistor. This initial arc heats up the mercury and vaporizes it and this mercury vapor helps to strike the main arc soon. But the resistance for the main arc current control resistor is somewhat less than the resistance of the resistor used in the initial arc current control purpose. For this reason initial arc stops and main arc continues to operate. It takes 5 to 7 minutes to make all of the mercury to be vaporized completely. The lamp gets its state of its operational stability. The mercury vapor arc gives visible spectra of green, yellow and violet. But there may be still some invisible ultraviolet radiation during discharging process of **mercury vapour** so phosphor coating may be provided on outer glass cover to improve efficiency of the mercury lamp. There are five lamps with phosphor coating to provide improved color performance. As the wattage increases the initial lumen ratings for the phosphor coated lamps get available with 4200, 8600, 12100, 22500 and 63000. The average life of mercury lamp is 24000 hours i.e. 2 years 8 months.

2.4.4 FLUORESCENT LAMP

What is Fluorescent Lamp?

Tube shaped florescent lamp is termed as tube light. **Tube light** is a lamp that works on low pressure mercury vapor discharge phenomenon and converts ultra violate ray into visible ray with the help of phosphor coated inside glass tube.

Material Used Inside the Fluorescent Lamp

The materials used to build a tube light are given below.

1. Filament coils as electrodes
2. Phosphor coated glass bulb
3. Mercury drop
4. Inert gases (argon)
5. Electrode shield
6. End cap
7. Glass stem

Glass

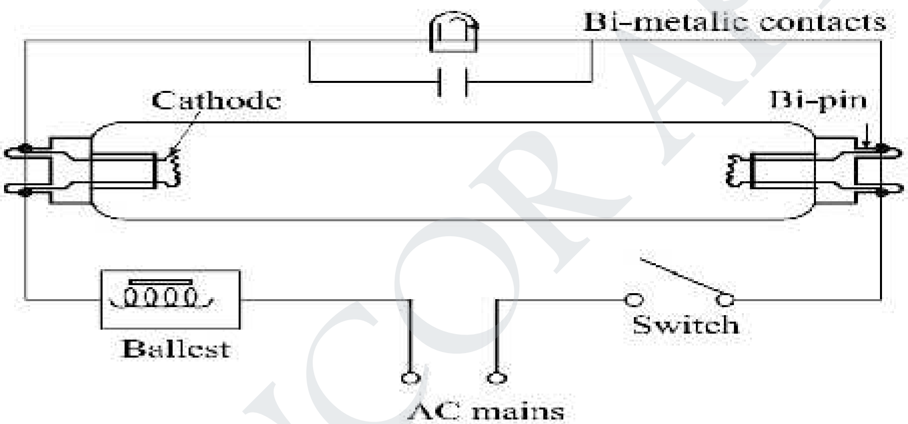
Fig. 2.53 Fluorescent Lamp

Auxiliary Electrical Components along with Fluorescent Lamp

The tube light does not work directly on power supply. It needs some auxiliary components to work. They are-

✓ **Ballast:** It may be electromagnetic ballast or electronic ballast.

✓ **Starter:** The starter is a small neon glow up lamp that contains a fixed contact,



a bimetallic strip and a small capacitor.

Fig. 2.54 Circuit diagram for Fluorescent Lamp

Working Principle of Fluorescent Lamp

When the switch is ON, full voltage will come across the tube light through ballast and fluorescent lamp starter. No discharge happens initially i.e. no lumen output from the lamp.

✓ At that full voltage first the glow discharge is established in the starter. This is because the electrodes gap in the neon bulb of starter is much lesser than that of inside the fluorescent lamp.

✓ Then gas inside the starter gets ionized due to this full voltage and heats the bimetallic strip that is caused to be bent to connect to the fixed contact. Current starts flowing through the starter. Although the ionization potential of the neon is little bit more than that of the argon but still due to small electrode gap high voltage gradient is appeared in the neon bulb and hence glow discharge is started first in starter.

✓ As voltage gets reduced due to the current causes a voltage drop across the inductor, the strip cools and breaks away from the fixed contact. At that moment a large L di/dt voltage surge comes across the inductor at the time of breaking.

✓ This high valued surge comes across the tube light electrodes and strike penning mixture (mixture argon gas and mercury vapor).

✓ Gas discharge process continues and current gets path to flow through the tube light gas only due to low resistance as compared to resistance of starter.

✓ The discharge of mercury atoms produces ultra violet radiation which in turn excites the phosphor powder coating to radiate visible light.

✓ Starter gets inactive during operation of **tube light**.

TYPES OF LIGHTING SCHEMES:

Depending upon the requirements and the way of light reaching the surface, Lighting schemes are classified as follows,

(i) Direct lighting

(ii) Semidirect lighting

(iii) Indirect lighting

(iv) Semi – indirect lighting and

(v) General lighting.

Direct lighting:

In the direct lighting system, the luminaries direct the 90 to 100% of the light output of the lamp towards downward (light falls just below the lamp). This scheme is more efficient but it suffers from hard shadows and glare. It is mainly used for industrial and general outdoor lighting.

Semidirect lighting scheme:

In semidirect lighting scheme, about 60 – 90% lamps luminous flux is made to fall downwards directly by using some reflectors and the rest of the light is used to illuminate the walls and ceiling. This type of light scheme is employed in rooms with high ceiling. This scheme will improve not only the brightness but also the efficiency.

Indirect lighting schemes:

In this lighting scheme, 90% of the light output from the lamp is directed upward to the ceiling and upper side of walls and reflected back to the working plane area. In such scheme, the ceiling acts as the lighting source and glare is reduced to minimum.

Semi – indirect lighting scheme.

In semi – indirect lighting scheme, the luminaries direct the light output of the lamp partially (10 to 30%) downward, but with a major portion of light output (70 to 90 %) upward. Glare will be completely eliminated with such type of lighting scheme. This scheme is widely preferred for indoor lighting decoration purpose.

General lighting scheme:

In this scheme, lamps made of diffusing glass are used which are nearly equal illumination in all directions. Mounting height of the source should be much above eye level to avoid glare.

Lamp fittings of various lighting schemes are shown in Fig. 2.35.

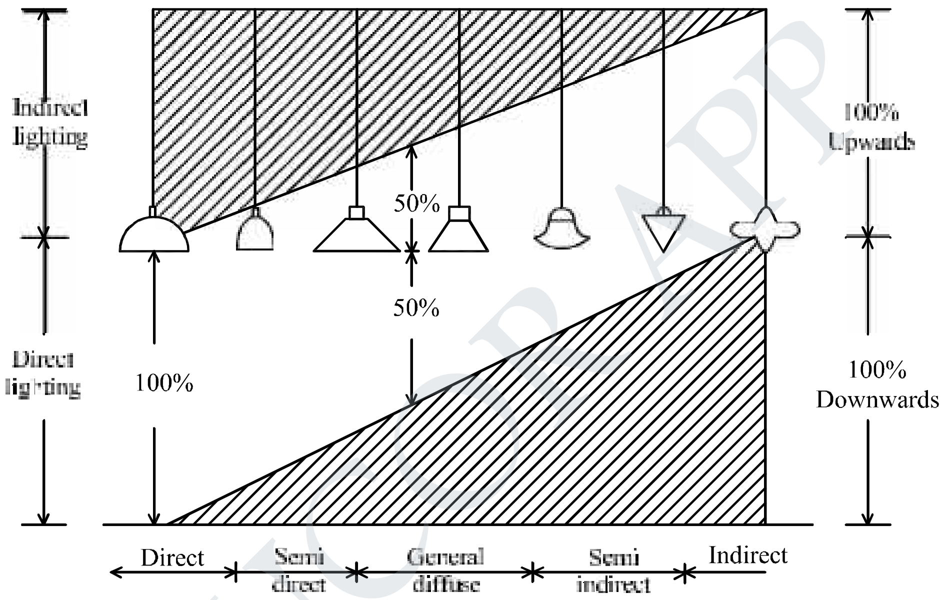


Fig. 2.35 Lighting schemes

2.5 DESIGN OF ILLUMNATION SYSTEMS

Objectives are,

- ✓ To provide adequate illumination
- ✓ To provide light distribution all over the area uniformly
- ✓ To provide light of suitable color
- ✓ To avoid glare and hard shadows

2.5.1 Design methodology:

1. Calculate area to be illuminated
2. Decide the level of illumination.
3. Total illumination = Area illumination level.

4. Select utilization factor and depreciation factor
5. Divide total illumination by utilization factor and depreciation factor.
6. If D.F is greater than 1, then it find gross lumen, it is multiplied with total lumen instead of division.
7. Select lamp and luminaries.
8. Determine number of lamps.
9. Decide arrangements of lamps for uniform distribution considering space to height ratio.

2.5.2 Requirements of Good Lighting

The following factors are required to be considers while designing the lighting scheme.

1. Illumination level,
2. Uniformity of illumination,
3. Color of light,
4. Shadows,
5. Glare,
6. Mounting height,
7. Spacing of luminaries, and
8. Colour of surrounding walls.

2.6 INDOOR LIGHTING SCHEMES

2.6.1Residential lighting

The light in home can be peaceful, comfortable, romantic and intimate or cheerful and festive. Light can turn strangers away and welcome friends inside. Options for lighting each room are as varied as the colours of paint and features of carpet selected.

Rating of lamps for illuminating a lightly coloured drawing room of size 8m long, 3m wide 3.5 m high.

Following data may be assumed:

- ✓ Required illumination level 100 lumens/m^2
- ✓ Coefficient of utilisation on horizontal plane 0.5
- ✓ Type of lamps - standard fluorescent lamps: 40 W, 1600 W per lamp.

2.6.2 Commercial lighting

In commercial shopping complex, each shop has a different image to convey and different product to sell. Each aspect of a shop should be carefully designed with its client or customers in mind. Shops also carry their own identity. Lighting supports a shop in its identity, shows off the shop's merchandise to its best advantage, serving as a true magnet, drawing customers into the shop and persuading them to buy.

Recommended lamps for commercial buildings

- For general purpose lighting – Fluorescent Lamps
- For display lighting – LV Halogen Lamp
- For boarding & hoarding – Metal Halide Lamp
- For textile shops – Filament/LV Halogen Lamp

2.6.3 Office lighting

Office lighting provides working environment that empowers people to function to the very best of their abilities. Lighting contributes to the principle needs such as performance, comfort, ambience and cost effectiveness. Lighting contributes to the physical comfort of the employees promoting a sense of well being, safety and alertness.

Office lighting requirements differs between an open concept, closed room approach, meeting halls, lobbies, utilities etc. lighting control is becoming increasingly important to offer flexibility and energy management.

2.6.4 Factory lighting:

Industry (or) factory lighting must satisfy the following aspects.

1. The quality of work is to be improved
2. Accidents must be reduced.
3. The productivity of labour should be increased.

The above requirements can be meet by the factory lighting only when the lighting schemes provides:

(i) Adequate illumination on the working plane, (ii)

Minimum glare,

(iii) Clean and effective source fitting, and

(iv) Uniform distribution of light over the working plane.

The lamps used for factory lighting are fitted with specially designed reflectors and they can be easily cleaned.

- Industrial lighting fittings
- Standard reflectors
- Diffusing fittings
- Concentrating diffusing fittings
- Angle reflectors.

2.7. OUTDOOR LIGHTING SCHEME

2.7.1 Flood lighting:

Flood lighting means flooding of large surfaces with light from powerful projectors. A special reflector and housing is employed in flood lighting in order to concentrate the light emitted from the lamp into a relatively marrow beam, which is known as flood lighting projector.

It is employed to serve one or more of the following purposes.

1. Aesthetic flood lighting:

For enhancing beauty of building at night such as public places, ancient buildings and monuments, religious buildings on important festive occasions etc.

2. Industrial and commercial flood lighting

For illuminating railway yards, sports stadium, car parks, construction sites, quarries etc.

3. Advertising

They are used for illuminating showcases and advertisement boards and for the decoration of houses etc.

The projectors of floodlighting schemes are classified into

(a) Narrow beam projectors (b) Medium angle projectors (c) Wide angle projectors.

Flood Lighting Calculation

While calculating the number of projectors required for flood lightings, it is necessary to know the level of illumination required and it is depending on the type of building and the purpose of floodlighting. And also the type of projector and the selection of projector depend upon the beam size as well as the light output.

The three steps of lighting calculations are,

Step 1 : Illumination level required

Step 2 : Type of projector

Step 3 : Number of projector

1. Illumination level required:

The Illumination level in lumens/m^2 required depends upon the type of building, the purpose of the flood lighting. The amount of conflicting light in the vicinity etc.

2. Type of projector:

- Beam size

- Light output
- Based on the above two considerations, choice of projector is made. The beam size determine the area covered by the beam and the latter the illumination provided.

3. Number of projectors:

$$N = \frac{A \times E \times DF \times \text{Waste light factor}}{UF \times \text{Wastage of lamp} \times \text{Luminous efficiency of lamp}}$$

Table 2.3 Flood lighting application

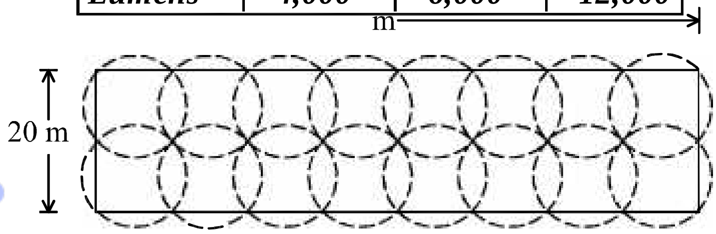
Commercial Social	Sports areas, Show areas, Railway yards, Gardens, Parking areas Advertising boards.
Industrial	Storage areas Quarries Entrances
Aesthetic	Monuments Buildings Churches Temples, etc
Security	Gates Stores Boundaries

2.7.2 Problems of flood lighting:

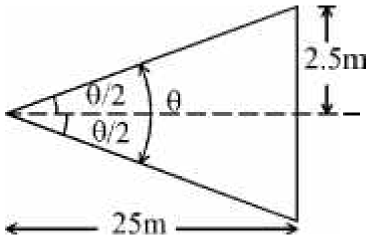
Problem 1

The front of a building 50 × 20 m² is desired to be illuminated by flood lighting projectors placed at a distance of 25 m from the wall. The average illumination required is 40 lux. Estimate the number and size of the projectors required. Assume that waste light factors is 1.2, depreciation factors is 1.4, and the coefficient of utilisation is 0.35.

Wattage	*250*	*500*	*1000*
Lumens	*4,000*	*6,000*	*12,000*



Solution:



(b)

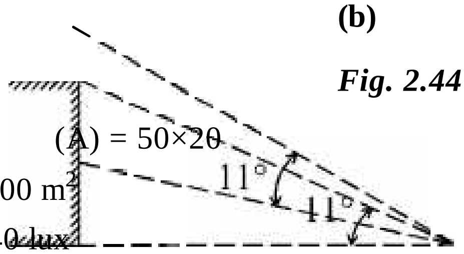


Fig. 2.44 Lamp arrangement

Area (A) = 50×20

= 1,000 m^2

E = 40 lux

Waste light factor = 1.2

DF = 1.4

UF = 0.35

The gross lumens emilted by the lamps (or) projectors.

$$= \frac{A \times E \times W \times DF}{UF}$$

$$= \frac{1000 \times 40 \times 1.2 \times 1.4}{0.35}$$

$= 192,000$ lumens

If the wattage of each lamp is 1,000W, then the number of projectors required is

$$= \frac{\phi}{\text{wattage of each lamp} \times \eta}$$

$$= \frac{192,000}{1000 \times 12} \quad \left[\text{For 1000 W lamp lumens/W} = \frac{12,000}{1000}\right.$$

η = 12 lumens/watts]

= 16 lamps

The angle of spread $(\theta) = \tan^{-1}\left[\frac{2.5}{}\right]$

MAINTENANCE OF LIGHTING SYSTEM:

Maintenance of lighting system provides better lighting efficiency, better apperance, less work interruptions.

The light losses are caused by the dirt, dust on the surface of lamps, reflectors, luminaries, wall surfaces, ceiling etc.,

The lamp - lumens get depreciated with time. This causes light losses in every installation.

The lighting system should be cleaned properly and regularly. This gives following benefits.

1. Better illumination with given energy - cleaning removes dust and dirt and gives better illumination.
2. Reduced maintenance costs - Regular and timely maintenance results in reduced replacement costs and therefore reduced maintenance costs.
3. Better appearance,

To improve the appearance, the walls, ceiling, lamps, luminaries should be cleaned. Old lamps should be replaced. This is called 'Relamping'.

Usually, group relamping is preferred to single spot relamping. Group relamping refers to replacing the lamps of a particular batch after certain working hours. Group relamping has following merits:

1. Reduced maintenance labour cost
2. More light efficiency
3. Lesser work shut-down
4. Better appearance

The maintenance of lighting system has the following steps.

1. Cleaning
2. Relamping
3. Maintenance of supply system - supply system should have good fuse protection and switch boards.
4. Fixtures, luminaires should be fixed rigidly without falling.
5. Electricians should be provided with safety belts, safe ladders etc.,

METHOD OF LIGHTING CALCULATIONS:

There are several methods have been employed for lighting calculation, some of those methods are as follows.

1. Watts - per square metre method
2. Lumen (or) light flux method
3. Point - to - point method

2.11.1 Watts - per square - metre method:

This method is more adaptive for rough calculation or checking and it is simple "Thumb rule" method of calculation.

It consists in making an allowance desired on the assumption of an average figure of overall efficiency of the system.

2.11.2 Lumen (or) light flux method:

This method is applicable to those cases where the sources of light are such as to produce an approximate uniform illumination over the working plane or where an average value is required.

Total lumens received on working plane

= Number of lamps × Wattage of each lamp × Efficiency of each lamp in terms of lumens/watt × Coefficient of utilisation × $\frac{1}{\text{Depreciation factor}}$

Also, The Total Lumens Received on Working plane

= Number of lamps × Wattage of each lamp × Efficiency of each lamp in terms of lumens/watt × Coefficient of utilisation × Maintenance factor

Where, Depreciation factor = $\frac{1}{\text{Maintenance factor}}$

It is defined as the ratio of lumens reaching the working plane to the total lumens given out by the lamp or lamps. It is known as utilisation factor or co-efficient of utilisation. Its value varies from 0.25 to 0.5 and from 0.1 to 0.25 for direct and indirect lighting schemes respectively.

(ii) Maintenance factor:

It is defined as the ratio of ultimate maintained metre-candles on the working plane to the initial metre-candles.

Its value is more if the lamp fittings are cleaned regularly, say 0.8, and less of there is much dust etc, say 0.6.

(iii) Depreciation factor:

This is merely the inverse of the maintenance factor and is defined as the ratio of the initial metre candles to the ultimate maintained metre-candles on the working plane. Its value is greater than unity.

Point to point (or) Inverse square law method:

This method is applicable where the illumination at a point due to one or more sources of light is required, the candle power of the sources in the particular direction under consideration being known.

This method is not much used (because of its complicated and cumbersome applications); it is employed only in some special problems such as flood lighting, yard lighting etc.,

Calculation of Illumination:

In general, illumination can be calculated by using the empirical formula:

$$N = \frac{E \times A}{\phi \times UF \times MF}$$

Where

N $\rightarrow$ Number of fittings required

E $\rightarrow$ Illumination required in lux

A $\rightarrow$ Area of the working plane in m^2

ϕ $\rightarrow$ luminous flux produced per lamp in lumens

UF $\rightarrow$ Utilisation factor

MF $\rightarrow$ Maintenance factor

2.7.2 Street lighting:

The main objectives of the street lighting are

1. In order to make the street more attractive, so that obstructions on the road clearly visible to the drivers of vehicles.
2. To increase the community value of the street
3. To clear the traffic easily in order to promote safety and convenience.

The two basic principles are usually employed for the street lighting design are given below:

(i) Diffusion principle (ii) Specular reflection principle.

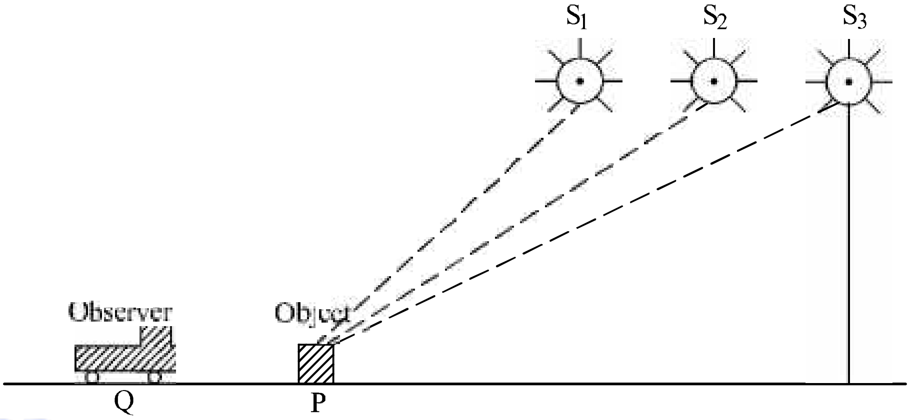
Diffusion principle:

In this method, light is directed downwards from the lamp by the suitably designed reflectors. The design of these reflectors are in such a way that they may reflect total light over the road surface uniformly as much as possible. The reflectors are made to have a cut off between 30^o and 45^o, so that the filament of the lamp is not visible expect just below the source, which results in eliminating glare. Illumination at any point on the road surface is calculated by applying inverse square law (or) point-by-point method.

Specular reflection principle:

The specular reflection principle enables a motorist to see an object about 30 m ahead. In this case, the reflectors are curved upwards, so that the light a thrown on the road at a very large angle of incidence. This can be explained with the help of Fig. 2.41. An object resides over the road at ‘P’ in between the lamps S_1, S_2 and S_3 the observer at ‘Q’

Thus, the object will appear immediately against the bright road surface due to the lamps at a longer distance. This method of lighting is only suitable for straight sections along the road. In this method, it is observed that the objects on the roadway can be seen by a smaller expenditure of power than by the diffusion method of lighting.



Illumination Level, Mounting Height and Types of Lamp for Street Lighting.

Normally illumination required depends upon the class of street lighting installation. The illumination reuqired for different areas of street lighting are given in table.

Table 2.1 Illumination required for different areas of street lighting.

	Area	Illumination (lumens/m^2)
1.	Road junction and important shopping centres.	30
2.	Poorly lighted sub-urban streets.	4
3.	Average well-lighted street.	8 – 15

Mounting height: Normally spacing for the standard lamps is 50 m with a mounting height of 8m. Lamp posts should be fixed at the junctions of roads.

Types of lamps: Mercury vapor and sodium vapor discharge lamps are preferable for street lighting. Since, the overall cost of the installation of discharge lamps are less than the filament lamps and also the less power consumption for a given amount of power output.

Table 2.2 Location of lamps for street lighting

	Type	Remarks
1.	Single Side Mounting	✓ Not for straight roads. ✓ Recommended for bends with radius less than 75 H, H = Height of mounting. ✓ Mounting outside the bend.
2.	Opposite Mounting	✓ Superior to other three methods. ✓ More number of lamps. ✓ Uniform illumination on road surface. ✓ Used for very wide roads when (3) is not suitable.
3.	Staggered Arrangement	✓ Lamps on alternate columns on the opposite side of central strip. ✓ Suitable and economical for road width of 15m between two foot paths at extreme ends.
4.	Central Mounting	✓ A central lamp post has two lamps back to back. ✓ Used for very wide roads. ✓ May be supplimented by staggered or opposite arrangement.

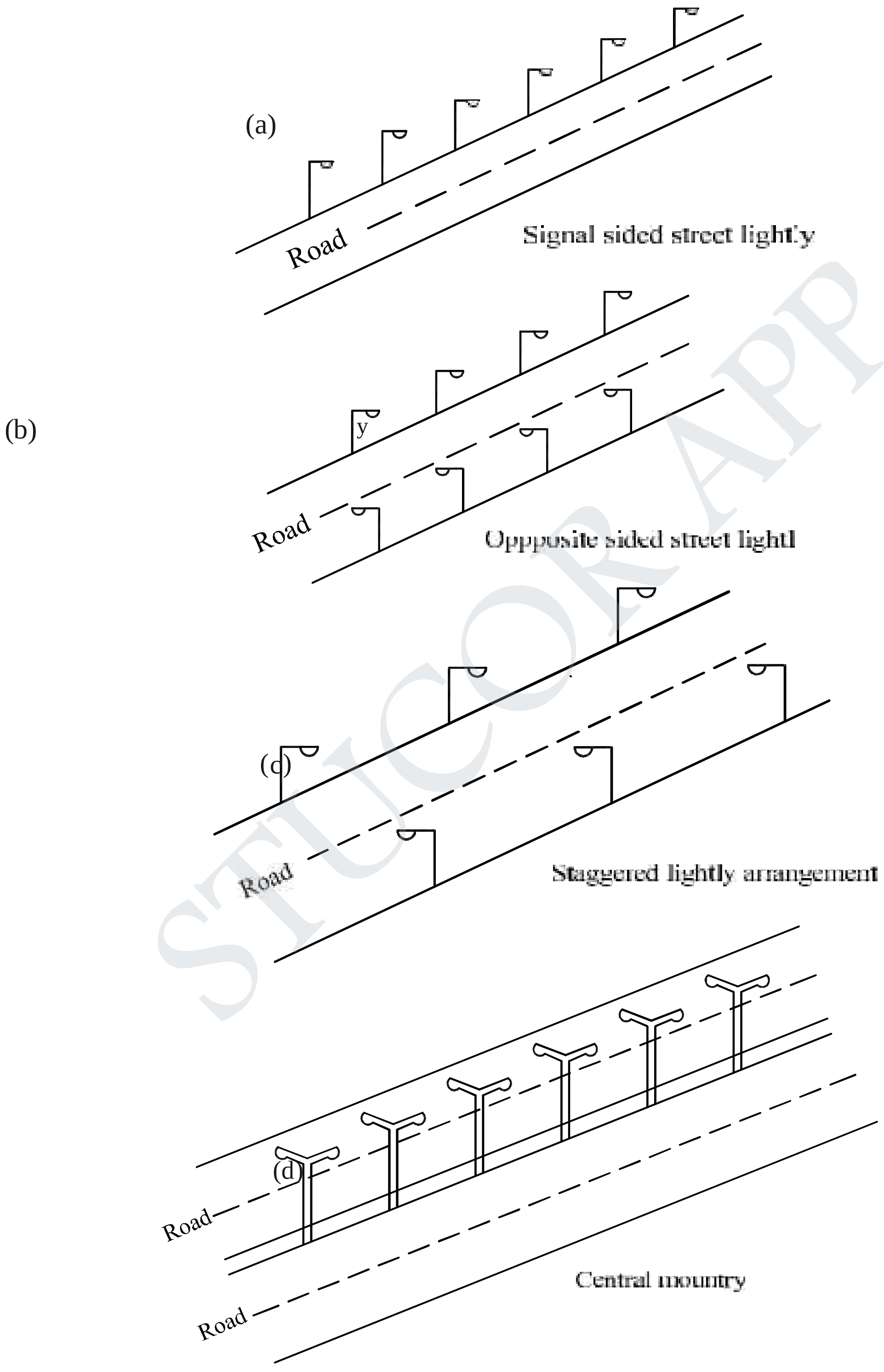


Fig. 2.42 Types of street lighting arrangements

2.8 ENERGY SAVING LAMPS

Electric lighting burns up to 25% of the average home energy budget.

The electricity used over the lifetime of a single incandescent bulb costs 5 to 10 times the original purchase price of the bulb itself.

Light Emitting Diode (LED) and Compact Fluorescent Lights (CFL) bulbs have revolutionized energy-efficient lighting.

CFLs are simply miniature versions of full-sized fluorescents. They screw into st andard lamp so ckets, and give off light that looks similar to the common incandescent bulbs - not like the fluorescent lighting we associate with factories and schools.

LEDs are small, very efficient solid bulbs. New LED bulbs are grouped in clusters with diffuser lenses which have broadened the applications for LED use in the home. LED technology is advancing rapidly, with many new bulb st yles available. Initially more expensive than CFLs, LEDs bring more value since they last longer. Also, the price of LED bulbs is going down each year as the manufacturing technology continues to improve.

2.8.1 LED Lighting

LEDs (Light Emitting Diodes) are solid light bulbs which are extremely energy-efficient. When first developed, LEDs were limited to single-bulb use in applications such as instrument panels, electronics, pen lights and, more recently, strings of indoor and outdoor Christmas lights.

Manufacturers have expanded the application of LEDs by “clustering” the small bulbs. The first clustered bulbs were used for battery powered items such as flashlights and headlamps. Today, LED bulbs are made using as many as 180 bulbs per cluster, and encased in diffuser lenses which spread the light in wider beams. Now available with standard bases which fit common household light fixtures, LEDs are the next generation in home lighting.

A significant feature of LEDs is that the light is directional, as opposed to incandescent bulbs which spread the light more spherically. This is an advantage with recessed lighting or under-cabinet lighting, but it is a disadvantage for table lamps. New LED bulb designs address the directional limitation by using diffuser lenses and reflectors to disperse the light more like an incandescent bulb.

The high cost of producing LEDs has been a roadblock to widespread use. However, researchers at Purdue University have developed a process for using inexpensive silicon wafers to replace the expensive sapphire-based technology. This promises to bring LEDs into competitive pricing with CFLs and incandescents. LEDs

may soon become the standard for most lighting needs. We are following these developments with interest and will report the latest updates in this research.

Benefits of LED lightbulbs

D bul bs last up to 10 times as long as compact fluorescents, and far longer than typical incandescents.

Durable - since LEDs do not have a filament, they are not damaged under circumstances when a regular incandescent bulb would be broken. Because they are solid, LED bulbs hold up well to jarring and bumping.

Cool - these bulbs do not cause heat build-up; LEDs produce 3.4 btu's/hour, compared to 85 for incandescent bulbs. Common incandescent bulbs get hot and contribute to heat build-up in a room. LEDs prevent this heat build-up, thereby helping to reduce air conditioning costs in the home.

Mercury-free - no mercury is used in the manufacturing of LEDs.

More efficient - LED light bulbs use only 2-17 watts of electricity (1/3rd to 1/30th of Incandescent or CFL). LED bulbs used in fixtures inside the home save electricity, remain cool and save money on replacement costs since LED bulbs last so long. Small LED flashlight bulbs will extend battery life 10 to 15 times longer than with incandescent bulbs.

Cost-effective - although LEDs are initially expensive, the cost is recouped over time and in battery savings. LED bulb use was first adopted commercially, where maintenance and replacement costs are expensive. But the cost of new LED bulbs has gone down considerably in the last few years. and are continuing to go down. Today, there are many new LED light bulbs for use in the home, and the cost is becoming less of an issue. To see a cost comparison between the different types of energy-saving light bulbs, see our Light Bulb Comparison Charts.

Light for remote areas and portable generators - because of the low power requirement for LEDs, using solar panels becomes more practical and less expensive than running an electric line or using a generator for lighting in remote or off-grid areas. LED light bulbs are also ideal for use with small portable generators which homeowners use for backup power in emergencies.

Choosing an LED lightbulb

Many different models and styles of LED bulbs are emerging in today's marketplace. When choosing a bulb, keep in mind the following:

✓ Estimate desired brightness - read the package to choose desired brightness level. You can use wattage to compare bulb illumination, for example, a 9W LED is equivalent in output to a 45 W incandescent. However, the new method for comparing bulbs is lumens. Lumens is the measuse of perceived brightness, and the higher the lumens, the brighter the bulb. The FTC has mandated that all light bulb packages display lumens as the primary measure for comparing bulbs. For more information about lumens, see LED Terminology further down this page.

✓ Do you need a 3-Way bulb? - new LED bulbs are available as combination 3-Way bulbs. These replace 30, 60 and 75-watt incandescent bulbs, while consuming 80% less power than an incandescent bulb! TheSwitch 3-Way LED is also omnidirectional, so it can be used anywhere you would use an incandescent.

✓ Choose between warm and cool light - new LED bulbs are available in 'cool' white light, which is ideal for task lighting, and 'warm' light commonly used for accent or small area lighting.

✓ Standard base or pin base - LEDs are available in several types of 'pin' sockets or the standard "screw' (Edison) bases for recessed or track lighting.

✓ Choose between standard and dimmable bulbs - some LED bulbs, such as the Switch, LEDnovation and FEIT LED bulbs, are now available as dimmable bulbs. They will work on your standard dimmer switch.

✓ Choose high quality bulbs or they will die prematurely - do not buy cheap bulbs from eBay or discounters. They are inexpensive because the bulbs use a low-quality chip which fails easily.

✓ Look for certifications - including FCC, Energy Star and UL.

The common styles of LED bulbs include the following:

1. Diffused bulbs

In this style LED bulb, clusters of LEDs are covered by a dimpled lens which spreads the light out over a wider area. Available in standard Edison bases, these bulbs have many uses, such as area lighting for rooms, porches, reading lamps, accent lamps, hallways and low-light applications where lights remain on for extended periods.

2. Dimmable Globe LED bulbs

Designed for bathroom vanities or anywhere a globe bulb is required, these bulbs produce light equivalent to a 40-watt incandescent bulb, yet only consume 10 watts of power. Dimmable from 100% to 10%, these bulbs have a 200 degree beam angle to cast light in a wide area.

3. Track Lighting, pin base

Available in MR-16 (pin base), LEDs are ideal for track lighting. LEDs do not contribute to heat buildup in a room because no matter how long they remain on, they do not get hot to the touch. Also, because they are 90% more efficient than incandescents, and last 10 times longer than CFLs, the frequency of changing bulbs is greatly reduced.

4. Flood Reflector LEDs for Recessed Cans and Track lights, screw-in base

LEDs are now available for standard recessed lighting pots and housings. They range from 7.5 to 17watts, with beam widths from PAR20 to PAR38. Several models are dimmable. Also, because they are 90% more efficient than incandescents. and last 10 times longer than CFLs, the frequency of changing bulbs is greatly reduced.

5. Flame Tip, Candelabra Base LEDs

Designed to replace incandescent candelabra bulbs, these flame tip LEDs deliver the equivalent light of 25 - 35 watt incandescents while only drawing 3.5 watts of electricity. Because of the heat sink in the base, light doesn't disperse downwards as much as a typical incandescent candelabra bulb.

6. LED Tube Lights

Designed to replace fluorescent tube bulbs, these LED tubes are available in 8 and 16 watts, which replace traditional 25-watt and 40-watt T8/T10/T12 fluorescent tubes. Because fluorescent lights are often installed in high ceilings in commercial sites, there are additional savings because the frequency of changing bulbs is greatly reduced.

Lumen Output: Comparing LED vs CFL vs Incandescent Wattage

Did you know watts don't tell you how bright a light will be?

To compare different light bulbs, you need to know about lumens. Lumens, not watts, tell you how bright a light bulb is, no matter the type of bulb. The more lumens, the brighter the light. Beginning in 2012, labels on the front of light bulb packages now state a bulb's brightness in lumens, instead of the bulb's energy usage in watts. For more information, read our article Lumens are the new watts.

While lumens is the best measurement of comparative lighting among the various bulbs, it is not always a perfect measure. Some floodlights in can lighting use an internal reflector in the bulb to send the light facing downward. When shopping for light bulbs, note that bulbs equipped with reflectors will deliver increased directional light.

The chart below shows the amount of brigthness in lumes you can expect from different wattage light bulbs. The LED bulbs require much less wattage than the CFL or Incandescent light bulbs, which is why LED bulbs are more energy-efficient and long lasting than the other types of bulb.

Incandescent Watts (Brightness)	**CFL Watts**	**LED Watts**	**Lumens**
40	8 - 12	6 - 9	400 - 500
60	13 - 18	8 - 12.5	650 - 900
75 - 100	18 - 22	13+	1100 -
100	23 -30	16 - 20	1750
150	30 - 55	25 - 28	1800 + 2780

2.8.2 BCFL Lighting: Benefits

Efficient: CFLs are four times more efficient and last up to 10 times longer than incandescents. A 22 watt CFL has about the same light output as a 100 watt incandescent. CFLs use 50 - 80% less energy than incandescents.

Less Expensive: Although initially more expensive, you save money in the long run because CFLs use 1/3 the electricity and last up to 10 times as long as incandescents. A single 18 watt CFL used in place of a 75 watt incandescent will save about 570 kWh over its lifetime. At 8 cents per kWh, that equates to a $45 savings.

Reduces Air and Water Pollution: Replacing a single incandescent bulb with a CFL will keep a half-ton of CO2 out of the atmosphere over the life of the bulb. If everyone in the U.S. used energy-efficient lighting, we could retire 90 average size power plants. Saving electricity reduces CO2 emissions, sulfur oxide and high-level nuclear waste.

High-Quality Light: Newer CFLs give a warm, inviting light instead of the "cool white" light of older fluorescents. They use rare earth phosphors for excellent color and warmth. New electronically ballasted CFLs don't flicker or hum.

Versatile: CFLs can be applied nearly anywhere that incandescent lights are used. Energy-efficient CFLs can be used in recessed fixtures, table lamps, track lighting, ceiling fixtures and porchlights. 3-way CFLs are also now available for lamps with 3-way settings. Dimmable CFLs are also available for lights using a dimmer switch

Choosing a CFL

CFLs come in many shapes and sizes. When purchasing CFLs, consult the seller for recommendations and consider the following:

Choose your preferred light quality

CFL bulbs have a Kelvin or 'K' number listed on the packaging. CFLs with K numbers between 2700-3000 give off a soft bright light like incandescents. CFLs with K numbers between 3500-6000 give off a bright light. As you go up the K number scale the light gets bluish and closer to daylight.

For example:

Approx. 2700K = Warm White (looks just like incandescent)

Approx. 5000K = Cool White (white/blue, bright light)

Choose the shape. CFLs are available in a variety of shapes to fit a range of lamps and lighting fixtures. See below on this page for the most popular CFL shapes.

Match lumens to the incandescent being replaced. Lumens indicate the amount of light being generated. (Watts is a measure of energy use, not light strength.) Lumen output is printed on the bulb package or on the bulb product page if purchasing bulbs online.

CFL Light Bulb Models

CFLs are available in a variety of styles or shapes. Some have two, four, or six tubes. Older models, and specialty models, have separate tubes and ballasts. Some CFLs have the tubes and ballast permanently connected. This allows you to change the tubes without changing the ballast. Others have circular or spiral-shaped tubes. In general, the size or total surface area of the tube determines how much light the bulb produces.

The following CFL bulb models come with standard sockets for easy installation in most common household applications.

1. Spiral Lamps

These bulbs are designed as a continuous tube in a spiral shape which has similar outside shape and light casting qualities to a standard incandescent bulb. Spiral CFL bulbs are made in several sizes to fit most common fixtures.

2. Triple Tube Lamps

These CFLs have more tubing in a smaller area, which generates even more light in a shorter bulb. They pack high light output into a very small space and can be used in fixtures designed for incandescent bulbs, such as table lamps, reading lamps, open hanging lamps, and bare bulb applications.

3. Standard Lamps

These are regular CFL spiral lamps which are placed inside a dome cover and fitted with a standard base which fits common lamp sockets. They are designed to give the appearance of the traditional light bulb for consumers looking for the more familiar light bulb appearance. The glass diffuser provides a quality of light similar to the 'soft-white' type of incandescent bulbs.

4. Globe Lamps

This shape is commonly used in bathroom vanity mirrors or open hanging lamps, and bare bulb applications. Bathroom vanities usually require multiple bulbs, which generate radiant heat. The CFL globe will reduce this heat buildup while saving energy. The glass diffuser provides a soft-white light.

5. Flood Lamps

These lamps are designed to be ideal for recessed and track lighting fixtures, indoors and outdoors. They provide diffused, soft, white light, and generate less heat than will an incandescent flood or a halogen bulb. CFL flood lamps are available in varying sizes and wattages.

6. Candelabra

The screw-in torpedo-shape and the small-base of this bulb is designed for smaller light fixtures throughout the house, from chandeliers to sconces. To use a smaller candelabra-based bulb in a regular socket, you can use a socket reducer.

Limitations of CFL lightbulbs

Although CFLs are an excellent source of energy-efficient lighting, they are not always the best choice for all lighting applications. Here are a few limitations to consider:

On/Off cycling: CFLs are sensitive to frequent on/off cycling. Their rated lifetimes of 10,000 hours are reduced in applications where the light is switched on and off very often. Closets and other places where lights are needed for brief illumination should use incandescent or LED bulbs.

Dimmers: Dimmable CFLs are available for lights using a dimmer switch, but check the package; not all CFLs can be used on dimmer switches. Using a regular CFL with a dimmer can shorten the bulb life span.

Outdoors: CFLs can be used outdoors, but should be covered or shaded from the elements. Low temperatures may reduce light levels - check the package label to see if the bulb is suited for outdoor use.

Retail lighting: CFLs are not spot lights. Retail store display lighting usually requires narrow focus beams for stronger spot lighting. CFLs are better for area lighting.

Mercury content: CFLs contain small amounts of mercury which is a toxic metal. This metal may be released if the bulb is broken, or during disposal. For more information about mercury and CFLs, see below.

The principle reason for reduced lifespan of CFLs is heat. CFLs exhibit shorter lifespans in light fixtures and sockets where there is low air-flow and heat build-up such as recessed lighting. For these types of sockets it is recommended to ues specially designed CFLs for recessed lighting or LEDs. Another main reason for reduced lifespan of CFLs is too-frequent on/off cycling. These bulbs should be used where they will be left on for steady periods without being flicked on and off.

Mercury and CFLs

Mercury is a toxic metal associated with contamination of water, fish, and food supplies, and can lead to adverse health affects. A CFL bulb generally contains an average of 5 mg of mercury (about one-fifth of that found in the average watch battery, and less than 1/100th of the mercury found in an amalgam dental filling). A power plant will emit 10mg of mercury to produce the electricity to run an incandescent bulb compared to only 2.4mg of mercury to run a CFL for the same time. The net benefit of using the more energy efficient lamp is positive, and this is especially true if the mercury in the fluorescent lamp is kept out of the waste stream when the lamp expires.

Handling and Disposal of CFLs

The mercury in compact fluorescent bulbs poses no threat while in the bulb, but if you break one:

- ✓ Open a window and leave the room for 15 minutes or more
- ✓ Use a wet rag to clean it up and put all of the pieces, and the rag, into a plastic bag
- ✓ Place all materials in a second sealed plastic bag
- ✓ Call your local recycling center to see if they accept this material, otherwise put it in your local trash. Wash your hands afterward.

Burned out CFLs can be dropped off at Home Depot and Ikea stores. Another solution is to save spent CFLs for a community household hazardous waste collection, which would then send the bulbs to facilities capable of treating, recovering or recycling them. For more information on CFL disposal or recycling, you can contact your local municipality.

UNIT III
HEATING AND WELDING

Introduction - advantages of electric heating – modes of heat transfer - methods of electric heating - resistance heating - arc furnaces - induction heating – dielectric heating - electric welding – types - resistance welding - arc welding - power supply for arc welding - radiation welding.

Electric Heating Introduction:

Electric heating is any process in which electrical energy is converted to heat. Common applications include heating of buildings, cooking, and industrial processes. An electric heater is an electrical appliance that converts electrical energy into heat. The heating element inside every electric heater is simply an electrical resistor, and works on the principle of Joule heating: an electric current through a resistor converts electrical energy into heat energy. Alternatively, a heat pump uses an electric motor to drive a refrigeration cycle, drawing heat from a source such as the ground or outside air and directing it into the space to be warmed.

Definition

Dielectric heating (also known as electronic heating, RF heating, high-frequency heating) is the process in which radiowave or microwave electromagnetic radiation heats a dielectric material. This heating is caused by dipole rotation.

Role electric heating for industrial applications:

- When current is passed through a conductor, the conductor becomes hot. When a magnetic material is brought in the vicinity of an alternating magnetic field, heat is produced in the magnetic material.

- Similarly it was found that when an electrically insulating material was subjected to electrical stresses, it too underwent a temperature rise (Dielectric heating).

There are various method of heating a material but electric heating is considered to be far superior for the following reasons:

(i)Cleanliness:

- Due to complete elimination of dust and ash, the charges to maintain cleanliness are minimum and the material to be heated does not get contaminated.

(ii)Ease of control:

- With the help of manual or automatic devices, it is possible to control and regulate the temperature of a furnace with great ease.

(iii)Uniform heating:

- Whereas in other forms of heating a temperature gradient is set up from the outer surface

(iv) Low attention and maintenance cost:

- Electric heating equipments normally do not require much attention and maintenance is also negligible.

- Hence labour charges on these items are negligibly small as compared to alternative methods of heating.

Requirement of Heating Material:

i) Low Temperature Coefficients of Resistance

- Resistance of conducting element varies with the temperature; this variation should be small in case of an element.

- Otherwise when switched ON from room temperature to go upto say 1200˚C, the low resistance at initial stage will draw excessively high currents at the same operating voltage.

ii) Resistance coefficient Positive

- If temperature is negative the element will draw more current when hot.

- A higher current means more voltage, a higher temperature or a still lower resistance, which can instability of operation.

iii) High Melting Point

- Its melting point should be sufficiently higher than its operating temperature. Otherwise a small rise in the operating voltage will destroy the element.

iv) High Specific Resistance

- The resistivity of the material used for making element should be high.

- This will require small lengths and shall give convenient size.

v) High Oxidizing Temperature

- Its oxidizing temperature should higher than its operating temperature.
- To have convenient shapes and sizes, the material used should have high ductility and flexibility.

- It should not be brittle and fragile.

vi) Should with stand Vibration

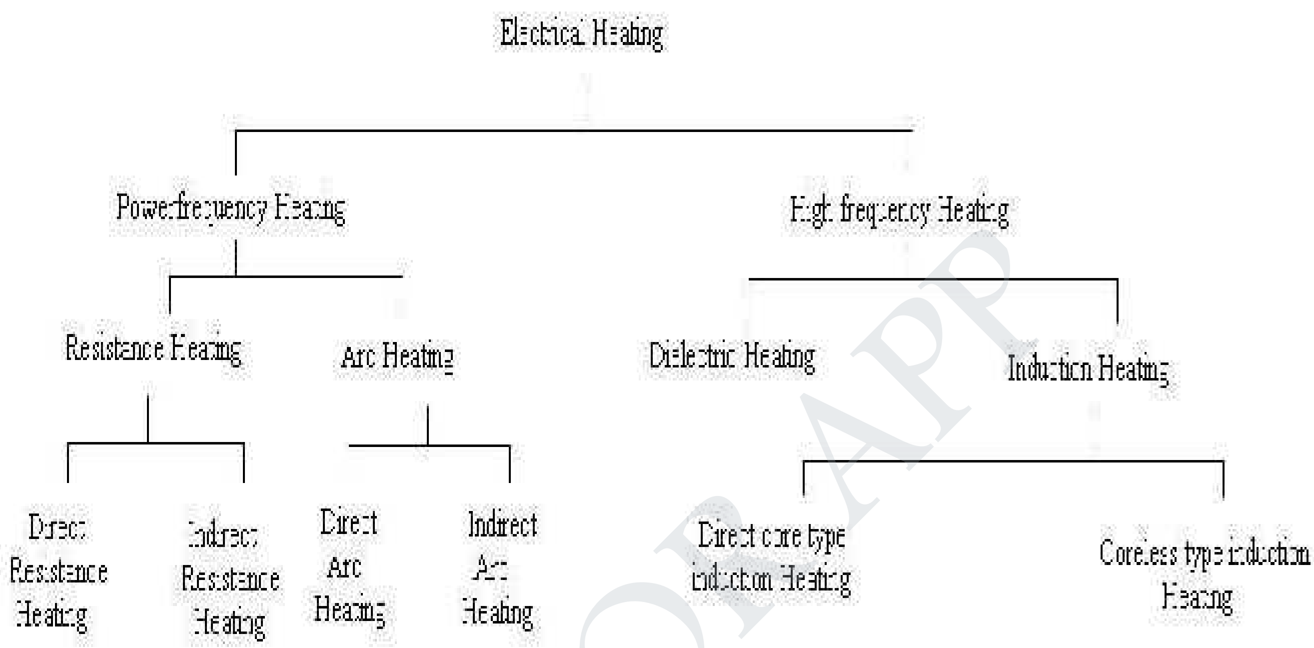
- In most industrial process quite strong vibrations are produced.

- Some furnaces have to open or rock while hot. The element material should withstand the vibrations while hot and should not break open.

vii) Mechanical Strength

- The material used should have sufficient mechanical strength of its own.

CLASSIFICATION OF METHODS OF ELECTRIC HEATING :



i) Power Frequency Method:

- Direct resistance heating, indirect resistance heating, direct arc heating, and indirect arc heating.

ii) High Frequency Heating:
- Induction heating and dielectric heating.

Resistance Heating:

- This method is based upon the I2R loss. Whenever current is passed through a resistive material heat is produced because of I2 R loss.

- There are two methods of resistance heating. They are

a. Direct Resistance Heating

b. Indirect Resistance Heating

Direct Resistance Heating:

In this method of heating the material or change to be heated is taken as a resistance and current is passed through it.

- The charge may be in the form of powder pieces or liquid. The two electrodes are immersed in the charge and connected to the supply.
- In case of D.C or single phase A.C two electrodes are required but there will be three electrodes in case of three phase supply.
- When metal pieces are to be heated a powder of high resistivity material is sprinkled over the surface of the charge to avoid direct short circuit.
- But it gives uniform heat and high temperature. One of the major applications of the process is salt bath furnaces having an operating temperature between 500˚C to 1400˚C.
- An immersed electrode type medium temperature salt bath furnace is shown in figure
- The bath makes use of supply voltage across two electrodes varying between 5 to 20 volts.
- For this purpose a special double wound transformer is required which makes use of 3Φ primary and single phase secondary. This speaks of an unbalanced load.
- The variation in the secondary voltage is done with the help of an off load tapping switch of the primary side. This is necessary for starting and regulating the bath load.

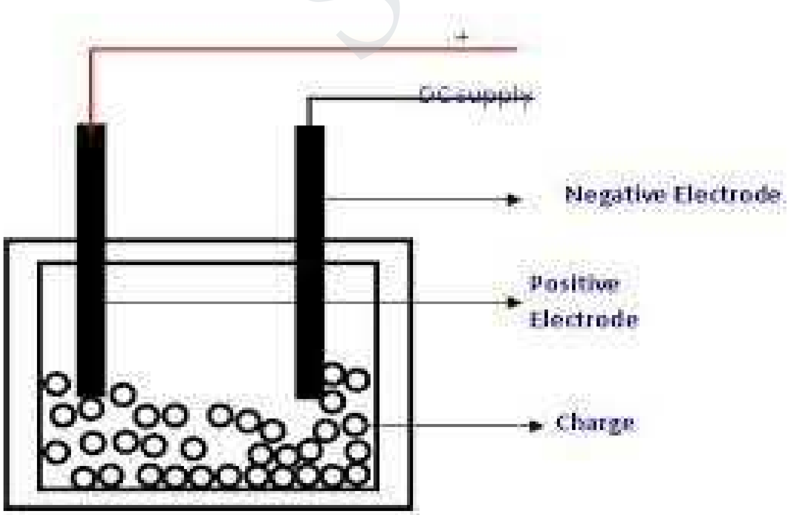
Advantages:

✓ High efficiency.

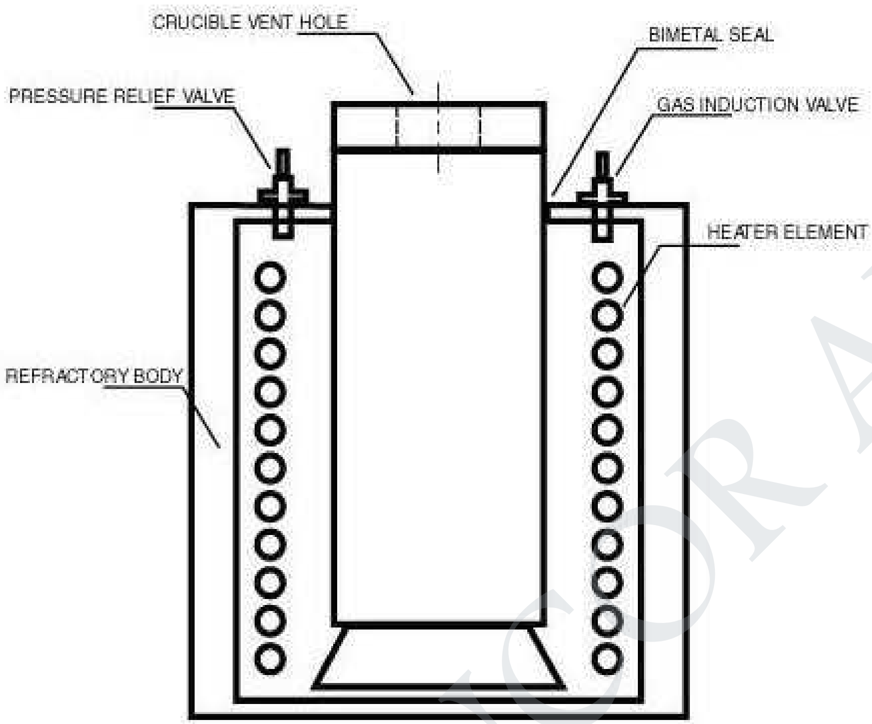
✓ It gives uniform heat and high temperature.

Application:

✓ It is mainly used in salt bath furnace and water heaters.



Indirect Resistance Heating:



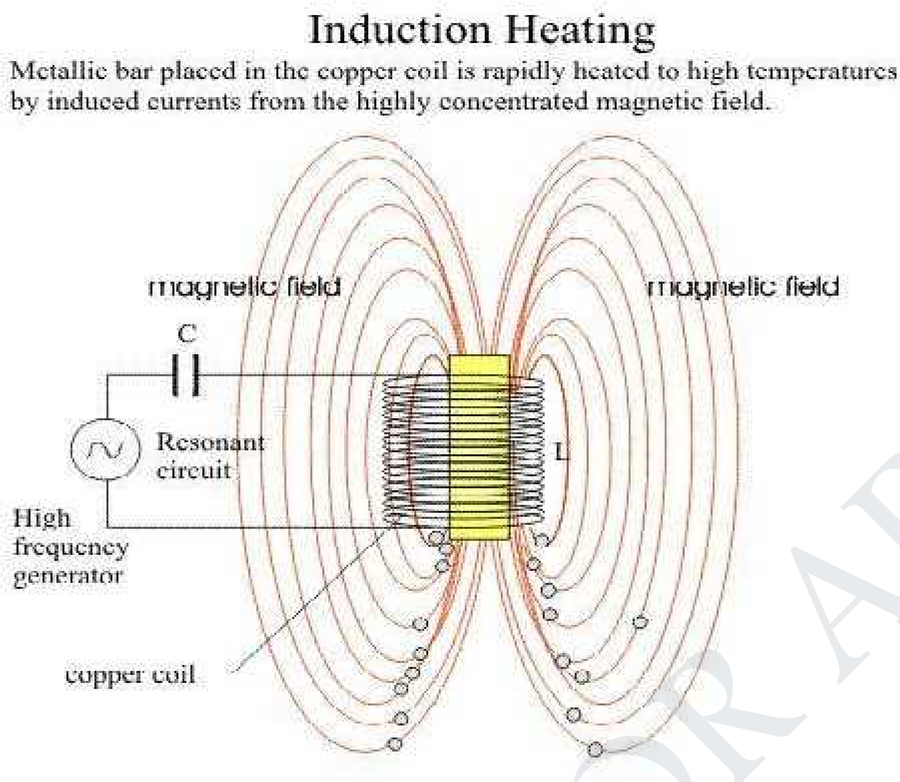
- In this method the current is passed through a highly resistance element which is either placed above or below the over depending upon the nature of the job to be performed.

- The heat proportional to I2R losses produced in heating element delivered to the charge either by radiation or by convection.

- Sometimes in case of industrial heating the resistance is placed in a cylinder which is surrounded by the charge placed in the jackes.The arrangement provides as uniform temperature.

- Automatic temperature control can be provided in this case
- This method is used in room heater, in bimetallic strip used in starters, immersion water heaters and in various types of resistance ovens used in domestic and commercial cooking.

Induction heating:



- Induction heating processes make use of currents induced by electromagnetic action in the material to be heated.

- Induction heating is based on the principle of transformers. There is a primary winding through which an a.c current is passed.

- The coil is magnetically coupled with the metal to be heated which acts as secondary.

- An electric current is induced in this metal when the a.c current is passed through the primary coil.

The following are different types of induction furnaces

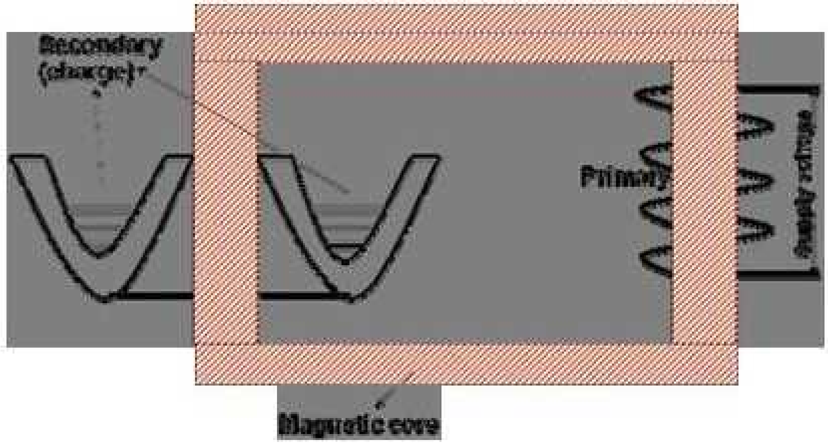
1. Core type furnaces
a. Direct core type induction furnace
b. Vertical core type induction furnace
c. Indirect core type induction furnace
2. Core less type furnaces

Direct core type:

The direct core type induction furnace is shown ion fig.

- It consist of an iron core, crucible and primary winding connected to an a.c supply.

The charge is kept in the cruicible, which forms a single turn short circuited secondary circuit.



- The current in the charge is very high in the order of several thousand amperes. The charge is magnetically coupled to the primary winding.
- The change is melted because of high current induced in it. When there is no molten metal, no current will flow in the secondary.

- To start the furnace molten metal is poured in the oven from the previous charge.

This type of furnace has the following drawbacks:

- The magnetic coupling between the primary and secondary is very weak, therefore the leakage reactance is very high. This causes low power factor.

- Low frequency supply is necessary because normal frequency causes turbulence of the charge.

- If current density exceeds about 5 amps/mm2 the electromagnetic force produced by this current density causes interruption of secondary current.

- Hence the heating of the metal is interrupted. It is called pinch effect.

- The crucible for the charge id of odd shape and inconvenient from the metallurgical point of view.

- The furnace cannot function if the secondary circuit is open.

- It must be closed. For starting the furnace either molten metal is poured into the crucible or sufficient molten metal is allowed to remain in the crucible from the previous operation.

Such furnace is not suitable for intermittent services.

Indirect core type induction furnace:

- I n this type of furnace induction principle has been used for heating metals.

- In such furnace an inductively heated element is made to transfer its heat to the change

When the primary winding is connected to the supply, current is induced in the secondary of the metal container.

- So heat is produced due to induced current. This heat is transmitted to the charge by radiation.

- The portion AB of the magnetic circuit is made up of a special alloy and is kept inside the chamber of the furnace.

- The special alloy will loose its magnetic properties at a particular temperature and the magnetic properties are regained when the alloy will cooled.
- As soon as the furnace attains the critical temperature the reluctance of the magnetic circuit increases many times and the inductive effect correspondingly decreases thereby cutting off the heat supply.

- The bar AB is removable type and can be replaced by other, having different critical temperature. Thus the temperature of the furnace can be controlled very effectively.

Coreless induction furnace:

- Coreless induction furnace also operates on the principle of transformer. In this furnace there is no core and thus the flux density will be low.

- Hence for compensating the low flux density, the current supplied to the primary should have sufficiently high frequency.

- The flux set up by the primary winding produces eddy currents in the charge. The heating effect of the eddy currents melts the charge.

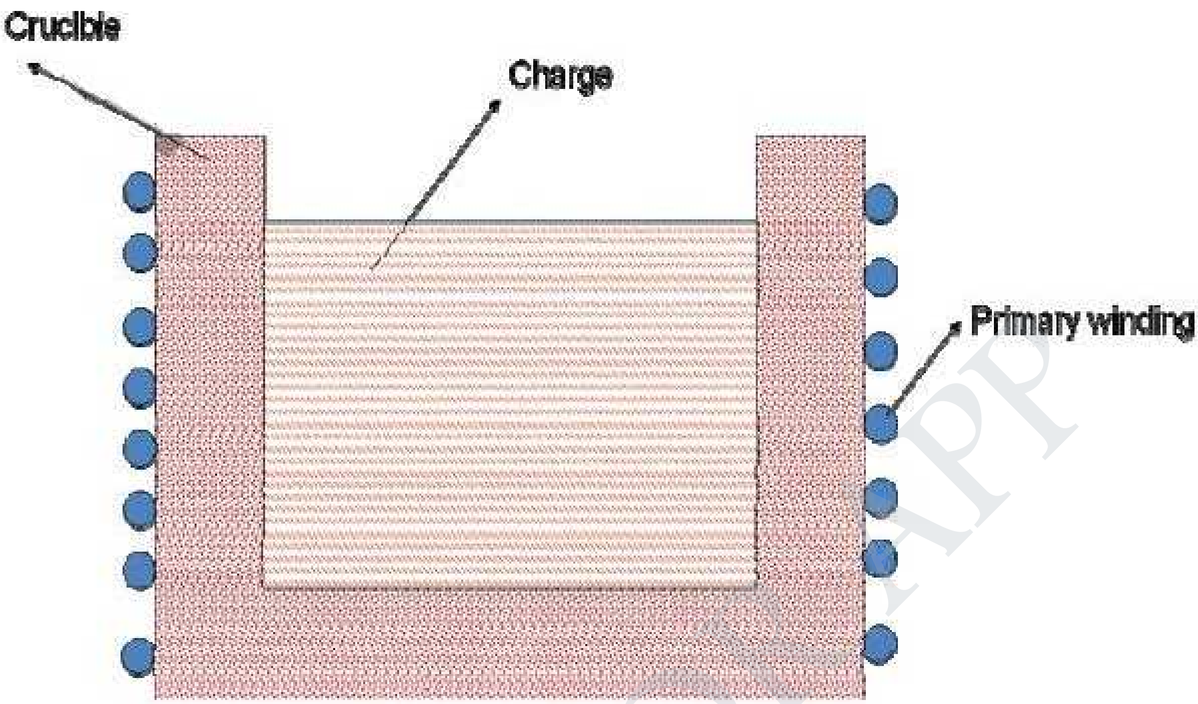
- Stirring of the metals takes place by the action of the electromagnetic forces. Coreless furnace may be having conducting or non conducting containers.

- Fig shows a coreless induction furnace in which container is made up of conducting material.

- The container acts as secondary winding and the charge can have either conducting or non conducting properties.

- Thus the container forms a short circuited single turn secondary. Hence heavy current induced in it and produce heat.
- The flux produced by the primary winding produces eddy currents in the charge. The heating effects of the eddy currents melt the charge.

Stirring action in the metals takes place by the action of the electromagnetic forces.



Advantages:

- ✓ Time taken to reach the melting temperature is less.
- ✓ Accurate power control is possible.
- ✓ Any shape of crucible can be used.
- ✓ The eddy currents in the charge results in automatic stirring.
- ✓ Absence of dirt, smoke, noise, etc.
- ✓ Erection cost is less.

Applications of Induction Heating

- ✓ Induction furnace
- ✓ Induction welding
- ✓ Induction cooking
- ✓ Induction brazing
- ✓ Induction sealing
- ✓ Heating to fit
- ✓ Heat treatment

Advantages of Induction Heating

- ✓ Optimized Consistency

- ✓ Maximized Productivity
- ✓ Improved Product Quality
- ✓ Extended Fixture Life
- ✓ Environmentally Sound
- ✓ Reduced Energy Consumption

Dielectric heating:

- Dielectric heating is also sometimes called as high frequency capacitance heating.

- If non metallic materials ie, insulators such as wood, plastics, china clay, glass, ceramics etc are subjected to high voltage A.C current, their temperature will increase in temperature is due to the conversion of dielectric loss into heat.

- The dielectric loss is dependent upon the frequency and high voltage. Therefore for obtaining high heating effect high voltage at high frequency is usually employed.

- The metal to be heated is placed between two sheet type electrodes which forms a capacitor as shown in fig. The equivalent circuit and vector diagram is also shown in fig.

- When A.C supply is connected across the two electrodes, the current drawn by it is leading the voltage exactly 90˚.

- The angle between voltage and current is slightly less than 90˚

- But at high frequencies, the loss becomes large, which is sufficient to heat the dielectric.

Advantages:

- ✓ Uniform heating is obtained.
- ✓ Running cost is low.
- ✓ Non conducting materials are heated within a short period.
- ✓ Easy heat control.

Applications:

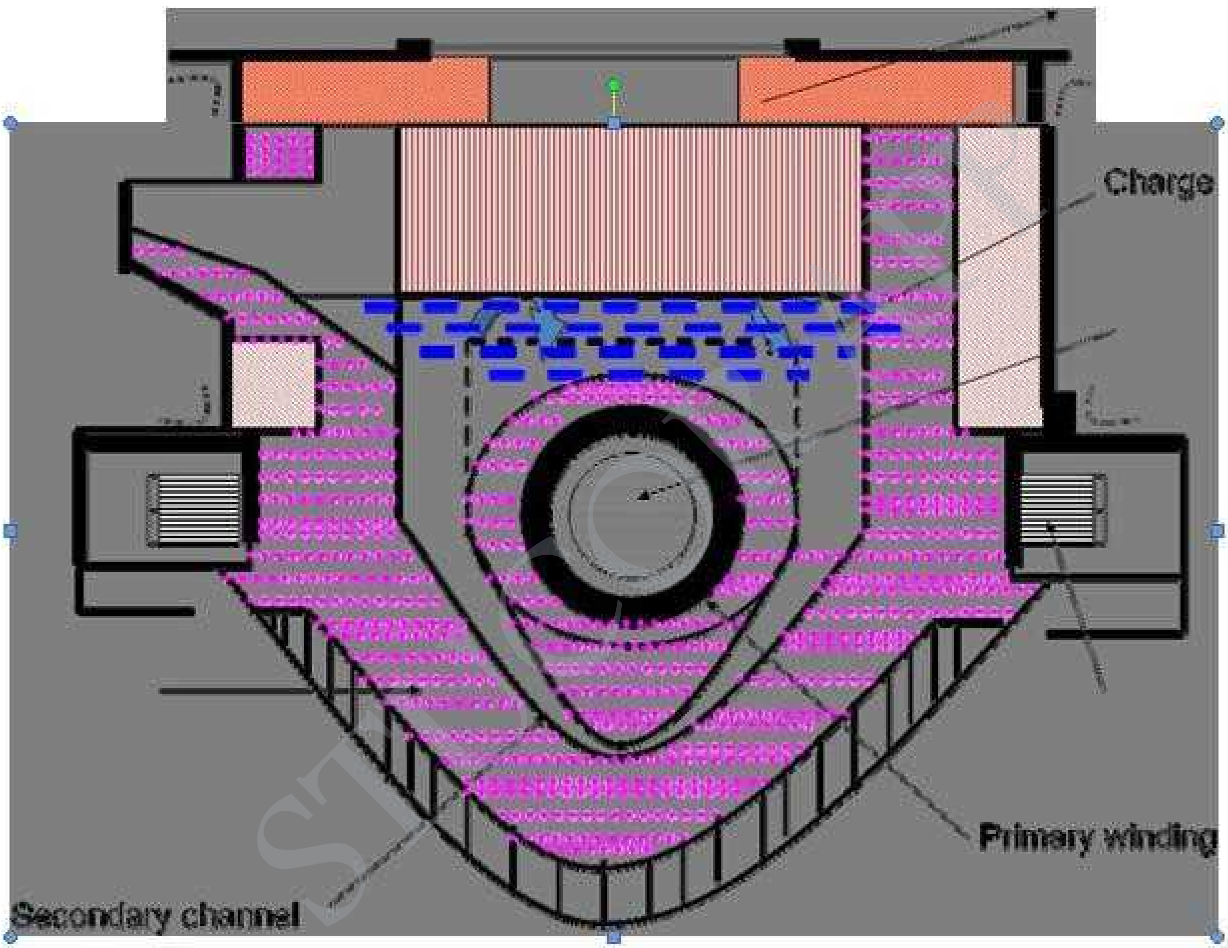
- ✓ For food processing.
- ✓ For wood processing.
- ✓ For drying purpose in textile industry.
- ✓ For electronic sewing.

Electric arc furnaces:

AJAX WYATT Vertical core type furnace:

- The principle of operation is that of a transformer in which the secondary turns are replaced by a closed loop of molten metal. The primary winding is placed on the central limb of the core.

- Hence leakage reactance is comparatively low and power factor is high. Inside of the furnace is lined with refractory depending upon the charge.



- The top of the furnace is covered with an insulated cover which can be removed for charging. Necessary arrangements are usually made for titling the furnace to take out the molten metal.
- The molten metal in the ‘V’ portion acts as a short circuited secondary. When primary is connected to the a.c supply, high current will be accumulated at the bottom and even a small amount of charge will keep the secondary completed.
- Hence a chance of discontinuity of the circuit is less.

Advantages:

✓ High efficiency and low operating cost.

- ✓ Since both primary and secondary are on the same central core, its power factor is better.
- ✓ The furnace is operated from the normal supply frequency.
- ✓ Chances of discontinuity of the secondary circuit is less, hence it is useful for intermittent operations.

Applications:

- ✓ This furnace is used for melting non ferrous metals like brass, zinc, tin, bronze, copper etc.

Introduction to electric welding:
Welding is the process of joining two similar metals by heating. The metal parts are heated to melting point. In some cases the pieces of metal to be joined are heated to plastic stage and are fused together.

The electric welding sets may be either dc or ac type. DC welding sets are of two types namely generator type welding set consisting of a differential compound wound dc generator, giving drooping volt-ampere characteristic, driven by any type of prime-mover (a squirrel cage induction motor or a petrol or diesel engine) and dry type rectifier (selenium rectifier) used in conjunction with a multiphase high leakage transformer. IN generator type welding sets the control may be obtained by tapping the series field or by providing a suitable shunt across the series field winding. In the rectifier type set dc voltage is controlled by regulating the transformer output. If supply from existing dc distribution system is to be used for welding then ballast (resistance) is put in series with the equipment and the control is affected by varying this external series resistance.
In electric welding process, electric current is used to produce large heat, required for joining two metal pieces. There are two methods by which electric welding can be carried out. These are

a) Resistance welding and

b) Arc welding.

Types of electric welding:

1. Resistance welding
a) Seam welding

b) Projection welding

c) Flash welding

2. Arc welding

a) Carbon arc welding

b) Metal arc welding
c) Atomic hydrogen arc welding

d) Inert gas metal arc welding

e) Submerged arc welding.

Resistance welding:

- In resistance welding heavy current is passed through the metal pieces to be welded. Heat will be developed by the resistance of the work piece to the flow of current.

- The heat produced for welding is given by

$H=I2_{Rt}$

Where,

H= Heat developed at the contact area.

I= Current in amperes.

R= Resistance in ohms.

t= time of flow of current.

Butt welding:

- In this process heat is generated by the contact resistance between two components.

- In this type of welding the metal parts to be joined end to end. Sufficient pressure is applied along the axial direction.

- A heavy current is passed from the welding transformer which creates the necessary heat at the joint due to high resistance of the contact area.
- Due to the pressure applied, the molten metal forced to produce a bulged joint.

- This method is suitable for welding pipes, wires and rods.

ii) Spot welding:

- Spot welding is usually employed for joining or fabricating sheet metal structure. This type of joint only provides mechanical strength and is not air or water tight.

- The plates to be welded are placed overlapping each other between two electrodes, sufficient mechanical pressure is applied through the electrodes.
- The welding current flows through electrodes tips producing a spot weld. The welding current and period of current flow depend on the thickness of the plates.

iii) Arc welding:

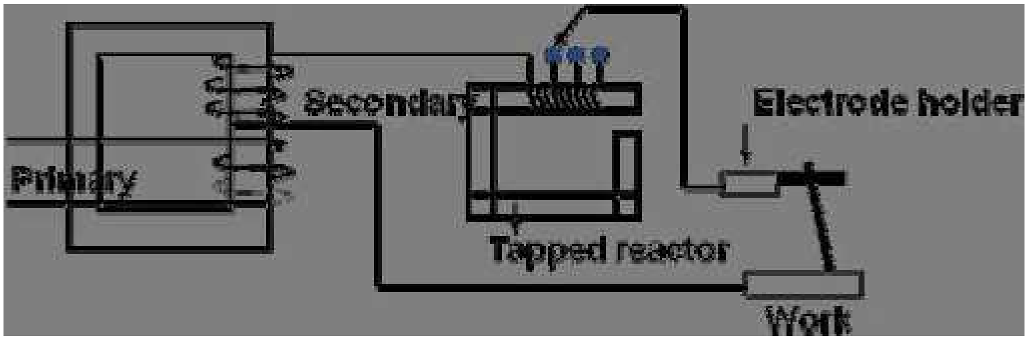
- An electric arc is the flow of electric current through gases.
- An electric arc is struck by short circuiting two electrodes and then with drawing them apart by small distance.
- The current continue to flow across the small gap and give intense heat.
- The heat developed by the arc is also used for cutting of metal.
- The electrode is made of carbon or graphite and is to be kept negative with respect of work. The work piece is connected to positive wir. Flux and filler are also used.
- Filler is made up of similar metal as that of metal to be welded.
- If the electrode is made positive then the carbon contents may flow into the weld and cause brittleness.
- The heat from the arc forms a molten pool and the extra metal required to make the weld is supplied by the filler rod.
- This type of welding is used for welding copper and its alloy.

iv)Metal arc welding:

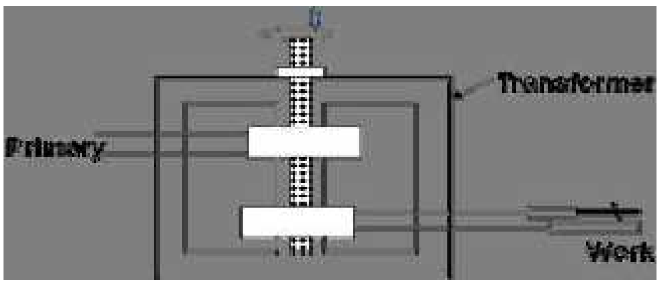
- In metal arc welding a metal rod of same material as being welded is used as an electrode.
- The electrode also serves the purpose of filler. For metal arc welding A.C or D.C can be used.
- Electric supply is connected between electrode and work piece.
- The work piece is then suddenly touched by the electrode and then separated from it a little. This results in an arc between the job and the electrode.
- A little portion of the work and the tip of the electrode melts due to the heat generated by the arc.
- When the electrode is removed the metal cools and solidifies giving a strong welded joint.

WELDING GENERATOR - A.C SUPPLY

In tapped reactor method, output current is regulated by taps on the reactor. This has limited number of current settings.

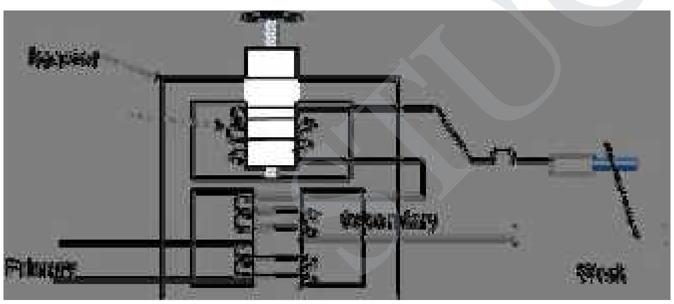


In the moving coil method of current control, relative distance between primary and secondary windings is changed. When coils are more separated out current is less.



In magnetic shunt method, position of central magnetic shunt can be adjusted. This changes the magnitude of shunt flux and therefore, output current. When central core is more inside, load current will be less and vice versa.

In **continuously variable reactor method**, output current is controlled by varying the height of the reactor. Greater the core insertion, greater the reactance and less the output current. Reverse is true for less height of core insertion



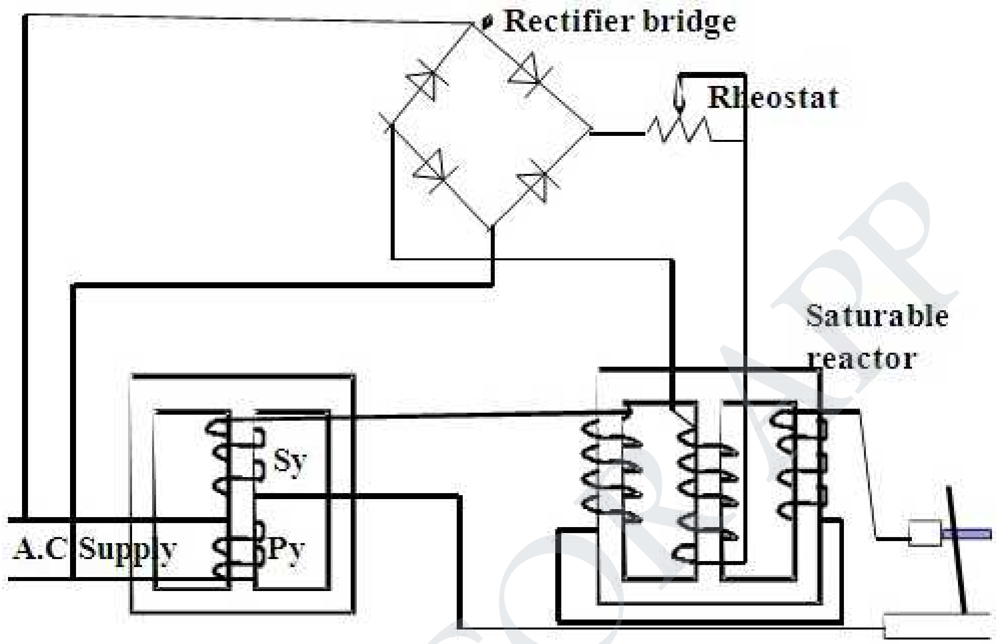
In saturable reactor method, the reactance of the reactor is adjusted by changing the value of d.c excitation obtained from bridge rectifiers by means of rheostat. When d.c current in the central winding of reactor is more, reactor approaches magnetic saturation. This means the reactance of reactor becomes less. Vice versa happens on the

A welding transformer is a step down transformer that reduces the voltage from the source voltage to a lower voltage that is suitable for welding, usually between 15 and 45 volts. The secondary current is quite high. 200 to 600 amps would be typical, but it could be much higher.The secondary may have several taps for adjusting the secondary voltage to control the welding current. The taps are typically connected to a several high-current plug receptacles or to a highcurrent switch. For welding with direct current (DC) a rectifier is connected to the secondary of the transformer.

There may also be a filter choke (inductor) to smooth the DC current. The entire transformer and rectifier assembly may be called a transformer or welder, but "welding power supply" would be more appropriate term.

WELDING TRANSFORMER:

The impedance of a welding transformer may be higher that the impedance of a transformer designed for some other purpose. The transformer impedance may play a role in the process of establishing an arc and controlling the current.



Special Features:

- Stepless current control within single range from front panel
- For its high permitted load, its ideal for fematic welding
- Phase compensation facility optional. It’s a good investment as the primary current and rated output can be reduced, resulting in reduced fuse size and cable diameter
- Provided with wheels and handle for easy mobility
- Sturdy design for all working environments
- Horizontal shunt core travel ensures precise setting after prolonged use
- Class 'H' insulation provides longer coil life
- Multi voltage input supply

UNIT IV
SOLAR RADIATION AND SOLAR ENERGY COLLECTORS

Introduction - solar constant - solar radiation at the Earth's surface - solar radiation geometry – estimation of average solar radiation - physical principles of the conversion of solar radiation into heat – flat-plate collectors - transmissivity of cover system - energy balance equation and collector efficiency - concentrating collector – advantages and disadvantages of concentrating collectors - performance analysis of a cylindrical - parabolic concentrating collector – Feeding Invertors.

4.1 INTRODUCTION

The solar collectors, solar photo voltaics and solar thermal devices are based on solar radiation. The technical and economic performance of these device depends on the amount of solar radiation falling at a given location and time.

4.1.1 The Sun

✓ The Sun is the star at the center of the solar system. It is seen in the sky and gives light to the Earth. When the Sun is in the sky, it is day. When the Sun is not in the sky, it is night. The Planets, including Earth, orbit around it.

✓ The Sun gives off energy (ie. Solar Energy) as electromagnetic radiation. Solar energy is a very large, inexhaustible source of energy. The power from the Sun intercepted by the earth is approximately 1.8×10^{11} MW, which is many thousands of times larger than the present consumption rate on the earth of all commercial energy sources.

✓ The Sun is a sphere of intensely hot gaseous matter with a diameter of 1.39×10^{9} m and, on an average, at a distance of 1.5×10^{11}m from the earth. An observed from the earth, the Sun rotates on its axis about once every four weeks, though, it does not rotate as a solid body. The equator takes about 27 days and the polar regions take about 30 days for each rotation.

✓ With an effective black body temperature T_S of 5777K, the Sun is effectively, a continuous fusion reactor. Several fusion have been suggested to supply the energy radiated by the sun; the most important being in which hydrogen (i.e., Four protons) combines to from helium (i.e., helium nucleus). The mass of the nucleus is less than that of four protons, mass having been lost in the reaction and converted to energy. The reaction is as follows:

$$4({}^{1}_{1}H) \rightarrow {}^{4}_{2}He + 26.7 \text{ MeV} \qquad \ldots (4.1)$$

✓ This energy is produced in the interior of the solar sphere, at temperature of many millions degrees. The produced energy must be transferred out to the surface and then be radiated into space, the prodeced energy (E) is given by,

$$E = \varepsilon \sigma T_s^4 \quad \ldots (4.2)$$

Where, ε and σ are emissivity of the surface and Stefan - Boltzmann constant.

✓ It is estimated that 90 percent of the Sun's energy is generated in the region 0 to 0.23 R (where, R being the radius of the Sun), the average density ρ and Temperature T in this region are 10^5 kg/m^3 and about 8×10^6 K to 40×10^6 K respectively. At a distance of about 0.7 R from the center, the temperature drops to about 1.3×10^5 K and the density to 70kg/m^3 . Hence for $r > 0.7$ R convection begins to be important and the region $0.7 R < r < R$ is known as the convective zone. The outer layer of this zone is called the photosphere. The edge of the photosphere is sharply defined, even though it is of low density. Above the photosphere is a layer of cooler gases several hundred kilometers deep called the reversing layer. Outside that, is a layer referred to as the chromospere, with a depth of about 10,000 km. This is a gaseous layer with temperatures somewhat higher than that of the photosphere and with lower density. Still further out is the corona, of very low density and of very high temperature (10^6 K).

A schematc diagram of the structure of the Sun is shown in Fig. 4.1.

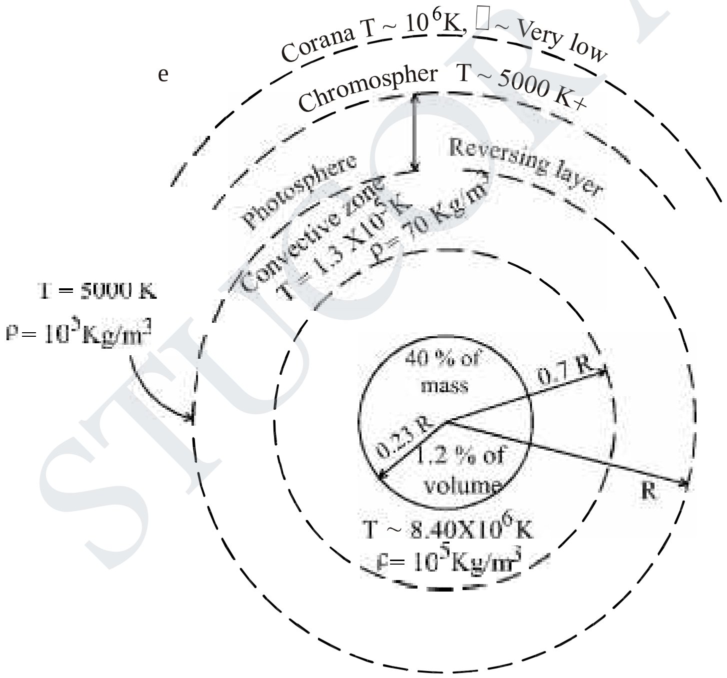


Fig. 4.1 The structure of Sun

4.1.2 The Earth

✓ Earth is the third planet from the Sun, the densest planet in the solar system, the largest of the solar system's four terrestrial planets and the only astronomical object known to harbor life.

✓ According to radiometeric dating and other sources of Evidence, Earth formed about 4.54 billion year ago.

✓ Earth gravitationally interacts with other objects in space, especially the Sun and the Moon. During one orbit around the Sun, earth rotates about its own axis 366.26 times, creating 365.26 solar days or one sidereal year. Earth's axis of rotation is tilted 23.4^{o} away from the perpendicular of its orbital plane, producing seasonal variations on the planet's surface with a period of one tropical year (365.24 solar days). The moon is earth's only permanent natural satellite. It's gravitational interaction with earth causes ocean tides, stabilizes the orientation of earth's rotational axis, and gradually slows earth's rotational rate.

✓ The internal structure of Earth is shown in Fig. 4.2.

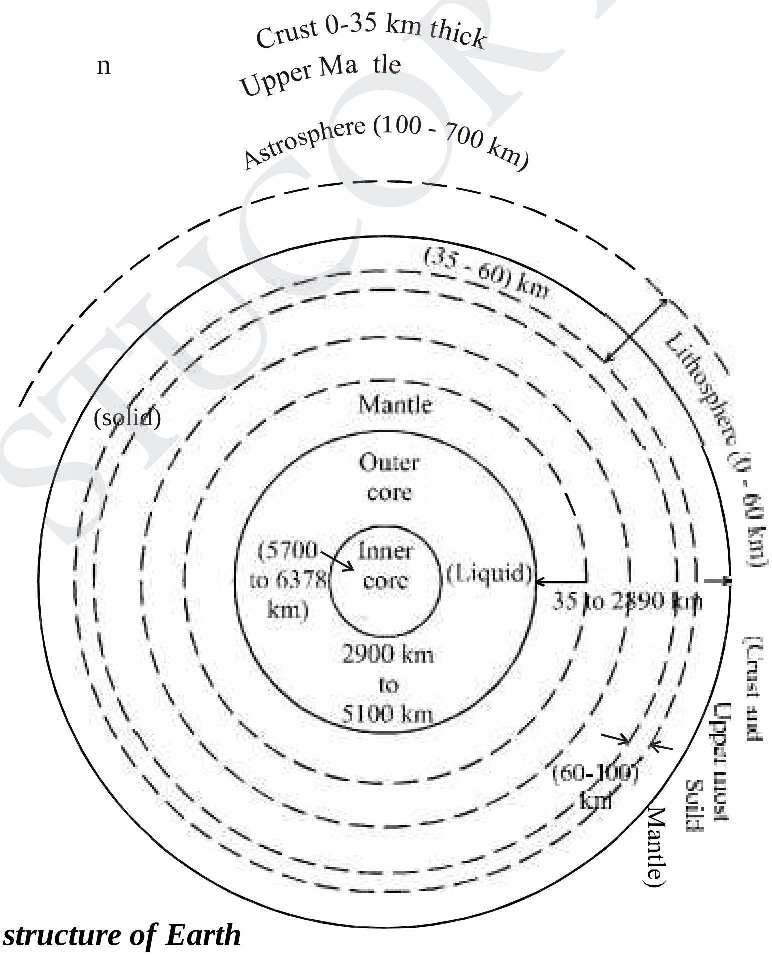


Fig. 4.2 The structure of Earth

✓ Earth's interior, like that of the other terrestrial planets, is divided into layers by their chemical or physical properties, but unlike the other terrestrial planets, it has a distinct outer and inter core.

✓ The outer layer is chemically distinct silicate solid crust, which is underlain by a highly viscous solid mantle. The curst is seperated from mantle. The crust is seperated from mantle by mohorovicic discontinuity (usually referred to as the Moho-the boundary between the earth's crust and the mantle), and the thickness of the crust varies: averaging 6 km under the oceans and 30-50 km on the continents. The crust and cold, rigid, top of the upper mantle are collectively known as the lithosphere and it is of lithosphere that the tectonic plates are composed.

✓ Beneath the lithosphere and it is the asthenosphere, a relatively low- viscosity layer on which the lithosphere rides.

✓ Important changes in crystal structure within the mantle occur at 410 and 660 km below the surface, spanning a transition zone that separates the upper and lower mantle.

✓ Beneath the mantle, an extrrmely low viscosity liquid outer core lies above a solid inner core. The inner core is a solid mass made of iron and nickle. Its outer core is made up of these two metals but in a melted state.

✓ The oldest rocks of sedimentary region appear to date from about 3.7×10^9 years ago covering maximum area with liquid water. The fossil (remains of blue–green algae and bacteria) have been found in rock/water at least 3×10^9 year ago. The existance of blue-green algoe marks the beginning of photosynthesis. As a result of photosynthesis, the level of 0_2 and 0_3 in the atmosphere is increased which blocks UV solar radiation coming from the Sun. This phenomenon of blocking of UV radiation happened about 420 million years ago and this allowed the planets to grow on earth. Below table 4.1 shows the geologic layer of Earth.

Table 4.1 Gologic layers of Earth

Depth(km)	Layer name	Density g/cm^3
0-60	Lithosphere	–
0-35	Crust	2.2 – 2.9
35-60	Upper Mantle	3.4 – 4.4
35-2890	Mantle	3.4 – 5.6
100-700	Asthenosphere	–
2890-5100	Outer core	9.9 – 12.2
5100-6378	Inner core	12.8 – 13.1

✓ The earth is almost round in shape having a diameter of about 13000 km. It revolves around the Sun once in about a year. Nearly 70 percent of the earth is covered by the water and remaining 30 percent is land. Half of the earth is lit by sunlight at a time. It reflects one third of the sunlight that falls on it. This is known as earth's albedo. The earth is spinning about its axis constantly. Its axis is inclined at an angle of 23.5^{o}. As a result, the length of days and nights keep changing.

✓ The point of closest distance between the Sun and the Earth in orbit is called Perihelion, and the point of farthest distance between the Sun and the Earth in orbit is called Aphelion. Over the average Sun-Earth distance is 1.495×10^{11}m.

✓ The amout of radiation intercepted by the earth varies inversely with the square of the distanced between the Sun and the Earth. Since, the Sun-Earth distance is not constant, the amount of radiation intercepted by the earth also varies although due to small ecentricity of elliptical orbit, the radiation is not much and accounts for only 5.9 percent.

SOLAR SPECTRUM

✓ The simplified picture of the Sun, its physical structure, temperature and density gradients indicate that the Sun, infact, does not function as a blackbody radiator at a fixed temperature.

✓ Rather, the emitted solar radiation is the composite result of the several layers that emit and absorb radiation of various wavelengths.

✓ The photosphere is the source of most solar radiation and is essentially opaque, as the gases, of which it was composed, are strongly inonized and able to absorb and emit a continuous spectrum of solar radiation.

✓ In addition to the total energy in the solar spectrum (i.e., Solar Constant) it is useful to know the spectral distribution of extraterrestrial radiation, that is the radiation that would be received in the absence of the atmosphere.

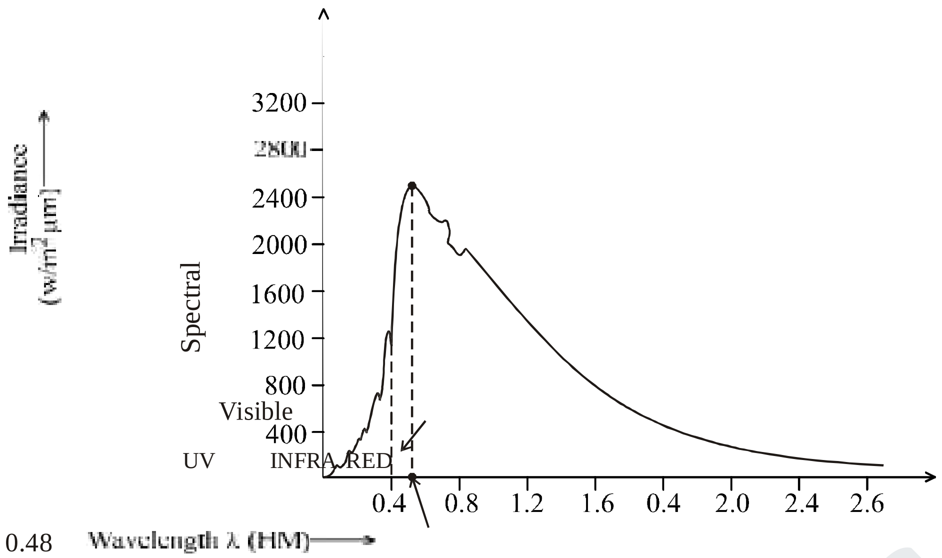


Fig. 4.3 Spectral Solar Irradiance

✓ Fig. 4.3, shows the maximum spectral intensity occurs at 0.48 μm wave length (λ) in the visible region. About 6.4 percent of total energy is contained in Ultra Violet (UV) region ($\lambda < 0.38\,\mu m$), another 48 percent is contained in the visible region ($0.38\ \mu m < \lambda < 0.78\,\mu m$) and the remaining 45.6 percent is contained in the Infrared region ($\lambda > 0.78\,\mu m$).

✓ The solar irradiance from the black body, in the present case either Sun or Earth, as a function of wavelength (μm) can be governed by Planck's Law of Radiation given by,

$$E_{\lambda b} = \frac{C_1}{\lambda^5 \left[\exp\{C_2/(\lambda T)\} - 1\right]} \qquad \ldots (4.3)$$

Where, $E_{\lambda b}$ represents the energy emitted per unit area per unit time per unit wavelength (μ m) interval at a given temperature, $C_1 = 3.742 \times 10^8$ W-$\mu m^4/m^2$ (or $3.7405 \times 10^{-16}\ m^2$ W) and $C_2 = 14387.9\ \mu m.K$ (0.0143879 mK).

✓ The variation of $E_{\lambda b}$ with wavelength in μm is shown in Fig.4.4. It is clear that from Fig.4.4(a) and Fig.4.4(b), that the wavelength of solar radiation emitted from the Sun at about 6000K and from the earth at 288K (15^o C) lies in the range of short wavelength and long wavelength range respectively as studied earlier. The comparison of these radiation from the Sun and Earth is shown in Fig.4.41(c).

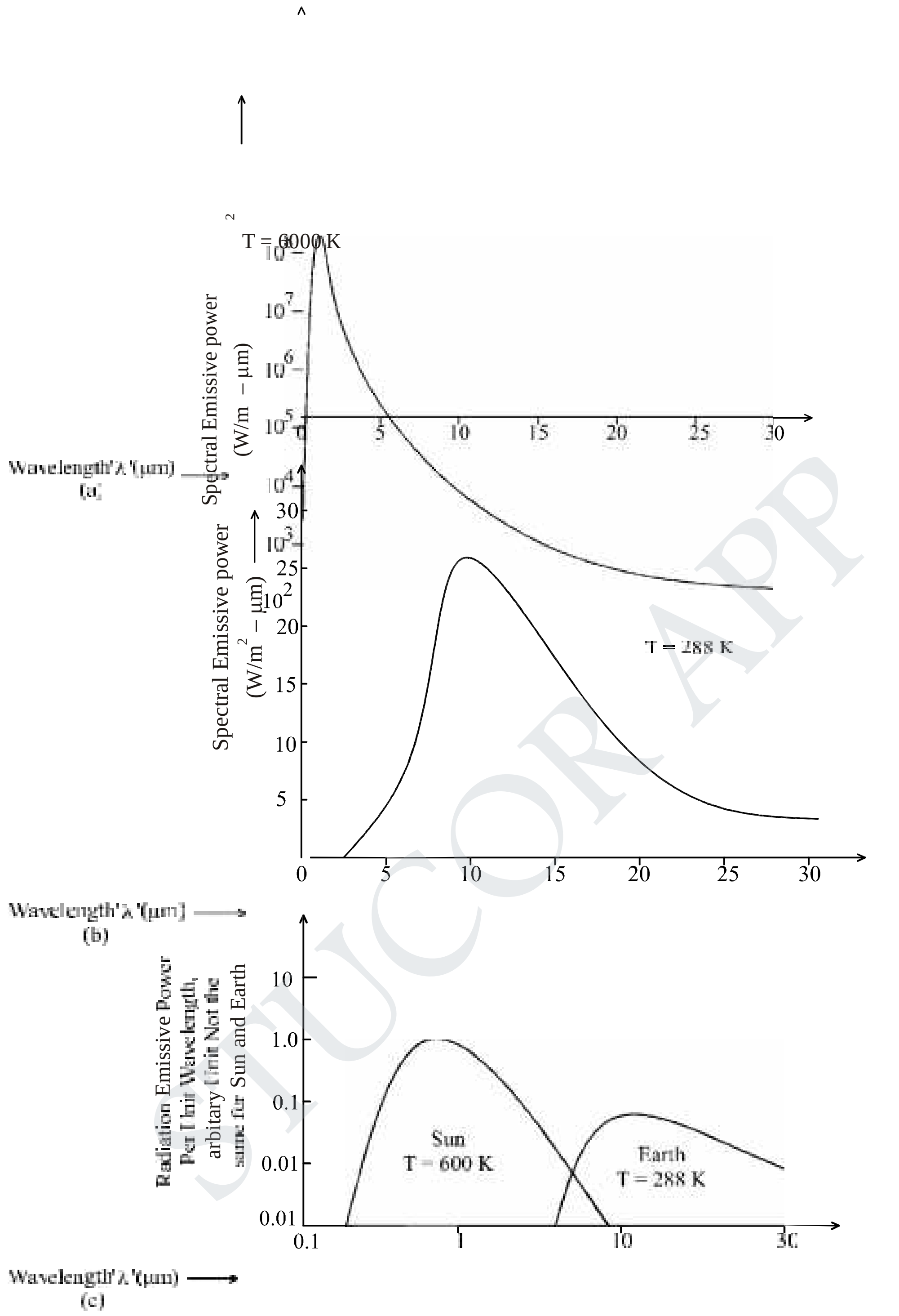


Fig. 4.4 Effect of temperature of block body on emissive power (a) T = 6000 K, (b) T = 288 K and (c) Comparision of Radiation from the Sun and Earth

✓ The total emitted radiation from zero to any wavelength λ, from the Sun can be obtained from the equation given below,

$$E_{0-\lambda,b} = \int_0^\lambda E_{\lambda b}\, d\lambda \qquad \text{... (4.4)}$$

✓ If the above equation is divided by σT^4 (where $\sigma = 5.67 \times 10^{-8}$ W/m^2. K^4), then integral can be made to be only a function of λT as follows,

✓ According to Wein's Displacement Law, the wavelength corresponding to the maximum of solar irradiance from the Sun can be obtained.

$$\lambda_{max} . T = 2897.6\ \mu m.K \qquad \text{... (4.6)}$$

✓ The solar radiation just outside the earth's is known as extra terrestrial solar radiation.

✓ The two important solar radiation terms are,

(1) Irradiance (or) solar constant:

It refers to the rate of energy received by a surface per unit area; essentially it is nothing but the flux of solar energy . It's unit is J/m^2–s (or) W/m^2.

(2) Irradiation or Insolation:

It is the amount of energy received by a surface over a given period of time. Thus it is the integrated irradiance over a time. Its unit is W–hr/m^2 per hour (or) per day (or) per month.

4.2 SOLAR CONSTANT

✓ Considering the Sun's temperature of 5760K, the total power emitted by thye Sun is about 3.8×10^{30} W (or) 6.25×10^{11} W/m^2. Because of large distance betweeen the Sun and the earth, the amount of solar radiation that reaches just outside the earths atmosphere is quite low.

✓ And also orientation of the earth's orbit around the Sun is such that the sun-earth distances vazries only by 1.7 percent and since the solar radiation outside the earth's atmosphere is nearly of fixed intensities, the radiant energy flux received per second by a surface of unit area held normal to the direction of sun's rays at the mean earth-Sun distance, outside the atmosphere, is practicallyconstant throughout the year. This is termed as the Solar Constant I_{sc} and its value is now adopted to be 1367W/m^2. It is measured at the surface perpendicular to the sunrays at the average sun-earth distance on the top of the atmosphere. Due to the variation in the Sun - earth distance over the years the actual radiation reaching the earth's atmosphere varies through out the year. Variation in the solar radiation is also caused by the difference in the emission intensity from the sun itself. The extra - teriestrial solar radiation increases to about 1367 W/m^2. The solar constant used for calculation is only the average values of extra -terrestrial solar radiation over a year. However, this extraterrestrial radiation suffers variation due to the fact that the earth revolves around the Sun not in a circular orbit but follows an elliptic path, with Sun at one of the foci. The indensity of extraterrestrial radiation I_{ext} measured on a plane normal to the radiation on the nth day of the year is given in terms of solar constant (I_{sc}) as follows,

$$I_{ext} = I_{sc}\left[1 + 0.033\cos\left(\frac{360n}{365}\right)\right] \quad \text{... (4.7)}$$

✓ The variation of extraterrestrial radiation with n^{th} day of the year is shown in Fig.4.5.

✓ Since, the cosine function varies from +1 to –1, the extraterrestrial radiation flux varies by ± 3.3 percent over a year.

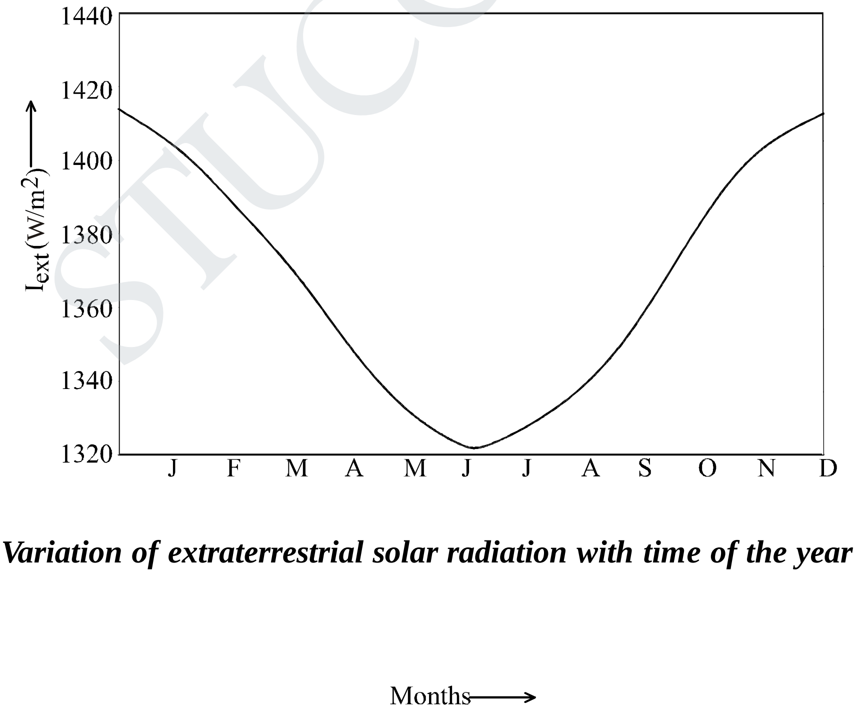


Fig. 4.5 Variation of extraterrestrial solar radiation with time of the year

Proplem :

Calculate the value of extraterrestrial radiation for the day given below. (i) For December 21,1995 and

(ii) For June 22, 1996.

Solution:

(i) For December 21, 1995

Day Number (n) = 355

$$\text{W.K.T,}\quad I_{ext} = I_{sc}\left[1 + 0.033\cos\left(\frac{360n}{365}\right)\right]$$

$$= 1367\left[1+0.033\cos\left(\frac{360\times355}{365}\right)\right]$$

$= 1411$ W/m^2

(ii) For June 22,1996

Year 1996–Leap year

Day Number (n) = 174

$$I_{ext} = 1367\left[1+0.033\cos\left(\frac{360\times174}{365}\right)\right]$$

$= 1322$ W/m^2

4.3 SOLAR RADIATION AT THE EARTH'S SURFACE

✓ Solar radiations while passing through the earth's atmosphere are subjected to the mechanism of atmospheric absorption and scattering. A fraction of the radiation reaching the earth's surface is reflected back into the atmosphere and is subjected to these atmospheric phenomenon again, the remainder is abosrbed by the earth's surface. Absorption occurs due to the presence of water vapour and ozone in the atmosphere and other particulate matter. The sattered radiation is redistributed in all directions, some going back into space and some reaching the earth surface.

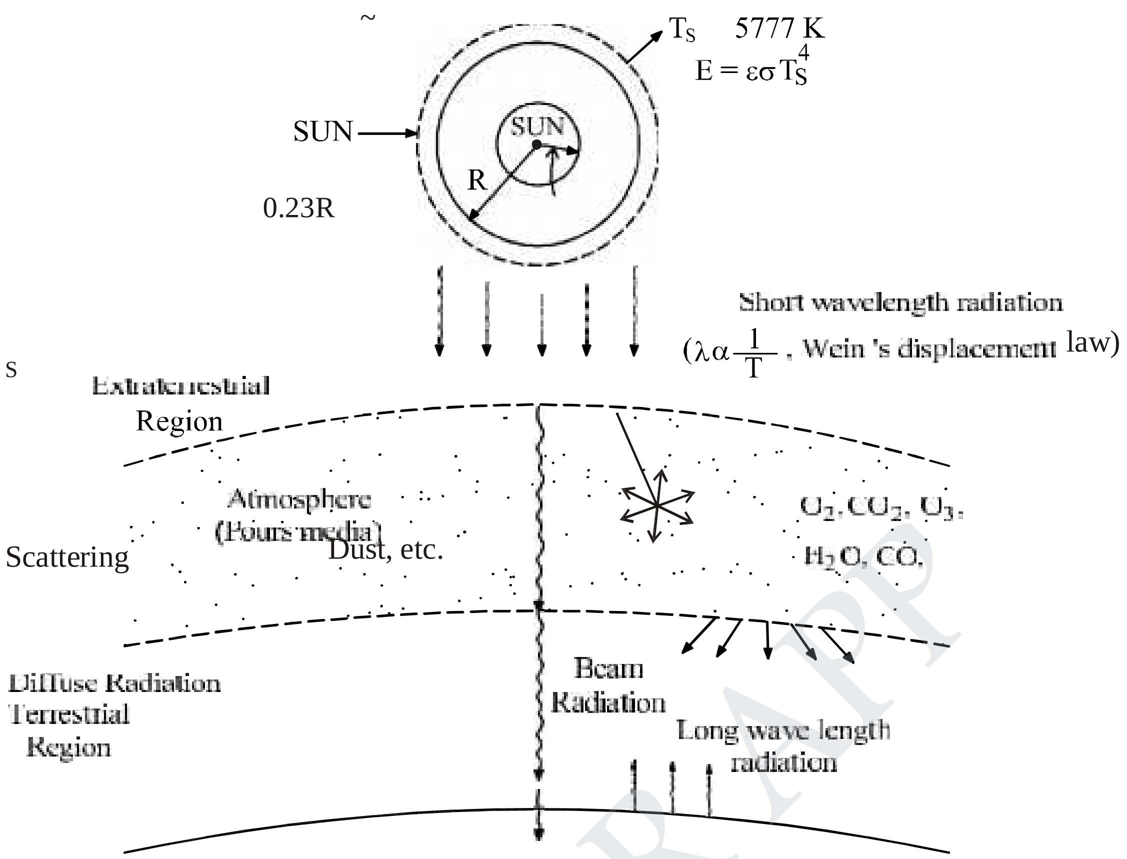


Fig. 4.6 Schematic representation of (i) Mechanisms of absorption and scattering (ii) Beam and diffuse radiation received all earth's surface

✓ Fig. 4.6 shows the position of terrestrial and extraterrestrial regions. The atmosphere abosrption is due to Ozone (O_3), Oxygen (O_2), Nitrogen (N_2), Carbon Disoxide (CO_2), Carbon Monoxide (CO) and Water Vapor (H_2O),and, the scattering is due to Air molecules, Dust and Water Droplets. The X-rays and extreme Ultra-Violet radiations of the Sun are abosrbed highly in the ionosphere by nitrogen, oxygen and other atmospheric gases: ozone and water vapours largely absorb ultraviolet ($\lambda < 0.4\,\mu$ m) and infrared radiations ($\lambda > 2.3$ µm) respectively. There is almost complete absorption of short wave radiations ($\lambda < 0.29$ µm) in the atmosphere. Hence, the energy in wavelength radiation below 0.29 µm and above 2.3 µm of the spectra of the solar radiation, incident on the earth's surface is negligible.

✓ Scattering by air molecules water vapours and dust particles result in the attenuation of radiation. The range of wavelength radiation emitted from the Sun, attenuation of its amplitude during propagation from the Sun to atmosphere and further attenuation of radiation in the atmosphere and also the long wavelength radiation emitted from the earth as shown in Fig. 4.6.

✓ The atmospheric attenuation is characterized by the term called Air Mass (AM or m).It is defined as the ratio of the optical thickness of the atmosphere through which beam radiation passes to the optical thickness if the Sun were at zenith. Large value of air mass indicates that solar radiation travel greater distance in atmosphere. Hence is prone to attenuation. An expression for air mass (Referring to Fig.4.7) is given by,

$$\text{Air Mass } (m) = \frac{AB}{AC} = \sec\phi = \frac{1}{\cos\phi} \quad \text{... (4.8)}$$

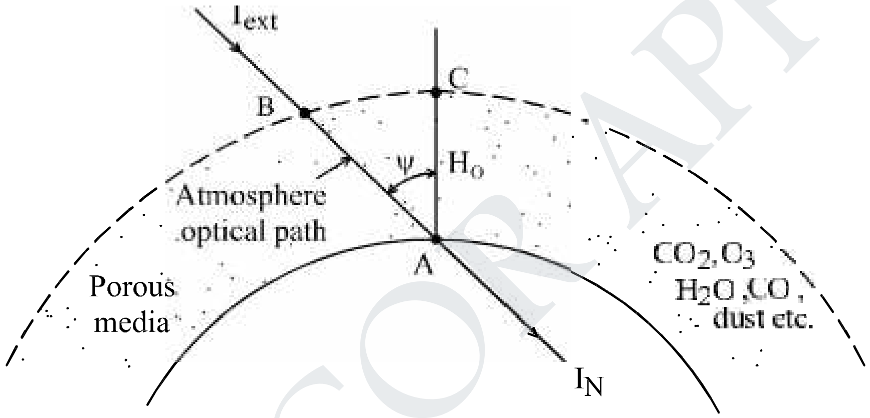


Fig. 4.7 Direction of Sun's ray with respect to atmosphere.

✓ At Noon, φ = 0, m = 1, for φ = 60°, m = 2 and m = 0 for outside earth atmosphere.

✓ Thus, from the view of terrestrial applications of solar energy, only radiation of wavelength between 0.29 and 2.3 μ m is significant.

✓ The solar radiation, through atmosphere reaching the earth's surface can be classified into two components, they are beam and diffuse radiation .

1. Beam Radiation (I_b) : It is the solar radiation propagating along the line joining the receiving surface and Sun. It is also referred to as direct radiation.

2. Diffuse Radiation (I_d) : It is the solar radiation scattered by aerosols, dust and molecules. It does not have unique direction.

✓ The total radiation I is the sum of the beam and diffuse radiation and is some times referred to as the global radiation or insolation.

Some of the terms used in solar energy applications are :

1. Irradiance (W/m^2): The rate at which radiant energy is incident on a surface per unit area of surface.

2. Irradiation (or) Radiant Exposure (J/m^2): The incident energy per unit area on a surface, found by the integration of irradiance over a specified time, usually an hour or a day. Insolation is a term applied specifically to solar energy irradiation. The symbol "H" is used for insolation for a day and "I" for insolation for an hour. Both H and I can represent beam, diffuse or total and can be on surfaces of any orientation.

3. Radiosity (or) Radiant exitance (W/m^2): The rate at which radiant energy leaves a surface per unit area, by combined emission, reflection and transmission.

4. Emissive power (or) Radiated self-exitance (W/m^2): The rate at which radiant energy leaves a surface per unit area, by emission only.

5. Albedo: The earth reflects about 30 percent of all the incoming solar radiation back to extra terrestrial region through atmosphere.

4.3.1 INSTRUMENTS FOR MEASURING SOLAR RADIATIONS AND SUNSHINE

✓ Solar radiation flux is usually measured with the help of a pyranometer or a pyrehelimeter and sunshine hours is measured by means of Sunshine Recorder.

Pyranometer

✓ A pyranometer is an instrument which measures either global or diffuse radiation falling on a horizontal surface over a hemispherical field of view. It consists of a black surface which heats up when exposed to solar radiation. Its temperature increases until the rate of heat gain by solar radiation equals the rate of heat loss by convection, conduction and reradiation. The hot junction of a thermopile are attached to the black surface, while the cold junctions are located under a guard plate so that they do not receive the radiation directly.

✓ The pyranometer shown in Fig. 4.8 is used commonly in India.

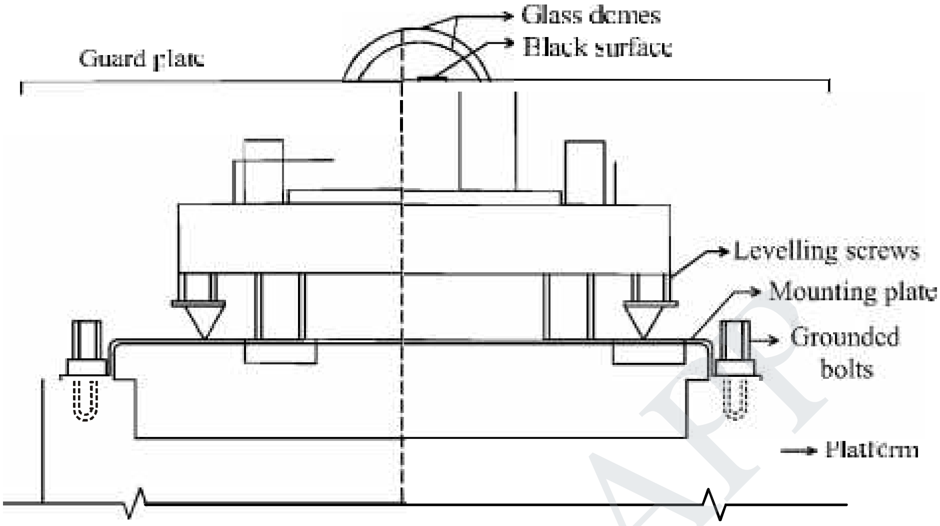
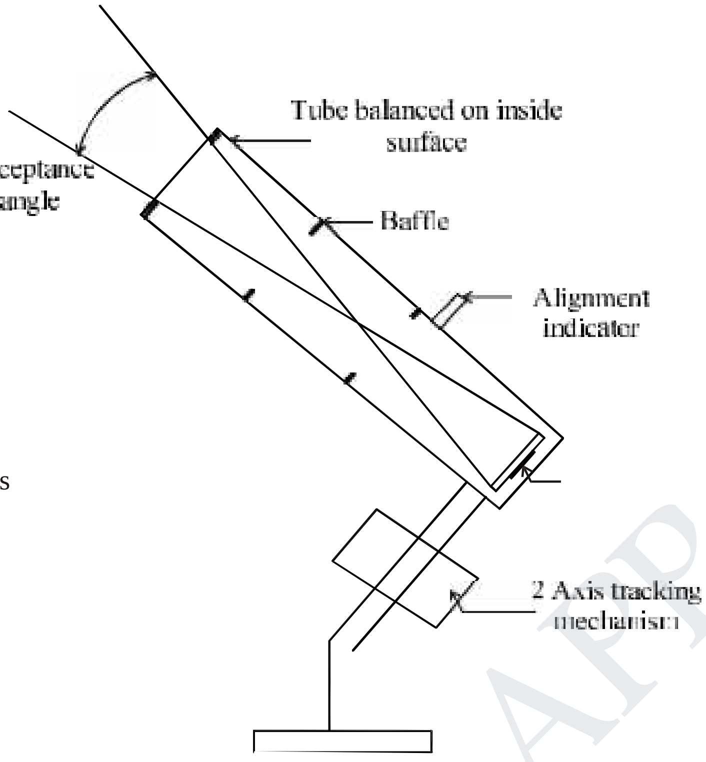


Fig. 4.8 Pyranometer for measuring global radiation

✓ Two concentric hemispheres 30 and 50 mm in diameter respectively, made of optical glass having excellent transmission characteristics are used to protect the disc surface from the weather. The device is used for the measurement of diffuse radiation. This is done by mounting it at the centre of a semi conductor shading ring. It is fixed in such a way that its plane is parallel to the plane of the path of the Sun's daily movement across the sky and it shades the thermopile element and the two glass domes of the pyranometer at all times from direct sunshine.

Pyrheliometer

Pyreheliometer is an instrument which measures beam, radiation falling on a surface normal to the Sun's rays. In contrast to a pyranometer the black absorber plate is located at the base of a collimating tube shown in Fig.4.9. The tube is aligned with the direction of the Sun's rays with the help of a two-axis tracking mechanism and an alignment indicator. Thus, the black plate receives only beam radiation and a small amount of diffuse radiation falling within the 'acceptance angle' of the instrument.



Thermopile junctions

Fig. 4.9 Pyrheliometer for measuring Beam Radiation

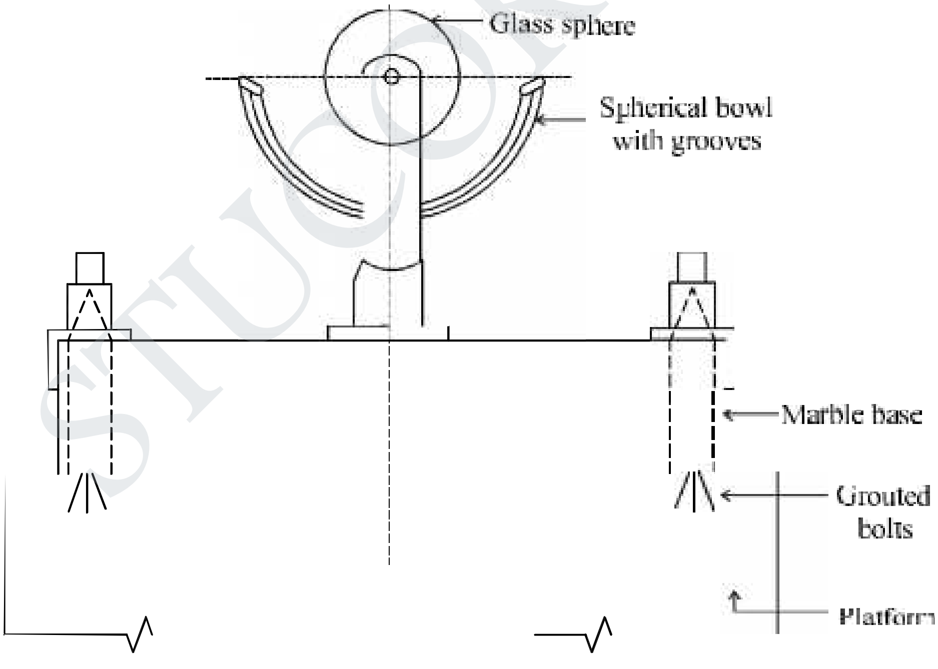


Fig. 4.10 Sunshine Recorder

Sunshine Recorder

The duration of bright sunshine in a day is measured by means of a sunshine recorder shown in Fig. 4.10. The Sun's rays are focussed by a glass sphere to a point on a card strip held in a groove in a spherical bowl mounted concentrically with the sphere. Whenever there is bright sunshine, the image formed is intense enough to brun a spot on the card strip. Through the day as the Sun moves across the sky, the image moves along the strip. Thus, a burnt trace whose length is propotional to the duration of sunshine is obtained on the strip.

4.4 SOLAR RADIATION GEOMETRY

✓ In order to find the beam energy falling on a surface having any orientation, it is necessary to convert the value of the beam flux coming from the direction of the Sun to an equivalent value corresponding to the normal direction to the surface.

✓ If 'θ' is the angle between an incident beam of flux 'I_{bn}' and the normal to a plane surface, then the equivalent flux falling normal to the surface is given by $I_{bn} \cos\theta$. The angle 'θ' can be related by a genertal equation to 'ϕ' latitude, 'β' the slope 'γ' the surface azimuth angle, 'δ' the declination and 'ω' the hour angle.

✓ The Latitude 'ϕ' of a location is the angle made by the radial line joining the location to the centre of the earth with the projection of the line on the equatorial plane. It varies from -90^o to $+90^o$. By convention, the latitude is measured as positive for the northern hemisphere.

✓ The Slope 'β' is the angle made by the plane surface with the horizontal. It varies from 0 to 180^o.

✓ The Surface Azimuth Angle 'γ' is the angle made in the horizontal plane between the horizontal line due south and the projection of the normal to the surface on the horizontal plane. It varies from -180^o to $+180^o$.

✓ We adopt the convention that the angle is Positive, if the normal is East of South and Negative if West of South.

✓ The Declination 'δ' is the angle made by the line joining the centres of the Sun and the Earth with the projection of this line on the equatorial plane.

$$\delta \text{ (in degrees)} = 23.45 \sin\left[\frac{360}{365}(284+n)\right] \quad \ldots (4.9)$$

where, n is the day of the year (or Day Number).

✓ The hour angle 'ω' is an angular measure of time. It varies from -90^o to $+90^o$.

✓ It is the angle through which the earth must be rotated to bring the meridian of plane directly under the Sun. In other words, it is the angular displacement of Sun east and west of the local meridian, due to the rotation of the earth on its axis 15^o per hour. The hour angle is zero at Solar Noon, negative in the morning and positive in the afternoon (Table 4.2) for northern hemisphere and vice-versa for southern hemisphere. Expression for hour angle is given by $\omega = (ST - 12)\, 15^o$.

Table 4.2 The value of hour angle (ω) with time of the day (For Northern Hemisphere)

Time of the day (Hours)	6	7	8	9	10	11	12	13	14	15	16	17	18
Hour angle ω in deg	–90	–75	–60	–45	–30	–15	0	+15	+30	+45	+60	+75	+90

✓ It can be shown that

$\cos\theta = \sin\phi\,(\sin\delta\,\cos\beta + \cos\delta\,\cos\gamma\,\cos\omega\,\sin\beta)$

$+ \cos\phi\,(\cos\delta\,\cos\omega\,\cos\beta - \sin\delta\,\cos\gamma\,\sin\beta)$

$+ \cos\delta\,\sin\omega\,\sin\beta\,\sin\gamma$ ... (4.10)

✓ Some special cases of Equ.(4.10) are follows

(i) For Vertical surface $\beta = 90^o$,

$\therefore \cos\theta = \sin\phi\,\cos\delta\,\cos\omega\,\cos\gamma - \cos\phi\,\sin\delta\,\cos\gamma + \cos\delta\,\sin\gamma\,\sin\omega$ ... (4.11)

(ii) For Horizontal surface $\beta = 0^o$ [Sun's Altitude Angle (α)],

$\sin\alpha = \cos\theta_z = \sin\phi\,\sin\delta + \cos\phi\,\cos\delta\,\cos\omega$ ... (4.12)

✓ The angle 'θ' in this case is the zenith angle θ_z. It is also called as the solar altitude.

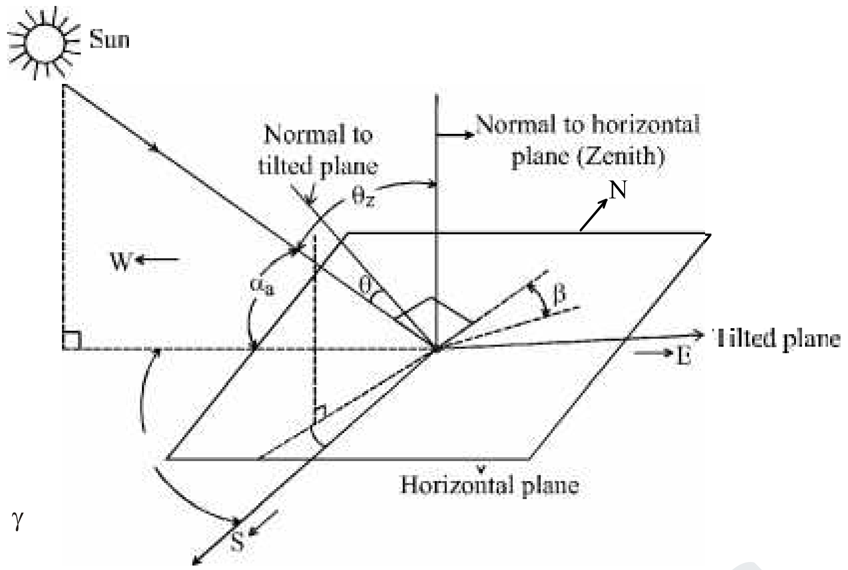


Fig. 4.11 Diagram illustrating the angle of incidance 'θ', the zenith angle 'θ_z', the solar altitude angle 'α_a', the slope 'β', the surface azimuth angle 'γ' and the solar azimuth angle 'γ_s'.

(iii) For Inclined surface facing due south, $\gamma = 0^\circ$

$\cos\theta = \sin\phi\ (\sin\delta\ \cos\beta\ + \cos\delta\ \cos\omega\ \sin\beta\ )$

$+ \cos\phi\ (\cos\delta\ \cos\omega\ \cos\beta\ - \sin\delta\ \sin\beta\ )$

$= \sin\delta\ \sin(\phi - \beta) + \cos\delta\ \cos\omega\ \cos(\phi - \beta)$ ... (4.13) (iv) For

Vertical surface facing due south, $\beta = 90^o$ and $\gamma = 0^o$.

$\cos\theta = \sin\phi\ \cos\delta\ \cos\omega - \cos\phi \sin\delta$ ... (4.14) (v)

For Inclined surface facing due worth $\gamma = 180^o$,

$\cos\theta = \sin\delta\ \sin(\phi + \beta) + \cos\delta\ \cos\omega\ \cos(\phi + \beta)$ ... (4.15)

"Braun" and "Mitchell" have shown that the angle if incidence 'θ' can also be expressed interms of 'θ_z', the zenith angle, β the slope, γ the surface azimuth angle, and γ_s the solar azimuth angle given by,

$\cos\theta = \cos\theta_z \cos\beta + \sin\theta_z \sin\beta\ \cos(\gamma_s - \gamma)$ ... (4.16)

✓ The solar azimuth angle γ_s is the angle made is the horizontal plane between the horizontal line due south and the projection of the line of sight of the Sun on the horizontal plane.

$\cos\gamma_s = (\cos\theta_z\ \sin\phi\ - \sin\delta)/ \sin\theta_z \cos\phi$ ... (4.17)

4.5.1 Apparent Motion of the Sun

✓ To an observer on the earth, on any given day, the Sun rises in the east, moves in a plane tilted at an angle of $(90^o - \phi)$ with the horizontal, and finally sets in the west. Thus the apparent plane in which the Sun moves intersects the horizontal plane in a line pointing east to west.

Sun rise, Sun set and day length:

(i) Horizontal surface :

✓ The angle hour corresponding to Sunrise or Sunset on a horizontal surface,

$$\cos\omega_s = -\tan\phi\tan\delta$$

$$\omega_s = \cos^{-1}(-\tan\phi\tan\delta) \quad \text{... (4.18)}$$

Equ. (4.18) yields a positive and negative value of 'ω_s', the positive value corresponding to Sun rise and the negative value corresponds to Sunset. Since 15^o of the hour angle is equivalent to 1 hour, the corresponding day length (in hours) is given by,

$$S_{max} = \frac{2}{15}\omega_s = \frac{2}{15}\cos(-\tan\phi \;\text{an}\; \delta) \quad \text{... (4.19)}$$

Where, ω_s is in degrees.

(ii) Inclined surface facing due south:

✓ The hour angle at sunrise or sunset as seen by an observer on as inclined surface facing south. Substituting, $\gamma = 0^o$, we get,

$$\cos\theta = \sin\phi\,(\sin\delta\cos\beta + \cos\delta\cos\omega\sin\beta)$$

$$+ \cos\phi\,(\cos\delta\cos\omega\cos\beta - \sin\delta\sin\beta)$$

$$= \sin\delta\sin(\phi-\beta) + \cos\delta\cos\omega\cos(\phi-\beta)$$

sub, $\theta = 90^o$ in Equ. (4.20) we get, ... (4.20)

$$\omega_{st} = \cos^{-1}\left[-\tan(\phi-\beta)\tan\delta\right] \quad \text{... (4.21)}$$

Thus the magnitude of ω_{st} for an inclined surface facing south $(\gamma = 0)$ is given by,

$$\therefore |\omega_{st}| = \min\left[\left|\cos^{-1}(-\tan\phi\tan\delta)\right|\right] \quad \text{... (4.22)}$$

(iii) Inclined surface facing due north:

Proceeding in the same manner as for an inclined surface facing due south,

$$|\omega_{st}| = \min\left[\left|\cos^{-1}(-\tan\phi\tan\delta)\right|, \left|\cos^{-1}\{-\tan(\phi+\beta)\tan\delta\}\right|\right] \text{... (4.23)}$$

4.5.2 Local Apparent Time (LAT)

✓ The time used for calculating the hour angle 'ω' is the Local Apparent Time. This can be obtained from the standard time observed on a clock by applying two corrections. The first correction arises because of the difference between the longtitude of a location and the meridian on which the standard time is based. The second correction is called the equation of time correction. Thus,

Local Apparent Time = Standard Time ± 4 (Standard Time Longtitude - Longitude of location) + (Equation of time correction).

✓ – ve sign is the first correction applicable for eastern hemisphere while the +ve sign is applicable for western hemisphere.

✓ The equation of time correction is E is given by,

$$E = 229.18\,(0.000075 + 0.001868\cos B - 0.032077\sin B - 0.014615\cos 2B - 0.04089\sin 2B) \quad \dots (4.24)$$

Where, $B = (n - 1)\,360/365$ ... (4.25)

n = Day of the year (or) Day Number.

4.7 SOLAR RADIATION DATA

✓ Most radiation data is measured for horizontal surfaces. A fair, smooth variation with the maximum occuring around noon is obtained on a clear day. In contrast, an irregular variation with many peaks and valley may be obtained on a cloudy day.

✓ Since solar radiation fluxes do not normally change rapidly with time, I_g and I_d represents hourly values also. These quantities are expressed in kWh/m^2 – h or kJ/m^2 – h. H_g and H_d represents global and diffuse flux respectively are shown in Fig.4.12.

✓ Solar radiation flux is sometimes reported in longleys per hour or per day (1 longley = 1 cal/m^2 = 1.163 × 10^{-2} kWh/m^2). The unit 'langley' has been adopted in honour of **Samuel Langley** who made the first measurement of the spectral distribution of the Sun.

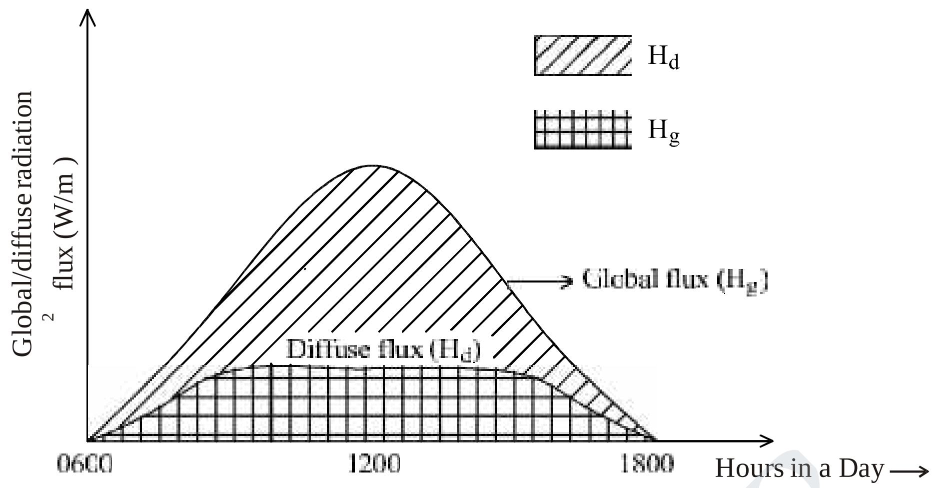


Fig. 4.12 Record of Global and Diffuse radiation flux measured on a clear day

✓ The maximum values measured over the whole country are about 300 langleys per day in Gujarat on July, while minimum values, between 75 and 100 langely per day, are measured over many parts of country during November and December as winter sets in.

4.7.1 Estimating Solar Radiation Empirically

✓ In order to calculate the amount of solar radiation falling on a collector at a given time and location the direct or beam radiation and diffuse radiation should be either measured or estimated using empirical equations.

Monthly average daily global radiation on horizontal surface

✓ The monthly average daily global radiation on a horizontal surface H_{ga} is given by the following equations.:

$$\left(\frac{H_{ga}}{H_{oa}}\right) = a + b\left(\frac{S_a}{S_{max\,a}}\right) \quad \text{... (4.26)}$$

Where,

H_{oa} → Monthly average extra - terrestrial solar radiation at horizontal surface

S_a, $S_{max\,a}$ → Monthly average daily sunshine hours and maximum possible daily sunshine hours at a given location.

a, b → Constants obtained by fitting data.

✓ Integration of extra - terrestrial radiation over a day will give the daily value of extra - teriestrial solar radiation. H_0 is given by,

$$H_0 = S_t \int \cos\theta \, dt$$

=

$$dt = \frac{180}{15\pi} d\omega$$

ie,
$$H_0 = \frac{24}{\pi} S \left(1 + 0.033\cos\frac{360n}{365}\right)\left(\omega_s \sin\phi \sin\delta + \cos\phi\cos\delta\sin\omega_s\right) \quad \ldots (4.27)$$

If 'S' is in W/m², 'H'$_0$ will be in W–h/m².

✓ Equ. (4.26), from which the monthly average solar radiation for a given location, if the data on sunshine hours are available and the constants for the location of nearby location, with similar climate are known.

Monthly average daily diffuse radiation on horizontal surface

✓ Estimate of the monthly average daily diffuse radiation on the horizontal surface, (H_{da}), can be obtained using the following relationships.

For $\omega_s \le 81.4$ and $0.3 \le K_T \le 0.8$

$$\frac{H_{da}}{H_{ga}} = 1.391 - 3.560\,K_T + 4.189\,K_T^2 - 2.137\,K_T^3 \quad \ldots (4.28)$$

For $\omega_s > 81.4^o$ and $0.3 \le K_T \le 0.8$

$$\frac{H_{da}}{H_{ga}} = 1.311 - 3.022\,K_T + 3.427\,K_T^2 - 1.821\,K_T^3 \quad \ldots (4.29)$$

Where, $\omega_s \rightarrow$ Sunrise hour angle

$K_T \rightarrow$ Sky monthly average clearness index.

✓ Thus, if clearness index of a location and its monthly average daily global radiation on horizontal surface is known, the monthly average daily diffuse radiation on the horizontal surface for a given location can be estimated. And also we can express equation interms of cleaness Index and sunshine ratio,

$$\frac{H_d}{H_g} = 0.87813 - 0.33280\,\bar{K}_T - 0.53030\left(\frac{\bar{S}}{S_{max}}\right) \quad \ldots (4.30)$$

[Empirial relation for estimating the difuse to global radiation on ratio]

Monthly Average Hourly Global and Diffuse Ratiation on Horizontal Surface.

✓ Estimate of the global hourly radiation Ig from global daily radiation data on a horizontal surface can be obtained using the following relationship,

$$I_g = r_t \times H_g \qquad \ldots (4.31)$$

$$a = \sin(\omega_s - 60) \times 0.5016 + 0.409$$

$$b = \sin(\omega_s - 60) \times 0.4767 + 0.660$$

✓ Similar the diffuse radiation can be written as,

$$I_d = r_d \times H_d \qquad \ldots (4.33)$$

$$r_d = \frac{\pi}{24}\left(\frac{\cos\omega - \cos\omega_s}{\sin\omega_s - \frac{\pi\omega_s}{180}\cos\omega_s}\right) \qquad \ldots (4.34)$$

where, r_d is defined at each hour of the day.

Solar Radiation on Tilted Surface

Many of the solar radiation measuring instruments also measure the radiation on horizontal surface. The radiation falling on tilted surface will be the sum of direct radiation and reflected radiation or albedo. These can be estimated as follows:

Direct Radiation :

The ratio of direct solar radiation falling on tilted surface to that falling on a horizontal surface is called the tilt factor r_b for the beam or direct radiation. The r_b for the collector surface facing south $(\gamma = 0^o)$ will be given as:

$$r_b = \frac{\cos\theta}{\cos\theta_z} = \frac{\sin\delta\sin(\phi-\beta) + \cos\delta\cos(\phi-\beta)\cos\omega}{\sin\delta\sin\phi + \cos\phi\cos\omega\cos\delta} \qquad \ldots (4.35)$$

Similarly, the r_b can be written for a situation where the collection is not facing the south direction, ie $\gamma \neq 0^o$. The beam radiation falling on a tilted surface will be given by $I_b \times r_b$, where, I_b is the instantaneous value of beam radiation.

Diffuse Radiation:

Similar to the tilt factor for the direct radiation tilt factor for the diffuse radiation r_d is defined as the ratio of the radiation flux falling on the horizontal surface. If the sky is considered as isotropic source of diffuse radiation, the r_d can be written as

$$r_d = \frac{1+\cos\beta}{2} \quad \text{... (4.36)}$$

The diffuse radiation falling on tilted surface will be given by $I_d r_d$, where, I_d is the instantaneous value of diffuse radiation.

Reflected Radiation

The reflected radiation from the ground and surrounding area can also reach the collector with tilted surface. The tilt factor for the reflected radiation r_d is given by

$$r_r = \rho\left(\frac{1-\cos\beta}{2}\right) \quad \text{... (4.37)}$$

Where, $\rho \rightarrow$ reflectivity of the surrounding in which the collector is located.

Total Radiation on Tilted Surface:

The total radiation on tiled surface of the collector will be the sum of direct, diffuse and reflected radiation. It will be given by

$$I_T = I_b r_b + I_d r_d + (I_b + r_b) I_r \quad \text{... (4.38 a)}$$

Where I_b, I_d, I_r are the instantaneous values of beam diffuse, direct and reflected radiations respectively.

The above equation is used to calculate the total hourly radiation falling on tilted surface, if the value of the hour angle ω is taken at the midpoint of the hour.

One difficulty associated with using equation (4.38 b) is that the value of the diffuse reflectivity ρ is not known for most situations. A value around 0.2 generally expected with surfaces of concrete or grass, can be used. Fortunately, the reflected radiation term does not very often contribute much to the total.

Equation (4.38a) can be used for calculating the hourly radiation falling on a tilted surface, if the value 'ω' is taken at the mid-point of the hour. It is also be used for calculating the monthly average hourly value ($\bar{I}_T$), if the calculations are done for the representative day of the month specified.

Equ. (4.38 a) is then used in the modified form,

$$\left(\frac{\bar{I}_T}{\bar{I}_g}\right) = \left(1 - \frac{\bar{I}_d}{\bar{I}_g}\right)\bar{r}_b + \frac{\bar{I}_d}{\bar{I}_g}\bar{r}_d + \bar{r}_r \qquad \text{... (4.38 b)}$$

where, $\bar{r}_b = r_b$ – on the representative day,

$\bar{r}_d = r_d$

$\bar{r}_r = r_r$

The daily radiation falling on a tilled surface is also of interest in many applications, **"Liu and Jordan"** have proposed that the ratio of the daily radiation falling on such a surface (H_T) to the daily global radiation on a horizontal surface (H_g) is given by an equation having a form similar to Equ. (4.38 a). Thus

$$\frac{H_T}{H_g} = \left(1 - \frac{H_d}{H_g}\right)R_b + \frac{H_d}{H_g}R_d + R_r \qquad \text{... (4.38 c)}$$

For south-facing surface $(\gamma = 0^o)$, "Liu and Jordan"

$$R_b = r_b = \frac{\sin\delta\sin(\phi-\beta) + \cos\delta\sin\omega\cos(\phi-\beta)}{\sin\phi\sin\delta + \cos\phi\cos\delta\sin\omega} \qquad \text{... (4.38 d)}$$

$$R_d = r_d = (1 + \cos\beta)/2 \qquad \text{... (4.38 e)}$$

$$R_r = r_r = \rho(1 - \cos\beta)/2 \qquad \text{... (4.38 f)}$$

where,

β = S = Tilt angle in degree

Equ. (4.38 c) can also used for calculating the monthly average daily radiation falling on a titled surface, if the values required are calculated for representative day of the month Equ. (4.38 c) is the used in the modified form

$$\left(\frac{\bar{H}_T}{\bar{H}_g}\right) = \left(1 - \frac{\bar{H}_d}{\bar{H}_g}\right)\bar{R}_b + \frac{\bar{H}_d}{\bar{H}_g}\bar{R}_d + \bar{R}_r$$

where, $\bar{R}_b = R_b$ on the representative day

$\bar{R}_d = R_d$

$\bar{R}_r = R_r$

Case (i):

Declination angle (δ) = 23.45 sin $\left[\frac{360}{365}(284+n)\right]$

$$= 23.45 \sin\left[\frac{360}{365}(284+121)\right]$$

$$= 14.90^o$$

For due South, $\gamma = 0$, from Equ. (4.13)

$\cos\theta = \sin\delta \sin(\phi-\beta) + \cos\delta \cos\omega \cos(\phi-\beta)$

$= \sin 14.90^o \sin(28.50^o - 36^o) + \cos 14.90^o \cos 45^o \cos(28.58^o - 36^o)$

$= 0.6444$

$$\theta = \cos^{-1}(0.6444) = 49.90^o$$

Case (ii)

W.K.T, Declination angle (δ) = 14.90^o

and, $\cos\theta = \sin\delta \sin(\phi - \beta) + \cos\delta \cos\omega \cos(\phi - \beta)$

$= \sin 14.90^o \sin(28.58^o) + \cos 14.90 \cos 0^o \cos(28.58^o - 36^o)$

$= 0.9251$

$\theta = \cos^{-1}(0.9251) = 22.3^o$

Problem

Calculate the hour angle at surise and sunset on June 21 and December 21 for a surface inclined at an angle of 10^o and facing due south. The surface is located in mumbai (19^o 07', 72^o 51' E).

Given:

Case (i) For June 21, Number of days (n) = 173.

Case (ii) For Dec 21, Number of fdays (n) = 355.

For due south $\gamma = 0^o$

Lattitude angle (ϕ) = 19.07^o

Inclination Angle (β) = 10^o

Solution:

Case (i)

Declination angle $(\delta) = 23.45 \sin\left[\frac{360}{365}(284+n)\right]$

$$= 23.45 \sin\left[\frac{360}{365}(284+173)\right]$$

$$= 23.45^o$$

Sunset or Sun rise time,

$$\omega_{st} = \text{Min}\left\{ \left|\cos^{-1}(-\tan\phi\tan\delta)\right|, \left|\cos^{-1}\{-\tan(\phi-\beta)\tan\delta\}\right| \right\}$$

$$= \text{Min}\left\{ \cos^{-1}(-\tan 19.07^o \tan 23.45), \cos^{-1}(-\tan[19.07^o - 10^o]\tan 23.45^o \right\}$$

$$= \text{Min}\,[98.6^o, 94.0^o]$$

$$= 94.0^o$$

$$\omega_{st} = \pm 94.0^o$$

Case(ii)

Declination angle $(\delta) = 23.45 \sin\left[\frac{360}{365}(284+n)\right]$

$$= 23.45 \sin\left[\frac{360}{365}(284+355)\right]$$

$$= -23.45^o$$

Sunset or Sun rise time

$$(\omega_{st}) = \text{Min}\left\{ \cos^{-1}(-\tan\phi\tan\delta),\ \cos^{-1}(-\tan(\phi-\beta)\tan\delta \right\}$$

$$= \text{Min}\left\{ \cos^{-1}(-\tan 19.12^\circ \tan(-2345^\circ)),\right.$$

$$\left.\cos^{-1}(-\tan(19.12-10^\circ)\tan(-23.45^\circ)\right\}$$

$$= \text{Min}\,(81.4^\circ, 86.0^\circ)$$

$$= 81.4^\circ$$

Problem

$$\omega_{st} = \pm 81.4^\circ$$

Problem

Determine the Local Apparent Time (LAT) corresponding to 1430h (IST) at Mumbai (19° 07' N, 72° 51' E) on July 1. In India standard time is based on 2.50° E.

Given:

Std. Time = 1430 *h*

Std. Time Longitude = 82.50°

Longitude of Location = 72.51° Day :

July 1

Solution:

For July 1, Number of days = 182

Equation of Time correction = 229.18 (0.000075+ 0.001868 cos B - 0.032077 sin B – 0.014615 cos 2B – 0.04089 sin 2 B)

$$\text{Where, } B = (n-1)\frac{360}{365} = 181 \times \frac{360}{365} = 178.5 \approx 179$$

Equation of Time correction = $229.18\,[0.000075 + -8.90 \times 10^{-4} - 0.02815 + 7.896 \times 10^{-3}$

= –2.9 minutes.

Local Apparent Time = Std. Time ± 4 (Std. Time Longitude - Longitude of Location) + Equation of Time correction

= 1430h – 4(82.50 – 72.85) Minutes + (–2.9) Minutes

= 1430 h – 38.6minutes – 2.9 minutes

= 1348h

4.6 PHYSICAL PRINCIPLES OF THE CONVERSION OF SOLAR RADIATION INTO HEAT

✓ To estimate the size, the efficiency and the cost of equipment necessary to transfer a specified amount of heat in a given time, a heat transfer analysis must be made. The dimensions of a solar collector, a heat exchanger or a refrigerator depend not so much on the amount of heat to be transmitted but rather on the rate at which heat is to be transferred under given external conditions. From an engineering view point, the determination of the rate of heat transfer at a specified temperature difference is the key problem in sizing a solar collector to provide a given temperature in a home or building.

✓ Heat transfer occurs mainly by three mechanisms. The first is by conduction through solid materials in the presence of a temperature difference. The second mechanism is radiation in which energy moves in space by electromagnetic waves. In a moving fluid, the fluid molecules gain heat or lose it by conduction or radiation and carry it by their movement from one place to another. This process, the third mechanism is called convection. The heat transfer may be accompanied by other physical phenomena such as heat generation within the medium, vapour condensation, liquid evaporation etc.

4.6.1 Conduction

The phenomenon of heat conduction is a process of propagation of energy between the particles of a body which are indirect contact and have different temperatures.

The Basic equation for steady state heat conduction is known as Fourier's equation. According to this, the quantity of heat (dQ), passing through an isothermal surface (dA), per time interval (dt) is proportional to the temperature gradient $\left(\frac{\delta T}{\delta n}\right)$ and can mathematically expressed as, $dQ = -K \frac{\delta T}{\delta n} dA\, dt$.

Where, the proportionality factor 'K' is the physical property of the substance, which defines the ability of the substance to conduct heat and is called thermal conductivity.

The heat flux q, defines as the rate of heat flow per unit area of the isothermal surface is given by,

$$q = -K_x A \frac{\delta T}{\delta x} \quad \ldots (4.39)$$

Where,

q → the rate of heat transfer,

K_x → the thermal conductivity of the material in the x - direction, A → the area normal to the direction of heat flow, and

$\frac{\delta T}{\delta x}$ → the temperature gradient in the direction of heat flow.

The direction of heat flux q is normal to the surface and is positive in the direction of decreasing temperature, which explains the negative sign on the right handside of equation.

Table 4.3 The heat transfer rate for different surfaces or configurations

S.No	Configuration	Heat transfer rate
3.	Conduction in extended surfaces (Heat flow in a uniform rectangular fin) 	$q = \frac{\tan hmL}{mL}\left[q_0 - h_a(T_r - T_a)\right]$ where $\frac{\tan hmL}{mL}$ → fin efficiency q_c → heat transfered from fin to atmosphere by convection. q_r → net radiation transfered by conduction through the fin. $m = \frac{h}{k\delta}$, h → convection head transfer co-efficient.

4.6.2 Radiation

✓ Radiation is a process by which heat flows from a body at a higher temperature to a body at a lower temperature when the bodies are separated in space or even a vacuum exists between them. The heat energy transmitted by radiation is called radiant heat.

✓ Radiation is the mode of heat transfer by which the Sun transfer energy to the Earth. The quantity of energy leaving a surface as radiant heat depends on the absolute temperature and the nature of the surface.

✓ A perfect radiator, so called black body emits radiant energy from its surface at a rate 'q' given by,

$$q = A\sigma T^4 \qquad \text{... (4.40)}$$

Where

A → Area of the body (m^2),

T → Absolute temperature (^oK), and

σ → Stefan Boltzmann constant = 56.7×10^{-9} $W/m^2\text{-}k^4$.

✓ Real bodies do not meet the specifications of an ideal radiator and emit radiation at a lower rather than do black bodies. The ratio of the radiation emission of a real body to the radiation emission of a black body at same temperature is called the emittance. Thus a real body emits radiation at a rate,

$$q = \varepsilon A \sigma T^4 \qquad \text{... (4.41)}$$

Where, ε is the average emittance of the surface

✓ For simplicity of linear equation, we define a radiant heat transfer coefficient h_r, which is given by,

$$q = h_r\,(T_1 - T_2) \qquad \dots (4.42)$$

where,

$$h_r = \frac{\sigma(T_1^2 + T_2^2)(T_1 + T_2)}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1} \qquad \dots (4.43)$$

ε_1 & ε_2 → Emittance of two surface.

4.6.3 Reception of radiant energy

✓ Radiation impinging on the surface of a body may be partly absorbed, partly transmitted and partly reflected as shown in Fig. 4.13.

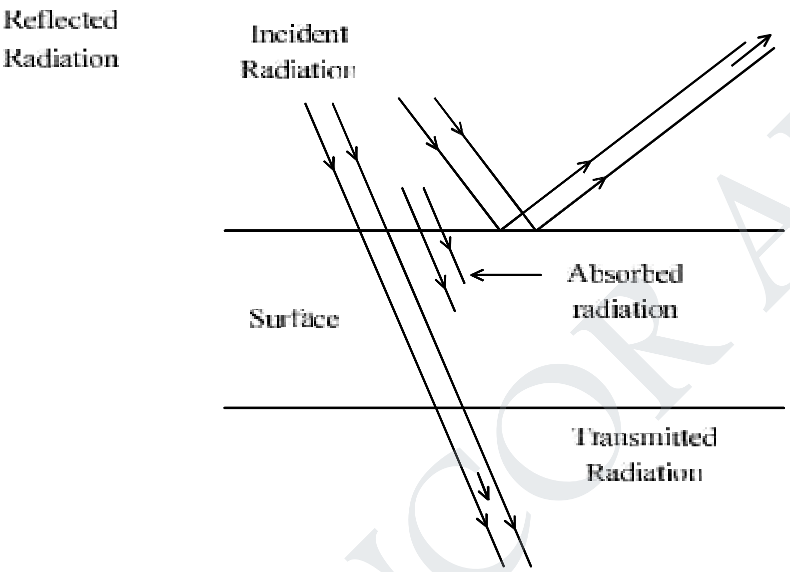


Fig. 4.13 Total radiation utilized in different ways

✓ The fraction of the incident radiation absorbed is called the absorpitivity 'α'. Similarly the fraction of the incident radiation reflected is called the reflectivity 'ρ' and the fraction transmitted is called the transmissivity 'τ'.

✓ If 'I' denotes the total incident radiation per unit time per unit area of a surface, and I_α, I_ρ and I_τ represent respectively the amount of radiation abosrbed, reflected and transmitted, then

$$\left.\begin{aligned}\alpha &= \frac{I_\alpha}{I}\\ \rho &= \frac{I_\rho}{I}\\ \tau &= \frac{I_\tau}{I}\end{aligned}\right\} \quad \ldots (4.44)$$

$$\left.\begin{aligned}\text{also,}\quad & I_\alpha + I_\rho + I_\tau = 1\\ \text{hence,}\quad & \alpha + \rho + \tau = 1\end{aligned}\right\} \quad \ldots (4.45)$$

✓ The relationship given in Equ. (4.45) hold for surfaces or for layer of finite thickness. The following point are to be noted:

(i) The values of α, ρ and τ are always positive and lie between the limits 0 and 1, i.e,

$0 \leq \rho, \tau, \alpha \leq 1$

(ii) $\rho = 0$ (i.e., $\tau + \alpha = 1$), represents of Non-reflecting surface.

$\rho = 1$ (i.e., $\tau = \alpha = 1$), represents a perfect reflector

(iii) (iv) $\tau = 0$ (i,e., $\rho + \alpha = 1$), represents an opaque surface.

$\tau = 1$ (i.e., $\rho = \alpha = 0$), represent a perfectly transparent surface.

$\alpha = 0$ (i.e., $\rho + \tau = 1$) represents a non-absorbing surface (also called the white surface it is diffuse).

$\alpha = 1$ (i.e., $\rho = \tau = 0$) represents a perfectly absorbing surface (also called a black surface it is diffuse).

4.6.4 Convection

✓ Convection is a process that transfer heat from one region to another by motion of a fluid. The rate of heat transfer by convection q_c, between a surface and a fluid can be calculated from the relation

$$q_c = h_c A (T_s - T_f) \quad \ldots (4.46)$$

Where,

$q_c \rightarrow$ Rate of heat transfer by convection (K.cal/hr), A $\rightarrow$ Base area of heat transfer by convection (m^2),

$T_s \rightarrow$ Surface temperature (^{o}C),

$T_f \rightarrow$ Fluid temperature (^{o}C), and

$h_c \rightarrow$ Convection heat transfer co-efficient (K.Cal/hr-m^2 - ^{o}C).

✓ The thermal resistance to connective heat transfer, R_c is given by,

$$R_c = \frac{1}{h_c A} \quad \text{... (4.47)}$$

✓ The usual dimensions groups used for convection studies are;

Nusselt number, $N_u = \frac{hL}{K}$ ... (4.48)

Reynold's number, $R_e = \frac{V.L.\rho}{\mu}$ ... (4.49)

Prandtl number, $P_r = \frac{\mu C_p}{K}$ ... (4.50)

Grashof number, $G_r = \frac{g\beta\Delta T L^2}{\gamma^2}$ ... (4.51)

$$G_r = \frac{g\beta\Delta T L^3 \rho^2}{\mu^2} \quad \text{... (4.52)}$$

Where,

h → Heat transfer coefficient

K → Thermal conductivity

β → Volumetric coefficient of expansion of air

ΔT → Temperature difference between plates

V → Fluid velocity

μ → Dynamic viscosity

C_p → Specific heat

ρ → Fluid density

γ → Kinematic viscosity

L → Plate spacing

✓ Another dimension group is Rayleigh number 'R_a',

$R_a = G_r.P_r$ ... (4.53) These dimensional numbers have following physical properties,

N_u → Non - dimensional heat transfer coefficient.

R_e → Ratio of inertia to viscous forces, used in the description of forced convection, where the fluid has an initial velocity with respect to the heated surface.

P_r → ratio of molecular diffusivities of momentum with respect to heat.

G_r → Ratio of buoyant to viscous force; Replace Re in the cases of natural convection

R_a → Ratio of thermal buoyance to viscus intertia.

✓ The Nusselt-Grashof relations can be represented as straight lines for a large number of Grashof numbers.

4.7 FLAT PLATE COLLECTORS

4.7.1 Introduction

✓ The flat plate Collectors forms the heart of any solar energy collection system designed for operation in the low temperature range, from ambient to 60^{o} C or the medium temperature, from ambient to 100^{o} C. A well engineered flat plate collector delivers heat at a relatively low cost for a long duration. The flat plate collector is basically a heat exchanger which transfer the radient energy of the incident sunlight to the sensible heat of a working fluid - liquid or air. The term 'flat plate' is slightly misleading in the sense that the surface may not be truly flat - it may be a combination of flat, grooved or of other shapes as the absorbing surface, with some kind of heat
removal device like tubes or channels . Flat plate collectors is used to convert as much solar radiation as possible into heat at the highest attainable temperature with the lowest possible investment in materials and labour.

✓ Flat plate collectors have the following advantages over other types of solar energy collectors:

(i) Absorb direct, diffuse and reflected components of solar radiation,

(ii) Are fixed in tilt and orientation and thus, there is no needed of tracking the Sun, (iii) Are easy to make and are low in cost,

(iv) Have comparatively low maintenance cost and Long life, and

(v) Operate at comparatively high efficiency.

4.7.2 Principle of Flat Plate Collector

✓ The principle behind a flat plate collector is simple. If a metal sheet is exposed to solar radiation, the temperature will rise until the rate at which energy is received is equal to the rate at which heat is lost from the plate; this temperature is termed as the 'equilibrium' temperature. If the back of the plate is protected by a heat insulating material , and the exposed surface of the plate is painted black and is covered by one or two glass sheets, then the equilibrium temperature will be much higher than that for the simple exposed sheet. This plate may be covered into a heat collector by adding a water circulaing system, either by making it hollow or by soldering metal pipes to the surface, and transferring the heated liquid to a tank for storage. For heat with withdrawal from the system the equilibrium temperature must decrease, since no useful heat can be extracted at the maximum equilibrium temperature at which the collection efficiency is zero. The other extreme condition is when the flow of liquid is so flat that the temperature rise is very small; in such a case, although the losses are small and the efficiency of the heat collection approaches 100 percent, yet no useful heat can be extracted. The optimum condition is approximately midway between the equilibrium temperature, whereby an output of hot liquid at a useful temperature is obtained.

4.7.3 Components of Liquid Flat Plate Collector

✓ A flat plat collector (Fig 4.14) usually consists of the following components:

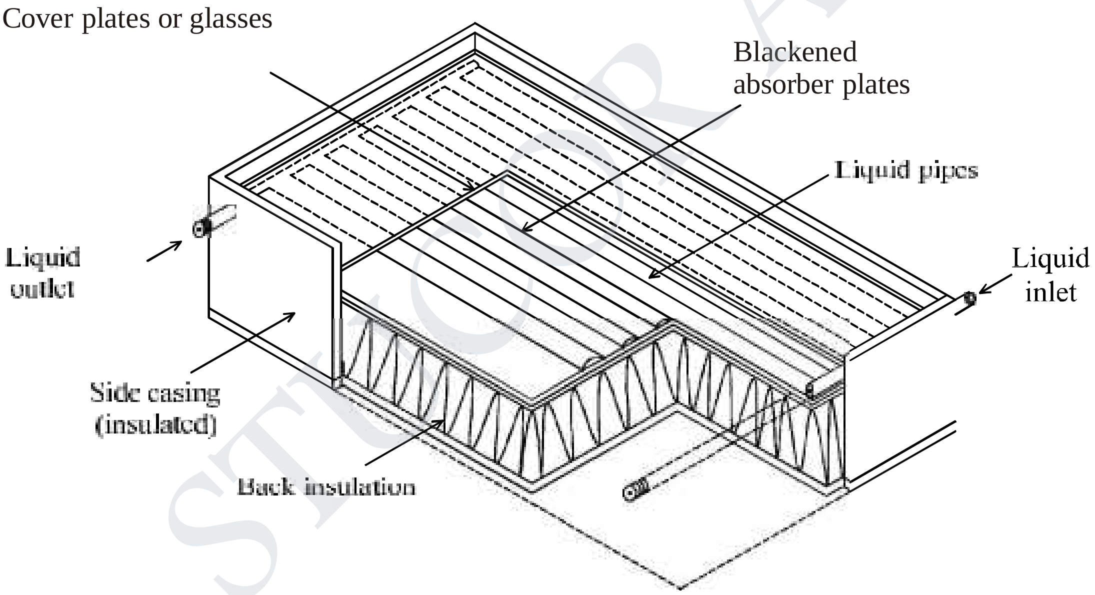


Fig. 4.14 A typical liquid flat plate collector

(i) Glazing, which may be one or more sheets of glass or other diathermanous (radiation transmitting)material (Fig. 4.15).

(ii) Tubes, fins or passages for conducting or directing the heat transfer fluid from the inlet to the outlet.

(iii) Absorber plate which may be flat, corrugated or grooved with tubes, fins or passages attached to it.

(iv) Header or manifolds, to admit and discharge the fluid.

(v) Insulation which minimizes heat loss from the back and sides of the collector

(vi) Container or casing which surrounds the various components and protects them from dust, moisture etc.

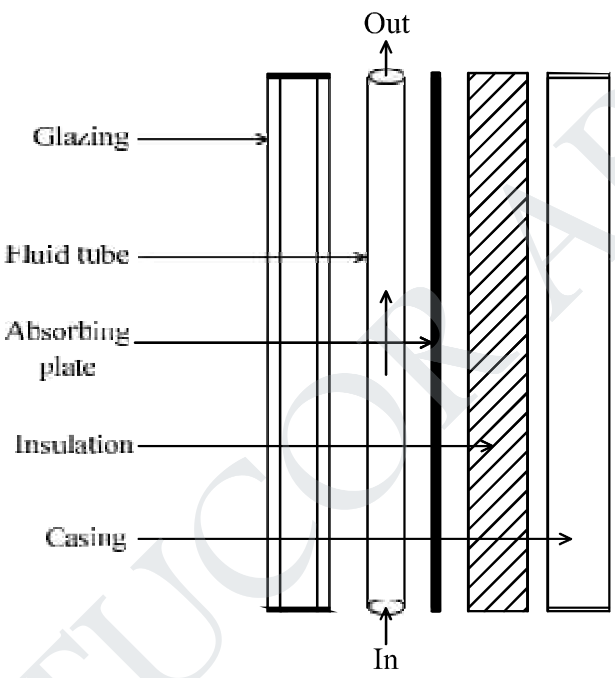


Fig. 4.15 Exposed cross section through double - glazed flat plate collector

✓ These liquid flat plate collectors are potentially useful in supplying the low grade thermal energy at temperatures generally less than 100 °C and may be used in systems for the supply of heated water for Domestic, Agricultural, Industrial applications, Space heating and Cooling applications.

4.7.4 Types of Flat - plate collectors

✓ In flat plate collectors, the heat loss by convection is more important in the determination of their performance. The convective heat loss may be decreased by using double glazing, but the radiation reaching the absorber is reduced due to double reflection. Hence, at low temperatures where this loss is small, use of single glazing gives a better efficiency than the double one while at higher temperature difference the use of glazing is advisable for better performance. Fig. 4.16 Compares the efficiencies of single and double galzing flat plate collector in different temperature ranges.

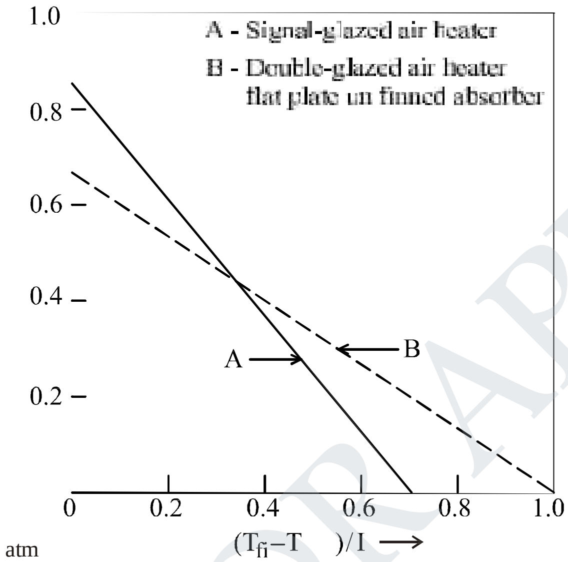
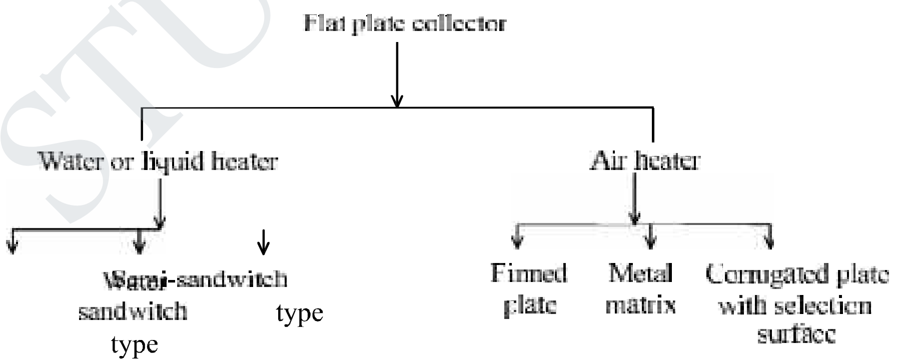


Fig. 4.16 Efficiency Vs (T_{fi} - T_{atm}) Characteristic Curve (ASHRAE Handbook)

✓ Flat-plate collectors are basically divided into two categories according to their use, (i) Water or liquid heaters and (ii) Air heaters. These collectors meant for these uses are sub-divided as follows :



Pipe and Fin type

sandwitch type

type

✓ The schematic diagram of all these collectors, with single glazing are shown in Fig. 4.17. These absorber plates can be broadly classified into three basic types as shown in Fig 4.18, depending on the extent of wetted surface area relative to the absorbing surface area.

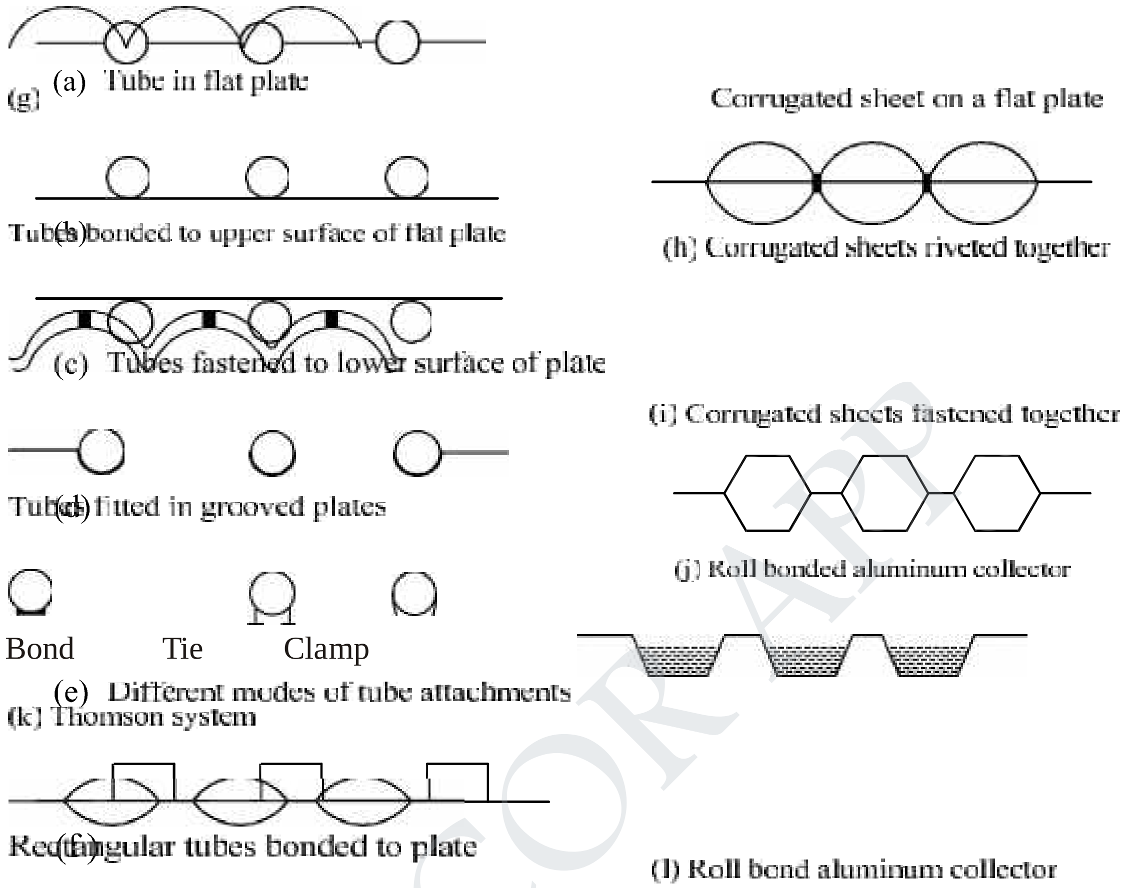


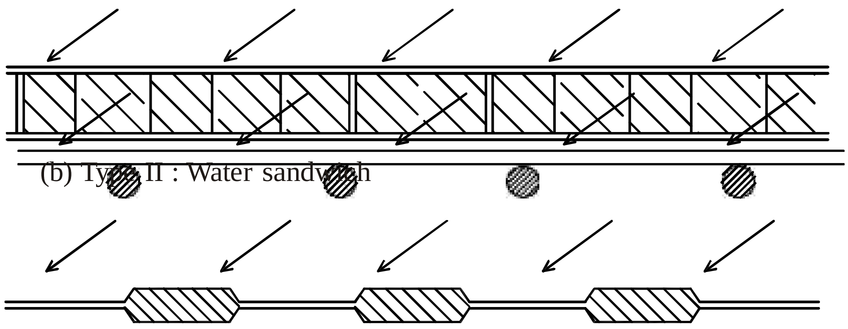
Fig. 4.17 Schematic diagram of different collector with single glazing

Type I : Pipe and fin type, in which the liquid flows only in the pipe and hence has comparatively low wetted area and liquid capacity, as shown in Fig. 4.18 (a).

Type II : Rectangular or cylindrical full sandwich type in which both the wetted area and the water capacity are high, as shown in Fig. 4.18 (b).

Type III : Roll bond type or semi - sandwich type, intermediate between types I and II, as shown in Fig. 4.18 (c).

(a) Type I : Pipe and fin



(c) Type III : Semi water sandwich

Fig. 4.18 Basic collector - absorber plate types

Table 4.4 Collector abosorber plate types - Advantages and Disadvantages

Type	Advantages	Disadvantages
I(a) Pipe and fin all copper	Good corrosion resistance, low thermal capacity.	Expensive
I(b) Pipe and fin composite e.g: Copper pipe and Aluminium fin	Fairly cheap, good internal corrsoion resistance, low thermal capacity flexibility in choice of materials.	Possibility of external bimetallic corrosion unless suitably protected
II Semi-water sandwich, Plastic.	Cheap and light	Limited of low temperature applications, liable to UV damage, high thermal expansio n, high thermal capacity
III (a) Semi-water sand-wich, steel (e.g: Pressed steel radiators)	Fairly cheap, readily available	Long-term corrosion problems, suitable for closed systems only, heavy high thermal capacity
III (b) Semi - water sandwich, aluminium (e.g: Roll bond type)	Fairly cheap, light weight.	Very susceptible to internal corrosion specially in mixed metal circuits.

✓ A brief comparative survey of the various types of abosrber plates is given in Table 4.4. The best choice of collector panel depends on the particular application. For low temperature requirements, such as in warming swimming pools, the plastic, full water sandwich panel may be the most appropriate choice. For domestic and industrial applications, higher temperatures are required and therefore, higher efficiency, realiability and long life are the main characteristics required. For such applications, pipe and fin type panel may be more suitable.

Performance Analysis

✓ The analysis will first be done for a steady state situation in which the liquid is flowing through tubes bonded on the under side of the absorber plate. Later on, the results for other types of flat -plate collectors will be given and transient effects will be considered.

✓ An energy balance on the absorber plate yields the following equation for steady state,

$$q_u = A_p S - q_l \quad \text{... (4.54)}$$

Where,

q_u → Useful heat gain, i.e., the rate of heat transfer to the working fluid,

A_p → Area of the absorber plate,

S → Incident solar flux absorbed in the absorber plate, and

q_l → Rate at which heat is lost by convection and re-radiation from the top and by conduction and convection from the bottom and sides.

✓ From Equ. (4.38a) the flux incident on the top cover of the collector is given by,

$$I_T = I_b r_b + I_d r_d + (I_b + I_d) r_r$$

✓ Each of the terms in the above equation is multiplied by a term called the transmissivity - absorptivity product ($\tau\alpha$) in order to determine the flux 'S' absorbed in the absorber plate. Thus,

$$S = I_b r_b (\tau\alpha)_b + \{I_d r_d + (I_b I_d) r_r\} (\tau\alpha)_d \quad \text{... (4.55)}$$

Where,

τ → Transmissitivity of the glass cover system, the ratio of the solar radiation coming through after reflection at the glass air interfaces and absorption in the glass to the radiation incident on the glass cover system,

α → Absorptivity of the absorber plate,

$(\tau\alpha)_b$ → Transmissivity - absorptivity product for beam radiation falling on the collector, and

$(\tau\alpha)_d$ → Transmissivity – absorptivity product for diffuse radiation falling on the collector.

✓ Thus, in order to evalute q_u in Equ. (4.54), it is necessary to derive expressions for calculating the values of $(\tau\alpha)_b$, $(\tau\alpha)_d$ and q_l.

✓ At this stage, it will be worthwile to define two terms, the instantaneous collection efficiency is given by,

$$\eta = \frac{\text{Useful heat gain}}{\text{Radiation incident on the collector}} = \frac{q_u}{A_C I_T} \quad \dots (4.56)$$

Where, A_c → Collector gross area (the area of the topmost cover including the frame). A_c is usually 15 to 20 percent more than A_P.

✓ If the liquid flow rate through the collector is stopped, there is no useful heat gain and the efficiency is zero. In this case, the absorber plate attains a temperature such that $A_p S = q_l$. This temperature is the highest that the absorber plate can attain and is sometimes referred as the "Stagnation Temperature'. Knowledge of the stagnation temperature is useful as an indicator for comparing different collector designs. It also helps in choosing proper materials for constructions of the collector.

✓ It has stated earlier, that many solar processes occur at a relatively slow pace. As a result, the time base of an hour is often convenient. Thus Equ. (4.56) is also valid as an expression for calculating the hourly collection efficiency, if q_u is the useful heat gain in one hour (KJ/h) and I_T is the energy inciedent on the collector face in one hour (KJ/m^2-h).

4.8. Transmissivity of the Cover System

✓ The transmissivity of the cover system of a collector can be obtained with adequate accuracy by considering reflection - refraction and abosrption separately and is given by the product form,

$$\tau = \tau_r \tau_a \quad \dots (4.57)$$

Where,

τ_r → Transmissivity obtained by considering only reflection and refraction and

τ_a → Transmissivity obtained by considering only absorption.

4.8.1 Transmissivity based on reflection - refraction

✓ When a beam of light of intensity I_{bn} travelling through a transparent medium 1 strikes the interface separating it from another transparent medium 2. It is reflected and refracted as shown in Fig.4.19. The reflected beam has a reduced indensity I_r and has a direction such that the angle of reflection is equal to the angle of incidence. On the other hand, the directions of the incident and refracted beams are related to each other by Snell's Law which states that,

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1} \qquad \text{... (4.58)}$$

Where, $\theta_1 \rightarrow$ Angle of incidence,

$\theta_2 \rightarrow$ Angle of refraction, and

$n_1, n_2 \rightarrow$ Refractive indices of the two media

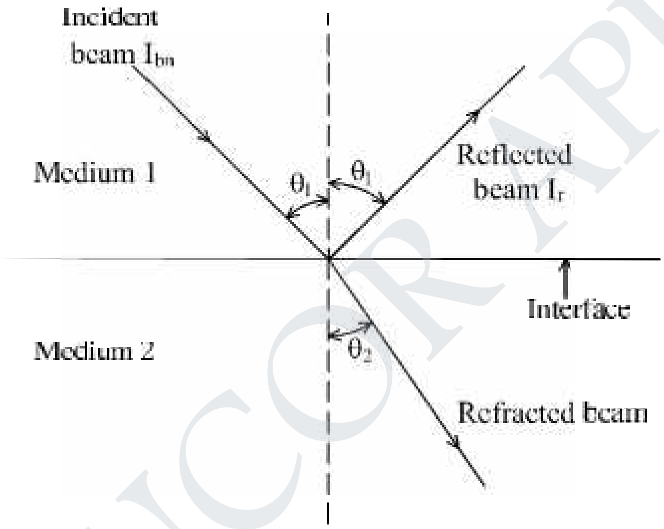


Fig. 4.19 Reflection and refraction at the interface of two media

✓ The reflectivity ρ $(= I_r / I_{bn})$ is related to the angles of incidence and refraction by the equations,

$$\rho = \frac{1}{2}(\rho_I + \rho_{II}) \qquad \text{... (4.59)}$$

$$\rho_I = \frac{\sin^2(\theta_2 - \theta_1)}{\sin^2(\theta_2 + \theta_1)} \qquad \text{... (4.60)}$$

$$\rho_{II} = \frac{\tan^2(\theta_2 - \theta_1)}{\tan^2(\theta_2 + \theta_1)} \qquad \text{... (4.61)}$$

Where,

ρ_I and ρ_{II} being the reflectivities of the two components of polarisation.

✓ For the special case of normal incidence $(\theta_1 = 0^o)$, it can be shown that,

$$\rho = \rho_I = \rho_{II} = \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2 \qquad \text{... (4.62)}$$

✓ The transmissivity (τ_r) is given by an expression similar to that for 'ρ'. Thus,

$$\tau_r = \frac{1}{2}(\tau_{rI} + \tau_{rII}) \qquad \text{... (4.63)}$$

✓ Consider one of the components of polarisation of a beam incident on a single refraction will occur as shown in Fig.4.20.

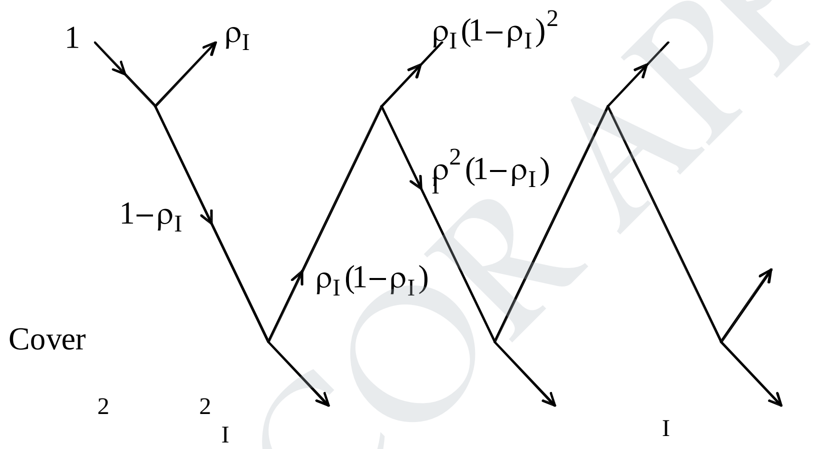


Fig. 4.20 Ray diagram showing transmission through a single cover considering reflection-refraction alone.

✓ Hence, $\tau_{rI} = (1-\rho_I)^2 + \rho_I^2(1-\rho_I)^2 + \rho_I^4(1-\rho_x)^2 + \cdots\cdots$

$$= (1-\rho_I)^2\left[1+\rho_I^2+\rho_I^4+\cdots\cdots\right] \quad \left(\because 1 + A + A^2 + \cdots = \frac{1}{1-A},\ A<1\right)$$

$$= \frac{(1-\rho_I)^2}{1-\rho_I^2} = \frac{(1-\rho_I)^2}{(1+\rho_I)(1-\rho_I)} = \frac{1-\rho_I}{1+\rho_I} \qquad \text{... (4.64)}$$

✓ Similarly, $\tau_{r\,II} = \frac{1-\rho_{II}}{1+\rho_{II}}$ ... (4.65)

✓ These results can be readily extended to a system of 'M' covers for which it can be shown that,

$$\tau_{r\,I} = \frac{1-\rho_{I}}{1+(2m-1)\rho_{I}} \quad \text{... (4.66)}$$

$$\tau_{r\,II} = \frac{1-\rho_{II}}{1+(2m-1)\rho_{II}} \quad \text{... (4.67)}$$

4.8.2 Transmissivity based on Absorption

✓ The transmissivity based on absorption can be obtained by assuming that the attenuation due to absorption is propotional to the local indensity (Bouger's Law). Consider a beam of indensity 'I_{bn}' incident normally on a transparent cover of thickness 'δ_c' and emerging with an indensity 'I_l' as shown in Fig.4.21.

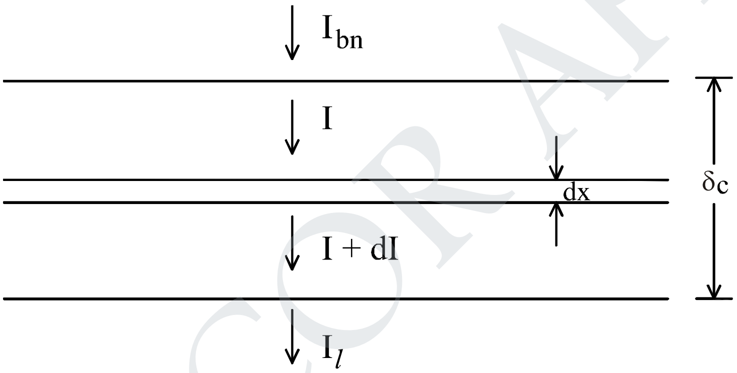


Fig. 4.21 Absorption in a transparent cover.

✓ From Bouger's Law,

$$dI = -K\,I\,dx \quad \text{... (4.68)}$$

Where, K is a constant of propotionality and is called the extinction coefficient. It will be assumed to have a value independent of wavelength. Integrating over the length traversed by the beam, we have

$$\tau_a = \frac{I_l}{I_{bn}} = e^{-K\delta_c} \quad \text{... (4.69)}$$

✓ In case the beam is incident at an angle θ_1, the path traversed through the cover would be $(\delta_c / \cos\theta_2)$, where θ_2 is the angle of refraction. Then Equ. (4.69) gets modified to the form,

$$\tau_a = e^{-K\,\delta_c / \cos\theta_2} \qquad \text{... (4.70)}$$

✓ The extinction coefficient K is a property of the cover material. Its value varies from about 4 to 25 cm^{-1} for different qualities of glass. A low value is obviously desirable.

✓ Equ. (4.69) and Equ. (4.70) are derived for one cover. If there are 'M' covers the exponent in these equations would be multiplied by 'M'.

4.8.3 Transmissivity for Diffuse Radiation

✓ The preceding considerations apply only to beam radiation. Calculation of the transmissivity of a cover system when diffuse radiation is incident on it presents some difficulty; because the radiation comes from many directions. The usual practice is to assume that the diffuse radiation is equivalent to beam radiation coming at an angle of incidence of 60^o. This angle is arrived at by considering the variation of 'τ' as shown in Fig.4.22, and by assuming that the amount of diffuse radiation coming from all directions is the same.

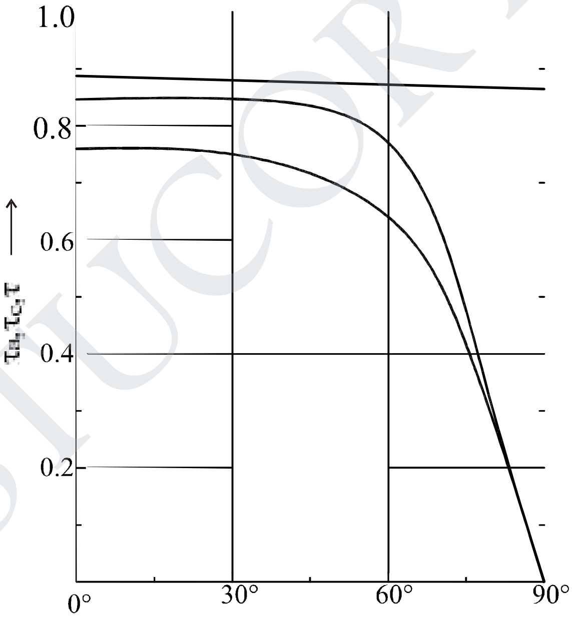


Fig. 4.22 Variation of τ_r, τ_a ***and*** τ ***with angle of incidence***

4.9 CONCENTRATING COLLECTORS

4.9.1 Introduction

✓ Concentration of solar radiation is achieved using a reflecting arrangement of mirrors or a refracting arrangement of lenses. The optical system directs the solar radiation on to an absorber of smaller area which is usually surrounded by a transparent cover. Because of optical system, certain losses (in addition to those which occur while the radition is transmitted through the cover) are introduced. These include reflection or absorption losses in the mirrors or lenses, and losses due to geometrical inperfections in the optical system. The combined effect of all such losses is indicated through the introduction of a term called "Optical Efficiency". The introduction of more optical losses is compensated for by the fact that the flux incident on the absorber surface is concentrated on a smaller area. As a result, the thermal loss terms do not dominate to the same extent as in a flat- plate collector and the collector efficiency is usually higher.

✓ It has been noted earlier that some of the attractive features of a flat - plate collector are simplicity of design and ease of maintenance. The same cannot be said of a concentrating collector. Because of the presence of an optical system, a concentrating collector usually has to follow or "track" the Sun so that the beam radiation is directed on to the absorber surface. The method of tracking adopted and the precision with which it has to be done varies considerably. In collectors giving a low degree of concentration, it is often adequate to make one or two adjustment of the collector orientation everyday. These can be made manually. On the other hand, with collectors giving a high degree of concentration, it is necessary

to make continuous adjustments of the collector orientation. The need for some form of tracking introduces a certain amount of complexity in the design. Maintenance requirements are also increased. All these factors add to the cost. An added disadvantages is the fact that much of the diffuse radiation is lost because it does not get focussed.

✓ In the last few years, significant advances have been made in the development of concentrating collectors and a number of types have been commercialised abroad. Almost all of them are line focussing Cylinderical Parabolic Collectors, and yield temperatures upto 400°C.

Definitions

✓ In order to be consistent in the use of terms, we will use the phrase 'Concentrating Collector' to denote the whole system. The term 'Concentrator' will be used only for the optical subsytem which directs the solar radiation on to the absorber, while the term 'Receiver' will normally be used to denote the subsystem consisting of the abosorber, it cover and accessories.

✓ We will now define four terms : Aperture, Area Concentration Ration, Intercept Factor and Acceptance Angle.

(i) Aperture (W): Aperture is the plane opening of the concentrator through which the solar radiation passes . For a cylindrical or linear concentrator it is characterised by the width, while for a surface of revolution, it is characterised by the diameter of the opening.

(ii) Area Concentration Ratio(C): It is the ratio of the effective area of the aperature to the surface area of the absorber. Values of the concentration ratio vary from unity (which is the limiting case for

a flat plate collector) to a few thousand for a paraboloid dish. This quantity is also referred to as the Geometric Concentration Ratio or simply Concentration Ratio.

(iii) Intercept Factor: The Intercept Factor (γ) is the fraction of the radiation, which is referred or refracted from the concentrator and is incident on the absorber. The value of the intercept factor is generally close to unity.

(iv) Acceptance Angle ($2\theta_a$): It is the angle over which beam radiation may deviate from the normal to the aperature plane and yet reach the absorber. Collectors with large acceptance angles require only occasional adjustments,
while collectors with small acceptance angles have to be adjusted continuously.

4.9.2 Types of Concentrating Collectors

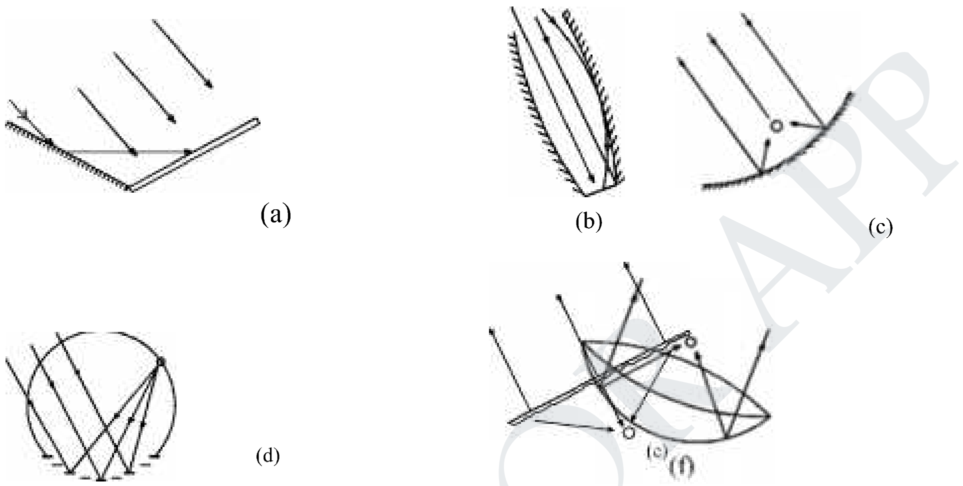


Fig. 4.29 Types of Concentrating Collectors

(a) Flat-Plate Collector with Plane Reflector (b) Compound Parabolic Collector (c) Cylindrical Parabolic Collector (d) Collector with Fixed Circular Concentrator and Moving Receiver (e) Fresnel lens Concentrating Collector (f) Paraboloid Dish Collector.

✓ The different types of concentrating collector geometrics are shown in Fig.4.29.

✓ The first type shown in Fig.4.29(a) is a flat - plate collector with adjustable mirrors at the edges to reflect radiation on to the absorber plate. It is simple in design, has a concentration ratio a little above unity and is useful for giving temperatures about 20^oC or 30^oC higher than those obtained from a flat - plate collector alone.

✓

A Compound Parabolic Concentrating Collector (CPC) is shown in Fig. 4.29(b). The concentrator consists of curved segments which are parts of two parabolas. Like the first type, this collector is also non-imaging. The concentration ratio is moderate and imaging. The concentration ratio is moderate and generally ranges from 3 to 10. The main advantage of the compound parabolic collector is that it has a high acceptance angle and consequently requires only occasional tracking. In addition, its concentration ratio is equal to the maximum value possible for a given acceptance angle.

✓ The next type of collector [Fig.4.29(c)] is a cylindrical parabolic collector in which the image is formed on the focal axis of the parabola. Many commercial versions of this type are now available.

✓ Unlike the cylindrical parabolic collector in which the concentrator has to rotate in order to track the Sun, the type shown in Fig.4.29(d) has a fixed concentrator and a moving receiver. The concentrator is an array of long, narrow, flat mirror strips fixed along the cylindrical surface. The strip produce a narrow line image which follows a circular path as the Sun moves. This path is on the same circle on which the mirror strips are fixed. Thus, the receiver has to be moved along the circular path in order to track the Sun.

✓ Concentration is also achieved by using lenses. The most commonly used device is the Fresnel lens shown in Fig.4.29(e). The one shown in the figure is a thin sheet, flat on one side and with fine longitudinal grooves on the other. The angles of these grooves are such that radiation is brought to a line focus. The lens is usually made of extruded acrylic plastic sheets. Line focussing collectors like the one shown in Fig.4.29(c), (d),(e) usually have concentration rations between 10 and 80 and yield temperature between 150^{o}C to 400^{o}C.

✓ In order to achieve higher concentration ratios and temperatures it becomes necessary to have point focussing rather than line focussing. A sketch is shown in Fig. 4.29(*f*). Such Collectors can have concentration ratios ranging from 100 to a few thousand and have yielded temperatures upto 2000^{o}C. However, from the point of view of the mechanical design, there are limitations to the size of the concentrator and hence the amount of energy which can be collected by one dish. Commercial Versions have been built with dish diameters up to 17*m*. In order to collect larger amounts of energy at one point, the central reciver concept has been adopted. In this case, beam radiation is reflected from a number of independently controlled mirrors called 'Heliostats' to a central receiver located at the top of a tower.

✓ **"Rabl"** has shown that for a given acceptance angle ($2\,\theta_a$), the maximum possible concentration ratio of a two - dimensional (line - focus) concentrator.

✓ The half - angle subtended by the Sun at the earth is 0.267^o. Sustituting this value in Equ. (4.104) and Equ. (4.105), we see that the maximum value of concentration ratio for a line - focus concentration is 215 and for a point - focus concentrator, it is 46000. In actual system, the values of concentration ratio are much lower, since the acceptance angle needs to be greater than 0.267^o for a number of reasons. These include tracking errors, imperfections in the reflecting or refracting component of the concentrator, mechanical misalignment between the concentrator and the receiver etc.

Thermal Analysis of Concentrating Collectors

✓ Like a flat - plate collector, an energy balance on the absorber yields the following equation under steady -state conditions

$q_u = A_a S - q_l$

Where,

$q_u \rightarrow$ Rate of useful heat gain,

... (4.106)

A_a → Effective area of the aperature of the concentrator,

S → Solar beam radiation per unit effective aperature area absorbed in the absorber, and

q_l → Rate of heat loss from the absorber.

✓ Equ. (4.106) is written under the assumption that the contribution of the diffuse component of solar radiation is negligible. Similar to Equ. (4.72), q_l can be written in terms of an overall loss coefficient defined by the equation

$$q_l = U_l A_p (T_{pm} - T_a) \quad \text{... (4.107)}$$

Where, U_l → Overall Loss coefficient,

A_p → Area of the absorber surface,

T_{pm} → Average temperature of the absorber surface, and

T_a → Temperature of the surrounding air.

✓ We combine Equ. (4.106) and Equ. (4.107) to obtain,

$$q = A_a \left[S - \frac{U_l}{C} (T_{pm} - T_a) \right] \quad \text{... (4.108)}$$

where, $C = \frac{A_a}{A_p}$ is Concentration Ratio.

4.10. Advantages and Disadvantages of Concentrating Collectors

Advantages:

(i) **No fuel cost:** Solar thermal concentrator does not require any fuel like most others sources of renewable energy. This is a huge advantages over other fossil fuels whose cost are increasing at drastic rate every year. Electricity prices are increasingly by radpidly in more parts of the world much faster than general inflation. Price shocks due to high fuel costs are a big risk with fossil fuel energy these days.

(ii) **Predictable 24/7 power:** Solar thermal energy can generate power 24hours a day. This is made possible as solar thermal power plants store the energy in the form of molten salt etc. Other forms of Renewable energy like solar PV and Wind energy are intermittent in nature.

(iii) **No pollution and Global Warning Effects:** Solar thermal energy does not cause pollution which is one of the biggest advantages. Note there are costs associate with the equipment used to buid and transport solar thermal energy equipment.

(iv) **Using Existing Industrial Base:** Solar Thermal energy uses equipment like solar thermal mirrors and turbines which is made in large scale at low cost by existing industrial base and require no major changes in equipment and materials unlike new techonologies such as CIGs panels.

(v) Concentrated solar power production have been shown to create more permanent job and stimulate the economy as compared to its natural gas counterparts.

(vi) The heat delivered by concentrating solar collectors is available at much higher temperature. Higher temperatures allow the use of power generation equipment to produce both electricity and heat.

(vii) Large economy of scale effects are observed when moving towards large concentration systems, rendering such technology very cost effective (Compared with PV for example).

Disadvantages:

(i) **High Costs:** Solar thermal energy cost atleat 3.5Euro/watt and has not declined too much in the last 3-4 years. However these costs are too high as solar PV already costs 2.5Euro/watt and even on a conservative basis will have it costs reduced by 5% in the next 10 years making it attain half the cost of solar thermal technology by 2020.

(ii) **Future Technology has a probability of marking CSP Obsolete:** Solar Energy has become a Hot bed of Innovation with daily news of some new breakthrough in materials and process in PV technology. **"Oerlikon"** has come out with a radial new a - Si Technology while CIGs players are touting increased efficiencies. Chinese solar companies have captured large chunks of the solar market through low cost leadership while number of Global Heavyweights like POSCO, Samsung, Hyundai, Sharp,GE, TSMC promise to further decrease these costs.

(iii) **Water Issue:** Solar thermal plant use lot of water which is major problem in desert areas. Using non-water cooling raises the cost of CSP projects too much. While using sea water has been proposed it remains to be seen if it possible to implement this solution as this would imply building plants very near the coastline.

(iv) **Ecological and Cultural Issue:** This Usuage of massive arrays of Mirrors is noted to heavily impact the Desert wildlife endangering the endangered species. California has already seen massive fight on this issue with project Developers Curtailing the size of their plants and spending money to move wildlife [applicable only to CSP].

(v) Since concentrators can focus only direct solar radiation, this performance is poor on cloudy days.

(vi) Tracking mechanisms must be used to move the collectors during the day to keep then focused on the Sun.

(vii) Maintenance and construction costs of the system is high.

(viii) Concentrators are only practical in areas of high direct insolation, such as arid and desert areas.

4.10 performance analysis of a cylindrical – parabolic concentrating collector

4.10.1 Introduction

✓ The Cylindrical Parabolic Collector (CPC) is also referred to a Parabolic Trough or a Linear Parabolic Collector as shown in Fig. 4.29 (c). The basic elements making up a conventional collector are (i) the absorber tube located at the focal axis through which the liquid to be heated flows, (ii) the concentric transparent cover, (iii) the reflector, and (iv) the support structure. Elements (i) and (ii) together constitute the receiver, while elements (iii) and (iv) constitute the concentrator.

✓ The collector are available over a wide range of aperture areas from about 1 to $60m^2$ and with widths ranging from 1 to 6m. Concentration ratios range from 10 to 80, and rim angles from 70 to 120, as shown in Fig. 4.30.

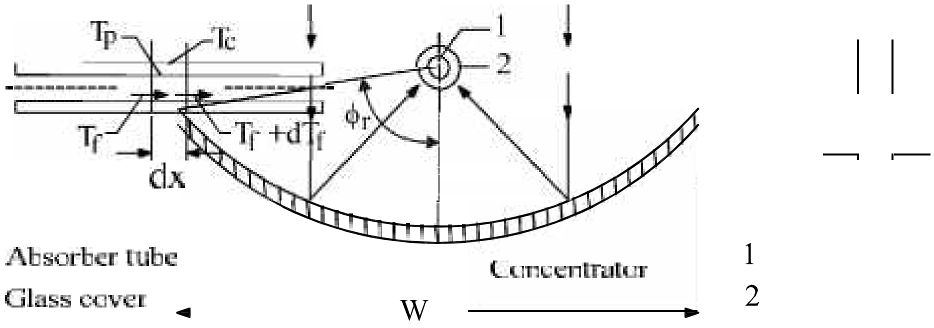


Fig. 4.30 Cylindrical Parabolic Collector Cross-Section

✓ The absorber tube is usually made of stainless steel or copper and has a diameter of 2.5 to 5cm. It is coated with a heat resistant black paint and is generally surrounded by a concentric glass cover with an annular gap of 1 or 2cm. In the case of high performance collectors, the absorber tube is coated with a selective surface and the space between the tube and the glass cover is evacuated. In some small collectors, the concentric cover is replaced by a glass or plastic sheet covering the whole aperture area of the collector. Such an arrangement helps in protecting the reflection surface from the weather.

✓ The liquid heated in the collector depends upon the temperature required. Usually organic heat transfer liquids (referred to as thermic fluids) are used. Because of their low thermal conductivities, these liquids yield low heat transfer coefficients. Augmentative devices in the form of twisted tapes or central plugs (Which create annular passages) are therefore used to increase the value of the heat transfer fluid.

✓ The reflecting surface is generally curved back slivered glass. It is fixed on light-weight structure usually made of aluminimum sections. The proper design of this supporting structure and of the system for its movement is important, since it influences the shape and orientation of the reflecting surface. Some of the factors to be considered in designing the structure are that it should not distort sighificantly due to its own weight and it should be able to withstand wind Loads.

✓ Compared to flat-plate collectors, there are very few manufacturers of concentrating collectors all over the world. The volume of production is also low. In India, many experimental collectors have been built and tested. However, commercial manufacture has not yet begun.

4.10.2 Orientation and Tracking Modes

✓ A cylindrical parabolic collector is oriented with its focal axis pointed either in ther East -West (E-W) or the North-South (N-S) direction. In the East-West orientation, the focal axis is horizontal, while in the North-South orientation, the focal axis may be horizontal or inclined. The various tracking modes, which can be adopted, are as follows:

Mode I:

✓ The focal axis is E-W and horizontal. The collector is rotated about a horizontal E-W axis and adjusted once every day so that the solar beam is normal to the collector aperture plane at solar noon on that day.

✓ In this mode, the aperture plane is an imaginary surface with either $\gamma = 0^o$ or $\gamma = 180^o$. In case of $\gamma = 0^o$ occurs when $(\phi - \delta) > 0$, while the case of $\gamma = 180^o$ occurs when $(\phi - \delta) < 0$, In order to find the slope β of the aperture plane, we substitue the condition at solar noon, viz., $\omega = 0^o$, $\theta = 0^o$ in Equ. (4.10). This yields,

$$\beta = (\phi - \delta) \text{ for } \gamma = 0^o \qquad \text{... (4.109 a)}$$

and $$\beta = (\delta - \phi) \text{ for } \gamma = 180^o \qquad \text{... (4.109 b)}$$

✓ The angle of incident of the beam radiation on the aperture plane through out the day is obtained by putting Equ. (4.109a) and Equ. (4.109b) in Equ. (4.10).

For both cases, $\gamma = 0^o$ and $\gamma = 180^o$, we obtain the same relation,

$$\cos\theta = \sin^2\delta + \cos^2\delta\cos\omega \qquad \text{... (4.110)}$$

Mode II:

✓ The focal axis E -W horizontal. The collector is rotated about a horizonal E-W axis and adjusted continuously, so that the solar beam makes the minimum angle of incidence with the aperture plane at all times.

✓ In this mode also, the aperture plane is an imaginary surface with either $\gamma = 0^o$ and $\gamma = 180^o$. Equ. (4.10) is applicable with $\gamma = 0^o$ or $\gamma = 180^o$. In order to find the condition to be satified for θ to be minimum, we differentiate the right hand side of the resulting equation with respect to β and equate it to zero. Thus we get,

$$\tan(\phi - \beta) = \frac{\tan\delta}{\cos\omega} \text{ for } \gamma = 0^o \qquad \text{... (4.111a)}$$

and $$\tan(\phi + \beta) = \frac{\tan\delta}{\cos\omega} \text{ for } \gamma = 180^o \qquad \text{... (4.111b)}$$

✓ Equ. (4.111a) and (4.111b) can be used for finding the slope of the aperture plane. Equ. (4.111a) corresponding to $\gamma = 0^o$ is used, if the magnitude of the solar azimuth angle γ_s is less than 90°, while Equ. (4.111b) corresponding to $\gamma = 180^o$ is used, if the magnitude of solar azimuth angle is greater than 90°.

✓ The expression for the corresponding minimum angle of incidence is obtained by substituting Equ. (4.111a) and Equ. (4.111b) in the Equ. (4.10). For both cases, we obtain

$$\cos\theta = (1 - \cos^2\delta \sin^2\omega)^{\frac{1}{2}} \quad \text{... (4.112)}$$

Mode III :

✓ The focal axis is N-S and horizontal. The collector is rotated about a horizontal N-S axis and adjusted continuously so that the solar beam makes the minimum angle of incidence with the aperture plane at all times.

✓ In this mode, the surface azimuth angle $\gamma = +90^o$ before Noon, and -90^o after Noon. Thus, before Noon, Equ. (4.10) becomes.

$$\cos\theta = (\sin\phi\sin\delta + \cos\phi\cos\delta\cos\omega)\cos\beta + \cos\delta\sin\omega\sin\beta \quad \text{... (4.113)}$$

✓ In order to find the condition to be satisfed for θ to be a minimum, we differentiate the right hand side of Equ. (4.13) with respect to β and equate it to zero. Thus we get,

$$\beta = \tan^{-1}\left[\frac{\cos\delta\sin\omega}{\sin\phi\sin\delta + \cos\phi\cos\delta\cos\omega}\right] \quad \text{... (4.114)}$$

✓ Equ (4.114) is used for finding the slope of the aperture plane at any time before Noon. The expression for the corresponding minimum angle of incidence is obtained by substituting Equ. (4.114) in Equ. (4.10), giving

$$\cos\theta = \left[(\sin\phi\sin\delta + \cos\phi\cos\delta\cos\omega)^2 + \cos^2\delta\sin^2\omega\right]^{\frac{1}{2}} \quad \text{... (4.115)}$$

✓ After Noon, i.e. with $\gamma = -90^o$, we would obtain

$$\beta = \tan^{-1}\left[\frac{-\cos\delta\sin\omega}{\sin\phi\sin\delta + \cos\phi\cos\delta\cos\omega}\right] \quad \text{... (4.116)}$$

✓ The expression for $\cos\theta$ remains the same.

Mode IV:

✓ The focal axis is N–S and inclined at a fixed angle equal to the lattitude. Thus, it is parallel to earth's axis. This orientation is sometimes referred to as a polar mount. The collector is rotated about an axis parallel to the earth's axis at an angular velocity equal and opposite to the earth's rate of rotation (15^o perhour). It is adjusted such that at Solar Noon the aperture plane is an inclined surface facing due South.

Thus putting $\beta = \phi$ and $\omega = 0$ in Equ. (4.13), we get,

$$\theta = \delta \qquad \text{... (4.117)}$$

✓ This is also seen from Fig. 4.31 in which the circle represents the longititude through the location of the collector. At all other times, since the collector is rotated at speed equal to the earth's rate of rotation and about an axis parallel to the the earth's axis, it follows that Equ. (4.117) is still valid.

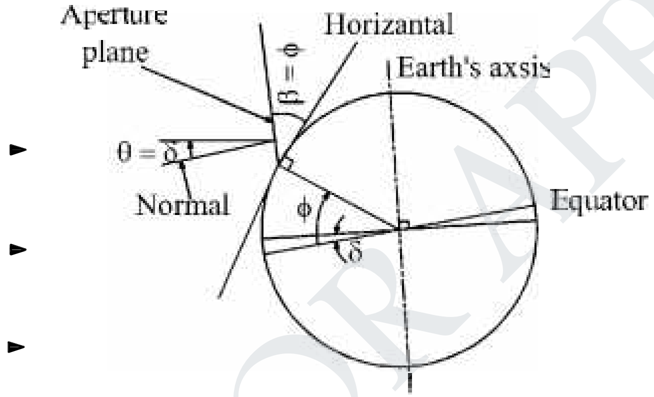


Fig. 4.31 Tracking mode IV for a Cylindrical Parabolic Collector (Angle of incidence ¯ is equal to the declination 'δ')

ModeV:

✓ The focal axis is N–S and inclined. The collector is rotated continuously (but not at a constant angular velocity) about an axis parallel to the focal axis, as well as about a horizontal axis perpendicular to this axis, and adjusted so that the solar beam is normal;ly incident on the aperture plane at all times. It this situation, obviously $\cos\theta = 1$. It is easy to show that at solar Noon,

$$\beta = |\phi - \delta| \qquad \text{... (4.118)}$$

✓ It is of interest to compare the amounts of beam radiation which could be incident on a collector's aperture plane over a day if one adopted the various traking modes.

4.11 Feed in Invertors

4.11.1 A Grid Tie Inverter for Solar PV System

Operating a renewable energy system in parallel with an electric grid requires special grid-interactive or grid tie inverters (GTI). The power processing circuits of a GTI are similar to that of a conventional portable DC-AC converter that operates as a stand- alone device. The main differences are in their control algorithm and safety features. A GTI basically takes a variable voltage from a DC source, such as solar panels array or a wind system, and inverts it to AC synchronized with the mains. It can provide power to

your loads and feed an excess of the electricity into the grid. Depending on power and voltage levels, GTIs circuits normally have from one to three stages. A conceptual power train schematic diagram below illustrates the principles of operation of a three-stage grid tie inverter. Such a topology can be useful for low-voltage inputs (such as 12V) in grounded systems. The control circuits and miscellaneous details are not shown here. As I mentioned above, there are also two-stage and single-stage configurations.

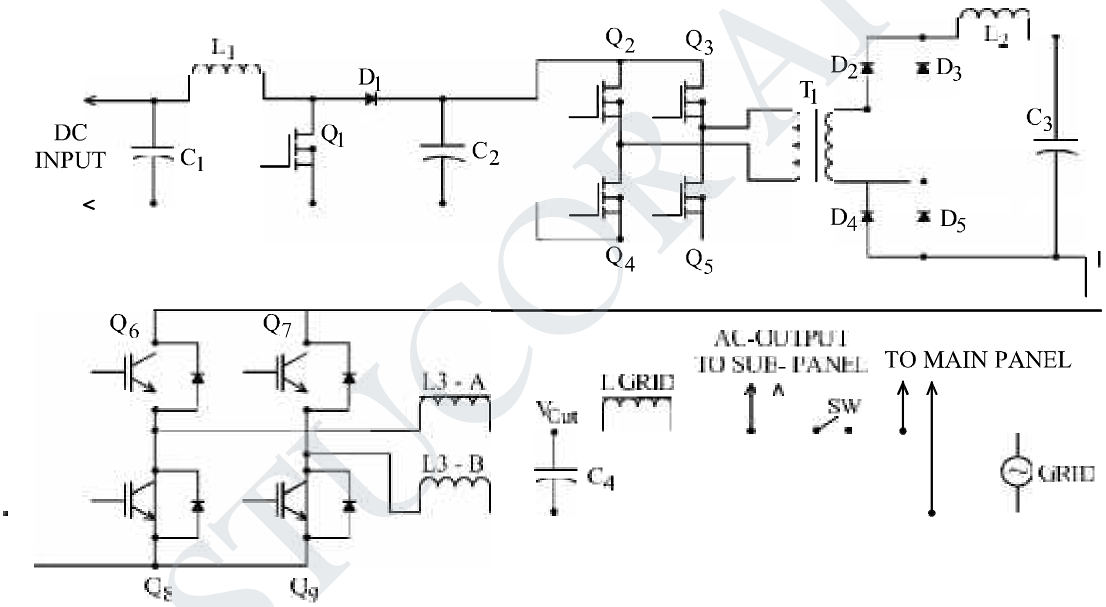


Fig. 4.32 A grid tie inverter for solar PV system

The input voltage is first raised by the boost converter formed with inductor L1, MOSFET Q1, diode D1 and capacitor C2. If a PV array is rated for more than 50V, generally one of the input direct current busses has to be grounded per National Electric Code®. The NEC® however allows some exceptions which we will discuss below. Although in theory either of two busses can be connected to earth, usually it is a negative one. It is important to remember that if DC input has a conduction pass to ground, the output AC conductors in utility-interactive configurations should be isolated from DC. In our example, a galvanic isolation is provided by a high frequency transformer in the second conversion stage. This stage is a basically a pulse-width modulated DC-DC converter. The schematic above shows a full bridge (also known as H-bridge) isolating converter comprised of Q2-Q5, T1, D2-D5, L2, and C3. For power levels under 1000 watt it could also be a half-bridge or a forward converter (for more details see SMPS types). Some commercial models use low-frequency (LF) transformer in the output stage instead of a high frequency one in the DC-DC section. With such a method, input is converted to 60 Hz AC, and then a LF transformer changes it to a required level and provides isolation at the same time.

The equipment with an LF transformer has a significantly larger weight and size, but it will not inject a DC component into the load. Here is a lesser known detail: UL 1741 does allow transformerless inverters and exempts them from dielectric voltage withstand test between input and output. Therefore the isolating stage can be eliminated. It is important to note that the conductors from PV array in non-isolated designs can't be bonded to earth. NEC® 690.41 allows ungrounded configurations is they comply with Article 690.35. The transformerless inverters of course feature lower weight and cost. They are especially popular in Europe where ungrounded electrical systems are common. However, because of the lack of the galvanic isolation, these models present potential electrical hazards. In such a setup if a person touches a terminal of the PV panel or the battery, he will appear under AC line potential. The transformerless systems require additional protection devices per NEC® Article 690.35 and special warning labels placed wherever energized circuits may be exposed during service.

T1 can be a so-called step-up type to amplify the input voltage. With a step-up T1, the first stage (boost converter) may be omitted. However, high turns ratio leads to large leakage inductance. This in turn causes voltage spikes on the FETs and rectifiers as well as other undesirable effects.

The regulated converter provides a DC-link to the output AC inverter. Its value must be higher than the peak of the utility AC voltage. For example, for 120VAC service, the Vdc should be $>120*\sqrt{2} = 168$V. Typical numbers are 180-200V. For 240VAC you would need 350-400 V. The third conversion stage turns DC into AC by using another full bridge converter. It consists of IGBT Q6-Q9 and LC-filter L3, C4.

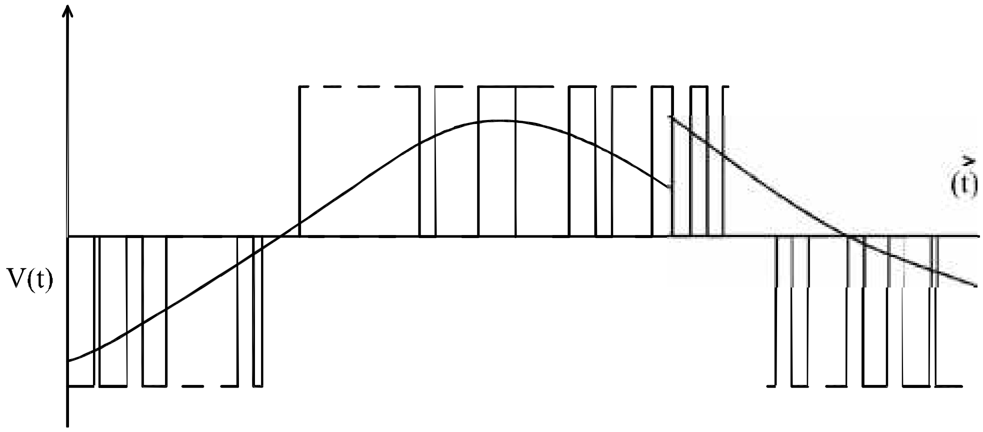


Fig. 4.33 PWM to synthcsize sinusoidal output

The IGBTs Q6-Q9 work as electronic switches that operate in PWM mode. This topology requires anti-parallel freewheeling diodes to provide an alternate path for the current when the switches are off. These diodes are either included within IGBTs or added externally. By controlling different switches in the H-bridge, a positive, negative, or zero potential can be applied across inductor L3. The output LC filter then reduces high frequency harmonics to produce a sinewave.

Any grid tie power source has to synchronize its frequency, phase and amplitude with the utility and feed a sinewave current into the load. Note that if inverter output (Vout) is higher than utility voltage, the GTI will be overloaded. If it is lower, the GTI may sink current rather than source it. In order to allow a limited current flow into the loads as well as back into the line, “Vout” has to be just slightly higher than the utility voltage. Usually there is an additional coupling inductor (Lgrid) between GTE and the mains that “absorbs” the extra AC voltage. It also reduces the current harmonics generated by the PWM. A drawback of “Lgrid” is it introduces extra poles in the control loop, which potentially may lead to the system instability. Because the grid acts as a source with a very low impedance, normally, a GTE is designed to work as a current controlled source, rather than a voltage source.

In solar applications, to maximize the system efficiency, a GTI also has to meet certain requirements defined by the photovoltaic panels. Solar panels provide different power in different points of their volt-ampere (V-I) characteristic. The point in the V-I curve where output power is maximum is called maximum power point (MPP). The solar inverter must assure that the PV modules are operated near their MPP. This is accomplished with a special control circuit in the first conversion stage called MPP tracker (MPPT).

A GTI also has to provide so-called anti-islanding protection. When mains fails or when its voltage level or frequency goes outside of acceptable limits, the automatic switch should SW quickly disconnect the system output from the line. The clearing time depends on the mains conditions and is specified by UL 1741. In the worse cases, when utility voltage drops below 0.5 of nominal, or its frequency deviates by +0.5 or -0.7 Hz from the rated value, GTI should cease to export power back to the grid in less than 100 milliseconds. An anti-islanding can be accomplished for example via AC undervoltage or output overcurrent detection functions. Our example depicts a system with power backup option: when contactor SW opens, the GTI will supply critical loads connected to the sub-panel. The implementation of control algorithm of grid tie inverters is quite complex and normally is done with micro-controllers.

4.11.2 Inverters and Grid Integration

Integrating increasing amounts of solar energy into the public power supply puts various demands on PV plants. For example, special protective devices are require d to prevent the risk of danger in the event of mains interference. The more PV plants feed into the public grid, the greater the demands placed on the grid services that they must perform. This is why inverters are incorporated into the grid management system.

4.11.3 High Demands for Feeding in Power

Guidelines and standards regulate exactly how PV plants should be connected to the public grid, which gives rise to two highly important requirements. Firstly, when solar power is fed into the grid the power quality of the grid should not be reduced. Secondly, personal safety must be ensured in the event of mains interference. Another requirement has also recently gained importance: Instead of shutting down at the first sign of a fault (fault ride through, FRT), PV plants should support the power grid and perform grid-related control functions.

The requirements for power feed-in are clearly defined: The grid requires sinusoidal AC with stable voltage and frequency, and the harmonic component limits are regulated in guidelines and standards. Modern inverters meet these power quality requirements, yet in some cases limits may be exceeded.

Voltage and frequency stabilities are high in the fully developed, close-meshed grid supplied by large thermal power stations, and solar power can usually also be injected without problems, even in large quantities.

The further away the feeding point from large power plants, the greater the requirements that are placed on grid feed-in. As a general rule, when electricity is drawn from the grid, the grid voltage falls, and when power is fed in it increases. Particularly when PV plants feed into rural grid structures or grid branch lines, this can cause an increase in voltage that exceeds the specified limits. If the feed-in power of connected PV plants exceeds the capacity of small local grids, adjustable local grid transformers can be employed that are ideally suited to regulating voltage and that prevent the upper limit being exceeded. The same task can also be performed by power storage systems in the local grid.

When a large amount of energy is consumed, the line voltage in these weak grid spurs decreases, thus the act of feeding in solar power counteracts this voltage drop and, in turn, supports the grid. When a large amount of energy is consumed, the voltage in these weak grid spurs decreases, meaning that the act of feeding in decentralized solar power supply counteracts this decrease in voltage and, in turn, supports the grid.

Measures need to be taken to inhibit excessive increases in voltage during periods in which an especially high level of power is being fed in and very little is actually being consumed. A further consequence is that-particularly when grid feed-in is high and consumption is low in a particular area of the grid-the flow of current can reverse in the power grid, and not all grids are prepared for this yet.

UNIT V
WIND ENERGY

Introduction - basic principles of wind energy conversion - site selection considerations - basic components of a WECS (Wind Energy Conversion System) - Classification of WECS - types of wind Turbines - analysis of aerodynamic forces acting on the blade - performances of wind.

5.1 INTRODUCTION

Winds are caused by pressure differences between different regions. They carry enormous quantity of energy. Regions in which strong winds prevails for a sufficient time during the year can profitably use wind energy for different purposes.

Wind results from air in motion. Air in motion arises from a pressure gradient. On a global basis one primary forcing function causing surface winds from the poles towards the equator, and this low density heated air is buoyed up. At the surface it is displaced by cooler more dense higher pressure air flowing from the poles. In the upper atmosphere near the equator the air thus tend to flow back toward the poles and away from the equator. The net result is a global convective circulation with surface winds from north to south in the northern hemisphere.

It is clear that from the above over simplified model that the wind is basically caused by the solar energy irradiating the earth. This is why wind utilization is considered a part of solar technology.

Local winds are caused by two mechanisms. They are

i) The differential heating of land and water. Solar radiation during the day is readily converted to sensible energy of the land surface but is partly absorbed in layers below the water surface and partly consumed in evaporating some of the water. The land mass becomes hotter than the water, which causes the air above the land to heat up and become warmer than the air above water. The warmer lighter air above the land rises, and the cooler heavier air above the water moves into replace it. This is the mechanism of shore breezes. At night, the direction of the breezes is reversed because the land mass cools to the sky more rapidly than the water, assuming a clear sky.

ii) The local winds is caused by hills and mountain sides. The air above the slopes heats up during the day and cools down at night, more rapidly than air above the low lands. This causes heated air the day to rise along the slopes and relatively cool heavy air to flow down at night.

5.1.1 Wind Speed Vs Height

Wind speed generally changes with height, which requires an equation that predicts the wind speed at one height in terms of the measured at another height. Under normal conditions, a wind speed is greater at higher distance above ground. This is largely because the effect of surface features and turbulence diminishes as the height increases. The variability depends on distance from the ground and roughness of the terrain.

original height h_0, and α is the surface roughness coefficient. The value of the exponent α varies from less than 0.10 over the tops of steep hills to over 0.25 in sheltered locations. The typical value for flat coastal regions is 0.143, which is termed the one-seventh power law. From measurements at different heights the exponent can be determined.

Wind power - what is it?

All renewable energy (except tidal and geothermal power), ultimately comes from the Sun. The Earth receives 1.74×10^{17} Watts of power (per hour) from the sun. About one or 2 percent of this energy is converted to wind energy (which is about 50-100 times more than the energy converted to biomass by all plants on earth.

Differential heating of the earth's surface and atmosphere induces vertical and horizontal air currents that are affected by the earth's rotation and contours of the land → WIND. e.g.: Land Sea Breeze Cycle. Winds are influenced by the ground surface at altitudes up to 100 meters. Wind is slowed by the surface roughness and obstacles.

When dealing with wind energy, we are concerned with surface winds. A wind turbine obtains its power input by converting the force of the wind into a torque (turning force) acting on the rotor blades. The amount of energy which the wind transfers to the rotor depends on the density of the air, the rotor area, and the wind speed.

The kinetic energy of a moving body is proportional to its mass (or weight). The kinetic energy in the wind thus depends on the density of the air, i.e. its mass per unit of volume. In other words, the "heavier" the air, the more energy is received by the turbine at 15°C air weights about 1.225 kg per cubic meter, but the density decreases slightly with increasing humidity.

A typical 600 kW wind turbine has a rotor diameter of 43-44 metres, i.e., a rotor area of some 1,500 square meters. Fig 5.1 shows the power generated by the wind mill with respect to the height.

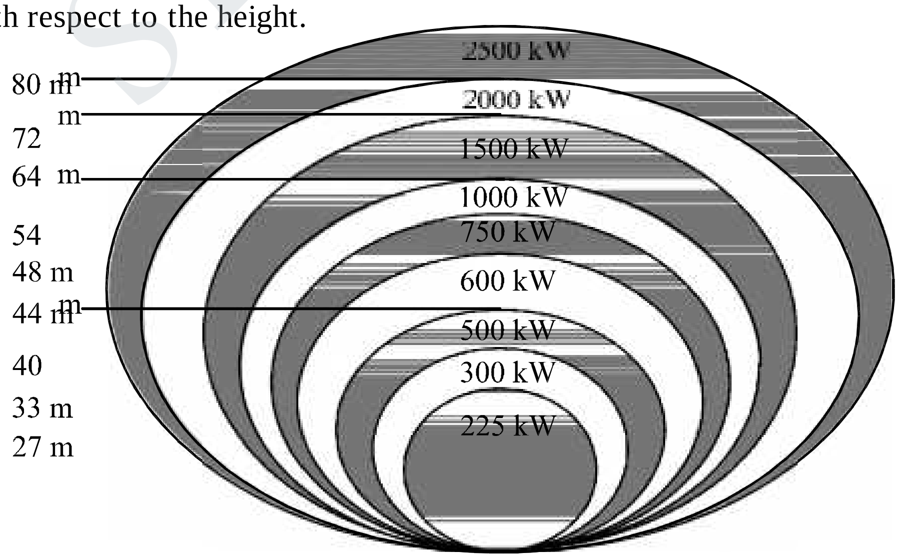


Fig. 5.1 Power generated by wind mill with respect to its height

The rotor area determines how much energy a wind turbine is able to harvest from the wind. Since the rotor area increases with the square of the rotor diameter, a turbine which is twice as large will receive $2^2 = 2 \times 2$ = Four times as much energy. To be considered a good location for wind energy, an area needs to have average annual wind speeds of at least 12 miles per hour.

They have traditionally been measured at a standard height of ten metres where they are found to be 20-25% greater than close to the surface. At a height of 60 metre they may be 30-60% higher because of the reduction in the drag effect of the earth surface.

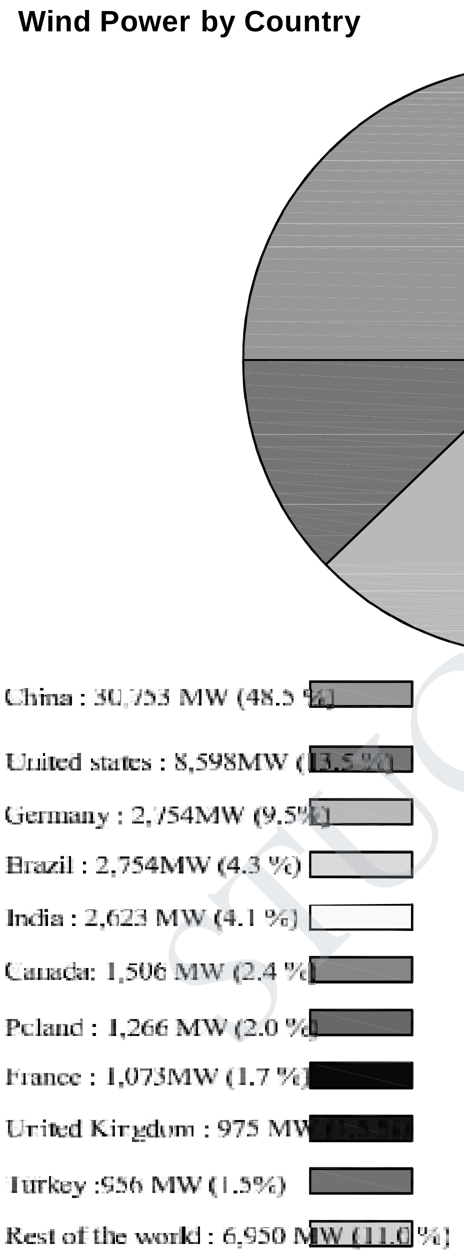


Fig. 5.2 Installed capacity (MW) by country in 2015 (JAN- DEC)

As of the end of 2015, the worldwide total cumulative installed electricity generation capacity from wind power amounted to 4,32,883 MW, an increase of 17% compared to the previous year. Global wind power installations increased by 63,330 MW, 51,447 MW and 35,467 MW in 2015, 2014 and 2013 respectively.

Since, 2010 more than half of all new wind power was added outside of the traditional markets of Europe and North America, mainly driven by the continuing boom in China and India. At the end of 2015, China had 145 GW of wind power installed. In 2015, China installed close to half of the world's added wind power capacity.

Several countries have achieved relatively high levels of wind power penetration, such as 39% of stationary electricity production in Denmark, 18% in Portugal, 16% in Spain, 14% in Ireland and 9% in Germany in 2010. As of 2011, 83 countries around the world are using wind power on a commercial basis. Wind power's share of worldwide electricity usage at the end of 2014 was 3.1%. Fig. …. Shows the end-of-year 2015, worldwide installed wind power capacity by country. The data is sourced from Global Wind Energy Council. In 2015, global wind power capacity increased by 63,330 MW or 17.14% from 369,553 MW to 432,883 MW.

5.2 BASIC PRINCIPLES OF WIND ENERGY CONVERSION

5.2.1 The nature of wind

The circulation of air in the atmosphere is caused by the non-uniform heating of the earth's surface by the sun. The air immediately above a warm area expands, it is forced upward by cool, denser air which flows in from surrounding areas causing wind.

The nature of the terrain, the degree of cloud cover and the angle of the sun in the sky are all factors which influence this process.

In general, during the day the air above the land mass tends to heat up more rapidly than the air over water. In coastal regions this manifests itself in a strong onshore wind. At night the process is reversed because the air cools down more rapidly over the land and the breeze therefore blows off shore.

Despite the wind's intermittent nature, wind patterns at any particular site remain remarkably constant year by year. Average wind speeds are greater in hilly and coastal areas than they are well inland. The winds also tend to blow more consistently and with greater strength over the surface of the water where there is a less surface drag.

5.2.2 The power in wind

Wind possesses energy by virtue of its motion. Any device capable of slowing down the mass of moving air, like a sail or propeller, can extract part of the energy and convert is into useful work.

There are three factors determine the output power generated from the wind mill, they are

(i) The wind speed,

(ii) The cross section of wind swept by rotor, and

(iii) The overall conversion efficiency of rotor, transmission system and generator or pump.

No device, however well-designed, can extract all of the wind's energy because the wind would have to be brought to a halt and this would prevent the passage of more air through the rotor. The most that is possible is for the rotor to decelerate to whole horizontal column of intercepted air to about one-third of its free velocity.

A 100% efficient aerogenerator would therefore only be able to convert up to a maximum of around 60% of the available energy in wind into mechanical energy.

A well - designed blades will typically extract 70% of the theoretical maximum, but losses incurred in the gear box, transmission system and generator or pump could decrease overall wind turbine efficiency to 35% or less.

Calculation of power in the wind

The power in the wind can be computed by using the concept of kinetics (kinetic means relating to or resulting from motion). The wind mill works on the principle of converting kinetic energy of the wind to mechanical energy.

We know that power is equal to energy per unit time. The energy available is the kinetic energy of the wind. The kinetic energy of any particle is equal to one half its mass times the square of its velocity.

i.e., Kinetic Energy of particle $= \frac{1}{2} mv^2$ ... (5.1)

Where,

m $\rightarrow$ Mass of particle (kg)

V $\rightarrow$ Velocity of particle (m/s)

The amount of air passing in unit time, through an area 'A', with velocity 'V' is A $\times$ V, and its mass 'm' is equal to its volume multiplied by its density 'ρ' of air.

i.e., $m = \rho AV$ ... (5.2)

Where, m is the mass of air transversing the area 'A' swept by the rotating blades of a wind mill type generator.

Substituting Equ. (5.2) in Equ. (5.1),

We get,

Kinetic Energy

$$= \frac{1}{2} \rho A V \times V^2$$

$$= \frac{1}{2} \rho A V^3 \text{ (Watts)} \qquad \text{... (5.3)}$$

Above Equ. (5.3), tells us that the maximum wind available the actual amount will be somewhat less because all the available energy is not extractable and is proportional to the cube of the wind speed. It is thus evident that small increase in wind speed can have a marked effect on the power in the wind.

Equ. (5.3), also tells us that the power available is proportional to air density 'ρ'. For example air density at sea level is 1.225 kg/m^3. It may vary 10%–15% during the year because of pressure and temperature change. It changes negligibly with water content.Equ. (5.3), also tells us that the wind power is proportional to the intercept area. Thus an aeroturbine with a large swept area has higher power than a smaller area machine; But, there are added implications. Since, the area is normally of circular of diameter 'D' in harizontal axis aeroturbines, then the area of aeroturbine is given by,

$$A = \frac{\pi}{4} D^2 \text{ (m}^2\text{)} \qquad \text{... (5.4)}$$

Substituting Equ. (5.4) in Equ. (5.3) gives,

Available Wind Power $$P_w = \frac{1}{2} \rho \frac{\pi D^2}{4} V^3 \text{ (watts)}$$

$$= \frac{1}{8} \rho \pi D^2 V^3 \qquad \text{... (5.5)}$$

Equ. (5.5), tells us that the maximum power available from the wind varies according to the square of the diameter of the intercept area (or square of rotor diameter), normally taken to be swept area of the aeroturbine. Thus doubling the diameter of the rotor will result in a four times increase in the available wind power.

From the above discussion gives us in sight into why the designer of an aeroturbine for wind electric use would place such great emphasis on the turbine diameter. The combined effects of wind speed and rotor diameter variation are shown in

Fig. 5.3.

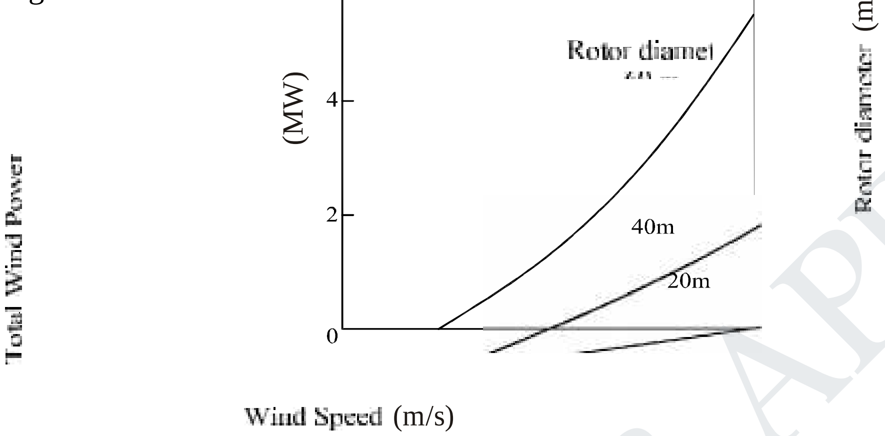


Fig. 5.3 Power variation corresponds to combined effect of rotor diameter and wind speed

Wind machines intended for generating substantial anounts of power should have large rotors and be located in areas of high wind speeds. Where low or moderate powers are adequate, these requirements can be relaxed.

The physical conditions in a wind turbine are such that only a fraction of the available wind power can be converted into useful power. As the free wind stream encounters and passes through a rotor, the wind transfer some of its energy to the rotor and its speed decreases to a minimum in the rotor wake subsequently, the wind stream regains energy from the surrounding air at a sufficient distance from the rotor the free wind speed is restored as shown in Fig. 5.4 (Upper Curve).

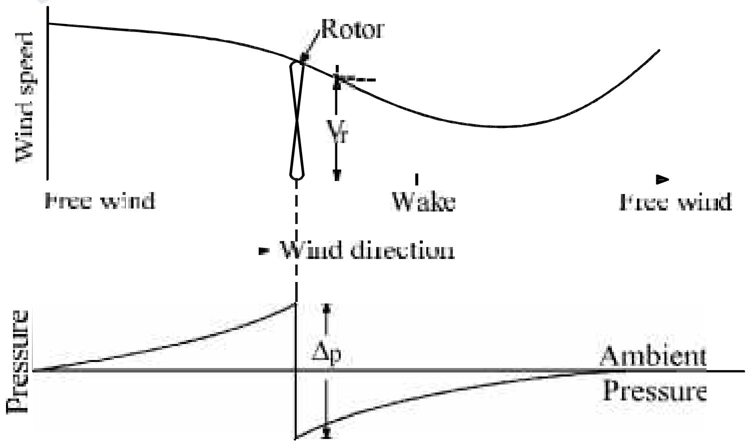


Fig. 5.4 Condition in traversing a wind power.

While the wind speed is decreasing, as just described, the air pressure in the wind stream changes in a different manner as shown in Fig 5.4 (Lower curve). It

e wind approaches the rotor and then drops sharply by an amount

ΔP as it passes through and energy is transferred to the rotor. Finally the pressure increases to the ambient atmospheric pressure.

The power extracted by the rotor is equal to the product of the wind speed as it passes through the rotor (ie. V_r in Fig. 5.4) and the pressure drop ΔP . In order to maximum the rotor power it would therefore be desirable to have both wind speed and pressure drop as large possible. However, as V is increased for a given value of the free wind speed (and air density), ΔP

ncreases at first, passes through a

maximum, and then decreases. Hence for the specified free-wind speed, there is a maximum value of the rotor power.

Power Coefficient

The fraction of the free-flow wind power that can be extracted by the rotor is called the power co-efficient; Thus,

$$\text{Power Coefficient} = \frac{\text{Power of wind rotor}}{\text{Power available in the wind}}$$

Where, power available is calculated from the air density, rotor diameter and free wind speed as discussed earlier. The maximum theoretical power coefficient is equal to 16/27 or 0.593. This value cannot be exceeded by a rotor in a free-flow wind-stream.

An ideal rotor, with propeller-type blades of proper aerodynamic design, would have a power co-efficient approaching 0.59. But such a rotor would not be strong enough to withstand the stresses to which it is subjected when rotating at a high rate in a high-speed wind stream.

For the best practical rotors, the power coefficient is about 0.4 to 0.45, so that the rotors cannot use more than 40 to 45% of the available wind power. In the conversion into electric power, some of the rotor energy is lost and the overall electric power, coefficient of an aerogenerator (i.e., electric power generated/available wind power in practice is about 0.35 (i.e., 35%).

Instantaneous Wind Power

In Equ. (5.5), but now recognizing that 'V', in actuality, is not constant but is represented by a statistically 'Noisy' wind speed time curve, $V_{(t)}$ then the instantaneous power, in the wind would be,

Since, we are normally more interested in average power, we must take time average of both sides of Equ. (5.6), signified by the bar, and written us,
Equ. (5.7) tells us that for a non-steady state wind, it is necessary to cube the measured wind speeds and take the average to find the average wind power available.

It is immediately obvious that this non-steady state case is more complex than the simple steady state case, and it is why for the former case such great emphasis is placed on anemometry data at a proposed Wind Energy Conversion System (WECS) site.
Equ. (5.8) says that the average available wind power per unit area is directly related to the average of wind speed cubed. This is one useful method to characterizing the potential specific power in the wind over geographic area.

In practice a wind turabine's output will vary. There will be periods when there is insufficient wind for the machine to generate any power at all, and times when the wind speeds are so high that the machince has to be shutdown to prevent damage.

There are clear advantages in selecting sites with annual mean wind speeds and building larger rather than smaller wind generators since;

1) The power available in the wind increases as cube of wind speed; Doubling the wind speed increases the power available by eight-times, and

2) Doubling the diameter of the turbine's rotor quadruples the swept area and hence the power output from the device (This law only applies to horizonal axis machines, for vertical axis machines the change in power output with diameter will be determined by the geometry of rotor).

5.3 SITE SELECTION CONSIDERATION FOR WECS

The power available in the wind increases rapidly with the speed, hence wind energy conversion machines should be located preferable in areas where the winds are strong and persistent. Although daily winds at a given site may be highly variable, the monthly and especially annual average speeds are remarkably constant from year to year.

The major controbution to the wind power available at a given site is actually made by winds with speeds above the average. Nevertheless, the most suitable sites for wind turbines would be found in areas where the annual average wind speeds are known to be moderately high or high.

The site choice for a single or a spatial array of WECS is an important matter when wind electrics is looked at from the systems point of view of aeroturbine generators feeding power into a convertional electric grid

If the WECS sites are wrongly or poorly chosen the net wind electrics generated energy per year may be sub optimal with resulting high capital cost for the WECS apparatus, high costs for wind generated electric energy, and low Returns on

Investment. Even if the WECS is to be a small generator not tied to the electric grid, the siting must be carefully chosen if inordinately long break even times are to be avoided. Technical, Economic, Environmental, Social and Other factors are examined before a decison is made to erect a generating plant on a specific site.

Some of the main site selection consideration are given below:

(1) High annual average wind speed:

The power generated by the wind mill depends on cubic value of velocity of wind, the small increases in velocity markedly affect the power in the wind. For example, Doubling the velocity, increases power by a factor of 8. It is obviously desirable to select a site for WECS with high wind velocity. Thus a high average wind velocity is the principle fundamental parameter of concern in initially appraising WECS site. For more detailed estimate value, one would like to have the average of the velocity cubed.

(2) Availability of anemometry data:

It is another important siting factor. Th aenometry data should be available over some time period at the precise spot where any proposed WECS is to be built and that this should be accomplished before a siting decision is made.

(3) Availability of wind $V_{(t)}$ Curve at the proposed site:

This important curve determines the maximum energy in the wind and hence is the principal initially controlling factor in predicting the electrical output and hence revenue return of the WECS machine.

It is desirable to have average wind speed 'V' such that $V \geq 12 - 16$ km/hr (3.5 – 4.5 m/sec) which is about the lower limit at which present large scale WECS generators 'cut in' i.e., start turning. The $V_{(t)}$ Curve also determines the reliability of the delivered WECS generator power, for if the $V_{(t)}$ curve goes to zero there will be no generated power during that time.

If there are long periods of calm the WECS reliability will be lower than if the calm periods are short. In making such realiability estimates it is desirable to have measured $V_{(t)}$ Curve over about a 5 year period for the highest confidence level in the reliability estimate.

(4) Wind structure at the proposed site:

The ideal case for the WECS would be a site such that the $V_{(t)}$ Curve was flat, i.e., a smooth steady wind that blows all the time; but a typical site is always less than ideal. Wind specially near the ground is turblent and gusty, and changes rapidly in direction and in velocity. This depature from homogeneous flow is collectively referred to as "the structure of the wind".

(5) Altitude of the proposed site:

It affects the air density and thus the power in the wind and hence the useful WECS electric power output. Also, as is well known, the wind tend to have higher velocities at higher altitudes. One must be careful to distinguish altitude from height above ground. They are not the same except for a sea level WECS site.

(6) Terrain and its aerodynamic:

One should know about terrain of the site to be chosen. If the WECS is to be placed near the top but not on the top of a not too blunt hill facing the prevailing wind, then it may be possible to obtain a 'speed-up' of the wind velocity over what it would otherwise be. Also the wind here may not flow harizontal making it necessary to tip the axis of the rotor so that the aeroturbine is always perpendicular to the actual wind flow.

It may be possible to make use of hills or mountains which channel the prevailing winds into a pass region, thereby obtaining higher wind power.

(7) Local Ecology:

If the surface is base rock it may mean lower hub heights hence lower structure cost. If trees or grass or vegetation are present, all of which tend to destructure the wind, the higher hub heights will be needed resulting in larges system costs than the bare ground case.

(8) Distance to road or railways:

This is another factor the system engineer must consider for heavy machinery, structures, materials, blades and other apparatus will have to be moved into any choosen WECS site.

(9) Nearness of site to local centre/users:

This obvious criterion minimizes transmission line length and hence losses and costs. After applying all the previous siting criteria, hopefully as one narrows the proposed WECS sites to one or two they would be relatively near to the user of the generated electric energy.

(10) Nature of ground:

Ground condition should be such that the foundations for a WECS are secured. Ground surface should be stable. Erosion problem should not be there, as it could possibly later wash out the foundation of a WECS, destroying the whole system.

(11) Favourable land cost:

Land cost should be favourable as this along with other siting costs, enters into the total WECS system cost.

(12) Other conditions such as icing problem, salt spray or blowing dust should not present at the site, as they may affect aeroturbine blades or environmental is generally adverse to machinery and electrical apparatus.

WIND ENERGY CONVERSION

The fact that the wind is variable and intermittent source of energy is immaterial for some application such as pumbing water for land drainage - provided, of course, that there is a broad match between the energy supplied over any critical period and the energy required. If the wind blows, the job gets done; if it does not, the job waits.

However, for many of the uses to which electricity is put, the interruption of supply may be highly inconvenient. Operators or users of wind turbines must ensure that there is some form of back-up can take the form of

(i) Battery storage,

(ii) Connection with the local electricity distribution system, or

(iii) A stand by generator powered by liquid or gaseous fuels.

For utilities responsible for public supply, the integration of medium sized and large wind turbines into their distribution network could require some additional plant which is capable of responding quickly to meet fluctuating demand.

Small Producers

Private citizens in several countries have won to right to operate wind generator and other renewable energy systems and to export power to the grid. For most small wind generators this requires that the output is conditioned, so that in conforms to the frequency and phase of the mains supply. Only few small units are designed to maintain a constant rotational rate, so that can be synchronized to the mains frequency and feed electricity directly into the grid. Most produce Direct Current (DC) or variable output Alternating Current (AC).

Power conditioning is redily achieved using an electronic black-box called a "Synchronous Inverter" and although this is an expensive item of equipment, it does eliminate the need for batteries and for conversion of home appliances to run on DC.

Where there is no grid connection, electricity that is surplus to immediately requirements must be stored on site using heavy duty batteries. It can be recovered later when the demand exceeds the supply. An alternative is to dump it (by generating and dissipating heat) or better, to convert it into heat that can be stored, for example as hot water in a well-insulated tank.

Large Producers

Large and medium - sized wind generators are designed to give a stable and constant electrical output over a wide range of wind speeds and to feed current directly into the grid. they operate primarily as fuel savers, reducing the utility's total fuel burn.

The choice of generator type depends on the size of the local distribution grid and its associated generating capacity.

An induction generator would normally be used where there is a significant amount of other generating capacity (which could provide the necessary reactive power for excitation). Induction generators are robust and reliable and require minimal control equipment.

For isolated networks where other local generating capacity is limited, a synchronous generator is more appropriate. Synchronous generator are more complex and therefore more expensive than induction machines.

Lift and Drag Force

The extraction of power, and hence energy, from the wind depends on creating certain forces and applying them to rotate (or to translate) a mechanism. There are two primary mechanisms for producing forces from the wind: Lift and Drag.

By definition of Lift forces act perpendicular to the air flow, while drag forces act in the direction flow.

Lift forces are produced by changing the velocity of the air stream flowing over either side of the lifting surface. Speeding up the air flow causes the pressure to drop, while slowing the air stream down leads to increase in pressure.

In other words, any change in velocity generates a pressure difference across the lifting surface. This pressure difference produces a force that begins to act on the high pressure side and moves towards the low pressure side of the lifting surface which is called an **airfoil**.

A Good airfoil has a high lift/drag ratio, in some cases it can generate lift forces perpendicular to the air stream direction that are 30 times as great as the drag force parallel to the flow. The lift increases as the angle formed at the junction of the airfoil and the air stream (the angle of attack) becomes less and less acute, upto the point where the angle of the airflow on the low pressure side becomes excessive. When this happens, the air flow breaks away from the low pressure side.

A lot of turbulence ensues, the lift decreases and the drag increases quite subtantially; this phenomenon is known as **Stalling**.

For efficient operation, a wind turbine blade needs to function with as much lift and as little drag as possible because drag dissipates energy. As lift does not involve anything more complex than deflecting the air flow, it is usually an efficient process. The design of each wind turbine specifies the angle at which the airfoil should bet set to achieve the maximum lift to drag ratio.

In addition to airfoils, there are two other mechanisms for creating lift. One is the so-called **Magnus Effect**, caused by spinning a cylinder in an air stream at a high-speed of rotation. The spinnings slows down the air speed on the side where the cylinder is moving into wind and increases it on the other side; the result is similar to an airfoil. This principle has been put to practical use in one or two cases but is not generally employed. The second way is to blow air through narrow slots in a cylinder, so that it emerges tangentially; this is known as a **Thwaits Slot**.Thwaits Slots also creates a rotation (or circulation) of airflow, which in turn generates lift. Because the lift drag ratio of airfoils is generally much better than those of rotating or slotted cylinders, the latter techniques probably have little practical potential. Fig. 5.6 and Fig. 5.7 shows the forces acting on the blade and cross section across A–A. The wind mill blade 'sees' the resultant vector 'V_r'. The blades need to be twisted because 'r' varies in proportion to radius.

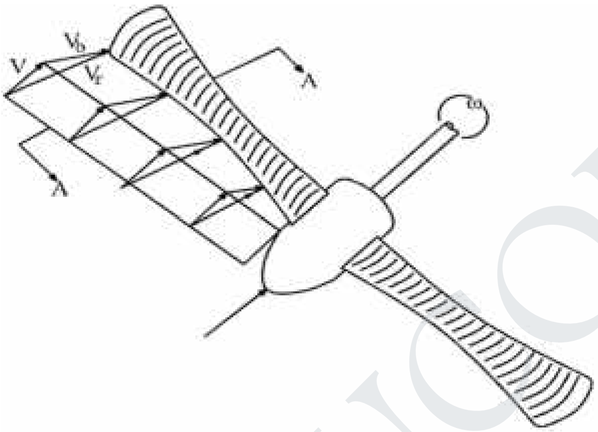
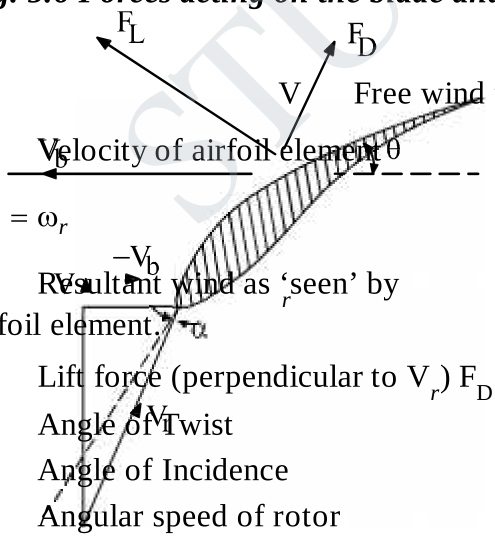


Fig. 5.6 Forces acting on the blade and cross-section across A–A.



Symbol

V Free wind velocity

V_b Velocity of airfoil element

$V_b = \omega_r$

V_r Resultant wind as 'seen' by airfoil element.

F_L Lift force (perpendicular to V_r) F_D Drag Force

θ Angle of Twist

α Angle of Incidence

ω Angular speed of rotor

r Distance of airfoil element from its axis of rotation.

Fig. 5.7 Forces acting on the blade and cross - section across A–A.

5.4. Basic components of a WECS (Wind Energy Conversion System)

The simple structure of Horizontal Axis Wind Turbine (Wind Mill) shown in Fig. 5.11.

The following components are used in a Wind Mill.

i. Anemometer

Measures the wind speed and transmits wind speed data to the controller.

ii. Blades

Most turbines have either two or three blades. Wind blowing over the blades causes the blades to “lift” and rotate.

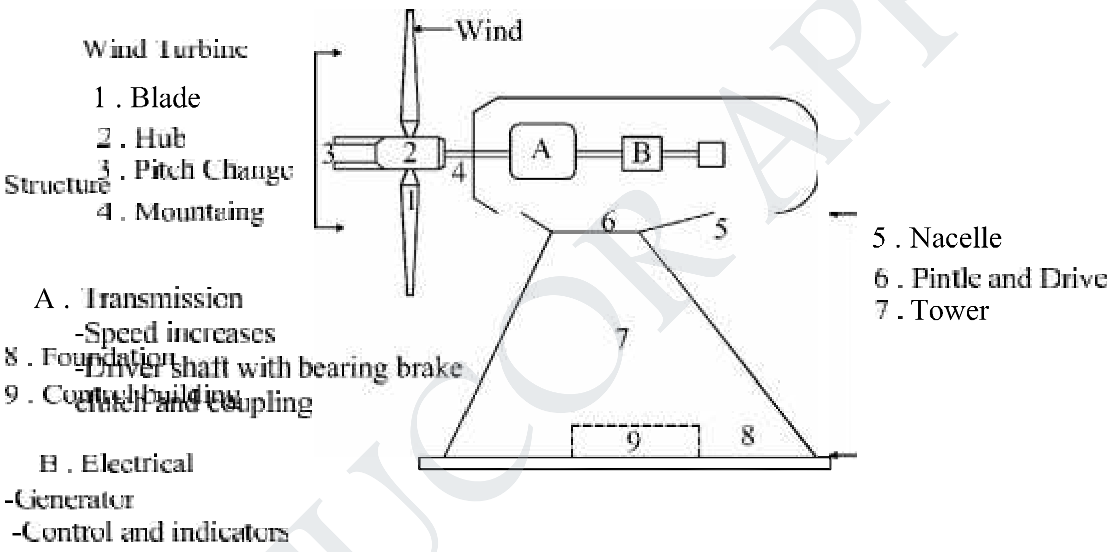


Fig. 5.11 Simple structure and components of a wind mill

iii. Brake

A disc brake, which can be applied mechanically, electrically, or hydraulically to stop the rotor in emergencies.

iv. Controller

The controller starts up the machine at wind speeds of abut 8 to 16 miles per hour (mph) and shuts off the machine at about 55 mph. Turbines do not operate at wind speeds above about 55 mph because they might be damaged by the high winds.

v. Gear box

Gears connect the low-speed shaft to the high-speed shaft and increase the rotational speeds from about 30 to 60 rotations per minute (rpm) to about 1000 to 1800 rpm, the rotational speed required by most generators to produce electricity. The gear box is a costly (and heavy) part of the wind turbine and engineers are exploring “direct-drive” generators that operate at lower rotational speeds and don’t need gear boxes.

vi. Generator

Usually an off-the-shelf induction generator that produces 60-cycle AC electricity.

vii. High-speed shaft

Drives the generator.

viii. Low-speed shaft

The rotor turns the low-speed shaft at about 30 to 60 Rotations per minute.

ix. Nacelle

The nacelle sits atop the tower and contains the gear box, low-and high-speed shafts, generator, controller, and brake. Some nacelles are large enough for a helicopter to land on.

x. Pitch

Blades are turned, or pitched, out of the wind to control the rotor speed and keep the rotor from turning in winds that are too high or too

xi. Rotor

The blades and the hub together are called the rotor.

xii. Tower

Towers are made from tubular steel (shown here), concrete, or steel lattice. Because wind speed increases with height, taller towers enable turbines to capture more energy and generate more electricity.

xiii. Wind direction

This is an "upwind" turbine, so-called because it operates facing into the wind. Other turbines are designed to run "downwind," facing away from the wind.

xiv. Wind vane

Measures wind direction and communicates with the yaw drive to orient the turbine properly with respect to the wind.

xv. Yaw drive

Upwind turbines face into the wind; the yaw drive is used to keep the rotor facing into the wind as the wind direction changes. Downwind turbines don't require a yaw drive, the wind blows the rotor downwind.

xvi. Yaw motor

Powers the yaw drive.

5.6 CLASSIFICATION OF WECS

1. Based on axis

a. Horizontal axis machines. b.

Vertical axis machines.

2. According to size

a. Small size machines(upto 2kW)

b. Medium size machines.(2 to 100kW)

c. Large size machines.(100kW and above)

i. Single generator at single site. ii.

Multiple generators

3. Type of output

a. DC output

i. DC generator

ii. Alternator rectifier

b. AC Output

i. Variable frequency, variable or constant voltage AC. ii.

Constant frequency, variable or constant voltage AC.

4. According to the rotational speed of the aero turbines

a. Constant speed and variable pitch blades.

b. Nearly constant speed with fixed pitch blades. c.

Variable speed with fixed pitch blades.

i. Field modulated system.

ii. Double output indication generator. iii. AC-

DC-AC link.

iv. AC commutator generator.

Variable speed constant frequency generating systems

5. As per the utilization of output.

a. Battery storage.

b. Direct conversion to an electro magnetic energy converter. c.

Thermal potential.

d. Inter convention with conventional electric utility guides.

5.6 TYPES OF WIND TURBINES

Wind turbines can be separated into two basic types determined by which way the turbine spins. Wind turbines that rotate around a horizontal axis are more common (like a wind mill), while vertical axis wind turbines are less frequently used (Savonius and Darrieus are the most common in the group).

5.6.1 Horizontal Axis Wind Turbines (HAWT)

Horizontal axis wind turbines, also shortened to HAWT, are the common style that most of us think of when we think of a wind turbine. A HAWT has a similar design to a windmill, it has blades that look like a propeller that spin on the horizontal axis as shown in Fig. 5.8.

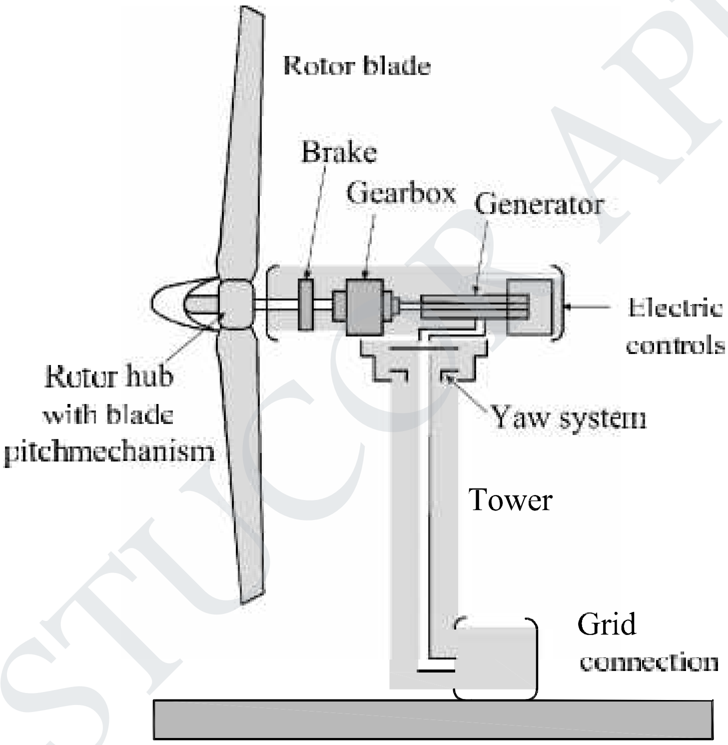


Fig. 5.8 Schematic Structure ofHorizontal Axis Wind Turbines

Horizontal axis wind turbines have the main rotor shaft and electrical generator at the top of a tower, and they must be pointed into the wind. Small turbines are pointed by a simple wind vane placed square with the rotor (blades), while large turbines generally use a wind sensor coupled with a servo motor to turn the turbine into the wind. Most large wind turbines have a gearbox, which turns the slow rotation of the rotor into a faster rotation that is more suitable to drive an electrical generator.

Since a tower produces turbulence behind it, the turbine is usually pointed upwind of the tower. Wind turbine blades are made stiff to prevent the blades from being pushed into the tower by high winds. Additionally, the blades are placed a considerable distance in front of the tower and are sometimes tilted up a small amount.

Downwind machines have been built, despite the problem of turbulence, because they don't need an additional mechanism for keeping them in line with the wind. Additionally, in high winds the blades can be allowed to bend which reduces their swept area and thus their wind resistance. Since turbulence leads to fatigue failures, and reliability is so important, most HAWTs are upwind machines.

Important point to remember recording HAWT :

- ✓ Lift is the main force
- ✓ Much lower cyclic stresses
- ✓ 95% of the existing turbines are HAWTs
- ✓ Nacelle is placed at the top of the tower
- ✓ Yaw mechanism is required

HAWT Advantages :

1. The tall tower base allows access to stronger wind in sites with wind shear. In some wind shear sites, every ten meters up the wind speed can increase by 20% and the power output by 34%.

2. High efficiency, since the blades always move perpendicularly to the wind, receiving power through the whole rotation. In contrast, all vertical axis wind turbines, and most proposed airborne wind turbine designs, involve various types of reciprocating actions, requiring airfoil surfaces to backtrack against the wind for part of the cycle. Backtracking against the wind leads to inherently lower efficiency.

HAWT Disadvantages :

1. Massive tower construction is required to support the heavy blades, gearbox, and generator.

2. Components of a horizontal axis wind turbine (gearbox, rotor shaft and brake assembly) being lifted into position.

3. Their height makes them obtrusively visible across large areas, disrupting the appearance of the landscape and sometimes creating local opposition.

4. Downwind variants suffer from fatigue and structural failure caused by

turbulence when a blade passes through the tower's wind shadow (for this reason, the majority of HAWTs use an upwind design, with the rotor facing the wind in front of the tower).

5. HAWTs require an additional yaw control mechanism to turn the blades toward the wind.

6. HAWTs generally require a braking or yawing device in high winds to stop the turbine from spinning and destroying or damaging itself.

5.6.2 Vertical Axis Wind Turbines (VAWT)

Verticalaxis wind turbines, as shortened to VAWTs, have the main rotor shaft arranged vertically as shown in Fig 5.9. The main advantage of this arrangement is that the wind turbine does not need to be pointed into the wind. This is an advantage on sites where the wind direction is highly variable or has turbulent winds.

With a vertical axis, the generator and other primary components can be placed near the ground, so the tower does not need to support it, also makes maintenance easier. The main drawback of a VAWT generally create drag when rotating into the wind. It is difficult to mount vertical-axis turbines on towers, meaning they are often installed nearer to the base on which they rest, such as the ground or a building rooftop. The wind speed is slower at a lower altitude, so less wind energy is available for a given size turbine. Air flow near the ground and other objects can create turbulent flow, which can introduce issues of vibration, including noise and bearing wear which may increase the maintenance or shorten its service life. However, when a turbine is mounted on a rooftop, the building generally redirects wind over the roof and this can double the wind speed at the turbine. If the height of the rooftop mounted turbine tower is approximately 50% of the building height, this is near the optimum for maximum wind energy and minimum wind turbulence.

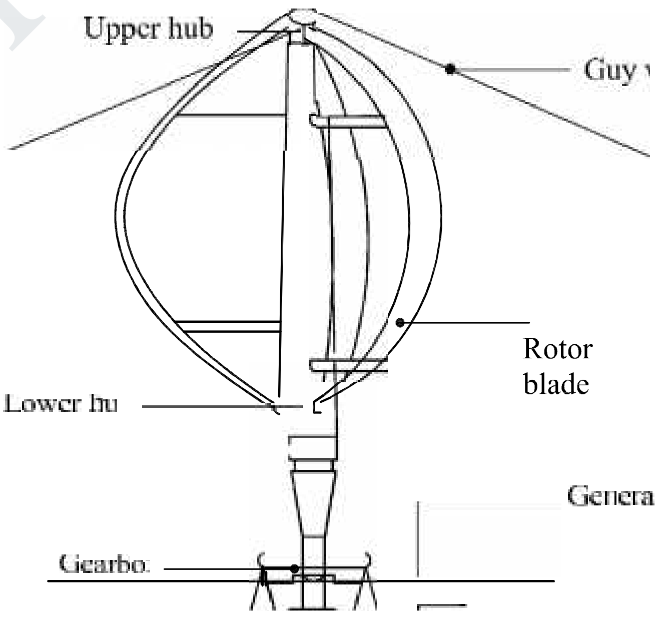


Fig. 5.9 Schematic Structure of Vertical Axis Wind Turbines (Darrieus wind turbine)

Important point to remember recording VAWT :

- ✓ Nacelle is placed at the bottom
- ✓ Drag is the main force
- ✓ Yaw mechanism is not required
- ✓ Lower starting torque
- ✓ Difficulty in mounting the turbine
- ✓ Unwanted fluctuations in the power output

VAWT Advantages

1. No yaw mechanisms is needed.

2. A VAWT can be located nearer the ground, making it easier to maintain the moving parts.

3. VAWTs have lower wind startup speeds than the typical the HAWTs.

4. VAWTs may be built at locations where taller structures are prohibited.

5. VAWTs situated close to the ground can take advantage of locations where rooftops, mesas, hilltops, ridgelines, and passes funnel the wind and increase wind velocity.

VAWT Disadvantages

1. Most VAWTs have a average decreased efficiency from a common HAWT, mainly because of the additional drag that they have as their blades rotate into the wind. Versions that reduce drag produce more energy, especially those that funnel wind into the collector area.

2. Having rotors located close to the ground where wind speeds are lower and do not take advantage of higher wind speeds above.

3. Because VAWTs are not commonly deployed due mainly to the serious disadvantages mentioned above, they appear novel to those not familiar with the wind industry. This has often made them the subject of wild claims and investment scams over the last 50 years.

5.6.3 VAWT Subtypes

Darrieus Wind Turbine

Darrieus turbine has long, thin blades in the shape of loops connected to the top and bottom of the axle; it is often called an "eggbeater windmill." It is named after the French engineer Georges Darrieus who patented the design in 1931. (It was manufactured by the US company FloWind which went bankrupt in 1997). The Darrieus turbine is characterized by its C-shaped rotor blades which give it its eggbeater appearance. It is normally built with two or three blades.

Darrieus wind turbines are commonly called “Eggbeater” turbines, because they look like a giant eggbeater. They have good efficiency, but produce large torque ripple and cyclic stress on the tower, which contributes to poor reliability. Also, they generally require some external power source, or an additional Savonius rotor, to start turning, because the starting torque is very low. The torque ripple is reduced by using three or more blades which results in a higher solidity for the rotor. Solidity is measured by blade area over the rotor area. Newer Darrieus type turbines are not held up by guy-wires but have an external superstructure connected to the top bearing.

One type of VAWT is the Darrieus wind turbine that uses the lift forces of the wind to rotate the aerofoils of the machine. The tip speed ratio (TSR) indicates the rotating velocity of the turbines to the velocity of the wind. In this case, the TSR has a higher value than 1, meaning that the velocity rotation here is greater than the velocity of wind and generates less torque. This makes Darrieus turbines excellent electricity generators. The turbine blades have to be reinforced in order to sustain the centrifugal forces generated during rotation, but the generator itself accepts a lower amount of force than the Savorius type. A drawback to the Darrieus wind turbines is the fact that they cannot start rotation on their own. A small motor, or another Savonious turbine, maybe needed to initiate rotation.

Advantages

1. The rotor shaft is vertical. Therefore it is possible to place the load, like a generator or a centrifugal pump at ground level. As the generator housing is not rotating, the cable to the load is not twisted and no brushes are required for large twisting angles.
2. The rotor can take wind from every direction.
3. The visual acceptation for placing of the windmill on a building might be larger than for an horizontal axis windmill.
4. Easily integrated into buildings

Disadvantages

1. Difficult start unlike the Savonius wind turbine
2. Low efficiency

Savonius Wind Turbine

The Savonius wind turbine is a type of vertical-axis wind turbine invented by the Finnish engineer SigurdSavonius in the 1920’s. It is one of the simplest wind turbine designs. It consists of two to three “scoops” that employ a drag action to convert wind energy into torque to drive a turbine. When looked at from above in cross-section, a two scoop Savonius turbine looks like an S-shape. Due to the curvature of the scoops, the turbine encounters less drag when moving against the wind than ...ses t... he turbine to spin in any wind regardless of facing.

Drag-type wind turbines such as the Savonius turbine are less efficient at using the wind's energy than lift-type wind turbines, which are the ones most commonly used in wind farms.

A Savonius is a drag type turbine, they are commonly used in cases of high reliability in many things such as ventilation and anemometers. Because they are a drag type turbine they are less efficient than the common HAWT. Savonius are excellent in areas of turbulent wind and self starting. The schematic diagram of Savonius wind turbine as shown in Fig. 5.10.

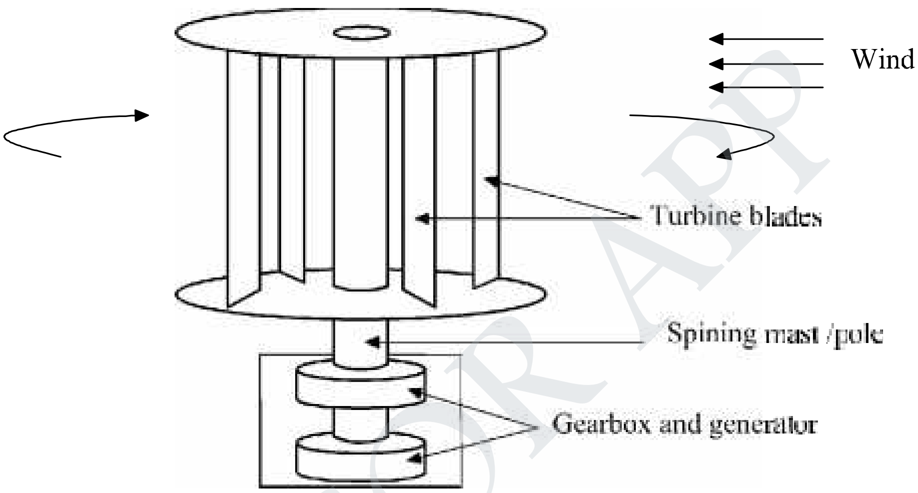


Fig. 5.10 Schematic Structure of Vertical Axis Wind Turbines (Savonius wind turbine)

Advantages

1. Having a vertical axis, the Savonius turbine continues to work effectively even if the wind changes direction.

2. Because the Savonius design works well even at low wind speeds, there's no need for a tower or other expensive structure to hold it in place, greatly reducing the initial setup cost.

3. The device is quiet, easy to build, and relatively small.

4. Because the turbine is close to the ground, maintenance is easy.

Disadvantage

The scoop system used to capture the wind's energy is half as efficient as a conventional turbine, resulting in less power generation.

5.7 ANALYSIS OF AERODYNAMIC FORCES ACTING ON THE BLADE

Aerodynamic forces acting on a blade element tending to make it rotate, these are important parameters for a system engineer. There are several basic types of blades on aeroturbine may have, e.g., sails, planes and aerodynamic surfaces based on the air craft wing cross-section for which there are many kinds. The early history of wind mills is based on the first two; modern higher efficiency wind-electric generators are based on use of blades with aerodynamic surfaces.

Consider the aerodynamic blade shown in Fig. 5.12. The blade can be thought of as a typical cross-sectional element of a two-bladed aeroturbine. The element shown is at some redius 'r' from the axis of rotation. It is moving to the left. Because the blade is moving in the plane of rotation it sees a tangential wind velocity, V_T, in the plane of rotation.

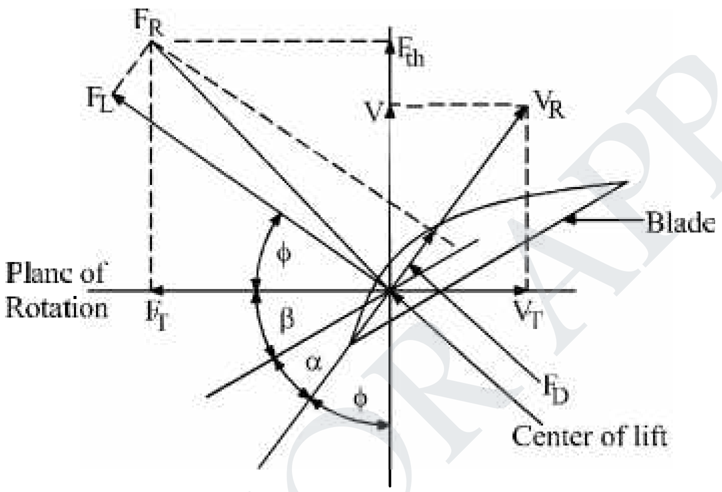


Fig. 5.12 Vector diagram of forces on a elemental blade section of an aeroturbine. (The blade is rotating to the left)

V → Impinging wind velocity,

V_T → Wind velocity in plane of rotation due to blade turning, V_R →

Resultant wind velocity seen by Aeroturbine blade,

F_L → Lift force (Normal to V_R),

F_D → Drag force (Parallel to V_R),

F_R → Resultant force on blade,

F_T → Torque producing component of F_R making aeroturbine rotate,

F_{th} → Thrust force component of F_R,

α → Angle of attack of blade, and

β → Blade pitch angle.

This component added vectorially to the impinging wind velocity gives the resulting wind velocity, V_R, seen by the rotating blade element. At right angles to V_R, is the lift force F_L caused by the aerodynamic shape of the blade. The drag force, F_D is parallel to V_R. The vector sum of F_L and F_D is F_R which has a torque producing component, F_T and a thrust producing component. The former is what drives the aero-turbine rotationally and the latter tends to flex the blade and also overturn the aerogenerator.

The vector diagram is centred on the centre of lift of the aerodynamic blade. As is well-known from aircraft wind theory, one of the critical parameters is 'α', the angle of attack of the aerodynamic element. It determines lift and drag forces and hence speed and torque output of the aeroturbine. These quantities can be varied by changing the blade pitch angle 'β', and this is the basic torque control method used on large variable pitch wind-electric generators. The torque would determine the AC output power if a synchronous generator was used.

Since V_T increases linearly as we go out radically, 'r', on an inclined aeroturbine blade, it is necessary to adjust 'β'

is made small while at small ‘r’, ‘β’ is large. Thus the blade ‘bites’ the air more in close than near the tips. These considerations result in an aeroturbine blade with an apparent twist in it. The need for twisting wind mills sails was recognised hundreds of years ago and widely used on Dutch wind mills.

Having now achieved an elementary understanding of the basics of what turns the aeroturbine, we see that the airfoil orientation for an aeroturbine driven by the wind is exactly opposite to the orientation of a classical airplane propeller which is mechanically driven and whose function is to give a lift force in the axial direction.

Thus, though aircraft wing theory is applicable to the operation of an aeroturbine, direct use of a classical aircraft propeller on an aeroturbine would not produce the most efficient aeroturbine because the aerodynamic surface is oriented backwards to what it should be

5.8 PERFORMANCE OF WIND-MACHINES

WECS efficiency is of interest to both aerogenerator designers and system engineers. As WECS is a capital intensive technology, it is desirable for the overall wind electric plant to have the highest efficiency possible, thus optimally utilizing capital resources and minimizing the busbar electric energy cost.

The overall conversion efficiency, η_0 of an aerogenerator of the general type is

$$\eta_0 = \frac{\text{Useful Output Power}}{\text{Wind Power Input}} = \eta_A \cdot \eta_G \cdot \eta_C \cdot \eta_{Gen}$$

Where,

η_A → Efficiency of the aeroturbine,

η_G → Efficiency of gearing,

η_C → Efficiency of the mechanical coupling, and

η_{Gen} → Efficiency of the generator.

Above equation shows an application of cascaded energy conversion, from which overall efficiency will be strongly determined by the lowest efficiency converter in the cascade. For the aerogenerator this is the aeroturbine; the efficiency of the remaining three elements can be made quite high but less than 100 percent. It is now evident why so much emphasis is placed on the efficiency of the aeroturbine in wind literature.

Consider an arbitary aeroturbine (Here Aeroturbine is not equal to aerogenerator) of cross-sectional area ‘A’ driven by the wind. Its efficiency would be:

$$\eta_A = \frac{\text{Useful shaft power output}}{\text{nd pow er input}}$$

Thus the coefficient of performance of an aeroturbine is the fraction of power in the wind through the swept area which is converted into useful mechanical shaft power.

The coefficient of performance is widely utilised throughout the recent wind research. We have seen that C_p for horizontal axis wind machine has theoretical maximum value = 0.593.

This theoretical efficiency limitation on a wind energy conversion system is loosely analogical similar to the thermodynamic carnot efficiency limitation on a conventional thermal power plant.

We know that the convertible power of energy is proportional to the cube of the wind speed. Thus if the wind speed decreases by 20%, the power output is reduced by almost 50%. The wind speed may very considerable from day to day and from season to season. The efficiency of a wind generator depends on the design of an wind rotor and rotation speed, expressed as the ratio of blade tip speed to wind speed i.e., $\frac{V_T}{V}$ (is called as TSR - Tip Speed Ratio), if n is the rotation frequency, ie., rotation per second, if a rotor diameter D metres, the tip speed is πnD m/sec.

The dependence of the power coefficient on the tip speed ratio (TSR) for some common rotor types is indicated in Fig. 5.13. It is seen that the two-bladed propeller type of rotor can attain a much higher power coefficient (i.e., it is more efficient) than the American multi-blade wind mill and the classical Dutch four-bladed windmill. In practice two-bladed propeller (horizontal axis) rotor are found to attain a maximum power coefficient of 0.40 to 0.45 at a tip speed ratio in the range a roughly 6 to 10.

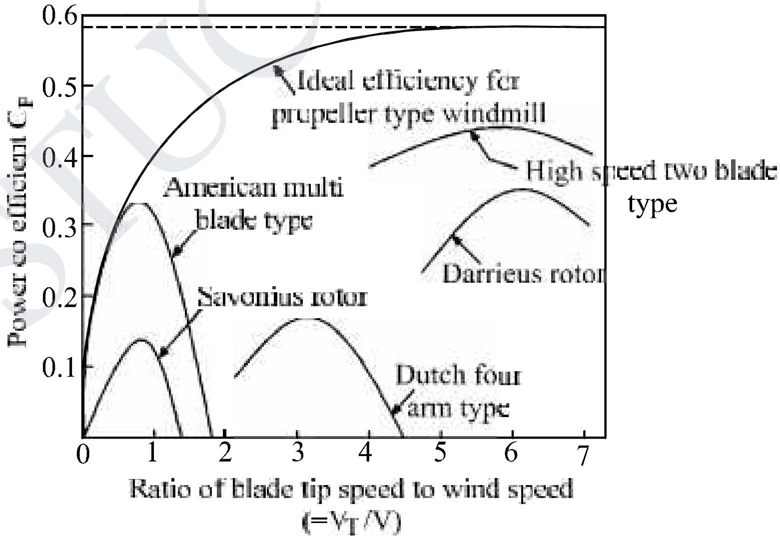


Fig. 5.13 Typical performance of wind machines

Golding has derived the expression for aeroturbine efficiency as,

$$\eta_A = \frac{1 - K\frac{V_T}{V}}{1 + K\frac{V}{V_T}} = CP \qquad \text{... (5.32)}$$

Where, $K = \frac{F_D}{F_L} = \frac{\text{Drag}}{\text{Lift}}$ ratio

Clearly if there were no drag, i.e., K = 0, then the efficiency would be unity $(\eta_A = 1)$. In actuality K can be made very small, depending on the airfoil choosen and the angle of attack. Also above equation tells us the efficiency would be low if $\frac{V_T}{V}$ were very large or again if it were small. One suspicians that there exists an optimum ratio of $\frac{V_T}{V}$ (i.e., TSR).

If one assembles models of various types of aeroturbine blades and puts them in a wind tunnel and runs carefully controlled experiments of their efficiencies as function of their TSR'S, then one obtains a family of curves similar to that shown in Fig. 5.14.

The various types of windmills performance characteristics with respect to TSR and torque coefficient are shown in Fig. 5.14.

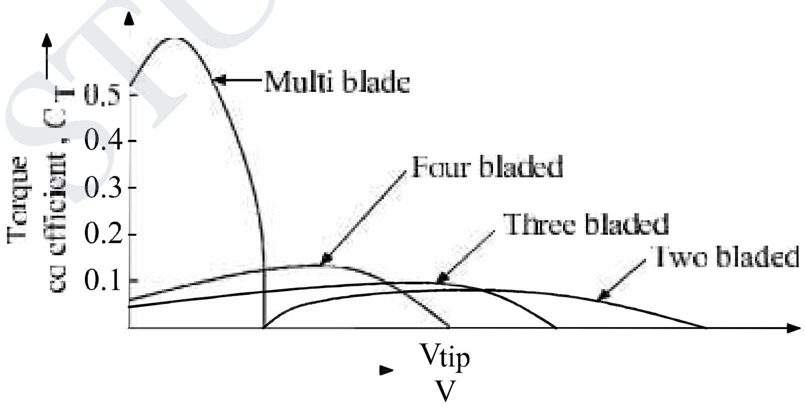


Fig. 5.14 Performance of wind machines

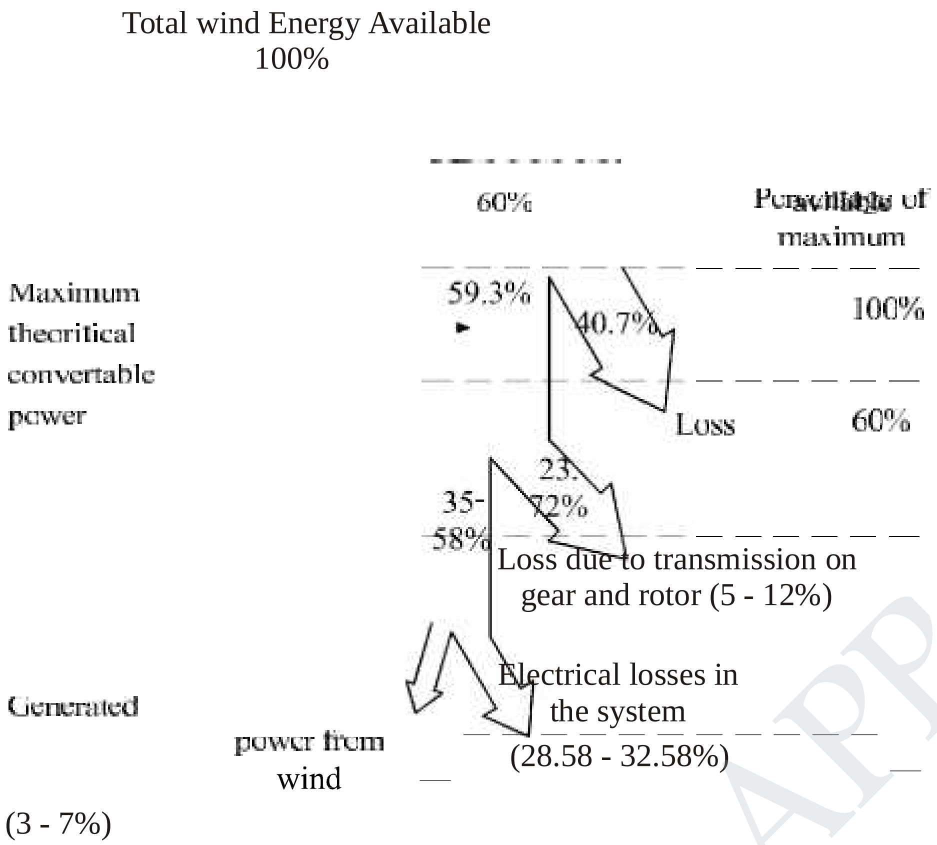


Fig. 5.15 Power generation from wind turbine considering losses (Power Flow Diagram)

Only at intermediate wind speed does the system efficiency reach its optimum and the power extracted then follows a V^3 law. The range of optimum operation depends on the engine which was selected so as to give optimum output over the year.

Considering the range of wind speed is 10–14 m/sec, 14 m/sec being the rated velocity maintained also at higher wind speeds. Only there depending on the degree of sophistication, could between 70 and 85% of the convertible wind energy by transforming into kinetic energy by rotor upto 20% of this energy would be lost in the gear type transmission, which connects the rotor shaft to the electric generator. The energy conversion from wind to utilities with losses in indicated by energy flow