Lecture Notes

on

UTILIZATION OF ELECTRICAL ENERGY

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Introduction
Utilization of Electrical Energy

UNIT-1

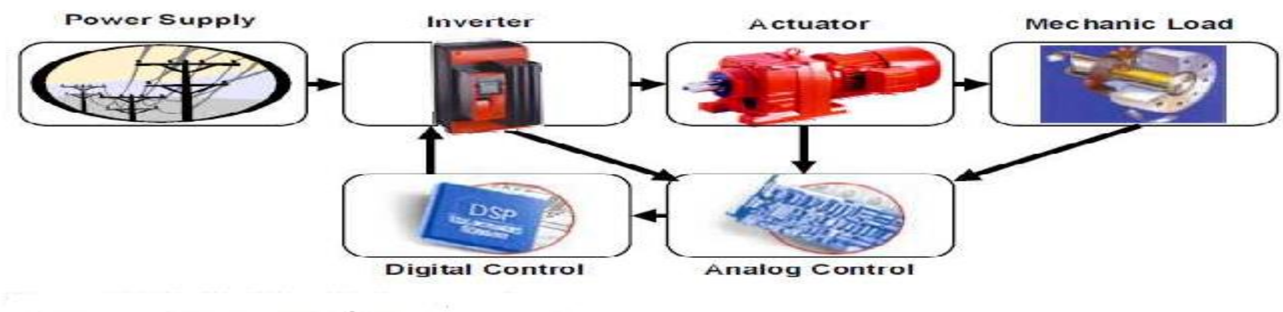
SELECTION OF MOTORS

- **Principles & characteristics of motors with respect to speed temperature & loading conditions**.

➢ Types & Applications of Electric drives.

➢ Types of Industrial loads.

➢ Load Equalization



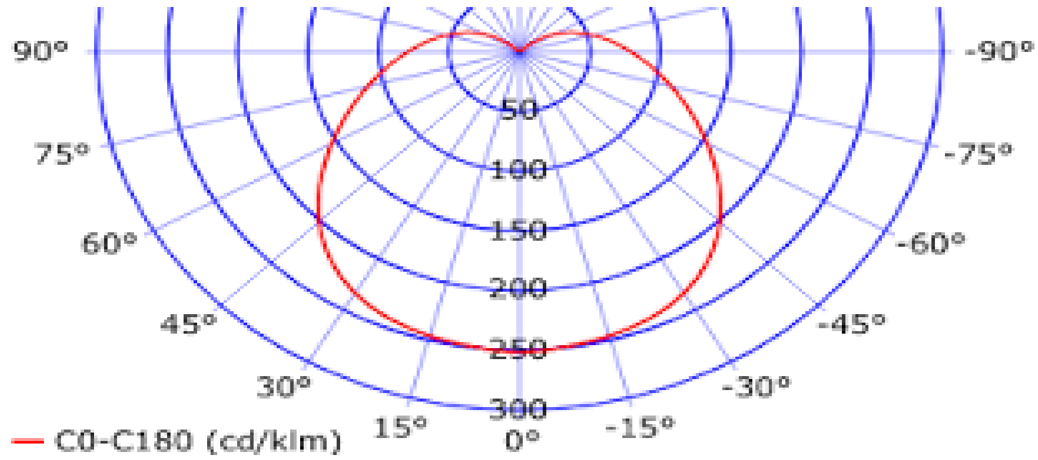
UNIT-2
ILLUMINATION FUNDAMENTALS

➢ Basic principles of Illumination & its measurement:

Laws of illumination: Inverse square law

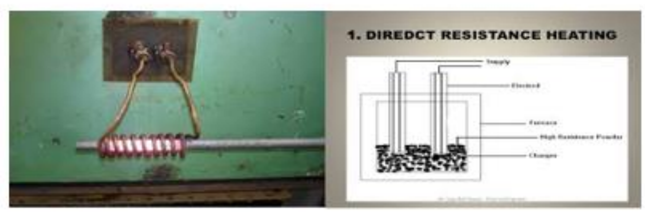
Lambert's cosines law.

polar curves

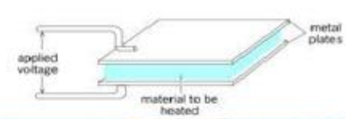


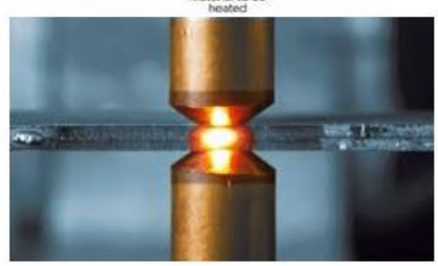
UNIT-3
ELECTRIC HEATING & ELECTRIC WELDING

<u>Types of Heating & welding techniques</u>.

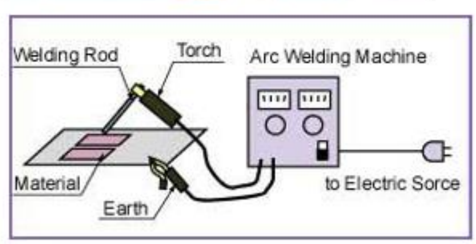


- Electric heating: Resistance heating
  Induction heating
  Dielectric heating





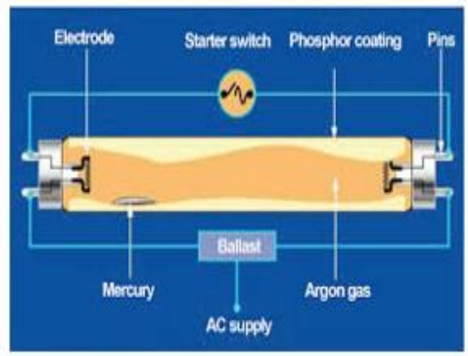
- Electric welding: Resistance welding
  Arc welding



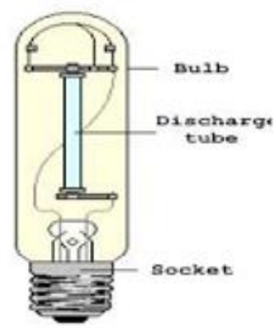
UNIT-4
Various Illumination methods

Different types of Lightining system including Design:

- Discharge lamps : **Filament Lamps** **Fluoroscent Lamps**



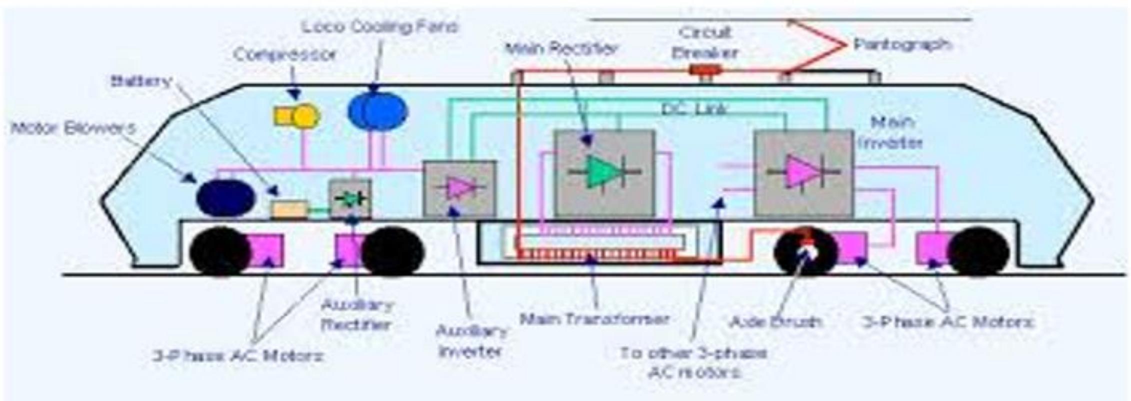
Mercury vapour Lamps **sodium vapour Lamps**



UNIT-5
ELECTRIC TRACTION-1

Basic principles of Electric traction including Speed-time curves of different traction services.

- Review of existing Electric traction systems.
- System of Electric traction & track electrification



Block Diagram of Modern AC Electric Locomotive

Calculation of various Traction systems:

- Tractive effort
- specific energy consumption & power
- Principles of energy efficient motors.

UNIT 1

Selection of Motors

1.1 INTRODUCTION

Motor control is required in large number of industrial and domestic applications such as transportation systems, rolling mills, paper machines, textile mills, machine tools, fans, pumps, robots, and washing machines. Systems employed for motion control are called *drives* and may employ any of the prime movers. Drives employing electric motors are known as electric drives.

Nowadays, in electric power stations generating large amounts of electric energy for agriculture, industry, domestic needs, and electrified traction facilities and in driving all kinds of working machines, electric motor is essential, which is the predominant type of drive so the term electric drive being applied to it.

Electric drive becomes more popular because of its simplicity, reliability, cleanliness, easiness, and smooth control. Both AC and DC motors are used as electric drives; however, the AC system is preferred because:

- It is cheaper.
- It can be easily transmitted with low-line losses.
- It can be easy to maintain the voltage at consumer premises within prescribed limits.
- It is possible to increase or decrease the voltage without appreciable loss of power.

In spite of the advantages of AC motor, sometimes DC motor is used because:

- In some processes, such as electrochemical and battery charging, DC is the only type of power that issuitable.
- The speed control of DC motors is easy rather than AC; thus, for variable speed applications such as liftand Ward Leonard system, the DC motors are preferred.
- DC series motor is suited for traction work because of high starting torque.

BLOCK DIAGRAM OF ELECTRIC DRIVE

Source

1-φ and 3-φ, 50-Hz AC supplies are readily available in most locations. Very low power drives are generally fed from 1-φ source; however, the high power drives are powered from 3-φsource;some of the drives are powered from a battery.

Ex: Fork lifts trucks and milk vans.

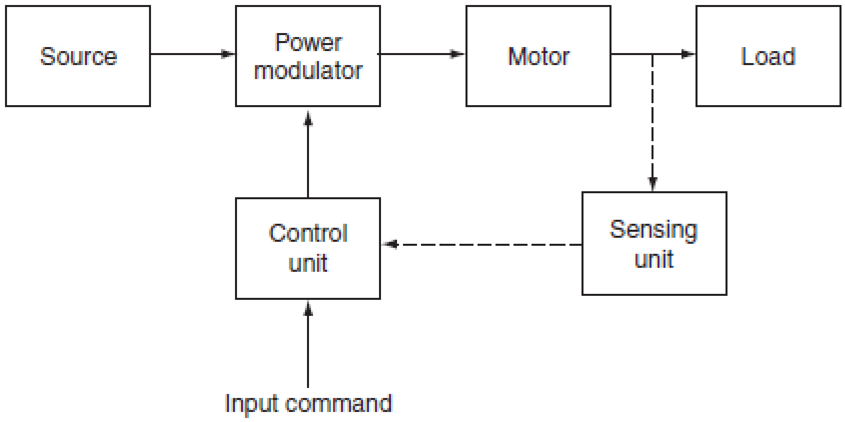


Fig. Block diagram of electric drive

Power modulator

Power modulator performs the following functions:

- It modulates flow of power from the source to the motor is impart speed–torque characteristics required by the load.
- It regulates source and motor currents within permissible values, such as starting, braking, and speed reversal conditions.
- Selects the mode of operation of motor, i.e., motoring or braking.
- Converts source energy in the form suitable to the motor.

Electrical motors:

Motors commonly used in electric drives are DC motors, induction motors, synchronous motors, blushless DC motors, stepper motors, and switched reluctance motors, etc. In olden days, induction and synchronous motors were employed mainly for constant speed drives but not for variable speed drives, because of poor efficiency and are too expensive. But in nowadays, AC motors employed in variable speed drives due to the development of semiconductors employing SCRs, power transistors, IGBTs, and GTO.

Load:

It is usually a machinery, such as fans, pumps, robots, and washing machines, designed to perform a given task, usually load requirements, can be specified in terms of speed and torque demands.

Control unit:

Control unit controls the function of power modulator. The nature of control unit for a particular drive depends on the type of power modulator used. When semiconductor converters are used, the control unit will consists of firing circuits. Microprocessors also used when sophisticated control is required.

Sensing unit:

Sensing unit consists of speed sensor or current sensor. The sensing of speed is required for the implementation of closed loop speed control schemes. Speed is usually sensed using tachometers coupled to the motor shaft. Current sensing is required for the implementation of current limit control.

Advantages of electric drives:

There are a number of inherent advantages that the electric drive possesses over the other forms of conventional drives are:

- They have comparatively long life than the mechanical drive.
- It is cleaner, as there are no flue gases, etc.
- It is more economical.
- They have flexible control characteristics.
- There is no need to store fuel or transportation.
- It requires less maintenance.
- Do not pollute environment.
- It is the reliable source of drive.
- The electrical energy can be easily transmitted by using transmission lines over long distances.
- Available in wide range of torque, speed, and power.
- High efficiency.
- Electric braking system is much superior and economical.
- Smooth speed control is easy.
- They can be started instantly and can immediately be fully loaded.
- They can operate in all the quadrants of speed torque plane.
- Being compactness, they require less space.
- They can be controlled remotely.

Disadvantages of electric drives

The two inherit disadvantages of the electric drive system are:

- The non-availability of drive on the failure of electrical power supply.
- It cannot be employed in distant places where electric power supply is not available.

1.2 TYPES OF ELECTRIC DRIVES

Depending on the type of equipment used to ran the electric motors in industrial purpose, they may be classified into three types. They are:

1. Group drives.
2. Individual drives.
3. Multi-motor drives.

Group drives:

Electric drive that is used to drive one or more than two machines from line shaft through belts and pulleys is known as *group drive.* It is also sometimes called the *line shaft drive.*This drive is economical in the consideration of the cost of motor and control gear. A single motor of large capacity cost is less than the total cost of a number of small motors of the same total capacity. In switch over from non-electric drive to electric drive, the simplest way is to replace the engine by means of motor and retaining the rest of power transmission system.

Advantages:

- The cost of installation is less. For example, if the power requirement of each machine is 10 HP and there are five machines in the group, then the cost of five motors will be more than one 50-HP motor.
- If it is operated at rated load, the efficiency and power factor of large group drive motor will be high.
- The maintenance cost of single large capacity motor is less than number of small capacity motors.
- It is used for the processes where the stoppage of one operation necessitates the stoppages of sequenceof operations as incase of textile mills.
- It has overload capacity.

Disadvantage:

Even though group drive has above advantages, it suffers from the following disadvantages.

- If there is any fault in the main motor, all the machines connected to the motor will fail to operate;thereby, paralyzing a part of industry until the fault is removed.
- It is not possible to install any machine at a distant place.
- The possibility of the installation of additional machines in an existing industry is limited.
- The level of noise produced at the work site is quite large.
- The speed control of different machines using belts and pulleys is difficult.
- The flexibility of layout is lost due to line shaft, belts, and pulleys.
-

Individual drive:

In individual drive, a single electric motor is used to drive one individual machine.
Such a drive is very common in most of the industries.

Advantages:

- It is more clean and safety.
- Machines can be located at convenient places.
- If there is a fault in one motor, the output and operation of the other motors will not be effected.
- The continuity in the production of the industry is ensured to a higher degree.
- Individual drive is preferred for new factories, as it causes some saving in the cost.

Disadvantages:

- Initial cost will be high.

- Power loss is high.

Multi-motor drive:

In multi-motor drives, several separate motors are provided for operating different parts of the same machine.

Ex: In traveling cranes, three motors are used for hoisting, long travel, and cross-travel motions. Multi-motor drive is used in complicated metal cutting machine tools, rolling mills, paper making machines, etc.

CHOICE OF MOTORS

The selection of the driving motor for a given service depends upon the conditions under which it has to operate. Due to the universal adoption of electric drive, it has become necessary for the manufacturer to manufacture motors of various designs according to the suitability and the use in various designs according to the suitability and the use in various classes of industry. This has resulted into numerous types of motors. For this reason, the selection of motor itself has become an important and tedious process. The conditions under which an electric motor has to operate and the type of load it has to handle, determine its selection.

While selecting a motor, the following factors must be taken into consideration:

Cost:

1.initial cost and

2.running cost.

Electric characteristics:

1.starting characteristics,

2. running characteristics,

3.speed control characteristics, and

4.braking characteristics.

Mechanical characteristics:

1.Type enclosure and bearings,

2.arrangement for the transmission of power,

3.noise, and

4.cooling.

Nature of supply.

From the above, it is seen that a large number of factors are to be considered in making the choice of an electric motor for a given drive. The motor selected must fulfill all the necessary load requirements and at the same time, it should not be very costly if it has to be a commercialsuccess. The factors motioned above will be individually discussed in the following sections tobring home to the reader the importance of each. While making the final choice of the motor, a satisfactory compromise may have to be made in some cases on account of the conflicting requirements.

1.3 Mechanical features of drives

Various types of enclosures:

he part of an electric motor that protects the motor from the contaminants in the environment in which it is operating and persons being from touch is called the **motor enclosure**.

The motor enclosures are necessary for the following reasons −

- It protects the motor against foreign body and severe conditions.
- It protects the inner parts of the motor.
- It protects the operating personal from live parts of the motor such as winding terminals, slip rings, brushes, etc.

Types of Motor Enclosures:

Indian Standards (IS) 4691 have described codes for different types of enclosures. The most common types of electric motor enclosures are given as follows −

- **Open Protected Type** − This enclosure provides free access to air and sufficient mechanical protection to the motor.
- **Scree Protected Type** − This type of enclosure provides addition protection to the motor. It has metal grids or perforated covers.
- **Drip Proof Type** − This type of enclosure has openings for ventilation which are so provided that it prevents vertically falling water or dirt from entering inside the motor.
- **Splash Proof Type** − With this type of enclosure, liquid or solid particles falling on the motor at any angle between the vertically downward direction and 100° from that direction cannot enter the motor.
- **Totally Enclosed Type** − In this type of enclosure, there will be no free circulation of air between the inside and outside of the motor.
- **Pipe Ventilated Type** − In this type of motor enclosure, pipes or ducts are provided for the continuous supply of fresh ventilating air.
- **Explosion Proof Type** − These enclosures are manufactured in such a way to withstand an internal explosion and the motor frame will not rupture or burst.
- **Weather Proof Type** − In these enclosures, additional screens are installed to prevent entrance of large particles of debris and rain into the motor.

Name plate details of Motor:

The nameplate of a motor typically contains essential information about its specifications and characteristics. Here are the common details you would find on a motor nameplate:

1. **Manufacturer's Name and Logo**: This identifies the company that produced the motor.
2. **Motor Type**: Indicates the type of motor (e.g., induction motor, synchronous motor).
3. **Model Number**: A specific identifier assigned by the manufacturer to distinguish different models of motors they produce.
4. **Rated Voltage**: The voltage at which the motor is designed to operate safely and efficiently.
5. **Rated Current**: The current (in amps) that the motor draws at rated voltage and load conditions.
6. **Rated Power (kW or HP)**: The electrical power output of the motor when operating at its rated conditions, expressed in kilowatts (kW) or horsepower (HP).
7. **Frequency**: The frequency of the electrical supply required for the motor to operate optimally (typically 50 Hz or 60 Hz).
8. **Speed**: The rotational speed of the motor's shaft when operating under full load conditions, usually measured in revolutions per minute (RPM).
9. **Efficiency Class**: Indicates the energy efficiency rating of the motor, such as IE1, IE2, IE3 (according to international standards like IEC 60034-30).
10. **Insulation Class**: The insulation rating of the motor windings, which determines its ability to withstand heat and electrical stress.
11. **Ambient Temperature Rating**: The maximum ambient temperature at which the motor is designed to operate effectively.
12. **Protection Class/IP Rating**: Specifies the level of protection against dust, moisture, and ingress of foreign objects, according to IP (Ingress Protection) standards.
13. **Connection Diagram**: A schematic diagram showing how the motor's terminals should be connected to the electrical supply and any optional accessories.
14. **Serial Number**: A unique identifier assigned to each motor for tracking purposes and warranty claims.
15. **Other Certifications and Standards**: Compliance markings indicating that the motor meets relevant safety, performance, and environmental standards (e.g., CE mark, UL listing).

These details are crucial for selecting, installing, operating, and maintaining the motor within its specified parameters to ensure optimal performance and long

1.4 Duty Cycle, Types of bearings,drive end and non-drive end

Duty cycle helps in determining the appropriate motor size and rating for an application. Motors subjected to higher duty cycles may require larger cooling systems or higher-rated components to manage heat buildup.

Types of Duty Cycles:

- **Continuous Duty**: Motors designed to operate continuously without rest under steady-state conditions.
- **Intermittent Duty**: Motors that operate for specific periods followed by periods of rest or no-load conditions. Examples include motors used in cyclic applications or machinery that operates in cycles.

Types of bearings :

1. **Ball Bearings**:

- **Deep Groove Ball Bearings**: These are the most common type of ball bearings, designed to handle radial and axial loads in both directions. They are suitable for high-speed applications and have low friction.
    - **Angular Contact Ball Bearings**: Designed to support combined radial and axial loads, these bearings have raceways inclined at an angle to the bearing axis. They can handle higher axial loads compared to deep groove ball bearings.
    - **Thrust Ball Bearings**: These bearings are designed to accommodate axial loads in one direction and are not suitable for radial loads.
2. **Roller Bearings**:
    - **Cylindrical Roller Bearings**: They have high radial load capacity and are suitable for applications where high speeds and moderate radial loads are present. They have cylindrical rollers as rolling elements.
    - **Tapered Roller Bearings**: These bearings can support high radial and axial loads and are designed to handle combined loads. They have tapered rollers and are used in automotive and industrial applications.
    - **Spherical Roller Bearings**: Designed to accommodate misalignment and heavy radial and axial loads, these bearings have barrel-shaped rolling elements.
    - **Needle Roller Bearings**: These have cylindrical rollers with a length much larger than their diameter. They are used where space is limited and high radial load capacity is required.
3. **Plain Bearings**:
    - **Bushings**: Also known as sleeve bearings, these are simple cylindrical bearings used to reduce friction between moving parts. They are typically made of metal, plastic, or composite materials.
    - **Thrust Washers**: Used to provide a bearing surface for rotary applications or sliding motions where axial loads are present.
4. **Specialized Bearings**:
    - **Linear Bearings**: Used to provide linear motion rather than rotational motion. Examples include linear ball bearings and linear roller bearings.
    - **Mounted Bearings**: These are bearings integrated into a housing unit, such as pillow block bearings, flanged bearings, and take-up bearings.
    - **Radial Bearings**: Designed to support radial loads, these bearings include all types that primarily support perpendicular loads to the shaft axis.

Each type of bearing has specific advantages and is chosen based on factors such as load capacity, speed requirements, precision, operating conditions (including temperature and lubrication), and installation constraints. Proper selection and maintenance of bearings are critical to ensure optimal performance and longevity in various industrial, automotive, and mechanical applications.

Drive End:

- The drive end of a motor is where the driving force is applied to rotate the shaft. This is typically where the motor is connected to a drive mechanism such as a pulley, gearbox, or coupling that transmits power to the motor shaft.
- In an electric motor, the drive end often houses the motor's shaft, rotor, and bearings that support the axial and radial loads created by the drive mechanism.
- It is important for the drive end to have robust bearings capable of handling the axial and radial forces generated by the motor operation.

Non-Drive End:

- The non-drive end of a motor is the opposite end of the drive end, where the motor shaft exits the motor casing.
- This end usually contains the bearings that support the opposite end of the motor shaft. These bearings are responsible for maintaining the shaft's alignment and stability during operation.
- In many motors, the non-drive end bearings are designed to primarily handle radial loads, although they may also bear some axial loads depending on the motor's configuration and operating conditions.

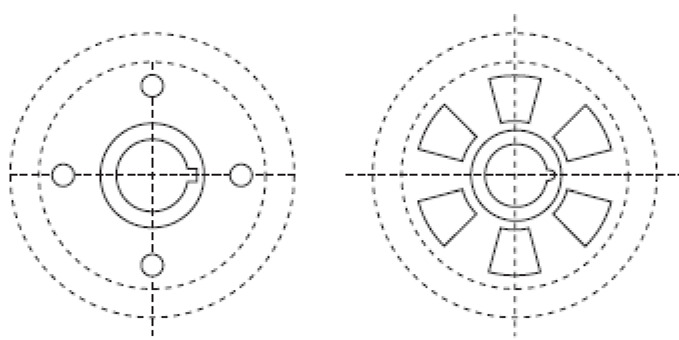
1.5 Load Equalization

The load fluctuations take place in many of the industrial drives such as rolling mills, planning machines presses, and reciprocating pumps, where the load on the motor varies widely within a span of few seconds. The sudden and peak load requires very large current from the supply results high voltage drop in the system or alternately would require very large size of cables. It is very essential to smooth out fluctuating load is known as '*load equalization*'. The load equalization involves the storage of energy during the off-peak period and gives out during the peak load period.

Load equalization process is commonly achieved by means of a flywheel. A flywheel is nothing but a big wheel that is mounted on the same shaft of motor, if the speed of the motor isnot to be reversed or a heavy rotating body that acts as a reservoir for absorbing and redistributing stored energy is also known as flywheel.

Function of flywheel

To operate the flywheel efficiently, the driving motor should have drooping speed characteristics. The various models of flywheel are shown in Fig. 8.42 (a) and (b). During the lightload, the acceleration of the flywheel is increased and it stores the kinetic energy and at the time of peak load, the flywheel slows down and the stored kinetic energy is given out to the load; so that, the demand of the load from the motor or supply is reduced.



(a) Small flywheel (b) Bigger flywheel

It is necessary that the motor used for load equalization should have drooping characteristics. The flywheel is not used with motors having constant speed for example synchronous motor. The torque developed by the motor and the load torque required as well as the speed variations with time are shown in above fig.

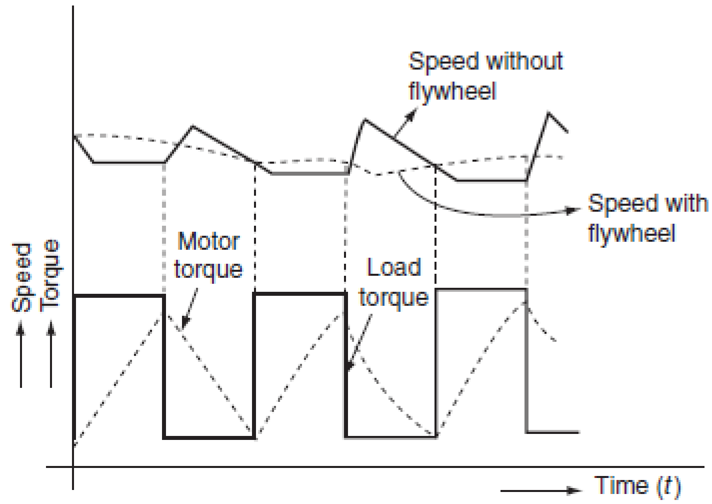


Fig. Motor torque, load torque, and speed variations against time

Flywheel calculations

Let us consider a flywheel is attached to a variable speed motor to achieve load equalization.

Let T_L be the load torque (assumed constant during particular interval) in N-m. T_M is the motor torque in N-m, T_F is the flywheel torque in N-m, T_0 is the no-load torque in N-m, ω_0 is the motor speed on no-load in rad/sec, ω is the motor speed at any instant in rad/sec, and $J$is the moment of inertia of flywheel in kg-m^2.

$$S = (\omega_0 - \omega) = \text{motor slip.}$$

Case (i): Let us consider that the load on the motor is increasing; during this period, the flywheel will decelerate and impart its stored kinetic energy to the load. The torque required to be supplied by the motor:

$$T_M = T_L - T_F.$$

The kinetic energy given by the flywheel when its speed reduced from ω_0 to ω is:

$$\mathrm{KE} = \frac{1}{2} J \left(\omega_0^2 - \omega^2\right)$$

$$= \frac{1}{2} J \left(\omega_0 + \omega\right)\left(\omega_0 - \omega\right)$$

$$= J \left(\frac{\omega_0 + \omega}{2}\right)\left(\omega_0 - \omega\right).$$

$$\text{Let } \left(\frac{\omega_0 + \omega}{2}\right) = \omega \qquad \text{(mean speed)}$$

$$\omega_0 - \omega = S \qquad \text{(Slip).}$$

(1.5.1)

$$KE = J\omega S. \qquad (1.5.2)$$

The power given out by the flywheel = the rate of change of the energy given up by the flywheel.

$$= \frac{d}{dt}(J\omega S)$$

$$= J\omega \frac{dS}{dt}.$$

$$\text{The flywheel torque } (T_F) = \frac{\text{power given out by flywheel}}{\omega}$$

$$= \frac{J\omega\left(\frac{dS}{dt}\right)}{\omega}$$

$$= J\frac{dS}{dt}. \qquad (1.5.3)$$

By substituting Equation (1.51) in Equation (1.5.3), we get

If the slip, i.e., drop in speed limited to 10%, then the slip is proportional to the motor torque:
i.e., $S \propto T_M$
$S = KT_M$.

$$\text{Then,} \quad T_M = T_L - J\frac{d(KT_M)}{dt}$$

$$T_M = T_L - JK\frac{dT_M}{dt}$$

$$T_L - T_M = JK\frac{dT_M}{dt}$$

$$\frac{dT_M}{T_L - T_M} = \frac{dt}{JK}. \qquad \textbf{(8.56)}$$

Integrating the Equation (8.56):

$$\int \frac{dT_M}{T_L - T_M} = \int \frac{dt}{JK}$$

$$-\log_e(T_L - T_M) = \frac{t}{JK} + C, \qquad \textbf{(8.57)}$$

where C is proportionality constant.

At time $t = 0$, the motor torque will be equals to the no-load torque:

i.e., at $t = 0$, $T_M = T_0$. **(8.58)**

The value of 'C' can be determined by using the initial conditions. Substituting Equation (8.58) in Equation (8.57):

$$-Log_e\left(T_L - T_0\right) = \frac{0}{JK} + C \qquad \textbf{(8.59)}$$

$$\therefore C = -\log_e (T_L - T_0).$$

Substituting 'C' value in Equation (8.57):

$$\therefore -\mathrm{Log}_e\left(T_L - T_M\right) = \frac{t}{JK} - \mathrm{Log}_e(T_L - T_0)$$

$$-\mathrm{Log}_e\left(T_L - T_0\right) + \log_e(T_L - T_M) = \frac{-t}{JK}$$

$$\mathrm{Log}_e\left[\frac{T_L - T_M}{T_L - T_0}\right] = \frac{-t}{JK}.$$

Applying exponentials on both sides:

$$\left[\frac{T_L - T_M}{T_L - T_0}\right] = e^{-t/JK}$$

$$T_L - T_M = \left(T_L - T_0\right)e^{-t/JK}. \qquad \textbf{(8.60)}$$

Case (ii): Now consider that the load is totally removed or decreasing, the motor starts accelerating and so the KE is stored by the flywheel.

Hence, the flywheel regains its normal speed; therefore, the slip decreases, i.e., $\frac{dS}{dt}$ is negative.

Now, motor torque will be:

$$T_M = T_0 + T_F. \tag{8.61}$$

But,

$$T_F = -J\frac{dS}{dt}. \tag{8.62}$$

Substitute Equation (8.62) in Equation (8.61):

$$\therefore T_M = T_0 - J\frac{dS}{dt}. \tag{8.63}$$

We know that S a T_M:

$$S = KT_M$$

$$\therefore T_M = T_0 - JK\frac{dT_M}{dt}$$

$$-JK\frac{dT_M}{dt} = T_M - T_0$$

$$\frac{dT_M}{T_M - T_0} = -\frac{dt}{JK}.$$

Integrating on both sides:

$$\int \frac{dT_M}{T_M - T_0} = -\int \frac{dt}{JK}$$

$$\text{Log}_e(T_M - T_0) = \frac{-t}{JK} + C_2, \tag{8.64}$$

where 'C_2' is integration constant.

At $t = 0$; $T_M = T_M^1$ (motor torque when load is decreased)

$$\therefore \text{Log}\left(T_M^1 - T_0\right) = \frac{0}{JK} + C_2$$

$$\therefore C_2 = \text{Log}_e\left(T_M^1 - T_0\right).$$

The value of constant can be obtained by substituting the initial conditions in Equation (8.64

By substituting 'C_2' in Equation (8.64), we get:

$$\text{Log}_e(T_M - T_0) = \frac{-t}{JK} + \text{Log}_e\left(T_M^1 - T_0\right)$$

$$\text{Log}_e(T_M - T_0) - \text{Log}_e\left(T_M^1 - T_0\right) = \frac{-t}{JK}$$

$$\text{Log}_e\left(\frac{T_M - T_0}{T_M^1 - T_0}\right) = \frac{-t}{JK}.$$

Applying exponentials on both sides:

$$\frac{T_M - T_0}{T_M^1 - T_0} = e^{-t/JK}$$

$$\therefore T_M - T_0 = \left(T_M^1 - T_0\right)\left(e^{-t/JK}\right)$$

$$\therefore T_M = T_0 + \left(T_M^1 - T_0\right)e^{-t/JK}. \qquad \textbf{(8.65)}$$

Problem:

A 15-HP, three-phase, eight-pole, and 50-Hz induction motor provided with a flywheel has to supply a load torque of 600 N-m for 10 s followed by a no-load during which the flywheel regains the full speed. The full-load slip of the motor is 4% and the torque–speed curve may be assumed linear over the working range. Find the moment of inertia of the flywheel if the motor torque is not to exceed twice the full-load torque.

Solution:

Given data:

P_0= 15 HP

= 15 × 735.5 = 11.03 kW.

No.of poles P = 8, f = 50 Hz, S_f = 0.04, t = 10 sec T_L = 600 N-mT_M = 2. TFL T_0 = 0.

$$\text{Now, synchronous speed } N_s = \frac{120f}{P}$$

$$= \frac{120 \times 50}{8} = 750 \text{ rpm.}$$

$$\text{Full-load torque } T_{FL} = \frac{60 \times P_0}{2\pi N_{FL}}$$

$$N_{FL} = N_s(1 - S_f) = 750(1 - 0.04)$$

$$= 720 \text{ rpm.}$$

$$T_{FL} = \frac{60 \times 11.03 \times 10^3}{2\pi \times 720} = 146.39 \text{ N-m.}$$

$\therefore T_M = 2T_{FL} = 2 \times 146.39 = 292.78$ N-m.

$$\text{Slip speed} = S_f \times N_s = 0.04 \times 750$$

$$= 30 \text{ rpm}$$

$$= \frac{30 \times 2\pi}{60} = 3.14 \text{ rad/s.}$$

$$\text{And,} \quad K = \frac{S}{T_{FL}} = \frac{3.14}{146.39} = 0.0214$$

$$\therefore T_M = T_L - (T_L - T_0)e^{-t/JK}$$

$$-t/JK = \ln\left(\frac{T_L - T_M}{T_L - T_0}\right)$$

$$-t/JK = \ln\left[\frac{600 - 292.78}{600}\right] = 0.669$$

$$J = \frac{t}{0.669 \times K} = \frac{10}{0.669 \times 0.0914} = 698.49 \text{ kg-m}^2.$$

$$T_M = T_L - (T_L - T_0)e^{-t/KJ}$$

$$e^{-t/JK} = \frac{T_L - T_M}{T_L - T_0}$$

$$e^{-t/JK} = \frac{800 - 600}{800 - 0} = 0.25$$

$$-t/JK = \ln(0.25) = \frac{5}{1.386 \times 0.01134}$$

$$J = 318.12 \text{ kg-m}^2.$$

RATING OF MOTOR

The selection of motor for particular drive application based on the size of motor depends upon the following two factors:

1. Maximum temperature raise for a given load.
2. Maximum torque required.

The size of motor and its rating are mainly dependent upon the raise in temperature. The temperature raise in turn depends upon the type of insulation used.

1.7 Temperature rise of motor

The various losses takes place in any motor will be converted into heat. The heat thus produced will increase the temperature of various parts of the motor. The increase in temperature is mainly dependent on the following two factors:

1. Amount of heat developed internally at uniform rate.
2. The amount of heat dissipated from the surface of the motor.

In fact, the continuous rating of a machine is that rating for which the final temperature raise is equal to or just below the permissible value of the temperature raise for the insulating material used in protection of motor windings. When the machine is overloaded for such a long time that its final temperature raise exceeds the permissible limit, it is likely to be damaged. Sometimes, it will results immediate breakdown of insulating material which will cause a sudden short circuit in the motor, which may also lead to a fire. Since temperature raise is one of the chief features in fixing the size of motor. The temperature raise will be high in the beginning and will decrease gradually with the passage of time and finally the temperature of the motor attains a steady-state value. At this point, the heat produced and dissipated will be equal.

The above circumstances make the heating calculations very complex and practically impossible unless certain assumptions are made as:

1. Heat developed, i.e., losses remains constant during temperature raise.
2. The heat dissipation is directly proportional to the difference in the temperature of motor and cooling medium, i.e., Newton's law of cooling hold's good.
3. The temperature of cooling medium remains unchanged.
4. The motor is assumed to be a homogeneous mass having the same and uniform temperature in all parts. It implies high thermal conductivity.
5. For the determination of an expression for the temperature raise of an electrical machine after time '*t*' seconds from the instance of switching it on.

Let *P* is the electrical power converted into heat (W or J/sec), *M* is the mass of active parts of motor (kg), *S* is the specific heat of material (J/kg/°C), *O* is the temperature raise above the cooling medium or ambient temperature (°C), A is the surface area of cooling, (m^2), θ_f is the final temperature raise with constant load (°C), and λ is the coefficient of cooling or the rate of heat dissipation (W/m²/°C raise).

Now, let us assume that the machine attains a temperature raise of θ°C above ambient temperature after 't' seconds of switching on the machine and further raise of temperature by dθ in very small time 'dt' seconds.

$$= MS\frac{d\theta}{dt}\text{ J/sec.}$$

The rate at which the loss takes place or the heat is absorbed by the motor The rate at which heat is dissipated = $A\theta\lambda$ J/sec.

But, the rate at which the electrical power converted into heat = the rate at which the heat is absorbed + the rate at which the heat dissipated by the motor.

$$P = MS\frac{d\theta}{dt} + A\lambda\theta \quad (8.29)$$

$$P - A\theta\lambda = MS\frac{d\theta}{dt}$$

$$dt = \frac{MSd\theta}{P - A\theta\lambda}. \quad (8.30)$$

Integrating the Equation (8.30):

$$\int dt = \int \frac{MS}{P - A\theta\lambda} d\theta$$

$$t = MS\log_e(P - A\theta\lambda) \times \left(\frac{-1}{A\lambda}\right) + K, \quad (8.31)$$

where K is the integration constant.

Initially, at time t = 0 sec, temperature raise θ = 0°C.

By substituting t = 0 and θ = 0 in Equation (8.31), we get the integration constant (K):

$$\text{i.e., } 0 = \frac{-MS}{A\lambda}\log_e(P - 0) + K$$

$$\text{or} \quad K = \frac{MS}{A\lambda}\log_e P.$$

Substituting the value of 'K' in Equation (8.31), we get:

$$t = \frac{-MS}{A\lambda}\log_e(P - A\lambda\theta) + \frac{MS}{A\lambda}\log_e P \quad (8.32)$$

By applying exponential on both side, we get:

When ‘t’ is infinity, ‘θ’ approaches to its final steady-state temperature ‘θ_f’. So, by substituting$t = \infty$ and $\theta = \theta_f$ in Equation (8.33), we get:

$$\theta_f = \frac{P}{A\lambda}\left[1 - e^{-\infty}\right]$$

$$= \frac{}{A\lambda}\left[\log_e(P - A\theta\lambda) - \log_e P\right]$$

$$= \frac{-MS}{A\lambda}\log_e\left[\frac{P - A\theta\lambda}{P}\right]$$

$$\therefore \frac{-A\lambda t}{MS} = \log_e\left[\frac{P - A\theta\lambda}{P}\right].$$

$$\theta = \frac{P}{A\lambda}\left(1 - e^{\frac{-A\lambda t}{MS}}\right). \qquad \textbf{(8.33)}$$

$$= \theta_f\left[1 - e^{\frac{-t}{T_h}}\right], \qquad \textbf{(8.35)}$$

Substituting $\theta_f = \dfrac{P}{A\lambda}$ in Equation (8.33), we get:

$$\theta = \theta_f\left[1 - e^{\frac{-A\lambda}{MS}t}\right]$$

$$= \theta_f\left[1 - e^{\frac{-t}{T_h}}\right], \qquad \textbf{(8.35)}$$

where ‘T_h’ $= \dfrac{MS}{A\lambda}$ is known as heating time constant of motor.

The above relation is the equation of temperature rise with time. The temperature raise time curve or heating curve is exponential in nature as shown in Fig. 8.29.

From the equation of temperature raise:

$$\theta = \theta_f \left[1 - e^{\frac{-t}{T_h}} \right].$$

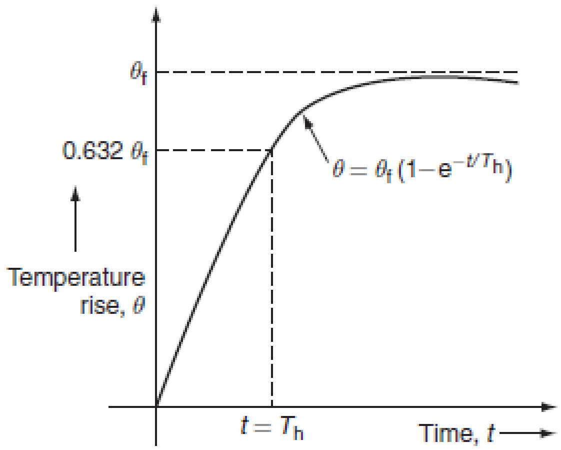


Fig. 8.29 Heating curve

At $t = T_h$, $\theta = \theta_f\,[1 - e^{-1}]$

$$\therefore \theta = 0.632\,\theta_f$$

Thus, *heating time constant* can be defined as follows:

The heating time constant is the time taken by the machine to attain 63.2% of its final steady temperature raise (θ_f).

The heating time constant of the conventional electrical machines is usually within the range of 0.5–3 for 4 h.

Cooling of motor:

Let us assume, if the supply to the motor is switched off, after attaining the final steady temperature raise of 'θ_f'', the motor starts cooling. When the machine is switched off, no heat is produced, therefore:

Heat absorbed + heat dissipated = 0

$$\therefore MS\frac{d\theta}{dt} + A\lambda'\theta = 0, \qquad \textbf{(8.36)}$$

where λ = heat dissipation during cooling of motor.

$$MSd\,\theta + A\lambda'\,\theta \cdot dt = 0$$

$$dt = -\frac{MS}{A\lambda'}d\theta. \qquad \textbf{(8.37)}$$

Integrating the Equation (8.37):

$$\int dt = \frac{-MS}{A\lambda^1}\int d\theta$$

$$t = \frac{-MS}{A\lambda^1}\log_e\theta + K^1, \qquad \textbf{(8.38)}$$

where K^1 is the integration constant.

The value of K_1 is obtained by using the initial conditions, when $t = 0$ and $\theta = \theta_f$, we get:

$$0 = \frac{-MS}{A\lambda^1} \log_e \theta_f + K^1$$

$$K^1 = \frac{MS}{A\lambda^1} \log_e \theta_f. \qquad \textbf{(8.39)}$$

Substituting Equation (8.39) in Equation (8.38):

$$t = \frac{-MS}{A\lambda^1} \log_e \theta + \frac{MS}{A\lambda^1} \log_e \theta_f$$

$$= \frac{-MS}{A\lambda^1} [\log_e \theta - \log_e \theta_f]$$

$$= \frac{-MS}{A\lambda^1} \log_e \left(\frac{\theta}{\theta_f}\right)$$

$$\therefore \frac{-A\lambda^1 t}{MS} = \log_e \left(\frac{\theta}{\theta_f}\right).$$

Applying exponentials on both side λ:

$$e^{\frac{-A\lambda^1}{MS} t} = \log_e e\left(\frac{\theta}{\theta_f}\right) \qquad [\therefore \log_e e^x = x]$$

$$\frac{\theta}{\theta_f} = e^{\frac{-A\lambda^1}{MS} t}$$

$$= \theta_f e^{\frac{-A\lambda^1}{MS} t}$$

$$= \theta_f e^{\frac{-t}{T_c}}, \qquad \textbf{(8.40)}$$

where $T_c = \frac{MS}{A\lambda^1}$ is know as cooling time constant.

The above relation is the equation of cooling of motor. The cooling curve is exponentially decaying in nature as shown in Fig. 8.30.

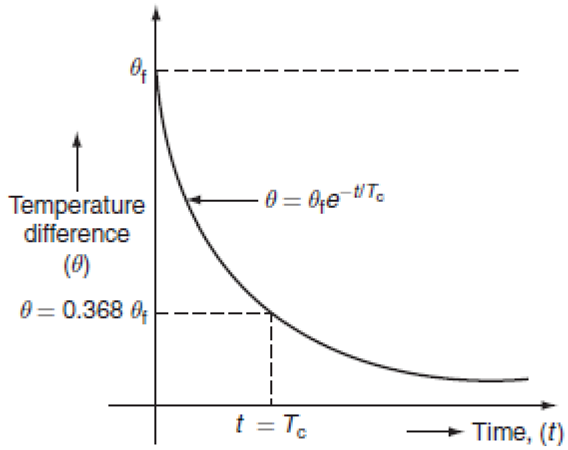


Fig. 8.30 Cooling curve

From the cooling equation, at time $t = T_c$:
We have $\theta = \theta_f\,(e^{-1})$

$$\therefore \theta = 0.368\theta_f.$$

Thus, we can define the *cooling time constant* as:

The cooling time constant is defined as the time required cooling the machine down to 36.8% of the initial temperature raise above the ambient temperature.

The heating and cooling curves follows an exponential law. Heating time constant and cooling time constant may be different for the same machine and also the cooling time constant of rotating machine is larger than its heating time constant, due to poorer ventilation conditions when the machine cools.

Figure 8.31 (a) and (b) shows the heating and cooling curves of a motor for short-time and intermittent loads.

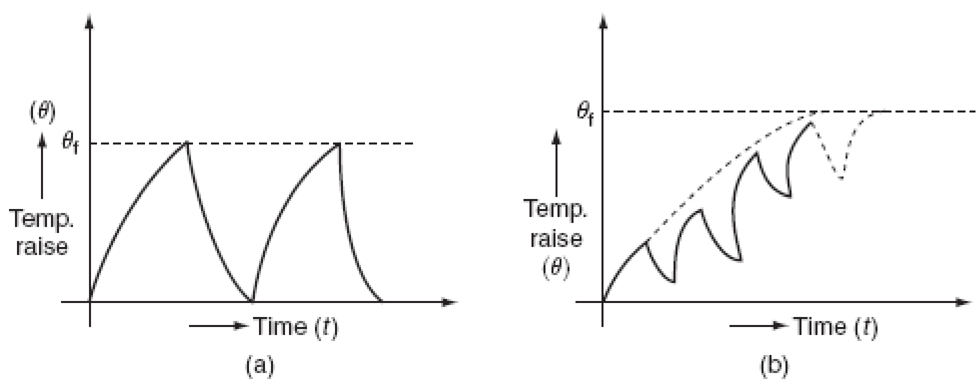


Fig. 8.31 (a) Short-time load motor (b) intermittent-time load motor

Problems:

1. An induction motor has a final steady-state temperature raise of 50°C when running at its rated output. Calculate its half-hour rating for the same temperature raise if the copper losses at the rated output are 1.5 times its constant losses. The heating time constant is 60min.

Solution:

Given data:

Final steady temperature (θ_f) = 50°C.Time constant (τ_h) = 60 min.

Rating(t) = $\frac{1}{2}$ hour = 30 min.

And, the copper loss = 1.5 × constant lossi.e., $W_{cu} = 1.5 \times W_i$

let 'P' be the rated output,

Total loss at full load = $W_{cu} + W_i$.

But, the temperature raise is proportional to the losses.

$\therefore \theta \propto W_{loss}$.

Let, θ_f be the temperature raise at full load.

θ_f^1 be the temperature raise with short-time rating.

$$\therefore \frac{\theta_f}{\theta_f^1} = \frac{W_{cu} + W_i}{x^2 W_{cu} + W_i}$$

$$= \frac{1.5 \times 1 + 1}{(1.5)x^2 + 1} \qquad [\because W_{cu} = 1.5 W_i]$$

$$= \frac{2.5}{1.5x^2 + 1}. \qquad \text{(i)}$$

The temperature raise after 30 min of operation should not exceed θ_f =50°C.

Now, from the equation of temperature raise of motor:

$$\theta_f = \theta_f^1 (1 - e^{-t/\tau_h})$$

$$50 = \theta_f^1 (1 - e^{-30/60}) = \theta_f^1 (1 - 0.606)$$

$$= \theta_f^1 \times 0.393.$$

$$\therefore \theta_f^1 = 128.07°\text{C}.$$

Substitute 'θ_f^1' in Equation (i):

$$\frac{\theta_f}{\theta_f^1} = \frac{2.5}{1.5x^2+1}$$

$$\theta_f^1 = \theta_f \times \left(\frac{1.5x^2+1}{2.5}\right)$$

$$1.5x^2 = 6.3537$$

$$x^2 = 4.235$$

$\therefore x = 2.058.$

2.A 10-kW motor has a heating time constant and cooling time constant of 45 and70 min, respectively. The final temperature attained is 60°C. Find the temperature of motor after 45 min full-load run and then switched of for 30 min.

Solution:

Given data:

$\tau_h = 45$min

$\tau_c = 70$ min

$\theta_f = 60°C$

$t = 45$ min.

We know that:

$$\theta = \theta_f\left(1-e^{-t/\tau_h}\right)$$

$$= 60\left(1-e^{-45/45}\right)$$

$$= 60 \times 0.632 = 37.927°C.$$

When the motor is switched off for 30 min, the temperature is:

$$\theta = \theta_f \quad e^{-t/\tau_c}$$

$$= 37.927 e^{-30/70}$$

$$= 37.927 \times 0.6514 = 24.707 \cong 25°C.$$

3. The heating time constant of a 80-kW motor is 60 min. The temperature raise is65°C when runs continuously on full load. Find the half-hour rating of motor for the temperature raise. Assume that the losses are proportional to the square of the load and the motorcools to ambient temperature between each load cycle.

Solution:

Let 'x' be the half-hour rating in kW.

$$\text{Losses at half-hour rating} = \left(\frac{x}{80}\right)^2 \times \text{losses at 80 kW.}$$

Let θ is the temperature raise at x kW and θ_f is the temperature raise at 80 kW. We know that the losses a $load_2$ and temperature raise a losses

$$\frac{\theta}{\theta_f} = \left(\frac{x}{80}\right)^2 \qquad \therefore \theta = \theta_f \times \left(\frac{x}{80}\right)^2$$

$$\therefore \theta = 65 \times \left(\frac{x}{80}\right)^2.$$

$$\text{Now, } 65 = \theta\left(1 - e^{-t/\tau_h}\right)$$

$$= 65\left(\frac{x^2}{80}\right)\left(1 - e^{-30/60}\right).$$

$$0 = \frac{x^2}{80}\left(1 - e^{-1/2}\right)$$

$$6{,}400 = x^2\,(1 - e^{-0.5}) = x^2\,(0.393)$$

$$x = \sqrt{\frac{6400}{0.393}}$$

$$= 127.5 \text{ kW.}$$

4. The heating time constant and final steady temperature of a motor on continuous running is 60 min and 40°C. Find out the temperature (i) after 25 min at this load, (ii) after 45 min at this load, (iii) if the temperature raise at half-hour rating is 40°C, find the maximum steady temperature, (iv) what will be the time required to increase the temperaturefrom 25°C to 40°C at one-and-half-hour rating.

Solution:

Given data:

$\theta_f = 40°C$
$t = 25$ min
$\tau_h = 60$ min.

We know that:

$$\theta = \theta_f\left(1 - e^{-t/\tau_h}\right)$$

$$= 60\left(1 - e^{-25/60}\right)$$

$$= 60 \times 0.340 = 20.44°C.$$

1. For 45 min at the same load:

$$\theta = \theta_f \left(1 - e^{-t/\tau_h}\right)$$

$$= 60\left(1 - e^{-45/60}\right)$$

$$= 31.658°C.$$

If the temperature raise is 40°C after half an hour, the maximum temperature:

$$\therefore \theta_f = \frac{\theta}{\left(1 - e^{-t/\tau_h}\right)} = \frac{40}{1 - e^{-30/60}}$$

$$= \frac{40}{1 - e^{-1/2}} = 101.65°C.$$

Given, time taken to attain temperature raise of 40°C is one-and-half hour. Then, the maximumtemperature θ_f is 101.65°C.

Let 't' be the taken in min needed to raise the temperature from 25°C to 40°C.

$$\theta = \theta_f \left(1 - e^{-t/\tau_h}\right)$$

$$25 = 40\left(1 - e^{-t/60}\right)$$

$$0.625 = \left(1 - e^{-t/60}\right)$$

$$e^{-t/60} = 0.375$$

$$-t/60 = \ln\left(0.375\right) = -0.98$$

$$\therefore t = 60 \times 0.98 = 58.84°C.$$

Thus, the temperature will increase from 25°C to 40°C in time, $t^1 = 90 - 58.84$
= 31.15 min.

5. The heating time constant of a motor is 90 min with 1-hr rating as 200 W. The maximum efficiency of motor occurs at 80% of full load. Determine the continuous rating of themotor.

Solution:

Given that, the maximum efficiency occurs at 80% of full load. Therefore, at 80% of full load, the copper loss is equal to the iron loss.
Let iron loss = copper loss = W_C W.

Copper loss at 80% of full load = W_C.

$$\text{Copper loss at full load} = \left(\frac{1}{0.8}\right)^2 \times W_C.$$

$$\text{Losses at full load } = W_C + \left(\frac{1}{0.8}\right)^2 \times W_C$$

$$= W_C\left(1 + \left(\frac{1}{0.8}\right)^2\right)$$

$$= 2.5625\ W_C.$$

$$\text{Losses at load of 200 W} = W_c + \left[\frac{200}{0.8 + \text{full load}}\right]^2 \times W_C.$$

$$\theta_f = \text{Total loss on full load.}$$

$$\theta_f^1 = \text{Total loss on 30 min rating.}$$

$$\frac{\theta_f^1}{\theta_f} = \frac{1}{1 - e^{-t/\tau_h}} = \frac{\text{total loss on 30 min rating}}{\text{total loss on full load}}$$

$$\frac{1}{1 - e^{-60/90}} = \frac{W_C + \left[\frac{200}{0.8 \times \text{full load}}\right]^2 \times W_C}{2.5625\ W_C}$$

$$2.055 = \frac{1 + \left(\frac{250}{\text{full load}}\right)^2}{2.5625}$$

$$5.265 = 1 + \left(\frac{250}{\text{full load}}\right)^2$$

$$\frac{250}{\text{full load}} = 4.265$$

$$\therefore \text{Full load} = \frac{250}{2.065} = 121.04\ \text{W.}$$

∴ Hence, the half-hour rating of machine is 2.058 times its continuous rating.

1.8 APPLICATIONS OF ELECTRIC DRIVES:

- **Industrial Automation**: Electric drives are extensively used in industrial automation for controlling various machines such as conveyor belts, robots, pumps, fans, and compressors. They offer precise control over speed and torque, improving efficiency and productivity.

- **Electric Vehicles**: In electric vehicles (EVs) and hybrid electric vehicles (HEVs), electric drives are crucial components that control the motors driving the wheels. They provide efficient power delivery and regenerative braking capabilities, enhancing overall vehicle performance and energy efficiency.

- **Renewable Energy Systems**: Electric drives are used in renewable energy applications such as wind turbines and solar tracking systems. They help in optimizing energy capture from variable renewable sources by adjusting rotor speeds and blade angles.

- **Home Appliances**: Many household appliances use electric drives for improved efficiency and control. Examples include washing machines, refrigerators, and air conditioners, where variable speed motors help in reducing energy consumption and noise.

- **HVAC Systems**: Heating, ventilation, and air conditioning (HVAC) systems utilize electric drives to control the speed of fans and pumps. This allows for precise regulation of airflow and water flow, resulting in energy savings and improved comfort.

- **Aerospace and Defense**: Electric drives are used in aircraft systems for actuating control surfaces, landing gear, and various other mechanisms. They offer reliability, precise control, and weight savings compared to traditional hydraulic or pneumatic systems.

- **Marine Propulsion**: Electric drives are increasingly used in ships and submarines for propulsion systems. They provide high torque at low speeds and can be integrated with energy storage systems for hybrid propulsion.

- **Medical Equipment**: Electric drives play a crucial role in medical devices such as MRI machines, robotic surgery systems, and prosthetic limbs. They enable precise movements and adjustments necessary for medical procedures.

- **Rail Transportation**: Electric drives are commonly used in electric trains and trams for propulsion and braking. They offer smooth acceleration, regenerative braking, and lower maintenance compared to diesel-powered systems.

- **Electric Power Generation**: In power generation plants, electric drives are used in turbine generators and pumps. They help in adjusting the speed and output of generators based on demand fluctuations, contributing to grid stability.

UNIT-II

ILLUMINATION

INTRODUCTION

Study of illumination engineering is necessary not only to understand the principles of light control as applied to interior lighting design such as domestic and factory lighting but also to understand outdoor applications such as highway lighting and flood lighting. Nowaday, the electrically produced light is preferred to the other source of illumination because of an account of its cleanliness, ease of control, steady light output, low cost, and reliability. The best illumination is that it produces no strain on the eyes. Apart from its esthetic and decorative aspects, good lighting has a strictly utilitarian value in reducing the fatigue of the workers, protecting their health, increasing production, etc. The science of illumination engineering is therefore becoming of major importance.

Nature of light

Light is a form of electromagnetic energy radiated from a body and human eye is capable of receiving it. Light is a prime factor in the human life as all activities of humanbeing ultimately depend upon the light.

Various forms of incandescent bodies are the sources of light and the light emitted by such bodies depends upon their temperature. A hot body about 500–800°C becomes a red hot and about 2,500–3,000°C the body becomes white hot. While the body is red- hot, the wavelength of the radiated energy will be sufficiently large and the energy available in the form of heat. Further, the temperature increases, the body changes from red-hot to white-hot state, the wavelength of the radiated energy becomes smaller and enters into the range of the wavelength of light. The wavelength of the light waves varying from 0.0004 to 0.00075 mm, i.e. 4,000-7,500 Å (1 Angstrom unit = 10^{-10} mm).

The eye discriminates between different wavelengths in this range by the sensation ofcolor. The whole of the energy radiated out is not useful for illumination purpose.
Radiations of very short wavelength varying from 0.0000156×10^{-6}m to 0.001×10^{-6} m are not in the visible range are called as rontgen or x-rays, which are having the propertyof penetrating through opaque bodies.

2.1 Definitions

Color: The energy radiation of the heated body is monochromatic, i.e. the radiation ofonly one wavelength emits specific color. The wavelength of visible light lies between

4,000 and 7,500 Å. The color of the radiation corresponding to the wavelength is shownin Fig. 6.1.

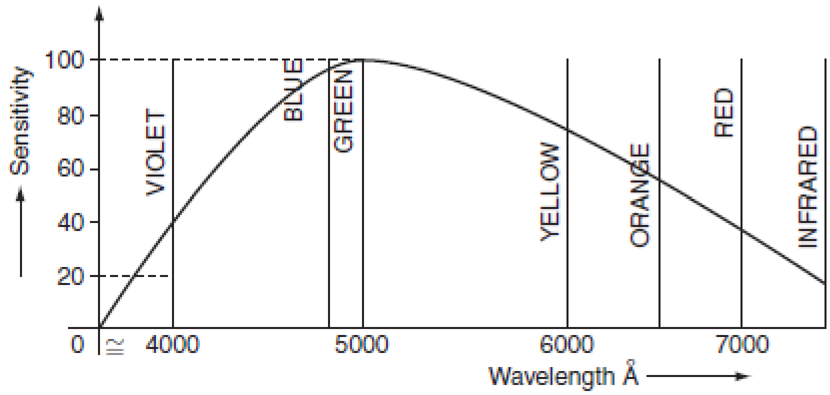


Fig. Wavelength

Relative sensitivity: The reacting power of the human eye to the light waves ofdifferent wavelengths varies from person to person, and also varies with age. Theaverage relative sensitivity is shown in Fig. 6.2.

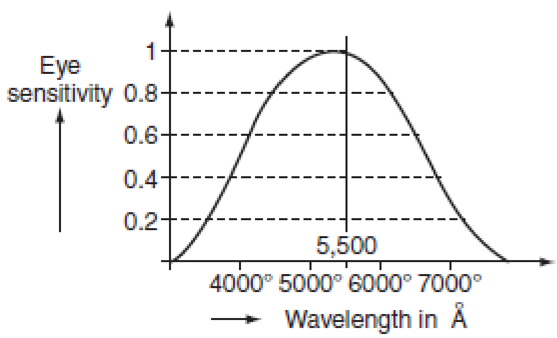


Fig. 6.2 The average relative sensitivity

The eye is most sensitive for a wavelength of 5,500 Å. So that, the relative sensitivityaccording to this wavelength is taken as unity.

Referred from Fig. 6.1, blue and violet corresponding to the short wavelengths and red to the long wavelengths, orange, yellow, and green being in the middle of the visible region of wavelength. The color corresponding to 5,500 Å is not suitable for most of the applications since yellowish green. The relative sensitivity at any particular wavelength(λ) is known as relative luminous factor $(K\lambda)$.

Light: It is defined as the radiant energy from a hot body that produces the visual sensation upon the human eye. It is expressed in lumen-hours and it analogous to watt- hours, which denoted by the symbol 'Q'.

Luminous flux: It is defined as the energy in the form of light waves radiated persecond from a luminous body. It is represented by the symbol 'φ' and measured in lumens.

Ex: Suppose the luminous body is an incandescent lamp.

The total electrical power input to the lamp is not converted to luminous flux, some ofthe power lost through conduction, convection, and radiation, etc. Afraction of the remaining radiant flux is in the form of light waves lies in between the visual range of wavelength, i.e. between 4,000 and 7,000 Å, as shown in Fig. 6.3.

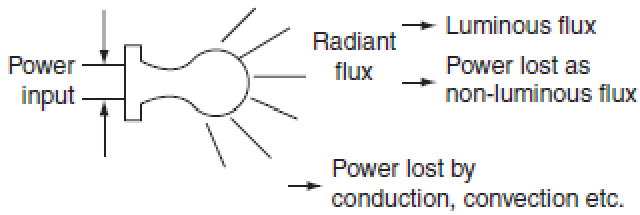


Fig. Flux diagram

Radiant efficiency:

When an electric current is passed through a conductor, some heat is produced to I^2R loss, which increases its temperature of the conductor. At low temperature, conductor radiates energy in the form of heat waves, but at very high temperatures, radiated energy will be in the form of light as well as heat waves.

'Radiant efficiency is defined as the ratio of energy radiated in the form of light, produces sensation of vision to the total energy radiated out by the luminous body'.

$$\text{Radiant efficiency} = \frac{\text{energy radiated in the form of light}}{\text{total energy radiated by the body}}.$$

Plane angle:

A plane angle is the angle subtended at a point in a plane by two converging lines (Fig.6.4). It is denoted by the Greek letter 'θ' (theta) and is usually measured in degrees or radians.

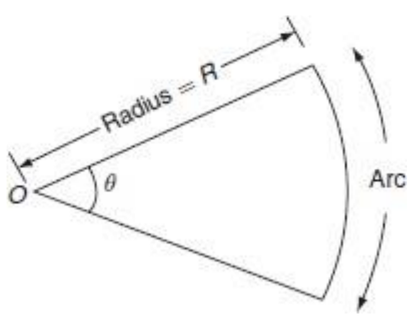


Fig. 6.4 Plane angle

$$\therefore \text{Plane angle } (\theta) = \frac{\text{arc}}{\text{radius}}. \qquad \textbf{(6.1)}$$

One radian is defined as the angle subtended by an arc of a circle whose length by an arcof a circle whose length is equals to the radius of the circle.

Solid angle:

Solid angle is the angle subtended at a point in space by an area, i.e., the angle enclosed in the volume formed by numerous lines lying on the surface and meeting at the point (Fig. 6.5). It is usually denoted by symbol 'ω' and is measured in steradian.

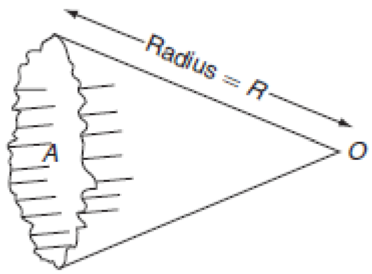


Fig. Solid angle

The largest solid angle subtended at the center of a sphere:

$$\omega = \frac{\text{area of sphere}}{\text{radius}^2} = \frac{4\pi r^2}{R^2} = 4\pi \text{ steradians.}$$

Relationship between plane angle and solid angle

Let us consider a curved surface of a spherical segment ABC of height 'h' and radius of the

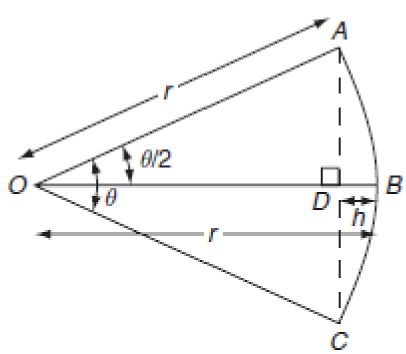


Fig. Sectional view for solid angle

sphere 'r' as shown in Fig. 6.6. The surface area of the curved surface of the spherical segment $ABC = 2\pi rh$. From the Fig. 6.6:

$$\therefore \text{Solid angle } (\omega) = \frac{\text{area}}{\text{radius}^2}. \qquad \textbf{(6.2)}$$

$$BD = OB - OD$$

$$h = r - r\cos\left(\frac{\theta}{2}\right) \quad \left[\therefore \text{From } \Delta ODA, OD = r\cos\theta/2\right]$$

$$= r\left(1 - \cos\frac{\theta}{2}\right).$$

$$\therefore \text{The surface area of the segment} = 2\pi rh$$

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

$$\text{We know solid angle } (\omega) = \frac{\text{area}}{(\text{radius})^2}$$

$$= \frac{2\pi r^2\left(1 - \cos\frac{\theta}{2}\right)}{r^2}$$

$$= 2\pi\left(1 - \cos\frac{\theta}{2}\right). \qquad \textbf{(6.3)}$$

From the Equation (6.3), the curve shows the variation of solid angle with plane angle is shown in Fig. 6.7.

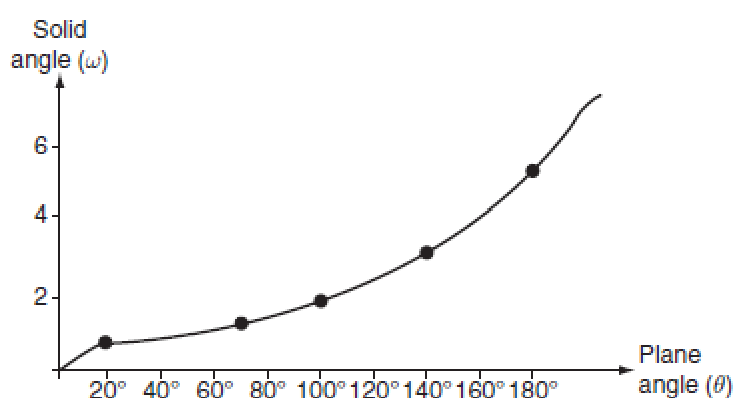


Fig. 6.7 Relation between solid angle and plane angle

Luminous intensity

Luminous intensity in a given direction is defined as the luminous flux emitted by the source per unit solid angle (Fig. 6.8).

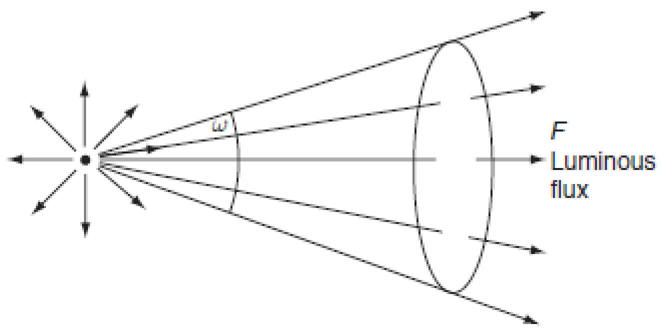


Fig. 6.8 Luminous flux emitting from the source

It is denoted by the symbol '*I*' and is usually measured in 'candela'.

Let '*F*' be the luminous flux crossing a spherical segment of solid angle 'ω'. Then luminous intensity $(I) = \frac{\phi}{\omega}$ lumen/steradian or candela.

Lumen: It is the unit of luminous flux.

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

Lumen = candle power of source × solid angle. Lumen =

CP × ω

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

Candle power (CP)

The CP of a source is defined as the total luminous flux lines emitted by that source in a unit solid angle.

$$CP = \frac{\text{lumen}}{\omega} \text{ lumen/steradian or candela.}$$

Illumination:

Illumination is defined as the luminous flux received by the surface per unit area.

It is usually denoted by the symbol '*E*' and is measured in lux or lumen/m^2 or meter candle or foot candle.

$$\text{Illumination, } E = \frac{\text{luminous flux}}{\text{area}}$$

$$= \frac{\phi}{A} = \frac{CP \times \omega}{A} \text{ lux.}$$

Lux or meter candle:

It is defined as the illumination of the inside of a sphere of radius 1 m and a source of 1 CP is fitted at the center of sphere.

Foot candle:

It is the unit of illumination and is defined as the illumination of the inside of a sphere of radius 1 foot, and a source of 1 CP is fitted at the center of it.

We know that 1 lux = 1 foot candle = 1 lumen/(ft)^2

$$1 \text{ foot candle } = \frac{\text{lumen}}{\left(\frac{1}{3.28}\right)^2 \text{m}^2} = 10.76 \text{ lux or m-candle}$$

$$\therefore 1 \text{ foot candle} = 10.76 \text{ lux.}$$

Brightness:

Brightness of any surface is defined as the luminous intensity pen unit surface area of the projected surface in the given direction. It is usually denoted by symbol '*L*'.

If the luminous intensity of source be '*I*' candela on an *area A*, then the projected area is *A*cos *θ*.

$$\therefore \text{Brightness, } L = \frac{I}{A\cos\theta}$$

The unit of brightness is candela/m^2 or candela/cm^2 or candela/(ft)^2.

Relation between I, E, and L:

Let us consider a uniform diffuse sphere with radius *r* meters, at the center a source of 1CP, and luminous intensity *I* candela.

$$\therefore \text{ Brightness } (L) = \frac{I}{\pi r^2}$$

$$\text{and Illumination } (E) = \frac{\phi}{A} = \frac{CP \times \omega}{A}$$

$$= \frac{I}{4\pi r^2} \times 4\pi = \frac{I}{r^2}$$

$$\therefore\ E = \frac{I}{r^2} = \frac{I}{\pi r^2} \times \pi = \pi L$$

$$\therefore\ E = \pi L = \frac{I}{r^2}. \qquad \textbf{(6.4)}$$

Mean horizontal candle power (MHCP):

MHCP is defined as the mean of the candle power of source in all directions inhorizontal plane.

Mean spherical candle power (MSCP)

MSCP is defined as the mean of the candle power of source in all directions in all planes.

Mean hemispherical candle power (MHSCP)

MHSCP is defined as the mean of the candle power of source in all directions above orbelow the horizontal plane.

Reduction factor

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

$$\text{i.e., reduction factor} = \frac{MSCP}{MHCP}.$$

Lamp efficiency

It is defined as the ratio of the total luminous flux emitting from the source to itselectrical power input in watts.

$$\therefore \text{Lamp efficiency} = \frac{\text{luminous flux}}{\text{power input}}.$$

It is expressed in lumen/W.

Specific consumption

It is defined as the ratio of electric power input to its average candle power.

Space to height ratio

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

$$\text{Space to height ratio} = \frac{\text{horizontal distance between two adjacent lamps}}{\text{mounting height of lamps above the working plane}}.$$

Coefficient of utilization or utilization factor

It is defined as the ratio of total number of lumens reaching the working plane to the total number of lumens emitting from source.

$$\text{Utilization factor} = \frac{\text{total lumens reaching the working plane}}{\text{total lumens emitting from source}}.$$

Maintenance factor

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

$$\text{Maintanance factor} = \frac{\text{illumination under normal working condition}}{\text{illumination under every thing is clean}}.$$

Its value is always less than 1, and it will be around 0.8. This is due to the accumulation of dust, dirt, and smoke on the lamps that emit less light than that they emit when they are so clean. Frequent cleaning of lamp will improve the maintenance factor.

Depreciation factor

It is defined as the ratio of initial illumination to the ultimate maintained illumination on the working plane.

$$\therefore \text{Depreciation factor} = \frac{1}{\text{maintenance factor}}.$$

Its values is always more than 1.

Waste light factor

When a surface is illuminated by several numbers of the sources of light, there is certain amount of wastage due to overlapping of light waves; the wastage of light is taken into account depending upon the type of area to be illuminated. Its value for rectangular area is 1.2 and for irregular area is 1.5 and objects such as statues, monuments, etc.

Absorption factor

Normally, when the atmosphere is full of smoke and fumes, there is a possibility of absorption of light. Hence, the total lumens available after absorption to the total lumens emitted by the lamp are known as absorption factor.

$$\text{Absorption factor} = \frac{\text{the total lumens available after absorption}}{\text{the total lumens given out by the lamp}}.$$

Reflection factor or coefficient of reflection

When light rays impinge on a surface, it is reflected from the surface at an angle of incidence shown in Fig. 6.9. A portion of incident light is absorbed by the surface.

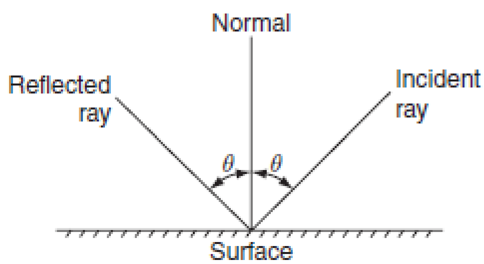


Fig. Reflected ray

The ratio of luminous flux leaving the surface to the luminous flux incident on it is known as reflection factor.

$$\text{Reflection factor} = \frac{\text{reflected light}}{\text{incident light}}.$$

Its value will be always less than 1.

Beam factor

It is defined as the ratio of 'lumens in the beam of a projector to the lumens given out by lamps'. Its value is usually varies from 0.3 to 0.6. This factor is taken into account for the absorption of light by reflector and front glass of the projector lamp.

Problems

1. A 200-V lamp takes a current of 1.2 A, it produces a total flux of 2,860lumens. Calculate:

1. the MSCPofthe lamp and
2. the efficiency of the lamp.

Solution:

Given V = 200 V

I = 1.2 A, flux = 2,860 lumens.

$$\text{(i) MSCP} = \frac{\text{total flux}}{4\pi} = \frac{2860}{4\pi} = 227.59.$$

2. A room with an area of 6 × 9 m is illustrated by ten 80-W lamps. The luminous efficiency of the lamp is 80 lumens/W and the coefficient of utilization is 0.65.Find the average illumination.

Solution:

Room area = 6 × 9 = 54 m^2.
Total wattage = 80 × 10 = 800 W.
Total flux emitted by ten lamps = 80 × 800 = 64,000 lumens.
Flux reaching the working plane = 64,000 × 0.65 = 41,600 lumens.

$$\therefore \text{Illumination, } E = \frac{\phi}{A} = \frac{41,600}{54} = 770.37 \text{ lux.}$$

3.The luminous intensity of a lamp is 600 CP. Find the flux given out. Also find the flux in the hemisphere containing the source of light and zero above thehorizontal.

Solution:

Flux emitted by source (lumen)
= Intensity (I) × solid angle (ω)
= 600 × 2 π = 3,769.911 lumens

∴ Flux emitted in the lower hemisphere = 3,769.911 lumens

.

4. The flux emitted by 100-W lamp is 1,400 lumens placed in a frosted globe of 40 cm diameter and gives uniform brightness of 250 milli-lumens/m^2 in all directions. Calculate the candel power of the globe and the percentage of light absorbedby the globe.

Solution:

Flux emitted by the globe

= brightness × globe area

$$= \left[\frac{250}{1,000}\right] \times \left[4\pi\left(\frac{40}{2}\right)^2\right]$$

= 1,256.63 lumens

Flux absorbed by the globe

= flux emitted by source – flux emitted by globe

= 1,400 – 1,256.63

= 143.36 lumens.

$$\therefore \text{The percentage of light absorbed by the globe} = \frac{143.36}{1,400} \times 100 = 10.24\%.$$

5. A surface inclined at an angle 40° to the rays is kept 6 m away from 150 candle power lamp. Find the average intensity of illumination on the surface.

Solution:

From the Fig. P.6.1:

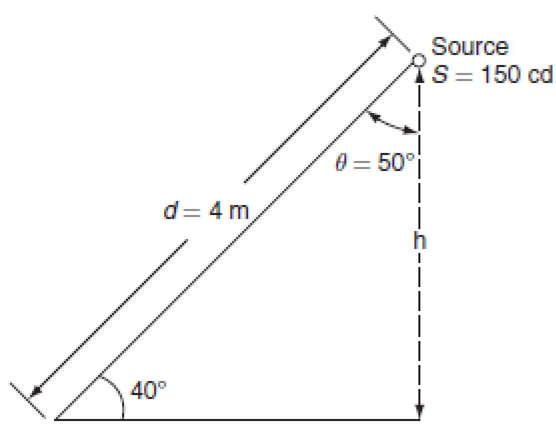
θ = (90° – 40°) = 50°.

∴ Average illumination:

$$E = \frac{I}{d^2} \times \cos\theta$$

$$= \frac{150}{(4)^2} \times \cos 50^\circ$$

$$= 6.026 \text{ lux.}$$



2.2 LAWS OF ILLUMINATION

Mainly there are two laws of illumination.

1. Inverse square law.

2. Lambert's cosine law.

Inverse square law

This law states that 'the illumination of a surface is inversely proportional to the square of distance between the surface and a point source'.

Proof:

Let, 'S' be a point source of luminous intensity 'I' candela, the luminous flux emitting from source crossing the three parallel plates having areas $A1$ $A2$, and $A3$ square meters, which are separated by a distances of d, $2d$, and $3d$ from the point source respectively as shown in Fig. 6.10.

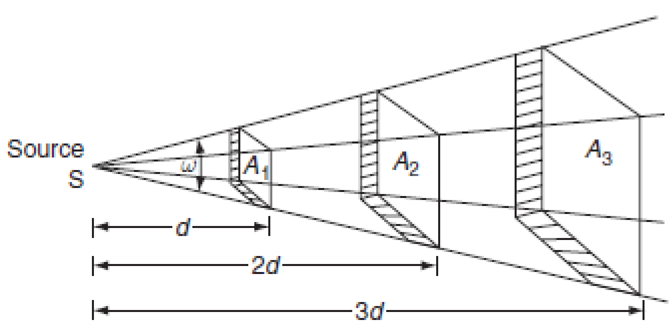


Fig. 6.10 Inverse square law

For area A_1, solid angle $\omega = \frac{A_1}{d^2}$.

Luminous flux reaching the area A1 = luminous intensity × solid angle

$$= I \times \omega = I \times \frac{A_1}{d^2}.$$

∴ Illumination '$E1$' on the surface area '$A1$' is:

$$E_1 = \frac{\text{flux}}{\text{area}} = \frac{IA_1}{d^2} \times \frac{1}{A_1}$$

$$\therefore E_1 = \frac{I}{d^2} \quad \text{lux.} \qquad \textbf{(6.5)}$$

Similarly, illumination '$E2$' on the surface *area* $A2$ is:

$$E_2 = \frac{I}{(2d)^2} \quad \text{lux} \qquad \textbf{(6.6)}$$

and illumination '$E3$' on the surface area $A3$ is:

$$E_3 = \frac{\text{I}}{(3d)^2} \quad \text{lux.} \qquad \textbf{(6.7)}$$

From Equations (6.5), (6.6), and (6.7)

$$E_1 : E_2 : E_3 = \frac{1}{d^2} : \frac{1}{(2d)^2} : \frac{1}{(3d)^2}. \qquad \textbf{(6.8)}$$

Hence, from Equation (6.8), illumination on any surface is inversely proportional to the square of distance between the surface and the source.

Lambert's cosine law

This law states that 'illumination, *E* at any point on a surface is directly proportional tothe cosine of the angle between the normal at that point and the line of flux'.

Proof:

While discussing, the Lambert's cosine law, let us assume that the surface is inclined atan angle 'θ' to the lines of flux as shown in Fig. 6.11.

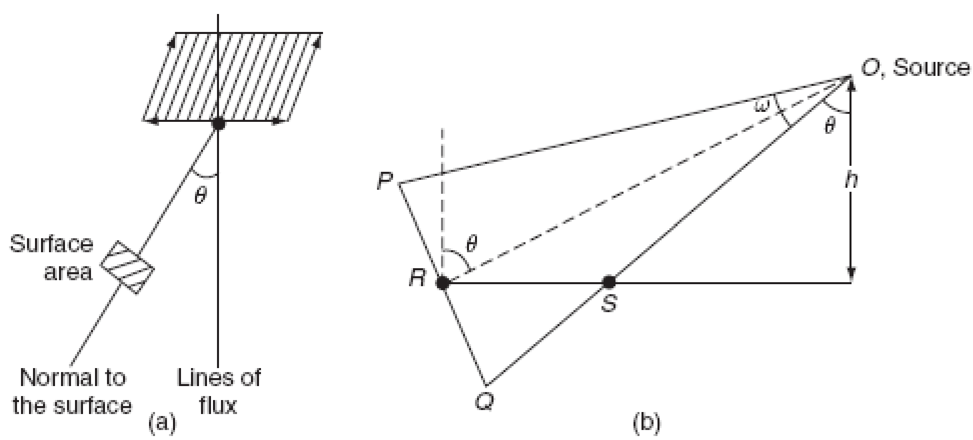


Fig. 6.11 Lambert's cosine law

Let *PQ* = The surface area normal to the source and inclined at 'θ' to the vertical axis.

RS = The surface area normal to the vertical axis and inclined at an angle θ to the source 'O'.

Therefore, from Fig. 6.11:

$$PQ = RS\cos\theta.$$

$$\therefore \text{The illumination of the surface } PQ, E_{PQ} = \frac{\text{flux}}{\text{area of } PQ}$$

$$= \frac{I \times \omega}{\text{area of } PQ} = \frac{I}{\text{area of } PQ} \times \frac{\text{area of } PQ}{d^2} \quad \left[\therefore \omega = \text{area/(radius)}^2\right]$$

$$= \frac{I}{d^2}. \quad \textbf{(6.9)}$$

$$\therefore \text{The illumination of the surface } RS, E_{RS} = \frac{\text{flux}}{\text{area of } RS} = \frac{\text{flux}}{\text{area of } PQ/\cos\theta}$$

$$[\therefore PQ = RS\cos\theta]$$

$$= \frac{I}{d^2}\cos\theta. \quad \textbf{(6.10)}$$

From Fig. 6.11(b):

$$\cos\theta = \frac{h}{d}$$

$$\text{or } d = \frac{h}{\cos\theta}.$$

Substituting '*d*' from the above equation in Equation (6.10):

$$\therefore E_{RS} = \frac{I}{(h/\cos\theta)^2} \times \cos\theta = \frac{I}{h^2}\cos^3\theta \quad \textbf{(6.11)}$$

$$\therefore E_{RS} = \frac{I}{d^2}\cos\theta = \frac{I}{h^2}\cos^3\theta \quad \textbf{(6.12)}$$

where *d* is the distance between the source and the surface in m, *h* is the height of source from the surface in m, and *I* is the luminous intensity in candela.

Hence, Equation (6.11) is also known as 'cosine cube' law. This law states that the 'illumination at any point on a surface is dependent on the cube of cosine of the angle between line of flux and normal at that point'.

Note: From the above laws of illumination, it is to be noted that inverse square law is only applicable for the surfaces if the surface is normal to the line of flux. And Lambert's cosine law is applicable for the surfaces if the surface is inclined an angle 'θ' to the line offlux.

6. The illumination at a point on a working plane directly below the lamp is to be 60 lumens/m^2. The lamp gives 130 CP uniformly below the horizontal plane.
Determine:

1. The height at which lamp is suspended.
2. The illumination at a point on the working plane 2.8 m away from the vertical axis of the lamp.

Solution:

Given data:

Candle power of the lamp = 130 CP.

The illumination just below the lamp, E = 60 lumen/m^2.

1. From the Fig. P.6.2, the illumination just below the lamp, i.e., at point *A*:

$$E_A = \frac{I}{h^2}$$

$$\therefore h = \sqrt{\frac{I}{EA}} = \sqrt{\frac{130}{60}} = 1.471 \text{ m.}$$

2. The illumination at point '*B*':

$$E_B = \frac{I}{h^2}\cos^3\theta$$

$$= \frac{130}{(2.8)^2}\left\{\frac{2.8}{\sqrt{2.8^2+1.471^2}}\right\}^3 = 11.504 \text{ lux.}$$

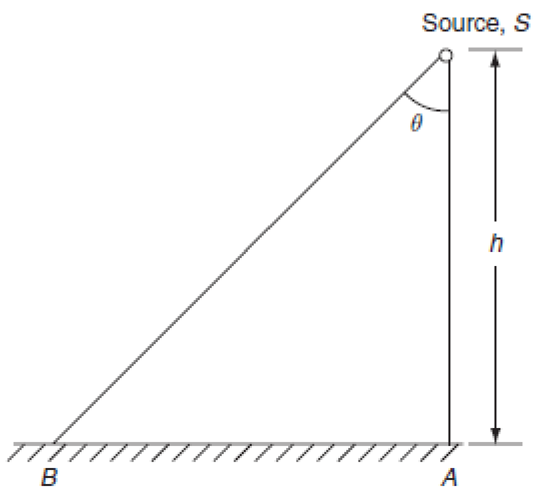


Fig. P.6.2

7. A lamp having a candle power of 300 in all directions is provided with a reflector that directs 70% of total light uniformly on a circular area 40-m diameter. The lamp is hung at 15 m above the area.

1. Calculate the illumination.

2.Also calculate the illumination at the center.

3.The illumination at the edge of the surface without reflector.

Solution:

Given data:

Candle power of the lamp = 300 CP.
Circular area diameter (D) = 40 m.
Height of mounting = 15 m.

1. The illumination on the circular area (Fig. P.6.3):

$$E = \frac{\text{flux}}{\text{area}} = \frac{CP \times \omega}{A}.$$

$$\text{Here, } A = \frac{\pi}{4} D^2 = \frac{\pi}{4} \times 40^2 = 400\ \pi \text{m}^2.$$

$$\text{Solid angle '}\omega\text{'} = 2\pi\,(1 - \cos\theta)$$

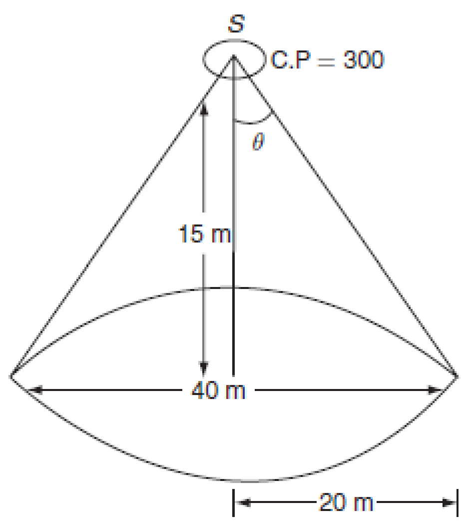
$$= 2\pi \left(1 - \frac{15}{\sqrt{15^2 + 20^2}} \right)$$

$$= 0.8\ \pi \text{ steradians.}$$

$$\therefore \text{Illumination } E = \frac{\text{flux}}{\text{area}} = \frac{CP \times \omega}{A}$$

$$= \frac{300 \times 0.8\pi}{400\pi}$$

$$= 0.6 \text{ lux.}$$



1. The illumination at the edge without reflector:

$$= \frac{CP}{d^2} \times \cos\theta$$

$$= \frac{300}{(\sqrt{15^2 + 10^2})^2} \times \frac{15}{\sqrt{15^2 + 10^2}}$$

$$= 0.768 \text{ lux.}$$

8: The luminous intensity of a source is 600 candela is placed in themiddle of a 10 × 6 × 2 m room. Calculate the illumination:

1. At each corner of the room.
2. At the middle of the 6-m wall.

Solution:

Given data:
Luminous intensity, (I) = 600 cd.
Room area = 10 × 6 × 2 m.

1. From the Fig. P.6.4:

$$OB = BD = \frac{\sqrt{10^2 + 6^2}}{2} = 5.83 \text{ m}$$

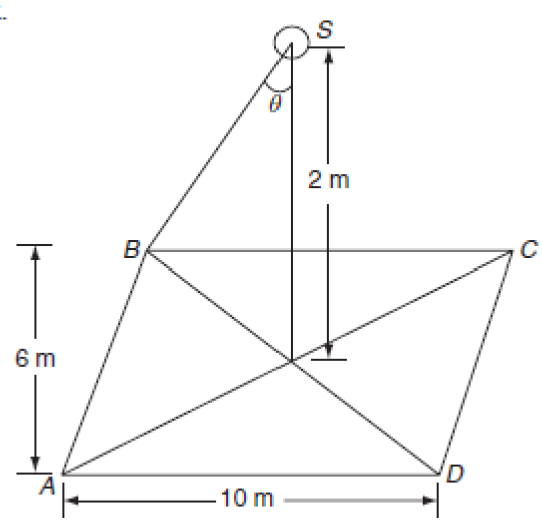
$$\text{BS} = \text{d} = \sqrt{2^2 + (5.38)^2} = 6.163 \text{ m.}$$

∴ The illumination at the corner 'B':

$$E_B = E_A = E_C = E_D$$

$$\frac{I}{d^2}\cos\theta = \frac{600}{(6.163)^2} \times \frac{2}{(6.163)}$$

$$= 5.126 \text{ lux.}$$



1. From Fig. P.6.5:

$$PS = \sqrt{2^2 + 5^2}$$

$$= 5.385 \text{ m.}$$

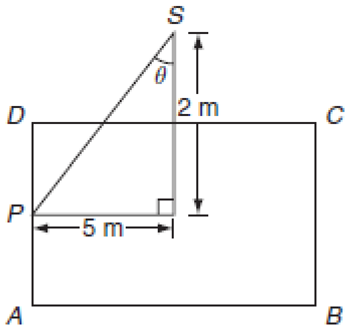


Fig. P.6.5

The illumintaion at the point '*P*', $E_p = \frac{I}{d^2}\cos\theta$

$$= \frac{600}{(5.385)^2} \times \frac{2}{(5.385)}$$

$$= 7.684 \text{ lux.}$$

9: The candle power of a source is 200 candela in all directions below the lamp. The mounting height of the lamp is 6 m. Find the illumination:

1. Just below the lamp.
2. 3 m horizontally away from the lamp on the ground.
3. The total luminous flux in an area of 1.5-m diameter around the lamp on the ground.

Solution:

The candle power of the source, *I* = 200 candela.

Mounting height (*h*) = 6 m.

1. The illumination just below the lamp, i.e., at point *'A':*

$$E_p = \frac{I}{d^2}\cos\theta$$

$$= \frac{600}{(5.385)^2} \times \frac{2}{(5.385)}$$

$$= 7.684 \text{ lux.}$$

2. From Fig. P.6.6:

$$d = \sqrt{3^2 + 6^2} = 6.708.$$

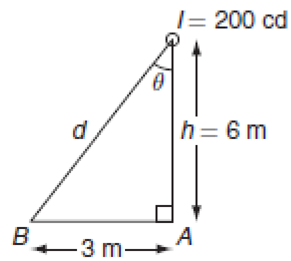
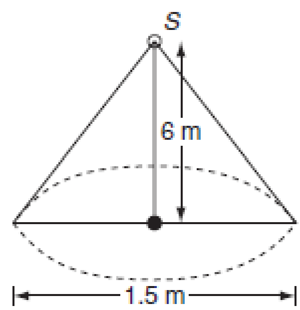


Fig. P.6.6

The illumination 3 m away from the lamp on the ground, i.e., at point '*B*' (Fig.P.6.7):

$$E_B = \frac{I}{d^2}\cos\theta$$



$$= \frac{200}{(6.708)^2} \times \frac{6}{(6.708)}$$

$$= 3.975 \text{ lux.}$$

Fig. P.6.7

$$\text{Surface area } = \frac{\pi}{4} d^2$$

$$= \frac{\pi}{4} \times (1.5)^2$$

$$= 1.767 \text{ m}^2.$$

3.The total flux reaching the area around the lamp:

= EA × surface area

= 5.55 × 1.767

= 9.80 lumens.

10: Two sources of candle power or luminous intensity 200 candela and250 candela are mounted at 8 and 10 m, respectively. The horizontal distance betweenthe lamp posts is 40 m, calculate the illumination in the middle of the posts.

Solution:

From Fig. P.6.8:

$$d_1 = \sqrt{8^2 + 20^2}$$

$$= 21.54.$$

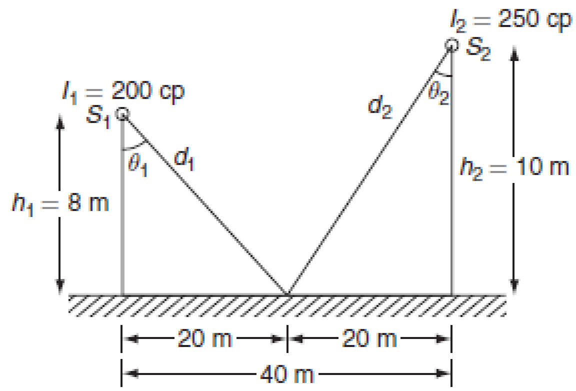


Fig. P.6.8

$$\cos\theta_1 = \frac{h_1}{d_1} = \frac{8}{21.54}$$

$$= 0.37.$$

$\therefore$ The illumination at the point 'P' due to the source 'S_1' $= \frac{I_1}{d_1^2}\cos\theta_1$

$$E_1 = \frac{200}{(21.54)^2} \times 0.37$$

$$= 0.159 \text{ lux}.$$

and $d_2 = \sqrt{10^2 + 20^2} = 22.36$

$$\cos\theta_2 = \frac{h_2}{d_2} = \frac{10}{22.36} = 0.447.$$

The illumination at the point '*P*' due to the source '*S*2':

$$E_2 = \frac{I_2}{d_2^2} \times \cos\theta_2$$

$$= \frac{250}{(22.36)^2} \times 0.447 = 0.2235 \text{ lux}.$$

The total illumination at '*P*' due to both the sources S_1 and S_2 = $E_1 + E_2$

= 0.159 + 0.2235

= 0.3825 lux.

11: Two sources of having luminous intensity 400 candela are hung at a height of 10 m. The distance between the two lamp posts is 20 m. Find the illumination
(i) beneath the lamp and (ii) in the middle of the posts.

Solution:

Given data:

Luminous intensity = 400 CP.
Mounting height = 10 m.
Distance between the lamp posts = 20 m.

1. From Fig. P.6.9:

$$d_1 = \sqrt{10^2 + 20^2} = 22.36.$$

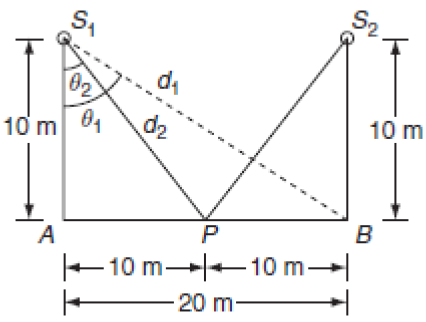


Fig. P.6.9

$$\cos\theta_1 = \frac{h}{d_1} = \frac{10}{22.36} = 0.4472.$$

The illumination at '*B*' due to 'S_1':

$$E_1 = \frac{I}{d_1^2}\cos\theta_1$$

$$= \frac{400}{(22.36)^2} \times 0.4472$$

$$= 0.35778 \text{ lux.}$$

The illumination at ‘B’ due to ‘$S2$':

$$E_2 = \frac{400}{10^2} = 4 \text{ lux.}$$

$$\therefore \text{The total illumination at 'B'} = E_1 + E_2$$
$$= 0.3577 + 4$$
$$= 4.3577 \text{ lux.}$$

$$d_2 = \sqrt{10^2 + 10^2} = 14.14.$$

$$\cos\theta_2 = \frac{10}{14.14} = 0.707.$$

$$E_1 = \frac{I}{d_2^2} \times \cos\theta_2$$

$$= \frac{400}{(14.14)^2} \times 0.707 = 1.414 \text{ lux.}$$

The illumination at ‘P’ due to $S2$, ‘$E2$’ will be same as $E1$

∴ The illumination at ‘P’ due to both $S1$ and $S2$:
= $E1$+ $E2$ = $E1$+ $E1$
= $2E1$ = 2 × 1.414
= 2.828 lux.

POLAR CURVES

The luminous flux emitted by a source can be determined using the intensity distribution curve. Till now we assumed that the luminous intensity or the candle power from a source is distributed uniformly over the surrounding surface. But due to its s not
uniform in all directions. The luminous intensity or the distribution of the light can be represented with the help of the polar curves.

The polar curves are drawn by taking luminous intensities in various directions at an equal angular displacement in the sphere. A radial ordinate pointing in any particular direction on a polar curve represents the luminous intensity of the source when it is viewed from that direction. Accordingly, there are two different types of polar curves and they are:

1. A curve is plotted between the candle power and the angular position, if the luminous intensity, i.e., candle power is measured in the horizontal plane about the vertical axis, called *'horizontal polar curve'.*
2. curve is plotted between the candle power, if it is measured in the vertical plane and the angular position is known as *'verticalpolar curve'.*

Figure 6.12 shows the typical polar curves for an ordinary lamp.

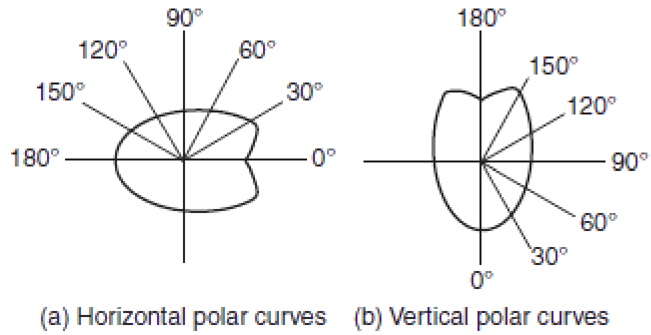


Fig Polar curves

Depression at 180° in the vertical polar curve is due to the lamp holder. Slight depression at 0° in horizontal polar curve is because of coiled coil filament.

Polar curves are used to determine the actual illumination of a surface by employing the candle power in that particular direction as read from the vertical polar curve. These are also used to determine mean horizontal candle power (MHCP) and mean spherical candle power (MSCP).

The mean horizontal candle power of a lamp can be determined from the horizontal polar curve by considering the mean value of all the candle powers in a horizontal direction.

The mean spherical candle power of a symmetrical source of a light can be found outfrom the polar curve by means of a Rousseau's construction.

2.4 Various types of Lamps

Light plays major role in human life. Natural light restricted for some duration in a day, it is very difficult to do any work by human being without light. So, it is necessary to have substitute for natural light. Light from incandescent bodies produced electrically, which playing important role in everyday life due to its controlled output, reliability, and cleanliness nowadays; various sources are producing artificial light. Each source has its own characteristics and specific importance.

IncandescentLamps:

When the filaments of these lamps are heated to high temperature, they emit light that falls in the visible region of wavelength. Tungsten-filament lamps are operating on this principle.
These lamps are temperature-dependent sources. When electric current is made to flow through a fine metallic wire, which is known as *filament*, its temperature increases. At low temperatures, it emits only heat energy, but at very high temperature, the metallic wire emits both heat and light energy. These incandescent lamps are also known as *temperature radiators.*

Construction

Figure 7.3 shows the construction of the pure tungsten filament incandescent lamp. It consists of an evacuated glass bulb and an aluminum or brass cap is provided with two pins to insert the bulb into the socket. The inner side of the bulb consists of a tungsten filament and the support wires are made of molybdenum to hold the filament in proper position. A glass button is provided in which the support wires are inserted. A stem tube forms an air-tight seal around the filament whenever the glass is melted.

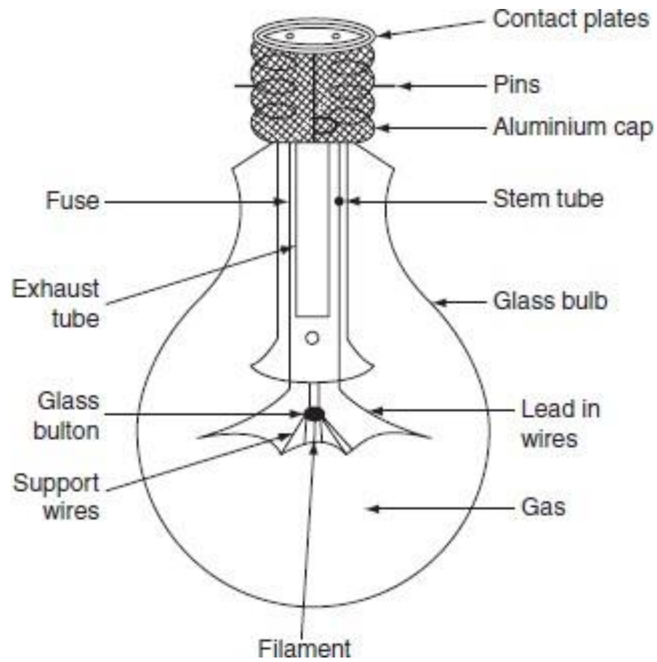


Fig. 7.3 Incandescent lamp

Operation

When electric current is made to flow through the fine metallic tungsten filament, its temperature increases. At very high temperature, the filament emits both heat and light radiations, which fall in the visible region. The maximum temperature at which the filament can be worked without oxidization is 2,000°C, i.e., beyond this temperature, the tungsten filament blackens the inside of the bulb. The tungsten filament lamps can be operated efficiently beyond 2,000°C, it can be attained by inserting a small quantity of inert gas nitrogen with small quantity of organ. But if gas is inserted instead of vacuum in the inner side of the bulb, the heat of the lamp is conducted away and it reduces the efficiency of the lamp. To reduce this loss of heat by conduction and convection, as far as possible, the filament should be so wound that it takes very little space. This is achieved by using a single-coil filament instead of a straight wire filament as shown in Fig.

7.4(a). This single-coil filament is used in vacuum bulbs up to 25 W and gas filled bulbs from 300 to 1,000 W.

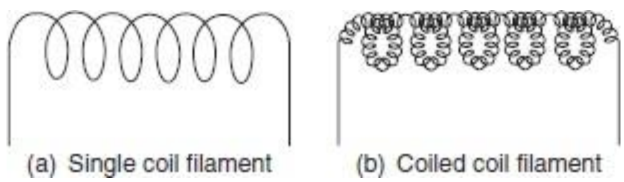


Fig. 7.4 Various filaments used in incandescent lamps

On further development of the incandescent lamps, the shortening of the length of the filament was achieved by adopting a coiled coil or a double coil filament as shown in Fig. 7.4(b). The use of coiled coil filament not only improves the efficiency of the lamp but also reduces the number of filament supports and thus simplified interior construction because the double coil reduces the filament mounting length in the ratio of 1:25 as compared to the straight wire filaments.

Usually, the tungsten filament lamp suffers from 'aging effect', the output of the light an incandescent lamp decreases as the lamp ages. The output of the light of the lamp decreases due to two reasons.

- At very high temperature, the vaporization of filament decreases the coil diameter so that resistance of the filament increases and hence its draws less current from the supply, so the temperature of the filament and the light output of the bulb decrease.
- The current drawn from the mains and the power consumed by the filament decrease, which decrease the efficiency of the lamp with the passage of time. In addition, the evaporation of the filament at high temperature blackens the inside of the bulb.

The effects of voltage variations

The variations in normal supply voltages will affect the operating characteristics of incandescent lamps. The performance characteristic of an incandescent lamp, when it is subjected to voltage other than normal voltage, is shown in Fig. .

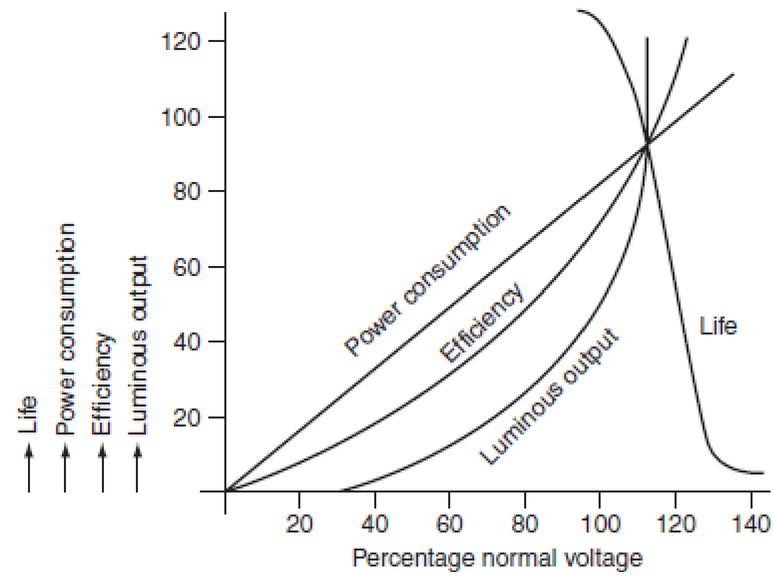


Fig Performance characteristics of incandescent lamp

With an increase in the voltage owing to the increase in the temperature, the luminous output of the incandescent lamps, and the efficiency and power consumption, but its life span decreases.

The depreciation in the light output is around 15% over the useful life of the lamp. The above-stated factors are related to the variations of voltage are given as:

- Lumens output a $(\text{voltage})^{3.55}$.
- Power consumption a $(\text{voltage})^{1.55}$.
- Luminous efficiency a $(\text{voltage})^{2}$.
- Life a $(\text{voltage})^{-13}$ (for vacuum lamps).
- Life a $(\text{voltage})^{-14}$ (for gas filled lamps).

The advantages of the incandescent lamps

- These lamps are available in various shapes and sizes.
- These are operating at unity power factor.
- These lamps are not affected by surrounding air temperature.
- Different colored light output can be obtained by using different colored glasses.

Filament dimensions

Let us consider a lamp, which is connected to the mains, is given the steady light output, i.e., whatever the heat produced, it is dissipated and the filament temperature is not going to be increase further. It is found to be the existence of a definite relation between the diameter of a given filament and the current through it.

The input wattage to the lamp is expressed as:

$$I^2R = I^2\frac{\rho l}{a} \qquad \left(\because\ R = \rho\frac{l}{a}\right)$$

$$= \frac{I^2 \times \rho l}{(\pi d^2/4)}$$

$$= I^2 \times \frac{4\rho l}{\pi d^2}, \qquad \textbf{(7.1)}$$

where I is the current taken by the lamp A, a is the filament cross-section, sq. m, ρ is the resistivity of the filament at working temperature Ω-m, l is the length of the filament m, and$d$ isthe diameter of the filament.

Let the emissivity of the material be 'e'. Total heat dissipated will depend upon the surface area and the emissivity of the material

∴ Heat dissipated a surface area × emissivity:

$$\propto \pi dl \times e. \qquad \textbf{(7.2)}$$

At the steady state condition, the power input should be equal to the heat dissipated. From Equations (7.1) and (7.2), we can write that:

$$I^2\frac{4\rho l}{\pi d^2} \propto \pi dl \times e$$

$$I^2 \propto d^3 \quad \text{or} \quad I \propto d^{3/2}. \qquad \textbf{(7.3)}$$

If two filaments are made up of same material, working at same temperature and efficiency but with different diameters, then from Equation (7.3):

$$\frac{I_1}{I_2} = \left(\frac{d_1}{d_2}\right)^{3/2} \qquad \textbf{(7.4)}$$

If two filaments are working at the same temperature, then their luminous output must be sameeven though their lengths are different.

$$\therefore \text{Lumen output} \propto l_1 d_1 \propto l_2\, d_2$$

$$\therefore l_1 d_1 \propto l_2\, d_2 = \text{constant}. \qquad \textbf{(7.5)}$$

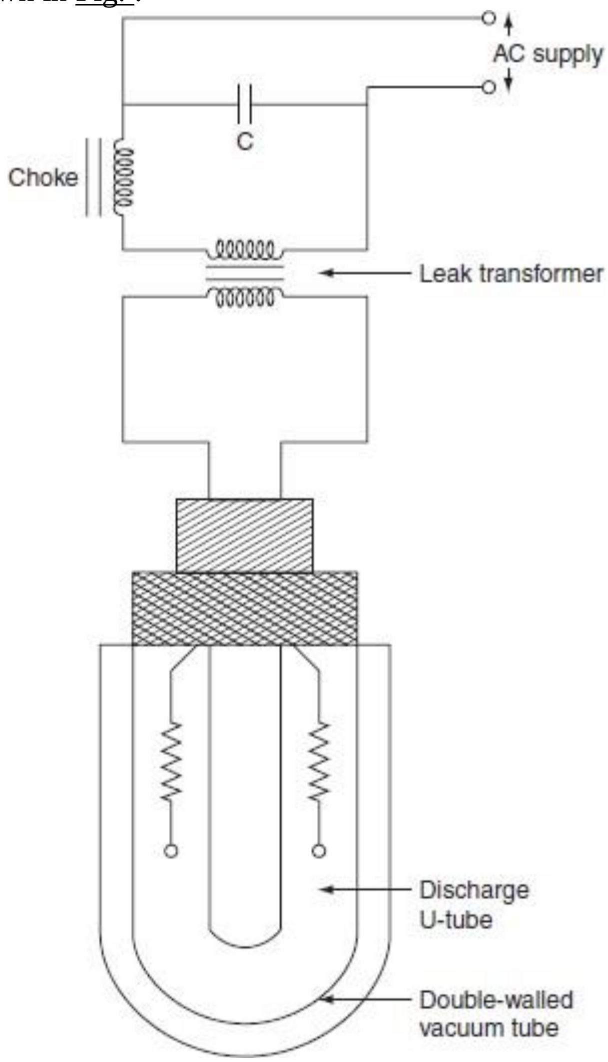
Limitations

The incandescent lamp suffers from the following drawbacks:

- Low efficiency.
- Colored light can be obtained by using different colored glass enclosures only.

2.5 sodium vapour lamp

A sodium vapor lamp is a cold cathode and low-pressure lamp. A sodium vapor discharge lamp consists of a *U*-shaped tube enclosed in a double-walled vacuum flask, to keep the temperature of the tube within the working region. The inner *U*-tube consists of two oxide-coated electrodes, which are sealed with the ends. These electrodes are connected to a pin type base construction of sodium vapor lamp is shown in Fig. .



This sodium vapor lamp is low luminosity lamp, so that the length of the lamp should be more. In order to get the desired length, it is made in the form of a *U*-shaped tube. This long*U*-tube consists of a small amount of neon gas and metallic sodium. At the time of start, the neon gas vaporizes and develops sufficient heat to vaporize metallic sodium in the *U*-shaped tube.

Working

Initially, the sodium is in the form of a solid, deposited on the walls of inner tube. When sufficient voltage is impressed across the electrodes, the discharge starts in the inert gas, i.e., neon; it operates as a low-pressure neon lamp with pink color. The temperature of the lamp increases gradually and the metallic sodium vaporizes and then ionizes thereby producing the monochromatic yellow light. This lamp takes 10–15 min to give its full light output. The yellowish output of the lamp makes the object appears gray.

In order to start the lamp, 380 – 450 V of striking voltage required for 40- and 100-W lamps. These voltages can be obtained from a high reactance transformer or an auto transformer. The operating power factor of the lamp is very poor, so that a capacitor is placed to improve the power factor to above 0.8. More care should be taken while replacing the inner tube, if it is broken, then sodium comes in contact with the moisture; therefore, fire will result. The lamp must be operated horizontally or nearly so, to spread out the sodium well along the tube.

The efficiency of sodium vapor lamp is lies between 40 and 50 lumens/W. Normally, these lamps are manufactured in 45-, 60-, 85- and 140-W ratings. The normal operating temperatures of these lamps are 300°C. In general, the average life of the sodium vapor lamp is 3,000 hr and such bulbs are not affected by voltage variations.

Following are the causes of failure to operate the lamp, when:

- The cathode fails to emit the electrons.
- The filament breaks or burns out.
- All the particles of sodium are concentrated on one side of the inner tube.
- The life of the lamp increases due to aging.

The average light output of the lamp is reduced by 15% due to aging. These lamps are mainly used for highway and street lighting, parks, railway yards, general outdoor lighting, etc.

FLUORESCENT LAMP

Construction:

It consists of a long horizontal tube, due to low pressure maintained inside of the bulb; it is made in the form of a long tube.

The tube consists of two spiral tungsten electrode coated with electron emissive material and are placed at the two edges of long tube. The tube contains small quantity of argon gas and certain amount of mercury, at a pressure of 2.5 mm of mercury. The construction of fluorescent lamp is shown in Fig. 7.12. Normally, low-pressure mercury vapor lamps suffer from low efficiency and they produce an objectionable colored light. Such drawback is overcome by coating the inside of the tube with fluorescent powders. They are in the form of solids, which are usually knows as phosphors.

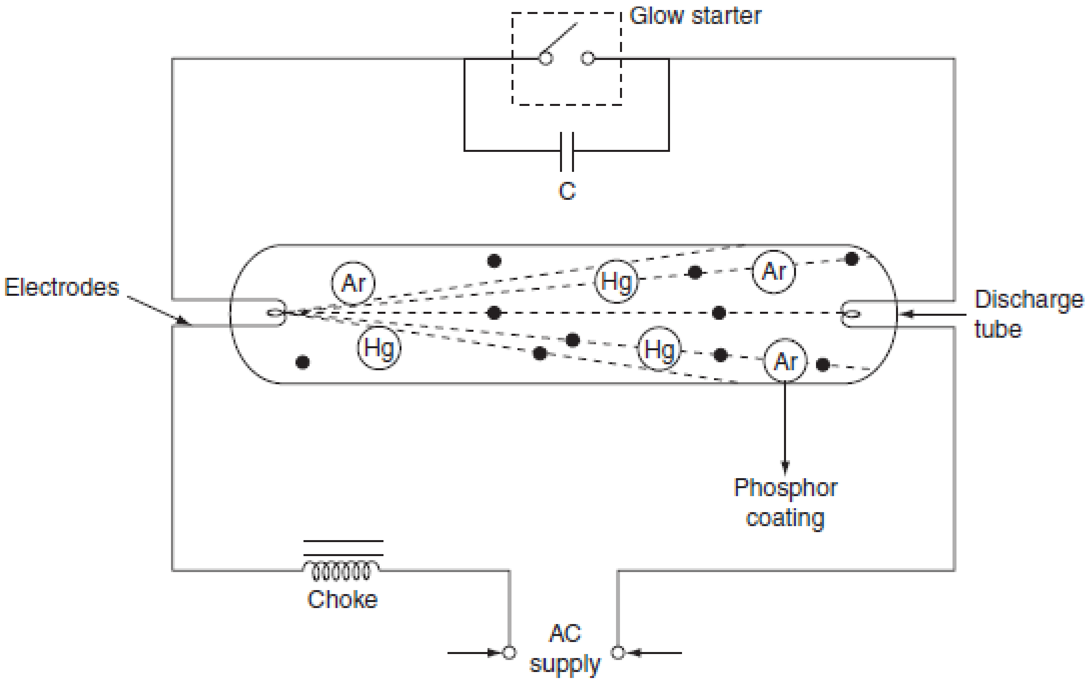


Fig. Fluorescent lamp

A glow starter switch contains small quantity of argon gas, having a small cathode glow lamp with bimetallic strip is connected in series with the electrodes, which puts the electrodes directly across the supply at the time of starting. A choke is connected in series that acts as ballast when the lamp is running, and it provides a voltage impulse for starting. A capacitor of 4μF is connected across the starter in order to improve the power factor.

Working

At the time of starting, when both the lamp and the glow starters are cold, the mercury is in the form of globules. When supply is switched on, the glow starter terminals are open circuited and full supply voltage appeared across these terminals, due to low resistance of electrodes and choke coil. The small quantity of argon gas gets ionized, which establishes an arc with a starting glow. This glow warms up the bimetallic strip thus glow starts gets short circuited. Hence, the two electrodes come in series and are connected across the supply voltage. Now, the two electrodes get heated and start emitting electrons due to the flow of current through them. These electrons collide with the argon atoms present in the long tube discharge that takes place through the argon gas. So, in the beginning, the lamp starts conduction with argon gas as the temperature increases, the mercury changes into vapor form and takes over the conduction of current.

In the mean time, the starter potential reaches to zero and the bimetallic strip gets cooling down. As a result, the starter terminals will open. This results breaking of the series circuit. A very high voltage around 1,000 V is induced, because of the sudden opening of starter terminals in the series circuit. But in the long tube, electrons are already present; this induced voltage is quite sufficient to break down the long gap. Thus, more number of electrons collide with argon and mercury vapor atoms. The excited atom of mercury gives UV radiation, which will not fall in the visible region.

Meanwhile, these UV rays are made to strike phosphor material; it causes the re-emission of light of different wavelengths producing illumination. The phenomenon of the emission is called as *luminescence.*

This luminescence is classified into two ways. They are:

1. **Fluorescence:** In this case, the excitation presents for the excited periods only.
2. **Phosphorescence:** In this case, even after the exciting source is removed, the excitation will present.

In a lamp, the re-emission of light causes fluorescence, then such lamp is known as*fluorescent lamp.*

Depending upon the type of phosphor material used, we get light of different colors as given in Table. .

Table Colors of light

	Phosphor material	***Color effect***
1.	Zinc silicate	Green
2.	Calcium tungstate	Green
3.	Magnesium tungstate	Bluish while
4.	Cadmium silicate	Yellowish pink
5.	Zinc beryllium silicate	Yellowish while
6.	Cadmium borate	Pink

Advantages of fluorescent lamp

The fluorescent lamp has the following advantages:

- High efficiency.
- The life of the lamp is three times of the ordinary filament lamp.

- The quality of the light obtained is much superior.
- Less chances of glare.
- These lamps can be mounted on low ceiling, where other light sources would be unsatisfactory.

Although the fluorescent lamp has the above advantages, it sufferers form the following disadvantages:

- The initial cost is high because of choke and starter.
- The starting time as well as the light output of the lamp will increases because of low ambient temperature.
- Because of the presence of choke, these lamps suffer from magnetic humming and may cause disturbance.
- The stroboscopic effect of this lamp is objectionable.

Stroboscopic effect

We all know that because of ‘the alternating nature of supply, it crosses zero two times in a cycle’. For 50-Hz frequency supply of the alternating current, a discharge lamp will be extinguished twice in a cycle and 100 times per second (for 50-Hz supply). A human eye cannot identify this extinguish phenomenon, because of the persistence of vision. If this light falls upon a moving object, the object appearing like slow moving or fast moving or moving in reverse direction, sometimes stationary. This effect is due to the extinguishing nature of the light of the lamp. This effect is called as ‘*stroboscopic effect*’.

This effect can be avoided by employing any of the two techniques listed below.

1. If we have three-phase supply, then the fluorescent lamps that are adjacent should be fed from different phases. Then, no two lamps will not be in same phase at zero instant of AC supply, so light is present at any instant.
2. If the available supply is single phase, then twin tube circuitry as shown in Fig. 7.13, we can eliminate stroboscopic effect.

COMPARISON BETWEEN TUNGSTEN FILAMENT LAMPS AND FLUORESCENT LAMPS

Incandescent lamp	***Fluorescent lamp***
1. Initial cost is less.	1. Initial cost is more.
2. Fluctuation in supply voltage has less effect on light output, as the variations in voltage are absorbed in choke.	2. Fluctuations in supply voltage has comparatively more effect on the light output.

Incandescent lamp	***Fluorescent lamp***
3. It radiates the light; the color of which resembles the natural light.	3. It does not give light close to the natural light.
4. It works on AC as well as DC.	4. Change of supply needs additional equipment.
5. The luminous efficiency of the lamp is high that is about 8 – 40 lumens/W.	5. The luminous efficiency is poor, which is about 8–10 lumen/W.
6. Different color lights can be obtained by using different colored glasses.	6. Different color lights can be obtained by using different composition of fluorescent powder.
7. Brightness of the lamp is more.	7. Brightness of the lamp is less.
8. The reduction in light output of the lamp is comparatively high, with the time.	8. The reduction in light output of the lamp is comparatively low, with the lamp.
9. The working temperature is about 2,000°C.	9. The working temperature is about 50°C.
10. The normal working life is 1,000 hr.	10. The normal working life is 5,000–7,500 hr.
11. No stroboscopic effect.	11. Stroboscopic effect is present.
12. These lamps are widely used for domestic, industrial, and street lighting.	12. They find wide application in domestic, industrial, and floodlighting.
13. The luminous efficiency increases with the increase in the voltage of the lamp.	13. The luminous efficiency increase with the increase in voltage and the increase in the length of tube.

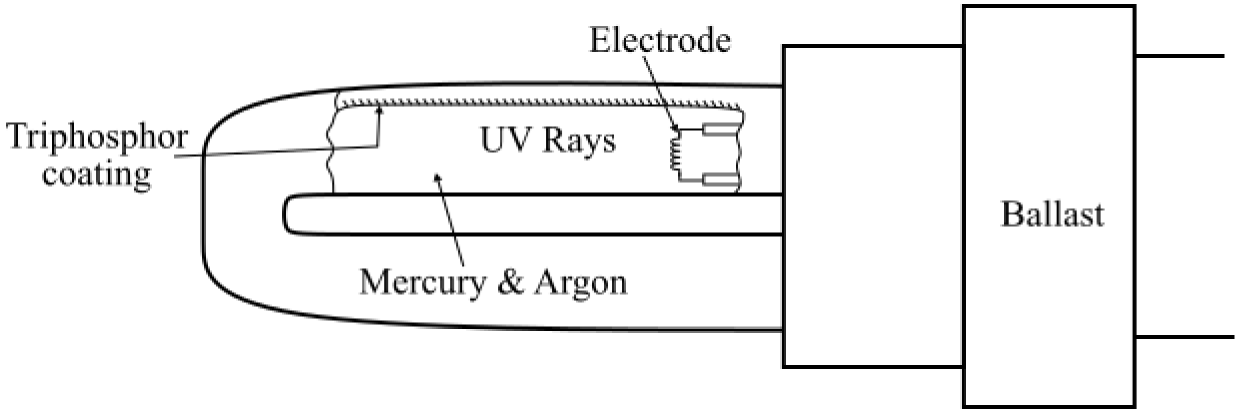
2.6 CFL (Compact Fluoroscent Lamp):

A **compact fluorescent lamp (CFL)** is a type of fluorescent lamp that has been compressed into the size of an ordinary incandescent lamp. It works on the principle of **gas discharge**, i.e., ionization of gas by the electric current.

- The modern CFL was invented by **Edward E. Hammer** in 1973.
- CFLs are the lamps of choice for those looking for an energy efficient alternative to incandescent lamps.
- CFLs consume very less power than an incandescent lamp.
- The increasing variety of shape and color and small size of CFL have made them more versatile and acceptable than the conventional long tube fluorescent lamps.

Construction and Working of CFL

CFLs are widely used for residential as well as commercial lighting. The following figure shows the construction of a modern CFL –



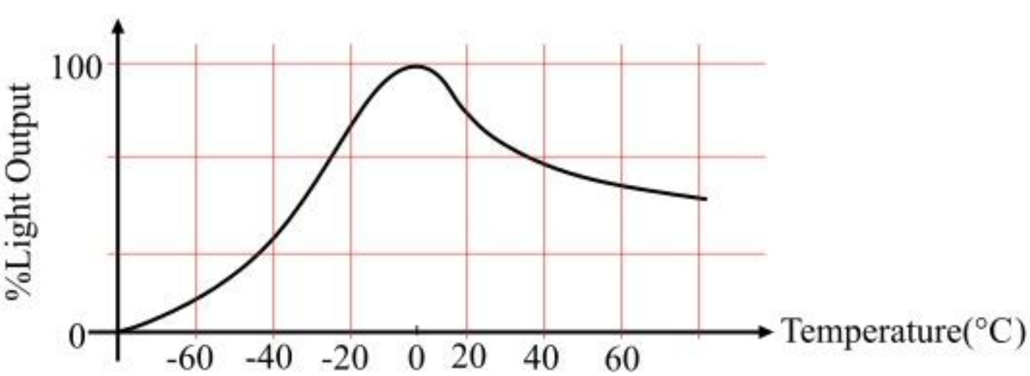
A typical CFL consists of a gas filled tube with two electrodes mounted in an end cap. The tube contains a mixture of argon gas, mercury vapor and liquid mercury at low pressure. The tube is also coated on the inside with three different phosphors.

When the electric supply is connected to the electrodes, an electric arc is created between two electrodes. The electric arc produces the flow of electrons. When the mercury atoms inside the tube are bombarded by these electrons produce ultraviolet radiation. The phosphor coating inside the tube give off light when exposed to the UV radiation.

The circuit of the CFL contains a ballast which provides the high initial voltage required to create the starting arc and then limit the current to prevent the lamp from self-destruction

Effect of Temperature on CFL Performance

The following characteristic curve shows the variation in the CFL output with the change in temperature.



Temperature - Light Output Characteristics

From the graph, it is clear that the ambient temperature around a CFL can have significant effect on the light output and efficiency of the lamp. The optimum lamp wall temperature for a CFL is generally 38 °C.

At very low temperature, the light output from the CFL can decline to about 1/3rd of the rated value. Since at the temperatures below the optimum value, the mercury vapor will condense at cold spot, reducing the number of mercury atoms available to emit UV rays and hence the light output reduces.

Advantages of Compact Fluorescent Lamp

The main advantages of using a CFL are listed here −

- CFLs are the energy efficient lamps. The operating cost of CFLs is very less. CFLs save a lot of electricity.
- CFLs produce less heat as compared to incandescent bulbs.
- The lamp efficiency of the CFL is fairly high, about 50 to 75 lumens per Watt.
- CFL lamps do not require the starting gear. CFL lamps start immediately.
- CFLs have longer lifespan.

Disadvantages of Compact Fluorescent Lamp (CFL)

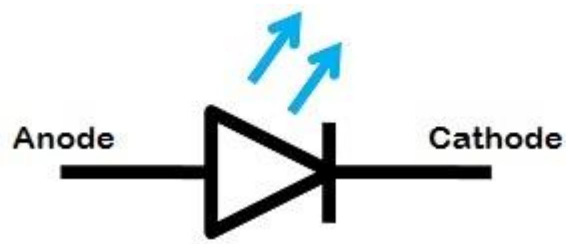
The disadvantages of using a CFL are as follows -

- The initial cost of installing CFL lamps is high.
- CFLs are not environment friendly as they have mercury content.
- CFLs can fail prematurely if overheated.
- CFL lamps cannot be used with timer switches since these can reduce the lifespan of the CFL.

LED (Light Emitting diode)

The Light-emitting diode is a two-lead semiconductor light source. In 1962, Nick Holonyak has come up with the idea of a light-emitting diode, and he was working for the general electric company. The LED is a special type of diode and they have similar electrical characteristics to a PN junction diode. Hence the LED allows the flow of current in the forward direction and blocks the current in the reverse direction. The LED occupies a small area which is less than **1 mm^2**. The applications of LEDs used to make various electrical and electronic projects. In this article, we will discuss the working principle of theLEDanditsapplications.

The LED symbol is similar to a diode symbol except for two small arrows that specify the emission of light, thus it is called LED (light-emitting diode). The LED includes two terminals namely anode (+) and the cathode (-). The LED symbol is shown below.



LED Symbol

Construction of LED

The construction of LED is very simple because it is designed through the deposition of three semiconductor material layers over a substrate. These three layers are arranged one by one where the top region is a P-type region, the middle region is active and finally, the bottom region is N-type. The three regions of semiconductor material can be observed in the construction. In the construction, the P-type region includes the holes; the N-type region includes elections whereas the active region includes both holes and electrons.

When the voltage is not applied to the LED, then there is no flow of electrons and holes so they are stable. Once the voltage is applied then the LED will forward biased, so the electrons in the N-region and holes from P-region will move to the active region. This region is also known as the depletion region. Because the charge carriers like holes include a positive charge whereas electrons have a negative charge so the light can be generated through the recombination of polarity charges.

2.7 Various lightning schemes-Domestic and industrial lamp fitting:

Domestic light fittings refer to the various types of fixtures and installations used in residential settings to provide illumination. These fittings come in a variety of styles and types to suit different aesthetic preferences and functional needs. Here are some common types of domestic light fittings:

1. **Ceiling Lights**: These are fixtures mounted on the ceiling and typically include flush mount or semi-flush mount options. They provide general ambient lighting for rooms such as living rooms, bedrooms, and hallways.
2. **Pendant Lights**: Pendant lights hang from the ceiling by a cord, chain, or rod, often used for task lighting over dining tables, kitchen islands, or as decorative elements in living spaces.
3. **Chandeliers**: Chandeliers are elaborate ceiling-mounted fixtures with multiple arms and often adorned with crystals or decorative elements. They are used in dining rooms, entryways, or large living spaces for both ambient and decorative lighting.
4. **Wall Sconces**: Wall-mounted fixtures that provide ambient or accent lighting, commonly used in hallways, staircases, bedrooms, and bathrooms. They come in various styles to complement different decor themes.
5. **Track Lighting**: Track lighting systems consist of multiple adjustable light fixtures mounted on a track. They are versatile for highlighting artwork, task lighting in kitchens, or providing general lighting in living spaces.

6. **Recessed Lighting**: Recessed lights are installed flush with the ceiling or wall, offering a minimalist look while providing ambient or accent lighting. They are popular in kitchens, bathrooms, and areas where a clean and unobtrusive appearance is desired.
7. **Table Lamps**: Portable lamps placed on tables, desks, or nightstands for task lighting or accentuating decor. They come in various sizes, styles, and materials to match different room aesthetics.
8. **Floor Lamps**: These freestanding lamps are placed on the floor and provide ambient or task lighting in living rooms, bedrooms, and reading corners. They are available in adjustable, arc, or torchiere styles.
9. **Under-Cabinet Lighting**: Lighting fixtures installed underneath kitchen cabinets to illuminate countertops for task lighting, enhancing visibility while cooking or working.
10. **Outdoor Lighting**: Light fittings designed for outdoor use, including wall-mounted lanterns, post lights, pathway lights, and floodlights, to illuminate gardens, patios, driveways, and entryways.

Industrial Lamp fitting:

Industrial lamp fittings refer to lighting fixtures specifically designed for use in industrial environments. These fittings are built to withstand harsh conditions such as dust, humidity, vibrations, and high temperatures typically found in factories, warehouses, manufacturing plants, and other industrial settings. Here are some key features and types of industrial lamp fittings:

1. **High-Bay Lighting**: High-bay fixtures are typically mounted at high ceilings (typically 15 feet or higher) and provide powerful, uniform illumination over large areas. They are commonly used in warehouses, manufacturing facilities, and gymnasiums. High-bay lights often use metal halide, high-pressure sodium, LED, or fluorescent technology.
2. **Low-Bay Lighting**: Similar to high-bay lights but designed for lower ceiling heights (typically under 20 feet). They provide focused lighting for areas requiring less vertical clearance, such as production lines, workshops, and smaller warehouses.
3. **Task Lighting**: Task lights are used to provide focused illumination for specific tasks or workstations in industrial settings. They are often adjustable and can be mounted on machinery or workbenches to enhance visibility and productivity.
4. **Floodlights**: Industrial floodlights are used to illuminate outdoor areas such as loading docks, construction sites, and storage yards. They provide wide-area coverage and are designed to withstand weather elements.
5. **Strip Lights**: Industrial strip lights consist of linear fluorescent or LED fixtures mounted on ceilings or walls. They are used for general illumination in aisles, corridors, and storage areas, providing uniform light distribution.
6. **Vapor Tight Fixtures**: Vapor tight or weatherproof fixtures are sealed against dust, moisture, and humidity. They are ideal for environments where exposure to water, dirt, or debris is common, such as food processing facilities, car washes, and outdoor canopies.
7. **Emergency Lighting**: Emergency lighting fixtures are essential in industrial settings to provide illumination during power outages or emergencies. They include exit signs, emergency

2.8 Design and calculation of illumination:

There are a number of methods employed for lighting calculations, the three main methods are given as follows −

- Watt per Square Meter Method
- Lumen Method

- Point to Point Method

Watt per Square Meter Method
The watt per square meter method is fundamentally a rule of thumb method. This method of lighting calculation comes in handy when doing a quick calculation or double-check. It entails allocating watts per square metre of the area to be illuminated in accordance with the desired illumination, based on an average figure of overall system efficiency.

Lumen Method

The **lumen method**, also called the **light flux method**, is the method employed for lighting calculation 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.

Calculation −In lumen method of lighting calculation, the total lumens output is determined from the size of the lamp or lamps employed and from their efficiency. Now, the lumens received on the working plane are determined by multiplying the total lumens output from the source with the coefficient of utilization.

In the case, when the lamps and surroundings are not perfectly clean, then in the determination of the lumens received on the working plane, the depreciation factor or maintenance factor should be included.Thus, the lumens received on the working plane is given by,

Lumensreceived=Numberoflamps×Wattageofeachlamp×Efficiencyofeachlampintermsoflumensperwatt×
(Coefficient of utilization/Depreciation factor)

Lumensreceived=Numberoflamps×Wattageofeachlamp×Efficiencyofeachlampintermsoflumensperwatt×
(Coefficient of utilization/Depreciation factor)

Also, the lumens received on the working plane may be given as,

Lumensreceived=Numberoflamps×Wattageofeachlamp×Efficiencyofeachlampintermsoflumensperwatt×
Coefficientofutilization×MaintenancefactorLumensreceived=Numberoflamps×Wattageofeachlamp×Efficiencyofeachlampintermsoflumensperwatt×Coefficientofutilization×Maintenancefactor

Using either of the above expressions, the lumens received on the working plane can be determined.

2.9 Electronic ballast

An electronic ballast is a device used to control the starting and operation of fluorescent lamps, compact fluorescent lamps (CFLs), and some types of high-intensity discharge (HID) lamps. Unlike traditional magnetic ballasts, electronic ballasts operate at a higher frequency (typically 20,000 to 60,000 Hz) to improve lamp efficiency, reduce flickering, and eliminate the buzzing sound often associated with older fluorescent fixtures. Here are the key features and benefits of electronic ballasts:

Features and Benefits:

1. **Improved Efficiency**:
    - Electronic ballasts operate at higher frequencies, which results in improved lamp efficiency compared to magnetic ballasts. This efficiency translates into energy savings over the lifetime of the lamps.
2. **Reduced Flicker and Noise**:
    - High-frequency operation virtually eliminates the flickering and audible humming noise that can be noticeable with magnetic ballasts. This contributes to better visual comfort and reduced distractions in environments lit by fluorescent lamps.
3. **Instant Start Capability**:
    - Electronic ballasts typically allow for instant starting of fluorescent lamps, even at low temperatures. This feature is beneficial in environments where rapid switching or frequent on/off cycles are required.
4. **Dimming Capability**:
    - Some electronic ballasts are compatible with dimming systems, allowing for flexibility in adjusting light levels to suit different tasks or preferences. This feature is particularly useful in commercial and residential settings.
5. **Compact Size**:
    - Electronic ballasts are generally smaller and lighter than magnetic ballasts, making them easier to install and integrate into various lighting fixtures and applications.
6. **Extended Lamp Life**:
    - The high-frequency operation of electronic ballasts can contribute to longer lamp life by reducing stress on the lamp electrodes and providing more stable operating conditions.
7. **Power Factor Correction**:
    - Many electronic ballasts include power factor correction (PFC) circuits, which improve the overall efficiency of the lighting system by minimizing reactive power consumption and optimizing energy use.
8. **Compatibility with Energy-saving Lamps**:
    - Electronic ballasts are compatible with various energy-saving lamps, including CFLs and newer types of fluorescent lamps designed for improved efficiency and color rendering.

Applications:

- **Commercial Buildings**: Offices, retail stores, schools, and hospitals benefit from the energy savings and improved lighting quality provided by electronic ballasts.
- **Industrial Facilities**: Used in factories, warehouses, and manufacturing plants where efficient and reliable lighting is essential for productivity and safety.
- **Residential Lighting**: Found in residential settings for overhead lighting fixtures, task lighting, and ambient lighting applications.
- **Outdoor Lighting**: Electronic ballasts are used in outdoor applications such as streetlights and area lighting where reliability and efficiency are critical.
- **Specialty Applications**: In places where dimming capability or instant start features are required, such as theaters, restaurants, and museums.

2.10 problems

1: A room 20 × 10 m is illuminated by 60 W incandescent lamps of lumen output of1,600 lumens. The average illumination required at the workplace is 300 lux. Calculate the number of lamps required to be fitted in the room. Assume utilization and depreciation factors as 0.5 and 1, respectively.

Solution:

The area of the room (A) = 20 × 10 m

= 200 m^2.

Total illumination required (E) = 300 lux.

The wattage of each lamp = 60 W

The luminous output of the lamp (φ) = 1,600 lumens

UF = 0.5, DF = 1.

∴ Maintenance factor, $\text{MF} = \frac{1}{DF} = \frac{1}{1} = 1.$

∴ The number of lamps required:

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

$$= \frac{300 \times 200}{1{,}600 \times 1 \times 0.5} = 7.5 \text{ lamps.}$$

2: The front of a building 35 × 18 m is illuminated by 15 lamps; the wattage of eachlamp is 80 W. The lamps are arranged so that uniform illumination on the surface is obtained.
Assuming a luminous efficiency of 20 lumens/W, the coefficient of utilization is 0.8, the waste light factor is 1.25, DF = 0.9. Determine the illumination on the surface.

Solution:

Area = (A) = 35 × 18 = 630 m^2.

The number of lamps, N = 15.

Luminous efficiency, η = 20 lumens/W.

UF = 0.8, DF = 0.9.

Waste light factor = 1.25, E = ?

$$\therefore\ N = \frac{A \times E \times \text{DF} \times \text{waste light factor}}{\text{UF} \times \eta \times \text{wattage of each lamp}}$$

$$15 = \frac{630 \times E \times 1.25 \times 0.9}{0.8 \times 20 \times 80}$$

$$= 0.554\ E.$$

$$\therefore \text{E} = 27.07 \text{ lux (or) lumens/m}^2.$$

3: A room of size 10 × 4 m is to be illuminated by ten 150-W lamps. The MSCP ofeach lamp is 300. Assuming a depreciation factor of 0.8 and a utilization factor of 0.5. Find the average illumination produced on the floor.

Solution:

The area of the room (A) = 10 × 4 = 40 m^2.

The total luminous flux emitted by ten lamps (φ)

= 10 × 150 × 4π = 18, 849.5 lumens.

The total luminous flux reaching the working plane

$$= \frac{\phi \times \text{utilization factor}}{\text{depreciation factor}}$$

$$= \frac{18,849.5 \times 0.5}{0.8} = 11,780.97 \text{ lumens.}$$

The illumination on the working plane

$$E = \frac{\text{lumens on the working plane}}{\text{total area to be illuminated}}$$

$$= \frac{11,780.97}{40} = 294.52 \text{ lux.}$$

4: The front of a building 25 × 12 m is illuminated by 20 1,200-W lamps arranged so that uniform illumination on the surface is obtained. Assuming a luminous efficiency of 30 lumens/W and a coefficient of utilization of 0.75. Determine the illumination on the surface. Assume DF = 1.3 and waste light factor 1.2.

Solution:

Area to be illuminated = 25 × 12 = 300 m^2.

The total lumens given out by 20 lamps is:

φ = number of lamps × wattage of each lamp × efficiency of each lamp

= 20 × 30 × 1,200 = 720,000 lumens.

The total lumens reaching the surface to be illuminated

$$= \frac{\phi \times UF}{DF \times \text{waste light factor}}.$$

$$= \frac{7,20,000 \times 0.75}{1.3 \times 1.2}$$

$$= 3,46,153.84 \text{ lumens.}$$

The illumination on the surface:

$$E = \frac{3,46,153.84}{300} = 1,153.84 \text{ lux}.$$

5: An illumination of 40 lux is to be produced on the floor of a room 16 × 12 m. 15 lamps are required to produce this illumination in the room; 40% of the emitted light falls on the floor. Determine the power of the lamp in candela. Assume maintenance factor as unity.

Solution:

Given data

E = 40 lux

A = 16 × 12 = 192 m^2

Number of lamps, *N* = 15

UF = 0.4, MF = 1

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

$$15 = \frac{40 \times 192}{\phi \times 0.4 \times 1}$$

$$\therefore \phi = 1,280 \text{ lux}.$$

$$\text{So, the lumen output of the lamp in candela} = \frac{1,280}{4\pi} = 101.85 \text{ cd}.$$

6: A drawing, with an area of 18 × 12 m, is to be illuminated with an average illumination of about 150 lux. The lamps are to be fitted at 6 m height. Find out the number and size of incandescent lamps required for an efficiency of 20 lumens/W. UF = 0.6, MF = 0.75.

Solution:

Given data:

η = 120 lumens/W

E = 150 lux

A = 18 × 12 = 216 m^2

UF = 0.6

MF = 0.75

$$\text{The total gross lumens required } \phi = \frac{E \times A}{\text{UF} \times \text{MF}}.$$

$$= \frac{150 \times 216}{0.6 \times 0.75} = 72,000 \text{ lumens.}$$

$$\text{The total wattage required } = \frac{72,000}{\eta}$$

$$= \frac{72,000}{20} = 3,600 \text{ W.}$$

Let, if 24 lamps are arranged to illuminate the desired area. For space to height ratio unity, i.e., 6 lamps are taken along the length with a space of 18/6 = 3m, and 4 lamps are along the width giving a space of 12/4 = 3 m.

$$\therefore \text{The wattage of each lamp } = \frac{3,600}{24} = 150 \text{ W.}$$

The arrangement of 24 lamps in a hall of 18 × 12 m is shown in Fig. P.7.1

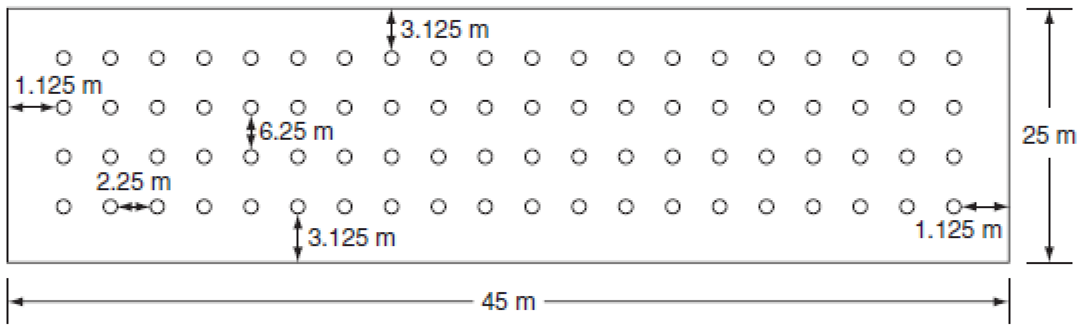


Fig. P.7.1 Lamp arrangement

7: A hall of 30 × 20 m area with a ceiling height of 6 m is to be provided with a general illumination of 200 lumens/m², taking a coefficient of utilization of 0.6 and depreciation factor of 1.6. Determine the number of fluorescent tubes required, their spacing, mounting height, and total wattage. Take luminous efficiency of fluorescent tube as 25 lumens/W for 300-W tube.

Solution:

Given data:

Area of hall (A) = 30 × 20 m = 600 m²

E = 200 lumens/m²
CU = 0.6
DF = 1.6
The wattage of fluorescent tube = 300 W
Efficiency η = 25 lumens/W

$$\therefore \text{Gross lumens required, } \phi = \frac{A \times E \times \text{DF}}{\text{UF}}$$

$$= \frac{600 \times 200 \times 1.6}{0.6} = 320{,}000 \text{ lux.}$$

$$\text{The total wattage required } = \frac{\phi}{\eta} = \frac{320{,}000}{25}.$$

$$\text{The number of tubes required } = \frac{\text{total wattage required}}{\text{wattage of each tube}}$$

$$= \frac{12{,}800}{300}$$

$$= 42.666 \cong 44.$$

Let us arrange 44 lamps in a 30 × 30 m hall, by taking 11 lamps along the length with spacing 30/11 = 2.727 m and 4 lamps along the width with spacing 20/4 = 5m. Here the space to height ratio with this arrangement is, 2.727/5 = 0.545. Disposition of lamps is shown in Fig. P.7.2.

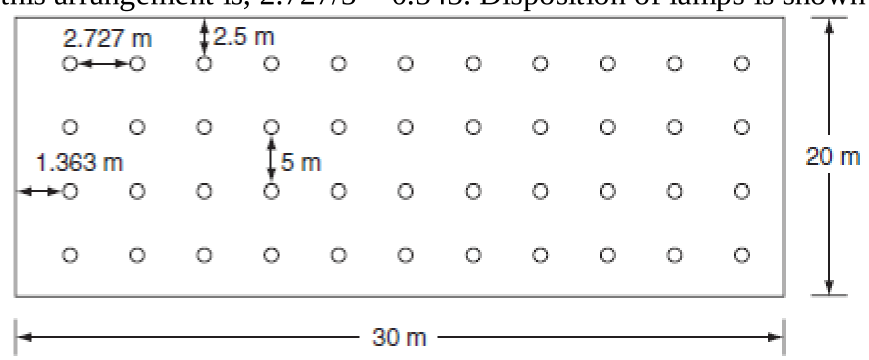


Fig. P.7.2 Lamp arrangement

UNIT-3
Electric Heating and Electric Welding

Heat plays a major role in everyday life. All heating requirements in domestic purposes such as cooking, room heater, immersion water heaters, and electric toasters and also in industrial purposes such as welding, melting of metals, tempering, hardening, and drying can be met easily by electric heating, over the other forms of conventional heating. Heat and electricity are interchangeable. Heat also can be produced by passing the current through material to be heated. This is called electric heating; there are various methods of heating a material but electric heating is considered far superior compared to the heat produced by coal, oil, and natural gas.

3.1 Advantages & methods of electric heating

The various advantages of electric heating over other the types of heating are:

Economical

Electric heating equipment is cheaper; they do not require much skilled persons; therefore, maintenance cost is less.

Cleanliness

Since dust and ash are completely eliminated in the electric heating, it keeps surroundings cleanly.

Pollution free

As there are no flue gases in the electric heating, atmosphere around is pollution free; no need of providing space for their exit.

Ease of control

*I*n this heating, temperature can be controlled and regulated accurately either manually or automatically.

Uniform heating

With electric heating, the substance can be heated uniformly, throughout whether it may be conducting or non-conducting material.

High efficiency

In non-electric heating, only 40–60% of heat is utilized but in electric heating 75–100% of heat can be successfully utilized. So, overall efficiency of electric heating is very high.

Automatic protection

Protection against over current and over heating can be provided by using fast control devices.

Heating of non-conducting materials

The heat developed in the non-conducting materials such as wood and porcelain is possible only through the electric heating.

Better working conditions

No irritating noise is produced with electric heating and also radiating losses are low.

Less floor area

Due to the compactness of electric furnace, floor area required is less.

High temperature

High temperature can be obtained by the electric heating except the ability of the material to withstand the heat.

Safety

The electric heating is quite safe.

MODES OF TRANSFER OF HEAT

The transmission of the heat energy from one body to another because of the temperature gradient takes place by any of the following methods:

1. conduction,
2. convection, or
3. radiation.

Conduction

In this mode, the heat transfers from one part of substance to another part without the movement in the molecules of substance. The rate of the conduction of heat along the substance depends upon the temperature gradient.

The amount of heat passed through a cubic body with two parallel faces with thickness '*t*' meters, having the cross-sectional area of '*A*' square meters and the temperature of its two faces T_1°C and T_2°C, during '*T*' hours is given by:

$$Q = \frac{k\,A}{t}(T_1 - T_2)\;T \text{ MJ},$$

where k is the coefficient of the thermal conductivity for the material and it is measured in $MJ/m^3/°C/hr$.

Ex: Refractory heating, the heating of insulating materials, etc.

Convection

In this mode, the heat transfer takes place from one part to another part of substance or fluid due to the actual motion of the molecules. The rate of conduction of heat depends mainly on the difference in the fluid density at different temperatures.

Ex: Immersion water heater.

The mount of heat absorbed by the water from heater through convection depends mainly upon the temperature of heating element and also depends partly on the position of the heater.

Heat dissipation is given by the following expression.

$H = a\,(T_1 - T_2)^b \text{ W/m}^2$,

where 'a' and 'b' are the constants whose values are depend upon the heating surface and $T_1$and T_2 are the temperatures of heating element and fluid in °C, respectively.

Radiation

In this mode, the heat transfers from source to the substance to be heated without heating the medium in between. It is dependent on surface.

Ex: Solar heaters.

The rate of heat dissipation through radiation is given by Stefan's Law.

$$\text{Heat dissipation, } H = 5.72 \times 10^4 k\,e\left[\left(\frac{T_1}{1,000}\right)^4 - \left(\frac{T_2}{1,000}\right)^4\right] \text{W/m}^2, \quad \textbf{(4.1)}$$

where T_1 is the temperature of the source in kelvin, T_2 is the temperature of the substance to be heated in kelvin, and k is the radiant efficiency:

= 1, for single element

= 0.5–0.8, for several elements

e = emissivity = 1, for black body

= 0.9, for resistance heating element.

From Equation (4.1), the radiant heat is proportional to the difference of fourth power of the temperature, so it is very efficient heating at high temperature.

ESSENTIAL REQUIREMENTS OF GOOD HEATING ELEMENT

The materials used for heating element should have the following properties:

- **High-specific resistance**
  Material should have high-specific resistance so that small length of wire may be required to provide given amount of heat.
- **High-melting point**
  It should have high-melting point so that it can withstand for high temperature, a small increase in temperature will not destroy the element.
- **Low temperature coefficient of resistance**
  From Equation (4.1), the radiant heat is proportional to fourth powers of the temperatures, it is very efficient heating at high temperature.
  For accurate temperature control, the variation of resistance with the operating temperature should be very low. This can be obtained only if the material has low temperature coefficient of resistance
- **Free from oxidation**

The element material should not be oxidized when it is subjected to high temperatures; otherwise the formation of oxidized layers will shorten its life.

- **High-mechanical strength**

  The material should have high-mechanical strength and should withstand for mechanical vibrations.

- **Non-corrosive**

  The element should not corrode when exposed to atmosphere or any other chemical fumes.

- **Economical**

  The cost of material should not be so high.

MATERIAL FOR HEATING ELEMENTS

The selection of a material for heating element is depending upon the service conditions such as maximum operating temperature and the amount of charge to be heated, but no single element will not satisfy all the requirements of the heating elements. The materials normally used as heating elements are either alloys of nickel–chromium, nickel–chromium–iron, nickel–chromium–aluminum, or nickel–copper.

Nickel–chromium–iron alloy is cheaper when compared to simple nickel–chromium alloy. The use of iron in the alloy reduces the cost of final product but, reduces the life of the alloy, as it gets oxidized soon. We have different types of alloys for heating elements. Table 4.1 gives the relevant properties of some of the commercial heating elements.

Table : Properties of some heating elements

S. No.	*Type of alloy*	*Composition*	*Commercial name*	*Max. operating temperature*	*Resistivity at 20°C*	*Specific gravity*
1	Nickel chromium (Ni–Cr)	80% Ni 20% Cr	Nichrome	1,150°C	1.03 μΩ-m	8.35
2	Nickel chromium iron (Ni–Cr–Fe)	60% Ni 16% Cr 24% Fe	—	950°C	1.06 μΩ-m	8.27
3	Nickel	45% Ni	Eureka or constantan	400°C	0.49 μΩ-m	8.88
	Copper (Ni–Cu)	55% Cu				
4	Iron chromium aluminum (Fe–Cr–Al)	70% Fe 25% Cr 5% Al	Kanthal	1,200°C	1.4 μΩ-m	7.20

The properties of some commercial heating element materials commonly employed for low and medium temperatures up to 1,200°C are Ni–Cr and an alloy of Ni–Cr–Fe composition of these alloys are given in Table 4.1. For operating temperatures above 1,200°C, the heating elements are made up of silicon carbide, molebdenum, tungsten, and graphite. (Ni–Cu alloy is frequently used for heating elements operating at low temperatures. Its most important property is that it has virtually zero resistance and temperature coefficient.)

CAUSES OF FAILURE OF HEATING ELEMENTS

Heating element may fail due to any one of the following reasons.

1. Formation of hot spots.
2. Oxidation of the element and intermittency of operation.
3. Embrittlement caused by gain growth.
4. Contamination and corrosion.

Formation of hotspots

Hotspots are the points on the heating element generally at a higher temperature than the main body. The main reasons of the formation of hotspot in the heating element are the high rate of the local oxidation causing reduction in the area of cross-section of the element leading to the increase in the resistance at that spot. It gives rise to the damage of heating element due to the generation of more heat at spot. Another reason is the shielding of element by supports, etc., which reduces the local heat loss by radiation and hence the temperature of the shielded portion of the element will increase. So that the minimum number of supports should be used without producing the distortion of the element. The sagging and wrapping of the material arise due to the insufficient support for the element (or) selection of wrong fuse material may lead to the uneven spacing of sections thereby developing the hotspots on the element.

Oxidation and intermittency of operation

A continuous oxide layer is formed on the surface of the element at very high temperatures such layer is so strong that it prevents further oxidation of the inner metal of the element. If the element is used quite often, the oxide layer is subjected to thermal stresses; thus, the layer cracks and flakes off, thereby exposing fresh metal to oxidation. Thus, the local oxidation of the metal increases producing the hotspots.

Embrittlement causing grain growth

In general, most of the alloys containing iron tend to form large brittle grains at high temperatures. When cold, the elements are very brittle and liable to rupture easily on the slightest handling and jerks.

contamination and corrosion

The heating elements may be subjected to dry corrosion produced by their contamination with the gases of the controlled atmosphere prevailing in annealing furnaces.

DESIGN OF HEATING ELEMENTS

By knowing the voltage and electrical energy input, the design of the heating element for an electric furnace is required to determine the size and length of the heating element. The wire employed may be circular or rectangular like a ribbon. The ribbon-type heating element permits the use of higher wattage per unit area compared to the circular-type element.

Circular-type heating element

Initially when the heating element is connected to the supply, the temperature goes on increasing and finally reaches high temperature.

Let V be the supply voltage of the system and R be the resistance of the element, then electric power input, $P = \frac{V^2}{R}$ W.

If ρ is the resistivity of the element, l is the length, 'a' is the area, and d is the diameter of the element, then:

$$R = \rho \frac{l}{a} = \frac{\rho l}{\frac{\pi d^2}{4}}.$$

Therefore, power input,

$$P = \frac{V^2 \pi d^2}{4 \rho l}. \qquad \textbf{(4.2)}$$

By rearranging the above equation, we get:

$$\frac{l}{d^2} = \frac{\pi V^2}{4P\ \rho}, \qquad \textbf{(4.3)}$$

1: A 4.5-kW, 200-V, and 1-φ resistance oven is to have nichrome wire heating elements. If the wire temperature is to be 1,000°C and that of the charge 500°C. Estimate the diameter and length of the wire. The resistivy of the nichrome alloy is 42.5 μΩ-m. Assume theradiating efficiency and the emissivity of the element as 1.0 and 0.9, respectively.

Solution:

Given data

Power input (P) = 4.5 kW
Supply voltage (V) = 200 V
Temperature of the source (T_1) = 1,000 + 273

= 1,273 K.

Temperature of the charge T_2 = 500 + 273

= 773 K.

According to the Stefan's law,

$$\text{Power, } P = \frac{V^2}{R}$$

$$= \frac{V^2}{\frac{\rho l}{A}} \qquad \left(R = \frac{\rho l}{A}\right)$$

$$= \frac{V^2 A}{\rho l}$$

$$= \frac{V^2 \pi d^2}{4\rho l} \qquad \left[\because \text{The area of circular type element} = \frac{\pi}{4} d^2\right]$$

$$\frac{d^2}{l} = \frac{4P\rho}{V^2 \pi}$$

$$= \frac{4 \times 42.5 \times 10^{-6} \times 4.5 \times 10^3}{(200)^2\, 3.14}$$

$$= 6.09 \times 10^{-9}. \qquad (1)$$

$$\text{The amount of heat dissipation } (H) = 5.72 \times 10^4 \times k e \left[\left(\frac{T_1}{1,000}\right)^4 - \left(\frac{T_2}{1,000}\right)^4\right] \text{W/m}^2$$

$$H = 5.72 \times 10^4 \times 0.1 \times 0.9 \left[\left(\frac{1,273}{1,000}\right)^4 - \left(\frac{773}{1,000}\right)^4\right]$$

$$= 11.68 \times 10^3 \text{ W/m}^2.$$

The heat dissipation is given by:

$$P = H \times S \qquad (S = \text{circular full-face area})$$
$$= H \times \pi dl$$
$$dl = \frac{P}{H\pi} = \frac{4.5 \times 10^3}{3.14 \times 11.68 \times 10^3}$$
$$l = 0.1226. \qquad (2)$$

By solving Equations (1) and (2):

$d^3 = 0.7466$

$d = 0.907$ mm.

Substitute the value of 'd' in Equation (2):

$l = 135.14$ m.

2: A20-kW, 230-V, and single-phase resistance oven employs nickel—chrome strip25-mm thick is used, for its heating elements. If the wire temperature is not to exceed 1,200°C and the temperature of the charge is to be 700°C. Calculate the width and length of the wire.
Assume the radiating efficiency as 0.6 and emissivity as 0.9. Determine also the temperature of the wire when the charge is cold.

Solution:
Power supplied, $P = 20 \times 10^3$ W.

Let 'w' be the width in meters, t be the thickness in meters, and 'l' be the length also in meters. Then:

$$P = \frac{V^2}{R}$$
$$= \frac{V^2}{\frac{\rho 1}{A}}$$
$$= \frac{V^2 \times wt}{\rho l} \qquad (\text{since } A = w \times t)$$
$$\frac{w}{l} = \frac{P\rho}{V^2 t}$$
$$= \frac{20 \times 10^3 \times 1.016 \times 10^{-6}}{(230)^2 \times 0.25 \times 10^{-3}}$$
$$= 1.536 \times 10^{-3}. \qquad (1)$$

According to the Stefan's law of heat radiation

$$H = 5.72 \times 10^4 \times ke\left[\left(\frac{T_1}{1,000}\right)^4 - \left(\frac{T_2}{1,000}\right)^4\right] \text{W/m}^2$$

$$H = 5.72 \times 10^4 \times 0.6 \times 0.9\left[\left(\frac{1,200+273}{1,000}\right)^4 - \left(\frac{700+273}{1,000}\right)^4\right]$$

$(\because T_1 = 1{,}200 + 273 = 1{,}473 \text{ K}, \quad T_2 = 700 + 273 = 973 \text{ K})$

$H = 117.714 \text{ kW/m}^2.$

The total amount of the heat dissipation × the surface area of strip = power supplied

$P = H \times S$

$= H \times 2\,lw$ (S = surface area of strip = $2lw$)

$$lw = \frac{P}{2H}$$

$$= \frac{20 \times 10^3}{2 \times 117.714 \times 10^3}$$

$$= 0.0849. \qquad (2)$$

From Equations (1) and (2):

$$\frac{w}{l} \times lw = 1.536 \times 10^{-3} \times 0.0849$$

$$w^2 = 1.304 \times 10^{-4}$$

$$w = 11.42 \text{ mm.}$$

Substitute the value of 'w' in Equation (2) then:

$l = 7.435$ m.

When the charge is cold, it would be at normal temperature, say 25°C.

$$117.714 \times 10^3 = 5.72 \times 10^4 \times 0.6 \times 0.9 \left[\left(\frac{T_1}{1,000} \right)^4 - \left(\frac{273 + 25}{1,000} \right)^4 \right]$$

$$\left(\frac{T_1}{1,000} \right)^4 - 0.00788 = 3.8109$$

$$\left(\frac{T_1}{1,000} \right)^4 = 3.818$$

$$T_1 = 1,397.9169 \text{ K absolute}$$

Or, $T_1 = 1,124.9°\text{C}.$

where P is the electrical power input per phase (watt), V is the operating voltage per phase (volts), R is the resistance of the element (Ω), l is the length of the element (m), a is the area of cross-section (m^2), d is the diameter of the element (m), and ρ is the specific resistance (Ω-m)

According to Stefan's law, heat dissipated per unit area is

$$H = 5.72 \times 10^4 \, k \, e \left[\left(\frac{T_1}{1,000} \right)^4 - \left(\frac{T_2}{1,000} \right)^4 \right] \text{W/m}^2, \qquad \textbf{(4.4)}$$

where T_1 is the absolute temperature of the element (K), T_2 is the absolute temperature of the charge (K), e is the emissivity, and k is the radiant efficiency.

The surface area of the circular heating element:

$S = \pi dl.$

∴ Total heat dissipated = surface area × H

$= H\pi dl.$

Under thermal equilibrium,

Power input = heat dissipated

$P = H \times \pi dl.$

Substituting P from Equation (4.2) in above equation:

$$\frac{V^2}{\rho \, l} \left(\frac{\pi \, d^2}{4} \right) = H \times \pi \, dl$$

$$\therefore \frac{d}{l^2} = \frac{4\,\rho\, H}{V^2}. \qquad \textbf{(4.5)}$$

By solving Equations (4.3) and (4.4), the length and diameter of the wire can be determined.

Ribbon-type element

Let '*w*' be the width and '*t*' be the thickness of the ribbon-type heating element.

$$\text{Electrical power input } P = \frac{V^2}{R}. \qquad \textbf{(4.6)}$$

We know that, (for ribbon or rectangular element, $a = w \times t$)

$$R = \frac{\rho l}{a} = \frac{\rho l}{w \times t}$$

$$\therefore P = \frac{V^2}{\left(\dfrac{\rho\, l}{w \times t}\right)}$$

$$\therefore \frac{l}{w} = \frac{V^2\ t}{P\ \rho}. \qquad \textbf{(4.7)}$$

The surface area of the rectangular element (S) = 2 $l \times w$.

∴ Total heat dissipated = $H \times S$

= $H \times 2\, lw$.

∴ Under the thermal equilibrium,

Electrical power input = heat dissipated

$P = H \times 2\, lw$

By solving Equations (4.7) and (4.8), the length and width of the heating element can bedetermined

3.2 Resistance & Arc heating

METHODS OF ELECTRIC HEATING

Heat can be generated by passing the current through a resistance or induced currents. The initiation of an arc between two electrodes also develops heat. The bombardment by some heat energy particles such as α, γ, β, and x-rays or accelerating ion can produce heat on a surface.

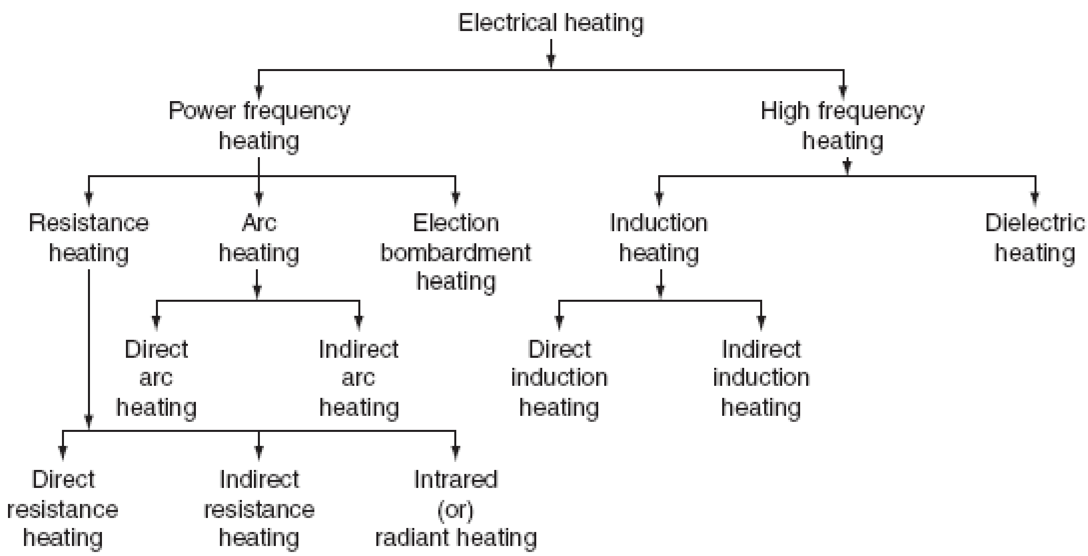
Electric heating can be broadly classified as follows.

(i) Direct resistance heating

In this method, the electric current is made to pass through the charge (or) substance to be heated. This principle of heating is employed in electrode boiler.

(ii) Indirect resistance heating

In this method, the electric current is made to pass through a wire or high-resistance heating element, the heat so developed is transferred to charge from the heating element by convection or radiation. This method of heating is employed in immersion water heaters.



RESISTANCE HEATING

When the electric current is made to pass through a high-resistive body (or) substance, a power loss takes place in it, which results in the form of heat energy, i.e., resistance heating is passed upon the I^2R effect. This method of heating has wide applications such as drying, baking of potteries, commercial and domestic cooking, and the heat treatment of metals such as annealing and hardening. In oven where wire resistances are employed for heating, temperature up to about 1,000°C can be obtained.

The resistance heating is further classified as:

1. direct resistance heating,
2. indirect resistance heating, and

3. infrared (or) radiant heating.

Direct resistance heating

In this method, electrodes are immersed in a material or charge to be heated. The charge may be in the form of powder, pieces, or liquid. The electrodes are connected to AC or DC supply as shown in Fig. 4.1(a). In case of DC or 1-φ AC, two electrodes are immersed and three electrodes are immersed in the charge and connected to supply in case of availability of 3-φsupply. When metal pieces are to be heated, the powder of lightly resistive is sprinkled over the surface of the charge (or) pieces to avoid direct short circuit. The current flows through the charge and heat is produced in the charge itself. So, this method has high efficiency. As the current in this case is not variable, so that automatic temperature control is not possible. This method of heating is employed in salt bath furnace and electrode boiler for heating water.

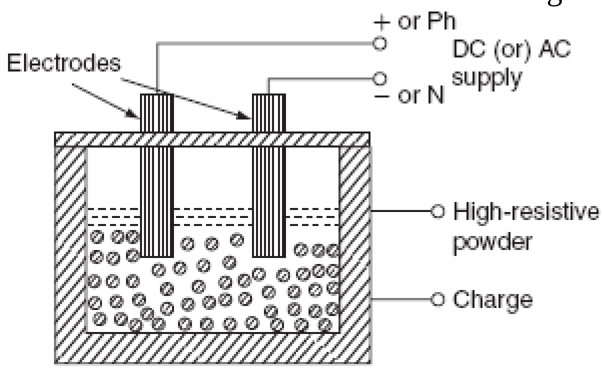


Fig. (a) Direct resistance heating

Salt bath furnace

This type of furnace consists of a bath and containing some salt such as molten sodium chloride and two electrodes immersed in it.

Such salt have a fusing point of about 1,000–1,500°C depending upon the type of salt used. When the current is passed between the electrodes immersed in the salt, heat is developed and the temperature of the salt bath may be increased. Such an arrangement is known as a salt bath furnace.

In this bath, the material or job to be heated is dipped. The electrodes should be carefully immersed in the bath in such a way that the current flows through the salt and not through the job being heated. As DC will cause electrolysis so, low-voltage AC up to 20 V and current up to 3,000 A is adopted depending upon the type of furnaces.

The resistance of the salt decreases with increase in the temperature of the salt, therefore, in order to maintain the constant power input, the voltage can be controlled by providing a tap changing transformer. The control of power input is also affected by varying the depth of immersion and the distance between the electrodes.

Indirect resistance heating

In the indirect resistance heating method, high current is passed through the heating element. In case of industrial heating, some times the heating element is placed in a cylinder which is surrounded by the charge placed in a jacket is known as heating chamber is shown inFig. 4.3. The heat is proportional to power loss produced in the heating element is delivered to the chargeby one or more of the modes of the transfer of heat viz. conduction, convection, and radiation.

This arrangement provides uniform temperature and automatic temperature control. Generally, this method of heating is used in immersion water heaters, room heaters, and the resistance ovens used in domestic and commercial cooling and salt bath furnace.

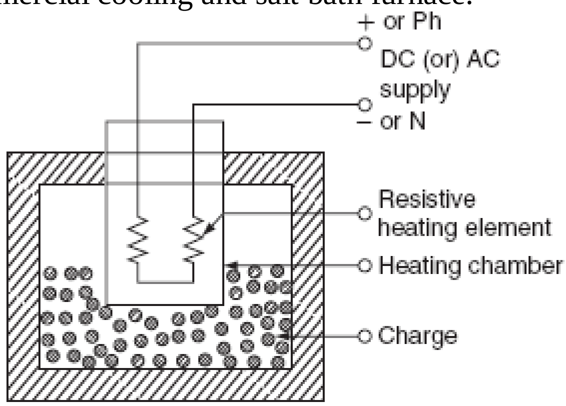


Fig. 4.3 Indirect resistance heating

Direct arc furnace

When supply is given to the electrodes, two arcs are established and current passes through the charge, as shown in Fig. 4.5. As the arc is in direct contact with the charge and heat is also produced by current flowing through the charge itself, it is known as *direct arc furnace.*

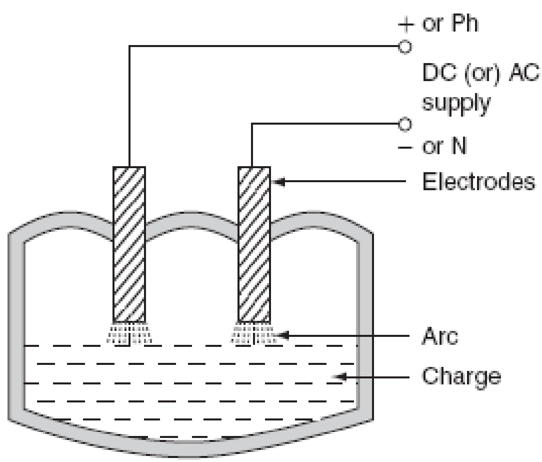


Fig. Direct arc furnace

If the available supply is DC or 1-φ, AC, two electrodes are sufficient, if the supply is 3-φ, AC, three electrodes are placed at three vertices of an equilateral triangle. The most important feature of the direct arc furnace is that the current flows through the charge, the stirring action is inherent due to the electromagnetic force setup by the current, such furnace is used for manufacturing alloy steel and gives purer product.

It is very simple and easy to control the composition of the final product during refining process operating the power factor of arc furnace is 0.8 lagging. For 1-ton furnace, the power required is about 200 kW and the energy consumed is 1.0 MWh/ton.

Indirect arc furnace

In indirect arc furnace, the arc strikes between two electrodes by bringing momentarily in contact and then with drawing them heat so developed, due to the striking of arc across air gap is transferred to charge is purely by radiation. A simple indirect arc furnace is shown in Fig. 4.6.

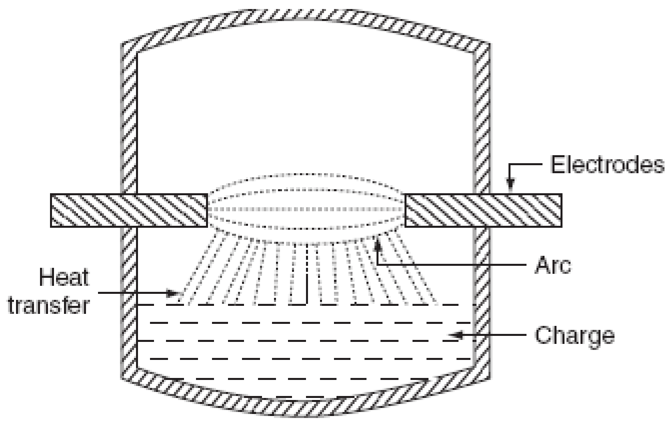


Fig. 4.6 Indirect arc furnace

These furnaces are usually l-*φ* and hence their size is limited by the amount of one-phase load which can be taken from one point. There is no inherent stirring action provided in this furnace, as current does not flow through the charge and the furnace must be rocked mechanically. The electrodes are projected through this chamber at each end along the horizontal axis. This furnace is also sometimes called as *rocking arc furnace.* The charge in this furnace is heated not only by radiation from the arc between electrode tips but also by conduction from the heated refractory during rocking action; so, the efficiency of such furnace is high. The arc is produced by bringing electrodes into solid contact and then withdrawing them; power input to the furnace is regulated by adjusting the arc length by moving the electrodes.

Even though it can be used in iron foundries where small quantities of iron are required frequently, the main application of this furnace is the melting of non-ferrous metals.

3.3 Induction and dielectric heating

Induction Heating

The induction heating process makes use of the currents induced by the electromagnetic action in the material to be heated. To develop sufficient amount of heat, the resistance of the material must be low $\left(\because \text{power drawn}=\frac{V^2}{R}\right)$, which is possible only with the metals, and the voltage must be higher, which can be obtained by employing higher flux and higher frequency. Therefore, the magnetic materials can be heated than non-magnetic materials due to their high permeability.

In order to analyze the factors affecting induction heating, let us consider a circular disc to be heated carrying a current of '*I*' amps at a frequency '*f*' Hz. As shown in Fig. 4.9.

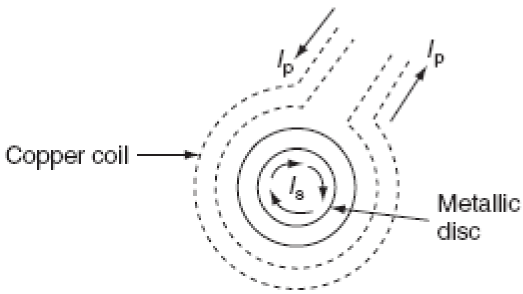


Fig. 4.9 Induction heating

Heat developed in the disc is depending upon the following factors

- Primary coil current.
- The number of the turns of the coil.
- Supply frequency.
- The magnetic coupling between the coil and the disc.
- The high electrical resistivity of the disc.

If the charge to be heated is non-magnetic, then the heat developed is due to eddy current loss, whereas if it is magnetic material, there will be hysteresis loss in addition to eddy current loss. Both hysteresis and eddy current loss are depended upon frequency, but at high-frequency hysteresis, loss is very small as compared to eddy currents.

The depth of penetration of induced currents into the disc is given by:

$$d = \frac{1}{2\pi}\sqrt{\frac{\rho \times 10^9}{\mu f}} \text{ cm}$$

$$\text{i.e., } d \ \mu \frac{1}{\sqrt{f}},$$

where ρ is the specific resistance in Ω-cm, f is the frequency in Hz, and μ is the permeability ofthe charge.

DIELECTRIC HEATING

When non-metallic materials i.e., insulators such as wood, plastics, and china glass are subjected to high-voltage alternating electric field, the atoms get stresses, and due to interatomic friction caused by the repeated deformation and the rotation of atomic structure (polarization), heat is produced. This is known as dielectric loss. This dielectric loss in insulators corresponds to hysteresis loss in ferro-magnetic materials. This loss is due to the reversal of magnetism or magneto molecular friction. These losses developed in a material that has to be heated.

An atom of any material is neutral, since the central positive charge is equals to the negative charge. So that, the centers of positive and negative charges coincide as long as there is no external field is applied, as shown in Fig. (a). When this atom is subjected to the influence of the electric field, the positive charge of the nucleus is acted upon by some force in the direction of negative charges in the opposite direction. Therefore, the effective centers of both positive and negative charges no longer coincident as shown in Fig. (b). The electric charge of an atom equivalent to Fig.(b) is shown in Fig. (c).

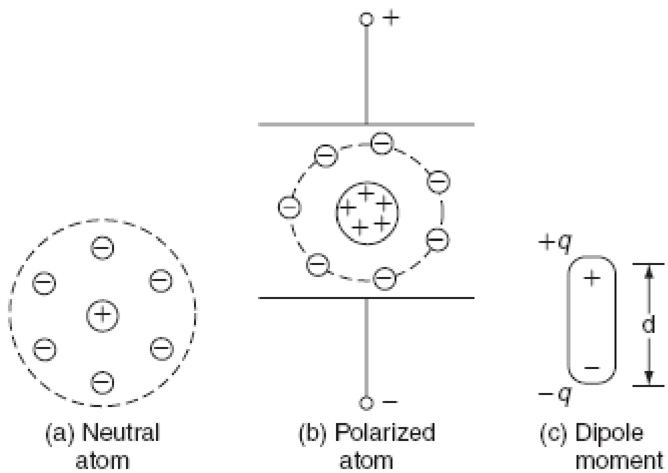


Fig. Polarization

This gives raise to an electric dipole moment equal to $P = q\,d$, where d is the distance between the two centers and q is the charge on the nucleus.

Now, the atom is said to be polarized atom. If we apply alternating voltage across the capacitor plate, we will get alternating electric field.

Electric dipoles will also try to change their orientation according to the direction of the impressed electric field. In doing so, some energy will be wasted as inter-atomic friction, which is called dielectric loss.

As there is no perfect conductor, so there is no perfect insulator. All the dielectric materials can be represented by a parallel combination of a leakage resistor 'R' and a capacitor 'C' as shown in Fig. 4.15 (a) and (b).

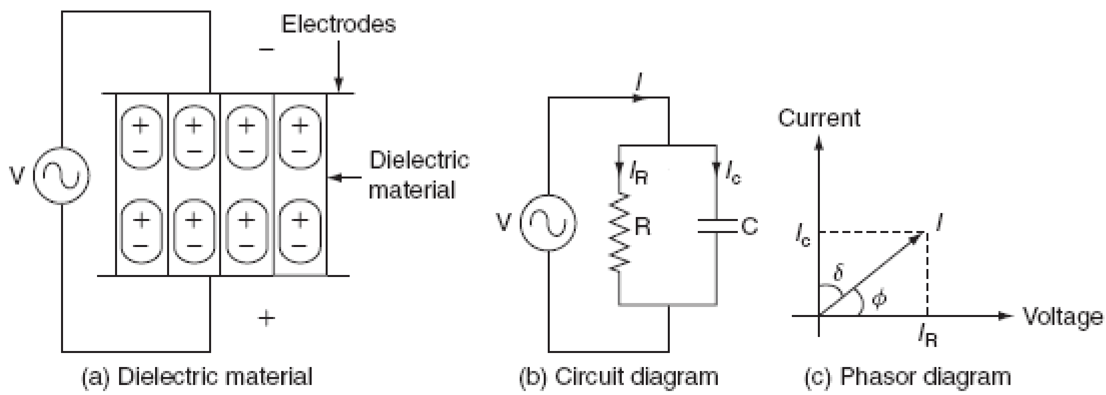


Fig. Dielectric heating

If an AC voltage is applied across a piece of insulator, an electric current flows; total current 'I' supposed to be made up of two components I_C and I_R, where I_C is the capacitive current leading the applied voltage by 90° and I_R is in phase with applied voltage as shown in Fig. 4.15(c).

$$\text{Dielectric loss, } P_L = VI\cos\phi$$

$$= VI_R \qquad [\because I_R = I\cos\phi]$$

$$= VI_C \tan\delta \qquad \left[\because \tan\delta = \frac{I_R}{I_C}\right].$$

$$V \cdot \left(\frac{V}{X_C}\right) \tan\delta \qquad \left[QI_C = \frac{V}{X_C}\right]$$

$$= V^2 \omega C \tan\delta \qquad \textbf{(4.13)}$$

$$= V^2 \times 2\pi f \times \frac{\varepsilon_0 \varepsilon_r A}{d} \times \delta \text{ W} \qquad \textbf{(4.14)}$$

where 'V' is the applied voltage in volts, 'f' is the supply frequency in Hz, ε_0 is the absolute permittivity of the medium = 8.854×10^{-12} F/m, ε_r is the relative permittivity of the medium = 1 for free space, A is the area of the plate or electrode (m^2), d is the thickness of the dielectric medium, and δ is the loss angle in radian.

From Equation (4.14):

$$P_L \propto V^2 \quad \text{and} \quad P_L \propto f. \qquad \textbf{(4.15)}$$

Normally frequency used for dielectric heating is in the range of 1–40 MHz. The use of high voltage is also limited due to the breakdown voltage of thin dielectric that is to be heated, under normal conditions; the voltage gradient used is limited to 18 kV/cm.

The advantages of the dielectric heating

- The heating of the non-conducting materials is very rapid.
- The uniform heating of material is possible.
- Heat is produced in the whole mass of the material.

The applications of the dielectric heating

- The drying of paper, wood, etc.
- The gluing of wood.
- The heat-sealing of plastic sheets.
- The heating for the general processing such as coffee roasting and chocolate industry.
- The heating for the dehydration such as milk, cream, and vegetables.
- The preparation of thermoplastic resins.

- The heating of bones and tissues.
- Diathermy, i.e., the heat treatment for certain body pains and diseases, etc.
- The sterilization of absorbent cotton, bandages, etc.
- The processing of rubber, synthetic materials, chemicals, etc.

3.4 Methods of temperature control, design of heating element

By knowing the voltage and electrical energy input, the design of the heating element for an electric furnace is required to determine the size and length of the heating element. The wire employed may be circular or rectangular like a ribbon. The ribbon-type heating element permits the use of higher wattage per unit area compared to the circular-type element.

Circular-type heating element

Initially when the heating element is connected to the supply, the temperature goes on increasing and finally reaches high temperature.

Let V be the supply voltage of the system and R be the resistance of the element, then electric power input, $P = \frac{V^2}{R}$ W.

If ρ is the resistivity of the element, l is the length, 'a' is the area, and d is the diameter of the element, then:

$$R = \rho \frac{l}{a} = \frac{\rho l}{\frac{\pi d^2}{4}}.$$

Therefore, power input,

$$P = \frac{V^2 \pi d^2}{4 \rho l}. \qquad \textbf{(4.2)}$$

By rearranging the above equation, we get:

$$\frac{l}{d^2} = \frac{\pi V^2}{4P\,\rho}, \qquad \textbf{(4.3)}$$

where P is the electrical power input per phase (watt), V is the operating voltage per phase (volts), R is the resistance of the element (Ω), l is the length of the element (m), a is the area of cross-section (m^2), d is the diameter of the element (m), and ρ is the specific resistance (Ω-m)

According to Stefan's law, heat dissipated per unit area is

$$H = 5.72 \times 10^4\ k\,e \left[\left(\frac{T_1}{1{,}000} \right)^4 - \left(\frac{T_2}{1{,}000} \right)^4 \right] \text{W/m}^2, \qquad \textbf{(4.4)}$$

where T_1 is the absolute temperature of the element (K), T_2 is the absolute temperature of the charge (K), e is the emissivity, and k is the radiant efficiency.

The surface area of the circular heating element:

$S = \pi dl.$

$\therefore$ Total heat dissipated = surface area × H

$= H\pi dl.$

Under thermal equilibrium,

Power input = heat dissipated

$P = H \times \pi dl.$

Substituting P from Equation (4.2) in above equation:

$$\frac{V^2}{\rho l}\left(\frac{\pi d^2}{4}\right) = H \times \pi dl$$

$$\therefore \frac{d}{l^2} = \frac{4 \rho H}{V^2}. \qquad \textbf{(4.5)}$$

By solving Equations (4.3) and (4.4), the length and diameter of the wire can be determined.

Ribbon-type element

Let 'w' be the width and 't' be the thickness of the ribbon-type heating element.

$$\text{Electrical power input } P = \frac{V^2}{R}. \qquad \textbf{(4.6)}$$

We know that, $R = \frac{\rho l}{a} = \frac{\rho l}{w \times t}$ (for ribbon or rectangular element, $a = w \times t$)

$$\therefore P = \frac{V^2}{\left(\frac{\rho l}{w \times t}\right)} \qquad \therefore \frac{l}{w} = \frac{V^2 t}{P \rho}. \qquad \textbf{(4.7)}$$

The surface area of the rectangular element (S) = 2 $l \times w$.

$\therefore$ Total heat dissipated = $H \times S$

$= H \times 2\, lw.$

$\therefore$ Under the thermal equilibrium, Electrical power input = heat dissipated

$$P = H \times 2\,lw$$

$$lw = \frac{P}{2\,H}. \qquad \textbf{(4.8)}$$

By solving Equations (4.7) and (4.8), the length and width of the heating element can be determined.

3.5 Applications of electric heating:

3.6 Types- Resistance Welding:

Welding is the process of joining two pieces of metal or non-metal together by heating them to their melting point. Filler metal may or may not be used to join two pieces. The physical and mechanical properties of a material to be welded such as melting temperature, density, thermal conductivity, and tensile strength take an important role in welding. Depending upon how the heat applied is created; we get different types of welding such as thermal welding, gas welding, and electric welding. Here in this chapter, we will discuss only about the electric welding and some introduction to other modern welding techniques. Welding is nowadays extensively used in automobile industry, pipe-line fabrication in thermal power plants, machine repair work, machine frames, etc.

ADVANTAGES AND DISADVANTAGES OF WELDING

Some of the advantages of welding are:

- Welding is the most economical method to permanently join two metal parts.
- It provides design flexibility.
- Welding equipment is not so costly.
- It joins all the commercial metals.
- Both similar and dissimilar metals can be joined by welding.
- Portable welding equipment are available.

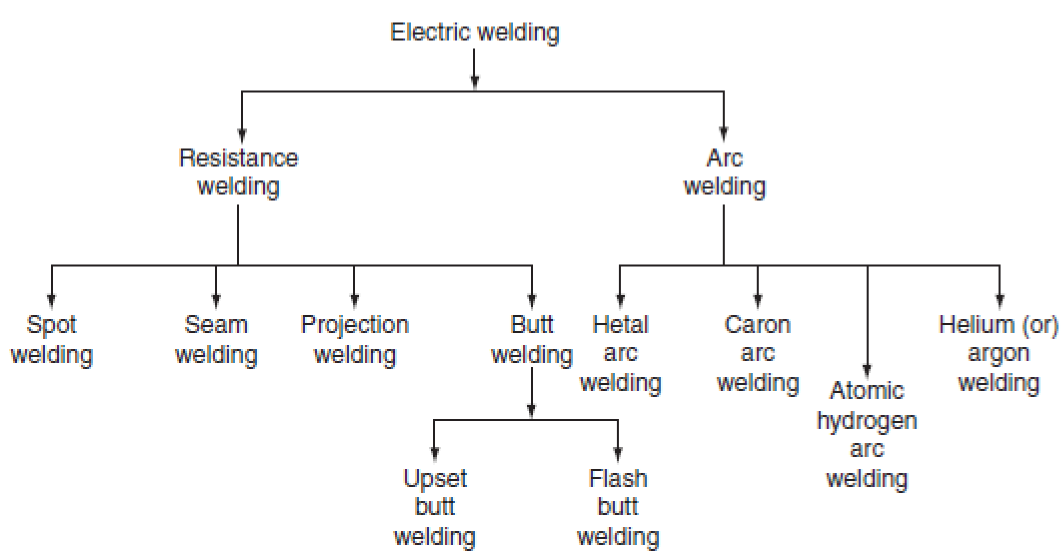
Some of the disadvantages of welding are:

- Welding gives out harmful radiations and fumes.
- Welding needs internal inspection.
- If welding is not done carefully, it may result in the distortion of workpiece.
- Skilled welding is necessary to produce good welding.

ELECTRIC WELDING

It is defined as the process of joining two metal pieces, in which the electrical energy is used to generate heat at the point of welding in order to melt the joint.

The classification of electric welding process is shown in fig.



The selection of proper welding process depends on the following factors.

- The type of metal to be joined.
- The techniques of welding adopted.
- The cost of equipment used.
- The nature of products to be fabricated.

RESISTANCE WELDING

Resistance welding is the process of joining two metals together by the heat produced due to the resistance offered to the flow of electric current at the junctions of two metals. The heat produced by the resistance to the flow of current is given by:

$$H = I^2Rt,$$

where *I* is the current through the electrodes, *R* is the contact resistance of the interface, and *t*isthe time for which current flows.

Here, the total resistance offered to the flow of current is made up of:

1. The resistance of current path in the work.
2. The resistance between the contact surfaces of the parts being welded.
3. The resistance between electrodes and the surface of parts being welded.

In this process of welding, the heat developed at the contact area between the pieces to be welded reduces the metal to plastic state or liquid state, then the pieces are pressed under high mechanical pressure to complete the weld. The electrical voltage input to the welding varies in between 4 and 12 V depending upon area, thickness, composition, etc. and usually power ranges from about 60 to 180 W for each sq. mm of area.

Any desired combination of voltage and current can be obtained by means of a suitable transformer in AC; hence, AC is found to be most suitable for the resistance welding. The magnitude of current is controlled by changing the primary voltage of the welding transformer, which can be done by using an auto-transformer or a tap-changing transformer. Automatic arrangements are provided to switch off the supply after a pre-determined time from applying the pressure, why because the duration of the current flow through the work is very important in the resistance welding.

The electrical circuit diagram for the resistance welding is shown in Fig. 5.2. This method of welding consists of a tap-changing transformer, a clamping device for holding the metal pieces, and some sort of mechanical arrangement for forcing the pieces to form a complete weld.

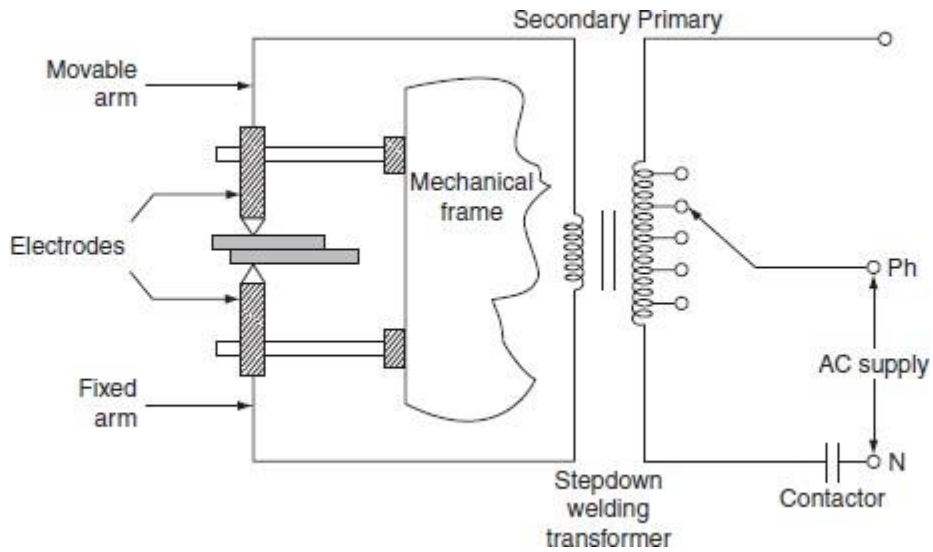


Fig. Electric circuit for resistance welding

Advantages

- Welding process is rapid and simple.
- Localized heating is possible, if required.
- No need of using filler metal.
- Both similar and dissimilar metals can be welded.
- Comparatively lesser skill is required.
- Maintenance cost is less.
- It can be employed for mass production.

However, the resistance welding has got some drawbacks and they are:

- Initial cost is very high.
- High maintenance cost.
- The workpiece with heavier thickness cannot be welded, since it requires high input current.

Applications

- It is used by many industries manufacturing products made up of thinner gauge metals.
- It is used for the manufacturing of tubes and smaller structural sections.

Types of resistance welding

Depending upon the method of weld obtained and the type of electrodes used, the resistance welding is classified as:

1. Spot welding.
2. Seam welding.
3. Projection welding.
4. Butt welding.

(i) Spot welding

Spot welding means the joining of two metal sheets and fusing them together between copper electrode tips at suitably spaced intervals by means of heavy electric current passed through the electrodes as shown in Fig. 5.3.

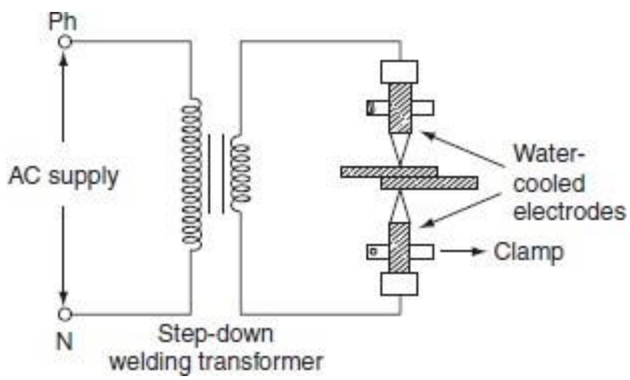


Fig. 5.3 Spot welding

This type of joint formed by the spot welding provides mechanical strength and not air or water tight, for such welding it is necessary to localize the welding current and to apply sufficient pressure on the sheet to be welded. The electrodes are made up of copper or copper alloy and are water cooled. The welding current varies widely depending upon the thickness and composition of the plates. It varies from 1,000 to 10,000 A, and voltage between the electrodes isusually less than 2 V. The period of the flow of current varies widely depending upon the thickness of sheets to be joined. A step-down transformer is used to reduce a high-voltage and low-current supply to low-voltage and high-current supply required. Since the heat developed being proportional to the product of welding time and square of the current. Good weld can be obtained by low currents for longer duration and high currents for shorter duration; longer welding time usually produces stronger weld but it involves high energy expenditure, electrode maintenance, and lot of distortion of workpiece.

Seam Welding:

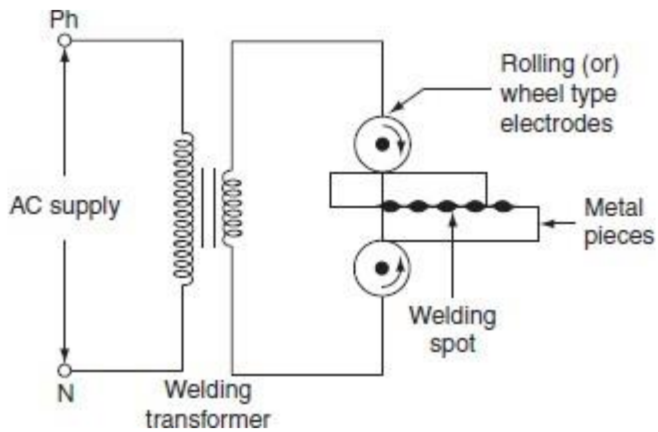


Fig. 5.5 *Seam welding*

Seam welding is obtained by keeping the job under electrodes. When these wheel type electrodes travel over the metal pieces which are under pressure, the current passing between them heats the two metal pieces to the plastic state and results into continuous spot welds.

In this welding, the contact area of electrodes should be small, which will localize the current pressure to the welding point. After forming weld at one point, the weld so obtained can be cooled by splashing water over the job by using cooling jets.

In general, it is not satisfactory to make a continuous weld, for which the flow of continuous current build up high heat that causes burning and wrapping of the metal piece. To avoid this difficulty, an interrupter is provided on the circuit which turns on supply for a period sufficient to heat the welding point. The series of weld spots depends upon the number of welding current pulses.

The two forms of welding currents are shown in Fig. 5.6(a) and (b).

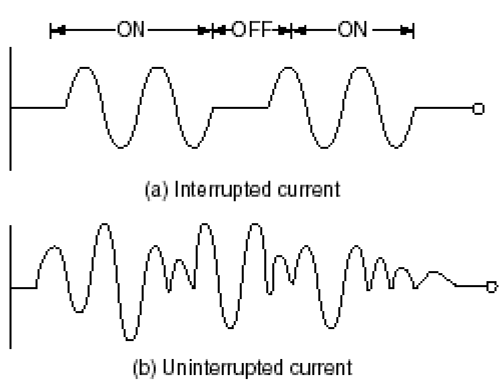


Fig. 5.6 Welding current

Welding cannot be made satisfactorily by using uninterrupted or un-modulated current, which builds up high heat as the welding progress; this will over heat the workpiece and cause distortion.

Seam welding is very important, as it provides leak proof joints. It is usually employed in welding of pressure tanks, transformers, condensers, evaporators, air craft tanks, refrigerators, varnish containers, etc.

(ii) Projection welding

It is a modified form of the spot welding. In the projection welding, both current and pressure are localized to the welding points as in the spot welding. But the only difference in the projection welding is the high mechanical pressure applied on the metal pieces to be welded, after the formation of weld. The electrodes used for such welding are flat metal plates known as *platens*.

The two pieces of base metal to be weld are held together in between the two platens, one is movable and the other is fixed, as shown in Fig. 5.7.

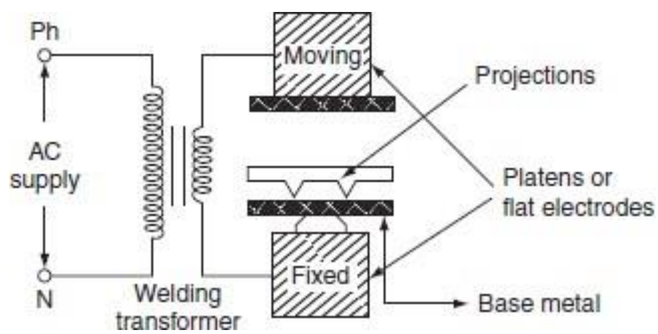


Fig. 5.7 Projection welding

One of the two pieces of metal is run through a machine that makes the bumps or projections of required shape and size in the metal. As current flows through the two metal parts to be welded, which heat up and melt. These weld points soon reach the plastic state, and the projection touches the metal then force applied by the two flat electrodes forms the complete weld.

The projection welding needs no protective atmosphere as in the spot welding to produce successful results. This welding process reduces the amount of current and pressure in order to join two metal surfaces, so that there is less chance of distortion of the surrounding areas of the weld zone. Due to this reason, it has been incorporated into many manufacturing process.

The projection welding has the following advantages over the spot welding.

- Simplicity in welding process.
- It is easy to weld some of the parts where the spot welding is not possible.
- It is possible to join several welding points.
- Welds are located automatically by the position of projection.
- As the electrodes used in the projection welding are flat type, the contact area over

the projection issufficient.

This type of welding is usually employed on punched, formed, or stamped parts where the projection automatically exists. The projection welding is particularly employed for mass production work, i.e., welding of refrigerators, condensers, crossed wire welding, refrigerator racks, grills, etc.

(iii) Butt welding

Butt welding is similar to the spot welding; however, the only difference is, in butt welding, instead of electrodes the metal parts that are to be joined or butted together are connected to the supply.

The three basic types of the butt welding process are:

1.Upset butt welding.

2. Flash butt welding.

3.Percussion butt welding.

(a) Upset butt welding

In upset welding, the two metal parts to be welded are joined end to end and are connected across the secondary of a welding transformer as shown in Fig. 5.8.

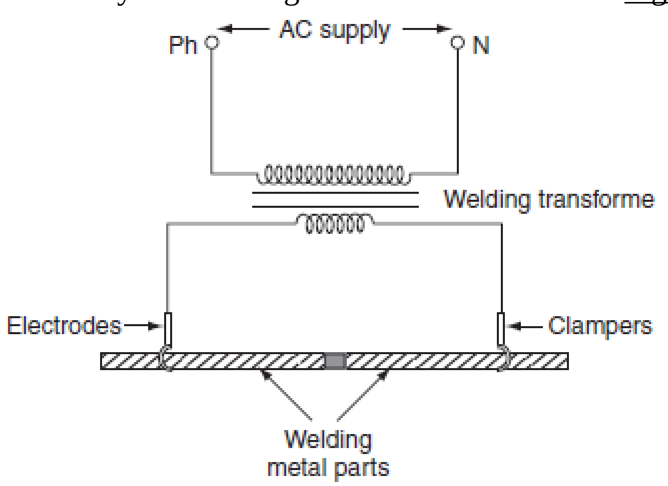


Fig. 5.8 Upset butt welding

Due to the contact resistance of the metals to be welded, heating effect is generated in this welding. When current is made to flow through the two electrodes, heat will develop due to the contact resistance of the two pieces and then melts. By applying high mechanical pressure eithermanually or by toggle mechanism, the two metal pieces are pressed. When jaw-type electrodes are used that introduce the high currents without treating any hot spot on the job.

This type of welding is usually employed for welding of rods, pipes, and wires and for joining metal parts end to end.

(b) Flash butt welding

Flash butt welding is a combination of resistance, arc, and pressure welding. This method of welding is mainly used in the production welding. A simple flash butt welding arrangement is shown in Fig. 5.9.

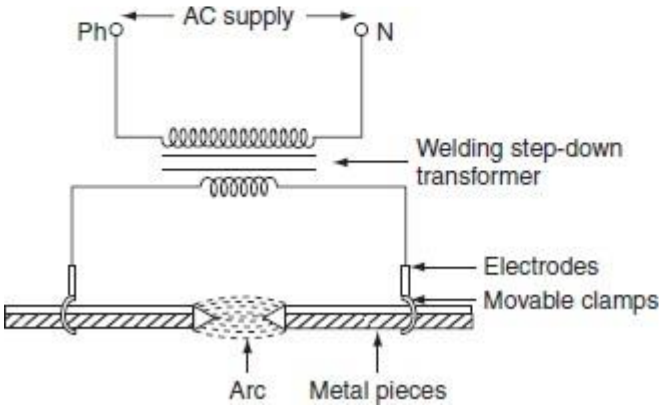


Fig. 5.9 Flash butt welding

In this method of welding, the two pieces to be welded are brought very nearer to each other under light mechanical pressure. These two pieces are placed in a conducting movable clamps. When high current is passed through the two metal pieces and they are separated by some distance, then arc established between them. This arc or flashing is allowed till the ends of the workpieces reach melting temperature, the supply will be switched off and the pieces are rapidly brought together under light pressure. As the pieces are moved together, the fused metal and slag come out of the joint making a good solid joint.

Following are the advantages of the flash butt welding over the upset welding.

- Less requirement of power.
- When the surfaces being joined, it requires only less attention.
- Weld obtained is so clean and pure; due to the foreign metals appearing on the surfaces will burn due to flash or arc.

(c) *Percussion welding*

It is a form of the flash butt welding, where high current of short duration is employed using stored energy principle. This is a self-timing spot welding method.

Percussion welding arrangement consists of one fixed holder and the other one is movable. The pieces to be welded are held apart, with the help of two holders, when the movable clamp is released, it moves rapidly carrying the piece to be welded. There is a sudden discharge of electrical energy, which establishes an arc between the two surfaces and heating them to their melting temperature, when the two pieces are separated by a distance of 1.5 mm apart. As the pieces come in contact with each other under heavy pressure, the arc is extinguished due to the percussion blow of the two parts and the force between them affects the weld. The percussion welding can be obtained in two methods; one is capacitor energy storage system and the other is magnetic energy storage system. The capacitor discharge circuit for percussion welding is shown in Fig. 5.10.

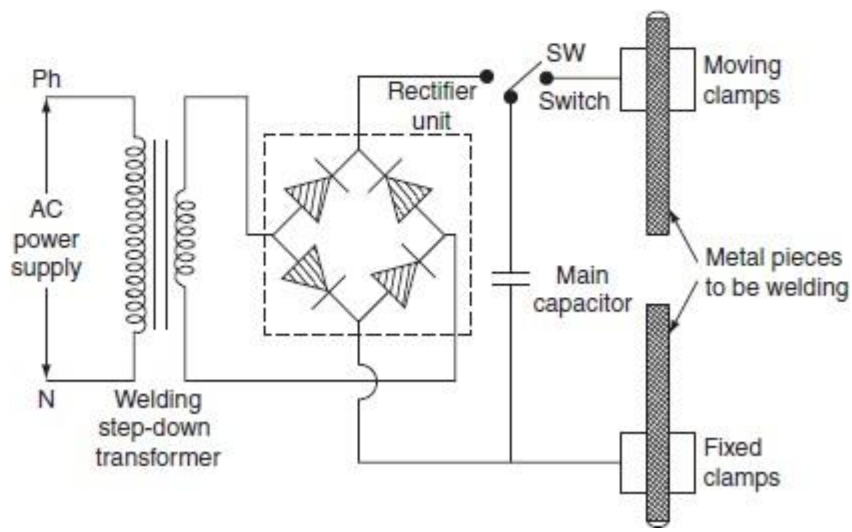


Fig. 5.10 Capacitor discharge circuit for percussion welding

The capacitor 'C' is charged to about 3,000 V from a controlled rectifier. The capacitor is connected to the primary of welding transformer through the switch and will discharge. This discharge will produce high transient current in the secondary to join the two metal pieces.

Percussion welding is difficult to obtain uniform flashing of the metal part areas of the cross-section grater than 3 sq. cm. Advantage of this welding is so fast, extremely shallow of heating is obtained with a span of about 0.1 sec. It can be used for welding a large number of dissimilar metals.

Applications

- It is useful for welding satellite tips to tools, sliver contact tips to copper, cast iron to steel, etc.
- Commonly used for electrical contacts.
- The metals such as copper alloys, aluminum alloys, and nickel alloys are percussion welded.

3.7 Electric arc Welding

Electric arc welding is the process of joining two metallic pieces or melting of metal is obtained due to the heat developed by an arc struck between an electrode and the metal to be welded or between the two electrodes as shown in Fig. 5.13 (a).

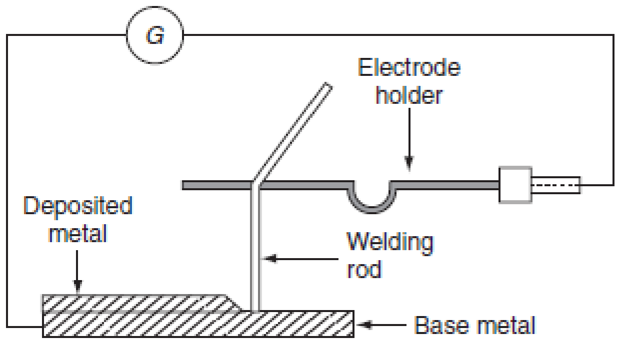


Fig. Arrangement of electric welding equipment

In this process, an electric arc is produced by bringing two conductors (electrode and metal piece) connected to a suitable source of electric current, momentarily in contact and then separated by a small gap, arc blows due to the ionization and give intense heat.

The heat so developed is utilized to melt the part of workpiece and filler metal and thus forms the weld.

In this method of welding, no mechanical pressure is employed; therefore, this type of welding is also known as *'non-pressure welding'*.

The length of the arc required for welding depends upon the following factors:

- The surface coating and the type of electrodes used.
- The position of welding.
- The amount of current used.

When the supply is given across the conductors separated by some distance apart, the air gap present between the two conductors gets ionized, as the arc welding is in progress, the ionization of the arc path and its surrounding area increases. This increase in ionization decreases the resistance of the path. Thus, current increases with the decrease in voltage of arc. This *V-I* characteristic of an arc is shown in Fig. (b), it also known as *negative resistance characteristics of an arc*. Thus, it will be seen that this decrease in resistance with increase in current does not remain the arc steadily. This difficulty cab be avoided, with the supply, it should fall rapidly withthe increase in the current so that any further increase in the current is restricted.

For the arc welding, the temperature of the arc should be 3,500°C. At this temperature, mechanical pressure for melting is not required. Both AC and DC can be used in the arc welding. Usually 70–100 V on AC supply and 50–60 V on DC supply system is sufficient to struck the arc in the air gap between the electrodes. Once the arc is struck, 20–30 V is only required to maintain it.

However, in certain cases, there is any danger of electric shock to the operator, low voltage should be used for the welding purpose. Thus, DC arc welding of low voltage is generally preferred.

Electric arc welding is extensively used for the joining of metal parts, the repair of fractured casting, and the fillings by the deposition of new metal on base metal, etc.

Various types of electric arc welding are:

1. Carbon arc welding.
2. Metal arc welding.

Carbon arc welding

It is one of the processes of arc welding in which arc is struck between two carbon electrodes or the carbon electrode and the base metal. The simple arrangement of the carbon arc welding is shown in Fig. 5.14.

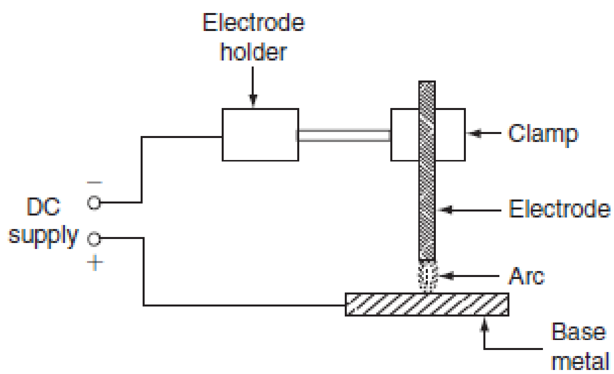


Fig. Carbon arc welding

In this process of welding, the electrodes are placed in an electrode holder used as negative electrode and the base metal being welded as positive. Unless, the electrode is negative relative to the work, due to high temperature, there is a tendency of the particles of carbon will fuse and mix up with the base metal, which causes brittleness; DC is preferred for carbon arc welding since there is no fixed polarity maintained in case of AC.

In the carbon arc welding, carbon or graphite rods are used as electrode. Due to longer life and low resistance, graphite electrodes are used, and thus capable of conducting more current. The arc produced between electrode and base metal; heat the metal to the melting temperature, on the negative electrode is 3,200°C and on the positive electrode is 3,900°C.

This process of welding is normally employed where addition of filler metal is not required. The carbon arc is easy to maintain, and also the length of the arc can be easily varied. One major problem with carbon arc is its instability which can be overcome by using an inductor in the electrode of 2.5-cm diameter and with the current of about of 500–800 A employed to deposit large amount of filler metal on the base metal.

Filler metal and flux may not be used depending upon the type of joint and material to be welded.

Advantages

- The heat developed during the welding can be easily controlled by adjusting the length of the arc.
- It is quite clean, simple, and less expensive when compared to other welding process.
- Easily adoptable for automation.
- Both the ferrous and the non-ferrous metals can be welded.

Disadvantages

- Input current required in this welding, for the workpiece to rise its temperature to melting/weldingtemperature, is approximately double the metal arc welding.
- In case of the ferrous metal, there is a chance of disintegrating the carbon at high temperature and transfer to the weld, which causes harder weld deposit and brittlement.
- A separate filler rod has to be used if any filler metal is required.

Applications

- It can be employed for the welding of stainless steel with thinner gauges.
- Useful for the welding of thin high-grade nickel alloys and for galvanized sheets using copper siliconmanganese alloy filler metal.

Metal arc welding

In metal arc welding, the electrodes used must be of the same metal as that of the work-piece to be welded. The electrode itself forms the filler metal. An electric arc is stuck by bringing the electrode connected to a suitable source of electric current, momentarily in contract with the workpieces to be welded and withdrawn apart. The circuit diagram for the metal arc welding is shown in Fig. 5.15.

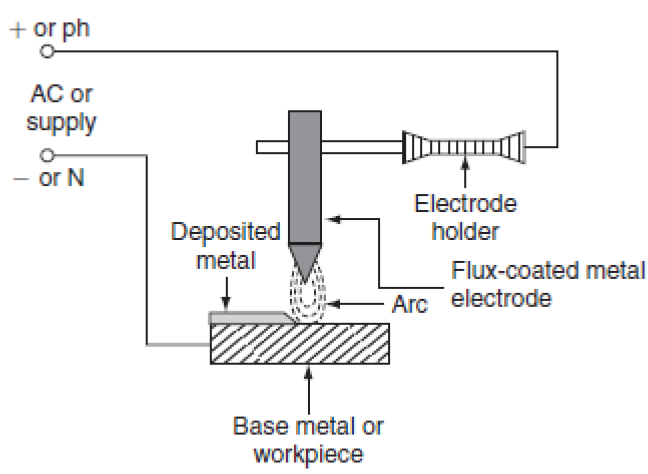


Fig. 5.15 Metal arc welding

The arc produced between the workpiece and the electrode results high temperature of the order of about 2,400°C at negative metal electrode and 2,600°C at positive base metal or workpiece.

This high temperature of the arc melts the metal as well as the tip of the electrode, then the electrode melts and deposited over the surface of the workpiece, forms complete weld.

Both AC and DC can be used for the metal arc welding. The voltage required for the DC metal arc welding is about 50–60 V and for the AC metal arc welding is about 80–90 V

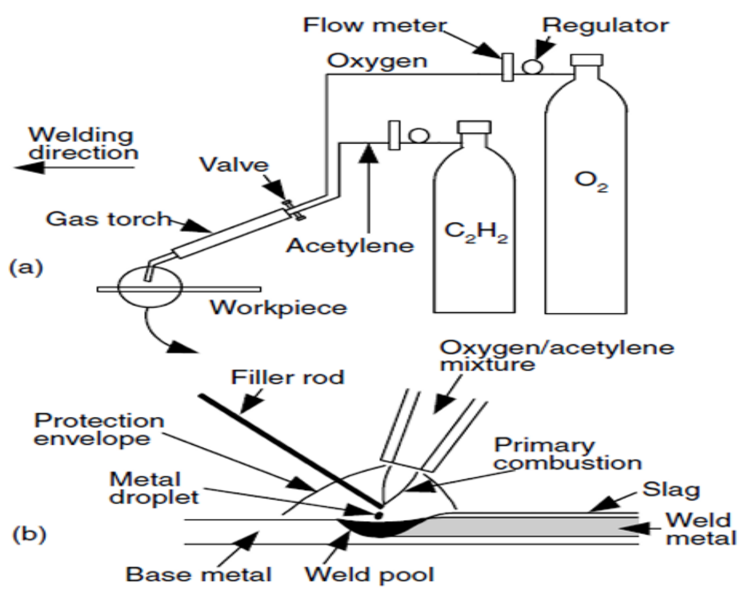
In order to maintain the voltage drop across the arc less than 13 V, the arc length should be kept as small as possible, otherwise the weld will be brittle. The current required for the welding varies from 10 to 500 A depending upon the type of work to be welded.

The main disadvantage in the DC metal arc welding is the presence of arc blow, i.e., distortion of arc stream from the intended path due to the magnetic forces of the non-uniform magnetic field with AC arc blow is considerably reduced. For obtaining good weld, the flux-coated electrodes must be used, so the metal which is melted is covered with slag produces a non-oxidizing gas or a molten slag to cover the weld, and also stabilizes the arc.

3.8 Gas welding, ultrasonic Welding

Gas welding is a metal joining method that involves melting metals with the use of fuel gases such as acetylene, propane, or hydrogen mixed with oxygen to form the weld. This welding technique is usually known as ‘Oxy Acetylene Welding’.Acetylene was first identified by Edmund Davy in 1836, and with the invention of the welding torch in 1900, it was put to practical use.

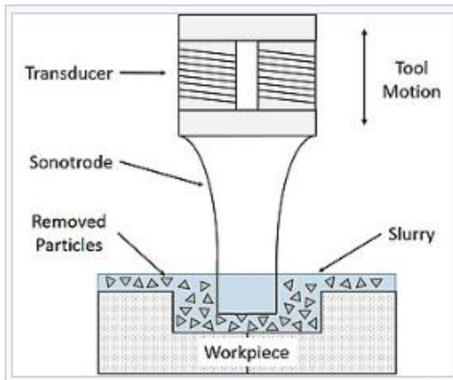
OXYACETYLENE WELDING The Process Gas welding is a welding process that melts and joins metals by heating them with a flame caused by the reaction between a fuel gas and oxygen. Oxyacetylene welding (OAW), shown in Figure 1, is the most commonly used gas welding process because of its high flame temperature. A flux may be used to deoxidize and cleanse the weld metal. The flux melts, solidifies, and forms a slag skin on the resultant weld metal. Figure 2 shows three different types of flames in oxyacetylene welding: neutral, reducing, andoxidizing.



ᵋ 3.1 Oxyacetylene welding: (*a*) overall process; (*b*) welding area enlarged.

Ultrasonic Welding

Ultrasonic welding is an industrial process whereby high-frequency ultrasonic acoustic vibrations are locally applied to work pieces being held together under pressure to create a solid-state weld. It is commonly used for plastics and metals, and especially for joining dissimilar materials. In ultrasonic welding, there are no connective bolts, nails, soldering materials, or adhesives necessary to bind the materials together. When used to join metals, the temperature stays well below the melting point of the involved materials, preventing any unwanted properties which may arise from high temperature exposure ofthemetal.



Ultrasonic Welding

Ultrasonic welding can be used for both hard and soft plastics, such as semicrystalline plastics, and metals. The understanding of ultrasonic welding has increased with research and testing. The invention of more sophisticated and inexpensive equipment and increased demand for plastic and electronic components has led to a growing knowledge of the fundamental process.[4] However, many aspects of ultrasonic welding still require more study, such as the relationship of weld quality to process parameters.

3.9 Advantages & disadvantages of electric welding

Advantages:

1. **Versatility:** Electric welding can be used on a wide range of metals and alloys, including steel, stainless steel, aluminum, and others.
2. **Speed:** It allows for fast welding once the setup is done, making it suitable for high-volume production environments.
3. **Control:** Welding parameters such as current, voltage, and electrode type can be precisely controlled, allowing for consistent weld quality.
4. **Portability:** Electric welding machines come in various sizes, from small portable units to large industrial welders, offering flexibility in different work environments.
5. **Less Fumes:** Compared to some other welding methods like gas welding, electric welding produces fewer fumes, making it safer for indoor use with proper ventilation.
6. **Cost-effective:** Initial setup costs for electric welding equipment can be lower compared to some other welding methods, especially for smaller-scale operations.

Disadvantages:

1. **Power Requirement:** Electric welding requires a stable power supply, which can be a limitation in remote locations or areas with unreliable electricity.
2. **Skill Requirement:** While the basics are relatively easy to learn, achieving high-quality welds consistently requires skill and experience.
3. **Surface Preparation:** Proper cleaning and preparation of the metal surfaces are critical to achieving strong welds, adding time and effort to the process.
4. **Safety Hazards:** Electric welding involves high temperatures and intense light, posing risks of burns, eye damage, and electrical shocks if proper safety precautions are not followed.
5. **Weld Quality:** Inexperienced welders may struggle to achieve strong and durable welds, leading to potential issues with weld strength and integrity.
6. **Environmental Impact:** While it produces fewer fumes compared to some methods, electric welding still contributes to local air quality concerns, especially in poorly ventilated areas.

4.Applications of electric welding

Electric welding, or arc welding, finds numerous applications across various industries due to its versatility and ability to join different types of metals. Some common applications include:

1. **Construction:** Electric welding is extensively used in the construction industry for fabricating structural steel components, assembling metal frameworks, and joining reinforcement bars in concrete structures.
2. **Manufacturing:** It plays a crucial role in manufacturing sectors for producing machinery, equipment, and metal components. Electric welding is used in the fabrication of automotive parts, appliances, industrial machinery, and consumer goods.
3. **Shipbuilding:** Electric welding is essential in shipyards for constructing ships, barges, and other marine vessels. It is used to weld steel hulls, decks, bulkheads, and other structural components.
4. **Aerospace:** In the aerospace industry, electric welding is employed to fabricate aircraft components, engine parts, and structural assemblies. It is used for both assembly and repair work.
5. **Infrastructure and Pipeline:** Electric welding is widely used in the construction and maintenance of pipelines, oil rigs, and infrastructure projects. It ensures strong and reliable welds for pipelines carrying oil, gas, water, and other fluids.
6. **Automotive:** Electric welding is integral to the automotive industry for manufacturing vehicle frames, chassis, exhaust systems, and various structural components. It is also used in vehicle repair and maintenance.
7. **Metal Fabrication:** It is a cornerstone of metal fabrication shops where components and assemblies are produced for a wide range of industries. This includes everything from small-scale custom projects to large-scale industrial installations.
8. **Repair and Maintenance:** Electric welding is essential for repairing metal components, machinery, and equipment in various industries. It allows for the restoration of worn-out parts and the reinforcement of existing structures.
9. **Artistic and Sculptural:** Artists and sculptors use electric welding techniques to create intricate metal sculptures and artworks. It offers flexibility in shaping and joining metal pieces to realize creative designs.
10. **DIY and Hobbyist Projects:** Electric welding is accessible to hobbyists and DIY enthusiasts for crafting metalwork, furniture, artwork, and other personal projects.

. **UNIT-4**

Electric Traction – I

4.1 Introduction, systems of electric traction

The system that causes the propulsion of a vehicle in which that driving force ortractive force is obtained from various devices such as electric motors, steam engine drives, diesel engine dives, etc. is known as traction system.

Traction system may be broadly classified into two types. They are electric- traction systems, which use electrical energy, and non-electric traction system, which does not use electrical energy for the propulsion of vehicle.

The requirements of ideal traction systems are:

- Ideal traction system should have the capability of developing high tractive effort in order to have rapid acceleration.
- The speed control of the traction motors should be easy.
- Vehicles should be able to run on any route, without interruption.
- Equipment required for traction system should be minimum with high efficiency.
- It must be free from smoke, ash, durt, etc.
- Regenerative braking should be possible and braking should be in such a way to cause minimum wear on the break shoe.
- Locomotive should be self-contained and it must be capable of withstanding overloads.
- Interference to the communication lines should be eliminated while the locomotive running along the track.

Advantages and Disadvantages of Electric Traction

Electric traction system has many advantages compared to non-electric tractionsystems. The following are the advantages of electric traction:

- Electric traction system is more clean and easy to handle.
- No need of storage of coal and water that in turn reduces the maintenance cost as well as the saving of high-grade coal.
- Electric energy drawn from the supply distribution system is sufficient to maintain the common necessities of locomotives such as fans and lights; therefore, there is no need of providing additional generators.
- The maintenance and running costs are comparatively low.
- The speed control of the electric motor is easy.
- Regenerative braking is possible so that the energy can be fed back to the supply system during the braking period.
- In electric traction system, in addition to the mechanical braking, electrical braking can also be used that reduces the wear on the brake shoes, wheels, etc.
- Electrically operated vehicles can withstand for overloads, as the system is capable of drawing more energy from the system.

In addition to the above advantages, the electric traction system suffers from thefollowing drawbacks:

- Electric traction system involves high erection cost of power system.
- Interference causes to the communication lines due to the overhead distribution networks.
- The failure of power supply brings whole traction system to stand still.
- In an electric traction system, the electrically operated vehicles have to move only on the electrified routes.
- Additional equipment should be needed for the provision of regenerative braking, it will increase the overall cost of installation.

REVIEW OF EXISTING ELECTRIC TRACTION SYSTEM IN INDIA

In olden days, first traction system was introduced by Britain in 1890 (600-V DC track). Electrification system was employed for the first traction vehicle. This traction system was introduced in India in the year 1925 and the first traction system employed in India was from Bombay VT to Igatpuri and Pune, with 1,500-V DC supply. This DC supply can be obtained for traction from substations equipped with rotary converters. Development in the rectifiers leads to the replacement of rotary converters by mercury arc rectifiers. But nowadays further development in the technology of semiconductors, these mercury arc valves are replaced by solid-state semiconductors devices due to fast traction system was introduced on 3,000-V DC. Further development in research on traction system by French international railways was suggested that, based on relative merits and demerits, it is advantageous to prefer to AC rather than DC both financially andoperationally.

Thus, Indian railways was introduced on 52-kV, 50-Hz single-phase AC systemin 1957; this system of track electrification leads to the reduction of the cost of overhead, locomotive equipment, etc. Various systems employed for track electrification are shown in Table .

Table Track electrification systems

S. no	System	Voltage	Frequency
1	DC system	600 V, 1,500 V, or 3,000 V	–
2	Single-phase AC system	15–25 kV is stepped down to 300–400 V	$\frac{162}{3}$ Hz and 25 Hz
3	Three-phase AC system	15–25 kV is stepped down to 3,300–3,600 V	$\frac{162}{3}$ Hz and 50 Hz

SYSTEM OF TRACTION

Traction system is normally classified into two types based on the type of energygiven as input to drive the system and they are:

1. **Non-electric traction system**
   Traction system develops the necessary propelling torque, which do notinvolve the use of electrical energy at any stage to drive the traction vehicle known as electric traction system.
   Ex: Direct steam engine drive and direct internal combustion enginedrive.
2. **Electric traction system**

   Traction system develops the necessary propelling torque, which involvesthe use of electrical energy at any stage to drive the traction vehicle, known as electric traction system.
   Based upon the type of sources used to feed electric supply for tractionsystem, electric traction may be classified into two groups:

   1. Self-contained locomotives.
   2. Electric vehicle fed from the distribution networks.

Self-contained locomotives

In this type, the locomotives or vehicles themselves having a capability of generating electrical energy for traction purpose. Examples for such type oflocomotives are:

1. **Steam electric drive**
   In steam electric locomotives, the steam turbine is employed for driving a generator used to feed the electric motors. Such types of locomotives are not generally used for traction because of some mechanical difficulties andmaintenance problems.
2. **Diesel electric trains**

   A few locomotives employing diesel engine coupled to DC generator usedto feed the electric motors producing necessary propelling torque. Diesel engine is a variable high-speed type that feeds the self- or separately excited DC generator. The excitation for generator can be supplied from any auxiliary devices and battery.
   Generally, this type of traction system is suggested in the areas wherecoal and steam tractions are not available. The advantages and disadvantages of the diesel engine drive are given below:

   Advantages

- As these are no overhead distribution system, initial cost is low.
- Easy speed control is possible.
- Power loss in speed control is very low
- Time taken to bring the locomotive into service is less.
- In this system, high acceleration and braking retardation can be obtained compared to steam locomotives.
- The overall efficiency is high compared to steam locomotives.

Disadvantages

- The overloading capability of the diesel engine is less.
- The running and maintenance costs are high.
- The regenerative braking cannot be employed for the diesel engine drives.

Petrol electric traction

This system of traction is used in road vehicles such as heavy lorries and buses. These vehicles are capable of handling overloads. At the same time, this system provides fine and smooth control so that they can run along roads without anyjerking.

Battery drives

In this drive, the locomotive consists of batteries used to supply power to DC motors employed for driving the vehicle. This type of drives can be preferred for frequently operated services such as local delivery goods traction in industrial works and mines, etc. This is due to the unreliability of supply source to feed theelectric motors.

Electric vehicles fed from distribution network

Vehicles in electrical traction system that receives power from over head distribution network fed or substations with suitable spacing. Based on the available supply, these groups of vehicles are further subdivided into:

1. System operating with DC supply. Ex: tramways, trolley buses, and railways.
2. System operating with AC supply. Ex: railways.

Systems operating with DC supply

In case if the available supply is DC, then the necessary propelling power can beobtained for the vehicles from DC system such as tram ways, trolley buses, and railways.

4.2 comparison between A. C. and D. C traction, special features of traction motors, the locomotive, transmission of drive

Comparison between AC Traction and DC Traction Systems

The following table compares and contrasts the various features of AC and DC traction systems –

Point of Comparison	DC Traction System	AC Traction System
Efficiency	DC traction system is more efficient.	AC traction system is less efficient.

Point of Comparison	DC Traction System	AC Traction System
Cost of motor	DC series motors are cheaper.	AC motors are expensive.
Maintenance	DC traction system requires less maintenance.	AC traction system needs more maintenance.
Speed control	The speed control of DC series motor is limited.	With the AC motors, wide range of speed control is possible.
Cost of system	The overall cost of the DC traction system is less.	The overall cost of the AC traction is more.
Overhead distribution	In DC traction system, overhead distribution of electrical power is possible.	In the AC traction system, overhead distribution is used.
Acceleration	DC traction system is capable of giving high acceleration.	AC traction system gives less acceleration.
Torque	DC series motor produces less torque.	The starting and running torque developed by AC motors is more.
Regenerative braking	DC series motors have more efficient regenerative braking.	In case of AC motors, the regenerative braking is less efficient.
Interference with communication lines	DC traction system causes less interference with the communication lines.	AC traction system produces more interference with communication lines.
Number of substations	DC traction system requires more number of substations for a given track distance.	AC traction system requires less number of substations for a given track distance.
Suitability	DC traction system is suitable for urban line railway service.	AC traction system is suitable for main line railway service.
Energy consumption	Energy consumption in DC traction system is less.	For same output, energy consumed by AC traction system is more.
Weight of locomotive	Weight of DC locomotive is less.	Weight of AC locomotive is more.
Capital cost of substation	For DC traction system, the capital cost of substation is more due to converting equipment.	Capital cost of AC substation is less.
Cost of conductor	In DC traction system, the cost of	AC traction system uses higher

Point of Comparison	DC Traction System	AC Traction System
	overhead conductor is more as the operating voltages are low.	voltages so the cost of conductor is reduced.

SPECIAL FEATURES OF TRACTION MOTORS

The general features of the electric motors used for traction purpose are:

1. Mechanical features.
2. Electrical features.

Mechanical features

1. A traction motor must be mechanically strong and robust and it should be capable of withstanding severe mechanical vibrations.
2. The traction motor should be completely enclosed type when placed beneath the locomotive to protect against dirt, dust, mud, etc.
3. In overall dimensions, the traction motor must have small diameter, to arrange easily beneath the motor coach.
4. A traction motor must have minimum weight so the weight of locomotive will decrease. Hence, the load carrying capability of the motor will increase.

Electrical features

High-starting torque

A traction motor must have high-starting torque, which is required to start themotor 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 necessaryfor the frequent starting and stopping of the motor in traction purpose.

Dynamic and regenerative braking

Traction motors should be able to provide easy simple rehostatic and regenerativebraking 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.

TRANSMISSION OF DRIVE

Drive is a system used to create the movement of electric train. The electric locomotives are specially designed to have springs between the driving axles and the main body. This arrangement of springs reduces the damage not only to the track wings but also to the hammer blows.

The power developed by the armature of the traction motors must be transferredto the driving axels through pinion and gear drive. There are several methods by which power developed by the armature can be transferred to the driving wheel.

Gearless drive

Gearless drives are of two types.

Direct drive

It is a simple drive. The armatures of the electric motors are mounted directly on the driving axle with the field attached to the frame of locomotive. In this system, the poles of electric motors should be flat so that the armature can be able to move freely without affecting of the operation. Here, the size of the armatures of the traction motor is limited by the diameter of the driving wheels. The arrangement ofdirect drive is shown in fig,

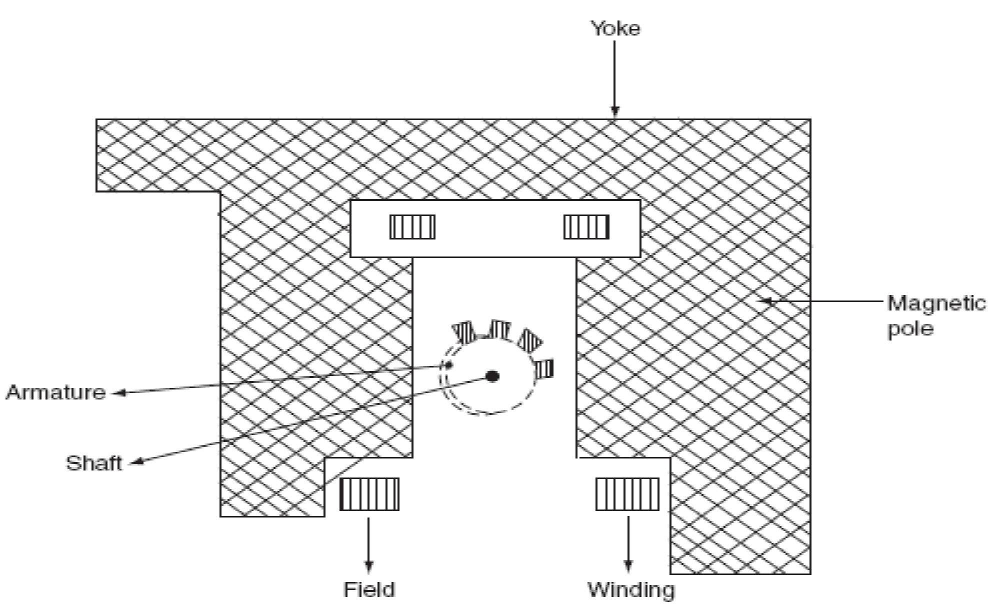


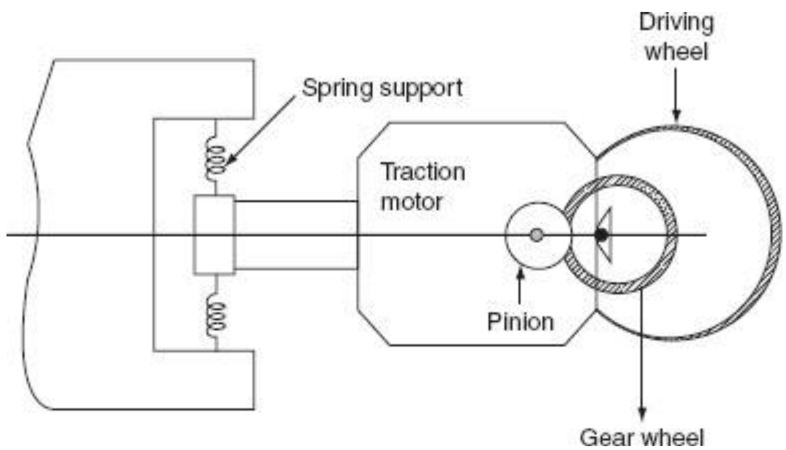
Fig. Direct drive

Direct quill drive

Quill is nothing but a hallow shaft. Driving axle is surrounded by the hollow shaftattached by springs. The armature of the motor is mounted on a quill. The speed and the size of the armature are limited by the diameter of the driving wheels.

Geared drive

In this drive, the armature of the traction motor is attached to the driving wheelthrough the gear wheel system. Now, the power developed by the armature is transferred to the driving wheel through the gear system. Here, gear drive is necessary to reduce the size of the motor for given output at high speeds (Fig. 9.33). The gear ratio of the system is usually 3–5:1.



Brown–Boveri individual drive

In this drive, a special link is provided between the gear wheel and driving wheel, which provides more flexibility of the system.

Parallel running

In traction work, more number of motors need to run in parallel to carry more load.Therefore, the traction motor should have such speed–torque and current–torque characteristics and those motors may share the total load almost equally.

Commutation

Traction motor should have the feature of better commutation, to avoid thesparking at the brushes and commutator segments.

4.3 Characteristics and control of locomotives

TRACTION MOTOR CONTROL

Normally, at the time of starting, the excessive current drawn by the electric motorfrom the main supply causes to the effects. So that, it is necessary to reduce the current drawn by the traction motor for its smooth control such as:

1. To achieve smooth acceleration without any jerking and sudden shocks.
2. To prevent damage to coupling.
3. To achieve various speed depending upon the type of services.

Control of DC motors

At the time of starting, excessive current is drawn by the traction motor when ratedvoltage is applied across its terminals. During the starting period, the current drawnby the motor is limited to its rated current. This can be achieved by placing a resistance in series with the armature winding. This is known as starting resistance;it will be cut off during the normal running period thereby applying rated voltage across its armature terminals. By the resistance of stating resistor, there is considerable loss of energy takes place in it.

∴ At the time of switching on, the back emf developed by the motor $E_b = 0$.

$$\therefore \text{Supply voltage, } V = I_a R_a + V_s, \qquad (9.11)$$

where V_s is the voltage drop across starting resistance and $I_a R_a$ is the voltage drop in armature.

During the running condition:

$$V = I_a R_a + V_s + E_b. \qquad (9.12)$$

At the end of accelerating period, the total starting resistance will be cut off fromthe armature then:

$$V = I_a R_a + E_b. \qquad (9.13)$$

1.Various drops during staring and running with armature resistance.
2.Various drops during staring and running with negligible armature resistance.

When armature resistance is neglected $R_a = 0$ and 't' is the time in seconds for starting, then total energy supplied is, $V_a I_a t$ watts-sec and the energy wasted in the starting resistance at the time of starting can be calculated from Fig. 9.21(b) as:

$$= \text{Area of } \Delta^{le} PQR \times I_a$$
$$= \frac{1}{2} tVI_a$$
$$= \frac{1}{2} VI_a t \ W\text{-sec.} \qquad \textbf{(9.14)}$$

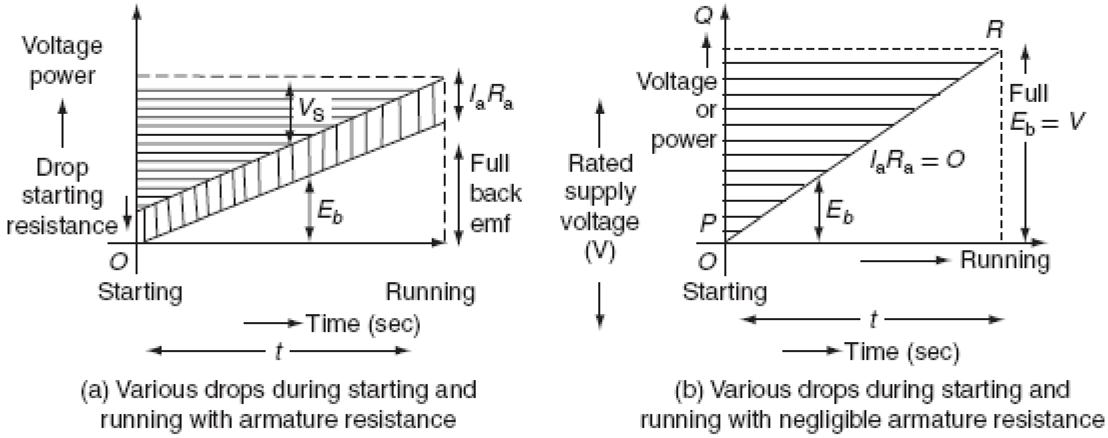


Fig Traction control of DC motor

That is whatever the electrical energy supplied to the motor, half of the energy iswasted during the starting resistor.

∴ The efficiency of the traction motor at time of starting, $\eta_{start} = 50\%$.

4.4 Track electrification

Now a days, based on the available supply, the track electrification system are categorized into.

1. DC system.
2. Single-phase AC system.
3. Three-phase AC system.
4. Composite system.

DC system

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 whereregenerative 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. In some cases, DC supply for traction motor can be obtained from substations equipped with rotary converters to convert AC power to DC. These substations receive AC power from 3-φ high- voltage line or single-phase overhead distribution network. The operating voltage for traction purpose can be justified by the spacing between stations and the type oftraction motors available. Theses substations are usually automatic and remote controlled and they are so costlier since they involve rotary converting equipment. The DC system is preferred for suburban services and road transport where stops are frequent and distance between the stops is small.

Single-phase 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 and hence the voltage drops directly and single-phase AC system is mainly preferred for main line services where the cost of overhead structure is not much importance moreover rapid acceleration andretardation is not required for suburban services.

Three-phase 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 motorsis 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.

Three-phase AC system is mainly adopted for the services where the outputpower required is high and regeneration of electrical energy is possible.

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.

1. Single-phase to DC system.
2. 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 minimumcost 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.

Single-phase to 3-φ system or kando system

In this system, 1-φ AC system is preferred for distribution network. Since single- phase overhead distribution system is cheap and 3-φ induction motors are employed as traction motor because of their simple, robust construction, and the provision of automatic regenerative braking.

The voltage used for the distribution network is about 15–25 kV at 50 Hz. This 1-φ supply is converted to 3-φ supply through the help of the phase converters and high voltage is stepped down transformers to feed the 3-φ induction motors.
Frequency converters are also employed to get high-starting torque and to achieve better speed control with the variable supply frequency.

4.5 DC Equipment, AC Equipment

AUXILIARY EQUIPMENT

A traction system comprises of the following auxiliary equipment in addition to themain traction motors required to be arranged in the locomotive are discussed below.

Motor–generator set

Motor–generator set consists of a series motor and shunt generator. It is mainly used for lighting, control system, and the other power circuits of low voltages inthe range 10–100 V. The voltage of generator is effectively controlled by automatic voltage regulator.

Battery

It is very important to use the battery as a source of energy for pantograph, to runauxiliary compressor, to operate air blast circuit breaker, etc. The capacity of battery used in the locomotive is depending on the vehicle. Normally, the batterymay be charged by a separate rectifier.

Rectifier unit

If the track electrification system is AC motors and available traction motors are DC motors, then rectifiers are to be equipped with the traction motors to convertAC supply to DC to feed the DC traction motors.

4.6 Electric Braking with DC Motors and AC Motors:

Electric braking can be applied to the traction vehicle, by any one of the followingmethods, namely:

1. Plugging.
2. Rehostatic braking.
3. Regenerative braking.

Plugging

In this method of braking, the electric motor is reconnected to the supply in such a way that it has to develop a torque in opposite direction to the movement of the rotor. Now, the motor will decelerates until zero speed is zero and then accelerates in opposite direction. Immediately, it is necessary to disconnect the motor from thesupply as soon as system comes to rest.

The main disadvantage of this method is that the kinetic energy of the rotating parts of the motor is wasted and an additional amount of energy from the supply isrequired to develop the torque in reverse direction, i.e., in this method, the motor should be connected to the supply during braking. This method can be applied to both DC and AC motors.

Plugging applied to DC motors

Pulling is nothing but reverse current braking. This method of braking can be applied to both DC shunt and DC series motors by reversing either the current through armature or the field winding in order to produce the torque in apposite direction, but not both. The connection diagrams for both DC shunt and DC seriesmotors during normal and braking periods are given as follows.

The connection diagram for normal running conditions of both DC shunt and DCseries motors are shown in Figs. 9.4 (a) and 9.5 (a). The back emf developed by the motor is equal in magnitude and same as to the direction of terminal or supply voltage. During the braking, the armatures of both shunt and series motors are reversed as shown in Fig. 9.4 (b) and Fig. 9.5 (b). Now, the back emf developed bythe motor direction of terminal voltage. A high resistance '*R*' is connected in serieswith the armature to limit high-starting current during the braking period.

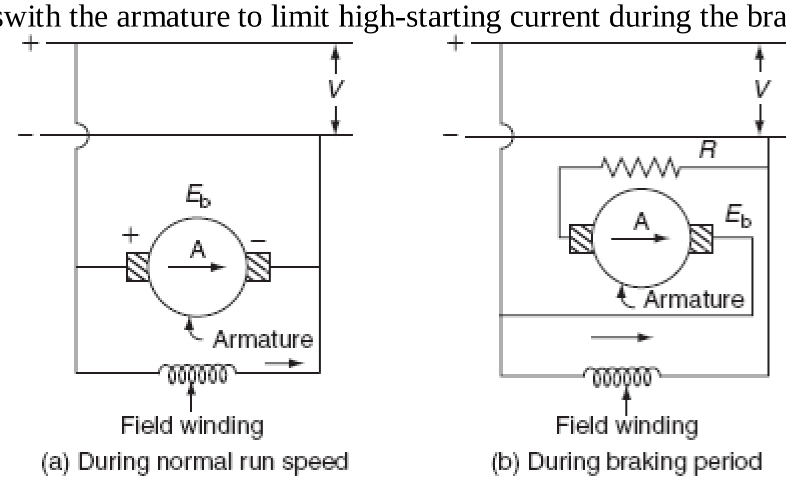
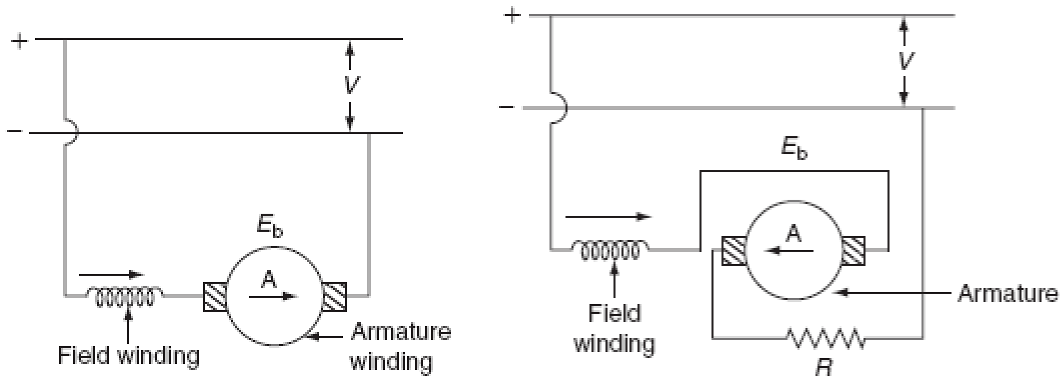


Fig. 9.4 Plugging of DC shunt motor



(a) During normal run period (b) During braking period

Fig. 9.5 Plugging of DC series motor

Current flowing through the armature during normal run condition:

$$I_1 = \frac{V - E_b}{R_a}, \quad \textbf{(9.1)}$$

where V is the supply voltage, E_b is the back emf, and R_a is the armature resistance.

Current flowing through the armature during braking period:

$$I_2 = \frac{V - (-E_b)}{R_a + R}$$

$$= \frac{V + E_b}{R_a + R} = \frac{V + E_b}{R'} \qquad [\because R' = R_a + R].$$

Electric braking torque, T_B a φI_2.

$$T_B = K_1 \phi I_2$$

$$= K_1 \phi \left(\frac{V + E_b}{R'} \right)$$

$$= \frac{K_1 \phi V}{R'} + \frac{K_1 \phi E_b}{R'}. \quad \textbf{(9.2)}$$

But we know that:

$$E_b \propto N\phi. \quad \textbf{(9.3)}$$

Substitute Equation (9. 3) in Equation (9.2):

$$\therefore T_B = \frac{K_1 \phi V}{R'} + \frac{K_1 K_2 \phi^2 N}{R'}$$

$$= \frac{K_1 \phi V}{R'} + \frac{K_3 \phi^2 N}{R'} \qquad [\because K_3 = K_1 K_2]$$

$$= K_4 \phi = K_5 \phi^2, \quad \textbf{(9.4)}$$

where $K_4 = \frac{K_1 V}{R'}$ and $K_4 = \frac{K_3 N}{R'}$.

We know that, in case of series motor flux (φ) developed by the winding isdepending the current flowing through it.

$$\therefore T_B = K_6 I_a + K_7 I_a^2. \quad (9.5)$$

In case of shunt motor, the flux remains constant.

$$\therefore T_B = K_4 + K_5 N. \quad (9.6)$$

Plugging applied to induction motor

During the normal operating condition, the rotating magnetic field developed by the stator and the rotation of rotor are in the same direction. But during the braking period, plugging is applied to an induction motor by reversing any two phases of the three phases of stator winding in order to change the direction of the rotating magnetic field as shown in Fig. 9.6. So that, the rotating magnetic filed and the rotor will be rotating in opposite direction. So that, the relative speed between emfand rotor is nearly twice the synchronous speed $N_S - (-N_S) = 2N_S$.

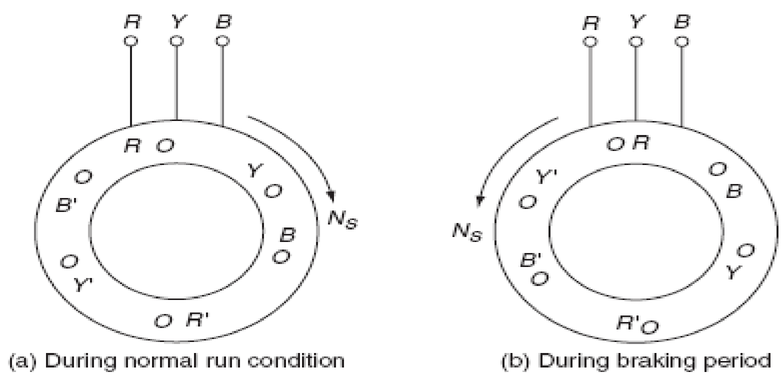


Fig. 9.6 Plugging applied to induction motor

∴ Slip during the braking period:

$$S = \frac{-N_s - N_s}{N_s} = \frac{-2N_s}{N_s} = -2.$$

But the voltage induced in the rotor (E2) is proportional to the slip (S) × stator voltage (V):

$$\therefore E2 \ \text{a} \ SV.$$

So, the rotor voltage during the braking period is twice the normal voltage. Toavoid the damage of the rotor winding, it should be provided with additional insulation, to withstand the high induced voltage.

The rotation of the magnetic field in the reverse direction produce torque in reverse direction; thereby applying the brakes to the motor. The braking of induction motor can be analyzed by the torque–slip characteristics shown in Fig.9.7.

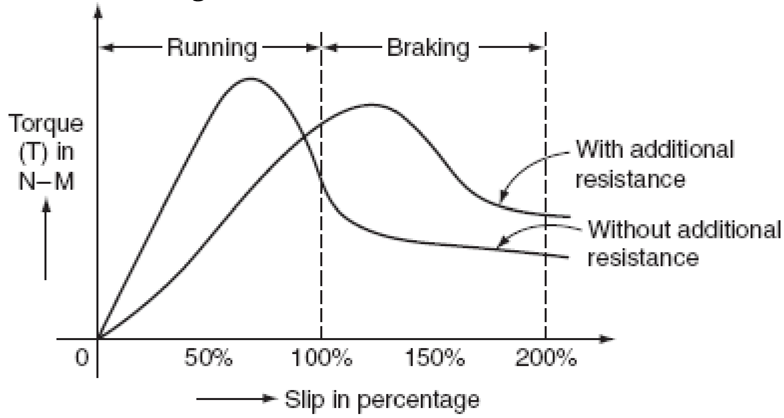


Fig. 9.7 Torque–slip characteristics

Rotor current during the braking period, $I_{2B} = \frac{SE_2}{\sqrt{R_2^2 + (SX^2)^2}}$.

The characteristic curve for the rotor current and the rotor voltage with the variation of the slip is shown in Fig. 9.8.

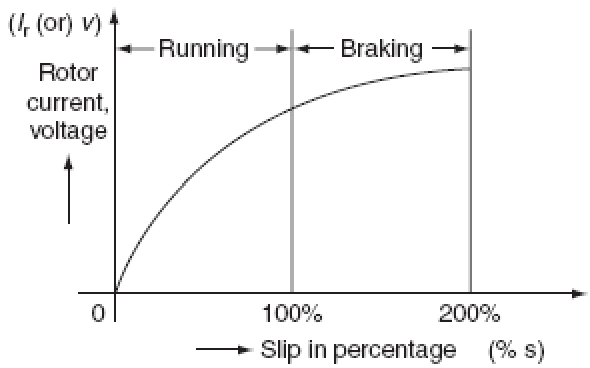


Fig. Rotor current–slip characteristics

Plugging applied to synchronous motor

Normally, the stator winding of the synchronous motor is fed with 3-φ AC supply to produce the rotating magnetic field that induces stator poles. And, the field winding is excited by giving the DC supply thereby inducing the rotor poles. At any instant, the stator poles gets locked with the rotor poles and the synchronous motor rotating at the synchronous speed. In this method of plugging applied to synchronous motor, simply it is not possible to produce the counter torque duringthe braking period by interchanging any two of three phases. This is due to the magnetic locking of stator and rotor poles (Fig. 9.9).

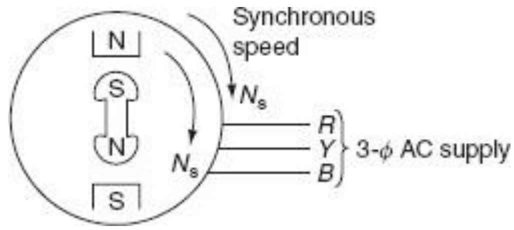


Fig. 9.9 Synchronous motor

In order to develop the counter torque, the rotor of synchronous motor should beprovided with damper winding. The EMF induced in the damper winding whenever there is any change, i.e., the reversal of the direction of the stator field. Now, according to Lenz's law, the emf induced in the damper winding opposes thechange which producing it. This emf induced in the damper winding produces the circulating current to produce the torque in the reverse direction. This torque is known as braking torque. This braking torque helps to bring the motor to rest.

Rheostatic or dynamic braking

In this method of braking, the electric motor is disconnected from the supply during the braking period and is reconnected across same electrical resistance. But field winding is continuously excited from the supply in the same direction. Thus,during the starts working as generator during the braking period and all the kineticenergy of the rotating parts is converted into electric energy and is dissipated across the external resistance.

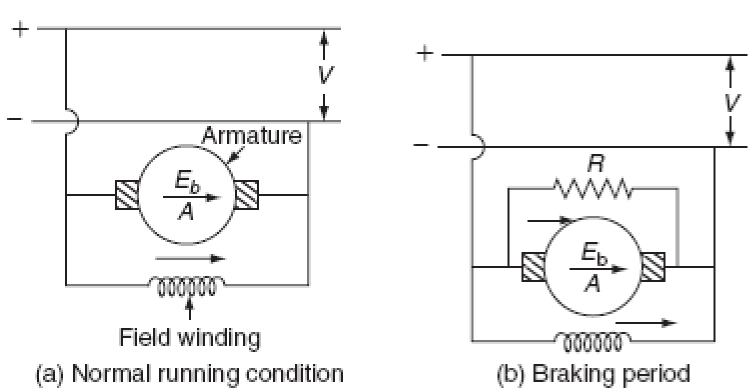
One of the main advantages of the rehostatic braking is electrical energy is notdrawn by the motor during braking period compared to plugging. The rehostaticbraking can be applied to various DC and AC motors.

Rehostatic braking applied to DC motors

The rheostatic braking can be applied to both DC shunt and DC series motors, by disconnecting the armature from the supply and reconnecting it across and externalresistance. This is required to dissipate the kinetic energy of all rotating parts thereby brining the motor to rest.

DC shunts motor

Figure 9.10 shows the connection diagram of the DC shunt motor during both normal and braking conditions. In case of DC shunt motor, both armature and fieldwindings are connected across the DC supply, as shown in Fig. 9.10 (a.)



During the braking period, the armature is disconnected from the supply and field winding is continuously excited by the supply in the same direction, as shown in Fig. 9.10 (b). The kinetic energy of all rotating parts is dissipated in the resistor '*R*' now the machine starts working as generator. Now, braking developed is proportional to the product of the field and the armature currents. But the shunt motor flux remains constant, so the braking torque is proportional to armature current at low-speeds braking torque is less and in order to maintain constant braking torque, the armature is gradually disconnected. Hence, the armature current remains same thereby maintaining the uniform braking torque.

DC series motor

In this braking, which is applied to DC series motor, the armature is disconnected from the supply and is reconnected across an external resistance '*R*' shown in Fig.9.11 (a) and (b). But, simply, it is not possible to develop the retarding torque by the DC series motor after connecting armature across the resistance as DC shunt motor.

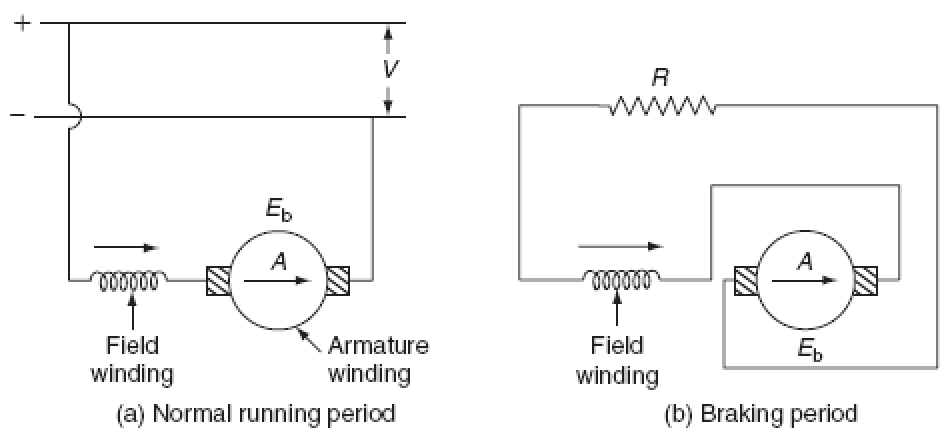
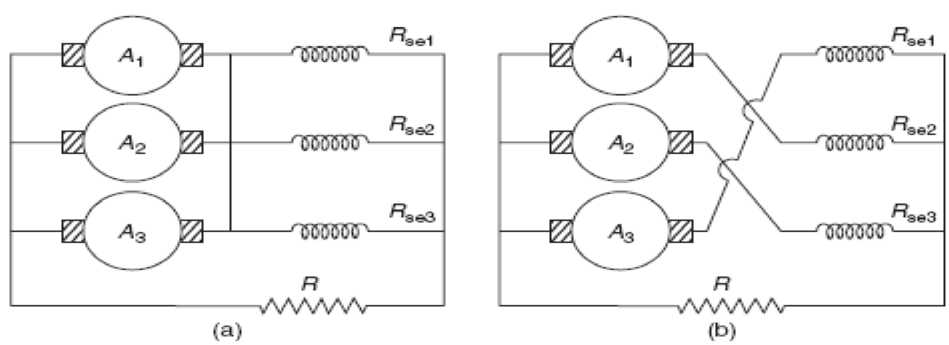


Fig. Rheostatic braking of DC series motor

In case of DC series motor, both the field and armature windings are connected across the resistance after disconnecting the same from the supply; current directions of both the field and armatures are reversed. This results in the production of torque in same direction as before. So, in order to produce the braking torque only the direction of current in the armature has to be reversed. Theconnection diagram of DC series is shown in Fig. 9.11.

If more than one motor has to be used as in electric traction. All motors can beconnected in equalizer connection as shown in Fig. 9.12. In this connection, onemachine is excited by the armature current of another machine.



Braking torque

The current flowing through the armature during braking period:

$$I_a = \frac{E_b}{R + R_a}, \qquad \textbf{(9.7)}$$

where E_b is the back emf developed, R is the external resistance, and R_a is the armature resistance.

And we know that, back emf $E_b \propto \phi N$

$$E_b = K_1 \phi N.$$

$$\therefore \text{Braking current } I_a = \frac{K_1 \phi N}{R + R_a}. \qquad \textbf{(9.8)}$$

Braking torque, T_B a φ I_a.

$$\therefore T_B = K_2 \phi I_a. \qquad \textbf{(9.9)}$$

Now, substitute Equation (9.8) in Equation (9.9):

$$\therefore T_B = K_2 \phi \left[\frac{K_1 \phi N}{R + R_a} \right]$$

$$= \frac{K_1 K_2 \phi^2 N}{R + R_a} = K_3 \phi^2 N \qquad \left[\because K_3 = \frac{K_1 K_2}{R + R_a} \right].$$

For shunt motor flux is practically constant:

$$\therefore T_B = K_5 I_a^2 N. \qquad \textbf{(9.10)}$$

DC series motor

In case of DC series motor, it is not easy to apply regenerative braking as of DC shunt motor. The main reasons of the difficulty of applying regenerative braking to DC series motor are:

1. During the braking period, the motor acts as generator by reversing the direction of current flowing through the armature, but at the same time, the current flowing through the field winding is also reversed; hence, there is no retarding torque. And, a short-circuit condition will set up both back emf and supply voltage will be added together. So that, during the braking period, it is necessary to reverse the terminals of field winding.
2. Some sort of compensating equipment must be incorporated to take care of large change in supply voltage.

On doing some modifications during the braking period, the regenerative brakingcan be applied to DC series motor. Any one of the following methods is used.

Method-I (French method)

If one or more series motors are running in parallel, during the braking period, the field windings, of all series motors, are connected across the supply in series with suitable resistance. Thereby converting all series machines in shunt machines asshown in Fig. 9.15.

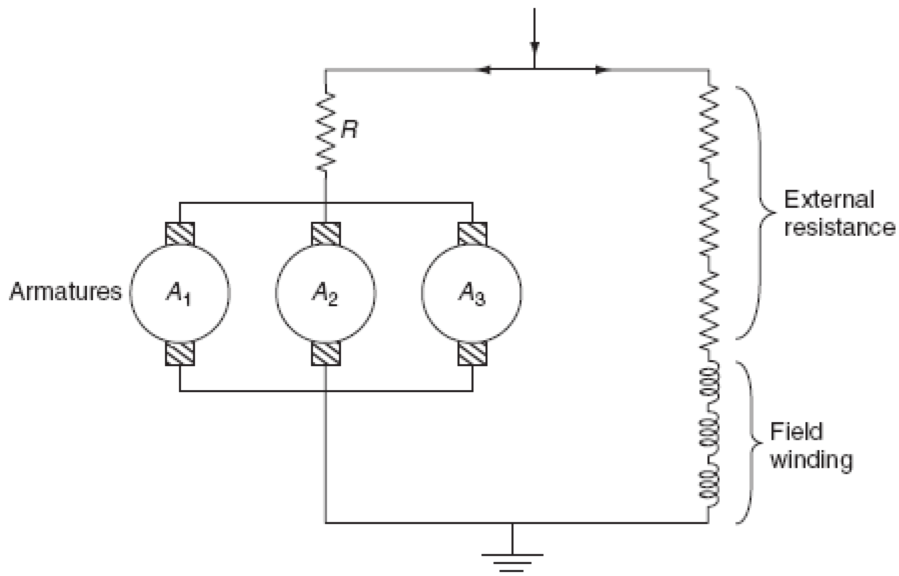


Fig. Regenerative braking of DC series motor

4.7 Overhead Equipment

Simplest type of overhead equipment in electric traction systems consists of a single contact wire supported either by bracket or by overhead span. The maximum distance between two consecutive supports with such a system is restricted to 30 m and speed is limited to 30 kmph. The single contact wire system, therefore, finds application for tramcars or in complicated yards and terminal stations where simplicity of layout is desired and speeds are low.

In order that the contact wire remains at the same level under all weather conditions, it is necessary to keep the tension in the catenary and contact wire constant under all temperatures likely to be encountered in service and allow movements of wires along the track which result due to changes in temperature. This is achieved by using regulated OHE at either end of the tension length (Fig. 15.20). The tensioning device consists of a pulley block or a winch with suitable reduction ratio (about 5). Increase in tension reduces the static elasticity of the OHE and makes it more uniform and thus improves the dynamic behaviour and current collection. Contact and catenary wires are given tension of about 1,000 kg each so as to limit the lateral stresses exerted on the masts and foundations due to increase in tension. Cast iron weights of 400 kg are required by the automatic tensioning device (Fig. 15.20) in order to develop tension of 1,000 kg in each of contact and catenary wire. In order to prevent longitudinal to and fro oscillations of OHE in the running condition of train, it is fixed in the centre, which is known as **anticreep** (Fig. 15.21). For the temperature range experienced in electrified sections in India, maximum distance between the anticreep and the end of tension length i.e., half tension length is restricted to 750 metres.

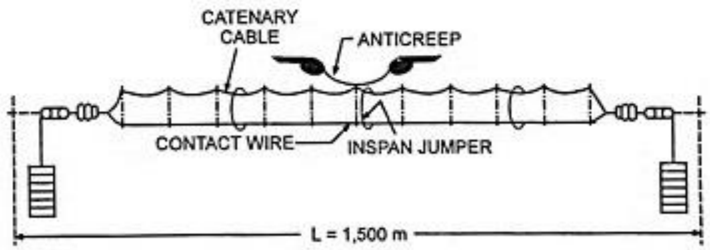
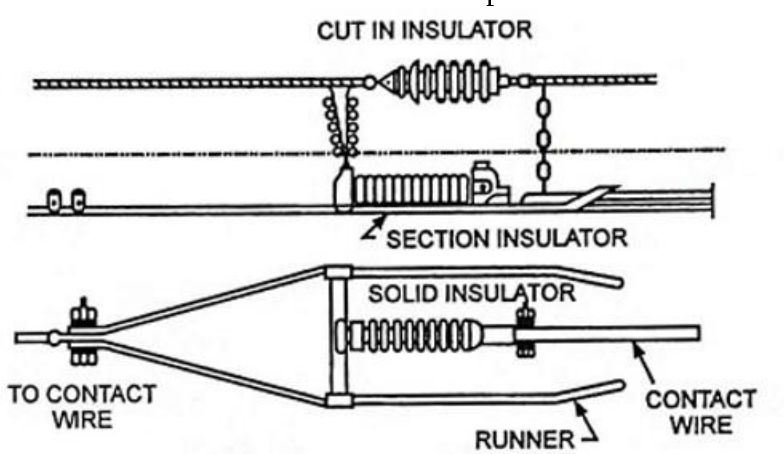


Fig. 15.21

Section Insulators

Section insulators in overhead equipment in electric traction are provided for insulating OHE of one elementary section from the OHE of another adjacent elementary section such that at cross-overs from one track to the other, from main line to siding etc. as shown in Fig. 15.17. Section insulator, as illustrated in Fig. 15.24, consists of straining insulator with two runners connected to one of the contact wires. Runners are at the same height as the contact wire on the other side and so shaped as to permit smoother passage of pantograph as the train passes underneath. Runners extend and overlap the contact wire on the other side so that the locomotive draws interruption free current.



4.8 Adhesive Weight & Dead Weight

Adhesive weight

The total weight to be carried out on the drive in wheels of a locomotive is known as adhesive weight. The maximum traction force of the mining electric locomotive is generally equal to the adhesive traction force. It can be said that the adhesive traction force determines the upper limit of the transportation capacity of the mining electric locomotive. Once the traction force required by the mining locomotive is greater than the sticking force, the mining locomotive will begin to slip. In addition to illegal driving conditions such as overloading, as the use time of the mining electric locomotive increases, its adhesive traction will also decrease, resulting in the occurrence of slippage

Dead Weight:

It is the total weight of train to be propelled by the locomotive. It is denoted by'*W*'.

Accelerating weight

It is the effective weight of train that has angular acceleration due to the rotationalinertia including the dead weight of the train. It is denoted by 'W_e'.

This effective train is also known as accelerating weight. The effective weight ofthe train will be more than the dead weight. Normally, it is taken as 5–10% of more than the dead weight.

Coefficient of adhesion

It is defined as the ratio of the tractive effort required to propel the wheel of alocomotive to its adhesive weight.

$$F_t \text{ a } W$$

$$= \mu W,$$

where F_t is the tractive effort and W is the adhesive weight.

$$\therefore \mu = \frac{F_t}{W}. \qquad \textbf{(10.22)}$$

4.9 Numerical Problems

1: A DC series motor drives a load. The motor takes a current of 13 Aand the speed is 620 rpm. The torque of the motor varies as the square of speed.The field winding is shunted by a diverter of the same resistance as that of the fieldwinding, then determine the motor speed and current. Neglect all motor losses and assume that the magnetic circuit is unsaturated.

Solution:

Before connecting field diverter:

Speed, N_1 = 620 rpm.

Series field current, I_{se1} = 13 A.

The same current flows through the armature; so that,

$I_1 = I_{sel} = I_{a1}$ = 13 A.

After connecting field diverter, the field winding is shunted by the diverter of thesame refinance; so that:

Series field current $= I_{se2} = \frac{1}{2} I_2$.

Since torque developed:

$$T \propto \phi I_a$$

$$\propto \phi I_1$$

$$\frac{T_2}{T_1} = \frac{T_2 I_2}{\phi_1 I_1} = \frac{\frac{1}{2} I_2^2}{2 I_1^2} \qquad \text{(i) } (\phi \propto I_{se} \text{ magnetic circuit is unsaturated}).$$

According to given data, the torque varies as the square of the speed.

$$\frac{T_2}{T_1} = \frac{N_2^2}{N_1^2}. \qquad \text{(ii)}$$

From Equations (i) and (ii):

$$\frac{N_2}{N_1} = \frac{I_2}{\sqrt{2I_1}}. \qquad \text{(iii)}$$

All the losses are neglected, and assume that the supply voltage is constant.

$$N \,\alpha\, \frac{1}{\phi}$$

$$\frac{N_2}{N_1} = \frac{\phi_1}{\phi_2}$$

$$= \frac{I_1}{\frac{1}{2} I_2}. \qquad \text{(iv)}$$

From Equations (iii) and (iv):

$$\frac{I_2}{\sqrt{2}I_1} = \frac{2I_1}{I_2}$$

$$I_2^2 = 2\sqrt{2}\, I_1^2$$

$$= 2 \times \sqrt{2} \times (13)^2$$

$$= 478.004.$$

$$\therefore I_2 = 21.86 \text{ A}.$$

From Equation (iv):

$$\frac{N_2}{N_2} = \frac{2I_1}{I_2}$$

$$N_2 = \frac{2I_1}{I_2} \times N_1$$

$$= 2 \times \frac{13}{21.86} \times 620$$

$$= 737.42 \text{ rpm}.$$

2. A series motor having a resistance of 0.8 Ω between its terminal drives. The torque of a fan is proportional to the square of the speed. At 220 V, its speed is 350 rpm and takes 12 A. The speed of the fan is to be raised to 400 rpm by supply voltage control. Estimate the supply voltage required.

Solution:

$R_a + R_{se} = 0.8\ \Omega$, $V_1 = 220$ V, $N_1 = 350$ rpm, $I_1 = I_{a1} = 12$ A

$N_2 = 400$ rpm.

Use the torque equation, $T \propto \phi I_a \propto I_a^2$ as $\phi \propto I_a$:

$$\frac{T_1}{T_2} = \left(\frac{I_{a1}}{I_{a2}}\right)^2 . \qquad \text{(i)}$$

Also $T \propto N^2$ (given)

$$\frac{T_1}{T_2} = \left(\frac{N_1}{N_2}\right)^2 . \qquad \text{(ii)}$$

Equating Equations (i) & (ii): $N \propto \frac{E_b}{\phi} \propto \frac{E_b}{I_a}$

$$\left(\frac{N_1}{N_2}\right)^2 = \left(\frac{I_{a1}}{I_{a2}}\right)^2$$

$$\left(\frac{350}{400}\right)^2 = \left(\frac{12}{I_{a2}}\right)^2$$

$$\therefore I_{a2} = 13.7 \text{ A.}$$

Use the speed equation

$$\frac{N_1}{N_2} = \frac{E_{b1}}{E_{b2}} \times \frac{I_{a2}}{I_{a1}} . \qquad \text{(iii)}$$

Now, $E_{b1} = V_1 - I_{a1}(R_a + R_{se})$

$= 220 - 12(0.8) = 210.4$ V.

In second case, the voltage is to be changed from V_1 to V_2.

$\therefore E_{b2} = V_2 - I_{a2}(R_a + R_{se})$

$= V_2 - 13.7(0.8) = V_2 - 10.96.$

E_{b1} and E_{b2} are substituted in Eq (iii):

$$\frac{350}{400} = \frac{210.4}{V_2 - 10.96} \times \frac{13.7}{12}$$

$$V_2 - 10.96 = 274.52$$

$$V_2 = 284.52 \text{ V.}$$

This is the new supply voltage required to raise the speed from 350 rpm to 400rpm.

3.A 230-V DC shunt motor takes a current of 20 A on a certain load. Thearmature resistance is 0.8 Ω and the field circuit resistance is 250 Ω. Find the resistance to be inserted in series with the armature to have the speed is half if the load torque is constant.

Solution:

I_{L1} = 20 A.

$$I_{sh} = \frac{V}{R_{sh}} = \frac{230}{250} = 0.92 \text{ A.}$$

$I_{a1} = I_{L1} - I_{sh}$ = 20 – 0.92 = 19.08.

$E_{b1} = V - I_{a1}R_a$ = 230 – 19.08(0.08) = 214.736 V.

T a φI_a a I_a (∵φ is constant).

$$\frac{T_1}{T_2} = \frac{I_{a1}}{I_{a2}} = 1$$ as torque is constant

$\therefore I_{a1} = I_{a2}$ = 19.08A.

R_x = external resistance in armature

$E_{b2} = V - I_{a2}(R_a + R_x$ = 230 – (19.08)(0.8 + R_x).

Now, $N \propto \frac{E_b}{\phi} \propto E_b$ (∵ ϕ is constant)

$$\therefore \frac{N_1}{N_2} = \frac{E_{b1}}{E_{b2}}$$

$$\frac{1}{0.5} = \frac{214.736}{230 - 19.08(0.8 + R_x)}$$

$$230 - 19.08\,(0.8 + R_x) = 214.736 \times 0.5 = 107.368$$

$$19.08\,(0.8 + R_x) = -\,107.368 + 230$$

$$= 122.632$$

$$0.8 + R_x = 6.43$$

$$R_x = 6.43 - 0.8$$

$$R_x = 5.62\ \Omega.$$

UNIT-5

ELECTRIC TRACTION-II

The movement of trains and their energy consumption can be most conveniently studied by means of the speed–distance and the speed–time curves. The motion of any vehicle may be at constant speed or it may consist of periodic acceleration and retardation. The speed–time curves have significant importance in traction. If the frictional resistance to the motion is known value, the energy required for motion of the vehicle can be determined from it. Moreover, this curve gives the speed at various time instants after the start of run directly.

5.1 Speed-Time Curves of Different Services

TYPES OF SERVICES

There are mainly three types of passenger services, by which the type of tractionsystem has to be selected, namely:

1. Main line service.
2. Urban or city service.
3. Suburban service.

Main line services

In the main line service, the distance between two stops is usually more than 10 km. High balancing speeds should be required. Acceleration and retardation are notso important.

Urban service

In the urban service, the distance between two stops is very less and it is less than 1km. It requires high average speed for frequent starting and stopping.

Suburban service

In the suburban service, the distance between two stations is between 1 and 8 km. This service requires rapid acceleration and retardation as frequent starting and stopping is required.

SPEED–TIME AND SPEED–DISTANCE CURVES FOR DIFFERENT SERVICES

The curve that shows the instantaneous speed of train in kmph along the ordinate and time in seconds along the abscissa is known as ‘*speed–time*’ curve.

The curve that shows the distance between two stations in km along the ordinate and time in seconds along the abscissa is known as ‘*speed–distance*’ curve.

The area under the speed–time curve gives the distance travelled during, given time internal and slope at any point on the curve toward abscissa gives the acceleration and retardation at the instance, out of the two speed–time curve is more important.

Speed–time curve for main line service

Typical speed–time curve of a train running on main line service is shown in Fig. 10.1. It mainly consists of the following time periods:

1. Constant accelerating period.
2. Acceleration on speed curve.
3. Free-running period.
4. Coasting period.
5. Braking period.

Crest speed

It is the maximum speed of train, which affects the schedule speed as for fixed acceleration, retardation, and constant distance between the stops. If the crest speed increases, the actual running time of train decreases. For the low crest speed of train it running so, the high crest speed of train will increases its schedule speed.

Duration of stops

If the duration of stops is more, then the running time of train will be less; so that,this leads to the low schedule speed.

Thus, for high schedule speed, its duration of stops must be low.

Distance between the stops

If the distance between the stops is more, then the running time of the train is less;hence, the schedule speed of train will be more.

Acceleration

If the acceleration of train increases, then the running time of the train decreases provided the distance between stops and crest speed is maintained as constant.Thus, the increase in acceleration will increase the schedule speed.

Braking retardation

High breaking retardation leads to the reduction of running time of train. These will cause high schedule speed provided the distance between the stops is small.

5.2 Trapezoidal Speed-Time Curve

Simplified speed–time curves gives the relationship between acceleration, retardation average speed, and the distance between the stop, which are needed to estimate the performance of a service at different schedule speeds. So that, the actual speed–time curves for the main line, urban, and suburban services are approximated to some from of the simplified curves. These curves may be of eithertrapezoidal or quadrilateral shape.

Trapezoidal speed–time curve can be approximated from the actual speed–timecurves of different services by assuming that:

- The acceleration and retardation periods of the simplified curve is kept same as to that of the actual curve.
- The running and coasting periods of the actual speed–time curve are replaced by the constant periods.

This known as trapezoidal approximation, a simplified trapezoidal speed–timecurve is shown in fig,

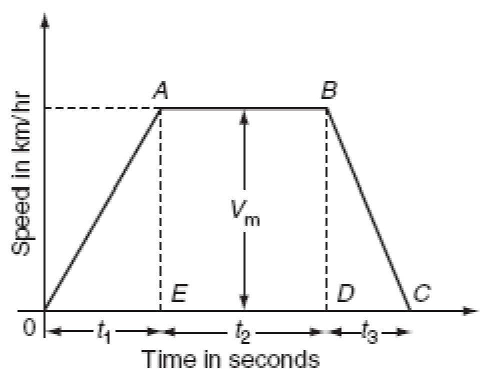


Fig. Trapezoidal speed–time curve

Calculations from the trapezoidal speed–time curve

Let D be the distance between the stops in km, T be the actual running time of train in second, α be the acceleration in km/h/sec, β be the retardation in km/h/sec, V_m be the maximum or the crest speed of train in km/h, and V_a be the average speed of train in km/h. From the Fig. 10.4:

Actual running time of train, $T = t_1 + t_2 + t_3$. **(10.1)**

Time for acceleration, $t_1 = \frac{V_m - 0}{\alpha} = \frac{V_m}{\alpha}$. **(10.2)**

Time for retardation, $t_3 = \frac{V_m - 0}{\beta} = \frac{V_m}{\beta}$. **(10.3)**

Area under the trapezoidal speed–time curve gives the total distance between thetwo stops (D).

∴ The distance between the stops (D) = area under triangle *OAE* + area ofrectangle *ABDE* + area of triangle *DBC*

= The distance travelled during acceleration + distance travelled during free-running period + distance travelled during retardation.

Now:

The distance travelled during acceleration = average speed during acceleratingperiod × time for acceleration

$$= \frac{0+V_{\text{m}}}{2} \times t_1 \text{ km/h} \times \text{sec}$$

$$= \frac{0+V_{\text{m}}}{2} \times \frac{t_1}{3,600} \text{ km.}$$

The distance travelled during free-running period = average speed × time of freerunning

$$= V_{\text{m}} \times t_2 \text{ km/h} \times \text{sec}$$

$$= V_{\text{m}} \times \frac{t_2}{3,600} \text{ km.}$$

$$= T - \left[\frac{V_{\text{m}}}{\alpha} + \frac{V_{\text{m}}}{\beta}\right]. \qquad \textbf{(10.4)}$$

The distance travelled during retardation period = average speed × time for retardation

$$= \frac{V_{\text{m}}+0}{2} \times t_3 \text{ km/h} \times \text{sec}$$

$$= \frac{0+V\text{m}}{2} \times \frac{t_3}{3,600} \text{ km.}$$

The distance between the two stops is:

$$D = \frac{V_{\text{m}} t_1}{7,200} + \frac{V_{\text{m}}}{3,600}\left[T - V_{\text{m}}(t_1 + t_2)\right] + \frac{V_{\text{m}} t_3}{7,200}$$

$$D = \frac{V_{\text{m}}^2}{7,200\alpha} + \frac{V_{\text{m}}}{3,600}\left[T - V_{\text{m}}\left(\frac{1}{\alpha} + \frac{1}{\beta}\right)\right] + \frac{V_{\text{m}}^2}{7,200\beta}$$

$$3,600 \times D = \frac{V_{\text{m}}^2}{2\alpha} + \frac{V_{\text{m}}^2}{\beta} - V_{\text{m}}^2\left(\frac{1}{\alpha} + \frac{1}{\beta}\right) + V_{\text{m}} T$$

$$3,600\ D = V_{\text{m}}^2\left(\frac{1}{2\alpha} - \frac{1}{\alpha}\right) + V_{\text{m}}^2\left(\frac{1}{2\beta} - \frac{1}{\beta}\right) + V_{\text{m}} T$$

$$3,600\ D = \frac{-V_{\text{m}}^2}{2\alpha} - \frac{V_{\text{m}}^2}{2\beta} + V_{\text{m}} T$$

$$\therefore V_{\text{m}}^2\left[\frac{1}{2\alpha} + \frac{1}{2\beta}\right] - V_{\text{m}} T + 3,600 D = 0.$$

Let $\dfrac{1}{2\alpha} + \dfrac{1}{2\beta} = X = \dfrac{\alpha + \beta}{2\alpha\beta}$

$$\therefore V_m^2 X - V_m T + 3,600D = 0. \quad \textbf{(10.5)}$$

Solving quadratic Equation (10.5), we get:

$$V_m = \frac{T + \sqrt{T^2 - 4 \times X \times 3,600D}}{2 \times X}.$$

$$= \frac{T}{2X} \pm \sqrt{\frac{T^2}{4X^2} - \frac{3,600D}{X}}.$$

By considering positive sign, we will get high values of crest speed, which ispractically not possible, so negative sign should be considered:

$$V_m = \frac{T}{2X} - \sqrt{\frac{T^2}{4X^2} - \frac{3,600D}{X}} \quad \textbf{(10.6)}$$

$$\text{Or,} \quad V_m = \frac{\alpha\beta}{\alpha+\beta}T - \sqrt{\left(\frac{\alpha\beta}{\alpha+\beta}\right)^2 T^2 - 7,200\left(\frac{\alpha\beta}{\alpha+\beta}\right)D}.$$

5.3 Quadrilateral speed–time curve

Quadrilateral speed–time curve for urban and suburban services for which the distance between two stops is less. The assumption for simplified quadrilateral speed–time curve is the initial acceleration and coasting retardation periods are extended, and there is no free-running period. Simplified quadrilateral speed–timecurve is shown in Fig. 10.5.

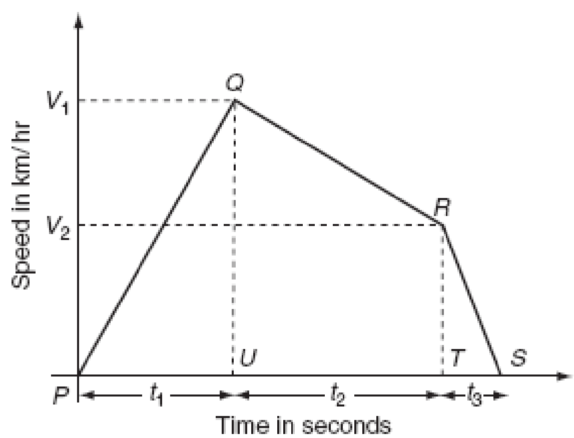


Fig. Quadrilateral speed–time curve

Let $V1$ be the speed at the end of accelerating period in km/h, $V2$ be the speed at the end of coasting retardation period in km/h, and βC be the coasting retardation in km/h/sec.

Time for acceleration, $t_1 = \frac{V_1 - 0}{\alpha} = \frac{V_1}{\alpha}.$

Time for coasting period, $t_2 = \frac{V_2 - V_1}{\beta}.$

Time period for braking retardation period, $t_3 = \frac{V_2 - 0}{\beta} = \frac{V_2}{\beta}$. Total distance travelled during the running period *D*:

= the area of triangle *PQU* + the area of rectangle *UQRS* + the area oftriangle *TRS*.

= the distance travelled during acceleration + the distance travelled duringcoastingretardation + the distance travelled during breaking retardation.

But, the distance travelled during acceleration = average speed × time foracceleration

$$= \frac{0 + V_1}{2} \times t_1 \text{ km/h} \times \text{sec}$$

$$= \frac{V_1}{2} \times \frac{t_1}{3,600} \text{km.}$$

The distance travelled during coasting retardation = $\frac{V_2 + V_1}{2} \times t_2 \text{ km/h} \times \text{sec}$

$$= \frac{V_2 + V_1}{2} \times \frac{t_2}{3,600} \text{km.}$$

The distance travelled during breaking retardation = average speed × time forbreaking retardation

$$= \frac{0 + V_2}{2} \times t_3 \text{km/h} \times \text{sec}$$

$$= \frac{V_2}{2} \times \frac{t_3}{3,600} \text{km.}$$

∴ Total distance travelled:

$$D = \frac{V_1}{2} \times \frac{t_1}{3,600} + \frac{(V_1 + V_2)}{2} \frac{(t_2)}{3,600} + \frac{V_2}{2} \times \frac{t_3}{3,600}$$

$$= \frac{V_1 t_1}{7,200} + \frac{(V_1 + V_2) t_2}{7,200} + \frac{V_2 t_3}{7,200}$$

$$= \frac{V_1}{7,200}(t_1 + t_2) + \frac{V_2}{7,200}(t_2 + t_3)$$

$$= \frac{V_1}{7,200}(T - t_3) + \frac{V_2}{7,200}(T - t_1)$$

$$= \frac{(V_1 + V_2)T}{7,200} - \frac{V_1 t_3}{7,200} - \frac{V_2 t_1}{7,200}$$

$$= \frac{(V_1 + V_2)T}{7,200} - \frac{V_1 V_2}{7,200\beta} - \frac{V_1 V_2}{7,200\alpha}$$

$$= \frac{\mathrm{T}}{7,200}(V_1 + V_2) - \frac{V_1 V_2}{7,200}\left(\frac{1}{\alpha} + \frac{1}{\beta}\right)$$

$$7,200D = (V_1 + V_2)\mathrm{T} - V_1 V_2 \left(\frac{1}{\alpha} + \frac{1}{\beta}\right). \qquad \textbf{(10.7)}$$

5.4 Numerical Problems

1:The distance between two stops is 1.2 km. A schedule speed of 40kmph is required to cover that distance. The stop is of 18-s duration. The values of the acceleration and retardation are 2 kmphp and 3 kmphp, respectively. Then, determine the maximum speed over the run. Assume a simplified trapezoidal speed–time curve.

Solution:

Acceleration α = 2.0 kmphp.
Retardation β = 3 kmphp.
Schedule speed V_S = 40 kmph.
Distance of run, D = 1.2 km.

$$\text{Schedule time, } T_s = \frac{D \times 3,600}{V_s}$$

$$= \frac{1.2 \times 3,600}{40}$$

$$= 108 \text{ s.}$$

Actual run time, $T = T_S$ – stop duration

= 108 – 18

= 90 s.

$$\text{Maximum speed } V_m = \frac{T}{2X} - \sqrt{\frac{T^2}{4X^2} - \frac{3{,}600D}{X}},$$

where

$$X = \frac{1}{2\alpha} + \frac{1}{2\beta}$$

$$= \frac{1}{2 \times 2} + \frac{1}{2 \times 3}$$

$$= 0.416.$$

$$\therefore V_m = \frac{90}{2 \times 0.416} - \sqrt{\frac{(90)^2}{4 \times (0.416)^2} - \frac{3,600 \times 1.2}{0.416}}$$

$$= 108.173 - \sqrt{(1,1701.414) - (1,0384.61)}$$

$$= 71.88 \text{ kmph.}$$

2.The speed–time curve of train carries of the following parameters:

1. Free running for 12 min.
2. Uniform acceleration of 6.5 kmphp for 20 s.
3. Uniform deceleration of 6.5 kmphp to stop the train.
4. A stop of 7 min.

Then, determine the distance between two stations, the average, and the schedulespeeds.

Solution:

Acceleration (α) = 6.5 kmphps.

Acceleration period t_1 = 20 s.

Maximum speed $V_m = \alpha t_1$

= 6.5 × 20 = 130 kmph.

Free-running time (t_2) = 12 × 60

= 720 s.

$$\text{Time for retardation, } (t_3) = \frac{V_m}{\beta}$$

$$= \frac{130}{6.5} = 20 \text{ s}.$$

The distance travelled during the acceleration period:

$$D_1 = \frac{1}{2} \frac{V_m t_1}{3,600}$$

$$= \frac{1}{2} \times \frac{130 \times 20}{3,600}$$

$$= 0.36 \text{ km.}$$

The distance travelled during the free-running period:

$$D_2 = \frac{V_m t_2}{3,600}$$

$$= \frac{130 \times 720}{3,600}$$

$$= 26 \text{ km.}$$

The distance travelled during the braking period $D_3 = \frac{V_m t_3}{7,200}$

$$= \frac{130 \times 20}{7,200}$$

$$= 0.362 \text{ km.}$$

The distance between the two stations:

$D = D1 + D2 + D3$

= 0.36 + 26 + 0.362

= 26.724 km.

$$\text{Average distance } (V_{avg}) = \frac{D \times 3600}{T}$$

$$= \frac{26.724 \times 3600}{20 + 720 + 20}$$

$$= 126.58 \text{ kmph.}$$

$$\text{Schedule speed } (V_s) = \frac{D \times 3600}{T + \text{stoptime}}$$

$$= \frac{26.724 \times 3,600}{20 + 720 + 20 + 70 \times 60}$$

$$= 81.53 \text{ kmph.}$$

3: An electric train is to have the acceleration and braking retardation of 0.6 km/hr/sec and 3 km/hr/sec, respectively. If the ratio of themaximum speed to the average speed is 1.3 and time for stop is 25 s. Then determine the schedule speed for a run of 1.6 km. Assume the simplified trapezoidal speed–time curve.

Solution:

Acceleration α = 0.6 km/hr/s.
Retardation β = 3 km/hr/s.
Distance of run D = 1.6 km.

Let the cultural time of run be 'T ' s.

$$\text{Average speed } V_a = \frac{3,600D}{T}$$

$$= \frac{3,600 \times 1.6}{T}$$

$$= \frac{5,760}{T} \text{ kmph.}$$

$$\text{Maximum speed} = 1.3V_a$$

$$= 1.3 \times \frac{5,760}{T}$$

$$= \frac{7,488}{T} \text{ km/hr}$$

$$V_m^2 \left[\frac{1}{2\alpha} + \frac{1}{2\beta}\right] - V_m\, T + 3,600 = D$$

$$V_m^2 = \frac{V_m T - 3,600D}{\left(\frac{1}{2\alpha} + \frac{1}{2\beta}\right)}$$

$$= \frac{\frac{7,488}{T} \times T - 3,600 \times 1.6}{\left(\frac{1}{2 \times 0.6} + \frac{1}{2 \times 3}\right)}$$

$$= \frac{7,488 - 5,760}{0.833 + 0.166}$$

$$= 1,729.729$$

$$\therefore V_m = 41.59 \text{ km/hr.}$$

$$\text{Average speed, } (V_a) = \frac{V_m}{1.3} = \frac{41.59}{1.3}$$

$$(V_a) = 31.9923 \text{ kmph.}$$

$$\text{Actual time of run } T = \frac{3,600D}{V_a}$$

$$= \frac{3,600 \times 1.6}{31.9923}$$

$$T = 180.0433 \text{ s.}$$

$$\text{Schedule time } T_s = \text{Actual time of run} + \text{time of stop}$$

$$= 180.0433 + 25$$

$$= 205.0433 \text{ s.}$$

$$\text{Schedule speed } V_s = \frac{D \times 3,600}{T_s}$$

$$= \frac{1.6 \times 3,600}{205.0433}$$

$$= 28.0916 \text{ kmph.}$$

5.5 Mechanics of Train Movement, Calculations of Tractive Effort

Mechanics of train movement

The essential driving mechanism of an electric locomotive is shown in Fig. 10.6. The electric locomotive consists of pinion and gear wheel meshed with the traction motor and the wheel of the locomotive. Here, the gear wheel transfers the tractive effort at the edge of the pinion to the driving wheel.

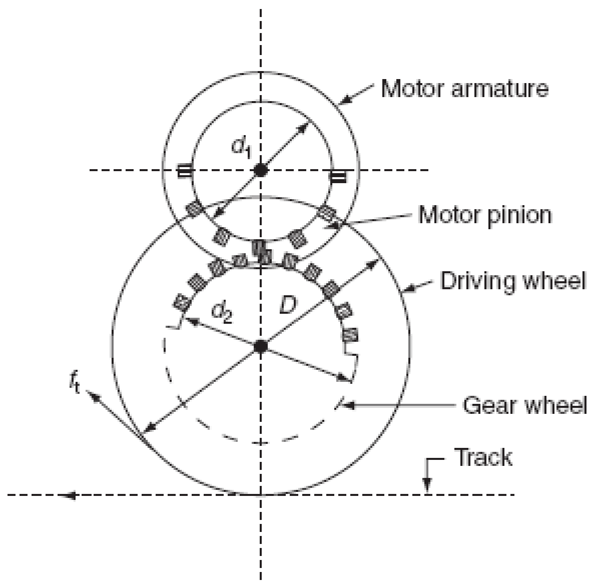


Fig. Driving mechanism of electric locomotives

Let T is the torque exerted by the motor in N-m, F_p is tractive effort at the edge of the pinion in Newton, F_t is the tractive effort at the wheel, D is the diameter of the driving wheel, d_1 and d_2 are the diameter of pinion and gear wheel, respectively, and η is the efficiency of the power transmission for the motor to the driving axle.

The tractive effort at the edge of the pinion transferred to the wheel of locomotiveis:

$$F_t = F_p \times \frac{d_2}{D} \text{ N.} \quad \textbf{(10.10)}$$

From Equations (10.9) and (10.10) $F_t = \eta \times \frac{2T}{d_1} \times \frac{d_2}{D}$

$$= \eta \cdot T \cdot \frac{2}{D}\left(\frac{d_2}{d_1}\right)$$

$$= \eta T \cdot \frac{2}{D} \cdot r,$$

Now, the torque developed by the motor $T = F_p \times \frac{d_1}{2}$ N-m.

$$\therefore F_p = \frac{2T}{d_1} \text{ N.} \quad \textbf{(10.9)}$$

where 'r'$= \left(\frac{d_2}{d_1}\right)$ is known as gear ratio.

$$\therefore F_t = 2\eta r \frac{T}{D} \text{ N.} \quad \textbf{(10.11)}$$

Calculations of Tractive Effort

TRACTIVE EEFFORT (FT)

It is the effective force acting on the wheel of locomotive, necessary to propel the train is known as '*tractive effort*'. It is denoted with the symbol F_t. The tractive effort is a vector quantity always acting tangential to the wheel of a locomotive. Itis measured in newton.

The net effective force or the total tractive effort (F_t) on the wheel of a locomotive or a train to run on the track is equals to the sum of tractive effort:

1. Required for linear and angular acceleration (F_a).
2. To overcome the effect of gravity (F_g).
3. To overcome the frictional resistance to the motion of the train (F_r).

$$\therefore F_t = F_a + F_g + F_r. \quad \textbf{(10.8)}$$

Force required for linear and angular acceleration (Fa)

According to the fundamental law of acceleration, the force required to acceleratethe motion of the body is given by:

Force = Mass × acceleration

F = *ma*.

Let the weight of train be '*W*' tons being accelerated at '*α*' kmphps:

$\therefore$ The mass of train $m = 1{,}000$ W kg.

And, the acceleration $= \alpha$ kmphps

$$= \alpha \times \frac{1{,}000}{3{,}600} \text{ m/s}^2$$

$$= 0.2788\alpha \text{ m/s}^2.$$

The tractive effort required for linear acceleration:

$$F_a = 1{,}000 \text{ W kg} \times 0.2778\alpha \text{ m/s}^2$$

$$= 27.88 \text{ W}\alpha \text{ kg} - \text{m/s}^2 \text{ (or) N.} \quad \textbf{(10.12)}$$

Equation (10.12) holds good only if the accelerating body has no rotating parts. Owing to the fact that the train has rotating parts such as motor armature, wheels,axels, and gear system. The weight of the body being accelerated including the rotating parts is known as *effective weight* or *accelerating weight*. It is denoted with 'W_e'. The accelerating weight '(W_e)' is much higher (about 8–15%) than the dead weight (W) of the train. Hence, these parts need to be given angular acceleration at the same time as the whole train is accelerated in linear direction.

∴ The tractive effort required-for linear and angular acceleration is:

$$F_a = 27.88\, W_e \alpha \text{ N}. \quad \textbf{(10.13)}$$

Tractive effort required to overcome the train resistance (Fr)

When the train is running at uniform speed on a level track, it has to overcome theopposing force due to the surface friction, i.e., the friction at various parts of the rolling stock, the fraction at the track, and also due to the wind resistance. The magnitude of the frictional resistance depends upon the shape, size, and conditionof the track and the velocity of the train, etc.

Let 'r' is the specific train resistance in N/ton of the dead weight and 'W' is thedead weight in ton.

∴ The tractive effort required to overcome the train resistance $F_r = Wr$ N. **(10.14)**

Tractive effort required to overcome the effect of gravity (Fg)

When the train is moving on up gradient as shown in Fig. 10.7, the gravity component of the dead weight opposes the motion of the train in upward direction. In order to prevent this opposition, the tractive effort should be acting in upward direction.

∴ The tractive effort required to overcome the effect of gravity:

$$F_g = \pm \text{ mg } \sin\theta \text{ N}$$
$$= \pm 1{,}000 \text{ Wg } \sin\theta \quad [\because m = 1{,}000 \text{ Wkg}]. \quad \textbf{(10.15)}$$

Now, from the Fig. 10.7:

$$\text{Gradient} = \sin\theta = \frac{BC}{AC} = \frac{\text{Elevation}}{\text{distance along the track}}$$

$$\% \text{ Gradient } G = \sin\theta \times 100. \quad \textbf{(10.16)}$$

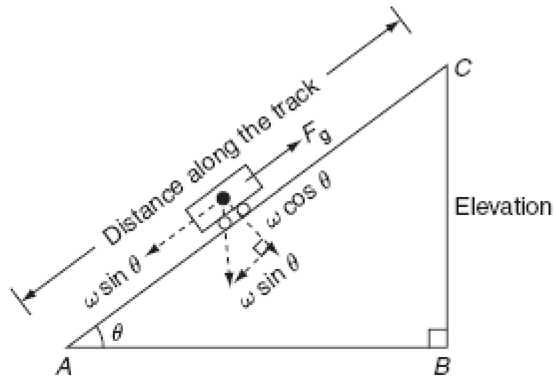


Fig. 10.7 Train moving on up gradient

From Equations (10.15) and (10.16):

$$\therefore F_g = \pm 1,000 \text{ W g} \times \frac{G}{100}$$

$$= \pm\ 10 \times 9.81 \text{ W}G$$

$$= \pm\ 98.1 \text{ W}G \text{ N} \qquad [\text{since } g = 9.81 \text{ m/s}^2]. \quad \textbf{(10.17)}$$

+ve sign for the train is moving on up gradient.

–ve sign for the train is moving on down gradient.

This is due to when the train is moving on up a gradient, the tractive effort showing Equation (10.17)will be required to oppose the force due to gravitationalforce, but while going down the gradient, the same force will be added to the totaltractive effort.

∴ The total tractive effort required for the propulsion of train $F_t = F_a + F_r \pm F_g$:

$$F_t = 277.8\ W_e\alpha + Wr \pm 98.1 \text{ W}G \text{ N}. \qquad \textbf{(10.18)}$$

5.6 Power, Specific Energy Consumption, Power output from the driving axle

Let F_t is the tractive effort in N and v is the speed of train in kmph.

∴ The power output (P) = rate of work done

$$= \text{Tractive effort} \times \frac{\text{distance}}{\text{time}}$$
$$= \text{Tractive effort} \times \text{speed}$$
$$= \frac{F_t \times \nu \times 1,000}{3,600} \text{W}$$
$$= \frac{F_t \times \nu}{3,600} \text{kW.} \qquad \textbf{(10.19)}$$

If 'v' is in m/s, then $P = F_t \times v$ W.

If 'η' is the efficiency of the gear transmission, then the power output ofmotors, $P = \frac{F_t \nu}{\eta}$ W:

:

$$= \frac{F_t \nu}{3,600\eta} \text{kW.} \qquad \textbf{(10.20)}$$

SPECIFIC ENERGY CONSUMPTION

The energy input to the motors is called the *energy consumption*. This is the energyconsumed by various parts of the train for its propulsion. The energy drawn from the distribution system should be equals to the energy consumed by the various parts of the train and the quantity of the energy required for lighting, heating, control, and braking. This quantity of energy consumed by the various parts of train per ton per kilometer is known as specific energy consumption. It is expressed in watt hours per ton per km.

$$\therefore \left.\begin{array}{r}\text{Specific energy}\\ \text{consumption}\end{array}\right\} = \frac{\text{total energy consumption in W} - \text{h}}{\text{the weight of the train in tons} \times \text{the distance covered by train in km}}$$

10.8.1 Determination of specific energy output from simplified speed–time curve

Energy output is the energy required for the propulsion of a train or vehicle is mainly for accelerating the rest to velocity 'V_m', which is the energy required to overcome the gradient and track resistance to motion.

Energy required for accelerating the train from rest to its crest speed 'Vm'

The energy required for accelerating the train = power × time

$$= \frac{\text{work done}}{\text{time}} \times \text{time}$$

$$= \text{tractive effort} \times \text{velocity} \times \text{time}$$

$$= F_t \times \frac{V_m}{3,600} \times t_1 \text{ N-km/h-sec}$$

$$= F_t \times \frac{1}{2} \times \frac{V_m}{3,200} \times \frac{t_1}{3,600} \text{ N-km (or) kW-hr}$$

$$= \frac{1}{2} \times \frac{V_m^{\ 2}}{(3,600)^2 \alpha} F_t \ \text{ kw-hr} \left[\because t_1 = \frac{V_m}{\alpha}\right]$$

$$= \frac{1}{2} \times \frac{V_m^{\ 2}}{(3,600)^2 \alpha} [277.8 W_e \alpha + 98.1\, WG + Wr] \text{kW-hr.}$$

$$[\because \ F_t = 277.8 W_e \, \alpha + 98.1 \ WG + Wr].$$

Energy required for overcoming the gradient and tracking resistance to motion

Energy required for overcoming the gradient and tracking resistance:

$$= \text{tractive effort} \times \text{velocity} \times \text{time}$$

$$= F_t' \times \frac{V_m}{3,600} \times \frac{t_2}{3,600} \text{kW-hr}$$

$$= \frac{V_m t_2}{(3,600)^2} [Wr + 98.1\, WG] \text{kW-hr,}$$

where F_t' is the tractive effort required to overcome the gradient and track resistance, *W* is the dead weight of train, *r* is the track resistance, and *G* is thepercentage gradient.

Total energy output = energy required for acceleration + energy required to overcome gradient and to resistance to motion.

$$= \frac{V_m^2}{2(3,600)^2 \alpha}[277.8\, W_e \alpha + 98.1\, WG + Wr] + \frac{V_m t_2}{(3,600)^2}[Wr + 98.1\, WG]\,\text{kW-hr}$$

$$= \frac{V_m^2(1,000)}{2(3,600)^2 \alpha}[277.8\, W_e \alpha + 98.1\, WG + Wr] + \frac{V_m t_2 \times 1,000}{(3,600)^r}[Wr + 98.1\, WG]\,\text{W-hr}$$

$$= \frac{V_m^2(1,000)}{2\alpha(3,600)^2}[27.8\, W_e \alpha] + \left[\frac{V_m^2(1,000)}{2\alpha(3,600)^2} + \frac{V_m t_2 \times 1,000}{(3,600)^2}\right][Wr + 98.1\, WG]\,\text{W-hr}$$

$$= 0.01072\ W_e V_m^2 + \frac{1,000}{(3,600)}[Wr + 98.1\, WG]\left[\frac{V_m^2}{2\alpha 3,600} + \frac{V_m t_2}{3,600}\right]\text{W-hr}$$

$$= 0.01072\ W_e V_m^2 + 0.2778[Wr + 98.1\, WG][D_1 + D_2]\,\text{W-hr},$$

where $D_1 = \frac{V_m^2}{2\alpha 3,600} = \frac{V_m^2}{7,200\alpha}$.

$D_2 = \frac{V_m t_2}{3,600}$.

$\therefore$ The specific energy output = $\frac{\text{energy output in Whr}}{\text{weight of train in tons} \times \text{distance of running}}$

$$= \frac{0.001072 V_m^2 W_e + 0.2778[98.1\, WG + Wr][D_1 + D_2]}{W \times D}$$

$$= \frac{0.001072 V_m^2}{D}\left[\frac{W_e}{W}\right] + \left[\frac{98.1\, G + r}{D}\right] \times 0.2778 \times D',$$

where $D' = D_1 + D_2$.

For uniform level track $G = 0$:

$\therefore$ The specific energy output $= \frac{0.001072 V_m^2}{D}\frac{W_e}{W} + 0.2778 r \times \frac{D'}{D}$ W-hr/ton-km.

$\therefore$ The specific energy consumption $= \frac{\text{specific energy output}}{\text{efficiency of motors}}$

$$= \frac{0.001072 V_m^2}{\eta D}\frac{W_e}{W} + 0.2778\frac{D'}{D}\frac{r}{\eta}\,\text{W-hr/ton-km.} \qquad \textbf{(10.21)}$$

Factors affecting the specific energy consumption Factors that affect

the specific energy consumption are given as follows.

Distance between stations

From equation specific energy consumption is inversely proportional to the distance between stations. Greater the distance between stops is, the lesser will bethe specific energy consumption. The typical values of the specific energy consumption is less for the main line service of 20–30 W-hr/ton-km and high for the urban and suburban services of 50–60 W-hr/ton-km.

Acceleration and retardation

For a given schedule speed, the specific energy consumption will accordingly be less for more acceleration and retardation.

Maximum speed

For a given distance between the stops, the specific energy consumption increaseswith the increase in the speed of train.

Gradient and train resistance

From the specific energy consumption, it is clear that both gradient and train resistance are proportional to the specific energy consumption. Normally, the coefficient of adhesion will be affected by the running of train, parentage gradient,condition of track, etc. for the wet and greasy track conditions. The value of thecoefficient of adhesion is much higher compared to dry and sandy conditions.

5.7 Effect of Varying Acceleration and Braking Retardation.

The effects of varying acceleration and braking retardation (deceleration) can be significant in different contexts, especially in transportation, physics, and engineering. Here’s a breakdown of their effects:

Acceleration:

1. **Motion and Velocity Changes**:
    - Acceleration directly affects how quickly an object's velocity changes over time. A higher acceleration means the object reaches a higher velocity in the same amount of time compared to lower acceleration.
    - Acceleration is a vector quantity, so its direction matters. Changes in acceleration can alter the direction of motion or the magnitude of velocity.
2. **Force and Energy**:

    - Acceleration requires force according to Newton's second law (F = ma), where 'm' is mass and 'a' is acceleration. Higher acceleration necessitates a greater force to achieve the same change in motion.
    - Acceleration also affects kinetic energy (E = 0.5 * m * v^2), where 'v' is velocity. Higher acceleration leads to quicker changes in kinetic energy.
3. **Human Factors**:
    - High accelerations can affect human passengers in vehicles or spacecraft, causing discomfort or physiological effects (e.g., G-forces experienced in aerospace).

Braking Retardation (Deceleration):

1. **Stopping Distance**:
    - Braking retardation determines how quickly an object can stop or slow down. Higher deceleration reduces the stopping distance for a given initial velocity.
    - In transportation, effective deceleration is crucial for safety and efficiency.
2. **Mechanical Stress**:
    - High deceleration imposes significant mechanical stress on braking systems and structures. This stress affects wear and tear, maintenance requirements, and the design of braking systems.
3. **Safety**:
    - In road vehicles, deceleration influences safety by affecting the time and distance required to avoid collisions. Emergency braking relies on effective deceleration.

Practical Applications:

- **Transportation**: Acceleration and deceleration are critical for vehicle performance, fuel efficiency, and passenger comfort.
- **Physics Experiments**: Controlling acceleration and deceleration precisely is essential for conducting experiments in physics, such as studying motion, forces, and energy transformations.
- **Engineering Design**: Engineers must consider acceleration and deceleration requirements when designing vehicles, machinery, and infrastructure.

5.8 General Comparison of Private Generating Plant and Public Supply

Private Generating Plant:

1. **Ownership and Control**:
    - **Ownership**: Private generating plants are owned and operated by private entities or individuals. They may range from small-scale generators (like solar panels or diesel generators at individual homes or businesses) to larger-scale facilities owned by corporations.
    - **Control**: Private generators have full control over their operations, including decisions related to maintenance, upgrades, and energy output.
2. **Cost and Investment**:

- **Initial Investment**: Setting up a private generating plant involves an initial capital investment by the owner. This can include the cost of purchasing equipment (e.g., solar panels, wind turbines, generators) and installation.
- **Operational Costs**: Owners bear the operational costs, such as fuel (for generators), maintenance, and insurance. These costs vary depending on the type and size of the plant.

3. **Flexibility and Reliability**:
    - **Flexibility**: Private generating plants offer flexibility in terms of location and technology choices. Owners can select renewable energy sources (like solar or wind) or conventional sources (like diesel or natural gas).
    - **Reliability**: Reliability can vary based on maintenance and the type of equipment used. Some private plants may experience downtime due to maintenance or fuel availability issues.
4. **Integration and Grid Connection**:
    - **Grid Connection**: Private generating plants may or may not be connected to the main electrical grid. Grid-connected plants can sell excess electricity back to the grid (net metering), providing potential revenue streams for owners.
    - **Integration Challenges**: Integration into the grid requires compliance with regulations and standards, ensuring safety and stability of the overall electrical system.

Public Supply (Utility):

1. **Ownership and Control**:
    - **Ownership**: Public supply systems are typically owned by government agencies or utilities (public or private utilities).
    - **Control**: Utility companies have centralized control over the generation, transmission, and distribution of electricity within their service areas. They operate under regulatory oversight.
2. **Cost and Investment**:
    - **Initial Investment**: Utility-scale power plants require substantial initial investment for construction, equipment, and infrastructure (e.g., transmission lines, substations).
    - **Operational Costs**: Operational costs are spread across a large customer base, covering maintenance, fuel (if applicable), labor, and compliance with regulatory standards.
3. **Reliability and Scale**:
    - **Reliability**: Public supply systems prioritize reliability through redundancy, backup systems, and grid management practices. They aim to minimize downtime and disruptions in service.
    - **Scale**: Utility-scale plants are often larger and can leverage economies of scale in generation and transmission, potentially offering more stable electricity prices.
4. **Regulation and Accessibility**:
    - **Regulation**: Public supply systems are subject to regulatory oversight to ensure safety, reliability, and fair pricing. Regulations govern aspects like emissions, customer service standards, and grid stability.
    - **Accessibility**: Public supply systems aim to provide universal access to electricity within their service territories, ensuring equitable distribution and affordability.

5.9 Initial Cost and Efficiency

Initial Cost:

1. **Private Generating Plants**:
   - **Initial Investment**: Private generating plants require upfront capital investment by the owner or entity installing the system. This includes the cost of purchasing equipment (e.g., solar panels, wind turbines, generators), inverters (for solar systems), battery storage (if applicable), and installation costs.
   - **Variability**: Costs can vary widely depending on the scale and technology chosen. Small-scale systems like residential solar panels or wind turbines may have lower initial costs compared to larger-scale systems like commercial solar farms or natural gas generators.
2. **Public Supply Systems (Utilities)**:
   - **Infrastructure Investment**: Public supply systems involve significant capital investment in infrastructure such as power plants (thermal, hydroelectric, nuclear), transmission lines, substations, and distribution networks.
   - **Economies of Scale**: Utilities benefit from economies of scale in large-scale generation and transmission infrastructure, which can spread out the initial investment costs over a large customer base.

Efficiency:

1. **Private Generating Plants**:
   - **Conversion Efficiency**: Efficiency in private generating plants refers to how effectively the system converts the primary energy source (e.g., sunlight, wind, fuel) into usable electricity. Solar panels, for instance, have a typical efficiency range of 15% to 20%.
   - **System Efficiency**: Overall system efficiency also considers factors such as energy storage losses (if batteries are used), inverter efficiency (for solar systems), and maintenance-related downtime.
2. **Public Supply Systems (Utilities)**:
   - **Generation Efficiency**: Utility-scale power plants often use efficient technologies (e.g., combined-cycle gas turbines, modern coal plants, nuclear reactors) to generate electricity. These plants can achieve high thermal efficiency, typically in the range of 30% to 60% depending on the technology.
   - **Transmission and Distribution Losses**: Efficiency in public supply systems also involves minimizing losses during transmission and distribution of electricity. Modern grid infrastructure aims to keep these losses low, typically around 5% to 10%.

5.10 Capitalization of Losses.

Capitalization of losses generally refers to the accounting treatment of losses incurred by a business or an entity. Here are a few contexts in which the term "capitalization of losses" might be used:

1. **Deferred Tax Asset**: If a business incurs a tax loss (where its tax deductions exceed its taxable income), it might create a deferred tax asset. This asset represents the future tax benefit the company expects to receive when it offsets future taxable income with the current year's losses. In this case, the losses are "capitalized" in the sense that they create a future financial benefit (the deferred tax asset).
2. **Start-up Costs and Organizational Expenses**: When a business starts, it incurs various expenses such as legal fees, registration costs, and initial marketing expenses. These expenses are often capitalized (recorded as assets) rather than expensed immediately. If the business fails or faces losses, these capitalized costs might be written off as losses, reducing the company's capitalization base.
3. **Research and Development (R&D)**: Some businesses capitalize their R&D expenses, meaning they treat them as assets on the balance sheet rather than expenses on the income statement. If these projects or initiatives fail to generate expected returns or prove unviable, the capitalized amounts may need to be written down as losses.
4. **Investment Losses**: In investment accounting, if an entity holds investments (such as stocks or bonds) that decline in value below their original purchase price and the decline is considered other-than-temporary, the entity may recognize a loss. This loss can be deducted against capital gains.