CHAPTER 9

Thermoelectric Systems for Direct Energy Conversion

9.1 INTRODUCTION

Thermoelectric, magnetohydrodynamic and thermionic systems help in direct conversion of thermal energy into electrical energy without need of any mechanical device. These systems do not have any moving parts. At the atomic scale, an applied temperature gradient causes charge carriers in the material to diffuse from hot side to cold side, thereby inducing a thermal current.

9.2 IMPORTANT PHYSICAL EFFECTS

- **Explain Seeback, Peltier and Thomson effects in relation to thermoelectric conversion.**

or

- **Discuss Peltier effect, Seeback effect and Thomson effect.**

The term "thermoelectric effect" encompasses three separately identified effects, namely, Seeback effect, Peltier effect and Thomson effect.

Seeback effect

It is the basic principle behind thermoelectric power generation. It states that whenever there exists a temperature difference between two junctions in a loop made of two dissimilar conductors, the electromotive force (emf) is produced in the loop. This type of loop is called a thermocouple. A thermocouple formed with p-type and n-type semiconductors can produce a fairly large emf. A thermocouple formed with p-type and n-type semiconductors is shown in Figure 9.1. The current flow is always in the direction of heat flow in n-type semiconductor. The amount of emf produced is always proportional to the temperature difference between the two junctions of the thermocouple. The emf produced can be given as follows:

$$E = \alpha + \Delta T$$

where α is the Seeback coefficient and ΔT is the temperature difference between the two junctions.

By measuring E, it is possible to determine the unknown temperature of hot body in reference to known temperature of cold body. This phenomenon can also be used to produce electrical energy directly from the heat of combustion and such device is called thermoelectric generator. The electric power of thermoelectric generator is given by

$$P \propto Q_{\text{input}} - Q_{\text{rejected}} = i^2 \times R$$

The thermal efficiency of thermoelectric generator is very low.

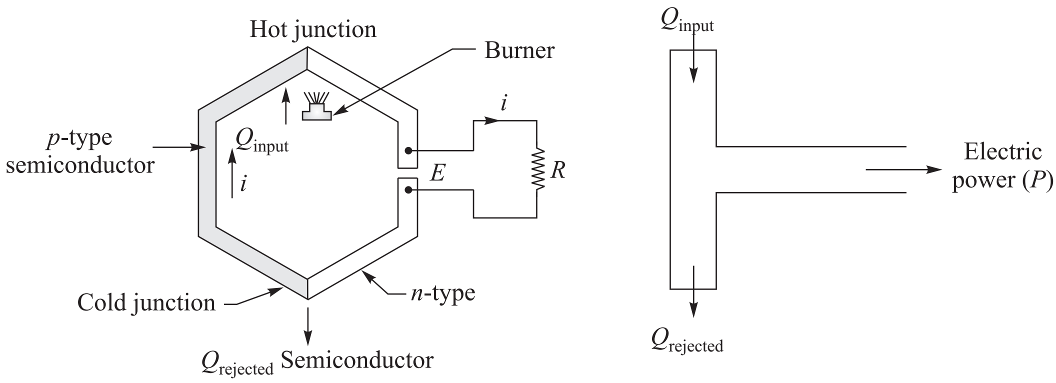

Figure 9.1 Seeback effect and the principle of thermoelectric.

Peltier effect

The Peltier effect is a temperature difference created by applying a voltage between two electrodes connected to n-type and p-type semiconductor materials. This phenomenon can be useful when it is necessary to transfer heat from one medium to another on a small scale. In a Peltier device, the electrodes are made of a metal having excellent conductivity. The semiconductor materials between the electrodes create two junctions with semiconductor materials having flow of electrons and holes with temperature gradient as shown in Figure 9.2. The movement of charge carriers creates a thermocouple voltage acting on the electrodes. This voltage difference drives current through the semiconductors, and so thermal energy starts flowing in the direction of the charge carriers. The Peltier devices can be used for thermoelectric cooling in electronic equipment and computers as other more conventional cooling methods are impractical in these devices.

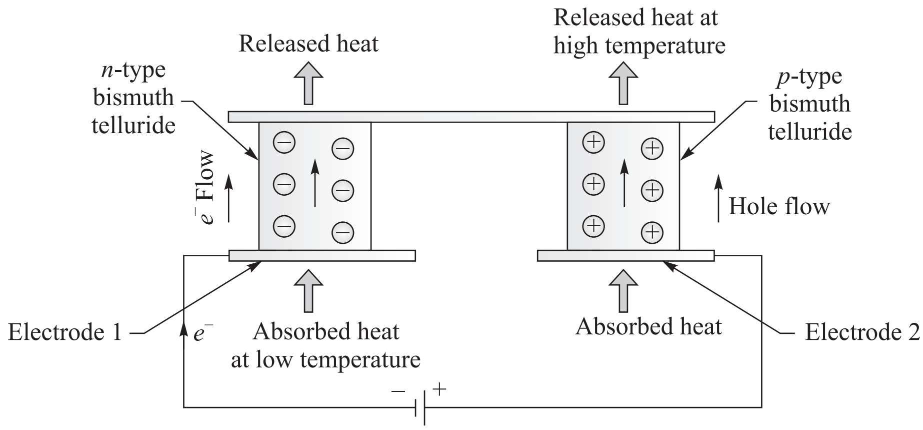

Figure 9.2 Peltier effect due to charge carriers transporting heat.

The Peltier effect can create heat flux at the junction between two different types of materials. A Peltier thermocooler or thermoheater (heat pump) is a solid–state active heat pump which transfers heat from one side of the device to the other side against the temperature gradient (from cold to hot side, that is, refrigeration effect) with consumption of electrical energy. Peltier device is a heat pump and it uses electric energy (direct current) to move heat from one side to the other. It can be used the purpose of heating or cooling. Solid-state Peltier refrigeration system based on the Peltier effect does not have any moving part.

The heat removed or absorbed at electrodes depends upon the magnitude of current and the direction of current. The heat is given by

$$Q = \alpha \times I$$

where α is the Peltier coefficient and I is the current.

Thomson effect

If a conductor has temperature gradient along its length and electric current flows through it, some heat will be absorbed or released due to the current flow. This phenomenon is called Thomson effect.

William Thomsom (Lord Kelvin) was led by thermodynamic reasoning to conclude that a source of emf exists in a thermoelectric circuit in addition to those located at the junctions. Therefore, he predicted, that an emf would also arise within a single conductor if a temperature gradient was maintained in it.

In Thomson effect, we deal only with metallic rod and not with thermocouples as in Peltier or Seeback effect. When a current flows through an unequally heated metal, an absorption or evolution of heat in the body of the metal takes place. The positive or negative Thomson effects are shown in Figure 9.3. When a rod is subjected to the steady current, heat is absorbed from the rod as current approaches the hot point and heat is evolved or transferred from the rod just beyond the hot point as shown in Figure 9.3(a). The Thomson effect is reversible as shown in Figure 9.3(b). The heat released or absorbed is given by the following relation:

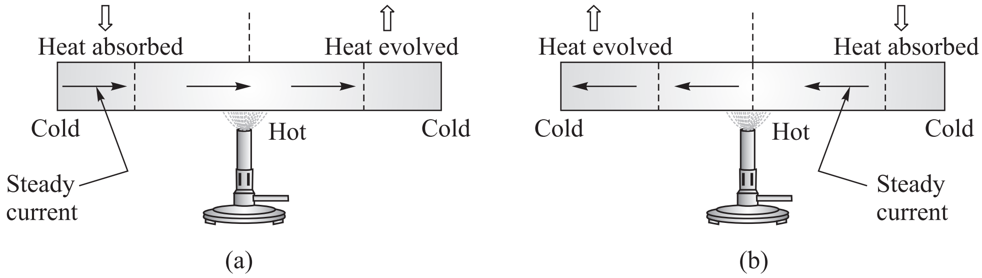

Figure 9.3 Thomson effect. (a) Positive Thomson effect and (b) Negative Thomson effect.

$$Q = I \times \int_{T_1}^{T_2} \sigma \times dT$$

where $\sigma \left(= \dfrac{dQ/dx}{dT/dx} \right)$ is the Thomson coefficient,

$\dfrac{dT}{dx}$ is the temperature gradient,

$\dfrac{dQ}{dx}$ is the heat flow per unit time and unit length and T_1 and T_2 are the temperatures at two points.

Thomson coefficient (σ) of a material is the amount of heat absorbed or released between two points of a rod having a unit temperature difference when a unit current is passed through the rod (Figure 9.4).

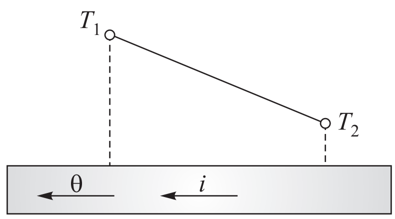

Figure 9.4 Thomson effect.

The Thomson effect can also be explained by the phenomenon in which a temperature gradient along a metallic wire or strip causes an electric potential gradient to form along its length. It is nothing but a thermoelectric conversion.

9.3 THERMOELECTRIC GENERATOR

- **Analyse the working of a thermoelectric generator. Derive an expression for its power output.**

Thermoelectric power generator consists of a number of thermocouples connected in series. The thermocouple has materials *A* and *B* which are joined to form a common hot junction while other ends are maintained at a cold temperature. According to Seeback effect, an electromotive force is generated between the cold ends. The current flow continues as long as heat is supplied to the hot junction. The power output can be measured by increasing the temperature difference between hot and cold ends. A typical thermocouple operating with hot and cold temperatures at junctions is shown in Figure 9.5 (about 800 and 200°C) and it can give output having 1 V and 2 amp (power = 0.1 × 2 = 05 W). To obtain higher output, a number of such thermocouples can be joined in series. A 1 kW device will require about 5000 such thermocouples in series (Figure 9.6).

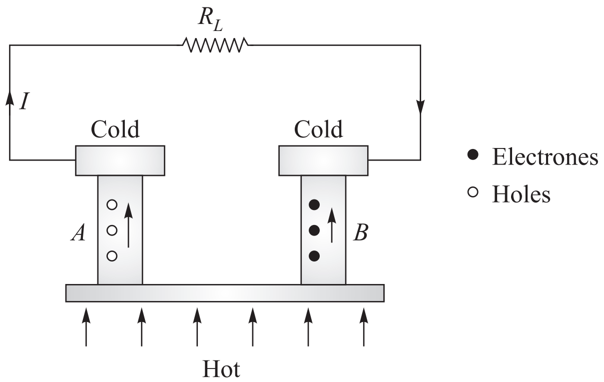

Figure 9.5 Thermocouple working.

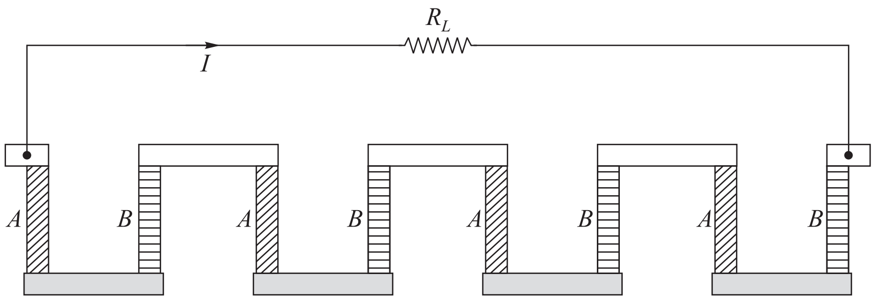

Figure 9.6 Thermocouples in series.

The open circuit emf (E) of a thermocouple consisting of A and B materials can be given by the following equation:

$$E = (\alpha_A - \alpha_B) \times \Delta T = \Delta\alpha \times \Delta T$$

where α_A is the absolute Seeback coefficient for material A,
α_B is the absolute Seeback coefficient for material B and
ΔT is the difference of temperatures at junctions.

If R_i and R_L are the internal and external resistances, power output (P) is given by

$$P = E \times I - I^2 \times R_i = I^2 \times R_L$$

$$= (\Delta\alpha \times \Delta T) \times I - I^2R_i = I^2R_L \qquad \text{(i)}$$

For maximum power output,

$$R_i = R_L \text{ and putting in equation (i)}$$

$$\therefore \qquad (\Delta\alpha \times \Delta T) \times I - I^2 R_i = I^2 \times R_i$$

or

$$I = \frac{(\Delta\alpha \times \Delta T)}{2 \times R_i}$$

Maximum output power is given by

$$P_{\max} = I^2 \times R_i$$

$$= \frac{(\Delta\alpha \times \Delta T)^2}{4R_i}$$

9.3.1 Materials for a Thermoelectric Generator

- **What are the properties of materials used in a thermoelectric generator?**

The properties required in a material used in the thermoelectric generator are as follows:

(i) It should be capable to withstand high temperatures.
(ii) Its thermal conductivity should be small.
(iii) It must have high mobility for charge carriers.
(iv) It can be a semiconductor of *n*-type and *p*-type.
(v) It should have low ionization energy.
(vi) It should have high corrosion resistance.

9.3.2 Characteristics of a Thermoelectric Generator

- **What are the characteristics of the thermoelectric generator?**

The characteristics of a thermoelectric generator are as follows:

(i) It has no moving parts.
(ii) It can be used in remote areas.
(iii) It can be used for aerospace applications.
(iv) It can be used as a system for waste heat recovery.
(v) It has low thermal efficiency.

9.3.3 Applications of a Thermoelectric Generator

- **Discuss the applications of a thermoelectric generator.**

The applications of a thermoelectric generator are as follows:

(i) Thermoelectric generator can be used with fuel elements of the nuclear reactor to obtain additional power.
(ii) Thermoelectric generator can also be used with steam power plant for obtaining higher efficiency.
(iii) Thermoelectric generator can be used to produce electricity using the waste heat from gas turbines, diesel engines and stack gases.

9.4.8 Materials for MHD Generators

- **What are the requirements of materials used in an MHD generator?**

The requirements of materials are as follows:

(a) **Electrodes**

(i) Should have high conductivity
(ii) Structurally stable at high temperature
(iii) Carbides, silicides and borides are used

(b) **Duct liner**

(i) Should be electrical insulator
(ii) Must be thermal insulator
(iii) Al_2O_3MgO and $MgAl_2O_3$ are used

(c) **Magnet**

(i) Stronger than permanent magnet or ferromagnet
(ii) Materials to have high melting point
(iii) Water–cooled electromagnets
(iv) Cryogenically cooled electromagnet
(v) Superconducting magnets.

9.5 THERMIONIC POWER CONVERSION

- **What do you understand by thermionic emission effect? Also, describe the working and construction details of a basic thermionic generator.**

A thermionic generator consists of two metals (called electrodes) which have different values of work function (work function is the energy needed to overcome the force of attraction acting on an electron in order to make it free). These metallic electrodes are sealed into an evacuated glass vessel. The electrode with the larger value of work function is maintained at a higher temperature compared to the electrode having the lower value of work of function. The hot electrode can now emit electrons due to supplied heat energy, and therefore this electrode is called emitter. The colder electrode can collect electrons, and therefore it is called collector. The emitter becomes positive on emitting electrons while the collector becomes negative due to collection of electrons. Owing to collection of charges, a voltage is developed between the electrodes and a direct current starts flowing in any external circuit connecting the electrodes. The developed voltage depends on the difference of work functions of the metal electrodes. The heat energy at the emitter must be sufficient to free electrons from the emitter surface, that is, more than the work function of the emitter electrode. When these electrons strike the collector, their kinetic energy must be higher than the work function of the collector so that electrons can be absorbed in the collector. The heat of absorption must be released from the low-temperature collector. The absorbed electrons cause higher energy level at collector than that at emitter, and so a potential difference is developed between collector and emitter, forcing electrons to move from collector to emitter through an external circuit with load. The output power depends on emitter temperature and work function magnitude between emitter and collector. Thermal efficiency of a thermionic power conversion system is in the range of 5–25% (Figure 9.12).

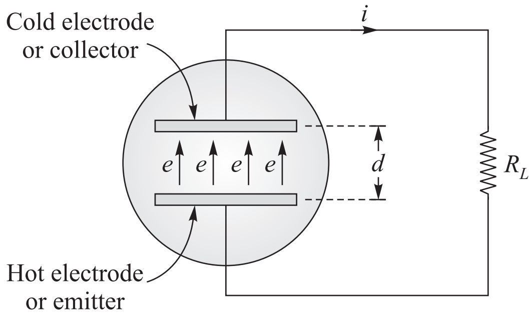

Figure 9.12 Principle of working of a thermionic converter.

The emission of electrons from emitter to collector is found to be inhibited by space charge created in the gap between emitter and collector. The space charge can be reduced by decreasing the gap and introducing a small quantity of cesium in the gap, which has low ionization potential.

9.5.1 Merits of Thermionic Converter

- **Mention the merits of a thermionic converter.**

The merits of a thermionic converter are as follows:

(i) It has no moving part.
(ii) It has quiet operation.
(iii) It has a long operation life.
(iv) It is reliable in operation.
(v) It has high power density.
(vi) It needs moderately high temperature difference between electrodes.
(vii) It can develop sufficiently low to high power when used in series.
(viii) It has comparatively low cost.
(ix) It has reasonable efficiency.
(x) It can withstand harsh environments.
(xi) It is more suitable at high temperatures compared to a thermoelectric converter.
(xii) Its efficiency increases with the increase in temperature.

9.5.2 Applications of the Thermionic Converter

- **What are the potential applications of thermionic converters?**

The thermionic converters can be used for harnessing primary heat and waste heat. The corresponding systems are based on cycles which are called topping cycle and bottoming cycle respectively. The applications of the thermionic converter are as follow:

(i) It can be used as a topping cycle system with a solar collector to generate electricity instead of a solar photovoltaic system. It can convert 20–25% solar energy into electricity and the rest of energy can be used as thermal energy for water or space heating in residential buildings.
(ii) It can also be used to harness primary heat utilising gas, oil or other fuels to generate electric power.
(iii) It has high power to weight ratio with low noise. It has great potential to be used in aerospace and military installations.
(iv) It can easily be used for portable power generation.
(v) It can be used to harness waste heat of various propulsion systems.
(vi) It can be used with conventional power plants to increase their efficiencies without any additional chemical emission.

CHAPTER 6

WIND ENERGY

6.1 INTRODUCTION

Wind is essentially air in motion. Hence, air has wind energy because air is in motion. The amount of energy available in the wind at any instant is proportional to cube power of the wind speed. Wind energy is in fact an indirect form of solar energy. A small part of solar radiation reaching the earth is converted into wind energy. Air motion or wind is generated owing to the differential heating of earth (and its atmosphere) by the sun. Wind energy is harnessed as mechanical energy with the help of windmill or turbine. The mechanical energy obtained from wind can be used to operate either mechanical devices such as water pumps and farm appliances or electric generators to generate electricity. Slow and strong winds cannot be utilized. Moderate to high speed winds having speed about 5–25 m/s are suitable to operate wind turbines. Hence, some storage device of wind energy is needed to meet the power requirement when wind turbine cannot operate during unfavourable wind conditions. The idea of harnessing wind energy is not new. It was one of the first natural energy sources to be used by mankind. Wind energy was even used to run water pumps, grind grains and sail ships about 5000 years ago.

6.2 ORIGIN OF WINDS

The winds can be classified as:

- Global winds
- Local winds

6.2.1 Global Winds

- **With the helps of a diagram, indicate the circulation of global winds. What are forces responsible for determining the speed and direction of global winds?**

The primary force for global winds is produced due to differential heating of the earth surface at equator (0° longitudes) and polar regions (about ± 90° longitude). More heating takes place near the regions of equator and less heating occurs at polar regions, and so cold winds move from polar to equatorial regions. The air in touch with ocean water is much colder than air in the plain areas, and so cold winds generated from ocean areas move towards plain areas.

The rotation of the earth on its axis produces Coriolis force and this force is responsible for forcing the global winds towards westernly direction. These air currents are also called trade winds as sailing ships in the past used these air currents for ship movement and trading. The global winds and circulations are shown in Figure 6.1.

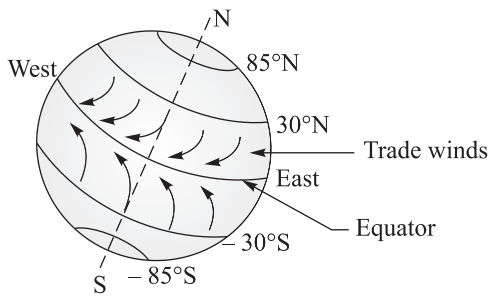

Figure 6.1 Global winds and their circulations.

6.2.2 Local Winds

- **Explain the mechanism of production of local winds.**

Local winds are generated due to uneven heating. Uneven heating occurs on land surface and water bodies due to solar radiation. As a result, cool and heavy air currents move from water bodies to land surface. At night, the direction of wind is reversed as land surface cools more rapidly than water bodies. The same conditions also prevail in hilly areas where hill slope heats up during the day and cools down during the night more rapidly than the low land. This temperature difference causes air currents to move to the hill slope during the day and to the low-lying land during night.

6.2.3 Distribution of Wind Energy

- **What are the factors responsible for distribution of wind energy on the surface of earth?**

The factors affecting the distribution of wind energy are as follows:

(i) The chain of mountains channelise the air currents
(ii) The hills, trees and building act as obstructions and change the direction of airflow

(iii) The frictional effect of the surface determines the wind speed. This is the reason why wind speed is quite high at seashore as frictional effect is less on smooth surface or sea surface.
(iv) Climatic disturbances resulting from rains affect wind speed.
(v) Topography of an area also affects wind speed, for example, wind can speed up when passing through narrow gap such as mountains gaps.

6.2.4 Nature of Wind

- **What do you understand by the behaviour and structure of wind?**

or

- **What are Beaufort numbers?**

Before installation of a wind turbine, it is essential to have full knowledge of the behaviour and structure of wind. The winds vary from place to place. The nature of wind at a site depends upon general climate of the region, physical geometry of the locality and terrain around the site. The wind intensity can be described by Beaufort number as per wind speed as given in Table 6.1.

TABLE 6.1 Wind description and Beaufort number

Beaufort number	*Wind description*	*Characteristics*	*Wind speed* (m/s)
1	More light	Smoke drifts	0.4–1.8
2	Less light	Slight movement of leaves	1.6–3.6
3	Light	Flag starts fluttering	3.6–5
4	Moderate	Moving of small branches of tree	5.8–6.5
6	Strong	Large branches sway	11–14
8	Gale	Twigs breaking off from trees	17–21
10	Strong gale	Trees are uprooted	25–29
12	Hurricane	Extensive damage to all structures	> 34

6.2.5 Meterological Data about Wind Speed

- **What do you understand by meteorological data on wind speed?**

or

- **What principles are used for measurement of wind speed?**

or

- **What is the standard height for the measurement of wind speed?**

or

- **What are the advantages of presenting wind data in the form of a wind rose?**

Every country has its meteorological department to record and publish weather data along with wind speed and direction prevalent at all places in the country. The wind speeds are recorded at three heights which are 10, 50 and 150 m during strong winds. These records are used to specify the nature of winds in these regions. The wind speed are measured using an instrument called anemometer and wind direction is measured using a wind vane or cock.

A typical anemograph consisting of wind speeds recorded at three heights during strong winds is shown in Figure 6.2. Following are the conclusions which can be drawn from this anemograph:

- Wind speeds are more at greater heights
- Wind speeds at all heights fluctuate or change with time
- The fluctuation of wind speeds can be high.

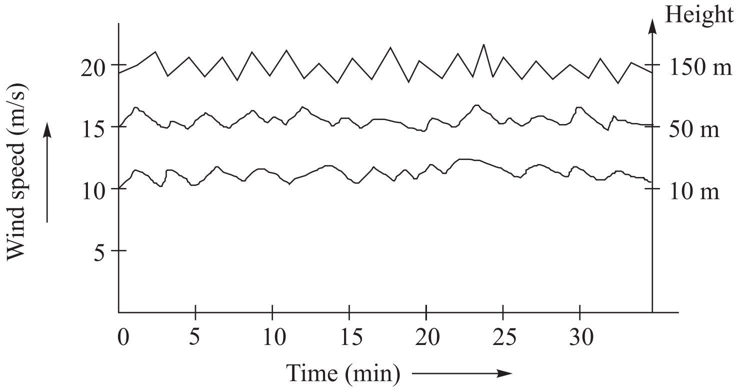

Figure 6.2 Anemograph of wind speeds at three heights.

Anemometer

It is a device to measure wind speeds. It can work using any of the following principles:

(i) When a swinging plate hinges along its top edge is hung vertically, the angle of deflection of the plate with respect to vertical axis is an indicator of wind speed.

(ii) When three or four cups are mounted symmetrically about a vertical axis, the speed of rotation of these cups is an indicator of wind speed.

(iii) When flat plate stops the wind, the wind pressure at the plate increases. The measured wind pressure is an indicator of wind speed.

(iv) When wind passes on a hot wire, the wire gets cooled depending upon the wind speed. By recording the cooling effect of the wind on hot wire, the wind speed can be determined.

(v) It is observed that wind with different speeds can create different sonic effects which can be recorded to determine wind speeds.

(vi) Use of laser technique with Doppler effect can help in determining wind speed.

Wind rose

The wind speed is measured and recorded at an effective height of 10 m from the ground. Wind rose is drawn showing mean wind speeds based on averaging period which may vary from 10 min to 1 h. The mean wind speed, its duration and its direction are depicted on a single graph as shown in Figure 6.3. The wind rose shows compass bearing from which the wind arrives (from all 6 directions) along with mean wind speed and duration in a year. The lengths of bars are drawn suitably to represent the percentage of duration of wind.

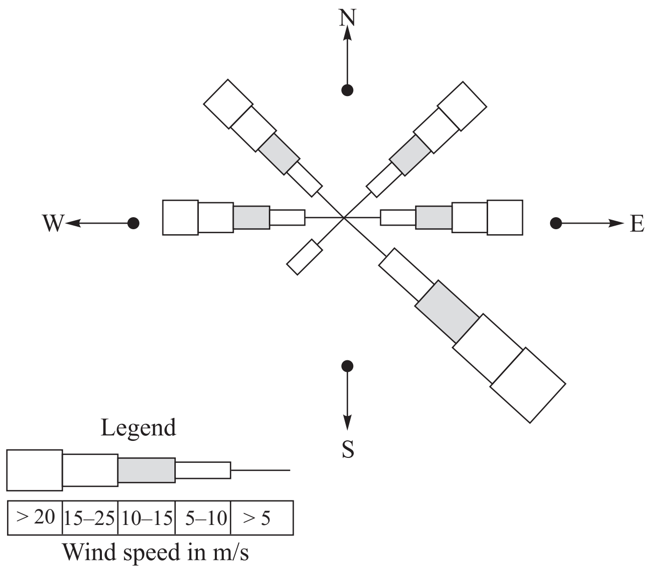

Figure 6.3 Wind rose describing mean wind speeds.

6.2.6 Wind Speed Variations with Height

- **With the help of a diagram, explain the variation of wind speed with height from the ground.**

or

- **Explain the terms (i) wind shear, (ii) gradient height, (iii) free atmosphere, (iv) planetary boundary, (v) surface layer and (vi) Ekman layer.**

Wind speed falls almost to zero at earth's surface and it increases as its height increases from the ground.

Wind shear

The rate of change of wind speed with height is called wind shear. The lower air layers moving slowly tends to retard air layer above them, resulting in the change in mean wind speed with height.

Gradient height

The wind speed increases as height increases because shear force reduces with height. At a certain height, the shear force reduces to zero and wind speed does not change above this height. This height is called the gradient height.

Free atmosphere

The gradient height is generally about 2000 m from the ground. Above this gradient height, any change in the ground conditions does not affect the wind speed; that is, wind speed is uniform above the gradient height. This atmosphere with uniform wind speed is called the free atmosphere.

Planetary boundary layer

The layer of air from ground to the gradient height is called the planetary boundary layer.

Surface layer

It is the air layer considered from the height of local obstruction to a height of about 100 m.

Ekman layer

It is the air layer from surface layer (100 m) that extends up to the gradient height. The variation of shear stress can be neglected in this layer, and the mean wind speed with height can be given by Prandtl logarithmic law:

$$u_z = V \log_e \frac{z-d}{z}$$

where u_z is the mean wind speed, V is the characteristic speed, z_0 is the roughness height of surface and d is the zero plane displacement.

The variation of mean wind speed with height is as shown in Figure 6.4.

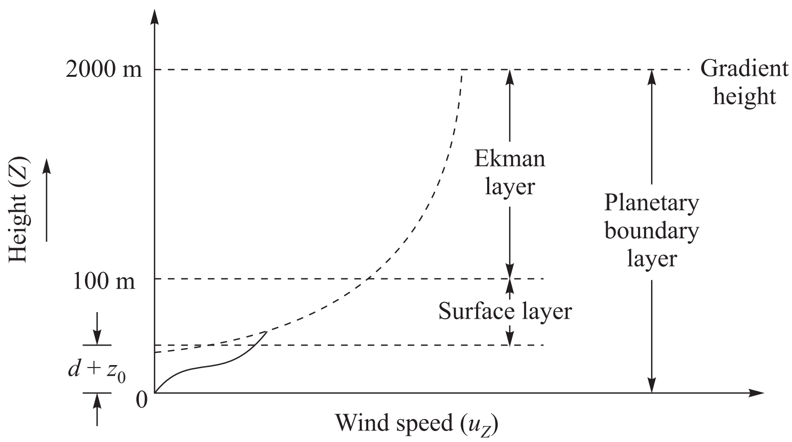

Figure 6.4 Logarithmic variation of wind speed with height.

As the wind speed is measured at a height of 10 m from the ground and also wind turbines are operated at a height of more than 10 m, a simpler empirical relation can be used to determine mean wind velocity at other heights, which is as follows:

$$u_z = u_H \left(\frac{z}{H}\right)^{\alpha}$$

where u_H is the wind velocity at the reference height H or 10 m,
α is the parameter that depends upon roughness and range of height (z) and
z is the height of the wind turbine.

6.3 WIND TURBINE SITING

- **What are the most favourable sites for installing wind turbines?**

or

- **Write criteria for site selection for setting up a wind farm.**

or

- **Describe the main consideration for selecting a site for wind generator.**

or

- **What are the criteria for site selection of a windmill?**

The main considerations for selecting a site for wind generator are as follows:

(i) **High annual mean wind speed.** A basic requirement for a successful use of a windmill or farm is an adequate supply of wind and good wind speeds. The wind power is proportional to the cubic power of wind speed.

(ii) **No obstruction.** There should not be any high structure to obstruct wind for a distance of 3 km to the windmilll.

(iii) **Open plain.** The site should be the open plain such as open sea shoreline where strong winds prevail.

(iv) **Height.** The wind speed increases with height, which can be obtained when the windmill is located on a hill or a ridge with gentle slope.

(v) **Near lake or ocean.** Differential heating of water and land generates wind of sufficient speeds.

(vi) **Topography.** Topography such as mountain gap helps to channelise and speed up winds.

(vii) **Favourable land cost.** It helps in restriction or reducing the cost of project.

(viii) **Nearness to load centre.** It reduces the cost of transmission of the generated power.

(ix) **Nearness to road or rail link.** It helps in installation of windmill.

(x) **Availability of wind rose.** It helps in designing of windmill as wind data of the site can be determined.

6.4 WIND TURBINE AERODYNAMICS

Wind carries with it kinetic energy. This wind energy is extracted when the direction of motion of wind is changed in accordance with the Newton's second law of motion; that is, the change of momentum of any body is equal to the force acting on it. The amount of energy extracted depends the amount of energy available in the wind on account of its speed.

6.4.1 Energy Available in Wind

- **Derive an expression for the total power of a wind stream.**

The wind has kinetic on account of its motion. This kinetic energy can be given by the following equation:

$$KE = P_0 = \frac{1}{2} \times \dot{m} u_0^2 \tag{6.1}$$

where $\dot{m}$ is the mass of air passing through an area A per unit time and
u_0 is the speed of free wind.

The mass of wind can be given as:

$$\dot{m} = \rho A u_0 \tag{6.2}$$

where ρ is the density of air. From Eqs. (6.1) and (6.2), we have

$$P_0 = \frac{1}{2} (\rho A u_0) u_0^2$$

$$= \frac{1}{2} \rho A u_0^3$$

or

$$\frac{P_0}{A} = \frac{1}{2} \rho u_0^3$$

The above relation indicates that the power available in wind per unit area is proportional to the cubic power of its speed.

6.4.2 Terms and Definitions of Fluid Mechanics

- **Discuss the following parameters used in rotor design: (i) rotor, (ii) solidity and (iii) tip speed ratio.**

or

- **With the help of a diagram, explain the terms free and relative wind velocities, drag and lift forces, solidity, pitch angle and chord.**

Rotor

The wind turbine extracts energy from the wind streams by transforming the kinetic energy of the wind into the rotational motion of the rotor of the wind turbine. The wind energy is extracted by the rotor of wind turbine as it has one, two or three blades having aerofoil shape and these blades are attached to hub. The wind moving over the surface of blades (aerofoils) attached to the rotor generates the requisite forces to turn the rotor.

Solidity

It is defined as the ratio of the projected area of the rotor blades on the rotor plane to the swept area of the rotor. High-solidity rotors use drag force for rotation and these rotors turn slower. Low-solidity rotors have slender aerofoil blades and these rotors use lift force for rotation. They turn faster.

Chord

It is the width of the blade which is across distance from one edge of the blade to the other edge as shown in Figure 6.5.

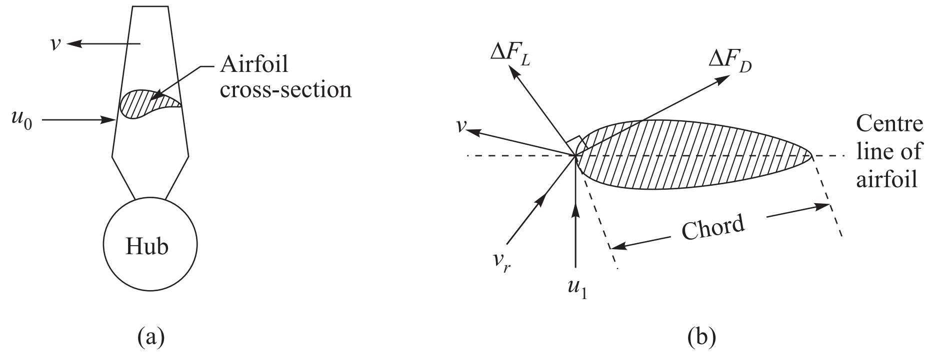

Figure 6.5 Rotor blade and its cross-section. (a) Rotor blade and (b) Aerofoil shape of blade's cross-section.

Different velocities

Various velocities are as follows:

(i) **Wind velocity (u_0).** The velocity of free air stream at sufficient distance away from wind turbine where there is no disturbance due to rotation of the wind turbine.

(ii) **Incident wind velocity (u_0).** It is the velocity at which the wind strikes the blade. This velocity is always slightly lower than the free air stream velocity (u_0).

(iii) **Blade linear velocity (v).** It is the tangential velocity of the blade due to the rotation of blade. If ω is the angular velocity of the blade and R is the length of the blade, then blade linear velocity $v = \omega \times R$.

(iv) **Relative velocity (v_r).** It is the relative velocity of wind with respect to the moving blade. It is the vector sum of incident wind velocity (u_1) and blade linear velocity (v). Mathematically, it can be given as:

$$\vec{v_r} = \vec{u_1} + \vec{v}$$

Angle of attack or angle of incidence (α)

It is the angle between the centreline of the aerofoil (blade cross-section and the relative wind velocity v_r) as shown in Figure 6.6. The airflow remains attached to the aerofoil for small angle of attack. The airflow is separated from the aerofoil for large angles of attack.

Pitch angle or blade setting angle (γ)

It is the angle between the centreline of the aerofoil and the direction of linear motion of the blade. The output of a turbine is greatly influenced by blade pitch angle. The blade pitch control is a very effective way to control. The output power, speed or torque of the turbine.

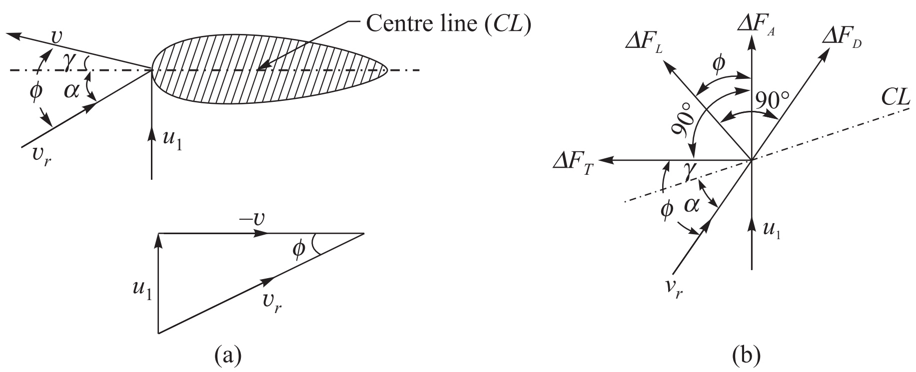

Figure 6.6 Velocities and forces acting on aerofoil (a) Various velocities and angles of aerofoils, (b) Various forces on aerofoil.

Drag force (ΔF_D)

When a body (aerofoil) is placed in uniform airflow, there are two forces acting on the body, namely, pressure force acting normally to the surface of the body, and shear force acting along the surface of the body. The pressure force and shear force can be combined to give the total force exerted by the wind on the body. This total force can be now resolved in the direction parallel to airflow and perpendicular to the airflow. The component of total force parallel to the direction of airflow is called drag force. The drag force always opposes the relative motion between the body and the air. It is given by the following equation:

$$\text{Drag} = \Delta F_D = C_D \times \frac{1}{2}\rho u_1^2 \cdot A$$

where C_D is the drag coefficient and
A is the projected area of the body aerofoil perpendicular the direction of airflow.

Lift force (ΔF_L)

The component of the total force (pressure force and shear force) on the body in the direction perpendicular to airflow is called lift force. As the name suggests, this force tries to lift the body. It is given by the following equation:

$$\text{Lift} = \Delta F_L = C_L \times \frac{1}{2}\rho \cdot u_1^2 \cdot A$$

where C_L is the lift coefficient.

Axial force (ΔF_A)

The total force (pressure force and shear force) can also be resolved along the axis of rotation of blade and perpendicular to it (tangential force on the blade). The component of total force acting on the blade along the axis of rotation of the blade is called the axial force. The axial force does not contribute to the rotation of the blade. It is also called thrust force and has to be balanced by a suitable reaction force generated by any thrust bearing provided on a rotor. The axial force contributes to waste energy which cannot be extracted from wind energy. Hence, axial force should be as less as possible. The axial force can be given as follows:

$$\Delta F_A = \Delta F_L \cos \phi + \Delta F_D \sin \phi$$

where $$\phi = \alpha + \gamma .$$

Tangential force (ΔF_T)

It is the component of total force on the blade acting tangential to its circular path of rotation. This is the force which contributes mainly to the useful energy extracted from the wind energy. It should be as high as possible. It is given by:

$$\Delta F_T = \Delta F_L \sin \phi - \Delta F_D \cos \phi$$

Tip speed ratio (λ)

The tip speed ratio is defined as the ratio of the speed of tip of the rotor blade to the speed of on coming air. Hence, tip speed ratio is:

$$\lambda = \frac{\omega \times R}{u_0}$$

For a particular wind speed, there exists an optimum turbine tip speed to produce the maximum output. It is important to match the rotation of wind turbine to the corresponding wind speed.

- **A windmill has rotor of 6 m with 30 blades. Each blade has width of 0.30 m, find the solidity. What is the implication of solidity?**

$$\text{Solidity} = \frac{\text{Projected area of blades}}{\text{Swept area}}$$

$$\text{Solidity} = \frac{30 \times 0.30}{\pi \times 6^2} \times 100\%$$

$$= 7.96\%$$

The greater is the solidity of a rotor, the slower it needs to turn to intercept the wind. When windwill has a lesser number of blades, it needs to rotate fast to intercept the wind so that wind should not be lost through the large gap existing between two blades without importing a part of wind power.

- **Find the tip-speed ratio if a 6 m diameter rotor has rotation of 20 rpm and the wind speed is 4 m/s. What is the implication of tip speed ratio?**

$$\text{Tip speed ratio} = \frac{W.R}{u_0}$$

$$\text{Tip speed ratio} = \frac{\frac{\pi R N}{60}}{4}$$

$$= \frac{\pi \times 6 \times 20}{60 \times 4} = 1.6$$

The windmill rotating fast has tip speed ratio greater than 1. Two or three-bladed rotors rotate faster, thereby having tip speed ratio ranging from 3 to 10. More bladed rotors rotate move slowly, thereby having tip speed ratio between 1 and 2.

6.4.3 Principle of Power Generation

- **How energy from wind can be extracted? Explain the process by using suitable diagram.**

or

- **Explain the principle of wind energy conversion.**

or

- **Explain Betz model of expanding airstream tube to determine extraction of wind energy by windmill.**

Wind turbine is used to extract useful energy from wind. The energy can be extracted by partially decelerating and expanding the airstream (reduction of pressure) using wind turbine. The rotor of the wind turbine collects wind from the whole area swept by the rotor. The area swept can be considered as airstream tube which is continuously expanding as shown in Figure 6.7. This airstream tube model is also called Betz model of expanding air. As air mass flow rate should be the same everywhere within the stream tube according to the Law of Continuity, the wind speed must decrease as air expands. As shown, airstream tube has area of A_0 at upstream, area of A_1 while passing through rotor blade (aerofoil) and area A_2 downstream.

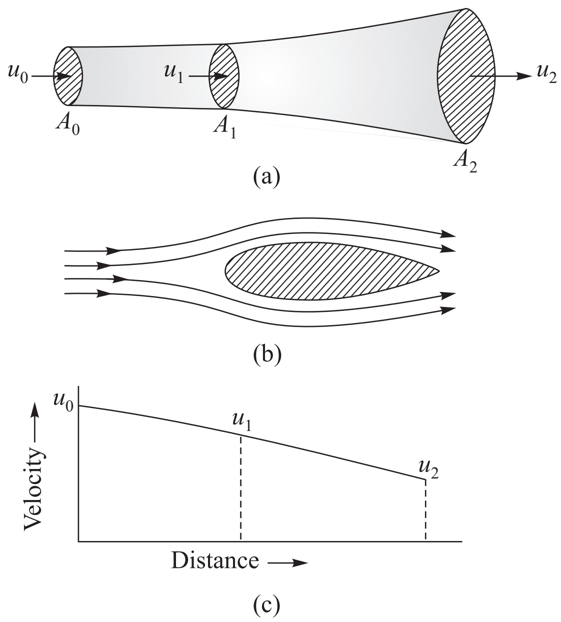

Figure 6.7 Extraction of wind energy and Betz model of expanding air. (a) Airstream tube, (b) Airstream on aerofoil, (c) Variation of wind velocity.

Consider that u_0 and u_2 are wind velocities at upstream and downstream. The velocity reduction from u_0 to u_2 means that there is a reduction in momentum of the wind as it passes through the wind turbine, resulting in a force being exerted on the blade of rotor, which is given by the following equation:

$$\text{Force} = F = \dot{m} \times u_0 - \dot{m} \times u_2 = \dot{m}\,(u_0 - u_2)$$

where $\dot{m}$ is the air mass flow per unit time through stream tube.

The above force is exerted at a uniform rate when airflow moves over the rotor blade with velocity of u_1. Therefore, the power extracted is equal to the work done by the airstream in moving for a distance of u_1 against force of F, which is given by:

$$\text{Power of turbine} = P_T = F \times u_1$$

or

$$P_T = \dot{m}\;(u_0 - u_2) \times u_1 \tag{6.3}$$

The power extracted by the wind turbine from the wind is also equal to the change or loss of kinetic energy of the wind.

$$\Delta KE = P_W = \frac{1}{2}\,\dot{m}\;(u_0^2 - u_2^2) \tag{6.4}$$

Now the energy extracted is equal to the energy lost by wind:

$$P_T = P_W$$

$$m\;(u_0 - u_2) \times u_1 = \frac{1}{2}\,\dot{m}\;(u_0^2 - u_2^2)$$

or

$$u_1 = \frac{u_0 + u_2}{2}$$

The above relation indicates that turbine velocity u_1 is the average of the entrance and exit velocities of stream tube. Putting the value of u_1 in Eq. (6.3), we get

$$P_T = \dot{m}\;(u_0 - u_2)\frac{(u_0 + u_2)}{2}$$

$$= \frac{1}{2} \times \dot{m} \times (u_0^2 - u_2^2) \tag{6.5}$$

The mass flow ($\dot{m}$) can be given as the product of area, velocity and density. Hence,

$$\dot{m} = A_1 \times u_1 \times \rho$$

$$= A_1 \times \frac{(u_0 + u_2)}{2} \times \rho \tag{6.6}$$

From Eqs. (6.5) and (6.6), we have

$$P_T = \frac{1}{4} \times A_1 \times \rho \times (u_0^2 - u_2^2)(u_0 + u_2)$$

Now suppose we have interference factor a, which is given by:

$$a = \frac{u_0 - u_1}{u_0}$$

Then $$u_1 = (1 - a) \times u_0$$

Also, $$a = 1 - \frac{u_1}{u_0} = 1 - \frac{u_0 + u_2}{2 \times u_0}$$

$$= \frac{u_0 - u_2}{2 \times u_0}$$

And $$u_2 = (1 - 2a) \times u_0$$

Then we have extracted turbine power as:

$$P_T = \frac{1}{4} \times A_1 \times \rho \times (2 \times a \times u_0)\ [u_0 + (1 - 2a)\ u_0]^2$$

$$= \frac{1}{2} \times A_1 \rho \times a \times u_0 \times u_0^2 \times 4\ (1 - a)^2$$

$$= 2 \times A_1 \rho \times a\ (1 - a)^2 \times u_0^3$$

$$= 4 \times a \times (1 - a)^2 \left[\frac{1}{2} \rho \times A_1 \times u_0^3\right] \tag{6.7}$$

But wind power is given by:

$$P_W = \frac{1}{2} \times \rho \times A_1 \times u_0^3 \tag{6.8}$$

From Eqs. (6.7) and (6.8), we have

$$P_T = 4a\ (1 - a)^2 \times P_W$$

$$= C_P \times P_W$$

where C_P is the power coefficient and it is given by

$$C_P = 4a\ (1 - a)^2$$

The power coefficient C_P indicates the portion or fraction of wind power which can be extracted by the wind turbine. Following conditions may result:

(i) When $a = 0$, then $u_1 = u_0$, $u_2 = u_0$ and no power generation takes place.

(ii) When $a = \frac{1}{3}$, then $u_1 = \frac{2}{3} u_0$, $u_2 = \frac{1}{3}\ u_0$ and maximum power generation takes place.

(iii) When $a = \frac{1}{2}$, then $u_1 = \frac{1}{2} \times u_0$, $u_2 = 0$ and only turbulence occurs at downstream.

(iv) When $a = 1$, then $u_1 = 0$ and it results in the stalling of turbine.

- **What is the condition of maximum output power from a wind turbine? Find its value.**

or

- **Show that a wind turbine cannot extract more than 59.3% wind energy.**

The power output from wind turbine is given as follows:

$$P_T = \frac{1}{4} \times A \times \rho \times (u_0^2 - u_2^2)(u_0 + u_2) \tag{6.9}$$

The power output depends on outlet velocity u_2. Hence, for the maximum power output

$$\frac{dP_T}{du_2} = 0$$

$$-2 \times u_2 (u_0 + u_2) + (u_0^2 - u_2^2) \times 1 = 0$$

$$-2 u_2 u_0 - 2u_2^2 + u_0^2 - u_2^2 = 0$$

$$3u_2^2 + 2u_2 u_0 - u_0^2 = 0$$

$$3u_2^2 + (3u_2 u_0 - u_2 u_0) - u_0^2 = 0$$

$$3u_2 (u_2 + u_0) - u_0 (u_2 + u_0) = 0$$

$$(u_2 + u_0) + (3u_2 - u_0) = 0$$

$\therefore$ $$u_2 = -u_0, \text{ which is impossible}$$

or $$u_2 = \frac{u_0}{3}$$

Hence, putting the value of u_2 in Eq. (6.9), we have

$$P_T = \frac{1}{4} \rho A \times \left[u_0^2 - \left(\frac{u_0}{3} \right)^2 \right] \left[u_0 + \frac{u_0}{3} \right]$$

$$= \frac{1}{4} \rho A \times \left(u_0^2 \times \frac{8}{9} \right) \left(\frac{4}{3} \times u_0 \right)$$

$$= \frac{8}{27} \rho A u_0^3$$

$$= \frac{16}{27}\left(\frac{1}{2}\rho A u_0^3\right)$$

$$= \frac{16}{27} \times P_W$$

$$= 59.3\% \times P_W$$

The power output of a wind turbine cannot be more than 59.3% of wind energy.

- **Find the maximum power output of a turbine if wind speed u_0 = 8 m/s, air density ρ = 1.2 kg/m^3 and rotor diameter = 60 m.**

$$A = \frac{\pi d^2}{4} = \frac{\pi \times 60^2}{4}$$

$$= 2826 \text{ m}^2$$

$$P_W = \frac{1}{2}\rho A \times u_0^2$$

$$= \frac{1}{2} \times 1.2 \times 2826 \times 8^2$$

$$= 108.52 \text{ kW}$$

$$P_T = \frac{16}{27} \times P_W$$

$$= \frac{16}{27} \times 108.52$$

$$= 64.31 \text{ kW}$$

6.4.4 Axial Thrust on Turbine

- **Derive the expression for maximum axial thrust experienced by a wind turbine and also find the condition for such operation.**

The Betz model of expanding airstream tube is shown in Figure 6.8. In case of no energy extraction and on applying the Bernoulli equation at upstream and downstream of the tube, we have

$$\frac{P_0}{\rho} + g \times z_0 + \frac{u_0^2}{2} = \frac{P_2}{\rho} + gz_2 + \frac{u_2^2}{2}$$

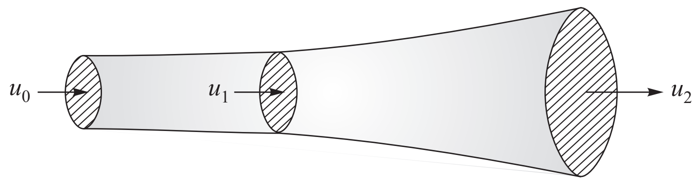

Figure 6.8 Betz model of expanding airstream tube.

Taking $z_0 = z_2$, we have

$$P_0 - P_2 = \Delta P = \frac{(u_0^2 - u_2^2) \times \rho}{2}$$

If $u_2 = 0$, we have

$$\Delta P = \frac{1}{2} \rho \times u_0^2$$

The maximum thrust on the blade is:

$$(F_A)_{\max} = \Delta P \times A_1$$

$$= \frac{1}{2} \times A_1 \rho u_0^2$$

When wind turbine is extracting power, the axial thrust is equal to the loss of momentum of the airstream, which is given by:

$$F_A = m \times u_0 - \dot{m} \times u_2 = \dot{m}\,(u_0 - u_2)$$

and

$$\dot{m} = A_1 \times u_1 \times \rho$$

$$= A_1 \times \frac{u_0 + u_2}{2} \times \rho$$

$$\therefore \quad = A_1 \times \rho \times \frac{u_0 + u_2}{2} \times (u_0 - u_2) \quad (6.10)$$

Putting $u_2 = (1 - 2a)\, u_0$ in Eq. (6.10), we get

$$F_A = 4a(1 - a) \left(\frac{1}{2} \times A_1\, \rho\, u_0^2 \right)$$

$$= C_F \times (F_A)_{\max}$$

$$\therefore \quad C_F = 4a(1 - a) = \text{Coefficient of axial thrust}$$

When $a = 0.5$, $C_F = 1$ and the maximum axial thrust occurs. When $a = \frac{1}{3}$ (condition for maximum power output), the axial thrust coefficient $= C_F = 8/9$.

6.4.5 Torque Generated by Wind Turbine

- **What do you understand by torque coefficient? How is it related to power coefficient?**

The maximum energy of wind is given by P_0 and it exerts torque at the blade of wind turbine. If $T_{\max}$ is the maximum torque exerted on turbine rotor at the tip of the blade having radius R, we have

$$T_{\max} = F_{\max} \times R$$

But wind maximum energy $\quad P_0 = F_{\max} \times u_0$

$$\therefore \qquad T_{\max} = \frac{P_0}{u_0} \times R \tag{6.11}$$

Now tip speed ratio is

$$\lambda = \frac{\omega \times R}{u_0} \tag{6.12}$$

where ω is the angular velocity of the rotor.

From Eqs. (6.8) and (6.9), we have

$$T_{\max} = \frac{P_0 \times \lambda}{\omega} \tag{6.13}$$

For a wind turbine which is producing torque T, less than $T_{\max}$ we have

$$T = C_T \times T_{\max} \tag{6.14}$$

where C_T is the torque coefficient.

In case wind turbine is producing power P_T, we have

$$P_T = C_P \times P_0 \tag{6.15}$$

From Eqs. (6.13) and (6.14), we have

$$P_T = C_P \times \frac{\omega \times T_{\max}}{\lambda} \tag{6.16}$$

From Eqs. (6.14) and (6.16), we have

$$P_T = \frac{C_P \times \omega}{\lambda} \times \frac{T}{C_T}$$

But $$P_T = \omega \times T$$

$\therefore$ $$\omega \times T = (\omega \times T) \times \frac{C_P}{C_T} \times \frac{1}{\lambda}$$

or $$C_T = \frac{C_P}{\lambda}$$

The above relation indicates that both C_T and C_P are functions of λ. The wind turbines havings high tip speed ratios will require low starting torque.

6.4.6 Tip Speed Ratio for Maximum Output

- **Explain the variation of output of a wind turbine with tip speed ratio of the rotor.**

A turbine should be designed in such a way that neither of the following conditions is met:

(i) If the blades are provided in excess or blades are rotated fast, this results in a blade moving in the air turbulence created by a proceeding blade.

(ii) If the blades are provided in less numbers or blades are rotated slowly, this results in a large amount of wind passing through the space between two blades without interacting with the blades.

If a wind turbine has "n" numbers of blades and it is rotating with angular velocity ω, the time (t_1) taken for a blade to move into the previously occupied blade's position is given by

$$t_1 = \frac{2}{n \times \omega} \tag{6.17}$$

If x is the length of the wind stream's disturbance created by a blade, the time (t_2) taken for this disturbance to move out is given by

$$t_2 = \frac{x}{u_0} \tag{6.18}$$

The maximum power output by the wind turbine will take place at the blade when we have

$$t_1 = t_2$$

or $$\frac{2}{n \times \omega} = \frac{x}{u_0}$$

or $$\frac{\omega}{u_0} = \frac{2}{n \times x}$$

Multiply with R, that is length of blade, we obtain

$$\frac{\omega \times R}{u_0} = \frac{2R}{n \times x}$$

$$\lambda_0 = \frac{2R}{n \times x}$$

where λ_0 is the tip speed ratio for the maximum output.

In case $x = \frac{R}{2\pi}$, we have

$$\lambda_0 = \frac{4\pi}{n}$$

The maximum power extraction will occur when tip speed ratios are:

(i) $\lambda_0 = \frac{4\pi}{2} = 2\pi$, where $n = 2$

(ii) $\lambda_0 = \frac{4\pi}{4} = \pi$, where $n = 4$

The maximum output is possible when power coefficient $C_P = 0.59$. The relationship between C_P and λ for ideal propeller type rotor and other wind turbines are as shown in the Figure 6.9.

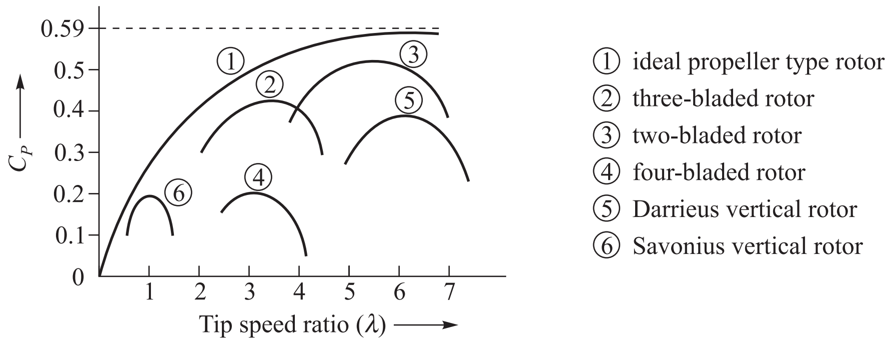

Figure 6.9 Variation of power coefficient with tip speed ratio.

6.4.7 Aerodynamic Considerations

- **Discuss the aerodynamic considerations in windmill design.**

or

- **What parameters should be considered while selecting a windmill?**

When wind moves on an aerofoil, it exerts two types of forces (i) lift force and (ii) drag force. The drag force acts in the direction of wind while lift force acts perpendicular to the direction of wind, trying to lift the aerofoil as shown in Figure 6.10. The relative magnitude of lift and drag forces depends upon the shape of the aerofoil. A streamlined aerofoil has a small drag force and a large lift force. Lift devices are more efficient as they have lower drag forces. The lift forces are created due to higher speed of airstreams moving at the top surface of the airfoils compared to lower speed of airstreams moving at the lower surface of the aerofoils, and so higher static pressure is created at the lower surface of the aerofoils to act upwards.

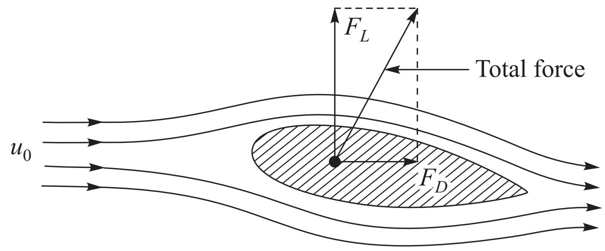

Figure 6.10 Lift and drag forces on an aerofoil.

The design parameters or aerodynamic considerations while designing a windmill are discussed next.

Pitch

The blades of a rotor are curved so that they can deflect the wind to create lift. The created lift force causes the rotor to rotate. To generate the maximum amount of lift, the blades are to be set at an appropriate angle to the wind direction, which is called pitch. The tips of the blades move faster than other points near the axis. Hence, pitch angle (γ) varies along the length of blade. The pitch angle should be large without taking any risk of stalling the rotor. To make the pitch angle large all the way along the blade, it has to be twisted. For rotor rotating fast as in two- or three-bladed windmills, the blades are to be given smaller pitch. Certain rotors are provided a mechanism to control the pitch depending upon the wind conditions. The effect of blade pitch on performance coefficient and tip speed ratio characteristics is as shown in Figure 6.11.

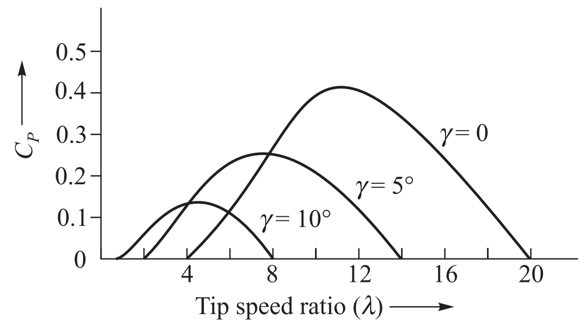

Figure 6.11 Effect of pitch angle on performance coefficient.

Solidity

The greater the solidity of a rotor due to the presence of multiple blades, the slower it needs to intercept the wind with the help of rotation. The windmills with low solidity such as two- or three-bladed rotors have to run rapidly to intercept the wind and to avoid any loss of wind energy through the large gaps existing between the blades.

Tip speed ratio (λ)

Faster rotating windmills have tip speed ratios of more than 1, while slower rotating windmills have tip speed ratios of less than 1. Rotors rotating with the help of drag force have lesser tip speed ratios (tip speed is less than wind speeds). Savonius and Darrieus rotors have low tip speed ratios. On the other hand, two- or three-bladed wind turbines rotate very fast and these have high tip speed ratios ranging from 3 to 10. Multibladed rotors have tip speed ratios between 1 and 2 and these are suitable for only wind pump applications. Each rotor has a certain optimum tip speed ratio at which it can give maximum output.

Performance coefficient

The performance coefficient indicates what fraction of wind energy passing through the rotor is converted into the output power. It depends upon the tip speed ratio and solidity. The range of tip speed ratios for optimum output or performance coefficient with rotors having different solidities is shown in Figure 6.12.

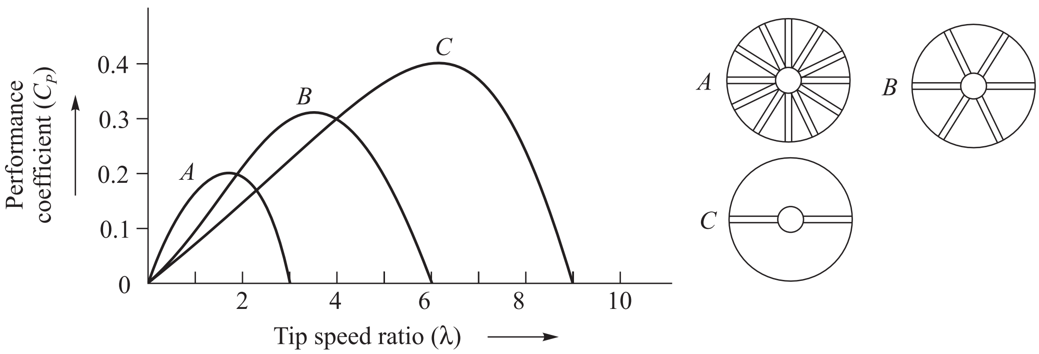

Figure 6.12 Variation of performance with solidity and tip speed ratios.

Torque

Torque is generated by tangential or turning force acting on the blades of a rotor. It depends on solidity and tip ratio of the rotor. High-solidity rotors with low tip speed ratios (as in multibladed rotors) produce much more torque compared to low-solidity rotors as shown in Figure 6.13. The high-speed wind turbines has higher performance coefficient (C_P) but has a low starting torque coefficient (C_T). On other words, high-solidity rotors produce high starting torque, but these have low performance coefficients.

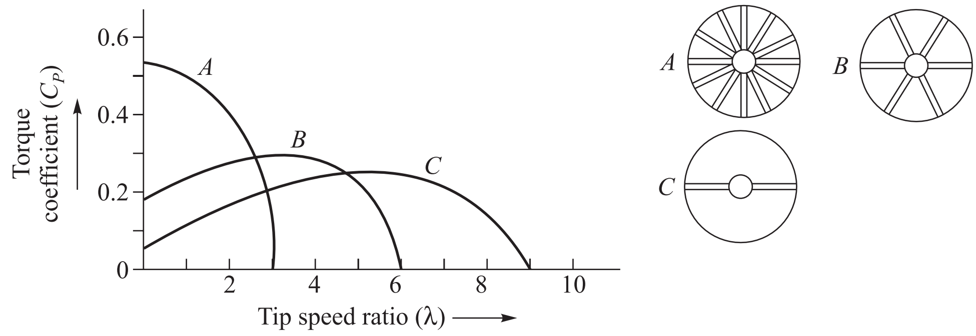

Figure 6.13 Variance of torque coefficient with solidity and tip speed ratios.

Load characteristics

The choice of rotor depends on the load characteristics. The loads requiring high torque (such as for piston pumps) have to be provided with rotors with either high solidity or some arrangement to detach the rotors from the load so that low starting torque windmills can be used. However, windmills used to generate electricity need low torque and high speed, which are met with wind rotors of low solidity and high tip speed ratios. In case of wind pumps, these require three times more torques than what are required for normal working. Hence, these windmills require low wind speeds for running but a gust of higher wind speeds to start them initially. High-speed windmills are unsuitable for running directly any reciprocating pump unless these produce electricity by generators.

6.5 TYPES OF WINDMILLS

- **How can windmills be classified?**

or

- **How wind energy conversion system is classified? Discuss in brief.**

The windmills can be mainly classified as horizontal axis wind turbine (HAWT) and vertical axis wind turbine (VAWT). When the axis of rotation is parallel to the airstream, the turbine is called HAWT and when it is perpendicular to the airstream, it is called VAWT. Horizontal axis windmills are the most commonly used machines and these have rotors similar to aircraft rotors. Vertical axis windmills have eggbeater type of rotors.

6.5.1 Horizontal Axis Wind Turbine

- **Describe the working of a wind power system with a neat sketch, including its various components.**

or

- **Describe the working of wind energy conversion system (WECS) with main components.**

or

- **Describe horizontal axis type aerogenerator.**

The constructional details of a three-bladed, horizontal axis wind turbine are shown in Figure 6.14. The components or main subsystems include turbine blades, hub, nacelle, yaw control mechanism, generator and tower.

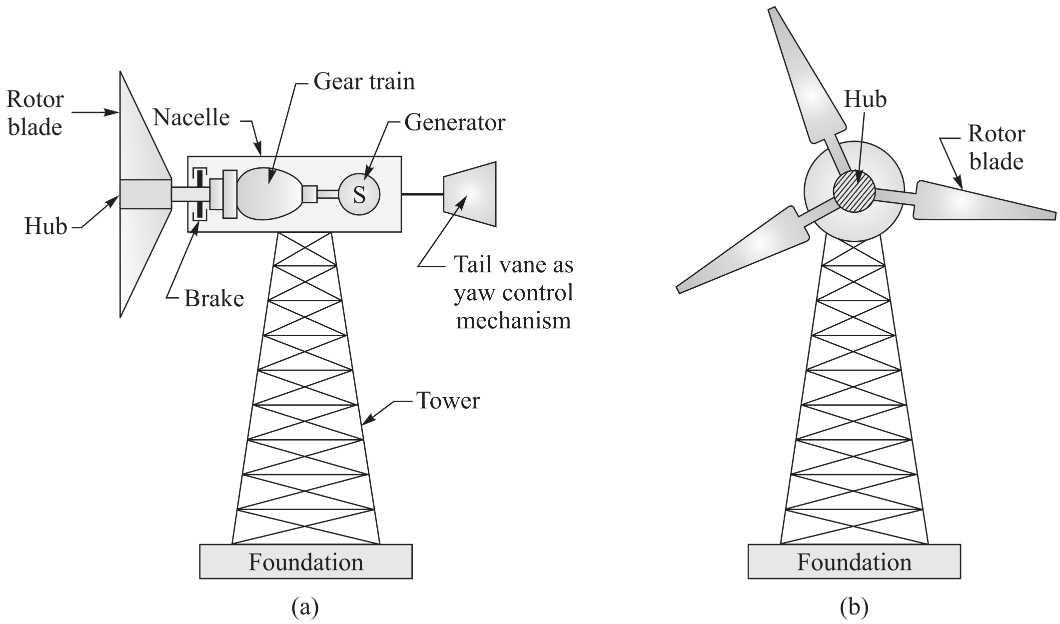

Figure 6.14 Wind turbine (a) Side view of the wind turbine, (b) Front view of the wind turbine.

Turbine blades

Turbine blades have aerofoil type cross section to extract energy from wind. These blades are made of high-density materials such as wood, glass fibre and epoxy composites. The blades are twisted from tip to root to maintain pitch angle. Most of wind turbines have two- or three-blades similar to the propeller of an old aeroplane, but blades of a wind turbine rotates very slowly compared to that of an aeroplane. A two-bladed rotors give much smoother power output compared to three-bladed rotors. A three-bladed rotor generates little more power output (more than 5%), but additional blade incorporation adds to substantial additional weight to the windmill (about 50% extra). A two-bladed rotor is also simpler to be constructed and erected on the ground.

Hub

The central solid portion of a rotor is called hub. It helps in the attachment of all blades and the incorporation of pitch angle control mechanism.

Nacelle

The rotor is attached to nacelle which is mounted at the top of a tower. It houses gearbox, generator, controls and brakes. The purpose of gearbox is to regulate the output rotation from the rotor with the speed of the generator. Electromagnetic brakes are provided for automatic application of brakes if the wind speeds exceed the designed speed.

Yaw control system

The yaw control system is provided to adjust the nacelle around the vertical axis so that rotor blades are always facing the wind stream. In small wind turbine, a tail vane is used as passive yaw control.

Tower

Tower is provided to support nacelle and rotor. The tower height should be sufficient so that enough wind speed can be intercepted by the rotor. For medium- and large-sized wind turbines, the tower is slightly taller than the rotor diameter, while in small sized wind turbines, the tower is much larger than the rotor diameter. There should not be any obstruction in the way of windstream in its approach to the rotor. Tower can be made of materials such as steel or concrete.

Electrical systems

The wind turbines are provided with induction generators to convert mechanical energy into electrical energy. Induction generation has brushless and rugged construction. It is also available at economical cost.

6.5.2 Rotors of HAWT

- **Discuss various designs of rotor and their relative merits and demerits.**

The rotors of HAWT can be (i) single blade rotor, (ii) two blades rotors, (iii) three blades rotors, (iv) Chalk multiblades rotor, (v) multibladed rotor and (vi) Dutch-type rotor as shown in Figure 6.15. The single, two-bladed, three-bladed and chalk multibladed rotors are relatively

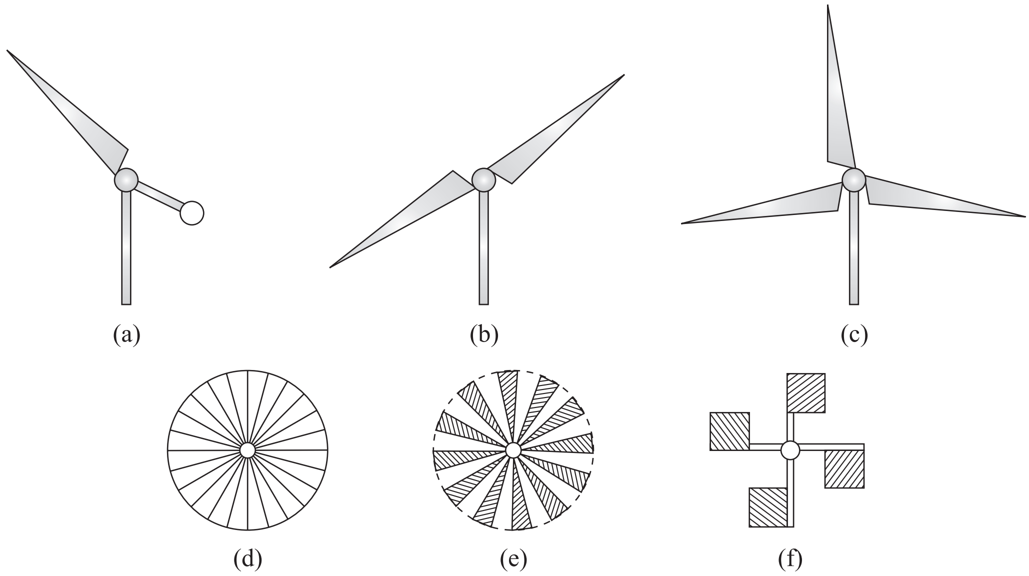

Figure 6.15 Different rotors used for HAWT. (a) Single-bladed rotor, (b) Two-bladed rotor, (c) Three-bladed rotor, (d) Chalk multi-blade rotor, (e) Multi-bladed rotor, (f) Dotch-type rotor.

high-speed machines and these machines are, therefore, suitable for applications such as electric power generation. HAWTs are commonly produced with two- and three-bladed rotors. A single-bladed rotor with balancing counterweight has simple construction and less cost, but it makes more noise during operation. It is used where small power is required. The multibladed and Dutch-type rotors are used where low speeds are required. Hence, these rotors are suitable for applications such as piston pumps where high starting torque is needed. As these rotors have high solidity, these can operate even when slow winds are present.

6.5.3 Vertical Axis Wind Turbine

- **Sketch the diagram of a VAWT and explain the functions of its main components.**

Vertical axis wind turbine has the axis of rotation of its rotor perpendicular to the wind stream. Vertical axis wind turbine is advantageous as (i) it can accept wind from any direction, thereby eliminating the necessity of any yaw control system and (ii) it can have its gearbox and generator system (nacelle) at the ground level, thereby eliminating the necessity of mounting the heavy nacelle (with gearbox and generator) at the top of the tower. These features of VAWT also help in the simpler design and installation of the wind turbine, the easier inspection and maintenance of the wind turbine and reducing the overall cost of the wind turbine.

A VAWT (Darrieus) with all its components is shown in Figure 6.16. The components and subsystems include tower blades and support structure.

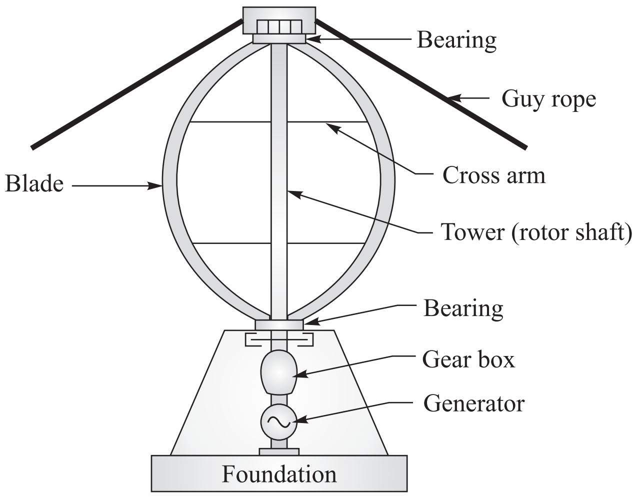

Figure 6.16 Vertical axis wind turbine.

Tower (rotor shaft)

The tower consists of a hollow vertical shaft which can rotate about its vertical axis between its bearings at top and bottom. It is provided with a support structure at the bottom and at the upper end, it is supported by guy ropes. The height of the tower is about 100 m.

Blades

The wind turbine has two or three blades which are thin and curved shaped similar to an "eggbeater". The blades are curved in such a way that minimum bending stresses are produced on rotation due to the centrifugal forces. The blades are designed in such a way that they offer aerofoil type cross section to wind stream. The height of blade is kept 94 m, diameter about 65 m and chord length about 2.4 m.

Support structure

It is provided with blades, gearbox and generator to support the weight of tower.

6.5.4 Rotor of VAWT

- **Explain various designs of blades of VAWTs and their relative features.**

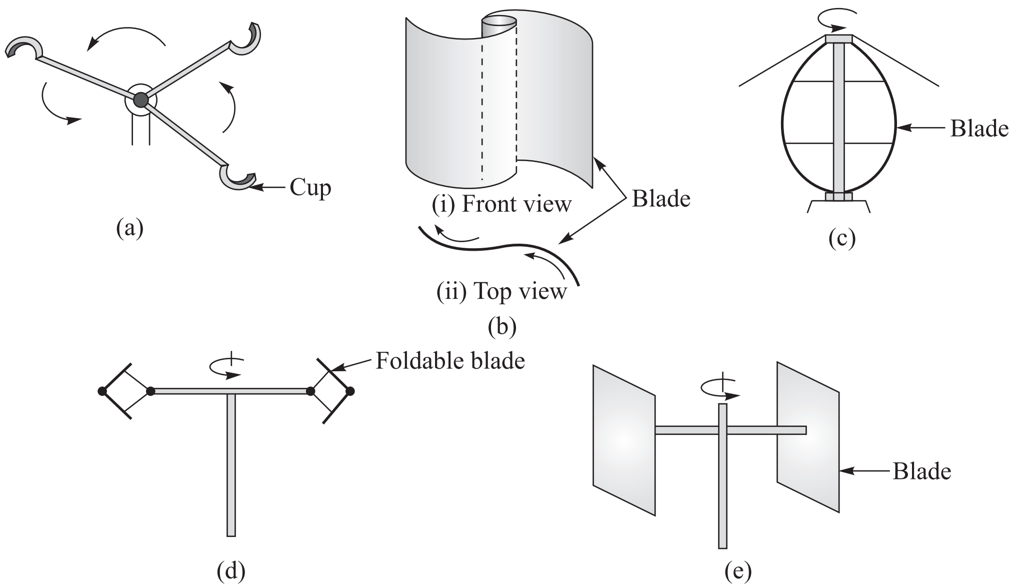

Figure 6.17 Various rotors of VAWT, (a) Cup type rotor, (b) Savonious rotor, (c) Darrieus rotor, (d) Musgrove (H-shaped) rotor, (e) Evans rotor (gryromill).

The VAWTs can have various types of rotors which include Cup type rotor, Savonious rotor, Darrieus rotor, Musgrove rotor and Evans rotor as shown in Figure 6.17. The simplest of all rotors is cup type rotor, which consists of three or four cup type structures attached symmetrically to a vertical shaft. It works on the principle that drag force on a large concave surface is more than that on a convex surface of the cup when wind stream strikes these surfaces, and so the rotor consisting of cups starts rotating. However, such rotors cannot extract enough energy from winds and therefore are not used for power generation. These devices are mainly used for wind speed measuring instruments such as the cup anemometer. The Savonius rotor (S-rotor) is formed with two half-cylinders attached to a vertical axis, but facing in opposite directions. S-rotor can produce high starting torque at low wind speed. It has also low efficiency of conversion of wind energy. As it can extract power even from low-speed winds, it can operate and deliver power throughout the day. Hence, such rotor is used for applications where low power is required, such as in wind pumping. Darrieus rotor consists of two or three curved blades attached to a rotor shaft similar to an eggbeater. It has good power coefficient and is used for large power generation. It also has a large tip speed ratio, thereby developing large bending stresses in the blades due to centrifugal forces formed. The main drawback of this rotor is that it is not self-starting due to lower starting torque developed by it. It has to be run generally by using its electrical generator as motor. The blades also have fixed pitch which cannot be changed. This results in unmanageable output at high wind speeds. Musgrove (H-shaped) rotor has fixed pitch on blades attached to rotor shaft, but the blades are foldable to control power. The Evans rotor has blades which are hinged on a vertical rotor shaft and the blade pitch is varied cyclically during rotation to regulate the power output. It is a self-starting rotor.

6.5.5 Comparison of HAWT and VAWT

- **Compare horizontal and vertical axis windmills.**

or

- **What are the relative features of drag and lift type machines?**

or

- **Discuss advantages of vertical axis windmill over horizontal type.**

The comparison of HAWT and VAWT is shown in Table 6.2.

TABLE 6.2 Comparison of HAWT and VAWT

HAWT	*VAWT*
Axis of rotation is parallel to the airstream	Axis of rotation is perpendicular to the airstream
These are commonly used and almost fully developed	These are under development stage
The rotor has to face wind stream. It is provided with yaw mechanism to keep it facing wind stream	The rotor can accept wind stream from any direction. There is no need of yaw mechanism
Nacelle carrying gear train, controls and generator has to be mounted on top of the tower	Gear train, controls and generator can be located at ground level
Tower has to be strong and designed properly	Tower is simple in construction and installation
Inspection and maintenance of windmill is difficult	Inspection and maintenance of windmill is easy
Costly	Less costly
Less noisy	More noisy
Extract more power from wind	Extract less power from wind
Technology is fully developed	Technology is under development
Less fatigue to parts due to wind action	More fatigue to parts due to wind action
Designed to use lift force	Designed to use drag force
More efficient	Less efficient
Smooth output	Fluctuating output
Produces lower starting torque	Produces high starting torque
Operates properly in moderate wind speeds	Can operate even in low wind speeds
Pitch of blade can be controlled	Pitch of blade cannot be controlled

6.5.6 Savonius Rotor

- **Write the advantages and disadvantages of Savonius rotor.**

Advantages

(i) It has vertical rotating rotor shaft which eliminates the need of any expensive transmission system from the rotor to generator.
(ii) It produces power effectively in slow wind speeds (as low as 8 km/h).
(iii) The generator can be located at ground level which helps in easy maintenance.
(iv) The tower is simple in construction and installation due to lower loads.
(v) The cost of construction and installation is low.
(vi) Yaw and pitch control mechanisms are not required.

Disadvantages

(i) It utilises drag force which results in its lower efficiency.
(ii) Power output is very low.
(iii) The power output is low as the pitch control of the blade is impossible.
(iv) It is unsuitable where tall installation is necessary due to wind conditions.
(v) It has low power to weight ratio.

6.5.7 Darrieus Rotor

- **What are the advantages and disadvantages of Darrieus rotor?**

or

- **What are the arrangements required for starting a Darrieus wind turbine?**

Advantages

(i) The rotor blade can accept the wind from any direction.
(ii) It does not require any yaw control mechanism.
(iii) The blades have constant pitch. There is no need of pitch control mechanism.
(iv) The gear train and generator are mounted at the ground level.
(v) The tower is simple in construction.
(vi) The cost of construction and installation is low.
(vii) It has higher power coefficient and tip speed ratio compared to S-rotor.

Disadvantages

(i) It is not self-starting machine.
(ii) It works on drag force and its efficiency to convert wind energy is low compared to horizontal axis rotors.
(iii) It can have limited height. It cannot utilize high wind speeds available at higher level.
(iv) It cannot be yawed out of the wind; special high torque braking system is required during the occurrence of high wind speeds.

Darrieus wind turbine operates on drag force created on it by wind stream. It also has full directional symmetry to capture wind energy, thereby resulting in presence of zero starting torque. Hence, Darrieus rotor requires some external arrangements for starting. Following are the arrangements for its starting:

(i) S-rotors have directional unsymmetry. Hence, these rotors can be attached at the top and bottom of the shaft of Darrieus rotor to help it start up. However, this method is successful only for small Darrieus rotors.
(ii) The generator can be designed to run as motor so as to start up the wind turbine initially and it can act as generator when the wind turbine picks up speed.
(iii) Its rotor is partly shielded from the windstream in the beginning to behave as unsymmetrical rotor so as to develop starting torque.

6.6 WIND ENERGY STORAGE

- **Explain how the energy produced by a wind turbine can be stored for reuse.**

or

- **Write a short note on wind energy storage.**

Wind energy is an intermittent source of power. There are variations in wind speeds on hourly, daily, monthly, yearly and seasonal basis. Therefore, the output of wind turbine varies according to wind speeds. Wind turbine is also non-operational during the periods of very high and low wind speeds. Hence, wind turbine needs some form of energy storage to meet the varying loads of its customers. The energy can be stored by following storage means:

(i) **Chemical energy.** The power output of wind turbines can be used to charge batteries which can store energy as chemical energy. The stored chemical energy can be converted into electrical energy to serve the varying loads of customers.
(ii) **Thermal energy.** The energy output from wind turbines can be stored by heating water. The water heating can be done either by passing power through a resistance or churning water. The heated water can be used for various purposes.
(iii) **Compressed air.** The energy can be stored as compressed air in a suitable storage tank. The stored compressed air can be utilised when required to drive an air turbine to generate electricity through a directly coupled generator.
(iv) **Electrolysis of water.** The output as electricity is used for electrolysis of water, which produces hydrogen and oxygen gases. These gases can be easily stored and converted into electric energy using fuel cells.
(v) **Pumping water.** The output can be used to pump water which can be stored in a high tank. The water can be used when it is needed for various purposes.
(vi) **Integration to electric grid.** The output of wind turbine is fed into any existing electric grid to store or meet peak demands.

6.7 ENVIRONMENTAL IMPACTS OF WIND TURBINES

- **Comment on the environmental impacts of wind energy.**

or

- **What are the demerits of wind farms?**

The environmental impacts of wind turbines are as follows:

(i) **Emission.** There is no pollution or emission of carbon dioxide during operation of wind turbine. Carbon dioxide emission only takes place during manufacturing and installation of wind turbine, which is also very low. Even energy used to construct and install wind turbine is low, which is also paid back by generating same amount of energy in a period of few months.

(ii) **Bird's life.** The rotating rotors pose a threat to bird's life. It has been reported that a large number of birds are killed every year when they fly into the fast rotating blades unknowningly.

(iii) **Noise.** The rotating blades create noise of high sound level due to movement of blades and churning of air (aerodynamic noise). The noise disturbances caused by a wind turbine are very high and unbearable. This is the reason why the wind turbine is not located close to any inhabited areas.

(iv) **Interference to transmission.** Wind turbine with high tower can interfere with the microwave signals of TV and communication, thereby adversely affecting the quality of radio and TV reception at nearby areas.

(v) **Visual intrusion.** Wind turbines with their high towers are visible over a wide area, thereby disturbing the natural beauty of a site.

(vi) **Safety.** The rotating blades may cause harm and injury when any of these blades may break or get damaged, specially during high wind conditions.

(vii) **Impact on ecosystem.** The wind is produced due to differential heating of the earth surface so that ecosystem is maintained. Hence, large-scale interception and use of wind energy can cause adverse impact on ecosystem.

6.8 RECENT DEVELOPMENT

- **What are the recent developments in the technology of large windmills?**

Large windmills use more sophisticated methods to speed control and provide safety measures specially during high wind speeds. These recently developed windmills have following features:

(i) **Yaw and tilt control.** The control is achieved by shifting the rotor axis out of wind direction by yaw control and by tilting the rotor plane with respect to normal plane when wind speeds are high enough to damage the machine.

(ii) **Pitch control.** The pitch of rotor blades can be regulated by a servo system to generate the maximum output. Large machines use pitch control to maintain constant turbine speed.

(iii) **Stall control.** The blades can be shifted to a position in which high winds cannot damage the machines.

(iv) **Fixed blades (constant pitch).** The twist and thickness of the blade are so designed and provided along blade length that the speed is maintained as constant as possible.

(v) **Eddy current braking system.** It is provided to control speeds so that wind mills can perform at high wind conditions.

(vi) **Variable speed drive system.** The system allows rotor speed to vary optimally with the wind speeds to capture maximum power. The variable speed drive helps in capturing more power compared to the fixed speed drive system.

- **What are the major factors that have led to the acceleration and development of the wind power?**

The major factors are as follows:

(i) **Improved materials.** Improved materials such as high-strength fibre composites are available that enable the production of large-sized rotor blades at low cost.
(ii) **Power electronics.** The power electronics to regulate and control the functioning of wind turbine are available at low cost.
(iii) **Variable speed drive system.** It helps wind turbines to capture maximum energy at various wind speeds.
(iv) **Bigger turbines.** Larger wind turbines are being produced to generate significant power output at an economical rate.
(v) **Short energy payback.** The wind turbine has shorter energy payback period of about 1 year.
(vi) **Improved plant.** Improved plant operations have ensured the supply of power from the wind turbine plant as high as 95%.
(vii) **More expertise.** The field trials and experiences have helped in the improved development, installation and operation of wind turbine plants.
(viii) **Renewable resource.** It is the fastest growing energy source among all renewable energy resources. It is now competing with conventional power sources.

- **How energy extracted from wind by turbine can be increased?**

The amount of energy extracted from wind power by a wind turbine can be increased by providing the following:

- Pitch control
- Yaw control
- Large size blades
- Variable speed drive
- Tilt control of blades
- Stall control by shifting of blades
- Eddy current bracking system to maintain speed
- Power electronics.

6.9 WIND ENERGY PROGRAMME IN INDIA

- **Discuss the prospects and status of wind energy in India.**

or

- **What do you know about Indian wind power programme?**

or

- **Write briefly about availability of wind energy in India.**

The wind energy potential in India is estimated to be about 2.5×10^4 MW. India is now the 5th country in the world having the largest wind power installed capacity. The installed capacity is now above 1870 MW.

Wind energy programme in India was started during 1983–1984 and has been implemented and managed by MNES. Many wind power projects are making their presence felt, with almost all new wind power projects coming up in the private sector. The role of government sector is that of a catalyst, providing technical and financial assistance. Nationwide wind mapping and wind monitoring activities are also undertaken to measure wind speeds at poteritial sites in various states. The assessment has enabled to identify about 53 sites suitable for wind power farming. The government has also started wind energy demonstration programme in which installation of wind pumps, wind battery chargers, stand-alone wind electric generators and wind farms has been undertaken to demonstrate the wind turbine technology. Over 3000 wind pumps have been installed. Over 120 wind battery chargers from 50 to 4000 W capacity and stand-alone generators of capacities ranging from 10 to 25 kW, with total capacity of 175 kW, have been installed. Wind farms of about 80 MW have been installed in various states. The government aims to generate about 7,000 MW from winds by 2012. A wind–diesel hybird project is under implementation at Sagar Island in West Bengal. Similar Projects are being prepared for islands of Lakshadweep and Andaman and Nicobar. About 21 Indian firms have tied up with foreign collaborators for joint venture to produce and install wind turbines. Several state governments have agreed to purchase power generated by the private sector. The central and state governments are offering a number of economic incentives such as subsides, land allotment, tax benefits and free imports to give a boost to the wind energy generation.