ME0048 – ALTERNATIVE SOURCES OF ENERGY

COURSE MATERIALS

UNIT I. BIOMASS

BIOMASS

The biomass is biological material derived from living or recently living organism. It's an organic matter derived from biological organism - plants, algae, animals etc. The biomass for energy mean plant based material but biomass can equally apply to both animal and vegetable derived material.

The sources of biomass are the forest and agricultural waste, animal waste, energy crops, co-products in the crop field or industrial process wastes or by-products.

There are five basic categories of biomass source materials:

1. Wood: From forestry, agricultural activities or from wood processing.
2. Energy crops: High yield crops grown specifically for energy applications.
3. Agricultural residues: Residues from agriculture harvesting or processing.
4. Food waste: Waste from food manufacture, preparation and processing as well as post-consumer wastes.
5. Industrial waste and co-products : From manufacturing and industrial processes

The energy conversion from biomass can be either bio-chemical (Fermentation or digestion) or thermo-chemical methods to covert the biomass (solid fuel) into liquid or gaseous fuels. For electricity generation, two most competitive technologies are direct combustion and gasification. Typical plant sizes at present range from 0.1 to 50 MW. Co-generation applications are very efficient and economical. Fluidized bed combustion (FBC) is efficient and flexible in accepting varied types of fuels. Gasifiers first convert solid biomass into gaseous fuels which is then used through a steam cycle or directly through gas turbine/I.C.engine. Biomass materials used for power generation include bagasse, rice husk, straw, cotton stalk, coconut shells, soya husk, de-oiled cakes, coffee waste, jute wastes, ground nut shells and saw dust etc.

Biomass is renewable, widely available, carbon-neutral and has the potential to provide significant employment in the rural areas. Biomass is also capable of providing firm energy. About 32% of the total primary energy use in the country is still derived from biomass and more than 70% of the country's population depends upon it for its energy needs.

Ministry of New and Renewable Energy has realised the potential and role of biomass energy in the Indian context and hence has initiated a number of programmes for promotion of efficient technologies for its use in various sectors of the economy to ensure derivation of maximum benefits Biomass power generation in India is an industry that attracts investments of over Rs.600 Crores every year, generating more than 5000 million units of electricity and yearly employment of more than 10 million man-days in the rural areas. For efficient utilization of biomass, bagasse based cogeneration in sugar mills and biomass power generation have been taken up under biomass power and cogeneration programme. The following diagram indicates various biomass energy sources.

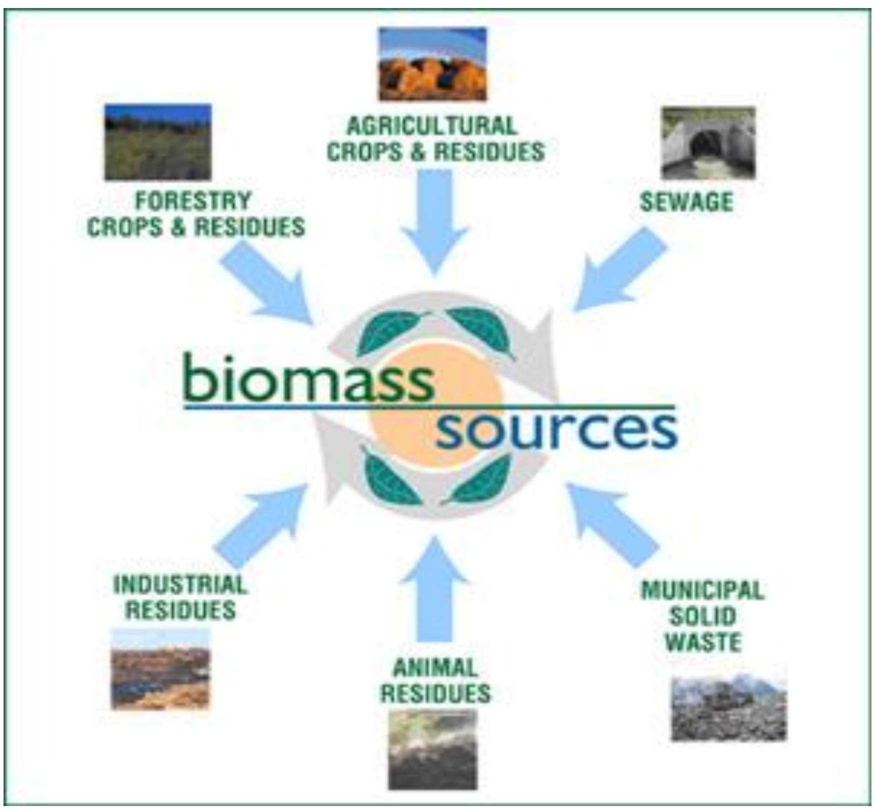


Fig.1.1 Sources of Biomass

FERMENTATION

The process of bio-chemical degradation or decomposition of organic matter with the help of micro-organisms (bacteria/yeast) is called fermentation.

e.g. Chemical equations fermentation

Starch into Dextrose in the presence of enzyme at 20-30^{0}C and then dextrose into ethanol in the presence of yeast at 20-30 ^{0}C in 50 hours.

$$\mathbf{(C_6H_{10}O_5)_n \text{ (Starch)} + nH_2O \text{ ------- } n\ C_6H_{12}O_6 \text{ (Dextrose)}}$$

$$\mathbf{(C_6H_{12}O_6)_n \text{ ----------------- } 2\ C_2H_5OH \text{ (Ethanol)} + 2\ CO_2}$$

PYROLYSIS

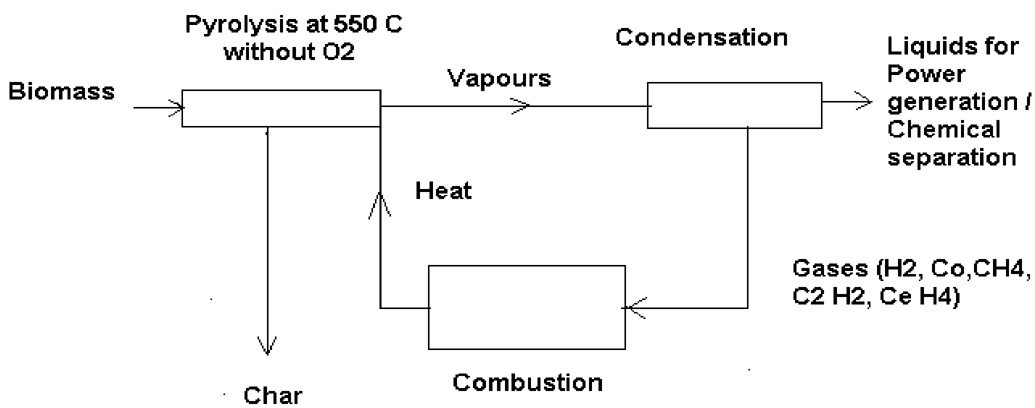
Pyrolysis is the thermal decomposition of biomass occurring in the absence of oxygen. It is the fundamental chemical reaction that is the precursor of both the combustion and gasification processes and occurs naturally in the first two seconds. A wide range of biomass feed stocks can be used in pyrolysis processes. The pyrolysis process is very dependent on the moisture content of the feedstock, which should be around 10%. The efficiency and nature of the pyrolysis process is dependent on the particle size of feedstocks. Most of the pyrolysis technologies can only process small particles to a maximum of 2 mm keeping in view the need for rapid heat transfer through the particle. The demand for small particle size means that the feedstock has to be size-reduced before being used for pyrolysis.

TYPES OF PYROLYSIS

Pyrolysis processes can be categorized as **slow pyrolysis** or **fast pyrolysis**. Fast pyrolysis is currently the most widely used pyrolysis system. Slow pyrolysis takes several hours to complete and results in biochar as the main product. On the other hand, fast pyrolysis yields 60% bio-oil and takes seconds for complete pyrolysis. In addition, it gives 20% biochar and 20% syngas. Fast pyrolysis processes include open-core fixed bed pyrolysis, ablative fast pyrolysis, cyclonic fast pyrolysis, and rotating core fast pyrolysis systems.

The essential features of a fast pyrolysis process are given below:

1. Very high heating and heat transfer rates, which require a finely ground feed
2. Carefully controlled reaction temperature of around 500°C in the vapour phase
3. Residence time of pyrolysis vapours in the reactor less than 1 sec
4. Quenching (rapid cooling) of the pyrolysis vapours to give the bio-oil product.



Pyrolysis of Biomass (Liquefaction - Conver ting solid to liquid fuel)

Fig.1.2. Biomass Pyrolysis flow chart

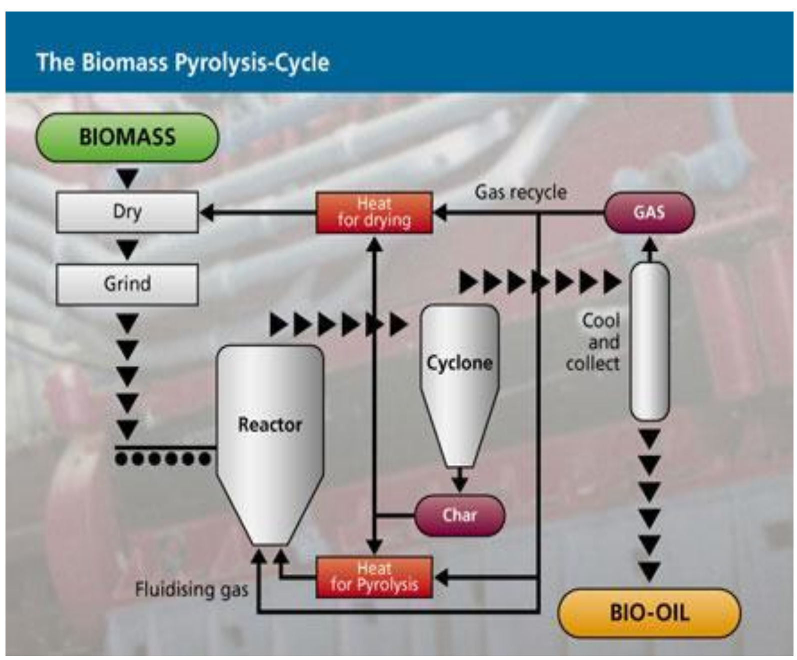


Fig.1.3 Biomass pyrolysis plant cycle

The products of biomass pyrolysis include biochar, bio-oil and gases including methane, hydrogen, carbon monoxide, and carbon dioxide. Depending on the thermal environment and the final temperature, pyrolysis will yield mainly biochar at low temperatures, less than 450^0C, when the heating rate is quite slow, and mainly gases at high temperatures, greater than 800^0C, with rapid heating rates. The processes in the pyrolysis chamber are given below:

1. The dehydration or drying process occurs at around 100°C by the resulting steam mixed into the gas flow and may be involved with subsequent chemical reactions, notably the water-gas reaction if the temperature is sufficiently high enough.
2. The pyrolysis (or devolatilization) process occurs at around 200-300°C. Volatiles are released and char is produced, resulting in up to 70% weight loss for coal.
3. The combustion process occurs as the volatile products and some of the char reacts with oxygen to primarily form carbon dioxide and small amounts of carbon monoxide, which provides heat for the subsequent gasification reactions. $C + O_2$ ------------ CO_2
4. The gasification process occurs as the char reacts with carbon and steam to produce carbon monoxide and hydrogen, via the reaction, $C + H_2O$ ------------ $CO + H_2$
5. In addition, the reversible gas phase water gas shift reaction reaches equilibrium very fast at the temperatures in a gasifier. This balances the concentrations of carbon monoxide, steam, carbon dioxide and hydrogen. $CO + H_2O$ ------------ $CO_2 + H_2$

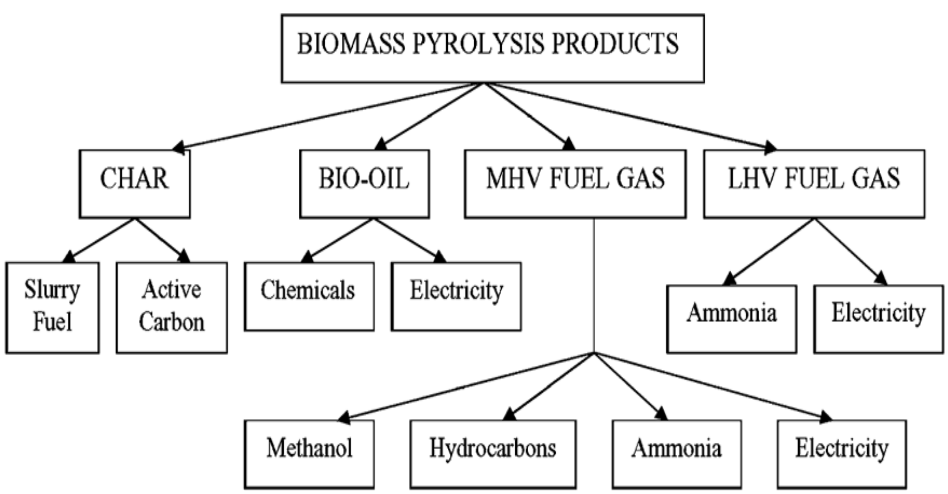


Fig.1.4 Biomass Pyrolysis Products

Pyrolysis can be performed at relatively small scale and at remote locations which enhance energy density of the biomass resource and reduce transport and handling costs. Heat transfer is a critical area in pyrolysis as the pyrolysis process is endothermic and sufficient heat transfer surface has to be provided to meet process heat needs.

Pyrolysis offers a flexible and attractive way of converting solid biomass into an easily stored and transported liquid, which can be successfully used for the production of heat, power and chemicals.

GASIFICATION

Gasification is thermo-chemical conversion process that converts organic or fossil based carbonaceous material into carbon monoxide, hydrogen and carbon dioxide (gaseous fuels). This is achieved by reacting the material at high temperatures (>700 °C), without combustion, with a controlled amount of oxygen and/or steam. The resulting gas mixture is called *syngas* (from *synthesis gas* or *synthetic gas*) or *producer gas* and is itself a fuel.

TYPES OF GASIFIERS

The gasifiers are classified based on the gas flow direction in the bed. The gas flow is upward in the up-draft, downward in down-draft, perpendicular in the cross flow type. A fixed bed of carbonaceous fuel (e.g. coal or biomass) through which the "gasification agent" (steam, oxygen and/or air) flows in counter-current configuration. The ash is either removed in the dry condition or as a slag.

The slagging gasifiers have a lower ratio of steam to carbon, achieving temperatures higher than the ash fusion temperature. Thermal efficiency is high as the temperatures in the gas exit are relatively low. In the gasification of fine, undensified biomass such as rice hulls, it is necessary to blow air into the reactor by means of a fan. This creates very high gasification temperature, as high as 1000 °C.

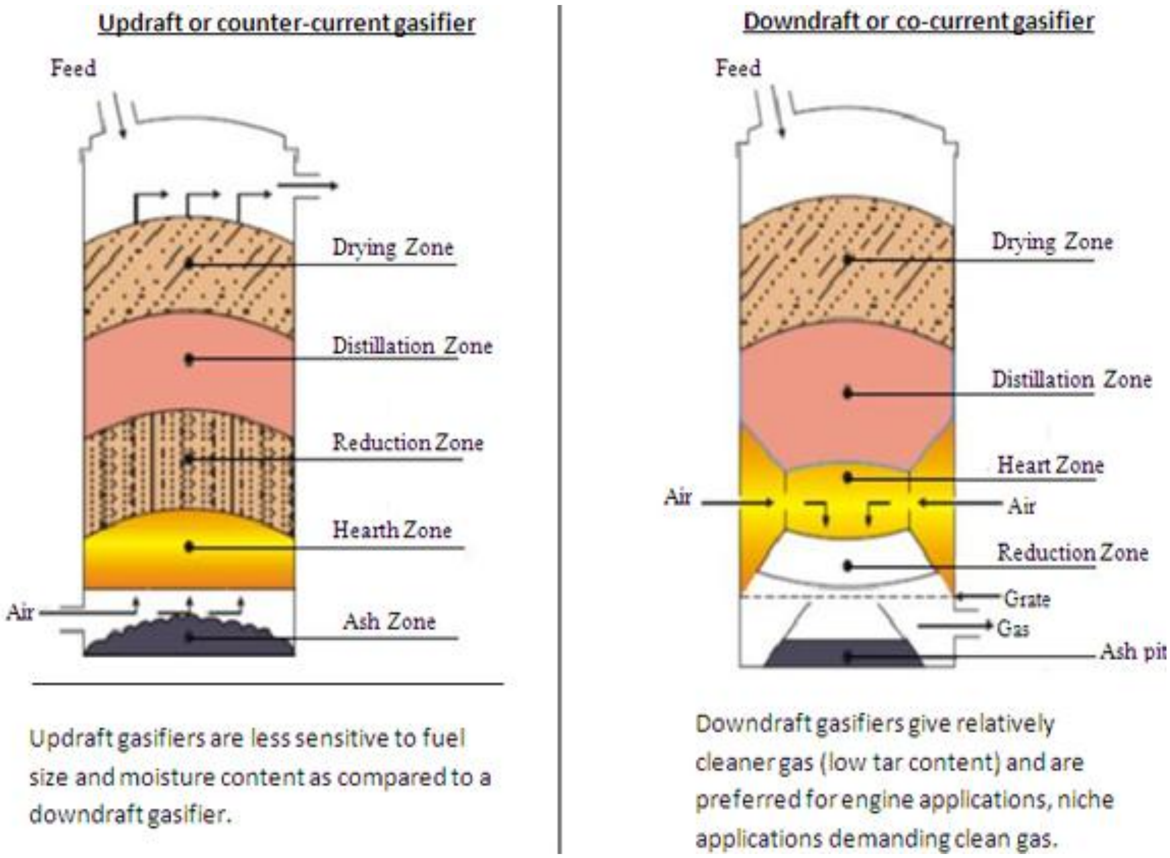


Fig.1.5. Updraft and Down Draft Gasifiers

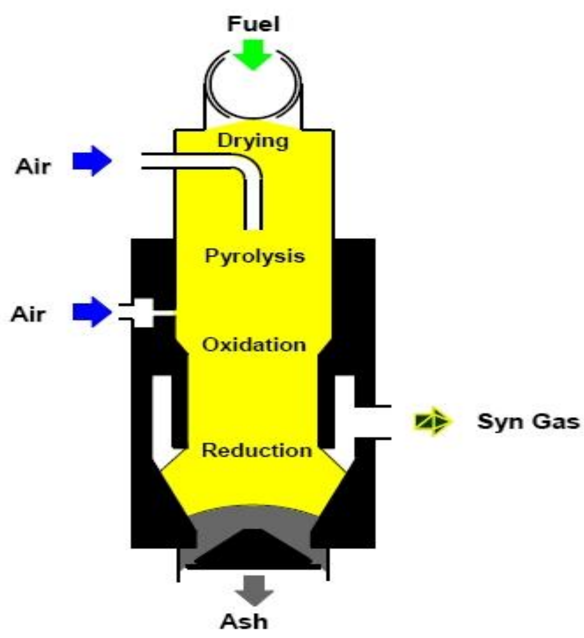


Fig.1.6 Cross Flow Gasifier

Comparison of advantages/disadvantages of updraft, downdraft and crossdraft gasifiers

Table 1.1. Comparison of conventional gasifiers

Type of Gasifiers	Advantages	Disadvantages
Updraft	Small pressure drop, good thermal efficiency, small tendency to slag	Great sensitivity to tar/moisture , long time, poor reaction capability
Downdraft	Flexible adaptation of gas production to load, low sensitivity to charcoal dust and tar content	Taller design, no feasibility for small particle size of fuel
Crossdraft	Shorter design height, quick response to loads, flexible gas production	Very high sensitivity to slag formation, high pressure drop

FLUIDIZED BED GASIFICATION/COMBUSTION

The fluidized bed can be classified as bubbling fluidized bed and circulation fluidized bed. The unburnt fuel particles and bed particles are recovered in circulating bed and this gives better conversion (gasification) efficiency than the bubbling bed gasifier. The prepared biomass fuel has been sent to the gasifier and the fluidization velocity is given to the bed through fan. The fluidized biomass particles are gasified through the partial combustion of biomass and the producer gas in cleaned through cyclone separator and scrubber/filters before admitting the gas to applications. In the fluidized bed concept, the biomass particles are gasified and burnt in the floating condition by supplying air with the fluidization velocity. The fluidized bed can be operated as atmospheric or pressurized bed conditions.

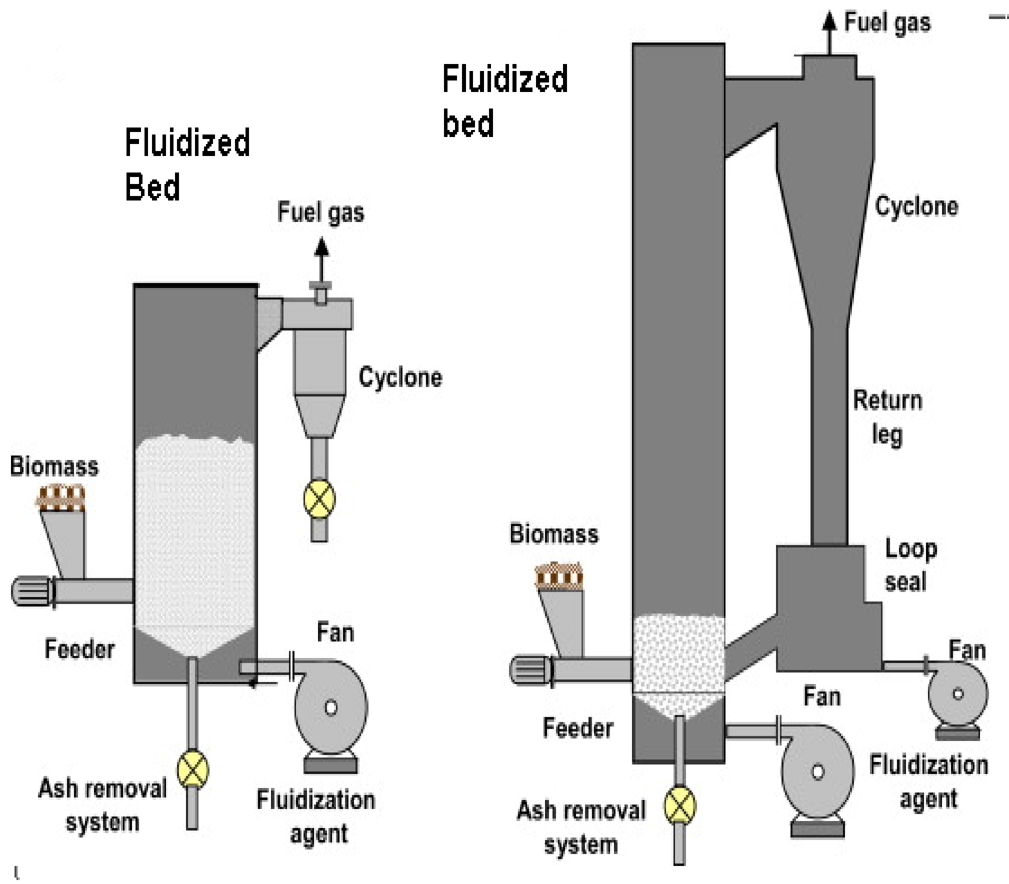


Fig.1.7. Bubbling and Circulating Fluidised Bed Gasification/Combustion

ADVANTAGES OF FLUIDIZED BED GISIFICATION/COMBUSTION

- Greater fuel flexibility and types of fuels of CV from 3,300 kJ/kg to 33,000 kJ/kg.
- Good heat storage capacity ensures complete combustion.
- Quick start up.
- Higher combustion efficiency (99%) and high output rate.
- Consistency in combustion rate and usage of high moisture fuels.
- Low temperature combustion leads to less corrosion due to alkali compounds.
- Less boiler floor area than other grate systems
- Uniform temperature throughout the furnace volume.
- Reduced emission due to NOx.
- Reduced SOx with less expense with limestone addition in bed.
- Operation is as simple as oil fired boiler.

CALORIFIC VALUE

The quantity of heat liberated during complete burning of 1 kg of fuel. The products of combustion is cooled to the original room temperature (initial condition) and the total heat value obtained is called as Gross calorific value (GCV) or Higher heating value whereas the products of combustion is not cooled and the heat obtained in this combustion process is called as Net calorific value (NCV) or lower heating value. The GCV is an indicative value and it can be calculated using Dulong's formula based on its components fraction. The NCV is useful while designing the furnace or combustor.

GCV = 33800 C + 144000 (H – O/8) + 9270 S …………… kJ/kg

NCV = GCV – 2466 x (9 H + Moisture) ………………………………. kJ/kg

Where, C, H, O and S are in mass fraction.

NCV for wood having 25% Moisture = 14000 kJ/kg

NVC for charcoal having 8% moisture = 28000 kJ/kg

BIOMASS FUEL PROPERTIES FOR BIOMASS GASIFIER SELECTION

Need for selection of right gasifier for each fuel. Biomass fuels available for gasification include charcoal, wood and wood waste (branches, twigs, roots, bark, wood shavings and sawdust) as well as a multitude of agricultural residues (maize cobs, coconut shells, coconut husks, cereal straws, rice husks, etc.) and peat. The following are the data required while choosing a fuel and gasifier and the producer gas produced is dependent on these:

1. Energy Content (Higher and lower heating values)
2. Moisture content
3. Volatile matter
4. Ash content and ash chemical composition
5. Reactivity
6. Particle size and distribution
7. Bulk density (e.g for Wood = 400 kg/m^3)

Gasifier Design Calculations

Let FCR - Fuel consumption rate in kg/h

SGR - Specific gasification rate in kg/m^2-h

Diameter of the Reactor, $D = (1.27 \times FCR / SGR)^{0.5}$

Height the reactor, $H = SGR \times T / \rho$

Time required to completely gasify the biomass, $T = \rho V_R / FCR$

(e.g. SGR - specific gasification rate of rice husk, 110-210 kg/m^2 –h)

H - Length of the reactor in m

T - Time required for consuming biomass in h

ρ – Density of biomass in kg/m^3

V_R – Volume of the reactor in m^3

TYPES OF BIOGAS DIGESTER PLANTS

1. Fixed Dome Digester plant
2. Floating Dome Digester plant

Floating gas-holder type of plant

A well is made out of concrete called the digester tank T, which is divided into two parts. One part is an inlet, from where the slurry is fed to the tank. The cylindrical dome H of the tank is made out of stainless steel that floats on the slurry and collects the gas generated. Hence it is called floating gas-holder type of bio gas plant. The slurry is fermented for about 50 days. As more gas is made by the bacterial fermentation, the pressure inside H increases. The gas can be taken out from outlet pipe V. The decomposed matter expands and overflows into the next chamber in tank T, which is removed by the outlet pipe to the overflow tank and used as manure for cultivation purposes.

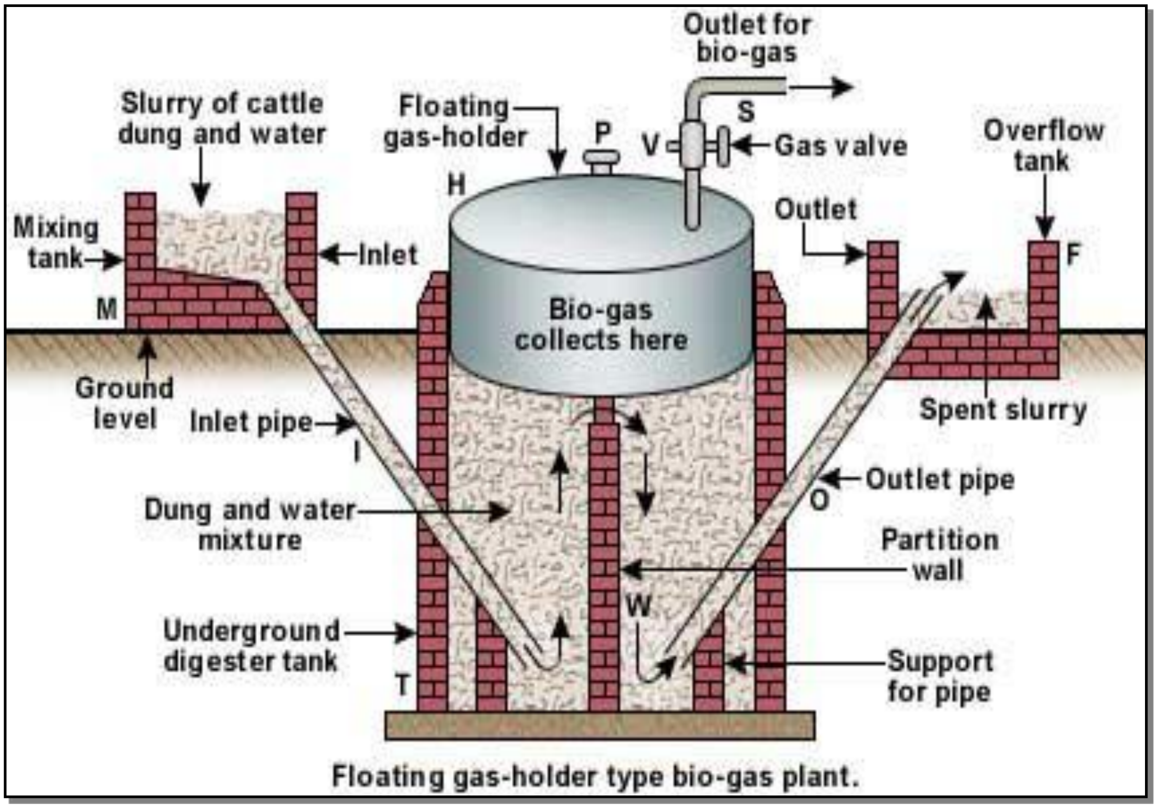


Fig.1.8 Floating dome type of plant

A well and a dome are made out of concrete called the digester tank T. This dome is fixed and thus it is called fixed dome type of bio gas plant. The function of the plant is similar to the floating holder type bio gas plant. The used slurry expands and overflows into the overflow tank. The cobar gas is cleaned by supplying through water and then used in cooking or heating applications.

In the floating gas-holder type of plant, the floating chamber is made of stainless steel. This is expensive and needs continuous maintenance and supervision for non-rust. This does not arise in the fixed dome type of bio gas plant as everything is made of concrete. The volume of fixed dome type of biogas is fixed. So if the gas pressure increases inside, it may cause damage to the concrete dome. This does not happen in the floating holder type of bio gas plant.

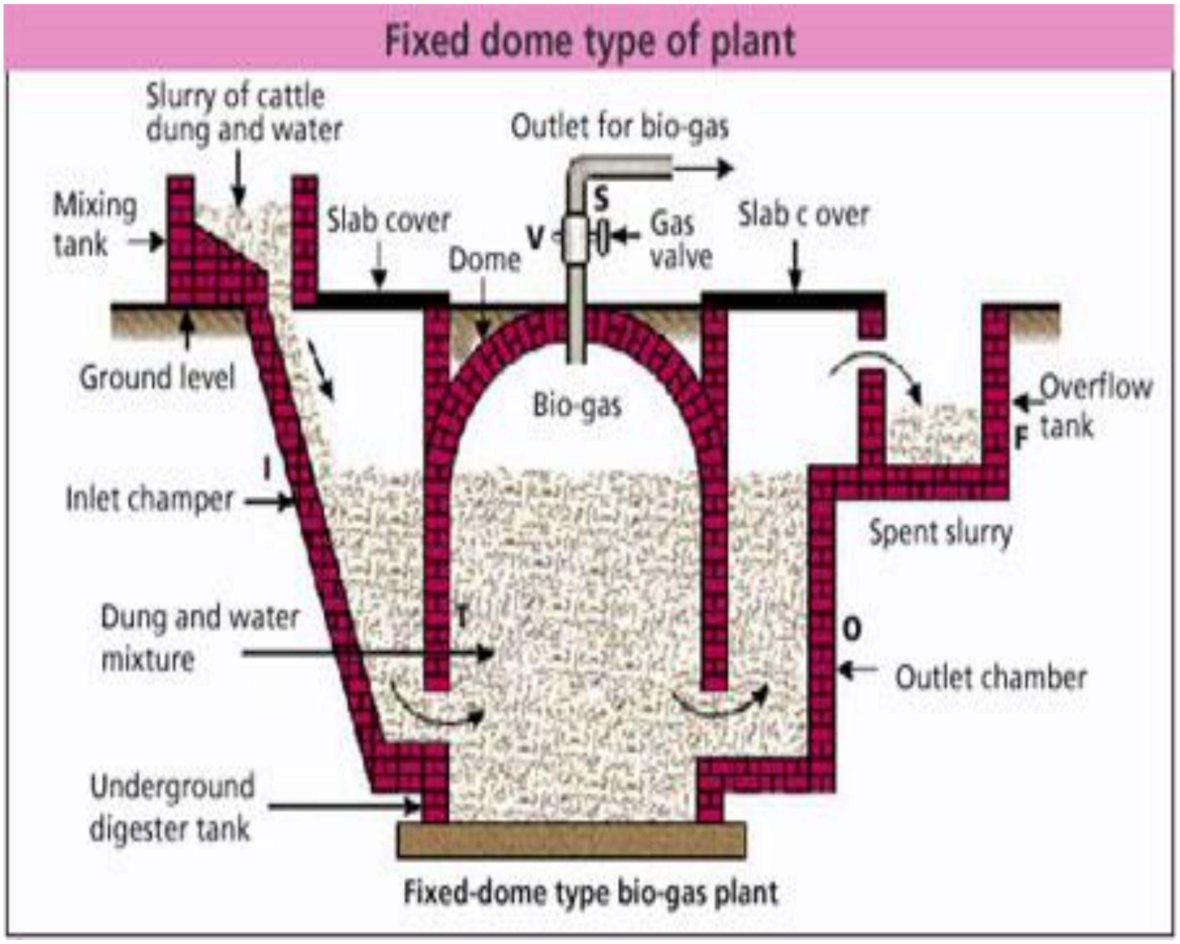


Fig.1.9. Fixed Digester biogas plant

BIOGAS

The biogas power plant works on fermentation concept. The feed is mixed with water and supplied to the digester and allowed there several days. The combustible gas contains methane comes out of it.

The typical composition of biogas is given below:

CH_4 = 60 %, CO_2 =35%, H_2 = 3.5%, N_2= 1%, H_2S = 0.3 %, CO = 0.2%.

The percent of methane gas plays major role in combustion and the quality of gas depends on the methane only.

Gross Calorific value: 23 MJ/m^3.

Ignition temperature: 650 °C.

Comparision of fixed dome and floating drum biogas plant

Table.1.2 Comparison of biogas plants

FIXED DOME BIOGAS PLANT	FLOATING DOME BIOGAS PLANT
Completely masonry concrete structure	Masonry digester with steel or composite or plastic gas holder
Lower cost	Higher cost 20-30% more than fixed dome
Low maintenance	High maintenance
Low reliability	Highly reliable
High masonry skill is required	Low masonry skill is required
High supervision is required	Less fabrication skill is required
Gas pressure is variable so complicated appliance design	Gas pressure is constant so simple appliance design

BIOGAS POWER PLANT

The biogas power plant consists of more number of biogas plants are connected to produce large quantity of biogas to produce electricity using IC engines and the effluent is de-watered and converted as compost and manure. The major parts of the plants are fuel preparation systems, anaerobic digester, anaerobic digestrate storage, power generation unit and effluent treatment systems.

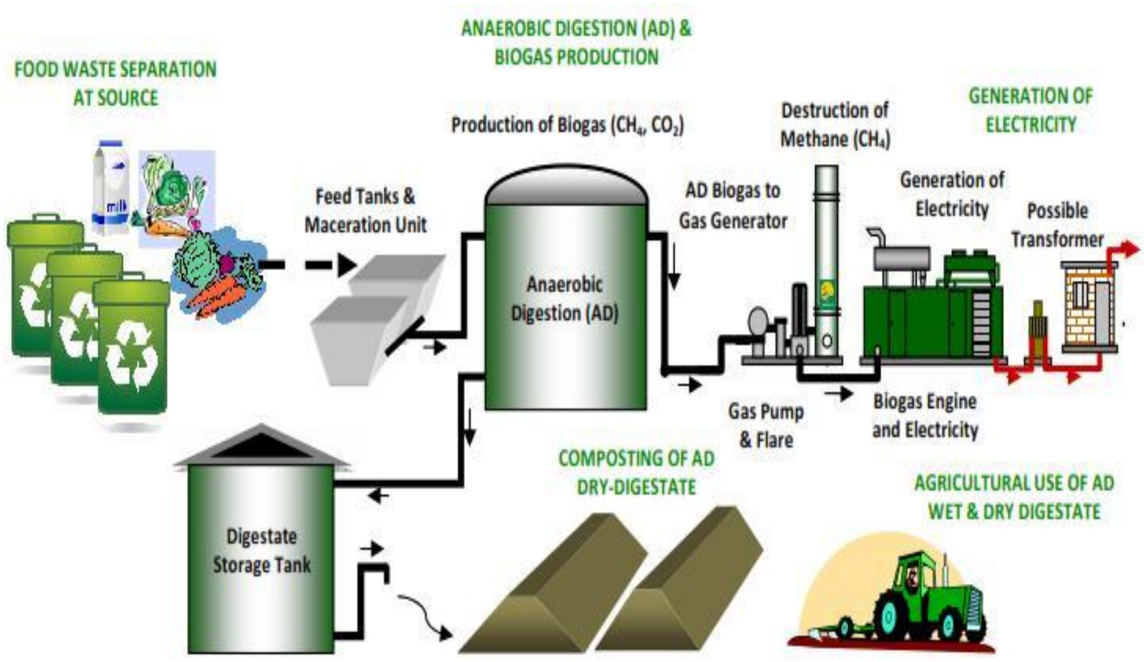


Fig.1.10 Anaerobic digester based biogas power plant (courtesy kznenergy.org.za)

Problems related to bio-gas plants operation:

All are controllable but reasons may be natural or man-made.

1. Handling of effluent slurry requires open space or compost pits to get the slurry dry.
2. Press filters and transportation are expensive.
3. Methanogenic bacteria are very sensitive to the temperatures. During the winter, the reduced temperature leads to reduced bacteria activity and less gas production. This effect can be reduced by any one of the following activities: a. Use of solar hot water to make slurry b. circulation of hot water from IC engines c. Green house effect. d. Manual or auto stirring of slurry e. Addition of various nutrients for bacteria f. Covering plant by rice straws to warm up in night time.
4. Lack of proper training of biogas plant owners.
5. Addition of urea mixed water or soap or shampoo water mixing may leads to reduced bio-gas production.
6. pH level and volatile fatty acids play important role in gas production. Lime can be added to maintain pH level above 6-7.
7. Leakage of gas from gas holder. Quality construction is important.
8. Slurry preparation in correct water content and periodic effluent removal are important.

Selection of site for a biogas plant

Considerable site selection factors are given below:

1. **Distance** between the plant and gas consumption should be less to minimize gas leakage and pumping power. e.g. Optimum distance is 10m for 2 m^3 plant capacity.
2. Preferred **minimum gradient** for conveying the gas is 1% for the line.
3. **Open space** is required for sun radiation to maintain temperature between 15 -30 °C.
4. **Water table** should not be less than 3 m. It leads to seepage of water into the plant and reduces the methane production.
5. Proper care is to be taken against **seasonal run-off**.
6. **Distance from wells** to avoid pollution of well water by entry of slurry. Keep 15 m distance from wells.
7. **Sufficient Space requirements.** 10-12 m2 area required per m3 of gas capacity.

8. **Availability of water**
9. **Source of cowdung/materials for biogas production.**

Digester design

Energy available from a biogas plant**, $\mathbf{E = \eta H_b V_b}$**

η - Combustion efficiency of burner (around 60%)

H_b – Heat of combustion per unit volume in kJ/m^3 = CV of methane x Fraction of methane

V_b - Volume of the biogas, $m^3 = C\ m_d$

Where C – Volume of biogas per unit dry mass (0.2-0.4 m^3 per kg)

m_d – Mass of dry input (kg)

Volume of fluid in the digester, $V_f = m_d / \rho$

Where ρ - density of dry material in the fluid (around 50 kg/m^3)

Volume of the digester, V_d = Volume flow rate of digester fluid x retention time

Retention time is usually 8 – 20 days.

<u>Problem.1.1</u>

The following data are given for a family biogas digester suitable for the output of five cows: 20 days retention time, 30 °C temperatures, 2 kg dry matter consumed per day, biogas yield 0.24 m3 per kg. The efficiency of burner is 60%, methane proportion is 0.8. Heat of combustion of methane is 28 MJ/m3. Find the volume of biogas plant digester and power available from the digester. Assume density of dry matter = 50 kg/m^3.

Solution:

Mass of dry input per day, m_d = 2 x 5 = 10 kg

Fluid volume, $Vf = m_d / \rho$ = 10/50 = 0.2 m^3.

Digester volume, V_d = 0.2 x 20 days **= 4 $\mathbf{m^3}$.**

Volume of biogas, $V_b = C\ m_d$ = 0.24 x 10 = 2.4 m^3 per day.

Power available from the digester, E = $\boldsymbol{\eta}$ $\mathbf{H_b}$ $\mathbf{V_b}$ **=** 0.6 x (28x0.8)x 2.4 **= 32.25 MJ/day**

E = 32.25/3.6 = **8.8 kWh per day**

E = 32.25 x 10^6 / (24 x 3600) **= 373 W. (Continuous thermal output)**

Problem 1.2

The following data are given for a community biogas digester suitable for the output of 125 cows: 20 days retention time, 30 °C temperatures, 2 kg dry matter consumed per day, biogas yield 0.25 m3 per kg. The efficiency of burner is 60%, methane proportion is 0.7. Heat of combustion of methane is 30 MJ/m3. Find the size of biogas plant digester and power available from the digester. Assume density of dry matter = 50 kg/m^3.

Solution:

Mass of dry input per day, m_d = 2 x 125 = 250 kg

Fluid volume, Vf = $m_{d\,/}\,\rho$ = 250/50 = 5 m^3.

Digester volume, V_d = 5 x 20 days = 100 m^3.

Volume of biogas, V_b = C m_d = 0.25 x 250 = 62.5 m^3 per day.

Power available from the digester, E = $\boldsymbol{\eta}$ $\mathbf{H_b}$ $\mathbf{V_b}$ **=** 0.6 x (30x0.7)x 62.5 **= 787.5 MJ/day**

E **=** 787.5 x 10^6 / (24 x 3600) **= 9115 W. (Continuous thermal output)**

Digester volume, V_d = π D^2 x H / 4 ….. (Cylindrical volume, D-Diameter, H-Height)

Preferred size is D = H, 100 = π D^3 / 4. D = $(4 \times 100 / \pi)^{1/3}$ = 5 m.

Size of digester: Diameter = 5m, Height = 5m.

Advantages of biomass energy

1. Versatile and renewable

2. No net CO_2 emissions (ideally) and emits less SO_2 and NO_x than fossil fuels

3. Production of alternate fuels like alcohol fuels.

4. Methanol and ethanol can be blended with diesel fuels for IC engine applications.

Disadvantages of biomass energy

1. Low energy density/yield

2. Land conversion (Biodiversity loss, possible decrease in agricultural food productivity)

3. Usual problems associated with intensive agriculture

- Nutrient pollution,
- Soil depletion,
- Soil erosion,
- Other water pollution problems etc.

UNIT II.SOLAR ENERGY

SOLAR RADIATION

The sun's surface temperature is around 5300° C. The solar radiation from the sun is around 178 TW. The solar rays reach the earth surface through the atmosphere. The radiation above the atmosphere is called as **extra terrestrial radiation** and the radiation below the atmosphere is called as **terrestrial radiation or global radiation**.

Global radiation = Beam or direct radiation + Diffuse or scattered radiation.

The direct radiation reaches the earth from sun directly but diffuse radiation is due to scattered effect of atmosphere and the particles in the air. The reflected rays by the earth surface is called albedo. The solar energy potential or intensity on earth surface is around 0-1 kW/m^2 (night to noon). The solar constant is defined as the solar radiation incidence per m^2 of atmosphere . Its value is 1367 W/m^2.

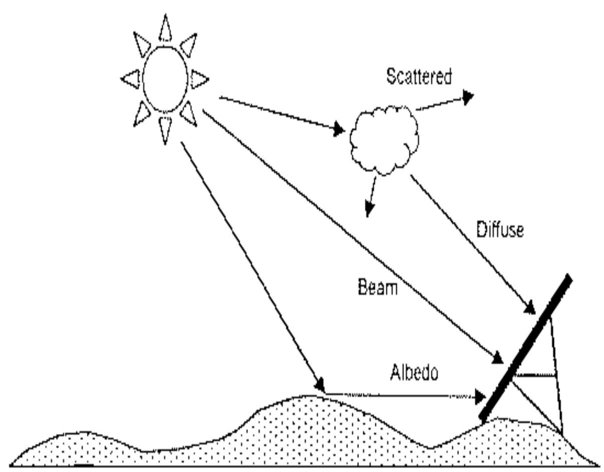


Fig.2.1. Solar radiation components

The angles in solar geometry:

Altitude angle (α): The angle between beam radiation and the ground.

Incidence angle: The angle of incidence of beam radiation from the zenith. In case of Horizontal surface collectors the incidence angle is equal to zenith angle.

Zenith angle: The angle between the beam radiation and Vertical plane.

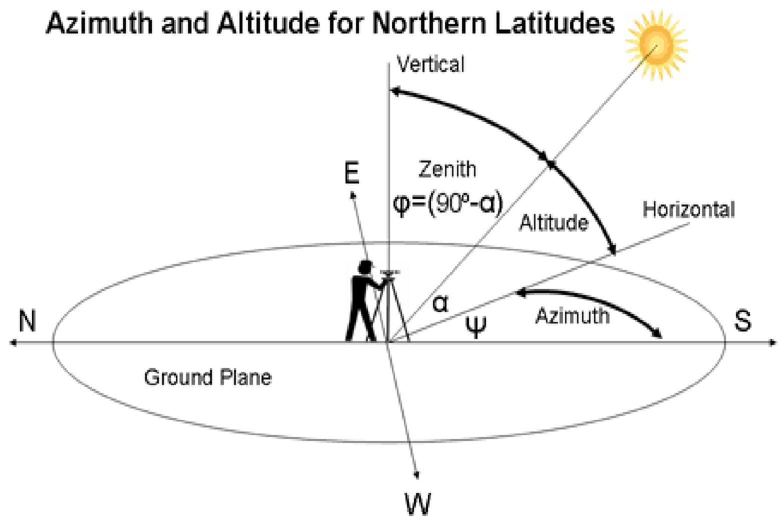


Fig.2.2. Solar Geometry

The **solar azimuth angle** is the azimuth angle of the sun. It defines in which *direction* the sun is, whereas the solar zenith angle or solar elevation defines how high the sun is. (The elevation is the complement of the zenith.) There are several conventions for the solar azimuth; however it is traditionally defined as the angle between a line due south and the shadow cast by a vertical rod on Earth.

SOLAR RADIATION MEASUREMENTS

1. **Pyranometer :** To measure global radiation (both beam and diffuse radiation)

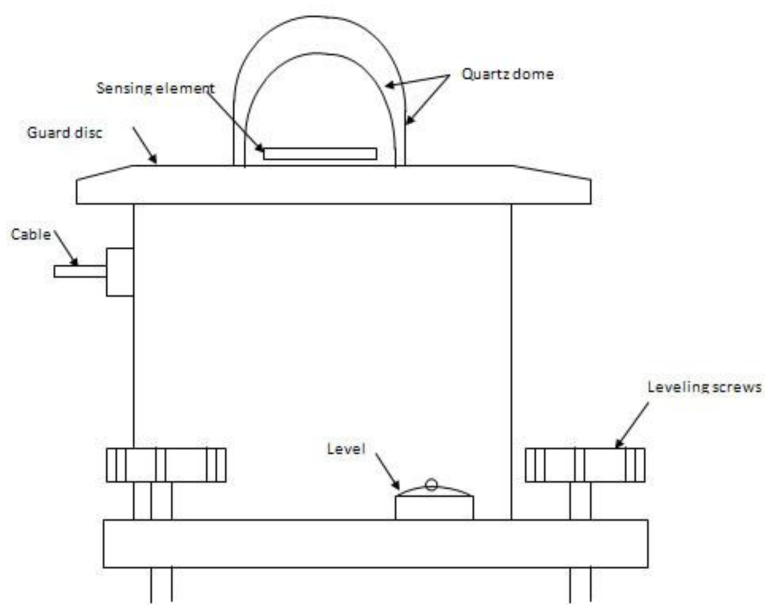


Fig.2.3. Pyranometer

The quartz domes collects the beam and diffuse incident solar radiations. The sensing element is subjected to heating by solar radiation and its thermal resistance is used to measure the global radiation by using the emf generated.

2. **Pyrheliometer :** To measure beam radiation.

Pyrheliometer has a collimator tube to collect the beam radiation component and the thermal resistance of black absorber plate is used to determine the intensity of the beam radiation. This narrow tube allows only beam radiation to reach the sensing element.

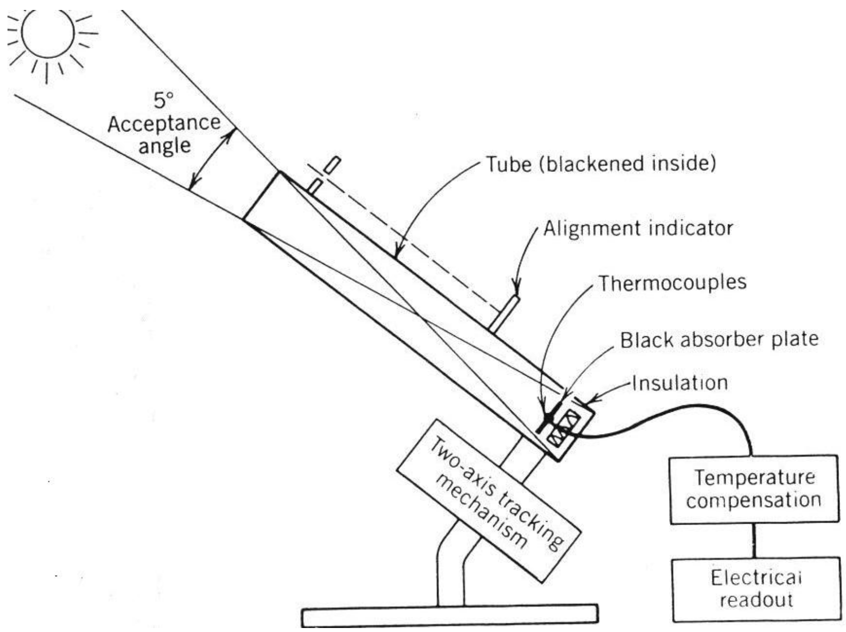


Fig.2.4. Pyrheliometer

3. Pyrgeometer: To measure IR and long wave radiation.

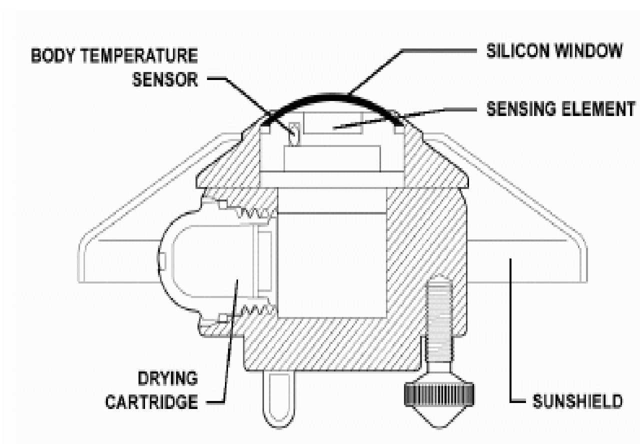


Fig.2.5. Pyrgeometer

4. Sunshine recorder: To measure the actual sunshine daily hours. The working principle is the based on the length of card board paper burnt in the spherical glass. The spherical bowl is calibrated in such a way that the length of paper burnt is directly proportional to the active solar hours.

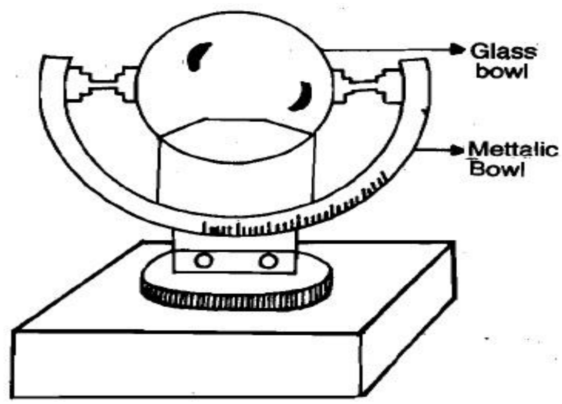


Fig.2.6. Sunshine recorder

SOLAR THERMAL ENERGY TECHNOLOGIES

The solar collectors are broadly classified as solar thermal collectors and photovoltaic cells. Then the thermal collectors are classified as follows:

I. Based on Concentration

- Non-concentrated .. Flat plate collectors
- Concentrated collectors … Parabolic collectors

II. Based on sun-tracking

- Single axis tracking . ….. Parabolic and cylindrical trough collectors
- Two-axis tracking …… Parabolic dish collectors, Heliostat Mirror field

SOLAR FLAT PLATE COLLECTORS

The flat plate collectors contains absorber plate (to increase the heat absorption rate) , absorber tube (to carry the heat transfer fluids), insulation on all sides except aperture area, glass cover (to transmit the incident rays and retain rays inside the collector) etc. The working temperature range of this collector is around 60-120 °C. The major classification is Flat plate collector, Evacuated tube collector, compound parabolic collectors. It’s suitable for mainly domestic thermal applications. The flat plate collectors can be classified further as liquid heaters and air heaters.

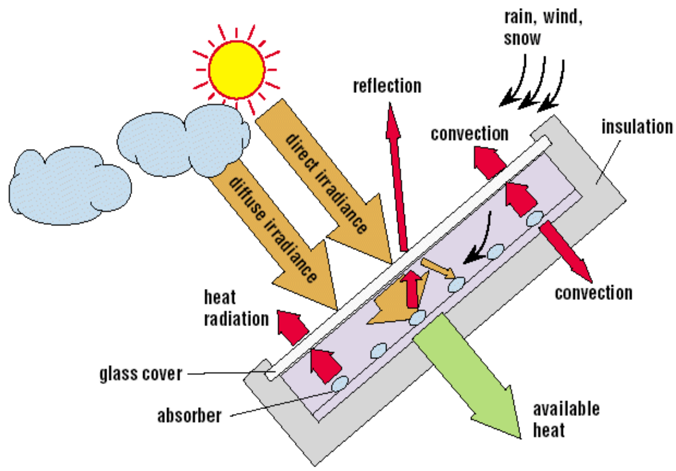


Fig.2.7.Solar flat plate collector

Derivation of collector efficiency and heat loss coefficients (Performance factors) of solar flat plate collector

The energy balance of the absorber can be represented by a mathematical equation:

$$\mathbf{Q_u = A_p\, S - Q_L} \text{ --------------- Eqn. 1}$$

Where,

Q_u = Useful heat delivered by the collector, Watts

A_p = Area of the absorber plate, m^2

S = Solar heat energy absorbed by the absorber plate, W/m^2

Q_L = Rate of heat loss by convection & re-radiation from the top, by conduction & convection from sides and by conduction & convection from the bottom, Watts

The solar flux falling on the top cover is given by

$$\mathbf{I_T = I_b *R_b + I_d * R_d + (I_b + I_d) * R_r} \qquad \text{--------------- Eqn. 2}$$

(Suffix "b" , "d" and "r" denote beam, diffused & tilt factor respectively.)

The flux absorbed is obtained in the above equation (2) to be multiplied by the transmittivity-absobvity product ($\tau\alpha$), then the equation (2) becomes,

$$\mathbf{S = I_b *R_b * (\tau * \alpha)_b + I_d * R_d * (\tau * \alpha)_d + (I_b + I_d) * R_r * (\tau * \alpha)_r} \qquad \text{--------------- Eqn. 3}$$

Now it is necessary to define the two terms – Instantaneous collector efficiency* and stagnation temperature#, which are required to indicate the performances of the collector and also for comparing the designs of different collectors.

$$\eta_i = Q_u / (A_p * I_T) \text{ --------------- Eqn. 4}$$

** "Instantaneous collector efficiency" is defined as the ratio of useful heat gain to radiation falling on the collector.*

 # The maximum temperature that the absorber can attain is called as "Stagnation temperature".

Ac is usually 15-20% more than Ap.

Total loss co-efficient and Heat losses

Heat loss from the collector using he total loss coefficient is given by the equation:

$$Q_L = U_T * A_p * \{ T_P - T_a \} \text{ --------------- Eqn. 5}$$

Where,

Q_L = Rate of heat loss by convection & re-radiation from the top (Q_t) + by conduction & convection from sides (Q_s) + by conduction & convection from the bottom (Q_b),Watts

U_T = Total loss coefficient

T_P = Average Mean temperature of the absorber plate, K or C

T_a = Surrounding or ambient temperature of air, K or C

A_p = Area of the absorber plate, m^2

The collector losses are from top, the bottom and the sides.

Total heat loss loss coefficient is given by $U_T = U_t + U_b + U_s$ --------------- Eqn. 6

Total heat loss, $Q_L = Q_t + Q_b + Q_s$ --------------- Eqn. 7

The total heat loss coefficient (U_t) ***normally ranges from 2 to 10 W/m²***.

To find out Q_t, Q_s & Q_b, the following equations can be used:

$Q_t = U_t * A_p * \{ T_P - T_a \}$ --------------- Eqn. 8

$Q_b = U_b * A_p * \{ T_P - T_a \}$ --------------- Eqn. 10

$Q_s = U_s * A_p * \{ T_P - T_a \}$ --------------- Eqn. 11

$U_b = k_i / x$ --------------- Eqn. 12

$U_s = (L_1 + L_2) * L_3 * k_i / (L_1 * L_2 * y)$ --------------- Eqn. 13

Where,

k_i = Thermal conductivity of Insulation, W/m.K

x & y = Thickness of Insulation, m

L_1, L_2 & L_3 = Length, width & height respectively, m

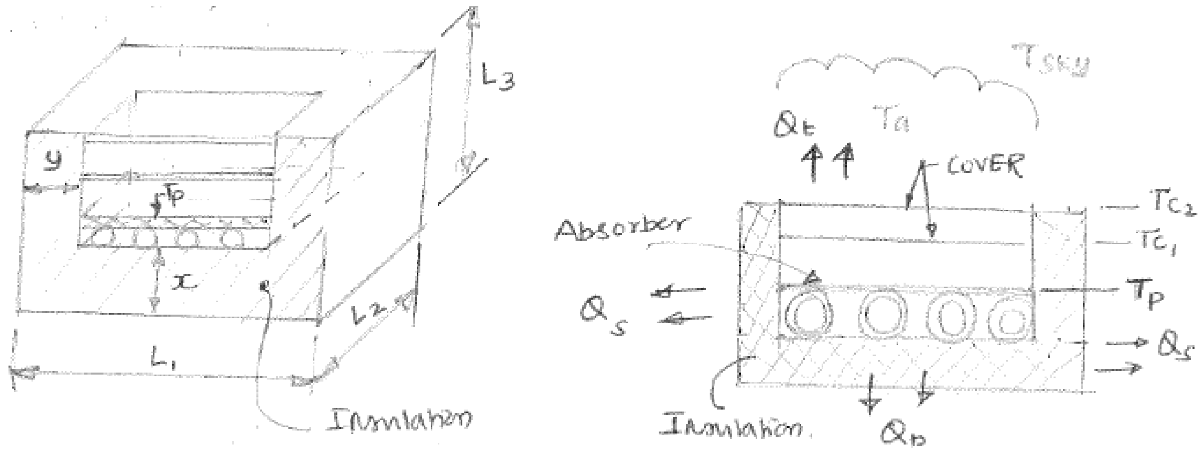


Fig.2.8 Flat plate collector dimensions

Heat loss coefficient ($\mathbf{U_{t1}}$) between absorber plate and top cover 1 is given by

$\mathbf{U_{t1} = h_{p\text{-}c1} * \{T_P - T_a\} + [\sigma \{T_P^{\,4} - T_{c1}^{\,4}\} / \{(1/\varepsilon_p + 1/\varepsilon_c) - 1\}]}$ --------------- Eqn. 14

Heat loss coefficient ($\mathbf{U_{t2}}$) between top cover 1 and top cover 2 is given by

$\mathbf{U_{t2} = h_{c1\text{-}c2} * \{T_{c1} - T_{c2}\} + [\sigma \{T_{c1}^{\,4} - T_{c2}^{\,4}\} / \{(1/\varepsilon_c + 1/\varepsilon_c) - 1\}]}$ --------------- Eqn. 15

Heat loss coefficient ($\mathbf{U_{t3}}$) between top cover 2 and air is given by

$\mathbf{U_{t3} = h_{c2\text{-}a} * \{T_{c2} - T_a\} + [\sigma * \varepsilon_c \{T_{c2}^{\,4} - T_{sky}^{\,4}\}]}$ --------------- Eqn. 15 and

$\mathbf{U_{t\,=}\, U_{t1} + U_{t2} + U_{t3}}$ --------------- Eqn. 16

Where,

$h_{p\text{-}c1}$ = Convective heat transfer co-efficient between absorber plate and top cover 1, W/m^2.K ,

$h_{c1\text{-}c2}$ = Convective heat transfer co-efficient between top cover 1 and top cover 2, W/m^2.K ,

$h_{c2\text{-}a}$ or h_w= Convective heat transfer co-efficient between top cover 2 and surroundings, W/m^2.K

T_{c1} & T_{c2} = Temperature of the top cover 1 and top cover 2 respectively, in K

T_{sky}= Temperature of the sky, in K

$\boldsymbol{\varepsilon_p}$ **&** $\boldsymbol{\varepsilon_{c1}}$ = Emissivity of absorber plate and cover plate,

$\mathbf{h_{c2\text{-}a}}$ **or** $\mathbf{h_w}$**= 5.7 + 3.8 *V**, W/m^2.K --------------- Eqn. 17

Where, V = Wind speed, m/s

Collector Heat Removal Factor

$$\mathbf{F_R = [(m * C_p) / (U_L * A_P)] * (1 - e^{\{(-F' * U_L * A_P) / (m * C_p)\}}} \text{ --------------- Eqn. 18}$$

Where,

F' = Collector efficient factor

m = mass flow rate

C_p = Specific heat

Problem. 2.1

In a solar water heater, the collector plate is at 87 °C and glass cover is at 67 °C. Heat from collector plate is lost to the air by convection and to the glass cover by radiation. If the heat transfer co-efficient by convection is 4.6 W/m^2 K, find the heat loss from the collector plate per hour per m^2 surface area. Also find the equivalent radiation heat transfer co-efficient. Assume emissivity of plate is 0.2 and emissivity of glass is 0.3 and radiation shape factor is 1.

Solution :

Suffix-p for Plate and g for Glass.

Equivalent emissivity, $\varepsilon_{equi} = 1/ \{ [1/\varepsilon_p + 1/ \varepsilon_g] -1 \} =$ 0.136

The radiation heat transfer coefficient

hr = $\sigma\ \varepsilon_{equi} (Tp^4 - Tg^4) / (Tp - Tg) =$ **1.32 W /m^2 –K**

Total heat loss by collector plate, Qt = (hc+hr) As (Tp – Tg) = **118.4 W/m^2.**

Problem 2.2

A solar water heating plant with a FPC has to be designed based on the following data:

Daily solar radiation = 5 kWh/m^2 per day
Hot water consumption = 1000 kg per day
Hot water temperature = 45 C
Cold water temperature = 14 C
Plant mean efficiency = 48 %.

Isobaric specific heat of water = 1.163 W h/kg-K
Determine total collector surface area and the number of solar collector modules required if a single module has an area of 2.2 m^2.

Solution:

Daily heat requirement,

Qhw = m Cp (Th – Tc)

= 1000 x 1.163 x (45-14) = 36053 W h /day

Daily useful heat output by ignoring heat losses,

Q = Incident radiation x Efficiency = 5 x 0.48 = 2.4 kWh/day

Required collector surface area, A = Qhw / Q = **15.02 m2**

No. of collector panels required, N = 15.02 / 2.2 = **7 collectors**

HEAT TRANSFER ANALYSIS OF CYLINDRICAL PARABOLIC COLLECTOR

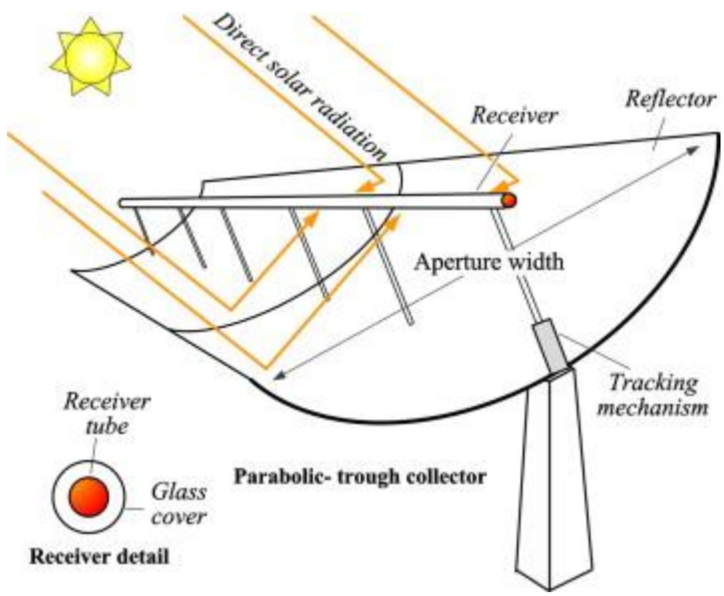


Fig.2.9 Solar Parabolic collector

Let W = Aperture width of the concentrator in m

L1 = Length of the concentrator in m

θ = Rim angle in degrees

d = Diameter of absorber tube in m

D = Diameter of glass tube in m

m = Mass flow rate of HTF in kg/s

Tfi, Tfo = HTF temperature at inlet and outlet respectively

Cp = Specific heat of HTF in kJ/kg-K

C = Concentration Ratio = Effective aperture area / Absorber tube area

I_b = Perpendicular incident solar beam radiation (W/m^2)

R_t= Tilt factor of the reflector

r = Reflectivity of the concentrator surface

F_i = Intercept factor. It is the fraction of the reflected radiation intercepted by the absorber tube.

$\alpha \tau$ = Product of absorptivity and transmissivity of absorbing surface for radiation

U = Overall heat transfer coefficient from the absorbing tube surface.

T_p = Local temperature of absorber tube

T_a = Ambient air temperature

T_f = Local temperature of the flowing fluid

Consider **dQu** is the useful heat gain for the length **dy** of the absorber tube

Heat gain by the absorber = Energy absorbed by the absorber tube +

Direct energy falling and absorbed by absorber -

Heat loss from the absorber tube

$dQu = dQ_1 + dQ_2 - dQ_{loss}$

dQ_2 can be neglected if C is very high and It can not be ignored if C is small.

Anyway dQ_2 is less than dQ_1.

$dQu = I_b [(W-d) dy] R_t r F_i (\alpha \tau) + I_b (d dy) R_t (\alpha \tau) – (\pi d dy) U (Tp – Ta)$ ……….1

If S is the solar flux falling on the concentrator and it is completely absorbed by the absorber tube, $dQ_{loss} = 0$,

$S (W-d) dy = I_b [(W-d) dy] R_t r F_i (\alpha \tau) + I_b (d dy) R_t (\alpha \tau)$

$S = I_b R_t r F_i (\alpha \tau) + I_b d R_t (\alpha \tau) / (W-d)$

$I_b R_t r F_i (\alpha \tau) = S - I_b d R_t (\alpha \tau) / (W-d)$

By substituting this in equ(1),

$dQu = (W-d) dy [S - U (Tp – Ta) / C]$

The useful heat gain also can be written as

dQu = Heat convected by the tube surface to the fluid = Heat gained by the fluid

$dQu = h_p (\pi d dy) (Tp – Tf) = m Cp dTf = m Cp (Tfo – Tfi)$

Where h_p : Convective heat transfer co-efficient on the pipe surface ($W /m^2 K$)

Collector Efficiency Factor, $F' = 1 / [1 + U / h_p]$

$m Cp dTf = F' (W-d) dy [S - U (Tp – Ta) / C]$

Heat Removal Factor (HRF), $F_R = P [1- \exp (- F'/P)]$ Where $P = m Cp / (\pi d L_1 U)$

Instantaneous collector efficiency, $\eta = Qu / [(I_b R_b + I_d R_d)W L]$

Problem 2.3

A solar concentrating collector consisting of a PTC and an absorber tube uses thermo-oil as HTF. The beam radiation intensity is 750 W/m^2. The unshaded area is 240 m^2 and the CR is 40. The inlet temperature of thermo-oil is 280 C, its mass flow rate is 0.6 kg/s and Cp is 3200 J/kg-K. The ambient is at 30 C. The optical efficiency is 0.74, heat loss coefficient of the absorber is 7 W / m^2-K and the HRF is 0.96. Determine the useful heat output of the collector and outlet temperature of the HTF?

Solution:

Solar concentrating collector:

$Q = F_R$ x A [I_b x Opt. Efficiency – (U_{loss}/ CR) (Ti – Ta) = **117792 W**

To = Ti + Q / (m Cp) = **341.35 C**

Problem.2.4

A cylindrical parabolic collector having 2.5 m width and 10 m long is used to heat fluid entering at 150 C with a flow rate of 7.5 kg/min (Cp = 1.25 kJ/kg.C). The diameter of the absorber tube is 6.5 cm which is covered with glass tube. Take the following data: Ib = 700 W /m2, Ta = 30 C, Optical properties $(\alpha\tau)_{ab}$ = 0.8, r_r = 0.93 and τ_g = 0.85. Also take collector efficiency factor, F' = 0.85, heat loss co-efficient = 8 W /m2-C, Tilt and intercept factor is 1. Find the useful heat gain, exit temperature of fluid and collector efficiency.

Solution:

Solar energy absorbed by the absorber,

$S = Ib\ Rt\ (\alpha\tau)_{ab}\ [r_r\ \tau_g\ Fi + (d / (W-d))]$ = **442.4 W/m2**

Heat removal factor, HRF , $F_R = P\ [\ 1 - \exp(- F'/ P\ ]$ = 0.813

(Where $P = m\ Cp / \pi\ d\ L\ U$ = 9.56)

Concentration Ratio, $CR = (W-d) / \pi d$ = 11.93

Useful heat gain, $Qu = F_R\ (W-d)\ L\ [\ S - U /CR\ (Ti - Ta)$ = **7167.6 W**

Exit temperature, $Qu = m\ Cp\ (To - Ti)$, **To = 196 °C**

Collector efficiency, $\eta = Qu / [Ib\ Rt\ W\ L]$ **= 0.41 %**

SOLAR PARABOLIC TROUGH POWER GENERATION

An array of parabolic trough collectors are used to achieve high temperature around 400 °C of water and an additional firing involved to run during non-solar times as well as lean solar time. The working principle is simple steam power cycle (Rankine cycle). The steam power cycle has the components like turbine, condenser, cooling tower and pump. This power cycle can employ a direct HTF from the collector to turbine or binary fluid as one HTF in the solar collector field and another HTF in turbine through a heat exchanger.

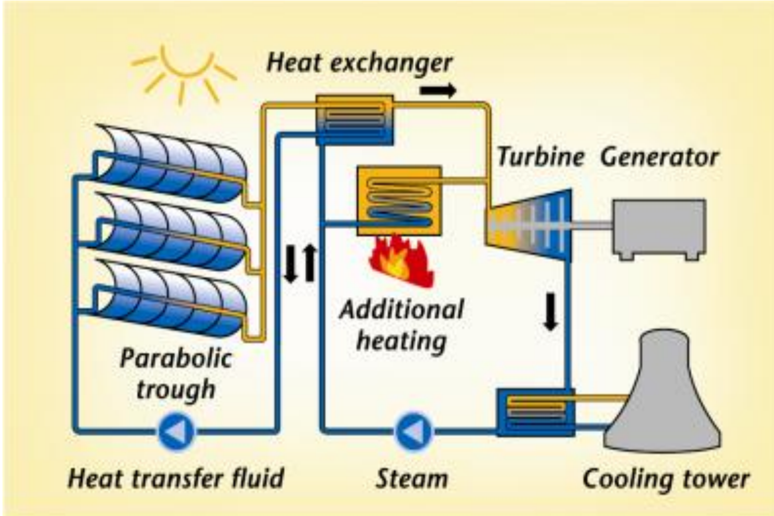


Fig.2.10.Parabolic trough power plant

SOLAR CENTRAL RECEIVER POWER PLANT

The boiler is placed centrally in the large mirrors field. Array of heliostat mirrors are used to focus the solar rays towards the central receiver to produce high temperature more than 500 °C in order to produce steam out of feed water. The generated steam is used to run a steam turbine and then the exhausted low pressure water is condensed in condenser and pumped back to the boiler.

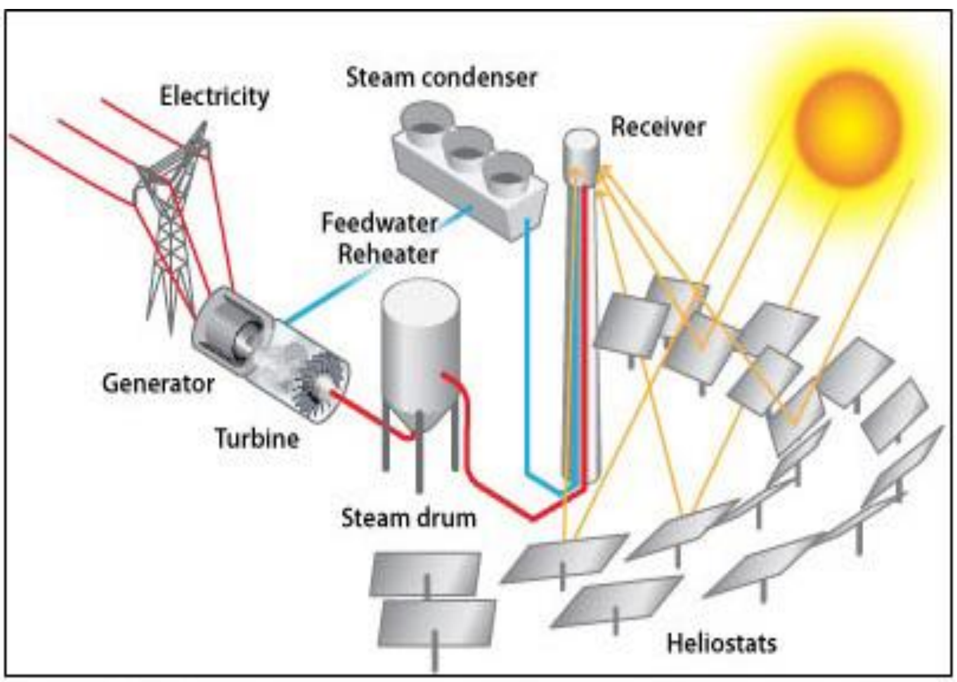


Fig.2.11.Solar tower (central receiver) power plant

SOLAR STILLS (SOLAR DESALINATION)

The working principle of solar stills is similar to rainfall. The evaporation and condensation of saline or sea water is used in the solar stills to produce potable water.

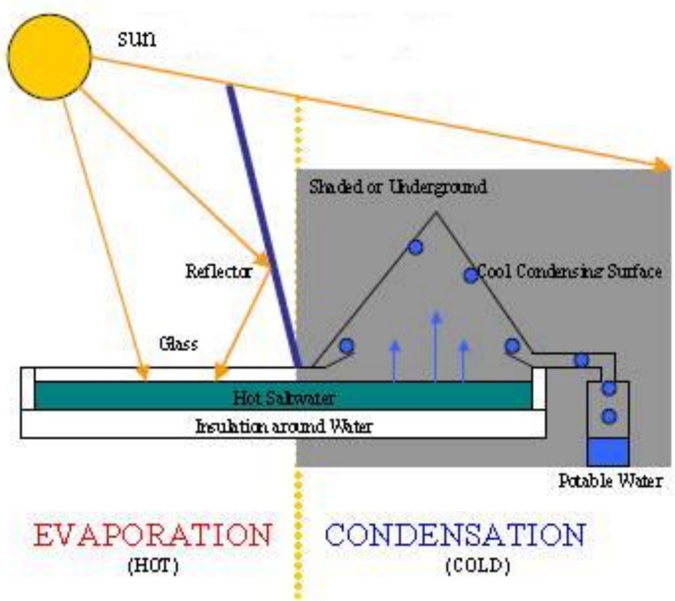


Fig.2.12. Solar Still

The solar energy is used to evaporate the salt water using the focused solar radiation and the condensation of that vapour takes place in the shaded or underground place. The shaded or cold surface is used as condensing surface. The condensed water is collected.

SOLAR COOLING AND REFRIGERATION

The solar cooling and refrigeration system operates based on vapour absorption refrigeration principle or vapour compression refrigeration principle.

The solar vapour absorption refrigerator has the following components:

1. Generator
2. Absorber
3. Condenser
4. Evaporator
5. Heat exchanger
6. Pump and throttle valves

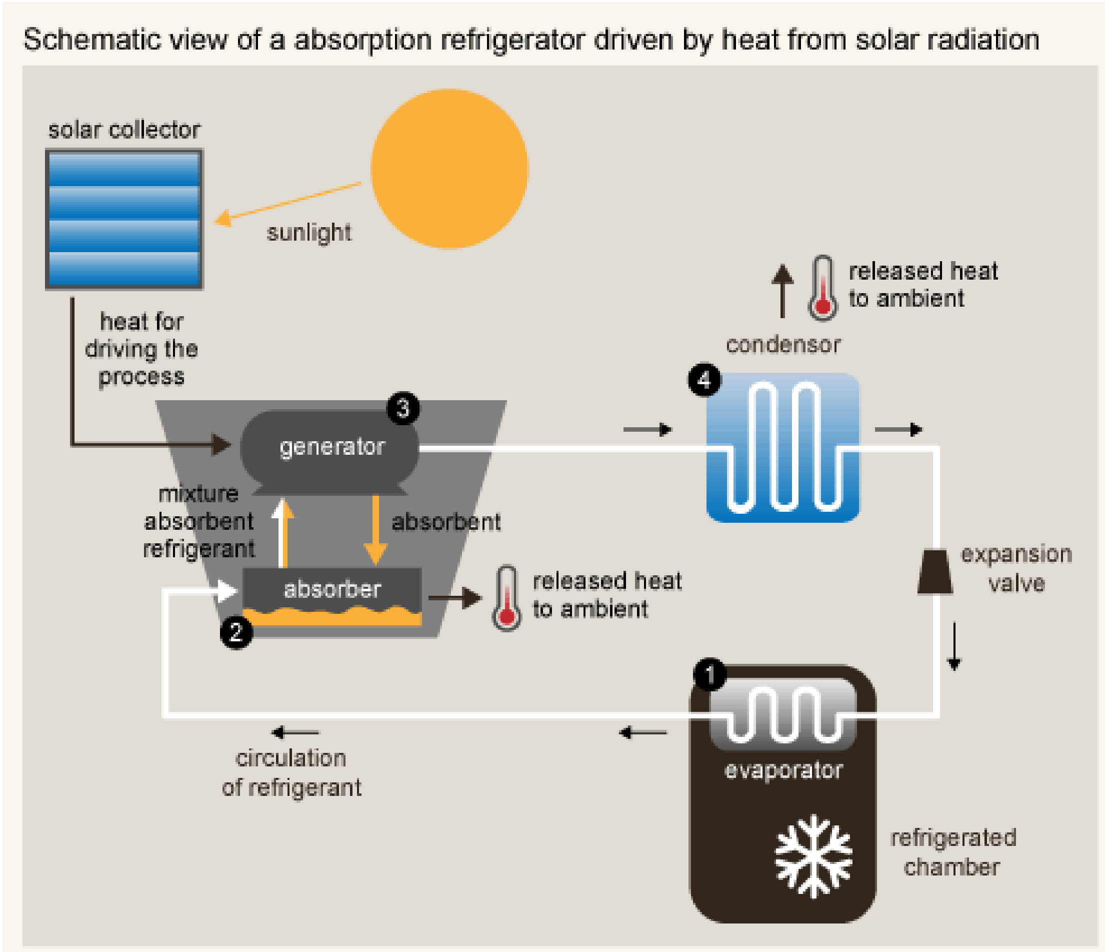


Fig.2.13. Solar Vapour absorption Refrigeration

Solar energy is used to run the vapour generator of the system. The high pressure hot water around 120°C is used in the generator to separate the refrigerant and absorbent. The absorbent material is having great affinity towards the refrigerant vapour. The strong mixture (rich refrigerant in the absorbent liquid) is pumped to the generator and then the refrigent vapour goes to the condenser and then its expanded to low pressure and temperature liquid in a throttle valve. This refrigerant liquid is absorbs the heat in the evaporator section and the refrigerant vapour is absorbed by the absorbent in the absorber and the cycle is repeated.

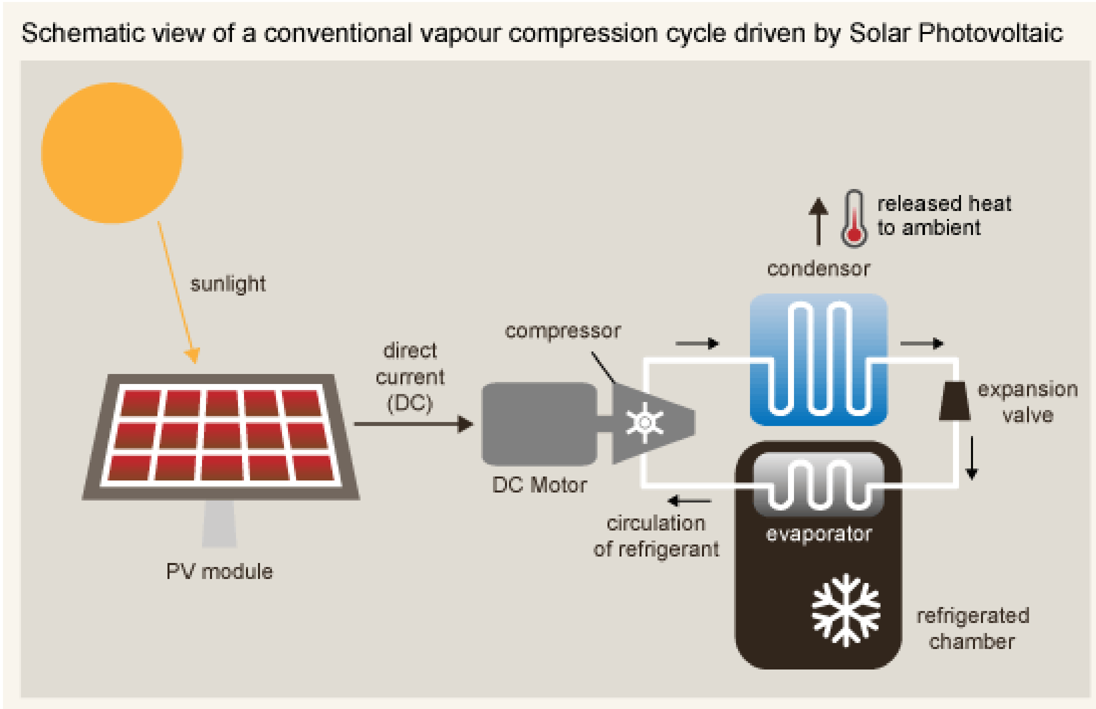


Fig.2.14 SPV operated vapour compression refrigeration system

The solar vapour compression refrigeration can be run by DC/AC motor (using solar photovoltaics) or using solar operated vapor turbine. The first case requires solar PV panels and or a battery. The second case requires a solar thermal steam generation systems with parabolic trough or dish system and the turbine is connected with the vapour compressor of the vapour compression refrigeration system.

SOLAR AIR-CONDITIONING SYSTEM

This solar HVAC consists of heat supply system, chilled water supply system, air-conditioned space. The chiller operates on vapour absorption refrigeration principle. The vapour absorption refrigeration based chiller is used to provide cold energy. The water passed to the chiller gets cooled and the cold water supplied to the room and the blower flows air over the cold water coils and the chilled air supplied to the room. The return air from the room exhausted to the atmosphere.

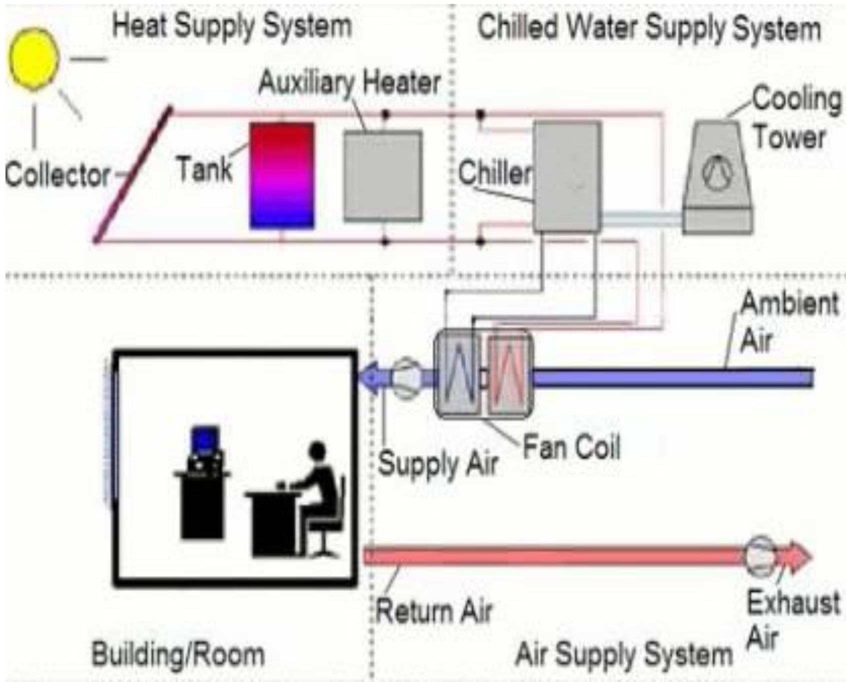


Fig 2.15. Solar A/C system

In case of solar combined heating and cooling, the vapour absorption chiller and a hot water coils are used. The hot water circuit used for the heating needs and the chiller provides the cooling needs.

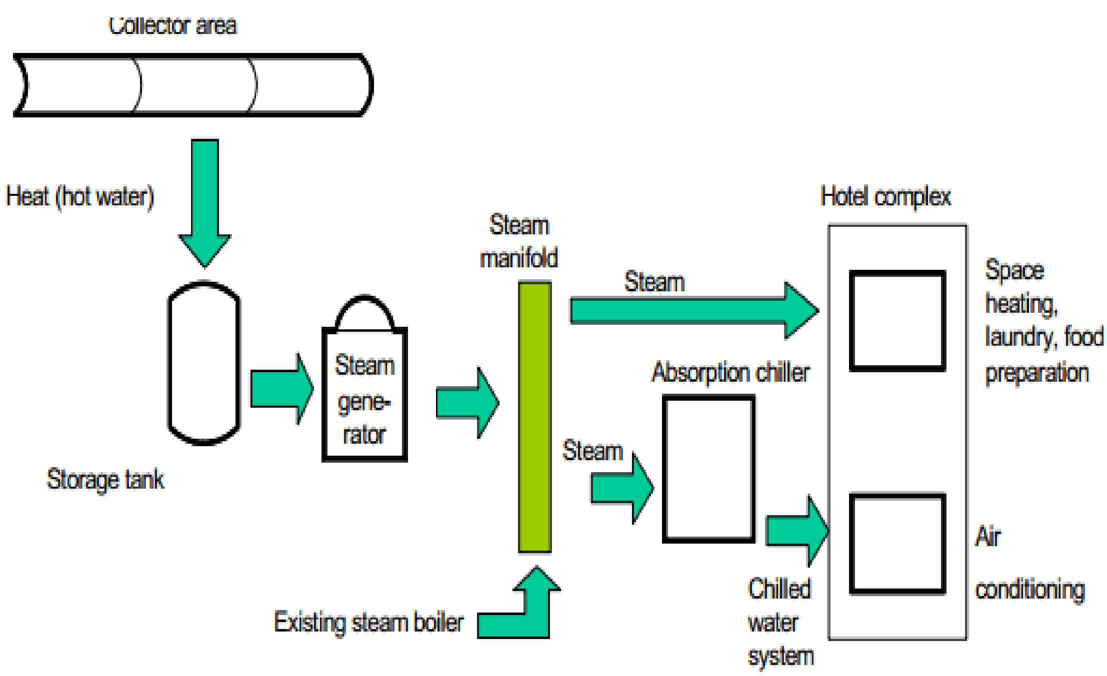


Fig.2.16. Solar heating and cooling in hotels (combined heating and cooling)

SOLAR PHOTOVOLTAIC SYSTEMS (SPV)

Semiconductor materials (Si) are capable of conducting electricity if the more than 1.12 eV is supplied. The semiconductors are doped with some impurities to make n (excess electron) or p (excess hole) type semiconductor. Doping materials Boron, Cadmium etc.

SPV Cells uses semi-conductor materials which is capable of free the electrons by use of light energy (Photon-light or sun rays into Electrons – electricity). The p-n type semiconductors are arranged and the n-type has mobile electrons and p-type has mobile holes and the photons (more than 2 eV) produces the DC electricity from the SPV panels. The arrangement of solar panels (multiple solar cells) will give the desired electric power.

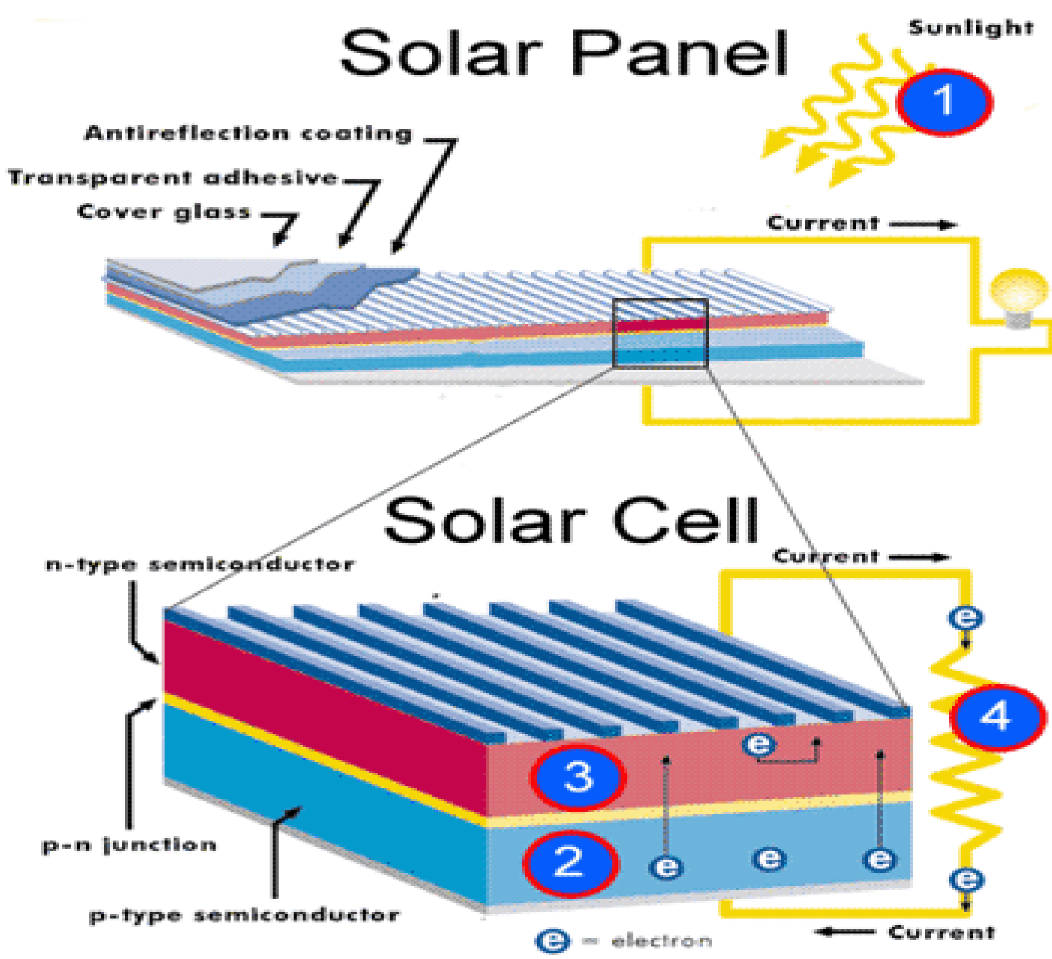


Fig.2.17. Solar Cell construction

Solar PV Modules, Panels and Array

Cells require protection from the environment and are usually packaged tightly behind a glass sheet. When more power is required than a single cell can deliver, cells are electrically connected together to form photovoltaic modules, or solar panels. A single module is enough to power an emergency telephone, but for a house or a power plant the modules must be arranged in multiples as arrays.

Cell : A single SPV cell.

Module: No. of interconnected encapsulated solar cells. A photovoltaic module is a packaged, connected assembly of solar cells.

Panel: Collection of modules. A solar panel is a set of solar photovoltaic modules electrically connected and mounted on a supporting structure.

Array: Collection of panels

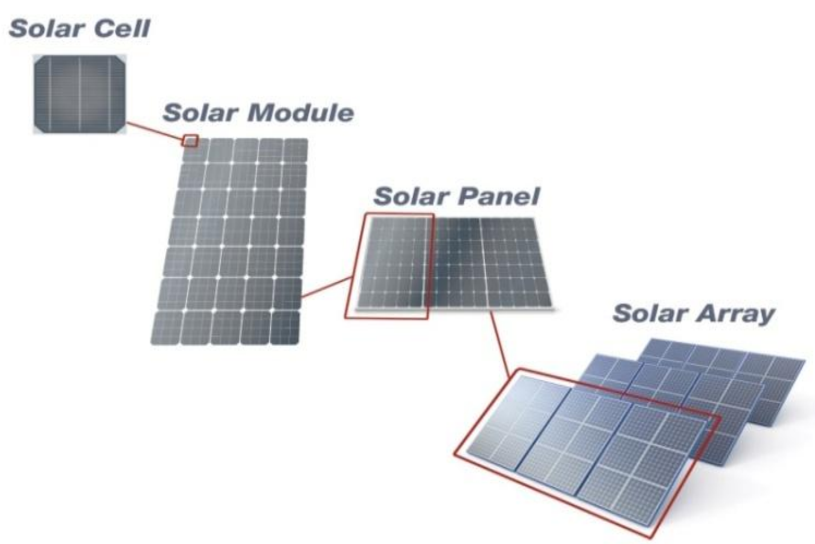


Fig. 2.18. SPV Construction

Photovoltaic power capacity is measured as maximum power output under standardized test conditions (STC) in "Wp" (Watts peak). The actual power output at a particular point in time may be less than or greater than this standardized, or "rated," value, depending on geographical location, time of day, weather conditions, and other factors. Solar photovoltaic array capacity factors are typically under 25%, which is lower than many other industrial sources of electricity. A photovoltaic system typically includes a panel or an array of solar modules, an inverter, and sometimes a battery and or solar tracker and interconnection wiring.

Types of SPV Cell technology

1. Crystalline Silicon solar cells - Single (Mono), Multi (Poly), Ribbon
2. Thin Film solar cells - Silicon, a-Si, m-Si, CdTe, CIGS
3. Concentrating solar cells - Si, GaAs
4. Dye, Organic, nano materials & other emerging solar cells

Characteristics of SPV

SC Current: The short-circuit current is the current through the solar cell when the voltage across the solar cell is zero (i.e., when the solar cell is short circuited). The short-circuit current is due to the generation and collection of light-generated carriers.The short-circuit current is the largest current which may be drawn from the solar cell.

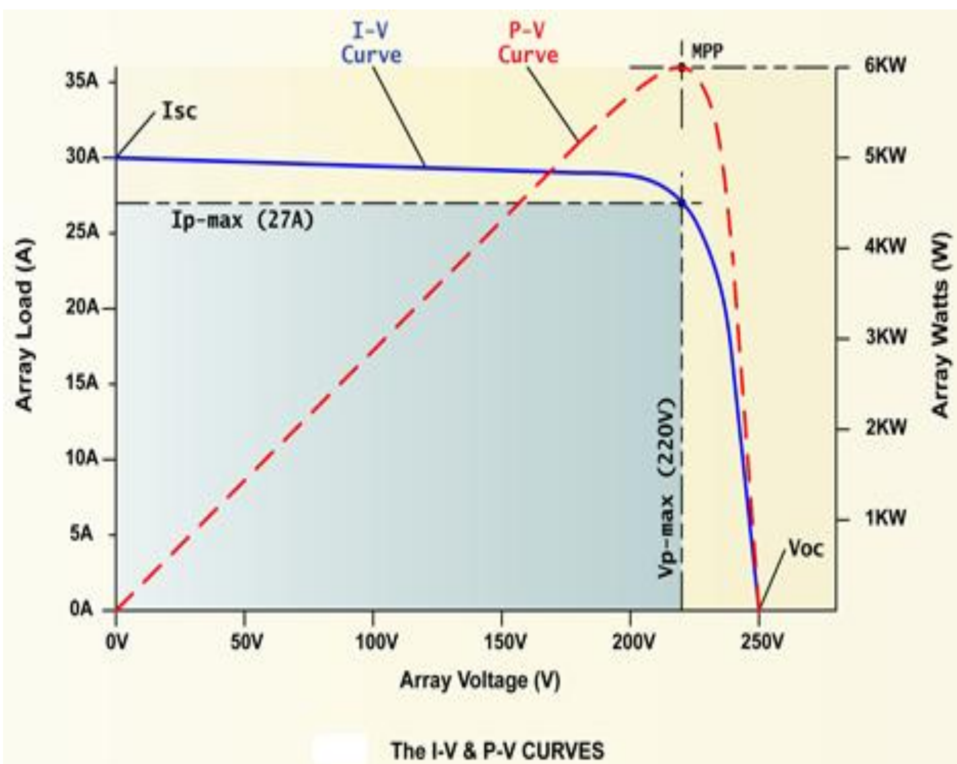


Fig.2.19 SPV I-V Curve and Power Curve

OC Voltage: The open-circuit voltage, Voc, is the maximum voltage available from a solar cell, and this occurs at zero current. The open-circuit voltage corresponds to the amount of forward bias on the solar cell junction due to illumination.

Maximum Power: Power out of a solar cell increases with voltage, reaches a maximum (Pm) and then decreases again.

Fill factor: The FF is defined as the ratio of the maximum power from the actual solar cell to the maximum power from a ideal solar cell.

FF = Im Vm / (Isc Voc)

PV Efficiency: Efficiency is defined as the ratio of energy output from the solar cell to input energy from the sun. Efficiency of a cell also depends on the solar spectrum, intensity of sunlight and the temperature of the solar cell.

Efficiency = Max cell power / Incident light energy

= Vm Im / Pi

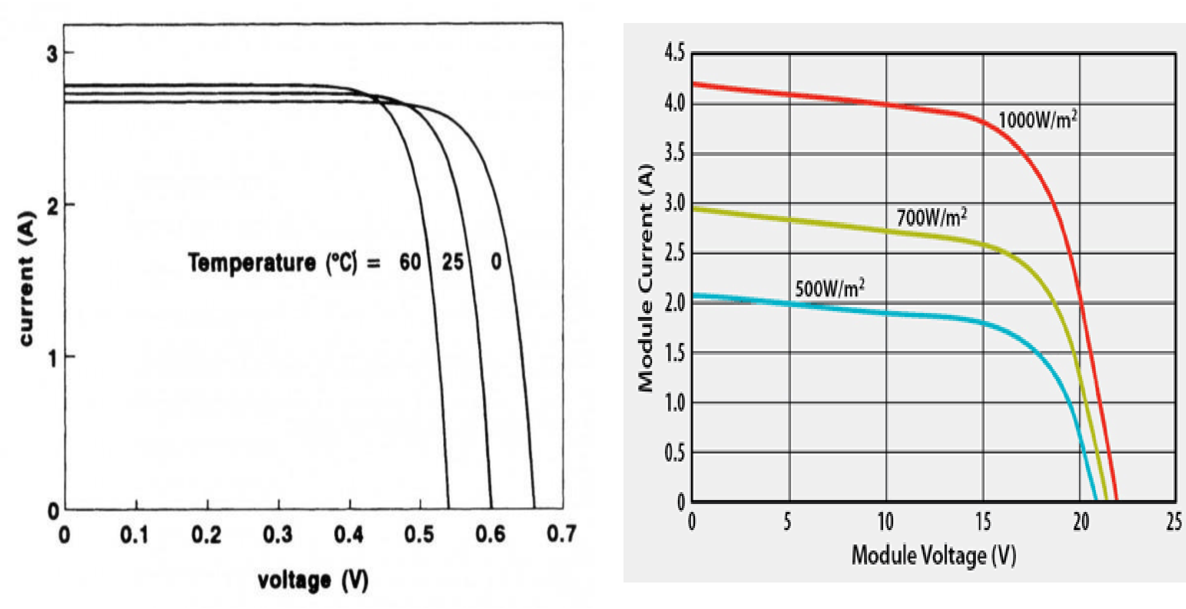


Fig.2.20 I-V characteristics for cell temperature and solar insolation

Effect of solar irradiance : PV power output increases with increase in Solar irradiance.

Effect of Cell temperature : Cell temperature increases means SC current increases and the power decreases.

The practical application of photovoltaic:

- To power orbiting satellites and other spacecraft,
- Used for grid connected power generation. (An inverter used to convert the DC to AC).
- For off-grid power for remote dwellings, boats, recreational vehicles, electric cars, roadside emergency telephones, remote sensing, and cathodic protection of pipelines.

PV CELLS/MODULES CONNECTIONS

Series connections: Adds Voltage

Parallel connections: Adds current

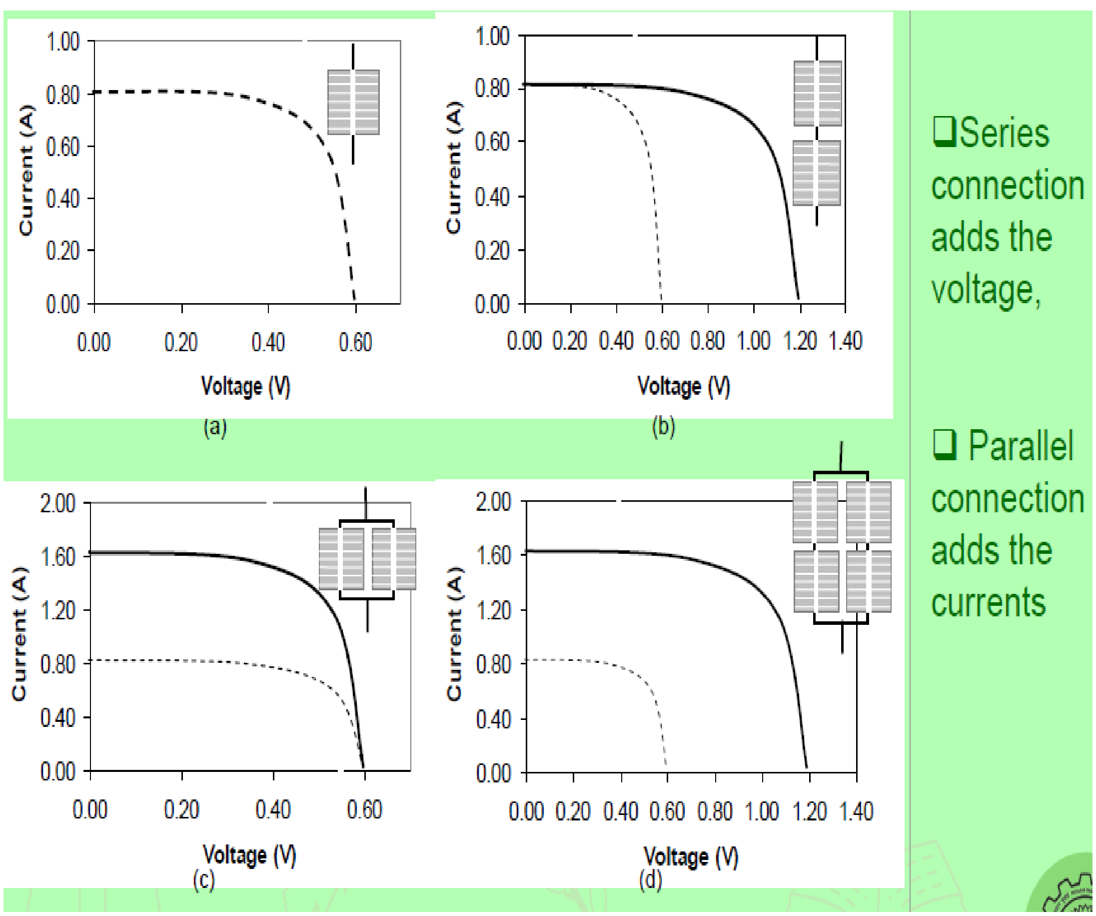


Fig. 2.21. Series and Parallel connections of SPV cell/module

Power electronic circuits of SPV system

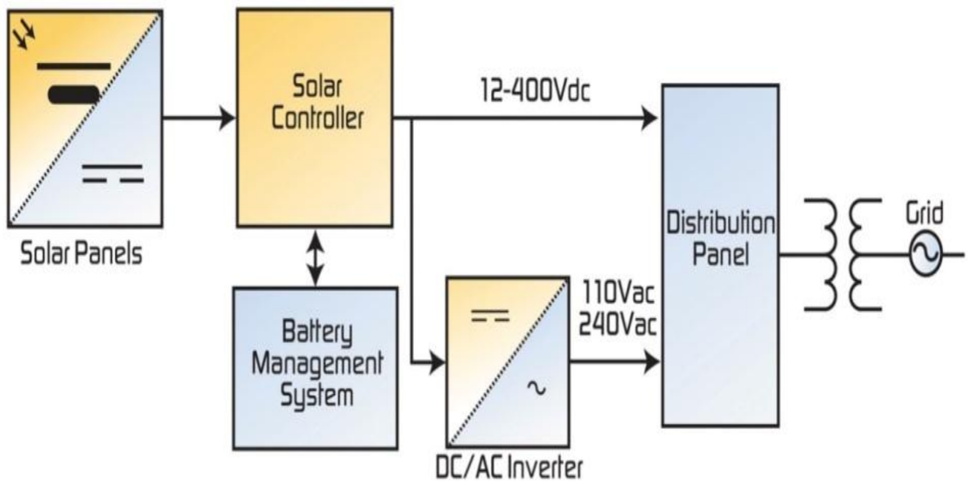


Fig.2.22 Solar PV system with battery / grid-tied

A photovoltaic (PV) system may be a combination of several components such as a battery system, DC/AC conversion circuits, and other power conditioning devices in addition to the solar panels themselves.

DC/DC converters are also useful in circuitry designed to draw maximum power from solar panels in what are called maximum power point trackers (MPPT). In the absence of a MPPT and depending on the load connected directly to solar panels, a great deal of the solar panel's electrical power may be dissipated in the form of heat. In the interest of maximizing energy efficiency, MPPTs are connected between the solar panels and load to ensure that the solar panels are producing their maximum power despite variations in light intensity and/or other factors that may vary within the system. MPPTs may be used in the presence or absence of battery charging systems but are more often used in grid-connected systems that have no batteries.

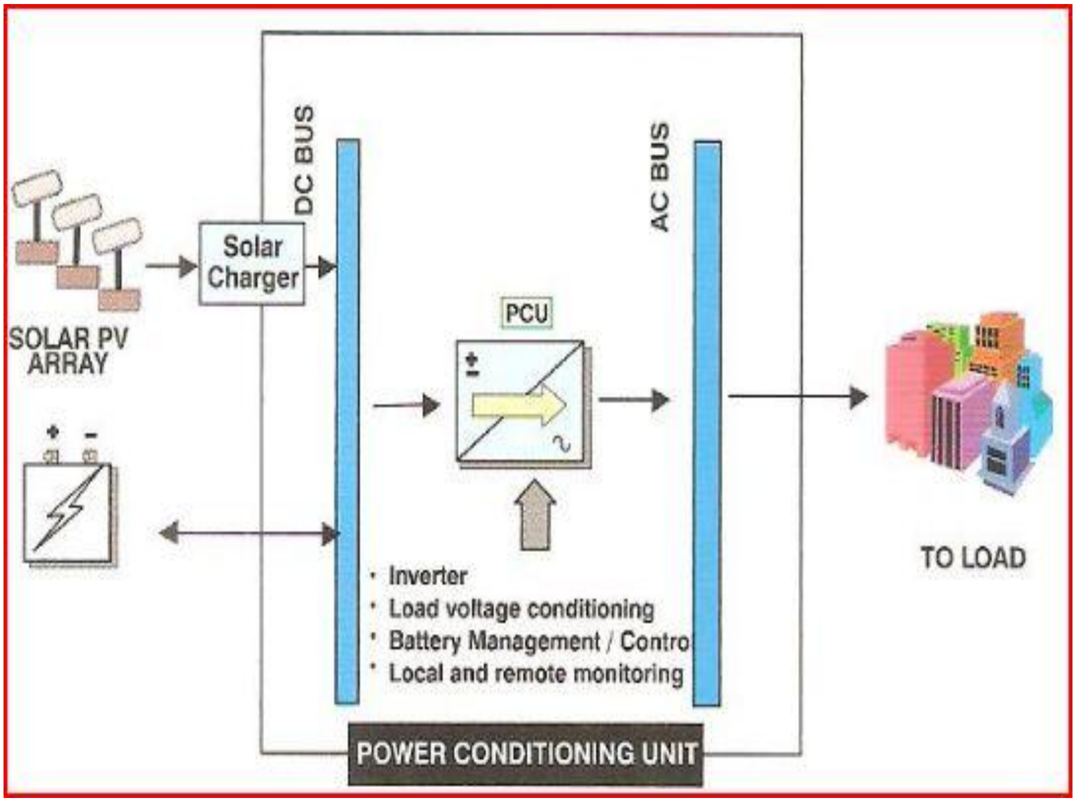


Fig.2.23. Solar PV Power conditioning Unit

Challenges in SPV technology

1. High cost per unit watt (high cost of material)
2. Moderate efficiencies ,
3. Availability of material ,
4. Long term stability,
5. Long energy payback period (high processing cost) & long money payback period etc.

SPV Applications: Power generation, Home lighting systems, Street and garden lighting system, Traffic control system, Railway signaling equipment, Battery charging e.g. Mobile, telephones.

Advantages of Solar Energy

1. Non-depleting sources of energy
2. Free of energy cost
3. No air pollution

4. No water pollution
5. No soil pollution
6. No fuel transport
7. No ash/waste disposal
8. Abundant sources of energy
9. Reduces the fossil fuel dependency
10. Useful for thermal and electricity need in remote places
11. Useful in space shuttles and ships
12. Cooling and heating possibility with solar energy
13. Useful in refinery processes
14. Used for power generation as well as process heating applications
15. Creates wind energy.

Limitations of solar energy

1. Availability – intermittent, available during day time
2. Dilute source – very low concentration of solar energy
3. Susceptible to climatic changes – clouds, rain etc.
4. Variable intensity throughout the day
5. Energy storage is required based on the demand
6. Conversion efficiency is very low (SPV $< 15\ \%$)
7. Costlier energy conversion equipment cost
8. Occupies larger area per kWh
9. Special coated solar grade mirrors required
10. Suitable corrosion resistant materials to be used

UNIT III.WIND ENERGY

WIND ENERGY

The alternate heating and cooling of earth by day and night causes the temperature as well as pressure difference in the atmospheric air and thus solar energy causes the wind energy. The wind flows from the high pressure area to low pressure areas. The Wind turbines convert wind movement (K.E.) into mechanical energy. Most modern wind turbines are used to create electricity. That is what is referred to as a wind generator. If the mechanical energy is used only for mechanical movement, it is a *windmill*. In the commonly used wind generator, the wind turns the blades, which turn the shaft. The shaft spins in a generator and electromagnetism in the generator produces electricity.

FACTORS INVOLVED IN SITE SELECTION FOR WIND MILLS

1. The availability of wind with sufficient kinetic energy.
2. The magnitude of wind velocity should be high
3. The wind availability is for throughout the year
4. The site should be free from the obstacles like mountain or tall buildings etc.
5. Availability of vast open land on a flat terrain at a lower land cost
6. The construction materials should be available and cheaper
7. A feasible site for transportation of materials
8. Availability of skilled workers
9. Away from the populated places but not away from load centre.
10. Free from natural calamities like storms, floods, earthquakes, volcanoes, etc.
11. Power transmission lines from the site to load.

WIND ENERGY TERMINOLOGY AND CALCULATIONS

1. Rotor Diameter (D): The Diameter of the rotor swept area
2. Wind speed (V_{air}): The speed at which the wind is flowing. This is called as free stream velocity.

3. Cut-in speed: The minimum speed of turbine at which the turbine starts developing power. e.g. 3 m/s
4. Cut-off (Furling) speed: The maximum speed of turbine at which the turbine stops developing power. e.g. 30 m/s . Its for safe operation of wind turbine rotors.
5. Kinetic Energy of wind, KE = ½ m V^2
6. The importance of accurate wind speed data becomes clear when one understands how the speed affects the power. Let A – Swept area of rotors, V-Velocity of wind.
   Power of wind, P = 0.5 ρ A V^3
7. Betz' limit or law: The theoretical maximum possible power can be extracted from the wind energy. Its value is 59.3% of power available in the wind.
8. Power co-efficient is the ratio of power output of the turbine to the power available in the wind.

   C_P = Power OP of turbine / Power of wind

9. Solidity ratio is the ratio of solid ratio in the swept area, S = N C / (π D). This can be also expressed as the ratio of total rotor area to the swept area of the blade.

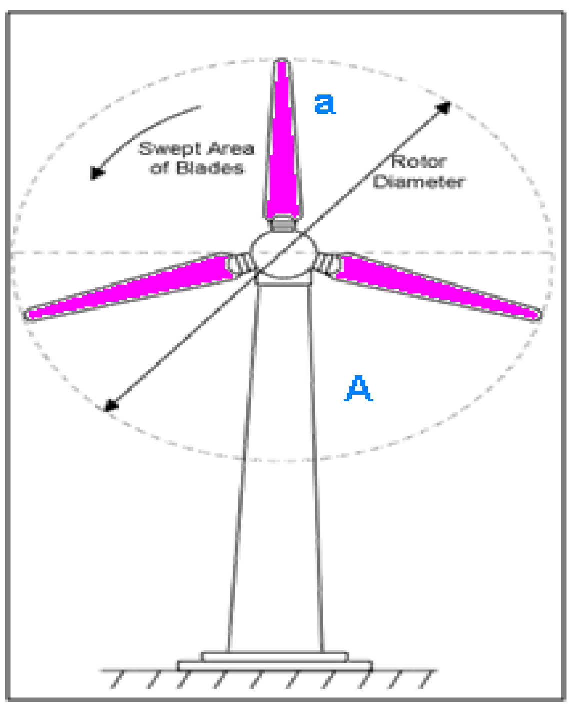


Fig. 3.1 Solidity Ratio, S = 3 a / A

Where, N – No. of blades, C – Average breadth of the blade, D – Diameter of the circle described by a blade.

10. Tip speed ratio (TSR) is defined as the ratio of rotor tip speed and the free stream velocity of wind at the site.

$TSR = V_{tip} / V_{air} = R\ \omega / V_{air}$

Where R – Rotor radius, ω - Rotational speed in radian/sec. If TSR increases, the rotational speed of rotor decreases.

Table 3.1 TSR and Speed

TSR	Speed N (rpm)
1	6 - 20
4	3-5
5-15	1-3

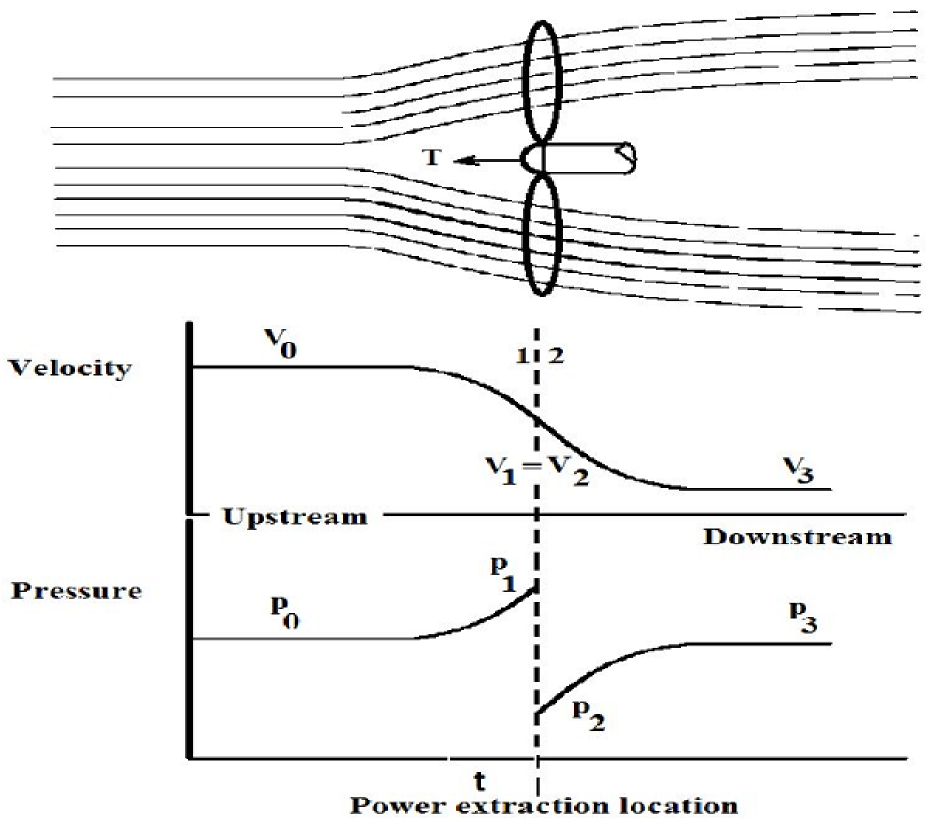


Fig. 3.2 Velocity and Pressure distribution across the wind rotor blades

11. Torque coefficient , C_T = Operational Torque / Maximum torque at max. efficiency

    $C_T = T / T\ max$

    Where, T = Power / Angular speed = $P / \omega = P / \pi D N$

    $T = \eta\ \rho A V^3_{air} / (2 \pi D N)$ where $A = \pi D^2 /4$

    Max efficiency (η_{max}) is 16/27 = 0.595 based on Betz limit.

    Max. torque, $T_{max} = 0.595\ \rho D V^3_{air} / (8 N/60)$

12. Axial thrust, $Fx = (\pi /8)\ \rho A (V^3_i - V^3_e)$

    At $\eta_{max,}$ Ve = Vi/3, where Vi and Ve : Velocity of air at upstream and downstream

    Max. axial thrust, $Fx_{max} = (\pi /9)\ \rho D^2\ V^2_i$

    The wind data includes wind speed, speed variation along the altitude, wind direction over the long term, air density, relative humidity and specific humidity, turbulence intensity.

Betz limit derivation

Betz's law calculates the maximum power that can be extracted from the wind, independent of the design of a wind turbine in open flow.

It shows the maximum possible energy — known as the **Betz limit** — that may be derived by means of an infinitely thin rotor from a fluid flowing at a certain speed.

In order to calculate the maximum theoretical efficiency of a thin rotor (of, for example, a windmill) one imagines it to be replaced by a disc that withdraws energy from the fluid passing through it. At a certain distance behind this disc the fluid that has passed through flows with a reduced velocity.

Assumptions

1. The rotor does not possess a hub, this is an ideal rotor, with an infinite number of blades which have no drag. Any resulting drag would only lower this idealized value.

2. The flow into and out of the rotor is axial. This is a control volume analysis, and to construct a solution the control volume must contain all flow going in and out, failure to account for that flow would violate the conservation equations.

3.The flow is incompressible. Density remains constant, and there is no heat transfer.

Application of conservation of mass (continuity equation)

Applying conservation of mass to this control volume, the mass flow rate (the mass of fluid flowing per unit time) is given by:

$$\dot{m} = \rho A_1 v_1 = \rho S v = \rho A_2 v_2$$

where v_1 is the speed in the front of the rotor and v_2 is the speed downstream of the rotor, and v is the speed at the fluid power device. ρ is the fluid density, and the area of the turbine is given by S.

The force exerted on the wind by the rotor may be written as

$$\begin{aligned} F &= ma \\ &= m\frac{dv}{dt} \\ &= \dot{m}\,\Delta v \\ &= \rho S v (v_1 - v_2) \end{aligned}$$

Power and work

The work done by the force may be written incrementally as

$$dE = F \cdot dx$$

and the power (rate of work done) of the wind is

$$P = \frac{dE}{dt} = F \cdot \frac{dx}{dt} = F \cdot v$$

Now substituting the force F computed above into the power equation will yield the power extracted from the wind:

$$P = \rho \cdot S \cdot v^2 \cdot (v_1 - v_2)$$

However, power can be computed another way, by using the kinetic energy. Applying the conservation of energy equation to the control volume yields

$$P = \frac{\Delta E}{\Delta t}$$

$$= \frac{1}{2} \cdot \dot{m} \cdot (v_1^2 - v_2^2)$$

Looking back at the continuity equation, a substitution for the mass flow rate yields the following

$$P = \frac{1}{2} \cdot \rho \cdot S \cdot v \cdot (v_1^2 - v_2^2)$$

Both of these expressions for power are completely valid, one was derived by examining the incremental work done and the other by the conservation of energy. Equating these two expressions yields

$$P = \frac{1}{2} \cdot \rho \cdot S \cdot v \cdot (v_1^2 - v_2^2) = \rho \cdot S \cdot v^2 \cdot (v_1 - v_2)$$

Examining the two equated expressions yields an interesting result, mainly

$$\frac{1}{2} \cdot (v_1^2 - v_2^2) = \frac{1}{2} \cdot (v_1 - v_2) \cdot (v_1 + v_2) = v \cdot (v_1 - v_2)$$

or

$$v = \frac{1}{2} \cdot (v_1 + v_2)$$

Therefore, the wind velocity at the rotor may be taken as the average of the upstream and downstream velocities.

Returning to the previous expression for power based on kinetic energy:

$$\dot{E} = \frac{1}{2} \cdot \dot{m} \cdot \left(v_1^2 - v_2^2\right)$$

$$= \frac{1}{2} \cdot \rho \cdot S \cdot v \cdot \left(v_1^2 - v_2^2\right)$$

$$= \frac{1}{4} \cdot \rho \cdot S \cdot (v_1 + v_2) \cdot \left(v_1^2 - v_2^2\right)$$

$$= \frac{1}{4} \cdot \rho \cdot S \cdot v_1^3 \cdot \left(1 - \left(\frac{v_2}{v_1}\right)^2 + \left(\frac{v_2}{v_1}\right) - \left(\frac{v_2}{v_1}\right)^3\right).$$

The horizontal axis reflects the ratio v_2/v_1, the vertical axis is the "power coefficient " C_p.

By differentiating $\dot{E}$ with respect to $\frac{v_2}{v_1}$ for a given fluid speed v_1 and a given area S one finds the *maximum* or *minimum* value for $\dot{E}$. The result is that $\dot{E}$ reaches maximum value when $\frac{v_2}{v_1} = \frac{1}{3}$.

Substituting this value results in:

$$P_{\max} = \frac{16}{27} \cdot \frac{1}{2} \cdot \rho \cdot S \cdot v_1^3.$$

The power obtainable from a cylinder of fluid with cross sectional area S and velocity v_1 is:

$$P = C_p \cdot \frac{1}{2} \cdot \rho \cdot S \cdot v_1^3.$$

The reference power for the betz efficiency calculation is the power in a moving fluid in a cylinder with cross sectional area S and velocity v_1:

$$P_{\text{wind}} = \frac{1}{2} \cdot \rho \cdot S \cdot v_1^3.$$

The *"power coefficient*[6]*"* C_p (= P/P_{wind}) has a maximum value of: $C_{p.max}$ = 16/27 = 0.593 (or 59.3%; however, coefficients of performance are usually expressed as a decimal, not a percentage).

Modern large wind turbines achieve peak values for C_p in the range of 0.45 to 0.50,[2] about 75% to 85% of the theoretically possible maximum. In high wind speed where the turbine is operating at its rated power the turbine rotates (pitches) its blades to lower C_p to protect itself from damage. The power in the wind increases by a factor of 8 from 12.5 to 25 m/s, so C_p must fall accordingly, getting as low as 0.06 for winds of 25 m/s.

TYPES OF WIND MILL

Based on no. of rotor blades: 1. Single blade 2. Multi-blade rotors

Based on axis of rotation : 1. Horizontal Axis (HWAT) 2. Vertical Axis (VWAT)

Based on power available from wind mills:

1. Small size (10-50 kW, Rotor diameter 1 -16 m)
2. Medium size (50-500 kW, Rotor diameter 16-50 m)
3. Large size (500 - 3000 kW, Rotor diameter 50 - 130 m)

COMPONENTS OF WIND TURBINES

1. Anemometer: Measures the wind speed and transmits wind speed data to the controller.

2. Blades: Most turbines have either two or three blades. Wind blowing over the blades causes the blades to "lift" and rotate.

3. Controller: The controller starts up the machine at wind speeds of about 8 to 16 miles per hour (mph) and shuts off the machine at about 65 mph. Turbines cannot operate at wind speeds above about 65 mph because their generators could overheat.

4. Gear box: Gears connect the low-speed shaft to the high- speed shaft and increase the rotational speeds from about 30 to 60 rotations per minute (rpm) to about 1200 to 1500 rpm, the rotational speed required by most generators to produce electricity. This is a costly (and heavy) part of the wind turbine and engineers are exploring “direct-drive” generators that operate at lower rotational speeds and don't need gear boxes.

5. Generator: Usually an off-the-shelf induction generator that produces 60-cycle AC electricity.

6. High-speed shaft: Drives the generator.

7. Low-speed shaft: The rotor turns the low-speed shaft at about 30 to 60 rotations per minute.

8. Nacelle: The rotor attaches to the nacelle, which sits atop the tower and includes the gear box, low- and high-speed shafts, generator, controller, and brake. A cover protects the components inside the nacelle. Some nacelles are large enough for a technician to stand inside while working.

9. Pitch: Blades are turned, or pitched, out of the wind to keep the rotor from turning in wind that is too high or too low to produce electricity.

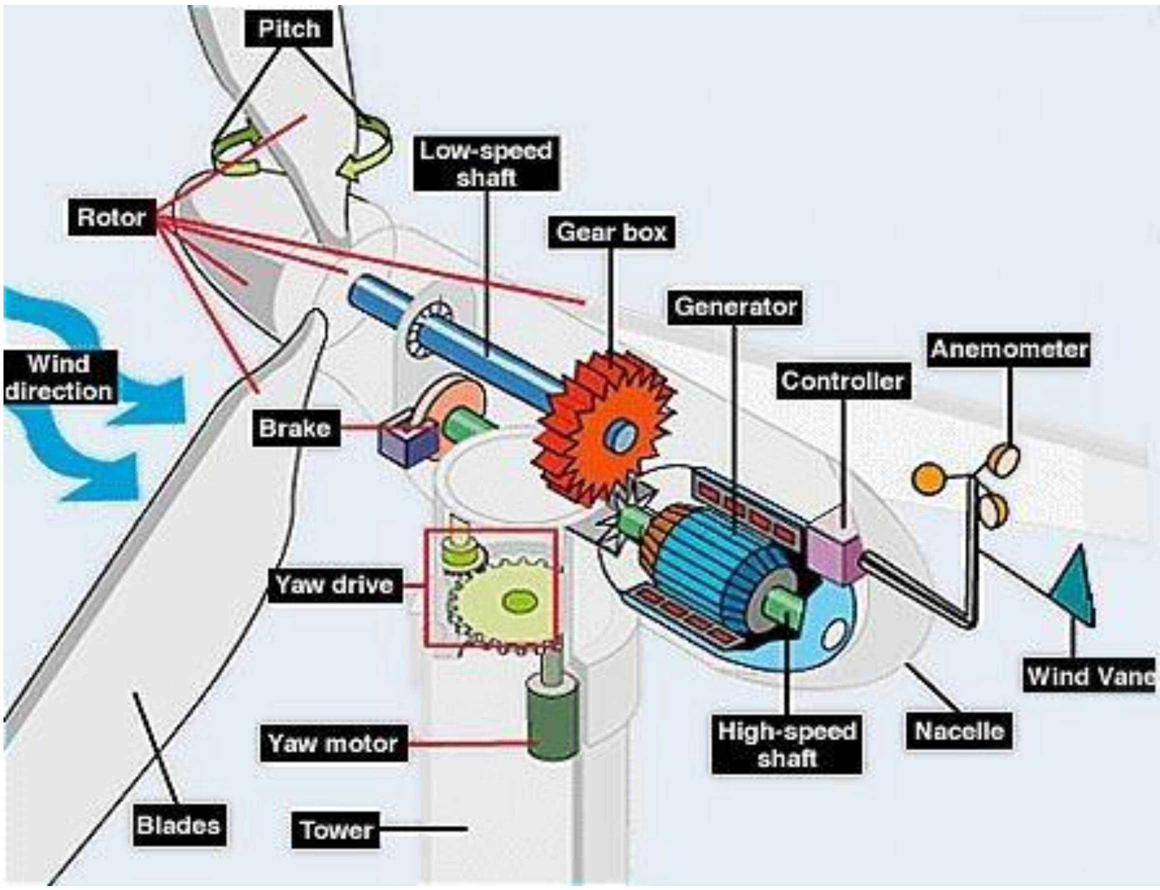


Fig.3.3 Components of HWAT

10. Rotor: The blades and the hub together are called the rotor.

11. Tower: Towers are made from tubular steel or steel lattice. Because wind speed increases with height, taller towers enable turbines to capture more energy and generate more electricity.

12. Wind direction: The upwind turbine means it operates facing into the wind. Other turbines are designed to run downwind facing away from the wind.

13. Wind vane: Measures wind direction and communicates with the yaw drive to orient the turbine properly with respect to the wind.

14. Yaw drive: Upwind turbines face into the wind; the yaw drive is used to keep the rotor facing into the wind as the wind direction changes. Downwind turbines don't require a yaw drive; the wind blows the rotor downwind. Yaw motor powers the yaw drive.

HORIZONTAL AXIS WIND TURBINE (HWAT)

The Rotor blades are fitted on the main shaft in a horizontal hub. This direction of wind is parallel to the axis of rotation of rotor blades. The horizontal hub is connected to a gearbox and generator, which are located inside the nacelle. The nacelle houses the electrical components and is mounted at the top of the tower. There is a supporting tower to withstand the rotor and nacelle as well as wind kinetic energy.

VERTICALAL AXIS WIND TURBINE (VWAT)

The Rotor blades are fitted on the main shaft in a vertical hub. This direction of wind is perpendicular to the axis of rotation of rotor blades. The main shaft is connected to a gearbox and generator. There is a supporting wire to withstand the rotor as well as wind kinetic energy.

Rotor diameters on modern turbines can be more than 80 meters. The turbines rotor diameter determines its swept area. The swept area is the area through which the rotors of a wind turbine rotate. Larger swept areas usually translate to higher output machines. Machine capacity can range anywhere from a few hundred kilowatts to 5 megawatts. Currently, 1.5-2 MW machines are quite popular. The blades rotate at a speed of 10-30 revolutions per minute at constant rate although an increasing number of machines operate at a variable speed.

The amount of power produced is a direct result of the wind speed. Excessive wind speeds, though, require the temporary shutdown of turbines to protect internal components. Most wind turbines have gearboxes, even though an increasing number of modern turbines operate using direct drive systems.

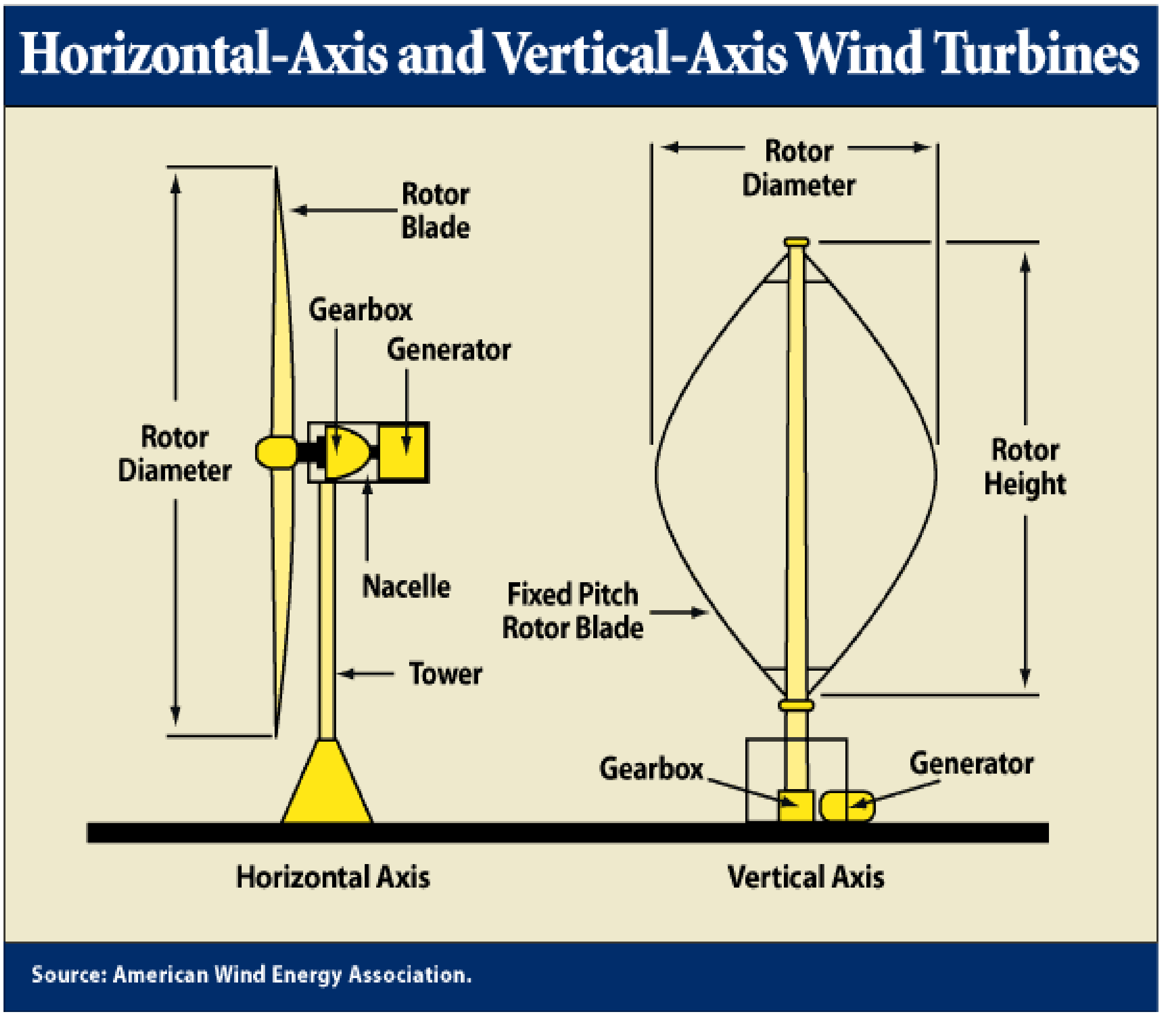


Fig. 3.4 HAWT and VAWT configurations

The **yaw** mechanism turns the turbine (horizontal motion) so that it faces the wind. Sensors are used to monitor wind direction and the tower head is turned to be in line with the wind. Towers are mostly cylindrical and made of steel, generally painted light grey. Lattice towers are used in some locations. Towers range from 25 to 75 meters in height.

There are many different turbine designs, with plenty of scope for innovation and technological development. The dominant wind turbine design is the up-wind, three bladed, **stall controlled**, constant speed machine. The next most common design is similar, but is **pitch controlled**. Gearless and variable speed machines follow, again with three blades. A smaller number of turbines have 2 blades, or use other concepts, such as a vertical axis.

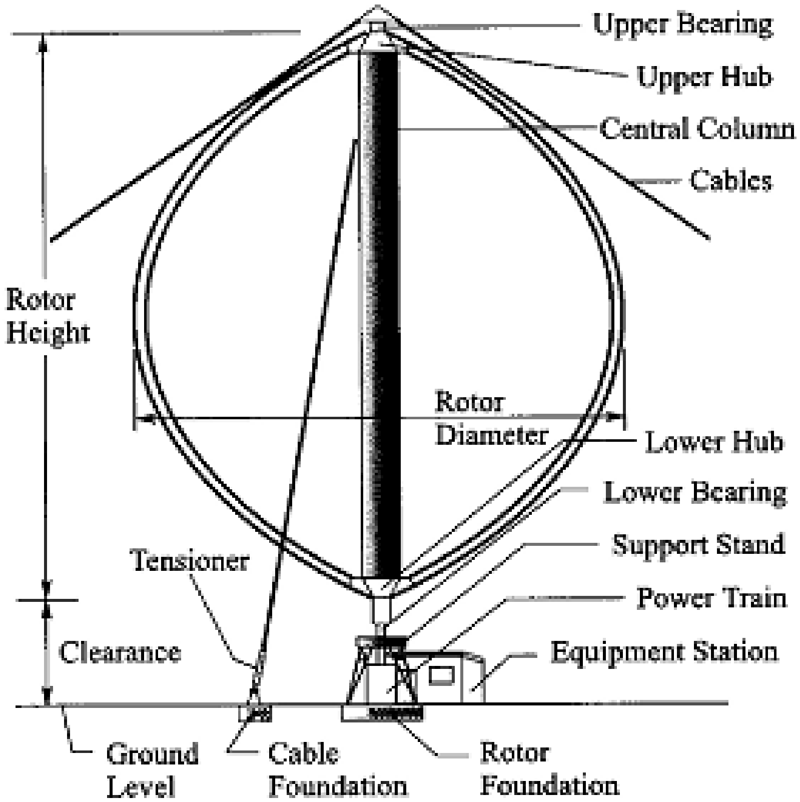


Fig.3.5 Components of VAWT

Factors control the output of wind energy converter

The efficiency of wind turbines depends on various factors such as location, geographical factors, mechanics, rotor shape/ size, etc. Output can be regulated by a constant or variable rotational speed, as well as adjustable and non-adjustable blades. The factors are given below:

1. The wind speed
2. Cross-section of the windswept by rotor
3. Conversion efficiently of rotor
4. Transmission system

Three mechanical controls of HWAT

1. **Pitch Control:** Tilting of rotor blade angles from 0 -30° to absorb more energy from the wind. The pitch angle is the angle between the direction of wind and the direction perpendicular to the planes of blades.

2. **Teethering Control:** The up and down movement (swinging motion like see-saw) of nacelle in the vertical direction. Higher wind speed, the nacelle is inclined.

3. **Yaw Control:** The horizontal movement of nacelle to face the wind. Its orientation or steering control for the axis of wind turbine in the direction of wind.

DESIGN CONSIDERATIONS IN HWAT

1. The height of the wind energy converter (WEC) should be more than 30 m altitude. There only the wind velocity is higher.

2. Few Narrow long blades to withstand the extreme winds

3. The structural dynamics to be studied completely to avoid fatigue failures of rotors

4. Three blade rotors are having better efficiency than single and two blade rotors with netter gyroscopic balance.

5. The angle of attack is to be optimum for maximized lift force and small drag forces.

6. The optimum tip speed ratio is desired at any distance / point along the rotor blades.

7. The aerodynamic design should have optimized to give the efficiency around 45 %.

8. The axial thrust limitation is there (for safety of rotor) eventhough the increased rotor diameter increases the power output.

9. The optimum solidity ratio is accounted. Low solidity ratio (0.1) produces the high speed and low torque whereas the high solidity ratio (more than 0.8) yields low speed and high torques.

10. The operation is to be performed at optimum TSR for the maximum conversion efficiency.

11. Lift force based HAWT is preferred due to more output power (high rotational speeds) per the given swept area.

12. Drag force based wind turbines are having more torques (twisting moments) and they are preferred for water pumping.

13. Tapered or twisted blades are preferred in lift type rotors due to less bending strains on the roots of the blades.

14. For high speed propeller rotors, the solidity is to be 0.01 to 0.1. The solidity should be small as 10% of swept area.

PERFORMANCES OF WIND TURBINES

The ideal efficiency of 59.3% is based on Betz's limit. And the various turbine configurations like single rotor, Darrius rotor, multi-blade rotors etc are given below:

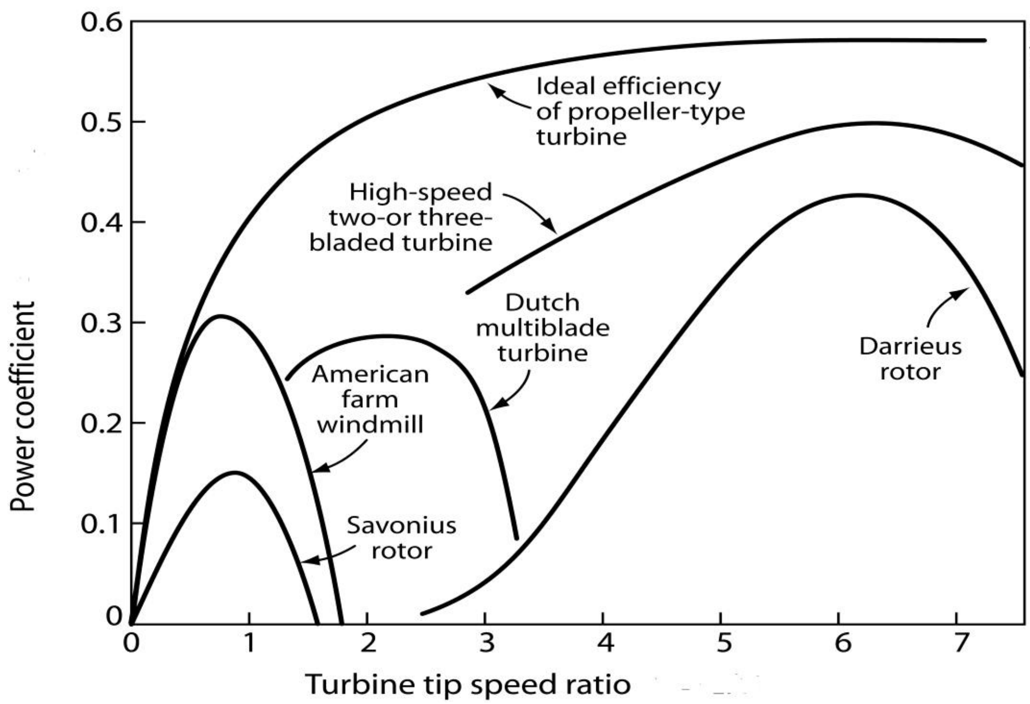


Fig.3.6 Performance curves of WT

The range of speed ratio with the power co-efficient is compared. The three blade rotor machine performs better in the speed ratio as well as power developed. The Savonius rotor works at lower speed ratio but the power co-efficient is also very low.

The torque coefficient (ratio of shaft torque to torque at maximum efficiency) is higher value for multi blade rotors and narrow tip speed ratio whereas the two blade rotors have wide operation tip speed ratio but lower torque.

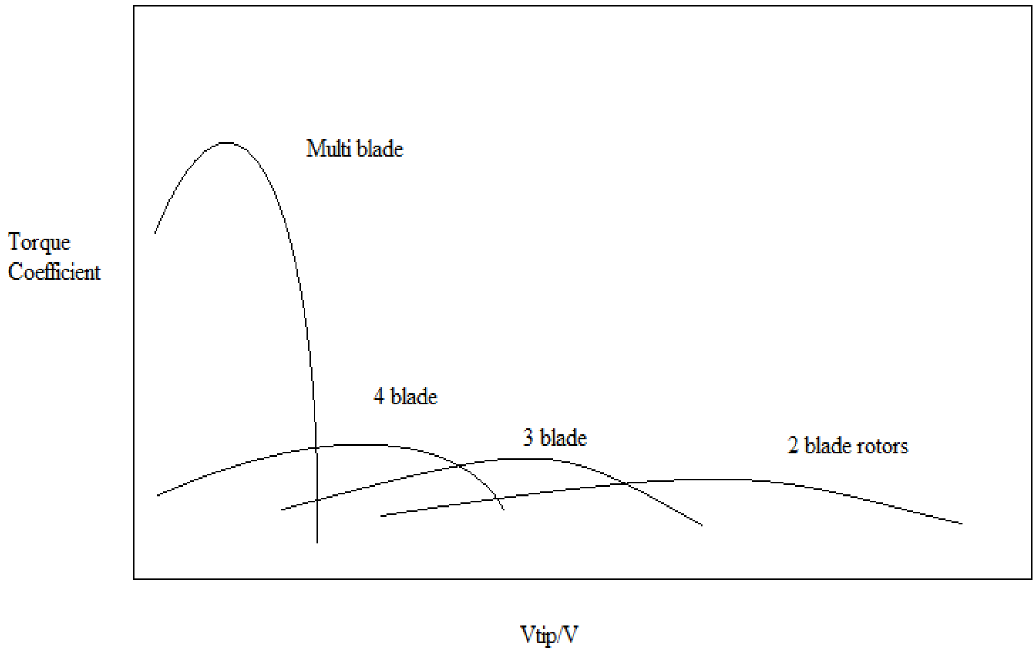


Fig. 3.7 Performance of wind machines

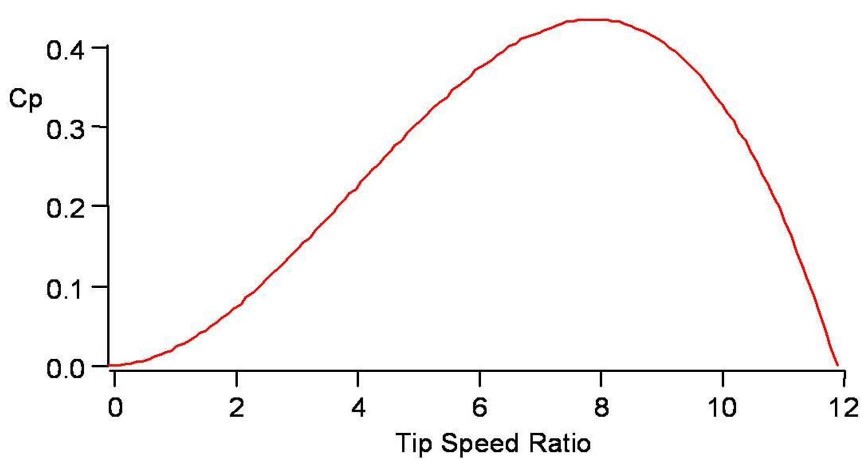


Fig. 3.8 TSR and Power coefficient characteristics

AERODYNAMICS OF BLADES

A careful choice of the shape of the blades is crucial for maximum efficiency. Initially, wind turbines used blade shapes, known as airfoils, based on the wings of airplanes. Today's wind turbines still use airfoils, but they are now specially designed for use on rotors. Airfoils use the concept of lift, as opposed to drag, to harness the wind's motion.

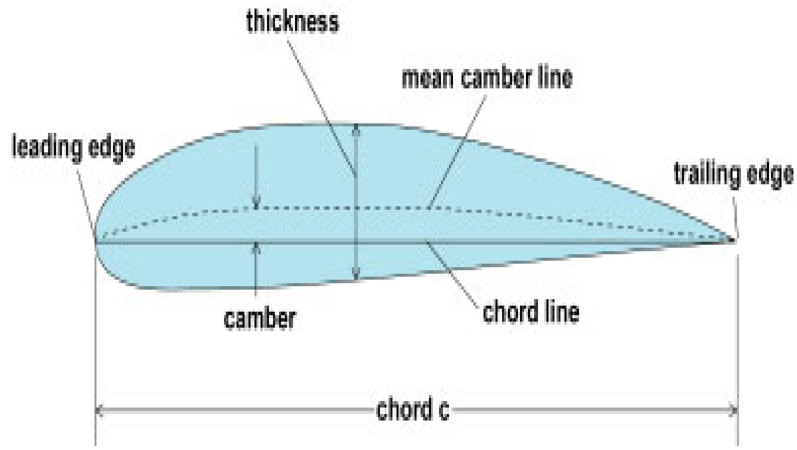


Fig.3.9 Thin aerofoil

The idea behind lift is that when the edge of the airfoil is angled very slightly out of the direction of the wind, the air moves more quickly on the downstream (upper) side creating a low pressure that essentially lifts the airfoil upward. The amount of lift for a given airfoil depends heavily on the angle that it makes with the direction of the relative wind, known as the angle of attack,? With a certain range, an increased angle of attack means increased lift, but also more drag, which detracts from the desired motion.

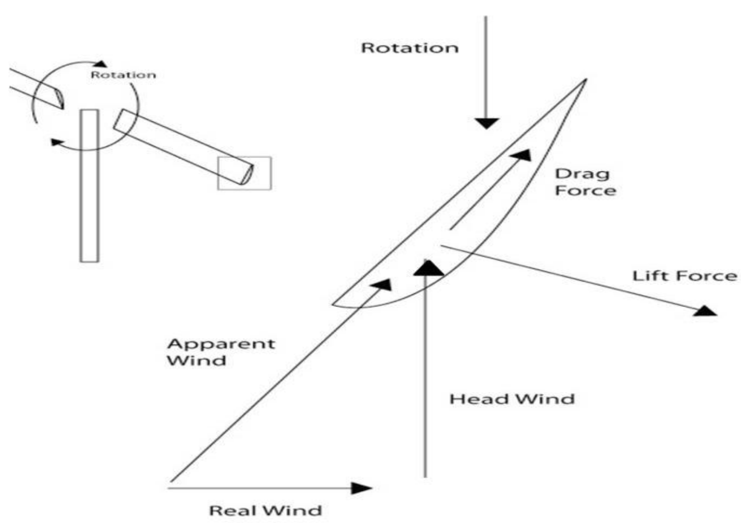


Fig.3.10 Lift/Drag forces acting on rotor blade

Lift force, $F_L = C_L \rho A V^3 / 2$

Drag Force, $F_D = C_D \rho A V^3 / 2$

Where C_L and C_D are the Lift and Drag coefficients respectively

When the angle of attack gets too large, turbulence develops and drag increases significantly, while lift is lost. The angle of attack on wind turbine blades can be changed either by creating a specific geometry for the blades along the longitudinal axis/ span, also known as pitch control, or by allowing them to rotate around the axis perpendicular to their cross sections (along the span). This movement of turning the wind turbine rotor against the wind is known as the yaw mechanism. The wind turbine is said to have a yaw error, if the rotor is not perpendicular to the wind. Changing the angle of attack is important to maintain a precise amount of lift so the rotor turns at a constant speed.

LOADS, STRESS, AND FATIGUE

Aside from optimizing the blade shape and the yaw direction, a vital consideration in the construction of a wind turbine is the lifetime of the machine. Wind turbines are currently designed to last at least 20 years. The blades must be strong enough to withstand all the loads and stresses from gravity, wind, and dynamic interactions. Blades are carefully manufactured and then extensively tested to make sure they can achieve the desired lifespan.

Types of loads are static, steady, cyclic, transient, impulsive, stochastic, and resonance induced. Static loads are constant and occur even with a non-moving turbine. These include steady wind and gravity. Steady loads are constant when the turbine is in motion and are caused by a steady wind. Cyclic loads are periodic, usually due to the rotation of the rotor. They occur from gravity, wind shear, yaw motion, and vibration of the structure. Transient loads are time varying with occasional oscillation. Braking by the inner gears and mechanics will cause this type of load. Impulsive loads are time varying on short scales, such as a blade being shadowed when passing the tower. Stochastic loads are random, usually around a constant mean value, and are primarily caused by turbulence. Resonance-induced loads, which are to be avoided as much as possible, occur when parts of the wind turbine are excited at their natural frequencies and then vibrate and can induce other parts to vibrate also, putting considerable stress on the turbine.

POWER CONTROL AND AERODYNAMIC BRAKING SYSTEM

As the angle of attack is one of the most important variables in determining the performance of a wind turbine, both in terms of power output and over-speed induced stress protection, it is important to understand the rotor pitch behavior.

An increasing number of larger wind turbines (1 MW and up) are being developed with an active stall power control mechanism. Technically the active stall machines resemble pitch controlled machines, since they have pitch able blades. In order to get a reasonably large torque (turning force) at low wind speeds, the machines will usually be programmed to pitch their blades much like a pitch controlled machine at low wind speeds. On a pitch controlled wind turbine, the turbine's electronic controller checks the power output of the turbine several times per second. When the power output becomes too high, it sends an order to the blade pitch mechanism which immediately pitches (turns) the rotor blades slightly out of the wind. This is actually the aerodynamic braking system, which is the primary braking system for most modern wind turbines. This essentially consists of turning the rotor blades about 90 degrees along their longitudinal axis. Conversely, the blades are turned back into the wind whenever the wind drops again. The rotor blades thus have to be able to turn around their longitudinal axis/ span (to pitch).

Problem 3.1

The wind velocity at a wind site is available at 12 m/s. The wind mill selected is 10 m diameter and 5 rps with maximum efficiency of 35%. Find the power output and axial thrust on the turbine?

Solution:

Power available, $P_{air} = 0.5\ \rho\ V^3 = 1054\ W/m^2$

Actual power density, Pact = P_{air} x Efficiency = $369\ W / m^2$

Power output, P = Pact x $\pi D^2/4$ = **28.53 kW**

Max. axial thrust, $Fx_{max} = (\pi /9)\ \rho\ D^2\ V^2_i$ = **11.05 kN**

Problem 3.2

At a particular site where atmospheric pressure 1.01325 bar, temperature 20 °C, the wind available at 8 m/s. Find the following:

a. Power density available in the wind,

b. Maximum power density possible,

c. Obtainable power density if overall efficiency is 35%,

d. Power capacity of wind mill if diameter is 30 m.

Solution:

Density of air, $\rho = p/ RT = 1.2\ kg/m^3$

Available power density, $P1 = 0.5\ \rho\ V^3$ = **307.2 W per m^2 swept area**

Maximum power density, $P2 = (8/27)\ \rho\ V^3$ = **182 W per m^2 swept area**

Actual power density, P3 = P1 x Overall efficiency = **107.5 W/m^2**

Power capacity if D=30 m, P = P3 A = **76 kW**

Problem 3.3

Wind at 1 standard atmospheric pressure and 15 °C has a velocity of 15 m/s. Wind turbine has 120 m diameter and its operating speed is 40 rpm at maximum efficiency. Calculate the following:

i. the total power density in the wind stream
ii. the maximum obtainable power density
iii. reasonably obtainable power density
iv. the total power
v. the torque
vi. the axial thrust

Solution:

Density of air, $\rho = p/RT = 1.226\ kg/m^3$

Total power density, $P1 = 0.5\ \rho\ V^3$ = **2069 W/m²**

Maximum power density, $P2 = (8/27)\ \rho\ V^3$ = **1226 W/m²**

Reasonable power density at 35% efficiency, P3 = P1 x 0.35 = **724 W/m²**

Total power, $P = P3 \times Area = P3 \times \pi D^2/4$ = **8188 kW**

Torque at maximum efficiency, $T_{max} = 0.595\ \rho\ D\ V^3_{air} / (8\ N/60)$ = **55394 N**

Maximum axial thrust, $Fx_{max} = (\pi/9)\ \rho\ D^2\ V^2_i$ = **1386.573 kN**

Advantages of wind mills:

1. Wind energy is at free of cost,
2. No air pollution,
3. No water required,
4. Low operating costs.
5. No GHG emissions
6. Wind farm fields can be used for cultivation also.
7. Power for remote places from conventional power lines
8. Easier and faster power plant build-up in the site
9. Land area occupied is less than other plants
10. Space occupied also less.

Disadvantages:

1. Fluctuation in wind speed affects the power output (Unreliability)
2. Bird –life is affected
3. Noisy operation
4. Lower electricity output
5. Expensive construction
6. Tall WT blocks the scenery views
7. Wind power storage and variable strength of wind and directions.

UNIT IV.OCEAN ENERGY

WAVE ENERGY

Wave energy is the transport of energy by ocean surface waves, and the capture of that energy to do useful work – for example, electricity generation, water desalination, or the pumping of water (into reservoirs). Machinery able to exploit wave power is generally known as a **wave energy converter** (WEC).

Waves are generated by wind passing over the surface of the sea. As long as the waves propagate slower than the wind speed just above the waves, there is an energy transfer from the wind to the waves. Both air pressure differences between the upwind and the lee side of a wave crest, as well as friction on the water surface by the wind, making the water to go into the shear stress causes the growth of the waves. Wave height is determined by wind speed, the duration of time the wind has been blowing, fetch (the distance over which the wind excites the waves) and by the depth and topography of the seafloor (which can focus or disperse the energy of the waves). A given wind speed has a matching practical limit over which time or distance will not produce larger waves. When this limit has been reached the sea is said to be "fully developed".

In general, larger waves are more powerful but wave power is also determined by wave speed, wavelength, and water density. The wave energy is the waves developed by the KE of wind passing on the surface of sea and around 5-15% wind KE is imparted to sea surface water. The waves are smaller amplitude around 2 m. Wave energy is produced when electricity generators are placed on the surface of the ocean. The energy provided is most often used in desalination plants, power plants and water pumps. Energy output is determined by wave height, wave speed, wavelength, and water density. The total power of waves breaking on the world's coastlines is estimated at 2 to 3 million megawatts. In favorable locations, wave energy density can average 65 megawatts per mile of coastline.

Wave energy Calculations

Potential Energy density per unit area, $PE/A = 0.25\ g\ \rho\ a^2$

Where, a – amplitude of wave in m (distance from crest to trough / 2)

Kinetic Energy per unit area, KE/A = $0.25\ g\ \rho\ a^2$

Total Energy density, E/A = PE/A + KE/A = $0.5\ g\ \rho\ a^2$

Total Power density, P = $0.5\ g\ \rho\ a^2\ f$

Where, f – Frequency of wave,

g – Gravitational acceleration in m/s2

ρ - Density of sea water in kg/m^3

OSCILLATING WATER COLUMN (OWC)

Oscillating Water Column (OWC) is one of the power generation method used to harvest the wave energy by running an aero-turbine. This system consists of a chamber built in shoreline with the layout shown above in figure 4.1.

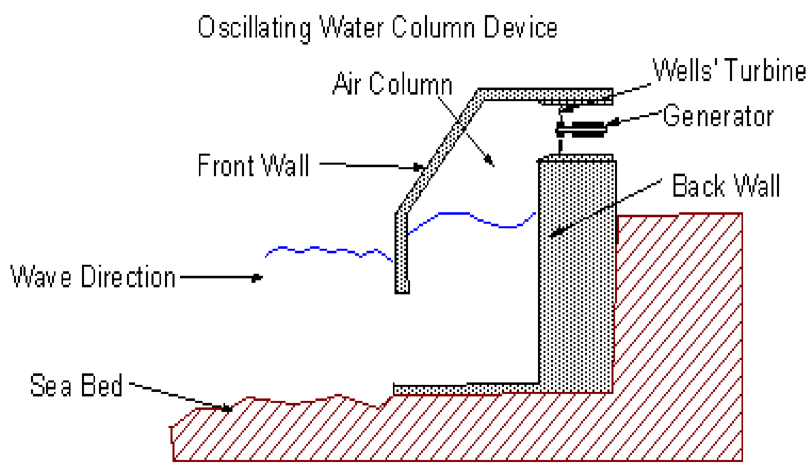


Fig.4.1 OWC of WEC

The motions of ocean/sea waves push an air pocket up and down behind a breakwater. Then the air passes through an air turbine. Next, when the wave returns to the sea, an air depression will circulate through the turbine in the opposite sense. However, this turbine has been designed to continue turning the same way irrespective of the direction of the airflow.

The oscillating water pushes air out from the column and sucks in during the forward and reverse movement of ocean wave. The power is generated by aero-generator due to the flow of air. This turbine is bi-directional turbine. OWC designs typically require high maintenance, costly, taut moorings or foundations for operation while only using the extreme upper strata of an ocean site for energy conversion. While focusing devices are less susceptible to storm damage, massive structuring renders them most costly among wave power plant types.

TAPERED CHANNEL WAVE POWER

These shoreline systems consist of a tapered channel which feeds into a reservoir constructed on a cliff. The narrowing of the channel causes the waves to increase their amplitude (wave height) as they move towards the cliff face which eventually spills over the walls of the channel and into the reservoir which is positioned several meters above mean sea level. The kinetic energy of the moving wave is converted into potential energy as the water is stored in the reservoir. The water then passes through hydroelectric turbines on the way back to sea level thus generating electricity.

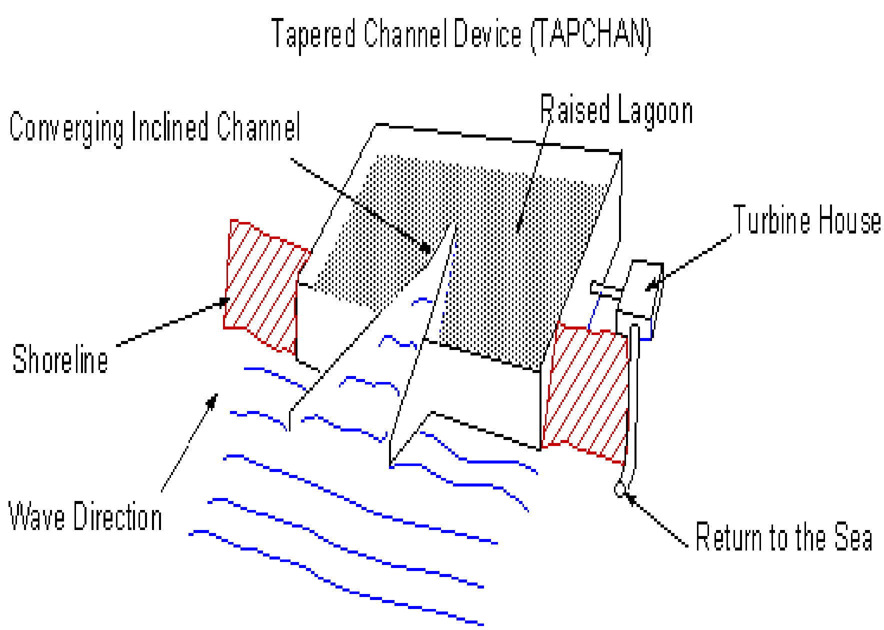


Fig.4.2 Tapered channel wave power

Advantages of wave power

1. The energy is free - no fuel needed, no waste produced.
2. Most designs are inexpensive to operate and maintain.
3. Waves can produce a great deal of energy.
4. There are minimal environmental impacts.

Disadvantages of wave power

1. Depends on the waves - sometimes you'll get loads of energy, sometimes nothing.
2. Needs a suitable site, where waves are consistently strong.
3. Must be able to withstand very rough weather.
4. Disturbance or destruction of marine life
5. Possible threat to navigation from collisions because the wave energy devices rise only a few feet above the water.
6. Degradation of scenic ocean front views from wave energy devices located near or on the shore, and from onshore overhead electric transmission lines.

TIDAL ENERGY

Tidal power is taken from the Earth's oceanic tides; tidal forces are periodic variations in gravitational attraction exerted by celestial bodies. These forces create corresponding motions or currents in the world's oceans. Due to the strong attraction to the oceans, a bulge in the water level is created, causing a temporary increase in sea level. When the sea level is raised, water from the middle of the ocean is forced to move toward the shorelines, creating a tide. This occurrence takes place in an unfailing manner, due to the consistent pattern of the moon’s orbit around the earth.

The magnitude and character of this motion reflects the changing positions of the Moon and Sun relative to the Earth, the effects of Earth's rotation, and local geography of the sea floor and coastlines. Tidal power is the only technology that draws on energy inherent in the orbital characteristics of the Earth–Moon system, and to a lesser extent in the Earth–Sun system.

Two types of tidal plant facilities

- Tidal barrages
- Tidal current turbines

Ideal sites are located at narrow channels and experience high variation in high and low tides.

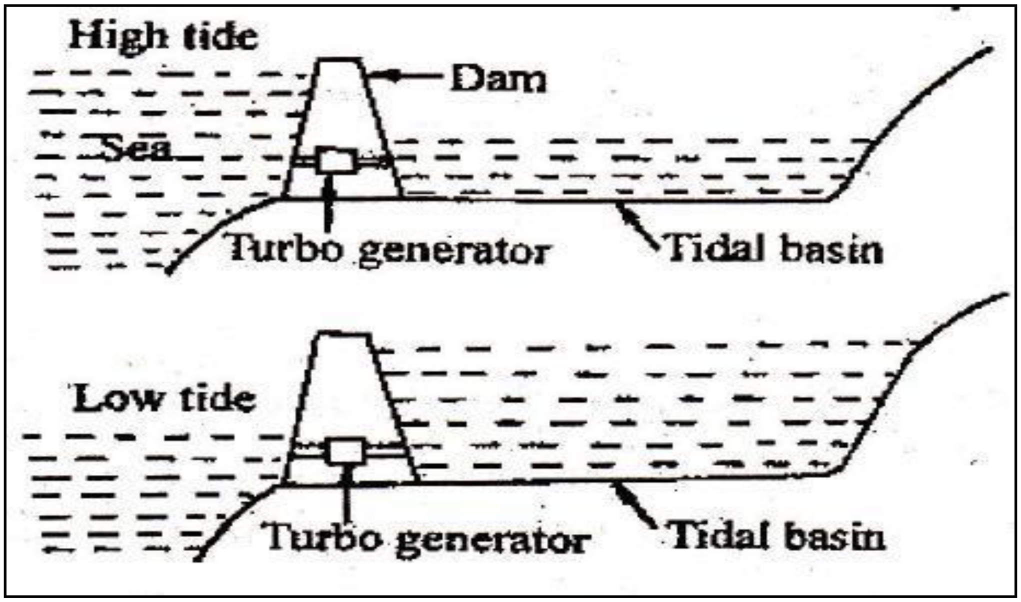


Fig.4.3 Tidal Power Plant (High & Low Tide)

The tidal energy is due to moon's attraction on the earth. Normally lesser tidal waves occur per day (around 2 tides). The amplitude of tidal waves is around 10 m. The tidal energy is harvested by tidal power plants where the high tides are allowed to run an axial turbine during water flows from sea to tidal basin as well as water flows from basin to sea due to the water level difference between the sea and basin.

Estimation of energy and power in a simple and single basin tidal system

Let R- Range of tide

r – lowest level where turbine stops power generation

h – Intermediate head in m

A – Basin surface area in m2

m- mass flow through the turbine in kg

Work done by water, $W = \int - \rho g A h \, dh = (½) \rho g A R^2$ (Integration limit is 0-min, R-max)

If the lowest head at which turbine stops its operation (r) is given means,

Integration limit is R to r, Work done by water, $W = \int - \rho g A h \, dh = (1/2) \rho g A (R^2 – r^2)$

Average theoretical power in Watts, Pav = W/time

Total time taken for each period = 6 h 12.5 min = 22350 s

So $Pav = 0.5 \rho g A R^2 / 22350 = \rho g A R^2 /44700$

Consider $g = 9.8 m/s^2$, $\rho = 1025 kg/m^3$.

Average Power per unit area, $Pav / A = 0.225 R^2$

Actual power generated, P = turbine-generator efficiency x Average power generated

Energy and power estimation of a double cycle system

Let

Volume of basin, $V = A h_0$

Where A – Average cross sectional area of the basin in m^2

h_0 – Difference between maximum and minimum water level in m

Average discharge, $Q = A h_0 / t$

Where t – Total duration of generation in one filling/emptying operation

Power generated at any instant, $P = \eta_0 \rho Q h$

Where h – Available head at any instant and η_0 - Overall efficiency

Problem 4.1

A tidal power plant of the simple single basin has basin area of 30 x 106 m2. The tide has a range of 12 m and the head at which the turbine cut off its power is 3 m. Calculate the energy generated in one filling or emptying process in kWh if turbine-generator efficiency is 76%.

Solution:

Assume, ρ = 1025 kg/m3, time, t = 44700 s.

Total theoretical work, W = (1/2) ρ g A ($R^2 – r^2$) = 40682250 x 10^6 W

Average power, Pav = W/t = 40682250 x 10^6 / 44700 = 910.12 x 10^6 W

To convert W into kWh, multiply by 3600 (seconds into hour) and divide by 1000 (W into kW),

Average power generated,

Pav = (3600/1000) x 910.12 x 10^6= 3276 x 10^6 kWh x 0.76 = 2490 x 10^6 kWh

Power generated,

P = Pav x turbine-generator efficiency = 3276 x 10^6 kWh x 0.76 **= 2490 x 10^6 kWh**

Problem 4.2

The observed difference between the high and low water tide is 8.5 m for a proposed site. The basin area is about 0.5 km^2 which can generate power for 3 hours in each cycle. The average available head is assumed to be 8 m, and overall efficiency of the generation to be 72%. Calculate the power at any instant and the yearly power output. Average specific weight of sea water is assumed to be 1025 kg/m^3.

Solution:

Volume of the basin, V = A h0 = 0.5 x 10^6 x 8.5 = 4.25 x 10^6 m^3

Average discharge, Q = A h0 / t = 4.25 x 10^6 / (3 x 3600) = 393.5 m^3/s

Power at any instant, P = ρ Q h η = 1025 x 393.5 x 8 x 0.72 = 2323.333 kW

Total energy in kWh/tidal cycle, E = 2323.333 x 3 = 6970 kWh/tidal cycle

Theoretical total power output per annum = 6970 kWh x **705 tidal cycles /year**

= 4913850 kWh per annum

Advantages of Tidal Power

1. No pollution
2. Energy is at free of cost
3. No Greenhouse gases
4. Not expensive to maintain
5. Renewable resource
6. More efficient than wind because of the density of water
7. Predictable source of energy vs. wind and solar
8. Turbines are financially viable and eco-friendly

Disadvantages of Tidal Power

1. Presently costly - Expensive to build and maintain
2. Connection to the grid
3. Technology is not fully developed
4. Barrage style only produces energy for about 10 hours out of the day
5. Barrage style has environmental affects
    a. Such as fish and plant migration
    b. Silt deposits
    c. Local tides change- affects still under study

OCEAN THERMAL ENRGY CONVERSION (OTEC)

There are 75% of the Earth Covered by water. Ocean water stores much more heat than the atmosphere. Thermo-cline circulation creates temperature differences throughout Earth's oceans. Ocean Thermal Energy Conversion is working based on the temperature gradient of the sea water. The surface water temperature is around 20-25°C and deep water temperature is around 5-10°C. This small temperature range is capable of operating low temperature power cycle. The organic fluids of low boiling point (e.g. NH_3 = - 33°C). The hot surface water is used in the evaporator to generate vapour out of working fluid and it drives a vapor turbine and then its condensed in the condenser which is operated by the deep see cold water.

The salient operations are summarized below:

- Hot surface water, boils low boiling point liquid
- Boiling liquid turns turbine which generates electricity
- Electricity carried to land through underwater cable
- Deep cold water used to cool and condense liquid

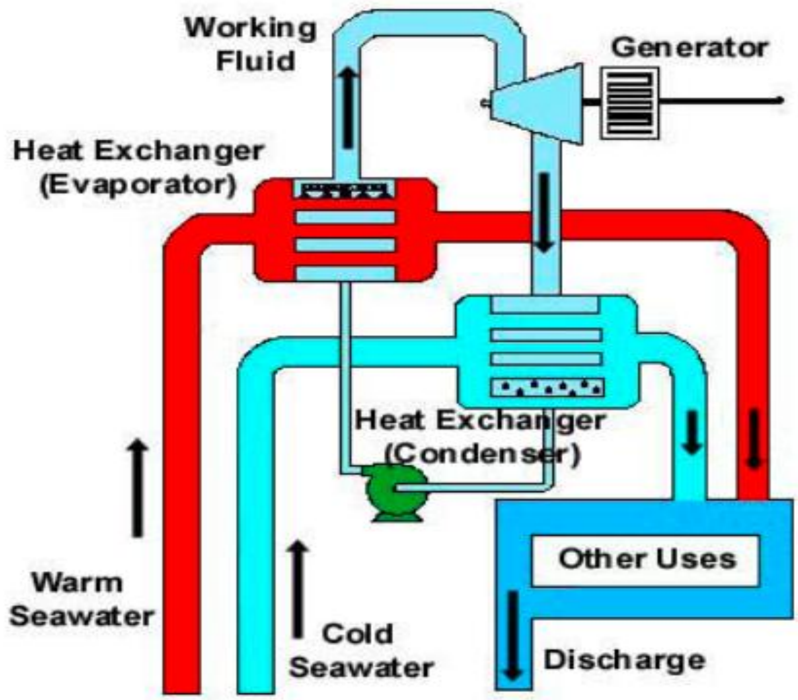


Fig.4.4 Closed OTEC plant

In closed OTEC, a low boiling point liquid is used whereas in open cycle OTEC, water is used as working fluid.

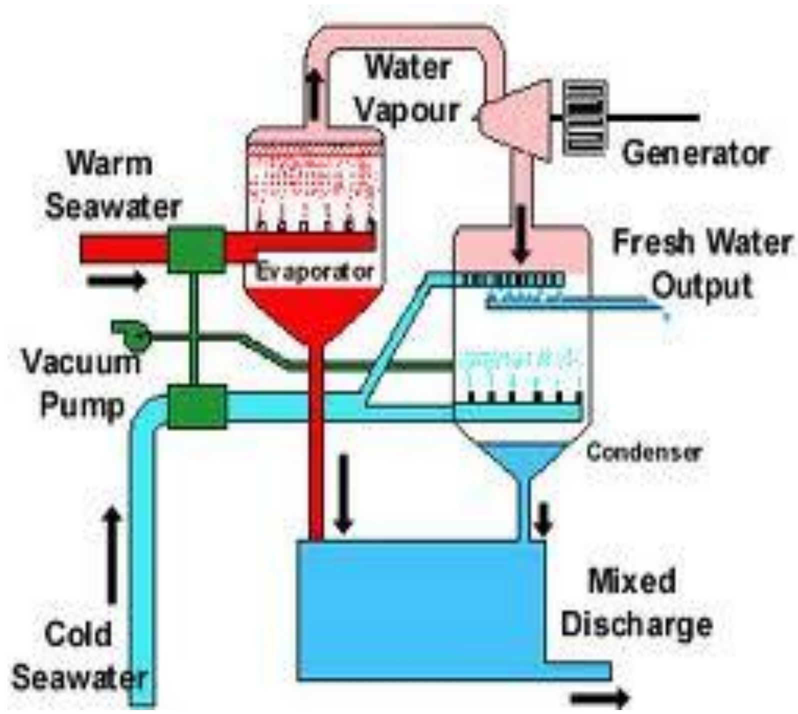


Fig.4.5 Open OTEC plant

Advantages of OTEC

1. Extremely benign impact on environment
2. No dependency on oil
3. Minimal maintenance costs compared to conventional power production plants
4. Open cycle OTEC systems can produce desalinated water which is very important in third-world countries

Disadvantages of OTEC

1. Low thermal efficiency due to small temperature gradient between heat sink and source
2. OTEC technology is only ideally suitable in equatorial waters
3. Only moderate power outputs are available
4. Currently this technology is not as monetarily feasible as conventional power production plants
5. The manufacturing and installation of the extremely long cold water pipes is extremely time consuming and costly.

GEOTHERMAL ENERGY

The geothermal energy is the heat energy available inside the earth. The thermal gradient is 1°C per 40 m depth (**25-30°C/km** depth). The water is sent in the bore wells and the steam out of it used to drive a steam turbine power cycle. **Geothermal energy** is thermal energy generated and stored in the Earth. Thermal energy is the energy that determines thetemperature of matter. The geothermal energy of the Earth's crust originates from the original formation of the planet (20%) and from radioactive decay of minerals (80%). The geothermal gradient, which is the difference in temperature between the core of the planet and its surface, drives a continuous conduction of thermal energy in the form of heat from the core to the surface. At the core of the Earth, thermal energy is created by radioactive decay and temperatures may reach over 5000 °C. Heat conducts from the core to surrounding cooler rock. The high temperature and pressure cause some rock to melt, creating magma convection upward since it is lighter than the solid rock. The magma heats rock and water in the crust, sometimes up to 370 °C.

TYPES OF GEOTHERMAL PLANTS

1. Dry steam (Vapour dominated) geothermal power plant
2. Wet steam – Single flash / Double flash (Liquid dominated) geothermal power plant
3. Binary Cycle geothermal power plant

Dry steam extracted from natural reservoir - 180-225 ºC , 4-8 MPa and the steam is used to drive a turbo-generator. Expanded steam is condensed and pumped back into the ground. We can achieve 1 kWh per 6.5 kg of steam and a 55 MW plant requires 100 kg/s of steam. The steam once it has been separated from the water is piped to the powerhouse where it is used to drive the steam turbine. The steam is condensed after leaving the turbine, creating a partial vacuum and thereby maximising the power generated by the turbine-generator. The steam is usually condensed either in a direct contact condenser, or a heat exchanger type condenser. In a direct contact condenser the cooling water from the cooling tower is sprayed onto and mixes with the steam.

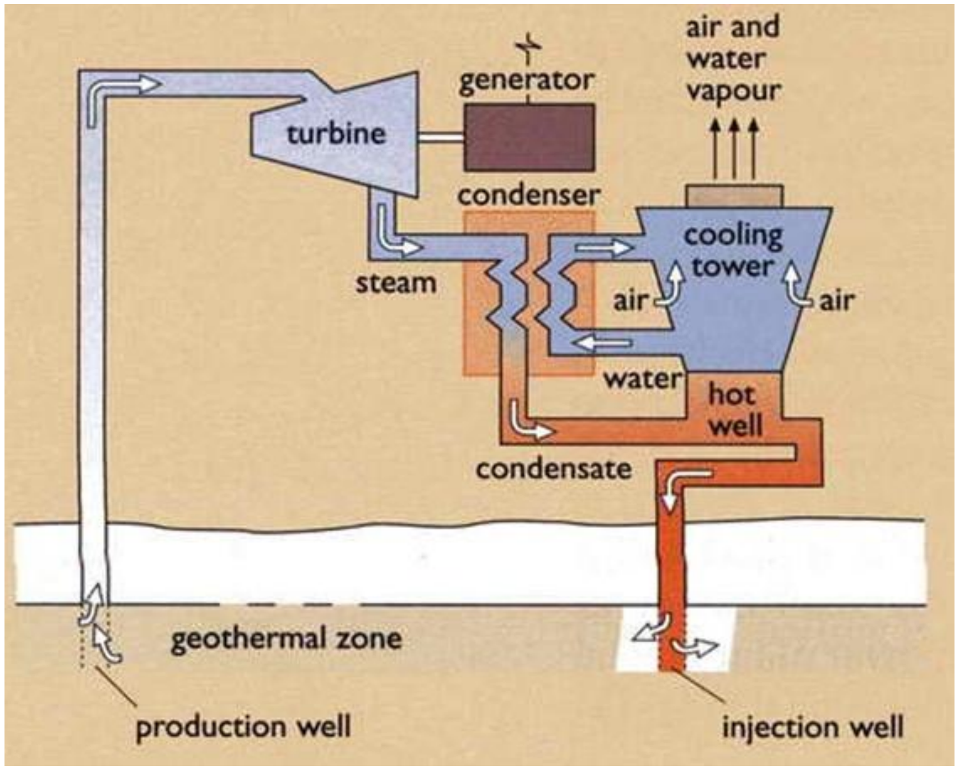


Fig. 4.6 Dry steam (Vapour dominated) geothermal power plant

The condensed steam then forms part of the cooling water circuit, and a substantial portion is subsequently evaporated and is dispersed into the atmosphere through the cooling tower. Excess cooling water called blow down is often disposed of in shallow injection wells. As an alternative to direct contact condensers shell and tube type condensers are sometimes used. In this type of plant, the condensed steam does not come into contact with the cooling water, and is disposed of in injection wells.

Flash geothermal power plant (Wet steam dominated geothermal plant)

This is the most common type of geothermal power plant (temperature below 180 °C). The illustration below shows the principal elements of this type of plant. The steam once it has been separated from the water is piped to the powerhouse where it is used to drive the steam turbine. The steam is condensed after leaving the turbine, creating a partial vacuum and thereby maximising the power generated by the turbine-generator. The steam is usually condensed either in a direct contact condenser, or a heat exchanger type condenser.

In a direct contact condenser the cooling water from the cooling tower is sprayed onto and mixes with the steam. The condensed steam then forms part of the cooling water circuit, and a substantial portion is subsequently evaporated and is dispersed into the atmosphere through the cooling tower. Excess cooling water called blow down is often disposed of in shallow injection wells.

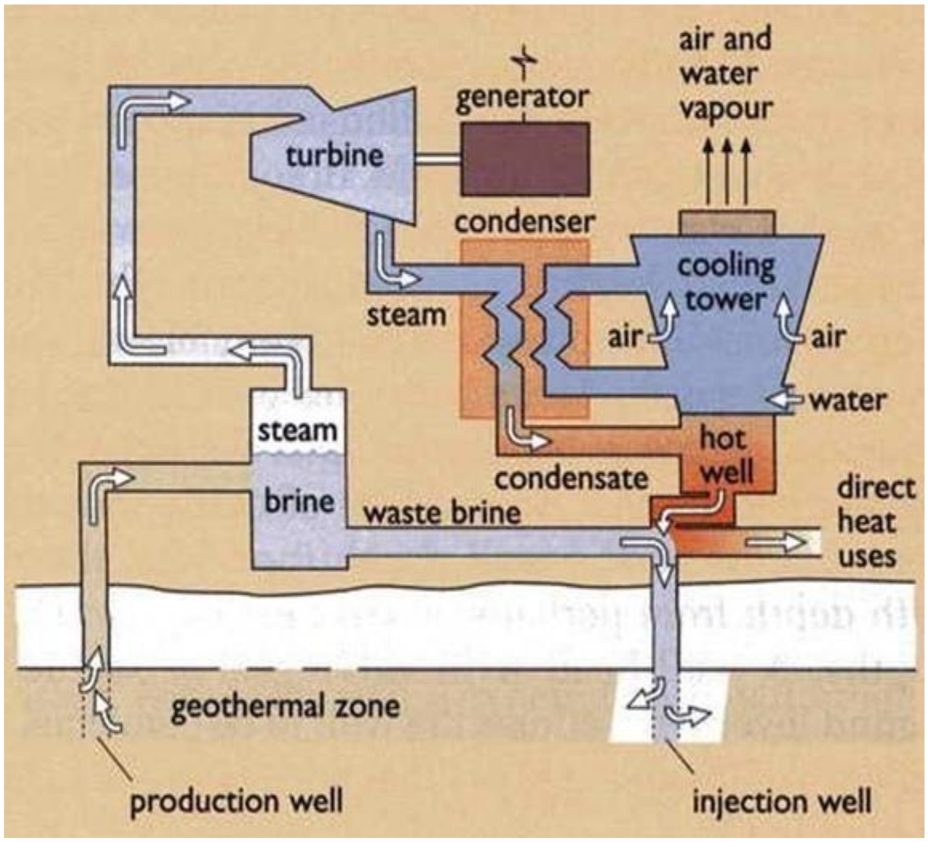


Fig.4.7 Single flash geothermal power plant

As an alternative to direct contact condensers shell and tube type condensers are sometimes used, as is shown in the schematic below. In this type of plant, the condensed steam does not come into contact with the cooling water, and is disposed of in injection wells.

Typically, flash condensing geothermal power plants vary in size from 5 MWe to over 100 MWe. Depending on the steam characteristics, gas content, pressures, and power plant design, between 6 and 9 tonne of steam each hour is required to produce each MW of electrical power.

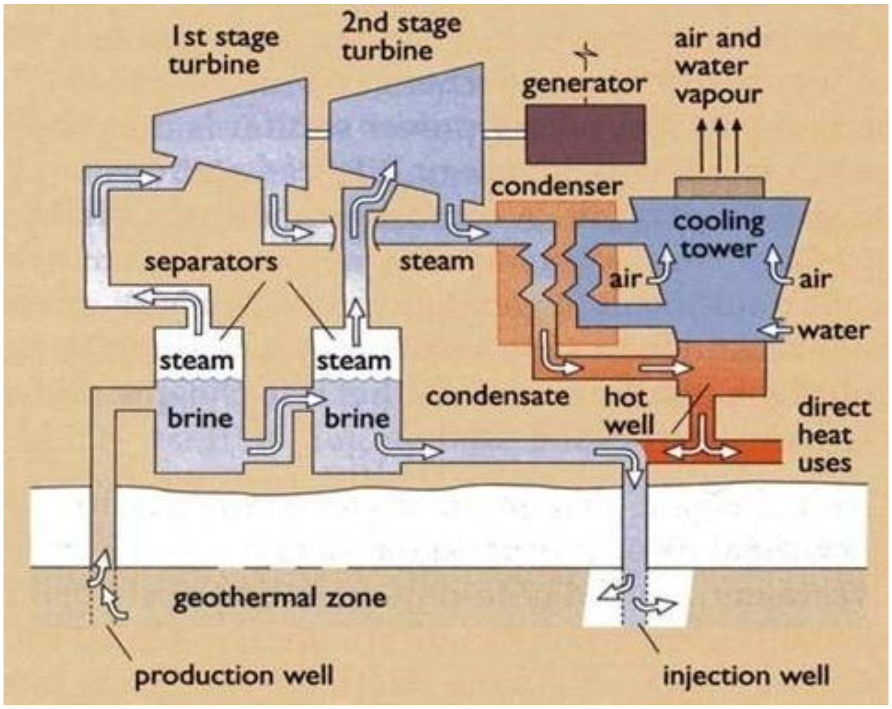


Fig. 4.8 Double flash geothermal power plant

Binary cycle geothermal power plant

In reservoirs where temperatures are typically less than 220^{o}C but greater than 100^{o}C. Binary cycle plants are often utilised. The illustration below shows the principal elements of this type of plant. The reservoir fluid (either steam or water or both) is passed through a heat exchanger which heats a secondary working fluid which has a boiling point lower than 100^{o}C. This is typically an organic fluid such as Isopentane, which is vaporised and is used to drive the turbine. The organic fluid is then condensed in a similar manner to the steam in the flash power plant described above, except that a shell and tube type condenser rather than direct contact is used.

The fluid in a binary plant is recycled back to the heat exchanger and forms a closed loop. The cooled reservoir fluid is again re-injected back into the reservoir. Binary cycle type plants are usually between 7 and 12 % efficient depending on the temperature of the primary (geothermal) fluid.

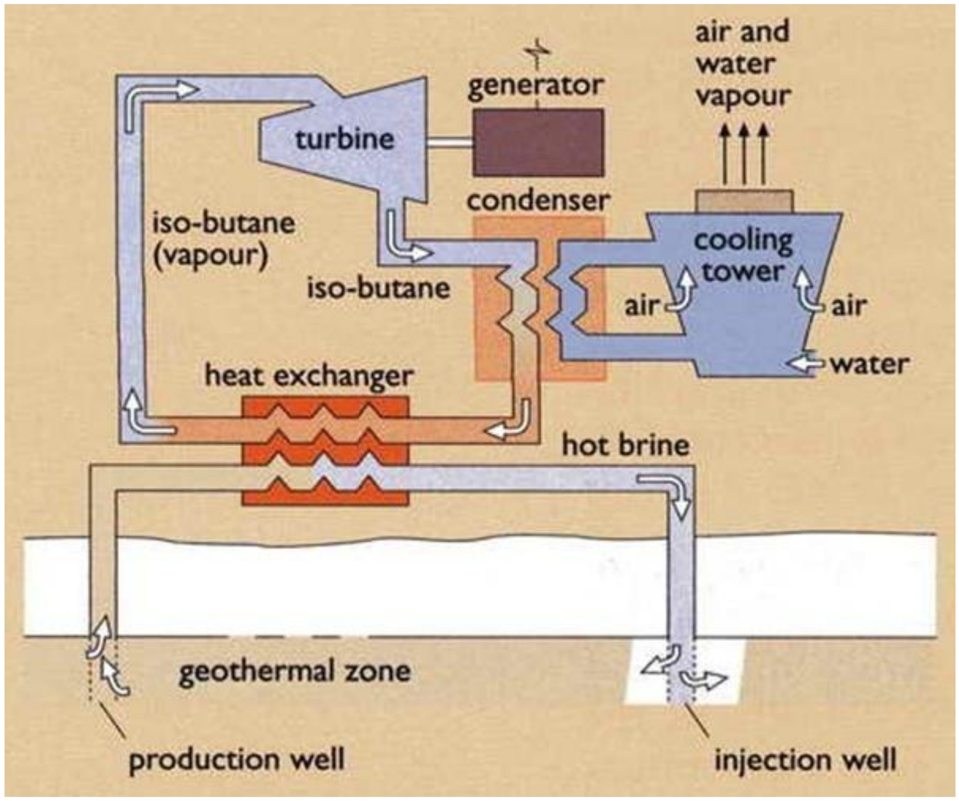


Fig.4.9 Binary cycle geothermal power plant

Advantages of geothermal energy

1. Useful minerals, such as zinc and silica, can be extracted from underground water.
2. Geothermal energy is "homegrown." This will create jobs, a better global trading position and less reliance on oil producing countries.
3. Geothermal plants can be online 100%-90% of the time. Coal plants can only be online 75% of the time and nuclear plants can only be online 65% of the time.
4. Flash and Dry Steam Power Plants emit 1000x to 2000x less carbon dioxide than fossil fuel plants, no nitrogen oxides and little SO_2.
5. Geothermal electric plants production in 13.380 g of Carbon dioxide per kWh, whereas the CO_2 emissions are 453 g/kWh for natural gas, 906g g/kWh for oil and 1042 g/kWh for coal.
6. Binary and Hot Dry Rock plants have no gaseous emission at all.
7. Geothermal plants do not require a lot of land, 400m^2 can produce a Giga Watt of energy over 30 years.

8. Electricity generated by geothermal plants saves 83.3 million barrels of fuel each year from being burned worldwide. This prevents 40.2 million tons of CO_2 from being emitted into the atmosphere.
9. Direct use of geothermal energy prevents 103.6 million barrels of fuel each year from being burned worldwide. This stops 49.6 tons of CO_2 from being emitted into the atmosphere.

Limitations of geothermal energy

1. Drilling wells and Maintenance of underground piping systems, contaminations of working fluids and treatment of working fluids.
2. Whether geothermal energy is utilised for power production or for direct use applications, there are issues in geothermal utilisation that often have technical implications.

   Geothermal fluids often contain significant quantities of gases such as hydrogen sulphide as well as dissolved chemicals and can sometimes be acidic. Because of this, corrosion, erosion and chemical deposition may be issues, which require attention at the design stage and during operation of the geothermal project.
3. Well casings and pipelines can suffer corrosion and /or scale deposition, and turbines, especially blades can suffer damage leading to higher maintenance costs and reduced power output.
4. However, provided careful consideration of such potential problems is made at the design stage, there are a number of technological solutions available. Such potential problems can be normally overcome by a combination of utilising corrosion resistant materials, careful control of brine temperatures, the use of steam scrubbers and occasionally using corrosion inhibitors.
5. Provided such readily available solutions are employed, geothermal projects generally have a very good history of operational reliability. Geothermal power plants for example, can boast of high capacity factors (typically 85-95%)

Potential Impact/ Mitigation / Remediation measures / Land requirement

1. Vegetation loss, Soil erosion, Landslides , Land ownership issues, Single drill pads – several wells , Re-vegetation programs, Adequate land compensation
2. Water take from streams/waterways for drilling purposes

3. Impact on local watershed, Damming and diverting local streams , Take from streams with high flow rates , Coincide drilling with rainy season not dry season , Build temporary reservoirs , Liaise with local farmers to take their usage into account
4. Water take from reservoir
5. Loss of natural features - Increase in steaming ground , Hydrothermal eruptions , Lowering of water table , Increase in steam zone , Subsidence , Saline intrusion , Avoid water take from outflows , Avoid areas where propensity for hydrothermal eruptions (which occur naturally also) , Careful sustainable management of resource, balancing recharge with take
6. Waste (brine & condensate) disposal into streams/ waterways
7. Biological effects , Chemical effects , Thermal effects , Effluent treatment and removal of undesirable constituents , Reinject all waste fluids , Cascaded uses of waste fluids eg. Fish farms, pools
8. Reinjection
9. Cooling of reservoir, Induced seismicity , Scaling , Careful planning of reinjection wells outside main reservoir , Monitor flow patterns before reinjection eg. Tracer tests , Anti-scale treatment of fluids.
10. Drilling effluent disposal into streams/waterways
11. Biological effects , Chemical effects, Contain in soakage ponds or in barrels for removal
12. Air emissions
13. Biological effects , Chemical effects , Localised slight heating of atmosphere , Localised fogging, Effluent treatment and removal of undesirable constituents , Minimise emissions by scrubbing H2S and treating other NCGs (Non Condensible Gases) .
14. Noise pollution
15. Disturbance to animals and humans, Impaired hearing , Muffling of noise eg. silencers

ECONOMICS INVOLVED IN GEOTHERMAL ENERGY

The cost of geothermal power developments is dependent upon many factors, the most important factors being:

· The temperature and depth of the resource. A shallow resource means minimum drilling costs. High temperatures (high enthalpies) mean higher energy capacity.

· The type of resource (steam, two phase or liquid). A dry steam resource is generally less expensive to develop as reinjection pipelines, separators and reinjection wells are not required.

· The chemistry of the geothermal fluid. A resource with high salinity fluids, high silica concentrations, high gas content, or acidic fluids can pose technical problems which may be costly to overcome.

· The permeability of the resource. A highly permeable resource means higher well productivity, and therefore fewer wells required to provide the steam for the power plant.

· The size of the plant to be built. As with most types of power plant, economies of scale means large power plants are generally cheaper in $/MW.

· The technology of the plant. There are a number of geothermal power technologies available, including simple back pressure plant with atmospheric exhaust, conventional condensing plant, binary cycle, combined cycle binary plants, Kalina Cycle, multi flash plants etc. Each technology has advantages and disadvantages and different cost structures.

· Infrastructure requirements (access roads, water and power services, proximity to adequate port facilities, proximity to a city). In isolated locations or small islands especially in developing countries, infrastructure may be a significant part of the total cost.

· Climatic conditions at the site. As with all types of power plants their cost and performance is dependent on the local climatic conditions. Low ambient wet bulb temperatures for example can lead to a less costly cooling system and a more efficient plant.

· Topography of the site. If the geothermal resource is sited in difficult terrain, civil development costs will be higher, pipelines may be more complex, of longer length with greater pressure drops and overall development costs may be higher.

· Environmental constraints. Environmental constraints on the siting, construction and operation of the geothermal power station can often result in increased development cost. A typical example may be the requirement for minimal discharge of geothermal gases (in particular hydrogen sulphide) to the environment. This may require the gases to be either reinjected into the reservoir (such as at the Puna plant in Hawaii) or costly hydrogen sulphide abatement systems to be installed.

· The proximity of the transmission lines. In isolated areas, it may be a requirement of the project to include for the construction of a lengthy transmission line to enable the power from the station to be fed into a grid servicing a sizeable load, possibly some distance away.

· Administration, management, legal, insurance, permitting, financing, local taxes and royalties and other indirect costs. The indirect costs of a power project, especially in developing countries can be a significant proportion of the overall project costs (up to 30%).

UNIT V.FUEL CELL AND MHD POWER GENERATION

FUEL CELLS

A fuel cell is a device that electrochemically converts the chemical energy of a fuel and an oxidant to electrical energy. The fuel and oxidant are typically stored outside of the fuel cell and transferred into the fuel cell as the reactants are consumed. The most common type of fuel cell uses the chemical energy of hydrogen and oxygen (H_2-O_2) to produce electricity, with water and heat as by-products. Fuel cells are unique in terms of the variety of their potential applications; they potentially can provide energy for systems as large as a utility power station and as small as a laptop computer.

Characteristics of Fuel Cells

1. High energy conversion efficiency
2. Modular design
3. Very low chemical and acoustical pollution
4. Fuel flexibility
5. Cogeneration capability
6. Rapid load response
7. Potable water as by-product

Working Principle of Fuel Cells

The design of fuel cell systems is complex and can vary significantly depending upon fuel cell type and application. However, most fuel cell systems consist of four basic components: Fuel cell stack, Fuel processor, Current converter, Heat recovery system. Most fuel cell systems also include other components and subsystems to control fuel cell humidity, temperature, gas pressure, and wastewater.

Fuel cells consist of an electrolyte material which is sandwiched in between two thin electrodes (porous anode and cathode). The input fuel passes over the anode (and oxygen over the cathode) where it catalytically splits into ions and electrons. The electrons go through an external circuit to serve an electric load while the ions move through the electrolyte toward the oppositely charged electrode. At the electrode, ions combine to create by-products, primarily water and CO_2. Depending on the input fuel and electrolyte, different chemical reactions will occur.

Types of Fuel Cells

The types of fuel cells are mostly named based on the electrolyte used in the fuel cells. The major five types are mentioned below:

1. Polymer Electrolyte Membrane Fuel Cells (PEMFC)
2. Alkaline Fuel Cells (AFC)
3. Phosphoric Acid Fuel Cell (PAFC)
4. Solid Oxide Fuel Cell (SOFC)
5. Molten Carbonate Fuel cells(MCFC)

Polymer Electrolyte Membrane (PEM) Fuel Cells

H_2-O_2 Fuel Cell or Polymer electrolyte membrane (PEM) fuel cells—also called Proton Exchange Membrane fuel cells—deliver high power density and offer the advantages of low weight and volume, compared to other fuel cells. PEM fuel cells use a solid polymer as an electrolyte and porous carbon electrodes containing a platinum catalyst. They need only hydrogen, oxygen from the air, and water to operate and do not require corrosive fluids like some fuel cells. They are typically fueled with pure hydrogen supplied from storage tanks or onboard reformers.

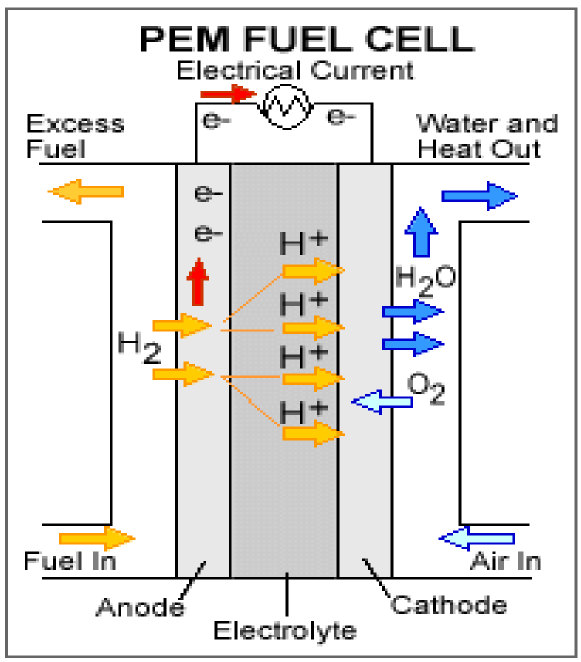


Fig.5.1 PEM FC

Alkaline Fuel Cells (AFC)

Alkaline fuel cells (AFCs) were one of the first fuel cell technologies developed, and they were widely used in the space program to produce electrical energy and water onboard spacecraft. These fuel cells use a solution of potassium hydroxide in water as the electrolyte and can use a variety of non-precious metals as a catalyst at the anode and cathode. High-temperature AFCs operate at temperatures between 50°C and 250°C. AFCs' high performance is due to the rate at which chemical reactions take place in the cell. They have also demonstrated efficiencies near 60 percent in space applications.

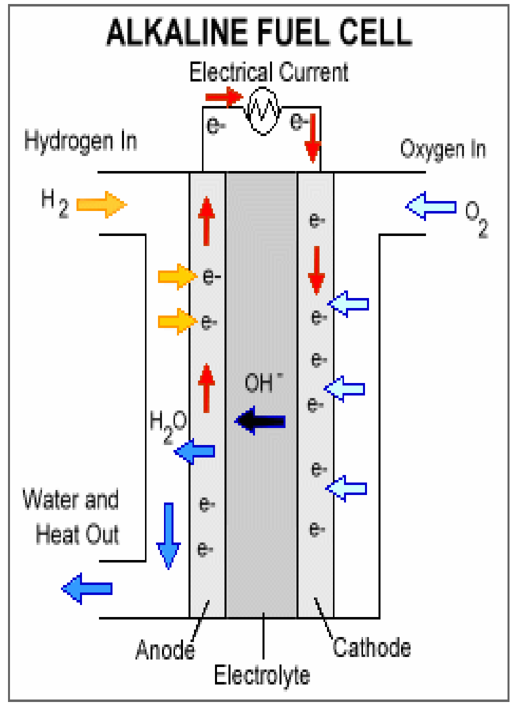


Fig.5.2 AFC

Phosphoric Acid Fuel Cells (PAFC)

Phosphoric acid fuel cells (PAFCs) use liquid phosphoric acid as an electrolyte—the acid is contained in a Teflon-bonded silicon carbide matrix—and porous carbon electrodes containing a platinum catalyst. The chemical reactions that take place in the cell are shown in the diagram to the right. The phosphoric acid fuel cell is considered the "first generation" of modern fuel cells. It is one of the most mature cell types and the first to be used commercially, with more units currently in use. This type of fuel cell is typically used for stationary power generation, but some PAFCs have been used to power large vehicles such as city buses.

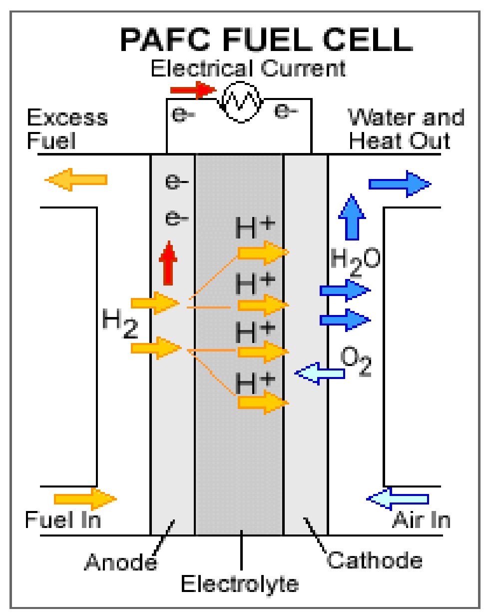


Fig.5.3 PAFC

Solid Oxide Fuel Cells

Solid oxide fuel cells (SOFCs) use a hard, non-porous ceramic compound as the electrolyte. Since the electrolyte is a solid, the cells do not have to be constructed in the plate-like configuration typical of other fuel cell types. SOFCs are expected to be around 50-60 percent efficient at converting fuel to electricity. In applications designed to capture and utilize the system's waste heat (co-generation), overall fuel use efficiencies is 80-85 percent. Solid oxide fuel cells operate at very high temperatures—around 1000°C.

High temperature operation removes the need for precious-metal catalyst, thereby reducing cost. It also allows SOFCs to reform fuels internally, which enables the use of a variety of fuels and reduces the cost associated with adding a reformer to the system. SOFCs are also the most sulfur-resistant fuel cell type; they can tolerate several orders of magnitude more sulfur than other cell types. In addition, they are not poisoned by carbon monoxide (CO), which can even be used as fuel. This allows SOFCs to use gases made from coal.

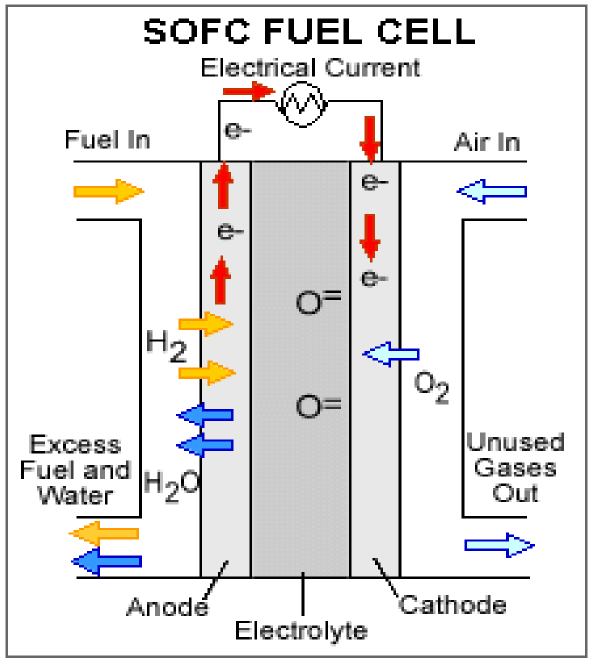


Fig.5.4 SOFC

Molten Carbonate Fuel Cells (MCFC)

MCFCs are high-temperature fuel cells that use an electrolyte composed of a molten carbonate salt mixture suspended in a porous, chemically inert ceramic matrix of beta-alumina solid electrolyte (BASE). Since they operate at extremely high temperatures of 650 °C and above, non-precious metals can be used as catalysts at the anode and cathode, reducing costs.

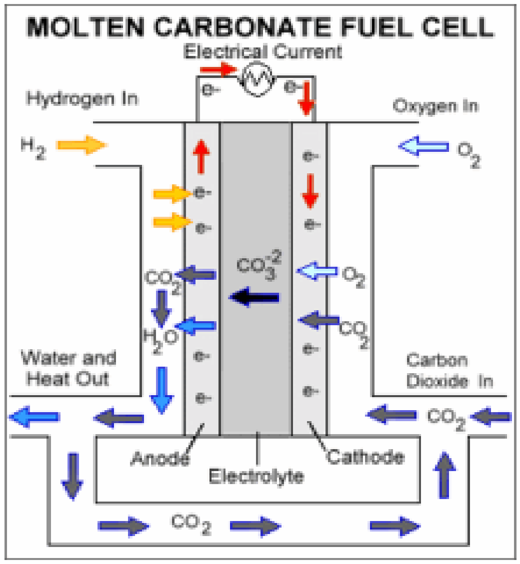


Fig.5.5 MCFC

Improved efficiency is another reason MCFCs offer significant cost reductions over phosphoric acid fuel cells (PAFCs). Molten carbonate fuel cells can reach efficiencies approaching 60%, considerably higher than the phosphoric acid fuel cell plant. When the waste heat is captured and used, overall fuel efficiencies can be as high as 85%. Unlike alkaline, phosphoric acid, and polymer electrolyte membrane fuel cells, MCFCs don't require an external reformer to convert more energy-dense fuels to hydrogen. Due to the high temperatures at which MCFCs operate, these fuels are converted to hydrogen within the fuel cell itself by a process called internal reforming, which also reduces cost.

Comparisons of various fuel cells (Table 5.1 Comparisons of various fuel cells)

Description	**PEM FC**	**AFC**	**PAFC**	**MCFC**	**SOFC**
Temperature	50 - 100°C	50 – 250 °C	100 – 200 °C	650 °C	500 -1000 °C
Efficiency	40 – 50%	70%	40-60%	60-80%	60%
Power OP	50 – 250 kW	0.3kW – 5 kW	11 MW	2-100 MW	100 kW
Electrolyte	Polymer	KOH	Phosporic acid	Molten Carbonate	Solid Oxide

Benefits of fuel cells

1. Fuel cell power plants produce dramatically fewer emissions, and their byproducts are primarily water and carbon dioxide.
2. Fuel cell power plants are nearly twice as efficient as conventional power plants.
3. Small-scale fuel cell plants are just as efficient as large ones, and operation at partial load is as efficient as at full load.
4. High-grade waste heat from fuel cell systems is perfect for use in cogeneration, heating, and air- conditioning.
5. The fuel cell stack is the basic component of a fuel cell power plant. Stacks are combined into modules, and the number of modules determines plant capacity.
6. The individual modules can go from ideal to full load in minutes.
7. Fuel cells are one of the most reliable power generation technologies.
8. Fuel cell power plants are reliable and safe, and can be sited in environmentally sensitive areas.
9. Fuel cell needs hydrogen, which can be generated internally from natural gas, coal, methanol, landfill gas or other fuels containing hydrocarbons.
10. Fuel cell technology meets public demand for clean, quiet and efficient power.
11. The average voltage per cell is 0.75 V. By joining a number of cells in series and parallel can provide any reasonable voltage and current.

Technology Challenges / Problems in fuel cells.

1. The fuel cell uses pure oxygen and hydrogen to produce electricity.
2. The oxygen required for a fuel cell comes from the air. In fact, in the PEM fuel cell, ordinary air is pumped into the cathode.
3. The hydrogen is not so readily available, however.
4. Hydrogen has some limitations that make it impractical for use in most applications. For instance, you don't have a hydrogen pipeline coming to your house, and you can't pull up to a hydrogen pump at your local gas station.

5. Hydrogen is difficult to store and distribute, so it would be much more convenient if fuel cells could use fuels that are more readily available. This problem is addressed by a device called a reformer. A reformer turns hydrocarbon or alcohol fuels into hydrogen, which is then fed to the fuel cell.
6. Cost is higher
7. Durability and Reliability issues
8. System Size determination
9. Air, Thermal, and Water Management challenges
10. Improved Heat Recovery Systems are required

Applications of Fuel Cells

1. Automotive power Transportation – cars, buses etc.
2. Stationary power plant as well as portable power
3. Cogeneration
4. Uninterrupted power supply
5. Emergency power supply
6. Micropower generation
7. Consumer electronics / domestic use
8. Waste heat recovery systems

<u>Problem 5.1</u>

A H_2-O_2 fuel cell operates at 25 °C. Calculate the voltage output of the cell, the efficiency and electric work output per mole of H_2 consumed and per mole of H_2O produced. Also find the heat transferred to the surroundings.

Take $\Delta H^0_{(298\ K)}$ = - 285.838 MJ/kg mole, $\Delta G^0_{(298\ K)}$ = - 237.191 MJ/kg mole. Faraday constant, F = 96500 coloumbs per gram-mole.

Solution:

$H_2 + 2OH^-$ ----------------- $2\ H_2O + 2\ e^-$.

There are 2 electrons transferred per molecule of H_2. So n = 2.

The cell voltage, $E = -\Delta G^0_{(298\ K)} / (n \times F) = 237191/ (2 \times 96.5) =$ **1.229 V**

Maximum efficiency, $\eta = \Delta G^0_{(298\ K)} / \Delta H^0_{(298\ K)}$ = **83 %**

Heat transferred, Q = T ΔS = $\Delta H^0_{(298\ K)} - \Delta G^0_{(298\ K)}$ **= - 4865 kJ/kg mole.**

Problem 5.2

Perform the necessary calculations to show that the maximum efficiency for methane fuel cell is 92% and the ideal cell voltage is 1.15 volts. What is the mass flow rate of methane and oxygen would be required to generate a power of 100 kW and what is the heat transfer rate at these conditions? Take $\Delta G^0_{(298\ K)} = -\ 818.320$ MJ/kg mole, $\Delta H^0_{(298\ K)} = -\ 889.478$ MJ/kg mole. F = 96 coloumbs per kg-mole.

SOLUTION:

$CH_4 + 2H_2O$ --------------------- $CO_2 + 8H^+ + 8e^-$

There are 8 electrons transferred per molecule of CH_4. So n = 8.

The cell voltage, $E = -\Delta G^0_{(298\ K)} / (n \times F) = 818320/ (8 \times 96.5) =$ **1.06 V**

Maximum efficiency, $\eta = \Delta G^0_{(298\ K)} / \Delta H^0_{(298\ K)}$ = **92 %**

This is also equal to the ratio of operating voltage to ideal or O.C. voltage

So the ideal or theoretical voltage = 1.06/0.92 = **1.15 V.**

Power developed, P = 100 kW = 100 kJ/s = 100 x 3600 = 360,000 kJ/hr

Required flow rate of methane, = P/ [$\Delta G^0_{(298\ K)}$ / No. of moles in methane]

No. of moles in methane, = 1 x 12 + 4 x 1 **= 16**

Required flow rate of methane = 360000 / [818320 / 16] = **7.04 kg/hr**

Heat transferred, Q = T ΔS = $\Delta H^0_{(298\ K)} - \Delta G^0_{(298\ K)}$ **= - 71158 kJ/kg mole.**

MAGNETO HYDRODYNAMIC (MHD) POWER GENERATION

Magneto hydrodynamic power generation provides a way of generating electricity directly from a fast moving stream of ionized gases without the need for any moving mechanical parts - no turbines and no rotary generators. MHD power generation has also been studied as a method for extracting electrical power from nuclear reactors and also from more conventional fuel combustion systems like gas turbine exhaust.

- The electro-magnetic induction principle is not limited to solid conductors. The movement of a conducting fluid through a magnetic field can also generate electrical energy.
- When a fluid is used for the energy conversion technique, it is called Magneto Hydro Dynamic (MHD), energy conversion.
- The flow direction is right angles to the magnetic fields direction. An electromotive force (or electric voltage) is induced in the direction at right angles to both flow and field directions.
- The conducting flow fluid is forced between the plates with a kinetic energy and pressure differential sufficient to overcome the magnetic induction force.
- An ionized gas is employed as the conducting fluid.
- Ionization is produced either by thermal means i.e. by an elevated temperature or by seeding with substance like Cesium or Potassium vapors which ionizes at relatively low temperatures.
- The atoms of seed element split off electrons. The presence of the negatively charged electrons makes the gas an electrical conductor.

The MHD generator can be considered to be a fluid dynamo. This is similar to a mechanical dynamo in which the motion of a metal conductor through a magnetic field creates a current in the conductor except that in the MHD generator the metal conductor is replaced by conducting gas plasma. When a conductor moves through a magnetic field it creates an electrical field perpendicular to the magnetic field and the direction of movement of the conductor. This is the principle, discovered by Michael Faraday, behind the conventional rotary electricity generator. Dutch physicist Antoon Lorentz provided the mathematical theory to quantify its effects.

The flow (motion) of the conducting plasma through a magnetic field causes a voltage to be generated (and an associated current to flow) across the plasma, perpendicular to both the plasma flow and the magnetic field according to Fleming's Right Hand Rule. Lorentz Law describing the effects of a charged particle moving in a constant magnetic field.

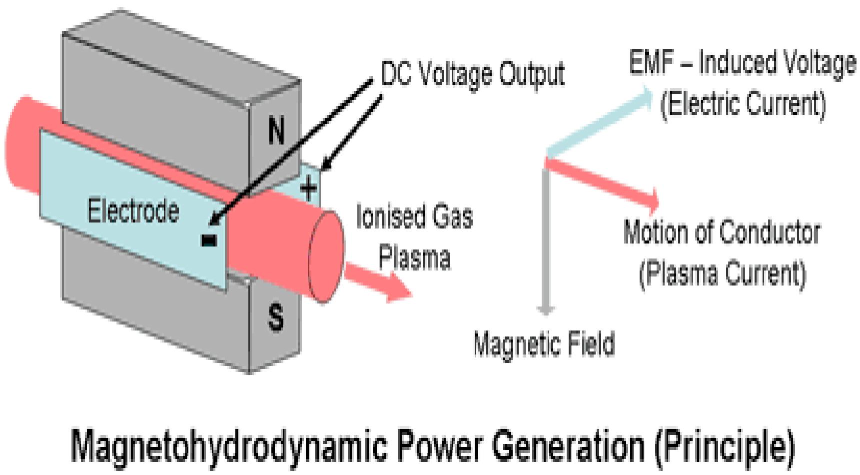


Fig. 5.6 MHD Operating principle

Lorentz Law

F is the force acting on the charged particle, **F = Q v B ,**

Where,

Q is charge of particle

v is velocity of particle

B is magnetic field

The MHD generator needs a high temperature gas source, which could be the coolant from a nuclear reactor or more likely high temperature combustion gases generated by burning fossil fuels, including coal, in a combustion chamber.

The expansion nozzle reduces the gas pressure and consequently increases the plasma speed (Bernoulli's Law) through the generator duct to increase the power output. Unfortunately, at the same time, the pressure drop causes the plasma temperature to fall (Gay-Lussac's Law) which also increases the plasma resistance, so a compromise between Bernoulli and Gay-Lussac must be found.

The exhaust heat from the working fluid is used to drive a compressor to increase the fuel combustion rate but much of the heat will be wasted unless it can be used in another process. The prime system requirement is creating and managing the conducting gas plasma since the system depends on the plasma having a high electrical conductivity. Suitable working fluids are gases derived from combustion, noble gases, and alkali metal vapours.

An MHD generator produces a DC output which needs an expensive high power inverter to convert the output into AC for connection to the grid. Typical efficiencies of MHD generators are around 10 to 20 percent mainly due to the heat lost through the high temperature exhaust.

The MHD systems are broadly classified into two types as follow:

1. Open cycle system
2. Closed cycle system

    - Seeded inert gas system
    - Liquid metal system

Open Cycle MHD System

The fuel used maybe oil through an oil tank or gasified coal through a coal gasification plant. The fuel (coal, oil or natural gas) is burnt in the combustor or combustion chamber. The hot gases from combustor are then seeded with a small amount of ionized alkali metal (cesium or potassium) to increase the electrical conductivity of the gas. The seed material, generally potassium carbonate is injected into the combustion chamber; the potassium is then ionized by the hot combustion gases at temperature of roughly 2300 to 2700 °C.

To attain such high temperatures, the compressed air is used to burn the coal in the combustion chamber, must be adequate to at least 1100°C. A lower preheat temperature would be adequate if the air is enriched in oxygen. An alternative is used to compress oxygen alone for combustion of fuel, little or no preheating is then required. The additional cost of oxygen might be balanced by saving on the preheater.

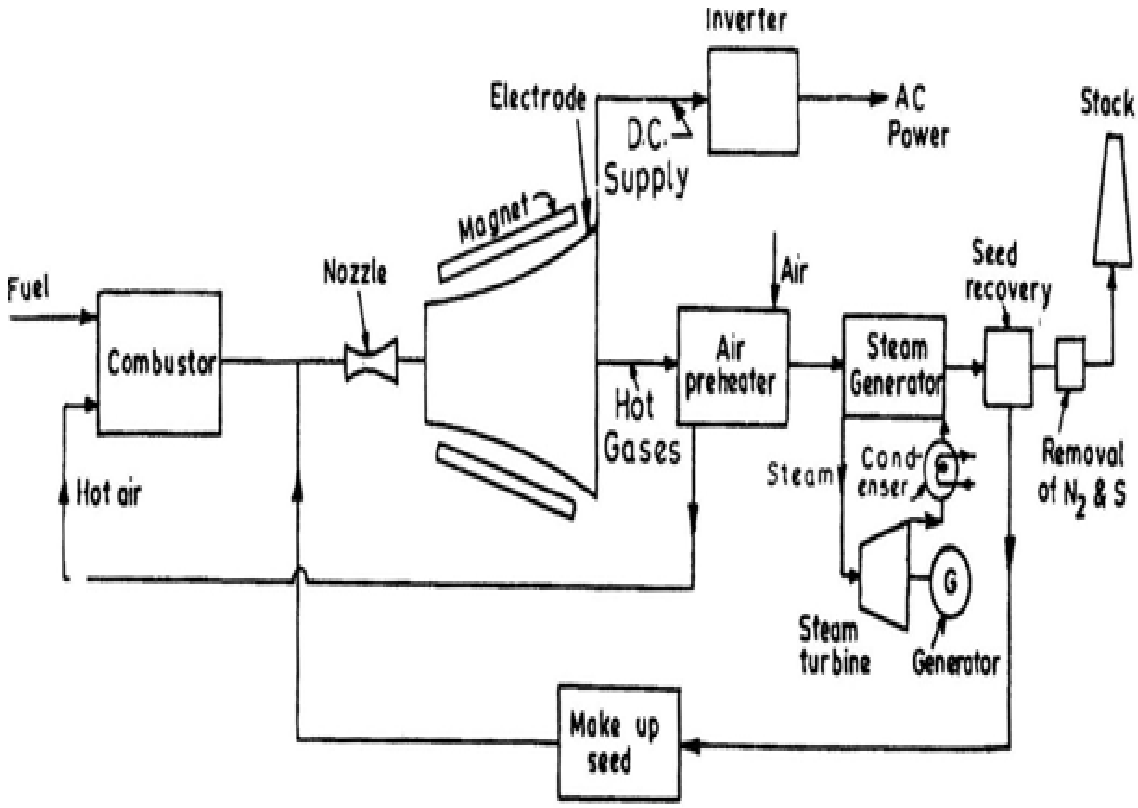


Fig. 5.7 Open Cycle MHD Power generation (Courtesy G.D.Rai et al., BHEL)

The hot pressurized working fluid living in the combustor flows through a convergent divergent nozzle. In passing through the nozzle, the random motion energy of the molecules in the hot gas is largely converted into directed, mass of energy. Thus, the gas emerges from the nozzle and enters the MHD generator unit at a high velocity.

Closed Cycle MHD Power generation

Two general types of closed cycle MHD generators are being investigated. Electrical conductivity is maintained in the working fluid by ionization of a seeded material, as in open cycle system. A liquid metal provides the conductivity. The carrier is usually a chemical inert gas, all through a liquid carrier is been used with a liquid metal conductor. The working fluid is circulated in a closed loop and is heated by the combustion gases using a heat exchanger. Hence the heat sources and the working fluid are independent. The working fluid is helium or argon with cesium seeding.

Seeded Inert Gas System

In a closed cycle system the carrier gas operates in the form of Brayton cycle. In a closed cycle system the gas is compressed and heat is supplied by the source, at essentially constant pressure, the compressed gas then expands in the MHD generator, and its pressure and temperature fall. After leaving this generator heat is removed from the gas by a cooler, this is the heat rejection stage of the cycle. Finally the gas is recompressed and returned for reheating.

The complete system has three distinct but interlocking loops. On the left is the external heating loop. Coal is gasified and the gas is burnt in the combustor to provide heat. In the primary heat exchanger, this heat is transferred to a carrier gas Argon or Helium of the MHD cycle. The combustion products after passing through the air preheated and purifier are discharged to atmosphere.

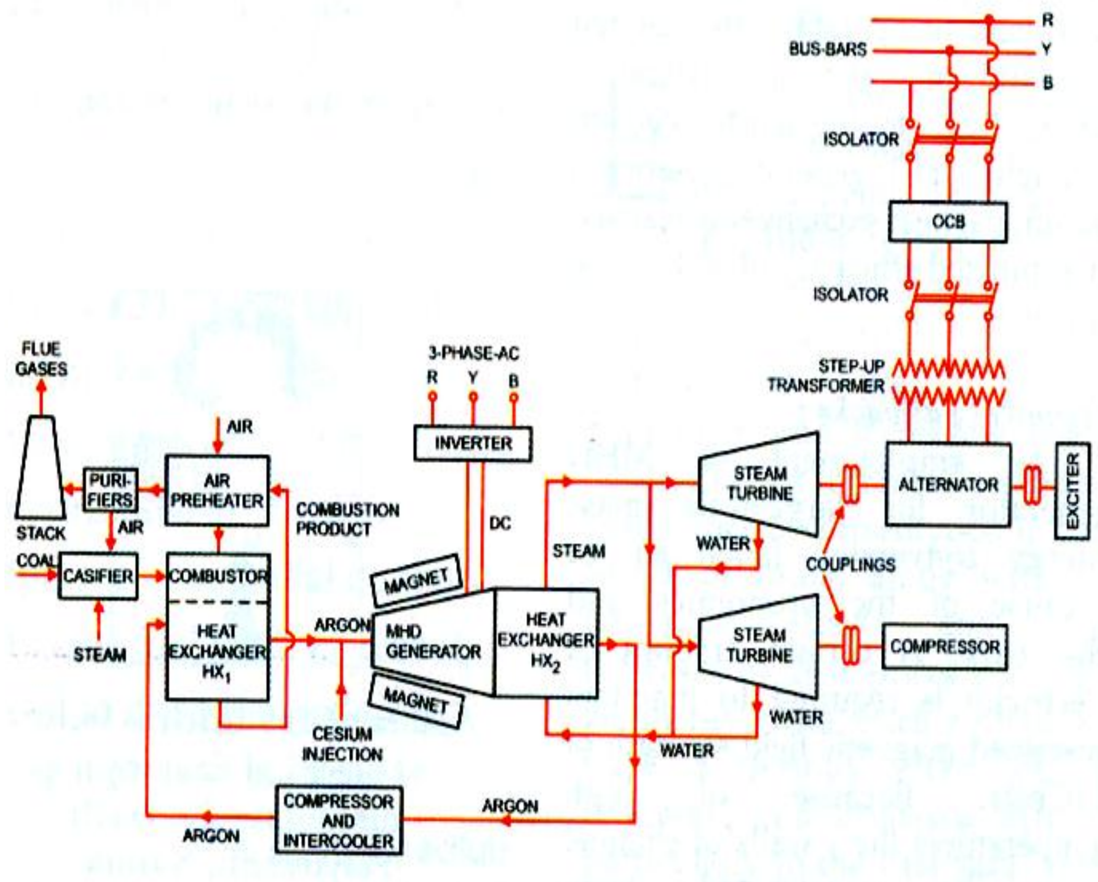


Fig.5.8 Seed inert gas MHD system

Liquid Metal System

When a liquid metal provides the electrical conductivity, it is called a liquid metal MHD system. An inert gas is a convenient carrier. The carrier gas is pressurized and heated by passage through a heat exchanger within combustion chamber. The hot gas is then incorporated into the liquid metal usually hot sodium to form the working fluid. The latter then consists of gas bubbles uniformly dispersed in an approximately equal volume of liquid sodium.

The working fluid is introduced into the MHD generator through a nozzle in the usual ways. The carrier gas then provides the required high direct velocity of the electrical conductor.

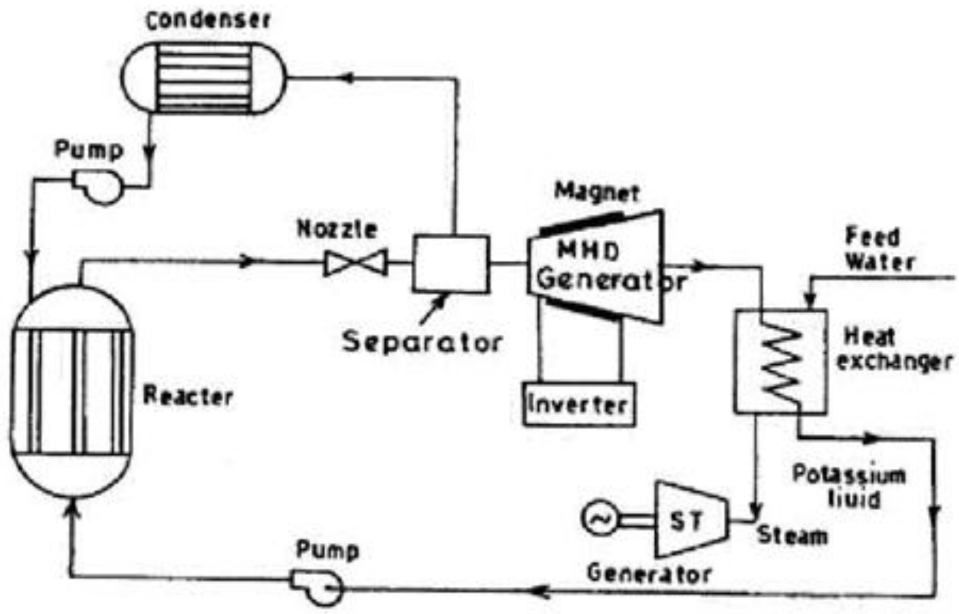


Fig.5.9. Liquid Metal MHD System

Comparison of Open and Closed cycle MHD power generation

Table 5.2 Comparison of Open and Closed cycle MHD power generation

Description	**Open cycle MHD**	**Closed cycle MHD**
Working fluid	Air + hot gases + seed material	Ar or He or Liquid metals (Na) + Cesium seed
Recirculation of working fluid	No	Yes
Operating temperature	2300 to 3000 °C	2000 °C
Technology developed	More	Less

Important selection factors of materials for MHD generators

1. Thermal shock resistance
2. Electrical conductivity
3. Corrosion resistance
4. Erosion resistance
5. Oxidation reduction resistance
6. Melting point of materials and density

CALCULATIONS IN MHD POWER GENERATION

Let

A - Plate area in m^2 ,

d- distance between plates in m,

B - flux density in Wb/m^2,

u - average gas velocity in m/s,

σ - gaseous electrical conductivity in Mho/m.

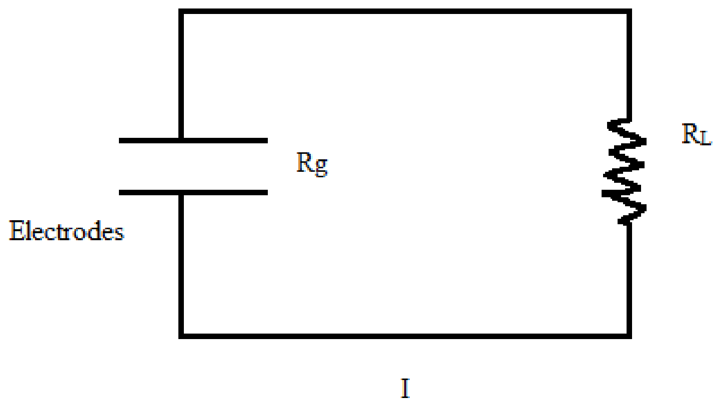


Fig. 5.10 Electrical circuit of generator

Open circuit voltage, **OC voltage**, $E_0 = B\ u\ d$

Generator internal resistance, Rg = d / (σ A) in Ohm

Maximum power, $P_{max} = E_0\ I = (I\ Rg)\ I = I^2\ Rg = [\ E_0 / (Rg + R_L)\ ]^2\ Rg$

For maximum power, internal resistance and total resistance are equal, $Rg = R_L$

Maximum power, $P_{max} = E_0^2 / 4\ Rg = 0.25\ \sigma\ u^2\ B^2$

Problem 5.3

Calculate the O.C. voltage and maximum power output for the given MHD generator specifications: Plate area =0.25 m^2 , distance between plates = 0.5 m, flux density = 2 Wb/m^2, average gas velocity = 1000 m/s, gaseous electrical conductivity = 10 Mho/m.

Solution:

OC voltage, $E_0 = B\ u\ d = 2 \times 1000 \times 0.5 =$ **1000 V = 1 kV**

Generator resistance, $R_g = d / (\sigma A) = 0.5 / (10 \times 0.25) = 0.2$ Ohm

Maximum power, $P_{max} = E_0^2 / 4 R_g = 1000^2 / (4 \times 0.20) =$ **1250 kW**

Advantages of MHD Systems

1. The conversion efficiency of a MHD system can be around 50% much higher compared to the most efficient steam plants. Still higher efficiencies are expected in future, around 60 – 65 %, with the improvements in experience and technology.
2. Large amount of power is generated.
3. It has no moving parts, so more reliable.
4. The closed cycle system produces power, free of pollution.
5. It has ability to reach the full power level as soon as started.
6. The size if the plant is considerably smaller than conventional fossil fuel plants
7. Although the cost cannot be predicted very accurately, yet it has been reported that capital costs of MHD plants will be competitive to conventional steam plants.
8. It has been estimated that the overall operational costs in a plant would be about 20% less than conventional steam plants.
9. Direct conversion of heat into electricity permits to eliminate the turbine (compared with a gas turbine power plant) or both the boiler and the turbine (compared with a steam power plant) elimination reduce losses of energy.
10. These systems permit better fuel utilization. The reduced fuel consumption would offer additional economic and special benefits and would also lead to conservation of energy resources.

11. It is possible to use MHD for peak power generations and emergency service. It has been estimated that MHD equipment for such duties is simpler, has capability of generating in large units and has the ability to make rapid start to full load.

Disadvantages of MHD Systems / Design challenges involved in MHD power

1. Suffers from reverse flow (short circuits) of electrons through the conducting fluids around the ends of the magnetic field.
2. Needs very large magnets and this is a major expense.
3. High friction and heat transfer losses.
4. Corrosion and erosion of components due to alkaline seeds and high velocity gases.
5. Achieving very high operating temperature (2000-3000°C).
6. Coal used as fuel poses problem of molten ash which may short circuit the electrodes. Hence, oil or natural gas are much better fuels for MHDs. Restriction on use of fuel makes the operation more expensive.
7. Seed materials attack the insulation.
8. Corrosion of electrodes by combustion gases.
9. Economics - additional investments if retrofit in existing power plants.
10. High temperature resistant materials are required for piping systems and components.
11. Requires very high temperature insulation.
12. Extremely vey high temperature involved extremely very large magnets etc. So the electrical, thermal, thermo-chemical stresses and corrosion are to be researched further to make MHD power successful.

Applications of MHD power

1. Power generation in land as well as spacecraft
2. Hypersonic wind tunnel applications
3. Defense applications.

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