RENEWABLE ENERGY SOURCES

by

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Module: I, II & III

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Renewable Energy Sources

Module I

Energy scenario and renewable energy sources: global and Indian situation. Potential of nonconventional energy sources, economics. Solar Radiation: Solar thermal process, heat transfer devices, solar radiation measurement, estimation of average solar radiation. Solar energy storage: stratified storage, well mixed storage, comparison.

Module II

Hot water system, Practical consideration, solar ponds, Non-convective solar pond, extraction of thermal energy and application of solar ponds. Wind energy: The nature of wind. Wind energy resources and modeling. Geothermal energy: Origin and types of geothermal energy and utilization.

Module III

OTEC: Ocean temperature differences. OTEC systems. Recent OTEC developments. Wave energy: Fundamentals. Availability Wave-energy conversion systems. Tidal energy: Fundamentals. Availability Tidal-energy conversion systems; Energy from biomass: Photosynthesis; Biomass resource; Utilization of biomass.

Books

S. P. Sukhatme, Solar Energy Principle of Thermal Collection and Storage‟, Tata McGraw Hill, 1990.

G. L. Johnson, Wind energy systems, Prentice Hall Inc. New Jersey.

J. M. Kriender, Principles of Solar Engineering‟, McGraw Hill, 1987.

Reference

V. S. Mangal, Solar Engineering‟, Tata McGraw Hill, 1992.

N. K. Bansal, Renewable Energy Source and Conversion Technology‟, Tata McGraw Hill, 1989.

P. J. Lunde, Solar Thermal Engineering‟, John Willey & Sons, New York, 1988.

J. A. Duffie and W. A. Beckman, Solar Engineering of Thermal Processes‟, Wiley & Sons, 1990.

ENERGY SCENERIO ACROSS THE GLOBE

1.Energy:
1.1 Global Scene:

Energy is highly essential for the growth of the developing and developed countries. This has direct impact on socioeconomic groups of nations. The demand of energy varies from country to country. The energy sources available are classified into two sources of energy.

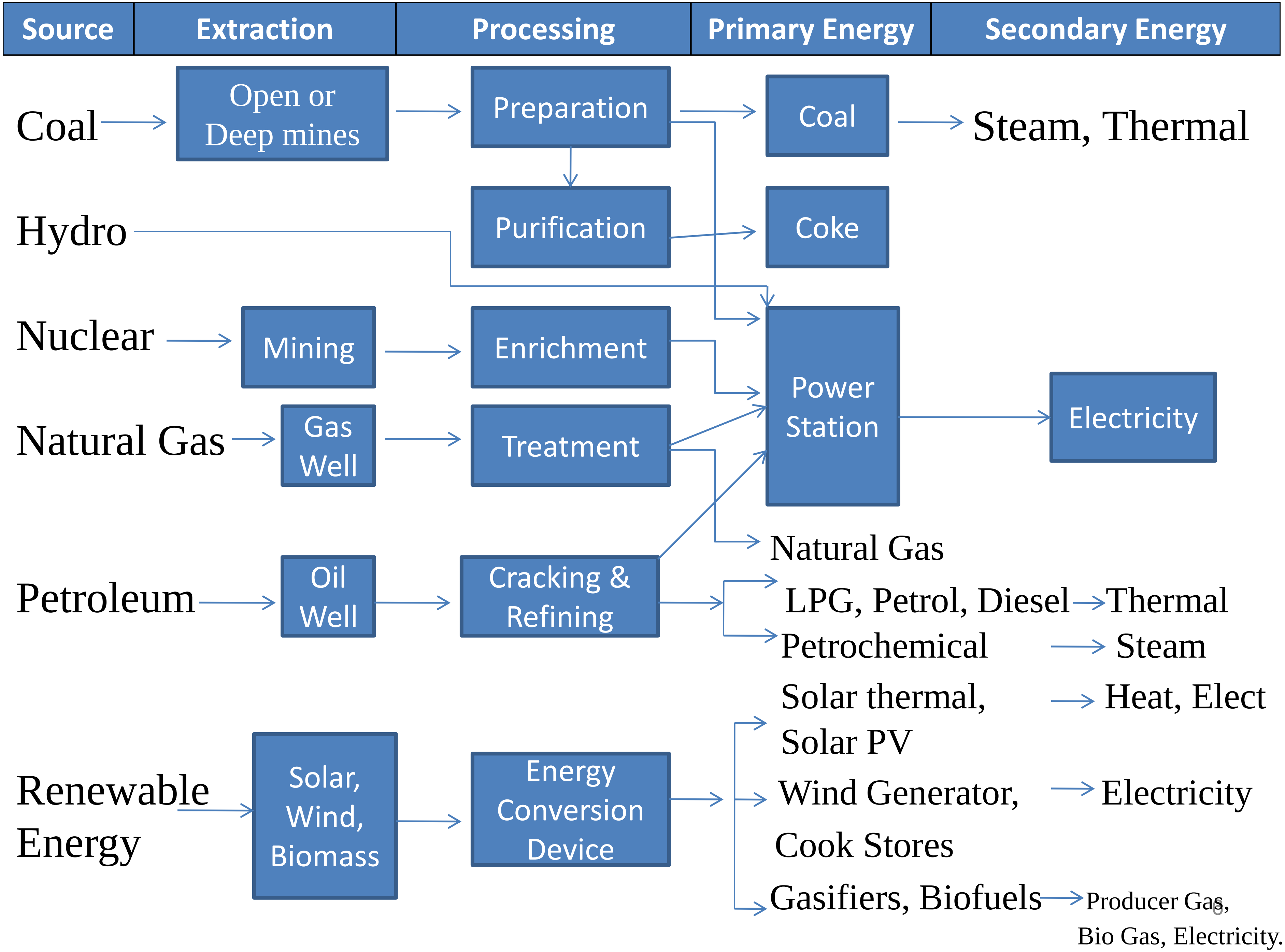
(a) Primary energy sources:

The energy sources are available in nature such as coal, oil, wind, solar, biogas, geothermal and ocean energy; are termed as primary energy sources. Some of these are directly used for energy supply like burning fuel in furnaces, transportation purposes etc.

(b) Secondary energy sources:

Burning of fuel produces heat which is utilized to produce steam in power plant and the electricity is generated. So heat and electricity are termed as secondary energy sources.

The table presented below for major primary and secondary energy sources in Global situation.


Source
Extraction
Processing
Primary Energy
Secondary Energy
Coal
Open or Deep mines
Preparation
Coal
Steam, Thermal
Hydro
Purification
Coke
Nuclear
Mining
Enrichment
Power Station
Electricity
Natural Gas
Gas Well
Treatment
Natural Gas
Petroleum
Oil Well
Cracking & Refining
LPG, Petrol, Diesel
Thermal
Petrochemical
Steam
Solar thermal, Solar PV
Heat, Elect
Renewable Energy
Solar, Wind, Biomass
Energy Conversion Device
Wind Generator,
Electricity
Cook Stores
Gasifiers, Biofuels
Producer Gas, Bio Gas, Electricity.

Non-Commercial and Commercial Energy Sources:

All energy sources which are available in nature like wind, sun, hydro etc. are *non-commercial energy sources*. Biomass like cattle dung, agricultural waste, fire woods etc are used by rural people for burning purposes and solar energy for drying purposes. These are also called as non-commercial energy sources because for production of heat or energy technology is not essential.

Applications of solar energy, wind energy, hydro energy for electricity and lifting water from the ground require technology are termed as *commercial energy sources*.

Renewable and Non-renewable Energy Sources:-

The energy sources like coal and petroleum products take million years for production. These energy sources are going to be exhausted after few years. These energy sources are termed as *non-renewable energy sources.*

Energy sources like solar, wind, hydro, various forms of biomass and marine energy (wave & tidal) are never exhaustible. These are termed as *renewable energy sources*. Geothermal and ocean thermal energy sources are also renewable energy sources.

* The global primary energy supply and consumption is in table below.

Table: Annual primary energy consumption by fuel (2012) in Mtoe*

Country	Oil	Natural Gas	Coal	Nuclear Energy	Hydro-Electric	Renewable & Waste	Total
USA	884	594	615.7	83.8	28.2	77.3	2,283
Canada	152	83	31	9.4	68.6	NA	344
France	83	45	12.4	43.9	14.8	67.4	266.5
Russian Federation	494	438	153	16.3	35.6	NA	1136.9
United Kingdom	76.8	71.2	39.1	20.1	1.3	NA	208.5
China*	436	98.1	2500	12.3	58.5	103.1	3208
India*	205.5	47.1	352	4.1	11.4	98.4	718.5
Japan	199	93	71.6	25.8	8.3	98.1	495.8
Others	1807.3	1276.6	114.5	501.4	70.0	524.1	4293.9
Total	4337.6	2746	3889.3	717.1	296.7	968.4	12995.1

Mtoe → Million tons of oil equivalent.

India's Energy Reserves:-

The Ministry of statistics and program Implementation, Govt. of India, 2012 has produced the following data.

Coal	Main fossil energy reserves in India at 286 billion tons and 41 billion tons of lignite. These are available in eastern and southern belts of the country.
Crude Oil	Limited to 757 million tons m^3.
Natural Gas	Limited to 1241 billion tons m^3.
Nuclear Energy	Uranium can fuel only 10,000 MW pressurized heavy water reactors (PHWR).

*India depends primarily on *Uranium* to run the reactors. *Thorium* is also another source for nuclear energy which runs in *fast breeder reactor*. The *fast breeder reactor* has been rejected by Europe and USA due to safety concerns.

Renewable Energy Sources:-

The capacity addition in renewable energy was about 27,300 MW in 2012.

Technology	Capacity Installed in MW by 2012.
Coal	11,202
Hydro	38,990
Renewable	27,300
Gas	18,381
Nuclear	4,780
Total	201,473

Table: India's Installed power generation capacity.

Thermal	54.4%
Hydro	21.60%
Renewable	10.90%
Gas	10.10%
nuclear	2.7%

So, total renewable energy's contribution becomes almost 33% (includes Hydro power), plan wise grid connected renewable energy contribution is given in Table below.

Table: Power densities of *renewable energy sources* and the *conventional energy forms*.

Renewable Energy Sources	in KW/m^2
Wave	< 100
Extra terrestrial solar radiation	< 1.35
Wind	< 3
Solar radiation	0.2
Tidal	0.002
Biomass Production	0.002
Geothermal heat	0.00006

Conventional Energy	in KWh/m^2
Hot Plate	100
Coal	500
Nuclear	650
Power Cable	1000,000

* Onshore wind energy potential is estimated to be around 49,130 MW at a height of 50 m. It is estimated that around 17% of wind energy is utilized whereas 25,000 MW Has been connected to the grid. Wind energy is considered to be a viable source to tackle the energy problems.

* About 1/4th of energy used in India is in the form of biomass that consists of firewood, cattle dung, agriculture waste etc. This sector is managed by rural people without any technology, management and investment. Indian Govt. is promoting to use biomass to make deficit of energy. Studies have estimated that the biomass has potential of generating 17,000MW from agro and forest residues alone. Biogas is a three decade old program across India which covers estimated 5 million installations.

* India has put a national policy to replace the diesel and petrol by the production of biodiesel from *Jatropha*, *Karanja* and *Mahua* which has been tried for last two decades; and ethanol was considered to be successful replacement of petrol in transportation sector. The technology has been developed by Brazil in 1976 for successful of petrol and diesel. About 95% of cars sold in Brazil are flexible to run in both ethanol and petrol but this is not successful in India.

* Solar energy is distributed over the entire geographical region at the rate of 5-6 kwh/m^2 /day. This can be utilized for the purpose of energy utilization in many thermal applications such as cooking or heating or in photovoltaic cells that convert sunlight to electricity.

India has launched a solar mission with an aim to install 20,000MW grid solar power, 2000MW off grid system, 20 million solar lights and 20 million m^2 solar thermal collector by 2020.

1.3 Origin of Renewable Energy Sources:-

All available energy sources in the world that come from three different primary energy sources.

(i) Isotropic dissociation in the core of the earth.

(ii) Movements of the planets

(iii) Thermonuclear reactions in the earth.

* The largest energy flow comes from solar radiation, which is also responsible for the development of fossil energy sources, namely oil, coal and gas due to bio conversion which has occurred million years ago. All available natural renewable energy sources are presented in the diagram and their conversion is also shown below.

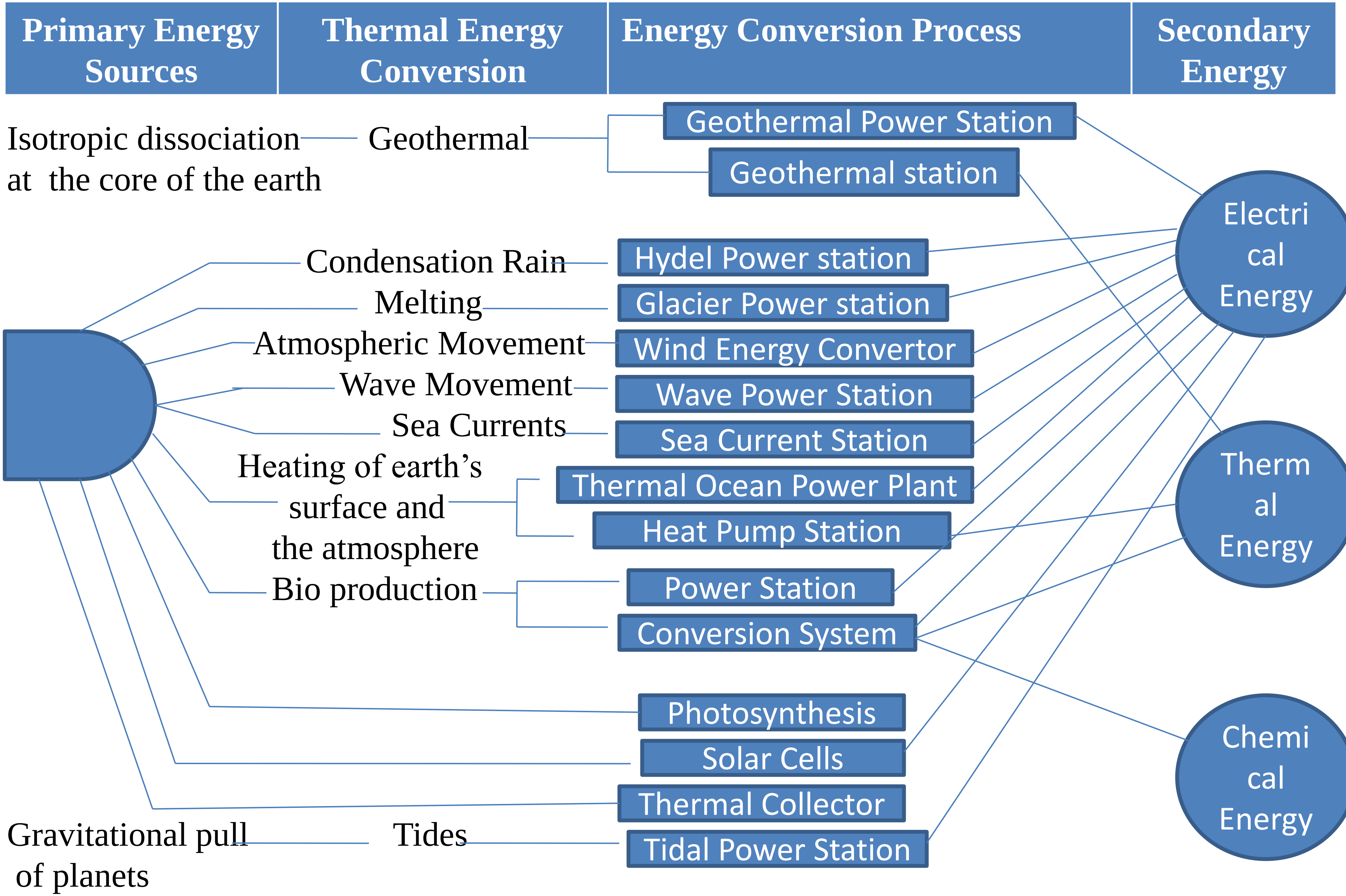


Fig: Use of renewable energy sources directly or indirectly through energy conversion process.

* Another source of energy is the geothermal energy originates from the earth's surface itself . The theoretical potential of geothermal energy is much lesser (less than by an order of 4) than the solar radiation.
* The third source of renewable energy is the movement of the planets . The force of attraction between planets and gravitational pull creates tide in the sea. This energy source magnitude is very less compared to geothermal energy.

Limitations:-

a) The real difficulty with the renewable energy sources are that the power density of those energies are very less in comparison to conventional energy sources.

b) Since the solar and wind energies fluctuate with respect to day and season; the surface area requirement will be large and so also storage device for heat and electricity. The thermal energy storage system (sensible heat storage systems) have low efficiency, while the phase change storage systems suffer density variations in two phases and stability over several cycles. Electrical storage device like batteries are heavy and not environment friendly.

GEOTHERMAL ENERGY

1.4 Potential of Renewable Energy Sources:-

Even though above limitations, there are certain applications where the renewable energy sources are employed efficiently and economically. So it is necessary to understand the fundamental aspects of the technology involved for the production of the renewable energy sources.

1.4.1 Geothermal Energy:-

Geothermal = Geo (earth) + therme (heat).

So the meaning of geothermal energy is the heat from the earth. The heat is generated at a depth of 6000km below the earth's surface due to continuous decay of radioactive particles. The temperature variations with depth are shown in Fig(a) and different layers of earth along depth is shown in Fig.(b).

The core has two layers: (i) Solid iron core and (ii) Magma (outer core made of very hot melted rock). Mantle consists of rock and magma, spreads over depth of 2600km. Crust is the outer most layer of the earth whose depth is 5-8 km under ocean or 25-60 km on the continents.

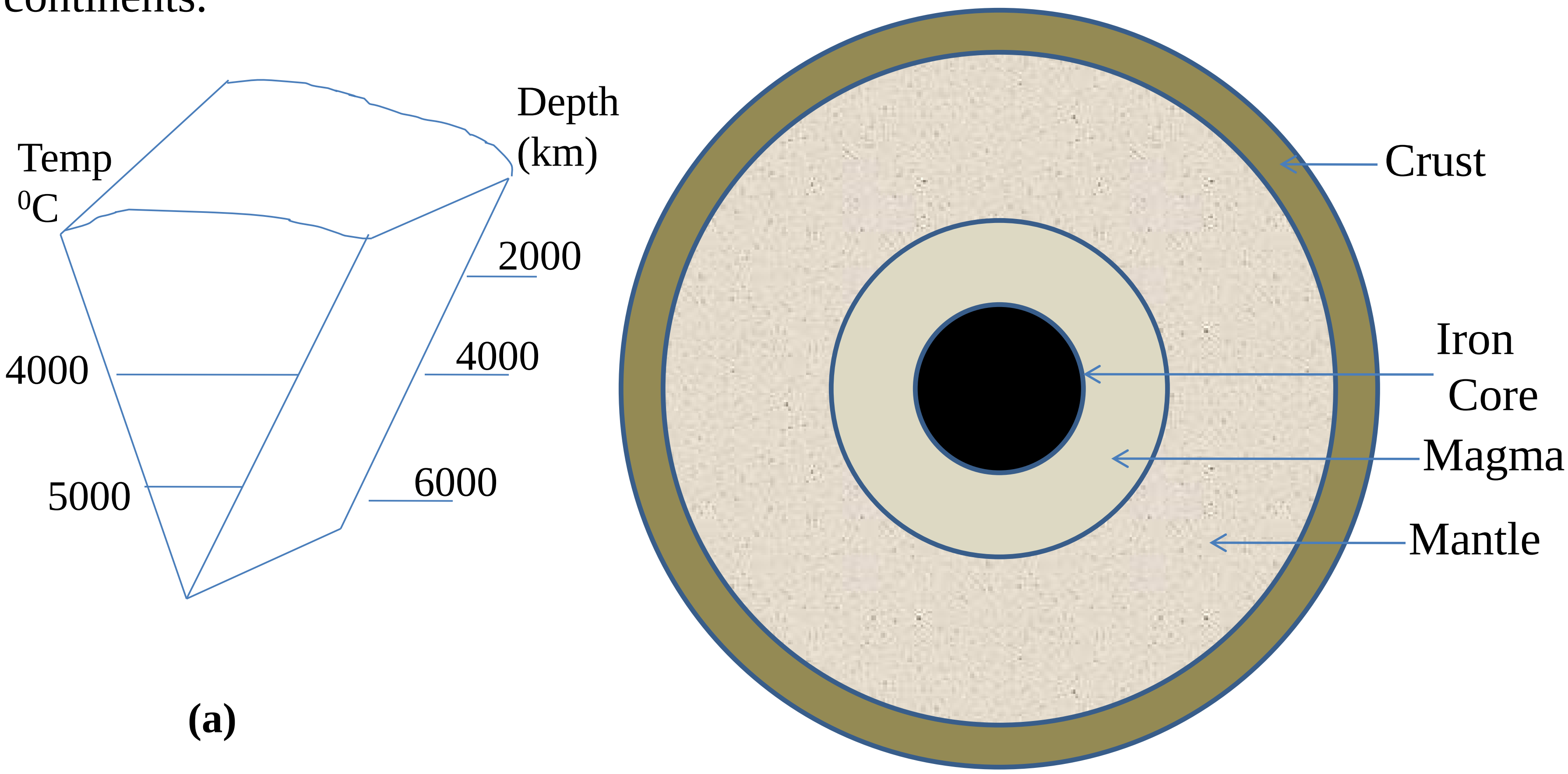


Fig: (a) Temperature distribution along depth of earth and **(b)** different layers of earth along depth

When there are cracks on the crust, the lavas (partly magmas) comes out to the surface through the gap is called volcanic eruption. All the under ground constituents absorbs heat from magmas.

1.4.1.2 Geothermal resources estimation:-

Let us assume a large mass close to the earth surface and spreads along the depth with density ρ_r , specific heat capacity C_r and a cross-sectional area A. Assuming uniform matrixial composition and no convection, the temperature variation is linear with depth y, which is expressed as:

$$T = T_0 = \frac{dT}{dy} y \text{................}(1)$$

where T_0 is the temperature at $y = 0$ and $\frac{dT}{dy}$ the temperature gradient inside the earth's surface.

So, at $y = y_1,\quad T_1 = T_0 + \frac{dT}{dy} y_1 \text{...........}(2)$

After rearrangement, $$y_1 = \frac{T_1 - T_0}{dT/dy}\text{..............(3)}$$

Consider an element *dy* on the earth's crust where the temperature is greater than $T_{1,}$ then the heat content *dE* can be written as:

$$dE = \left(\rho_r A dy\right)\ C_r\ \left(T - T_1\right),$$

And also $$dE = \left(\rho_r A dy\right) C_r \frac{dT}{dy}\left(y - y_1\right)\text{....................(4)}$$

The total useful heat in the rock is obtained by integration from y_1 to y_2 as:

$$\int dE = \int_{y_1}^{y_2}\left(\rho_r A dy\right) C_r \frac{dT}{dy}\left(y - y_1\right)\text{....................(5)}$$

Assuming $\frac{dT}{dy} = \text{constant} = \text{S (slope)}$; the energy of the rock is given by

$$E_r = \int dE = s\int_{y_1}^{y_2}\rho_r A C_r \left(y - y_1\right) dy = \rho_r s A C_r \left[\frac{\left(y - y_1\right)^2}{2}\right]_{y_1}^{y_2}$$

$$\Rightarrow E_r = \frac{1}{2} s \rho_r A C_r \left(y_2 - y_1\right)^2\text{.................(6)}$$

Where $s = \frac{dT}{dy}$ between y_1 and y_2

If the temperature of the rock remains uniform at T_r, then

$$E_R = C_{12} T_r$$

Where C_{12} is the thermal capacity between y_1 and y_2 which can be expressed as

$$C_{12} = A_r (y_1 - y_2) \rho_r C_r \text{......................} (7)$$

Since the temperature difference exists between earth's core and upper surface of the earth, there is a constant heat flow between these two with an average value of 63 KW/km^2 or 0.063 KW/m^2. If this heat flow is taken into account the annual available energy could be $3X10^{20}$J.

1.4.1.3 Technologies used for various geothermal resource types:-

The various types of geothermal energies and their uses are presented below.

Dry Steam Sources: These superheated steam sources can be extracted or comes out directly from geothermal reservoirs which may be used to run the turbines of the power plant to produce electricity.

Wet Steam Sources: Geothermal water is converted to wet steam due to high pressure and it has temperature range from ***180^0 C to 370^0C***. Steam after separation from the water is allowed to pass through the turbine to produce electricity or for process heating and the water can be used for absorption based refrigeration system.

Hot Water Resources: The geothermal hot water under normal pressure has temp range ***50^0C to 80^0C***. This hot water can be utilized for space heating or refrigeration process.

Hot Dry Rocks: The water is allowed to pass through the hot rocks to become hot and is used similar way like hot water resources.

Geo-pressurized Sources: Highly compressed and saturated water solution is found in deep sedimentary basin at a depth of > 5km. For high temperature and pressure devices these can be used.

Hot Magma Sources: At a depth of 5 km, molten rock can be used for extraction and subsequent use of thermal energy.

1.4.3 Power Generation Technology:

The different types technologies are used to generate electricity depending the type of resource at site.

1.4.3.1 Direct Steam Geothermal Plant:

If the steam is available from the geothermal site, then it is directly fed to the turbine to produce electricity. The stone and dust particles are removed from the steam before entering into the turbine.

1.4.3.2 Flash Steam Power Plant:

This type of power plant is used when high temperature hot water and a mixture of steam and water is available at the geothermal site The hot water is directly supplied to the flash tank where the water is separated in the flash chamber and some amount of water is converted into steam. The steam is directly fed into the turbine to produce electricity. Steam after passing through the turbine is brought into the condenser and then enter into the cooling tower. The condensed and cooled water is blow down to the well.

Flash steam water power plants for geothermal resources are available in the range from 5MW to 100 MW.

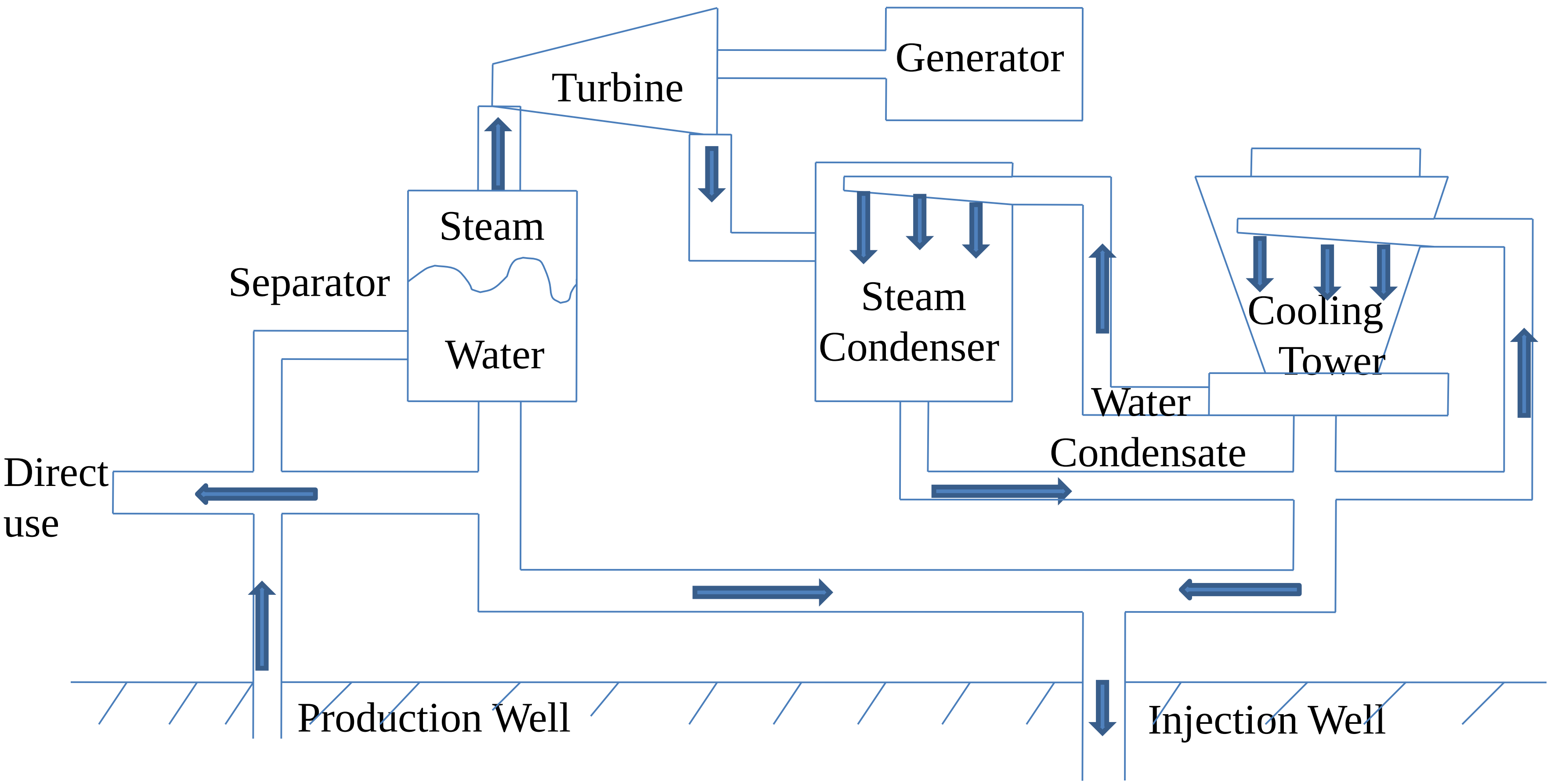


Fig: Schematic diagram of a single flash geothermal power plant.

1.4.3.3 Binary Cycle Power Plants:

The schematic diagram of the binary geothermal power plant is shown here. The secondary fluid normally organic working fluid (like CFC, HFC etc.) is converted into vapor in a boiler by the exchange of heat with the geothermal fluid or it may be pre-heated before entering into the boiler.

The vaporized organic working fluid is fed into the organic Rankine cycle turbine that produce mechanical work to produce electric generator. Organic fluid condenses in a condenser and cooling tower to produce the liquid which is again fed to the boiler in a closed loop cycle. Binary plant's size varies between 500 MW and 10 MW.

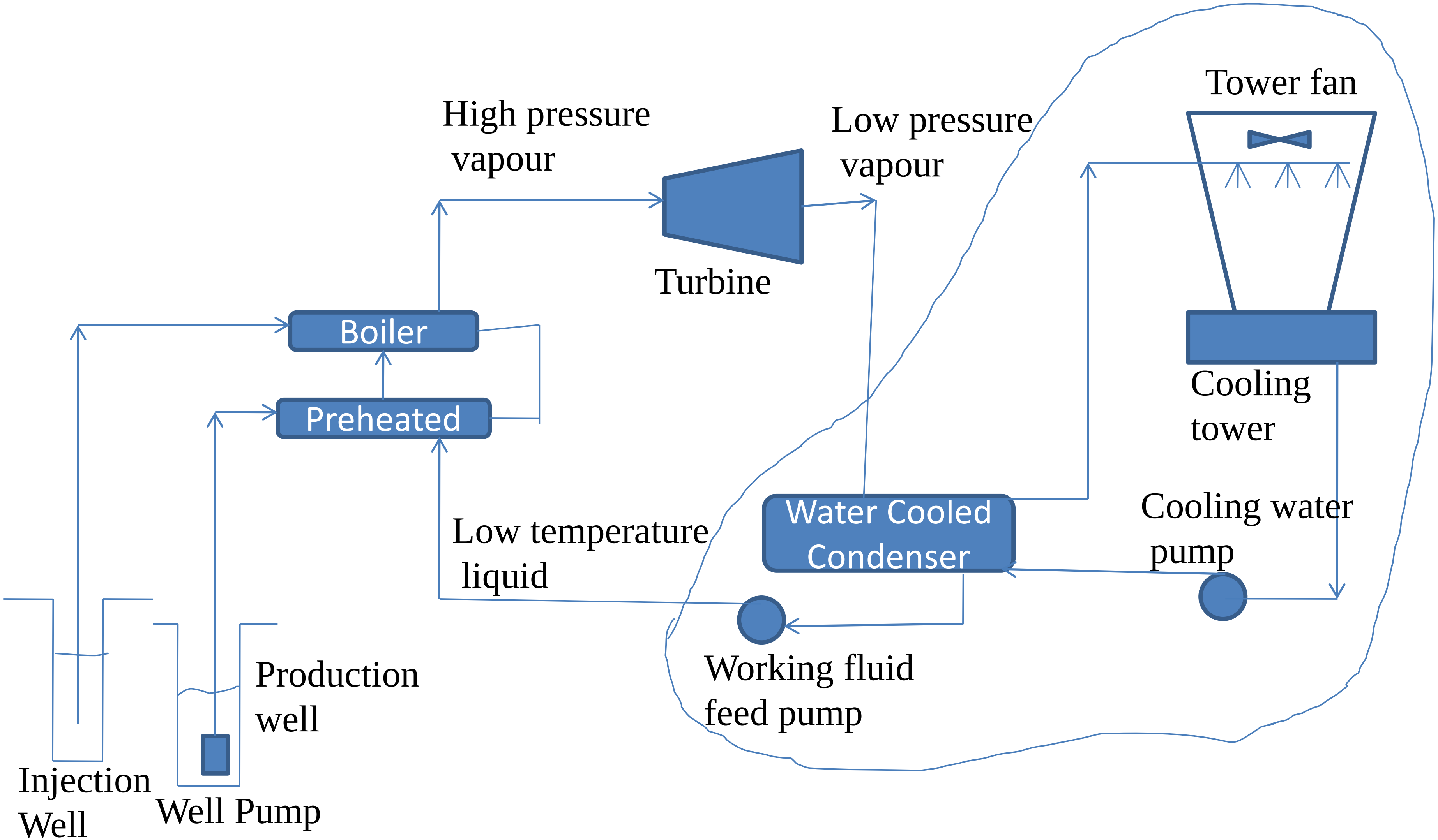


Fig: Binary geothermal power plant

TIDAL ENERGY

1.5 DIRECT USE TECHNOLOGY:-

The geothermal energy is directly used at the site of extraction by installation of plants because these are non-transportable to long distances. Some cases the available geothermal energy in the form of steam and hot water is not utilized directly because these are contaminated with chemicals, dirty water, stones etc. Heat exchangers are sometimes used to transfer of heat.

1.5.1 Tidal Energy:-

The tidal energy is developed due to rise and fall of water level in the sea. There is a force of attraction between the earth and sun. The water level in the sea is balanced by the gravitational force of attraction by earth. The tide in the sea is developed due to rotation of earth about itself which creates imbalance on the force of attraction due to variation of the distance.

* *So, the main period of tide is diurnal at about 24 hours and semidiurnal at 12 hours 25 minutes.*

* *The tidal range, R = Change in height between two successive high and low tides.*
* *The value of R in an open sea is 1 meter and near to coastal region 20 meter.*
* *The theoretical potential of tidal energy is estimated to be $3X10^6$ MW or 3.3 billion t COE/a.*

COE/a → Cost of Energy per annum.

1.5.2 Tidal Generating Force (Gjevik, 2011):-

From the figure in the next slide, consider the moon is located at **M**, **O** is the centre of the earth and **P** is a point on the surface of the earth. **R** is the distance connected between centres of the earth and moon; and ***d*** is the distance between the point **P** on the earth's surface to moon centre.

Let ***r*** be the magnitude of radius of the earth. Then in vector form we can write,

$$\vec{r} + \vec{d} = \vec{R} \quad \text{.........................(1)}$$

The gravitational force between earth and moon is:

$$G\frac{M_e M_M}{R^2}\cdot\frac{\vec{R}}{R} \quad \text{..............................(2)}$$

Where **G** is the gravitational constant. The acceleration at the center of the earth is:

$$\vec{a}_0 = G\frac{M_M}{R^2}\cdot\frac{\vec{R}}{R} \quad \text{..............................(3)}$$

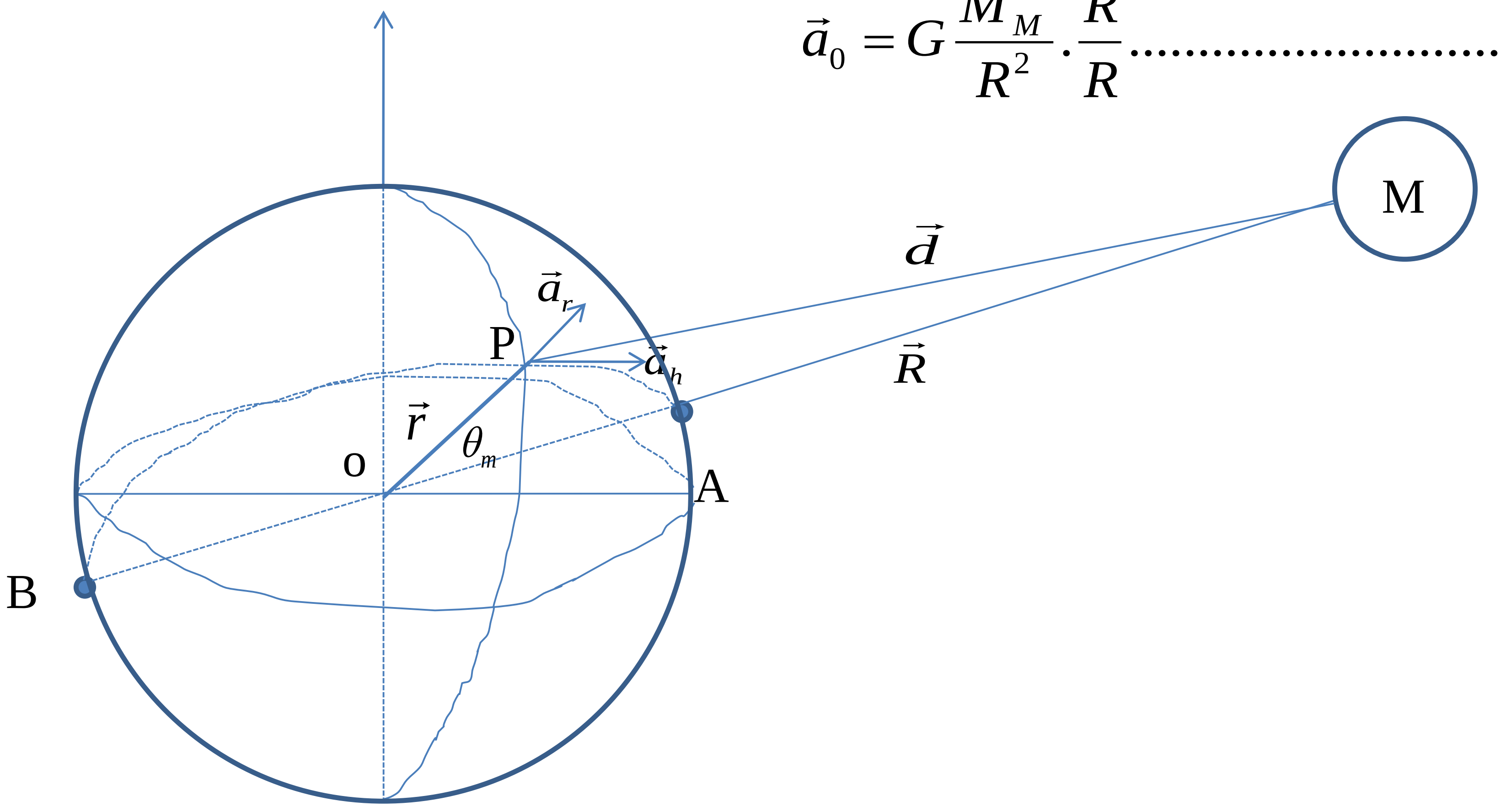


Fig: Moon and Earth system

In the same way the gravitational pull at the point **P** is:

$$\vec{a}_p = G\frac{M_M}{d^2}.\frac{\vec{d}}{d} \quad \text{..............................(4)}$$

Difference between $\mathbf{a_p}$ and $\mathbf{a_0}$ produces tidal acceleration or tidal force per unit mass:

$$\vec{a} = \vec{a}_p - \vec{a}_0 = GM_M\left[\frac{\vec{d}}{d^3} - \frac{\vec{R}}{R^3}\right] \quad \text{.............................(5)}$$

The vector **a** is contained in the plane **OPM**. From the trigonometric relation in the triangle **OPM,**

$$d^2 = R^2 + r^2 - 2Rr\cos\theta_m \quad \text{.......................(6)}$$

where θ_m is the angular zenith distance of the moon.

$$d^2 = R^2\left[1 - 2\frac{r}{R}\cos\theta_m + \frac{r^2}{R^2}\right]$$

$$\Rightarrow d = R\left[1 - 2\frac{r}{R}\cos\theta_m + \frac{r^2}{R^2}\right]^{\frac{1}{2}} \quad \text{........................(7)}$$

Using Binomial expansion, we get ,

$$d = R\left[1 - \frac{r}{R}\cos\theta_m\right] + o\left(\frac{r}{R}\right)^2 \quad \text{........................(8)} \quad \text{(Since } r << R\text{)}$$

Neglecting the truncation error term, using Binomial theorem we can also write:

$$\frac{1}{d^3} = \frac{1}{R^3\left(1-\frac{r}{R}\cos\theta_m\right)^3} = \frac{\left(1+\frac{3r}{R}\cos\theta_m\right)}{R^3} \quad \text{..................(9)}$$

From equation (5) & (9), we can also write:

$$\vec{a} = \frac{GM_M}{R^3}\left[\frac{R^3\vec{d}}{d^3} - \frac{\vec{R}}{1}\right] = \frac{GM_M r}{R^3}\left[\frac{R^3\vec{d}}{d^3} - \frac{\vec{R}}{1}\right] = \frac{GM_M r}{R^3}\left[3\frac{\vec{R}}{R}\cos\theta_m - \frac{\vec{r}}{r}\right] \quad \text{....(10)}$$

The acceleration due to gravity can be expressed as: $g = \frac{GM_e}{r^2}$

Equation (10) can be written as: $\vec{a} = g\frac{M_M}{M_e}\left(\frac{r}{R}\right)^3\left[3\frac{\vec{R}}{R}\cos\theta_m - \frac{\vec{r}}{r}\right]$............(11)

Taking the numerical values $\frac{M_M}{M_e} = 0.012, \frac{\vec{R}}{R} = 0.017;$ the fraction is on the order of 10^{-7}. The equation (11) shows that the direction of **a** is towards the center of the earth and towards moon for $\boldsymbol{\theta_m > \pi/2}$ along the direction of **R** and opposite of **R** for $\boldsymbol{\pi/2 < \theta_m < \pi}$**.** So, here **a** is towards the moon or towards **B** (other side of earth).

The vector has two components i.e. radial, $\mathbf{a_r}$ and horizontal, $\mathbf{a_h}$. The direction of $\mathbf{a_h}$ is along the circular arc APB.

$$a_r = \vec{a}\frac{\vec{r}}{\mathrm{r}} = g\frac{M_m}{M_e}\left(\frac{r}{R}\right)^3\left[3\cos^2\theta - 1\right] \quad \left(\because \vec{R}.\vec{r} = Rr\cos\theta\right) \text{.......(12)}$$

Again,

$$a_h = \left|\vec{a}\times\frac{\vec{r}}{r}\right| = \left(\frac{3}{2}\right)g\frac{M_m}{M_e}\left(\frac{r}{R}\right)^3 \sin 2\theta_m \quad \left(\because \left|\vec{R}\times\vec{r}\right| = R_r \sin\theta_m\right) \text{........(13)}$$

The following data are given:

Mass of the earth, M_e = 5.974 x 10^{24} kg

Mass of the sun , M_s = 1.991 x 10^{30} kg

Mass of the moon, M_m = 7.347 x 10^{22} kg

Mean distance earth-moon, R = 3.844 x 10^5 km

Mean distance earth-sun, R = 1.496 x 10^8 km

Radius of the earth r = 6.370 x 10^3 km

$$\theta_m = \frac{\pi}{2}$$

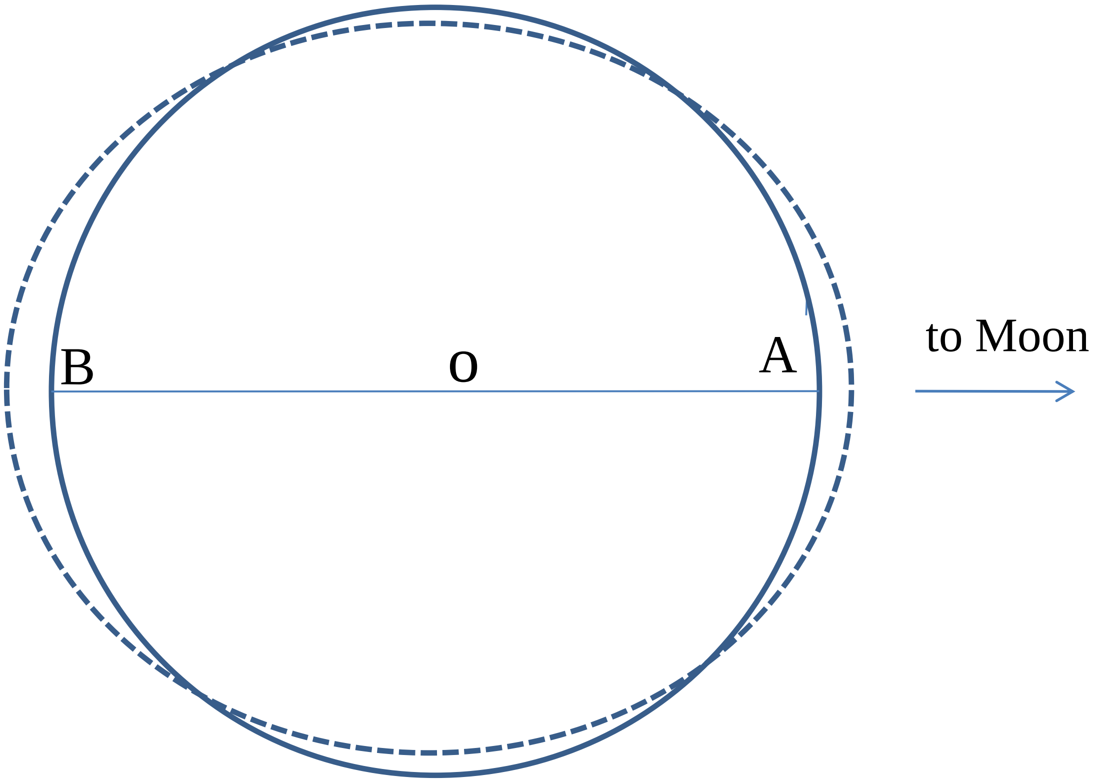


Fig: The equilibrium tide

Tidal Power:-

Consider a small volume of water in a basin within tidal range is shown in the diagram. Let the area of the basin be **S**, density **ρ** and range **A** has a mass **ρSA** at a centre of gravity of A/2.

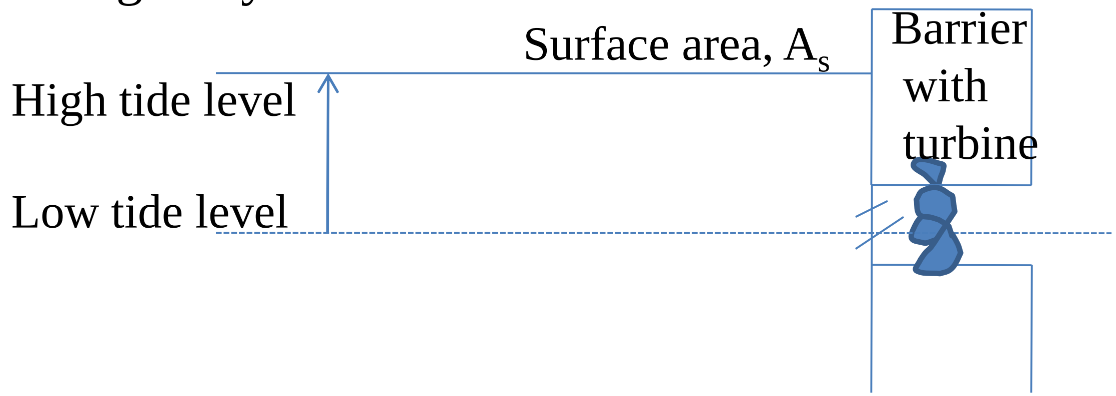


Fig: Principle of power generation from tide

If water falls through height A/2, the potential energy per tide is given by **(ρSA)g(A/2).**

If T is the time period then the average power of one is, $\overline{P_t} = \frac{\rho S A^2 g}{2T}$

The range of a tide, $A = A_s - A_n$.

Where A_s = Maximum height in for spring tide (the pull of the moon and sun which are aligned).

A_n = Minimum height for neap tides (the pull of the moon and the sun are at right angle to each other) .

The sinusoidal oscillation of tide is shown in the figure in the next slide.

At an instant of time t, the range of tide is given by: $\frac{A}{2} = \frac{A_s + A_n}{4} + \left(\frac{A_s - A_n}{4}\right)\sin\frac{4\pi t}{T}$

If $A_n = KA_s$, then the range, A is: $A = \frac{A_s}{2}\left[(1+K)+(1-K)\right]\sin\frac{4\pi t}{T}$

The mean square range for the time period of lunar month (T_m= 29.53 days) is:

$$\overline{A}^2 = \frac{A_s^2}{4}\frac{\int_0^{T_m}\left[(1+K)+(1-K)\sin\frac{4\pi t}{T}\right]^2 dt}{\int_0^{T_m} dt} = \frac{A_s^2}{8}\left(3+2K+3K^2\right)$$

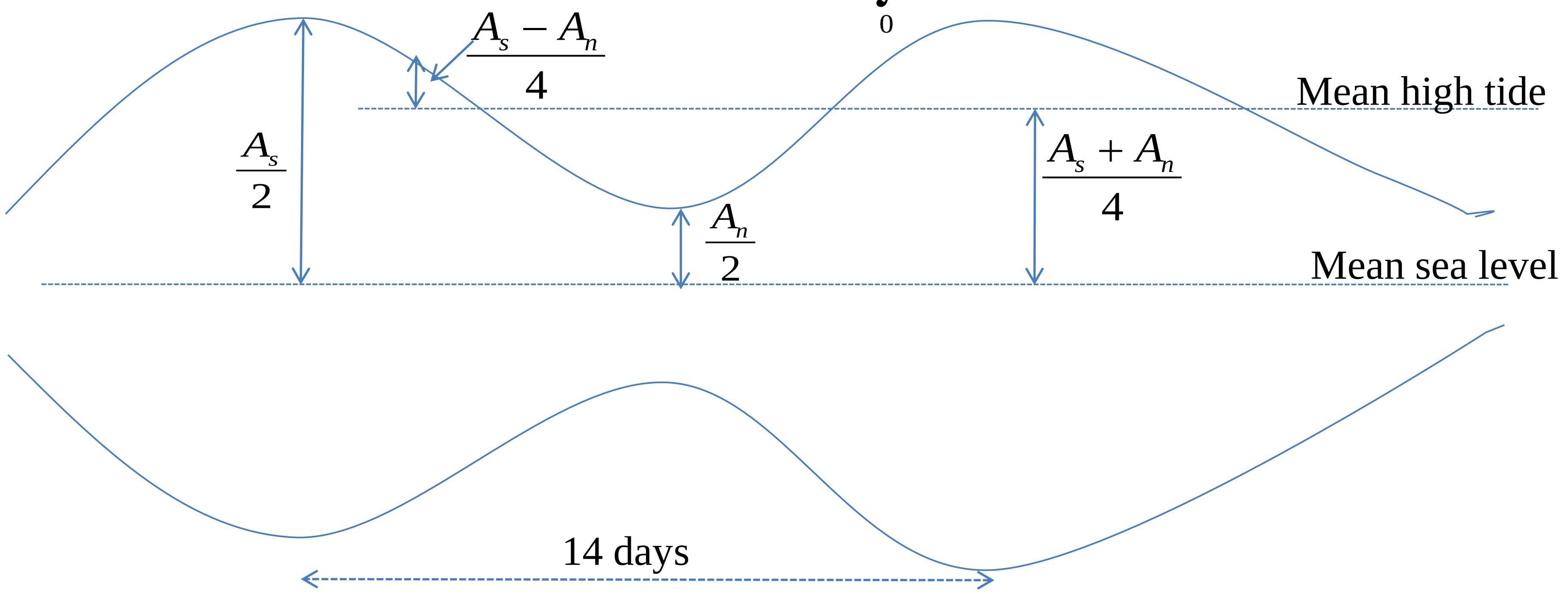


Fig: Sinusoidal variation of tidal range

The mean power produced over a period of one month,

$$\overline{P}_{month} = \frac{\rho Sg A_s^2}{2T8}\left(3 + 2K + 3K^2\right)$$

T is the inter-tidal period and normally one takes K = 0.5. So, $\overline{P} = \frac{\rho Sg}{2T}\left(\overline{A}\right)^2$

Since **A** is the mean range of all tides, $\overline{P} = \frac{\rho Sg}{2T}\left(\frac{A_{max}^2 + A_{min}^2}{2}\right)$,

Where $\boldsymbol{A}_{max}$ and $\mathbf{A}_{min}$ are the maximum and minimum tidal ranges respectively.

- During each lunar day, two tidal rises and two falls or one tidal rise and one fall occur. So, the duration between two consecutive rise and fall is 12 hours and 24 minutes (semidiurnal) or 24 hours 48 minutes (diurnal).
- Another type of tide occurs in the sea due to the force of attraction by sun whose magnitude is smaller by a factor of 2.17 due to longer distance between sun and moon.

Energy of Ocean Tides:-

Energy in the ocean is available in the form of tidal generating forces. The tidal energy varies from one geographical region to the other. Some part of the tidal energy is lost due to:

(i) Dissipation which results from friction between layers of flow,

(ii) Power interchange between the earth and its atmosphere, and

(iii) Change of energy from kinetic to potential form or vice-versa in the course of motion.

* The above factors can be taken into account while calculating the total tidal energy.
* The quantitative estimates of the energy flow are equal to 2.4 TW.
* *Dynamic Tidal Power* (DTP) is a theoretical generation technology which interacts between kinetic and potential energies in the tidal flows. According to this technology, a very long dam (30-35km) will be built from coasts to the inner side of the sea or ocean without an enclosing area. Tidal phase differences are allowed to

enter across the dam.

* Tidal power can generate energy for 10 hours per day when tide move in and out.
* The tidal power is economic when the mean tidal range 7m or more.

WIND ENERGY

Wind Power:-

Wind power is generated on account of flow of wind. The blow of wind takes place due to density difference at two places on the surface of the earth. The density difference occurs when the solar radiation differs on earth's surface. Most of the energy stored in wind is found in high altitudes, over flat areas. But most of the potential is close to the coastal areas, approximately equivalent to 72 TW, or 54,000 Mtoe per year. *The power of the wind is proportional to the cubic power of the velocity.* To assess the frequency of wind speeds at a particular location, a probability distribution function is often fit to the observed data. Different locations will have different wind speed distributions. The worldwide wind generation capacity is 1,94,400 MW. India's present installed capacity is 2,000 MW.

Off-shore Wind Power:-

Offshore wind power refers to the installation of wind power plant in the water. Better wind speeds are obtained if the installation is made in the water than the land. Induction generators are often used for power generation. The power generators behave differently due to fluctuation of wind speed during power generation. So, the installation of advanced electromechanical generators are highly essential.

The capacity factor of wind generator is the ratio of actual productivity in a year to the theoretical maximum. The capacity factor of a wind generator varies from 20-40%. The capacity factor arises due to the variation of wind speed at the site and the generator size. The smaller generator would be cheaper and achieve higher capacity factor. Conversely the larger generator would cost more and produce smaller capacity factor.

* The wind power has low operating cost but it carries high capital cost.

Origin of Wind:

The flow of air starts when there is pressure difference between two places. The region where solar radiation is less the atmospheric air gets low temperature and hence low pressure region. On the contrary where the solar radiation is high the atmospheric air gets heated and pressure is high. These differences in atmospheric air pressure (*pressure gradient*) cause acceleration of the air particles which is called wind.

The rotation of earth about its own axis creates Coriolis force which superimposes on the pressure gradient. The direction of wind motion is affected by this *Coriolis force*. In the Northern hemisphere, the moving object turns towards right due to the effect of the Coriolis force if the observer moves in the direction of wind movement. Similarly, the moving object turns towards left in the southern hemisphere.

* In a friction free, rectilinear and stationary wind movement, the force due to pressure gradient and Coriolis force are of same magnitude but in opposite direction. *The wind motion due to Coriolis force is known as geostropic wind*.

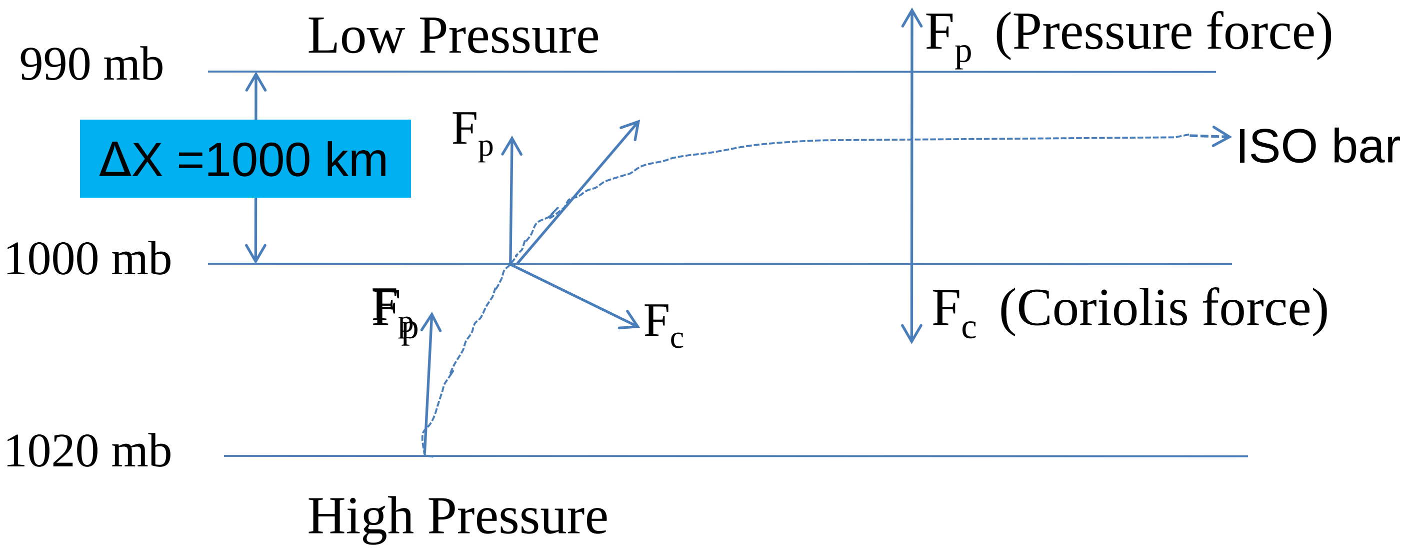


Fig: Geostropic wind on the northern hemisphere

As a result of pressure difference, the air first moves towards low pressure region. It then follows inclined movement towards right due to Coriolis force. This inclination towards right continues till the magnitude of Coriolis force is exactly equal to the pressure gradient force. At this point the wind moves in the direction of isobars whose motion is in the same direction as that of geotropic winds.

Consider a small air element whose Coriolis force is equal to the product of the Coriolis acceleration and mass of the air, i.e. $F_c = 2\omega \sin\phi \times v_g \times (\Delta X \Delta Y \Delta Z) \times \rho_a$

Where

F_c = Coriolis force in newton

$\omega \sin \phi$ = angular velocity of earth at the latitude ϕ (1/sec)

ϕ = latitude

$\Delta X \Delta Y \Delta Z$ = Volume of the considered small air element in (m^3)

ρ_a = density of air (m/sec)

v_g = geostropic wind velocity (m/sec)

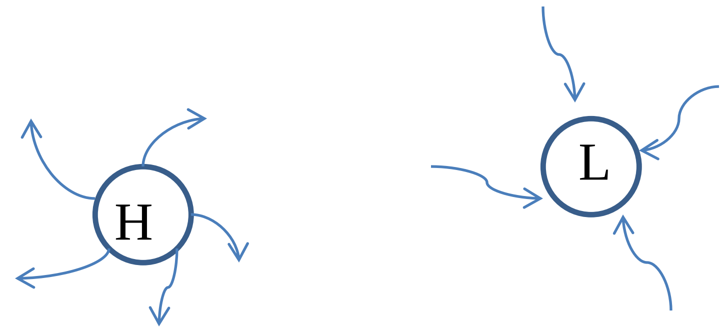
The pressure force (F_p) on the air element can be written as: $F_p = \Delta p \Delta Y \Delta Z$

Where Δp = pressure difference on the air element (N/m^2)

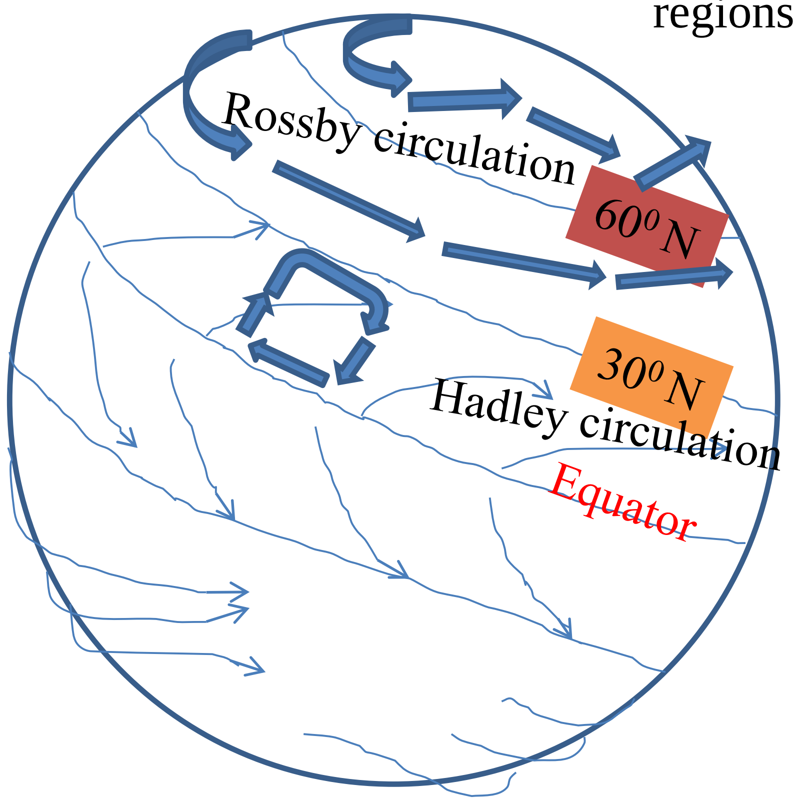
$\Delta Y \Delta Z$ = area of air element (m^2).

By equating, $F_c = F_p \Rightarrow 2\omega \sin\phi \, v_g \Delta X \rho_a = \Delta p \Rightarrow v_g = \dfrac{\Delta p}{\Delta X} \dfrac{1}{2\omega (\sin\phi) \, \rho_a}$

* *It is seen that the pressure gradient is directly proportional to the velocity of the geostropic wind.*



Fig(a): Wind stream flow patterns near the surface of the earth in high and low pressure regions in the northern hemisphere.



Fig(b): Simplified circulation system of the earth **(WMO 1981)**

If the path of the wind is curved, then the centrifugal force of the wind particle are also affected by the pressure force and Coriolis forces. The air particles close to the earth's surface are affected by the frictional forces. There is a formation of boundary layer over the surface due to these frictional forces. These collective forces creates a mechanism up to the range of heights *300m to 600m*. The wind velocity within this boundary layer is much smaller than that at higher altitudes. The air flow motion in the form of parallel isobars deviate with decreasing altitude.

In figure (a), the wind flow patterns near the surface of the earth at high and low pressure region have been shown in the hemisphere region.

In figure (b), the circulation system of the earth has been shown. It consists of two components: (i) *Hadley circulation* in the equator region and (ii) *Rossby circulation* in the upper and lower region of the earth.

The operating power of Hadley circulation is the strong solar radiation at the equator. The air gets heated, rises high and moves towards north and south, where it is deviated towards east as result of Coriolis force. The air gets cooled and sinks down in the latitude region $\pm 30^0$ (+ North, – South) and flows back towards the equator, where it is deviated towards west due to the Coriolis force. These are the regions where local storms overlap and wind-flows are not always predictable. In the northern and southern region around latitudes $\pm 60^0$ the westerly winds of Rossby circulation dominate the region. These winds have wave-form character and vary strongly in the flow patterns.

Wind Flow and Wind Direction:-

Wind speed is classified on representative scale of 12. The order of wind classification is in m/sec or knots (1 nautical miles = 1.852km/hr). The direction of wind are normally divided into eight segments: North, North-East, East, South-East, South, South-West, West and North-West.

Power Density of the Wind:-

Power density of the wind is calculated based on the normal area (A) to the direction of flow of wind stream. The kinetic energy (dE) contained within the mass of the element (dM) is:

$$dE = \frac{1}{2} dmv^2 ....(i)$$

Where

dE = Kinetic energy (joule)

dm = Elemental mass (kg)

$v = dx/dt$ = wind velocity (m/sec). (Here dx is the path travelled in the direction of wind in time dt).

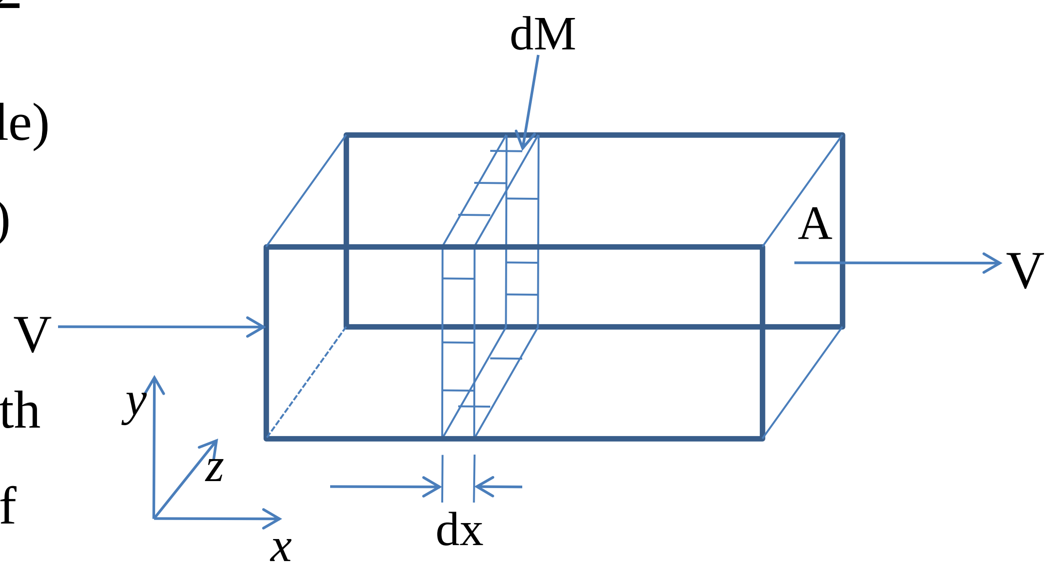


Fig: Derivation of power density

If the density of air is ρ_a and dv is the elemental volume in m^3

then $dv = A.dx$ and $dm = \rho_a \, dv$ ....(ii)

The mass element dm can be expressed as:

$$dm = A\rho_a .v.dt \text{ (kg)} \ldots\ldots\ldots\ldots\text{(iii)}$$

So the K.E. is: $dE = (1/2)\, \rho_a A v^3 dt$

The power, P is: $P = \frac{dE}{dt}$ *and power density in (w/m²) is:* $P = \frac{P}{A} = \frac{1}{2}\rho_a v^3$

It is seen that the wind power density (Pressure) depends upon the cube of wind velocity.

Wind Measurement: -

Wind pressure Measurement:- $P_t = P_s(\text{Static Pressure}) + (1/2)\rho_a v^2 \ldots\ldots\ldots(iv)$

Applying Bernoulli's equation the total pressure (P_t) can be calculated as:

and the velocity can be calculated as: $v = \sqrt{\frac{2(P_t - P_s)}{\rho_a}} \ldots\ldots\ldots\ldots\ldots\ldots(v)$

The velocity can be calculated if both the pressures are known. The Prandtl tube is used for pressure measurement.

The Prandtl's pressure tube contains two tubes. Both are concentric tubes. The inner tube converts the dynamic pressure ($(1/2)\rho_a V^2$) to the stagnation condition. This converts the kinetic energy to pressure energy. At the downstream end the inner

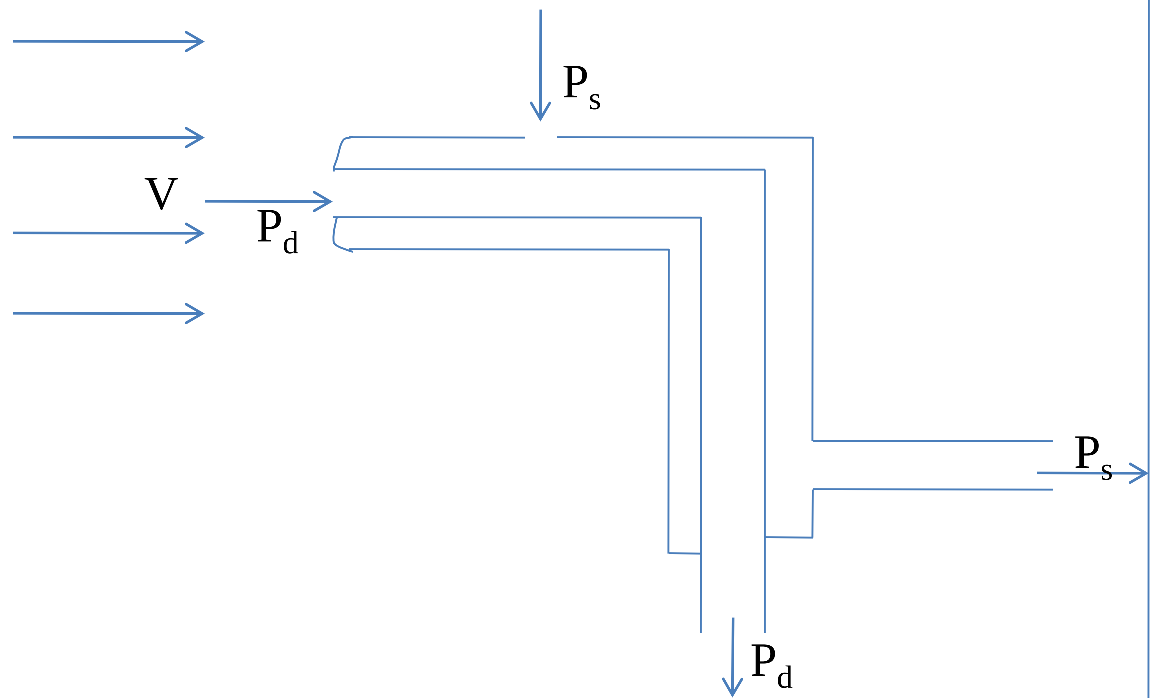


Fig: Prandtl tube for Pressure measurement

tube the pressure head is measured with the manometer. The outer tube measures the static pressure head (P_s) using a manometer.

Annual Average Wind Speed:

The annual average wind velocity at a particular plate can be calculated (in m/sec) by the formula:

$$\bar{v}_i = \frac{\int_{t_1}^{t_2} v\,dt}{t_2 - t_1}$$

Where,

v = Daily average wind velocity (m/sec),

t = time

$t_2 - t_1$ = time duration of one year (sec).

Such annual average values can be obtained for many years by taking average of values for total number of years, i.e.

$$\bar{v} = \frac{1}{n}\sum_{i=1}^{n} \bar{v}_i$$

Where

n = number of years,

$\bar{v}_i$ = annual average value for the year i in m/sec.

Altitude Dependence of Wind Speed:

The maximum velocity of jet stream occurs at a height of 10 km. The velocity there is nearly five times more than its magnitude at a height of 10 m. In the boundary layer the velocity of flow varies linearly on a log-log representation. It indicates the variation of wind velocity is exponential. The wind velocity at a height H is obtained as:

$$\bar{v}_H = \bar{v}_{10}\left[\frac{H}{10}\right]^{g^*} \quad \text{m/sec.}$$

Where

$\bar{v}_H$ = average annual velocity (in m/sec) at a height H (in m).

$\bar{v}_{10}$ = annual average velocity (in m/sec) at a height of 10 m.

H = height (m)

g^* = exponent.

The above equation is accurate up to height of 200m. The values of the exponent are given in table below.

Table: Boundary Layer Exponent for Different Ground Obstacles

Description of Land	Exponent
Open land with a few obstacles i.e. grass and field land with very few trees, coasts, deserts, islands etc.	0.16
Land with uniformly distributed obstacles upto the height of 15m such as building complexes, small cities, forests, bushes, trees and hatches.	0.28
Land with big and non-uniform obstacles such as centres of big cities, high obstacles like trees	0.40

Recording of wind data:

The wind speed is measured by an anemometer and wind direction is measured by a wind vane attached to a direction indicator. Anemometer works on one of the following principles.

(i) The oldest and simplest anemometer is a swinging plate hung vertically and hinged along its top edge. Wind speed is indicated by the angle of deflection of the plate with respect to the vertical.

(ii) A cup anemometer consists of three or four cups mounted symmetrically about a vertical axis. The speed of rotation indicates wind speed.

(iii) A hot-wire anemometer measures the wind speed by recording cooling effect of the wind on a hot-wire. The heat is produced by passing an electric current through the wire.

(iv) An anemometer can also be on sonic effect. Sound travels through still air at a known speed. However, if the air is moving, the speed decreases or increases accordingly.

(v) Wind speed can be recorded by measuring the wind pressure on a flat plate.

(vi) The other methods include the laser drop anemometer, the ultrasonic anemometer and the SODAR Doppler anemometer.

Applications of Wind Power: -

Mechanical Power:-

(i) Wind Pumps

(ii) Heating

(iii) Sea Transport

Off-grid Electrical Power Source:-

(i) Machines of lower power with rotor diameter of about 3 m to 40-1000 Watt rating can generate sufficient electrical energy for space heating and cooling of homes, water heating, battery charging and for operating domestic appliances such as fans, lights and small tools.

(ii) Applications of somewhat more powerful turbines of about 50 KW are producing electrical power for navigation signals, remote communication, weather stations and off-shore oil drilling platforms.

(iii) Intermediate power range, roughly 100 to 250 KW aero-generators can power to isolated populations, farm cooperatives, commercial refrigerators and to small industries.

(iii) For lifting water to hill, aero-generator is installed on the top of hill and electrical energy is transmitted to a pump fixed at lower level.

Grid-Connected Electrical Power Source.

(i) Large aero-generators in the range of a few hundred KW to a few MW are planned for supplying power to a utility grid. Large arrays of aero-generators, known as wind farms are being deployed in open plains or off-shore in shallow water for this purpose.

Wind Energy Converters:-

The wind energy converters convert wind energy to electrical and mechanical energies.

Maximum Power Coefficient:-

The maximum power coefficient of the wind energy can be defined as the ratio of the convertible power to the theoretically maximum power from the available wind energy.

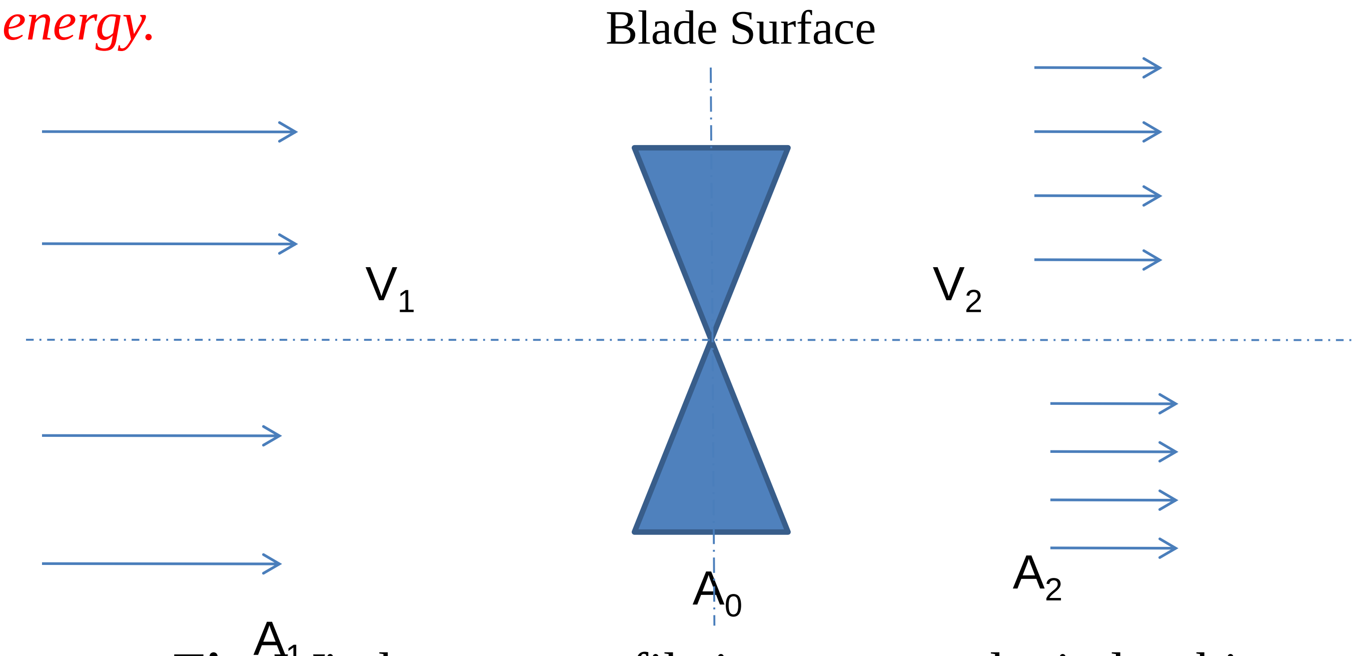


Fig: Wind stream profile in an external wind turbine

The *incompressible, friction free and one dimensional wave* is shown here. The flow is called *Rankine-Froude momentum* theory. The flow velocity (V_1 m/sec) and cross sectional area (A_1 m^2) enters into the surface of the wind blade and leaves out with velocity (V_2 m/sec) at a cross sectional area (A_2 m^2).

According to the equation of continuity: $\dot{m} = A_1 v_1 = A_2 v_2 \text{ m}^3/\text{sec}$............(vi)

At the surface of the rotor: $\dot{m} = \rho_a v_0 A_0 \text{ kg/sec}$........*(vii)*

Where ρ_a = air density (kg/m^3)

v_0 = Wind velocity at the surface of the rotor (m/sec)

A_0 = rotor disc area (m^2)

So v_0 can be written as: $v_0 = \frac{1}{2}(v_1 + v_2)$ m/sec..............*(viii)*

We know that the power density,

$$P_1 = \frac{1}{2}\rho_a v_1^3 A_1 \text{ (W) and } P_2 = \frac{1}{2}\rho_a v_2^3 A_2 (\text{W}) ....(ix)$$

The power of the rotor is:

$$P = P_1 - P_2 \text{ (W)} \quad \text{or } P = \frac{1}{2}\rho_a \left(A_1 v_1^3 - v_2^3 A_2\right) \text{ (W)}..........(x)$$

$$\text{Or} \quad P = \rho_a v_1 A_1 \frac{v_1^2}{2} - \rho_a v_2 A_2 \frac{v_2^2}{2} \text{ (W)}$$

$$\text{Or} \quad P = \frac{1}{2}\dot{m}\left(v_1^2 - v_2^2\right) \qquad \left(\because \dot{m} = A v \rho\right)$$

$$\text{Or} \quad P = \frac{1}{4}\rho_a A_0 \left(v_1 + v_2\right)\left(v_1^2 - v_2^2\right) \qquad \left(\because v_0 = \frac{1}{2}\left(v_1 + v_2\right)\right)$$

$$\text{Or} \quad P = \frac{1}{4}\rho_a A_0 v_1^3 \left(1 + \frac{v_2}{v_1}\right)\left(1 - \frac{v_2^2}{v_1^2}\right)\text{(W)} \text{.......................}(xi)$$

The maximum power is obtained when the wind speed (v_2) is zero.

$$P_{\max} = \frac{1}{4}\rho_a v_1^3 A_0 \text{ (W)}\text{.............}(xii)$$

The ideal power coefficient (C_p) of a wind machine is the ratio of the power P of the rotor to the maximum wind power, i.e.

$$C_p = \frac{P}{P_{\max}} = \frac{1}{2}\left(1 + \frac{v_2}{v_1}\right)\left(1 - \left(\frac{v_2}{v_1}\right)^2\right)\text{....}(xiii)$$

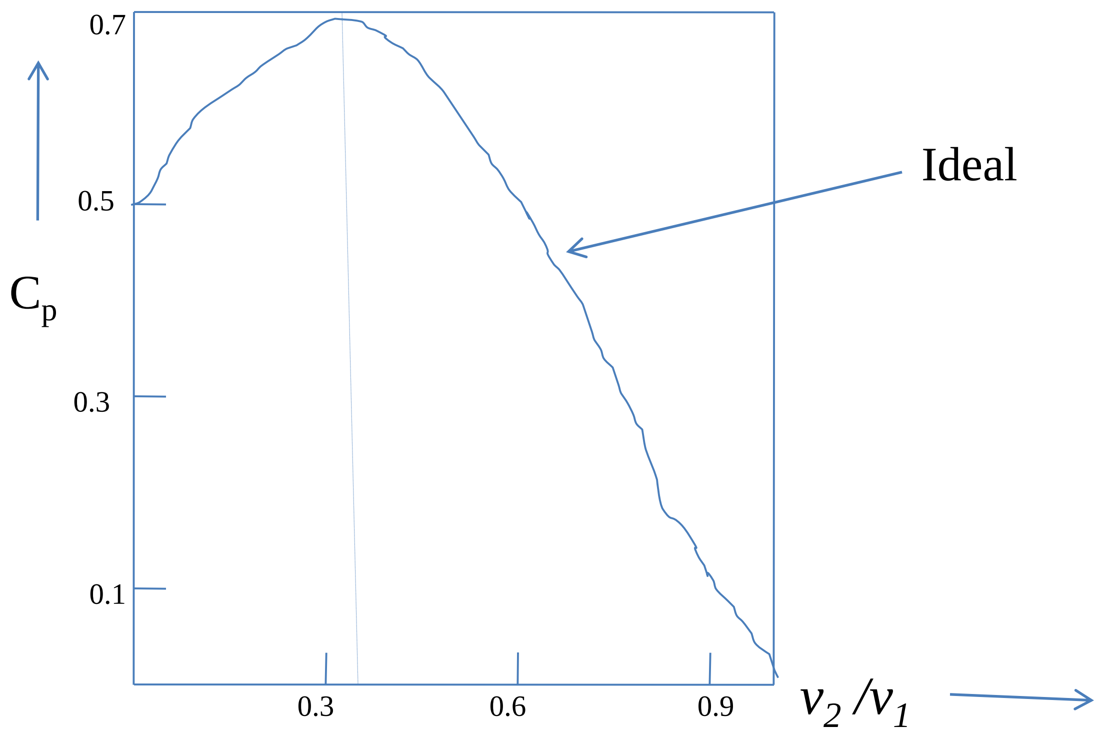
The maximum power coefficient (C_p) can be determined by differentiating Eq.(*xiii*) w.r.t. v_2/v_1. So,

$$\frac{\partial C_p}{\partial\left(v_2 / v_1\right)} = 0 \Rightarrow \frac{v_2}{v_1} = \frac{1}{3} \ldots\ldots(xiv)$$

From Eq.(xiii) and (xiv), we get

$$C_{pmax} = 0.593\ldots\ldots\ldots\ldots\ldots\ldots(xv)$$

So, it is clear that the maximum usable power from an ideal wind energy converter is 59.3%.



Power Coefficient of a Drag or Resistive type Rotor:-

For an oblique surface, the drag force is:

$$F_R = (1/2)\, C_R\, \rho_a\, v^2 A \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(xvi)$$

Where F_R = Drag force (N),

ρ_a = density of air (kg/m^3)

v = wind velocity (m/sec)

A = area of the resistance rotor (m^2)

C_R = drag coefficient (which depends upon the value of the geometry of the body)

If the motion of the linear speed (u) of the rotor is taken into account, then

$$F_R = \frac{1}{2} C_R \rho_a (v - u)^2 A. \quad \text{newton}\ldots\ldots(xvii)$$

The power produced by the drag is: $P = \frac{1}{2} \rho_a C_R (v-u)^2 .u.A$ (W)....$(xviii)$

The maximum power of the rotor at the surface of the blade is; $P = \frac{1}{2} \rho_a v^3 A$ (W)..(xix)

The power coefficient for the drag type rotor is the ratio of rotor power to the maximum power.

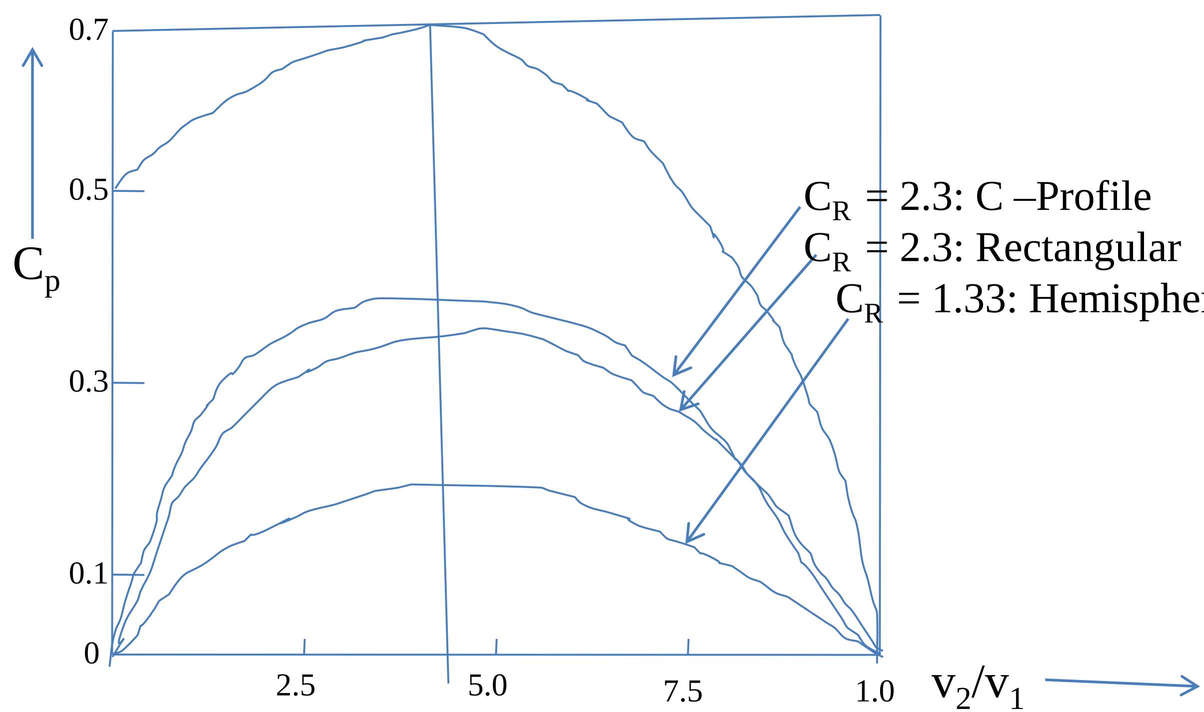
$$C_{PR} = \frac{P}{P_{\max}} = \frac{(1/2)\rho_a C_R (v-u)^2 uA}{(1/2)\rho_a v^3 A} = C_R(1-\frac{u^2}{v^2})\frac{u}{v} \text{........}(xx)$$

The maximum C_{PR} is obtained by setting $\frac{\partial C_{PR}}{\partial\left(\frac{u}{v}\right)} = 0 \text{.............}(xxi)$

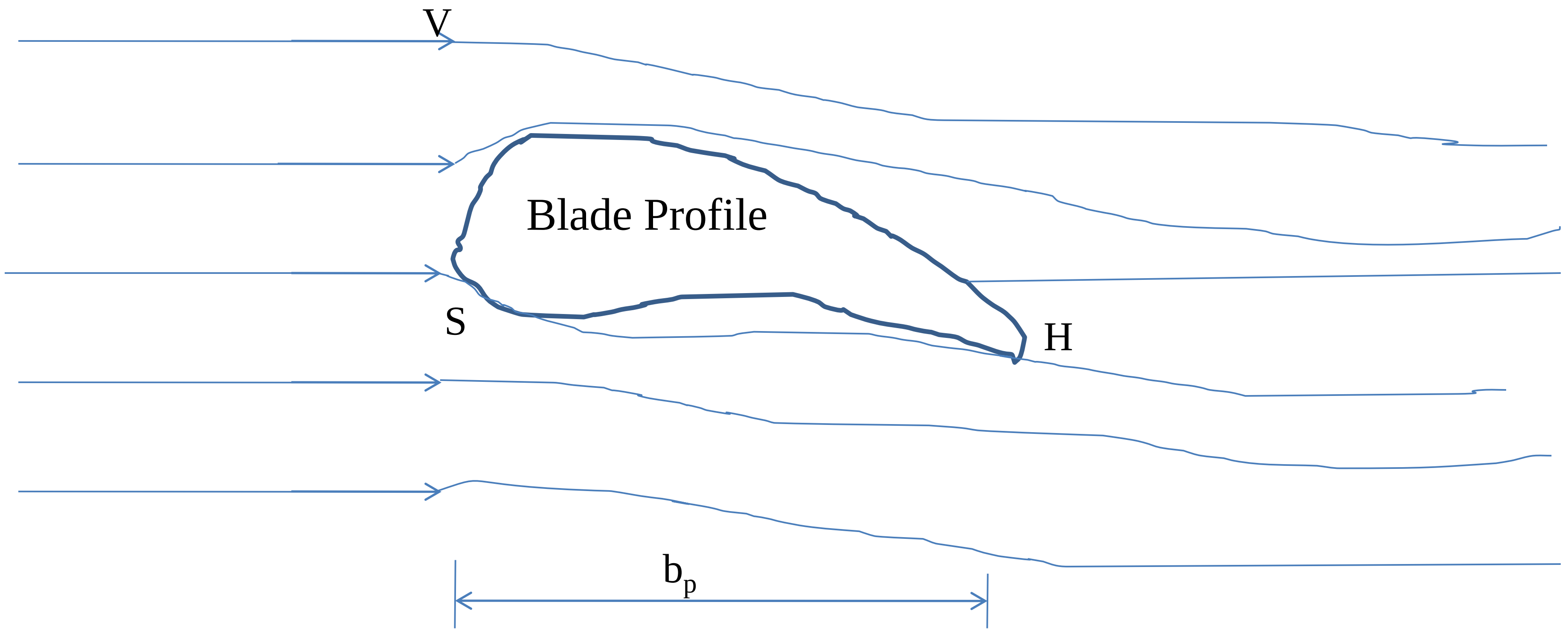
By solving we will get *u/v = 1/3*.

So the maximum value: C_{PR} max = (4/27) C_R ....*(xxii)*

Fig: Comparison of ideal power coefficient with maximum values of power coefficient of resistive rotors.



Wind Stream Profiles:-

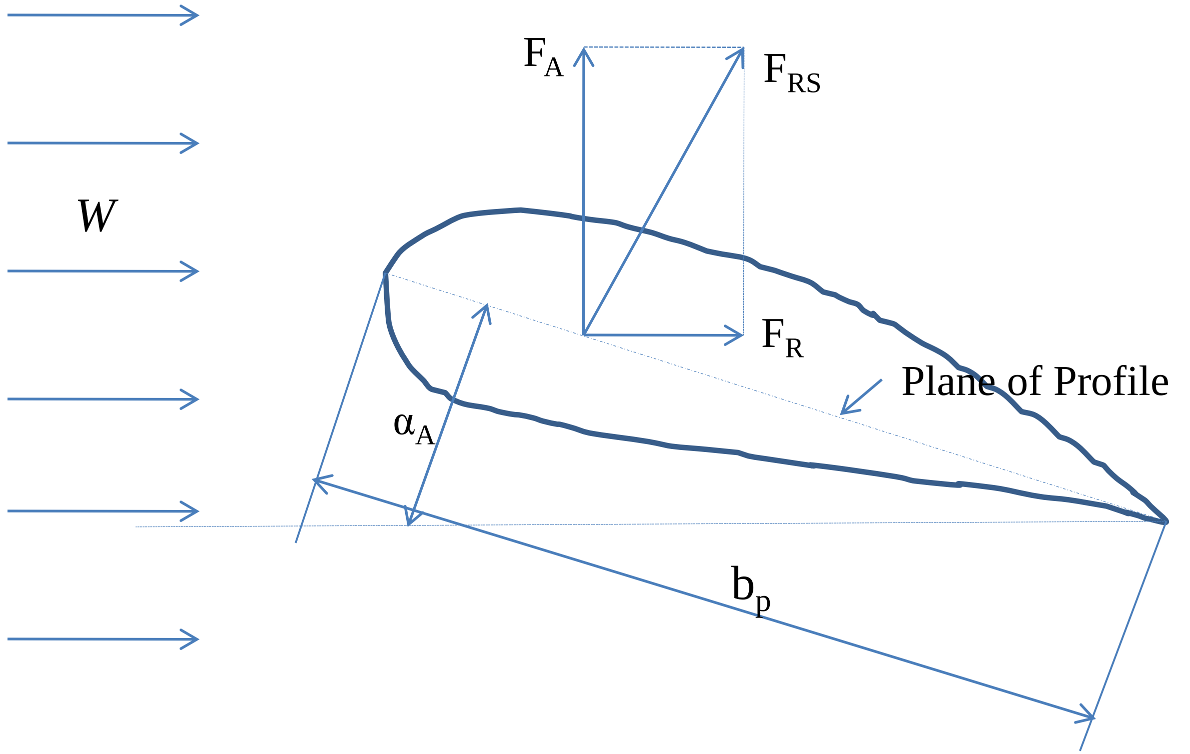


The lift force (F_A) is given by: $F_A = \int_0^{b_p} (P_L - P_u) L dx \ldots\ldots\ldots\ldots(xxiii)$

P_L = Pressure at the lower side of the profile (N/m^2) , P_u = Pressure at the upper side of the profile (N/m^2), L = Length (m), b_p = width of the profile (m).

* *The pressure is lower on the upper side than the lower side.*

Buoyancy Coefficient and the Drag Coefficient:-



For an asymmetrical profile, there exists two forces:

(1) The lift force (F_A) perpendicular to the direction of flow, and (2) the drag force (F_R) parallel in the direction of flow.

Let us assume: α_A = incident angle or angle of attack (angle between the profile and the flow direction).

w = apparent wind velocity (m/sec).

A = profile area (m^2) = $b_p L$.

P_a = air density (Kg/m^2).

L = length of the profile (m)

b_p = width of the profile (m)

C_R = drag coefficient (dimensionless).

The horizontal drag force (F_R) developed due to friction with the surface of the profile is:

$$F_R = \frac{1}{2}\rho_a C_R w^2 A = \frac{1}{2}\rho_a \mathrm{C_R} \mathrm{w}^2\ \mathrm{b_p L} \quad \text{(N)}$$

The vertical force lift (F_L) can be calculated as:

$$F_R = \frac{1}{2}\rho_a C_a w^2 A = \frac{1}{2}\rho_a \mathrm{C_a} \mathrm{w}^2\ \mathrm{b_p L} \quad \text{(N)}$$

The drag coefficient C_R and the lift coefficient C_a are determined experimentally for a particular profile. The values of C_R and C_a are determined from the polar diagram with angle of attack as a parameter which is shown in the next slide.

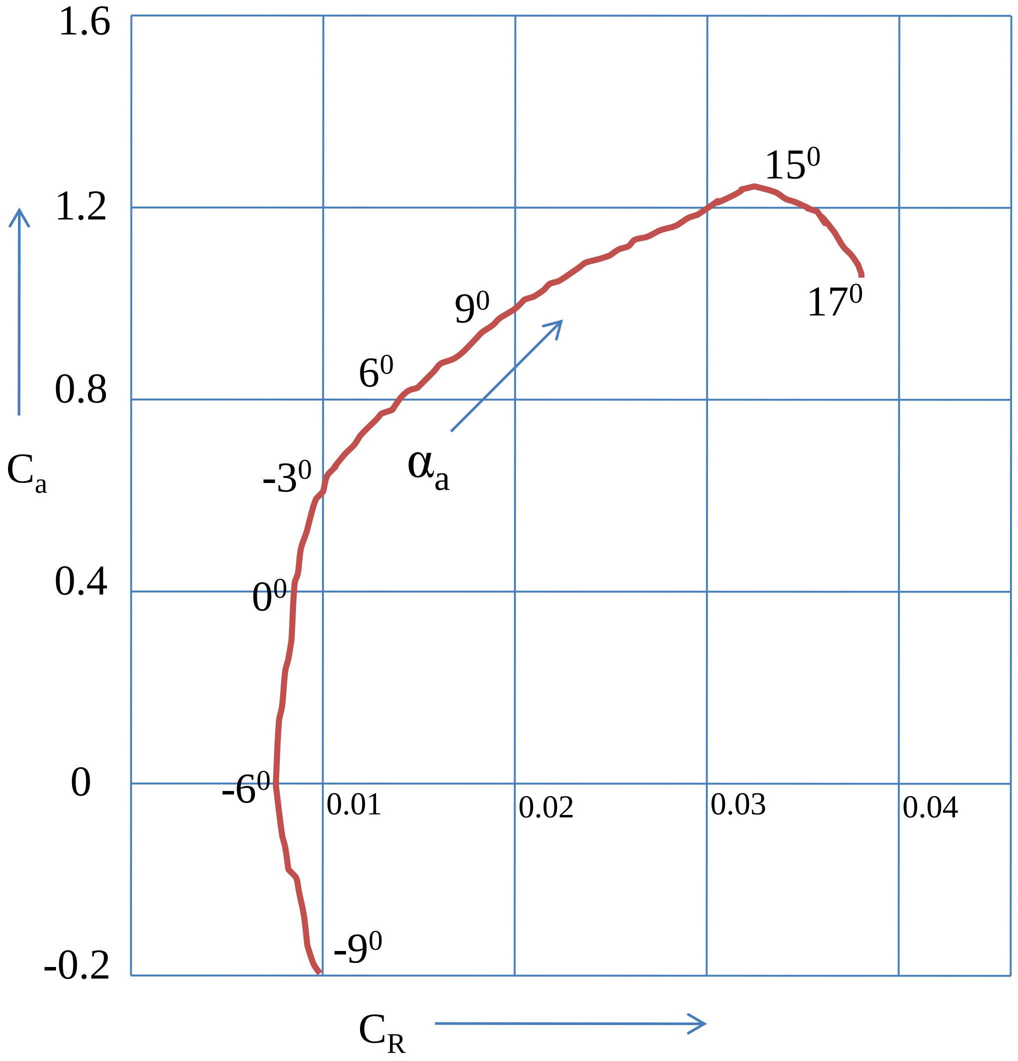


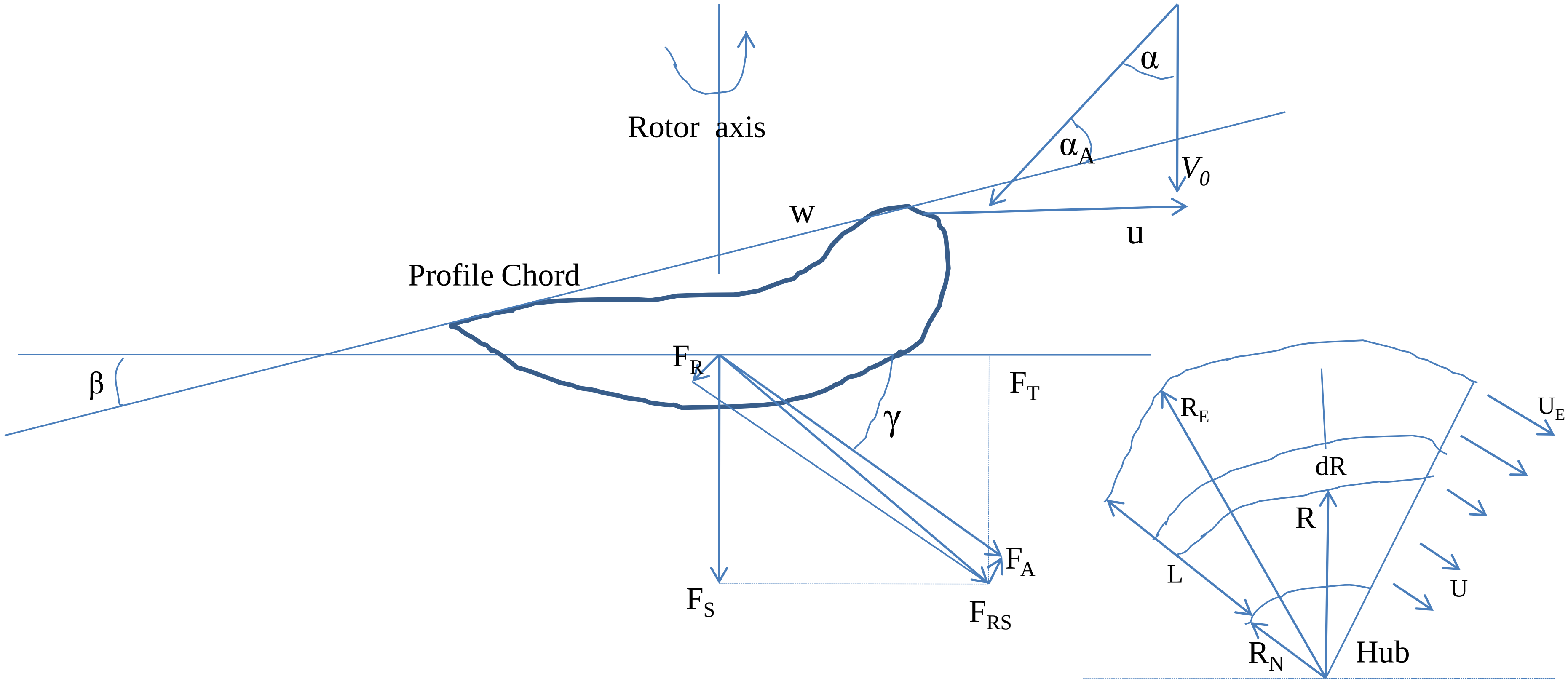
Fig: A Polar diagram of a simple blade profile (Re = 10^5).

The diagram is shown for the Reynolds number of the flow (Re) as:

$$Re = \frac{wb_p}{\nu}$$

Where ν is the kinematic viscosity (m^2/sec)

Velocities and Forces at the Rotor Blade:-



u = Circumferential velocity of rotor blade (m/sec), v_0 = Velocity of wind (m/sec), w = Approach velocity of wind (m/sec), β = Blade angle (Angle between profile plane and rotor plane), F_{RS} = Resultant of the F_A and F_R . F_s = Axial component of F_{RS} , R_E= Outer rotor radius, R_N = radius of the hub, u_E = Peripheral velocity at the edge of the blade, α_A = angle of attack, γ = angle between wind velocity v_0 and relative approach velocity, L = Rotor blade length, For an element which delivered power dP along the length dR of the rotor blade, one can write: $dP = u\, dF_T$ (W)

Where dF_T is an elemental tangential force. It is expressed as:

$$dF_T = dF_A \cos\gamma \quad \text{newton}$$

So the power produced is given by: $dP = u \cos\gamma\, dF_A$ (W)

Using the expression for dF_A we can write;

$$dP = u \cos\gamma \frac{C_A}{2} \rho_a w^2 dA \text{ (W)}$$

$$\text{Again,} \quad \cos\gamma = \frac{v_0}{w} = \frac{v_0}{\sqrt{u^2 + v_0^2}}$$

and for the area element: $dA = b_p N_R dR$

Where N_R is the number of rotor blades and dR is the length of the elemental rotor.

By substitution of dA in dP we can get power of an element,

$$dP = \frac{C_A}{2} \rho_a w^2 u \left(v_0 \Big/ \sqrt{u^2 + v_0^2} \right) b_p N_R dR \text{ (W)}$$

The total power of the rotor can be calculated by integration of dP from R_N to R_E.

So,

$$P = \int_{R_N}^{R_E} \frac{C_a}{2} \rho_a w^2 u \frac{v_0}{\sqrt{u^2 + v_0^2}} b_p N_R dR \qquad \text{(W)}$$

Similarly, thrust force can be calculated on the rotor blades along the vertical axis:

$$dF_s = dF_A \sin\gamma = \frac{C_a}{2} \rho_a w^2 dA \frac{u}{\sqrt{u^2 + v_0^2}} \qquad \text{(N)}$$

or

$$dF_s = \frac{C_a}{2} \rho_a w^2 (b_p N_R dR) \frac{u}{\sqrt{u^2 + v_0^2}} \qquad \text{(N)}$$

or

$$F_s = \int_{R_N}^{R_E} \frac{C_a}{2} \rho_a w^2 (b_p N_R) \frac{u}{\sqrt{u^2 + v_0^2}} dR \qquad \text{(N)}$$

Components of a Wind Power Plant:-

The different components of a wind converter are described below.

Wind Turbine:-

The wind rotors are various types depending upon number of blades, speed, control system, gear box (or gear less), type of generator etc. All the machines are based upon four basic concepts of rotor dynamics. These are given in the table below.

Table: Classification of selected wind power converters (Hau 2002).

Lift principle horizontal axis	High speed system, one-blade, two-blade or three –blade rotor, Low speed system, Historical wind mill, multiple rotor, Flettner rotor, sail rotor
Lift principle vertical axis	High speed systems, Darrieus rotor, H-rotor, three-blade rotor, low speed systems, Savonius rotor with lift principle.
Concentrating wind mill	Shrouded windmill, tornado type wind mill, delta concentrator wind mill, Berwian windmill.
Drag principle	Savonius windmill, cup anemometer windmill, half shielded windmill

* After extensive field experience, horizontal-axis, three-blade wind rotor has become an established system for field applications.
* In 1980s and 1990s, one and two-blade rotors were also developed because of higher rotational speed. But due to instability experience in operation, these were not used further.
* Gearless rotors are generally low speed converters which requires a special generator.

Tower: -

A component that sustains the whole weight of the rotor and its components is the tower. The tower should have sufficient height to operate the rotor at desired speed. The tower should also be strong enough to sustain the static and dynamic load of the rotor and vibrations during high and gusty winds. Tower are constructed from concrete or steel. Off-shore wind machines are of lower height because the wind speed is larger. So the foundations built in those cases are costly.

Electric Generators:-

Electrical generators convert the rotational energy into mechanical energy then to electrical energy. Commercially available generators with slight modification are used for converters with gear box. Specially designed three phase generators are used for gearless converters.

Synchronous Generator:-

These generators are equipped with a fixed stator at the outside and a rotor at the inside located on a pivoting shaft. Normally DC is supplied to the rotor to create a magnetic field. When the shaft drives the voltage is created in the stator whose frequency matches exactly the rotational speed of the rotor. This type of generators are used most of the places but the disadvantage is that it runs with constant speed of the rotor and fixed frequency. It is therefore not suitable for variable speed operations in the wind plants.

Asynchronous Generator:-

The asynchronous generator is electromagnetic generator. The stator of this generator is made of numerous coils with three groups and is supplied with three-phase current. The three coils are spread around the stator periphery and carry currents, which are not in phase with each other. This combination produces a rotating magnetic field, which is the key feature of the asynchronous generator. The angular speed of the rotating magnetic field is called the synchronous magnetic field and is given by:

$$N_s = 60\frac{f}{p} \quad \text{rpm}$$

Where f = frequency of the stator excitation, p = number of magnetic pole pairs.

The stator coils are embedded in slots of high permeability magnetic core to produce a required magnetic fields intensity with low exciting currents. The rotor in this generator is squirrel cage rotor with conducting bars embedded in the slots of the magnetic core. The bars are connected at ends by a conducting ring. The stator magnetic field rotates at the synchronous speed given above. The relative speed between the stator and the rotor induces a voltage in each rotor turn linking the stator flux $V = (-d\Phi/dt)$, Φ being the magnetic flux linking the rotor turn.

Foundations:-

The type of foundations required to anchor towers and thus wind energy converters, into the ground depends upon the plant size, meteorological and operational stress and local soil conditions. Erection of wind converters on a coastal line is much more costly. Depending on the soil conditions, there types of foundations namely gravity foundation, monopole foundation and tripod foundations are used . All these foundations are discussed in the beginning.

Turbine Rating:-

The normal rating of a wind turbine has no standard global rating. The power output of a turbine is proportional to the square of the rotor diameter and also to the cube of the wind speed.

* The rotor of a given diameter will generate different power at different wind speed (like 300 KW at 7m/sec and 450 KW at 8 m/sec).

* Many manufacturers mention a combined rating specification like 300/30 means 300 KW generator and 30 m rotor diameter.
* Specific rated capacity (SRC) is often used as a comparative index defined as:

SRC = Generator Electrical Capacity/Rotor Swept Area.

To be continued…….

WAVE ENERGY
&
OCEAN ENERGY

Wave Energy:-

The power in the wave (P) is proportional to the square of the amplitude (A) and to the period (T = 1/f, f = frequency) of the waves.

$$P \propto A^2 f$$

Where *A* is the amplitude of the wave in meter and *f* the wave frequency .

Ex:- the long period (~10 sec) and large amplitude (~2 m) waves found in deep sea area where the power generation with energy fluxes of 50-70 KW per metre width of incoming wave.

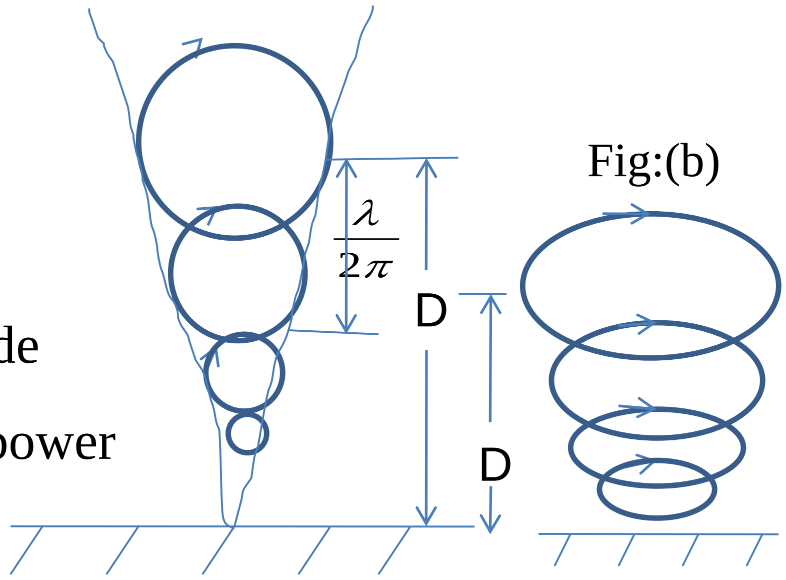


Fig: Water particles from a sphere of diameter '2r' in a sea wave.

* Deep water waves are found when the mean depth of sea bed (D) is more than about half the wavelength, λ.
* Deep water waves are available at a mean depth of 50m or more.

* The Fig:(b) in the previous page shows the motion of the water particles in the deep water wave. The motion of water particle is circular with an amplitude that decreases exponentially along the depth and becomes negligible for $D > (\lambda/2)$.
* In shallow water, the movement of water takes place elliptically and the water movement occurs against bottom of the sea, including friction and dissipation.
* The wave height is determined by wind speed, the duration of which the wind is blown, the distance over which the wind excites and the depth and topography of sea floor.
* When the wave speed reaches the maximum practical limit depending upon the time or distance, the wave is said to be *fully developed*.
* Oscillatory motion is highest at the surface and diminishes with depth exponentially.
* For standing waves near a reflecting coast, the wave energy is also present at great depth due to pressure fluctuations (very slow amount of wave but makes it count for wave power).

* Waves and wave power propagate horizontally on the ocean surface.

* The rate of transport of wave energy in a vertical plane of unit width parallel to the wave crest is called the wave energy flux or power.

Velocity of Water Waves:-

Considering the motion of the water particles may be circle as shown in the figure below, if a person moves along the direction of propagation of waves (V_w) the periphery of the water particles appear static.

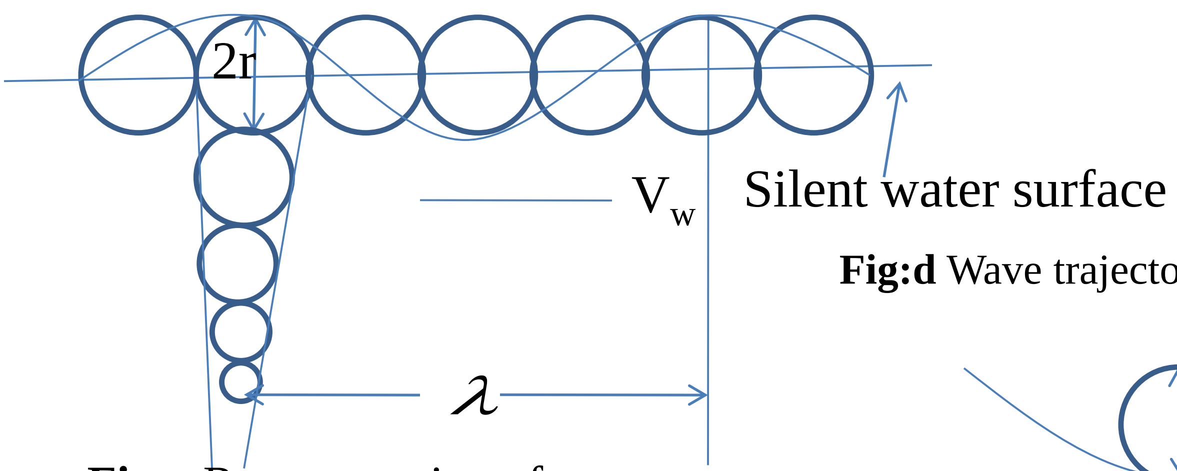
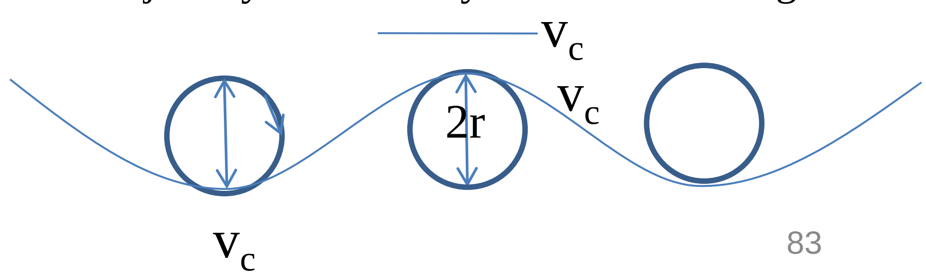


Fig:c Representation of water waves.

Fig:d Wave trajectory observed by a forward moving observer



Let

V_w → Velocity of the wave observed by the observer who moves in the direction of wave,

V_c = the peripheral velocity of water particles = $2\pi r\omega$,

$V_1 = V_w + V_c$ = Velocity of water particles measured by an observer at wave valley,

$V_2 = V_w - V_c$ = Velocity of water particles measured by an observer at wave peak,

The difference of kinetic energies at two positions is given by:

$$\frac{1}{2}m\left(v_1^2 - v_2^2\right) = \frac{1}{2}m\left[\left(v_w + v_c\right)^2 - \left(v_w + v_c\right)^2\right]$$

$$= 2mv_wv_c = 2mv_w\left(2\pi r\omega\right) = 4\pi rmv_w\omega$$

The gain in kinetic energy at the valley comes from the potential energy at the peak.

This potential energy is equivalent to: $E_{pot} = mg.2r$

So, we can write $E_{pot} = mg.2r = 4\pi rmv_w \Rightarrow v_w = g/(2\pi\omega)$

Assuming the wave as sine nature, the velocity of propagation is: $V_w = \omega\lambda$.

So, $$V_w = \sqrt{\frac{g\lambda}{2\pi}}$$

Power of Waves:-

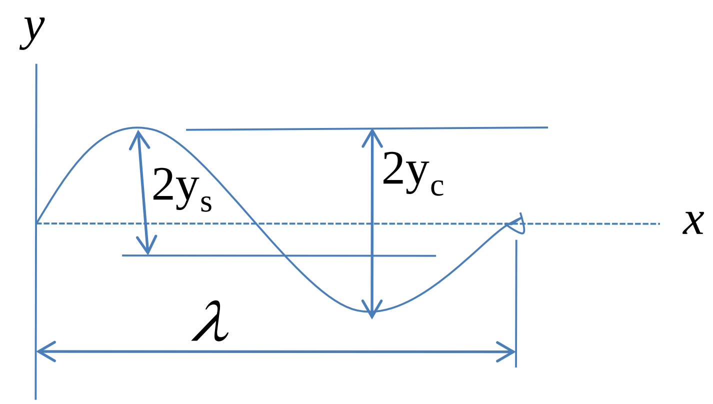


Fig: The centre of gravity of the peak falls down by $2y_s$ yielding work

The centre of the gravity of the peak from the figure can be calculated as

$$y_c = \frac{\int y\,dm}{\int dm} = \frac{\iint y\,dx\,dy}{\iint dx\,dy} = \frac{\frac{1}{2}\int y^2 dx}{\int y\,dx}$$

If ν is the frequency of the wave then the wave power is given by:

$$P = m.g.2y_s.\nu$$

Technology of Wave Power Plants:-

Several working models have been developed by the researchers and laboratory and numerical tests are also conducted to test the viability for the commercial purposes. The literature presents some of the commercial viable wave energy devices by their energy extraction method, size etc. According to the device location, it is classified as:

* Shoreline devices -----→ (oscillating water columns (OWC), tapered channel (TAPCHAN)),
* Bottom fixed near –shore devices -----→ pendulor,
* Off-shore devices.

Shoreline Devices:-

These type of devices require less maintenance and installation is also easy. The main type of shoreline devices are the OWC and TAPCHAN.

Oscillating Water Columns:-

The shoreline devices are partly submerged in structure . The air is trapped inside the open below free water surface as shown in the diagram. The incident water waves cause the height of the water surface to oscillate and the air is channeled through a turbine to drive the electric generator.

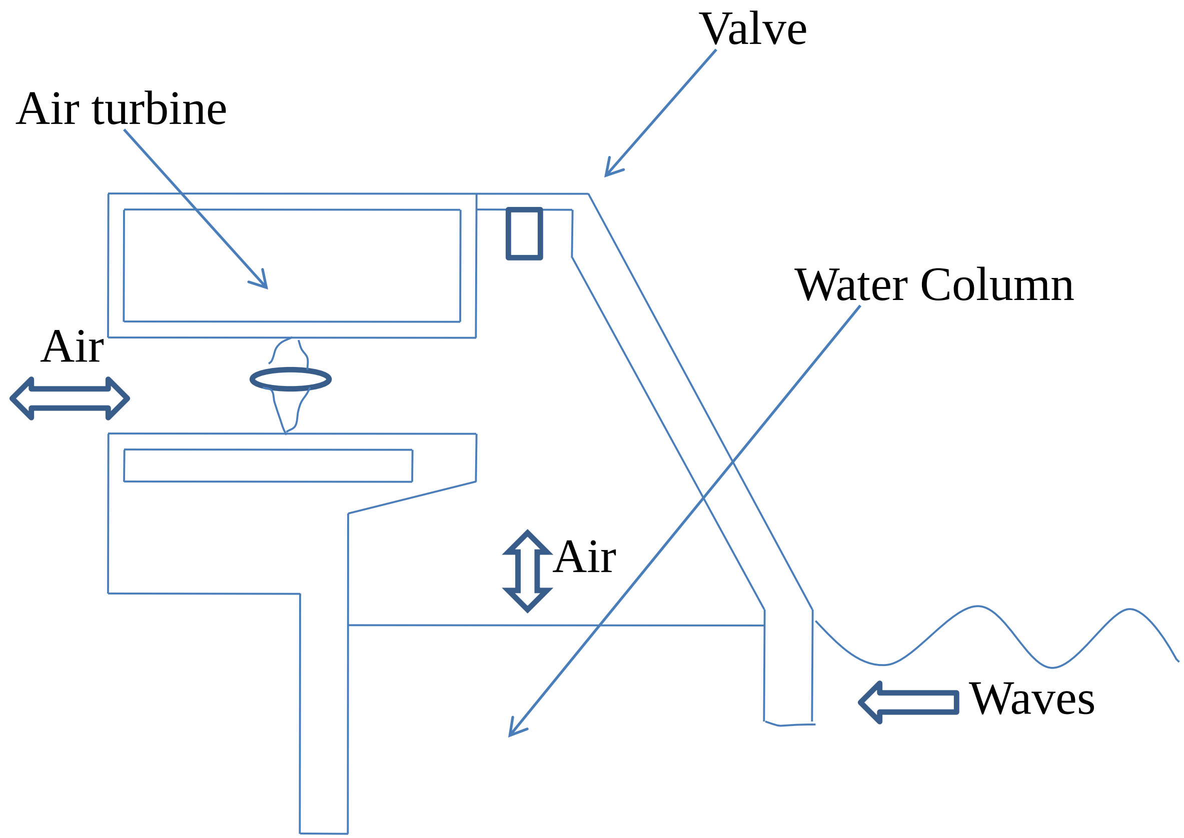


Fig: Oscillating water column device

The most significant parts of an OWC are as follows:

* The collector structure : The collector geometry depends upon the power capture and must be designed to suit the prevailing wave climate.
* The turbine: The bi-directional, axial flow wells turbine has been used in some OWC prototypes.

TAPCHAN:-

The TAPCHAN (TAPered CHANnel) is a structure which narrows its walls resulting the raising of mean level of water wave. As waves propagate up the channel the wave height is amplified until the wave crests spill over the walls into a reservoir. This supply of wave water provides a conventional low-head turbine. The power takeoff is akin to a small low-head scheme, the technology for which is relatively mature.

Bottom-fixed near-shore devices (Pendulor):-

The bottom fixed near shore devices are generally used in shallow waters typically10-25 m water. The bottom fixed near shore device is named as Pendulor.

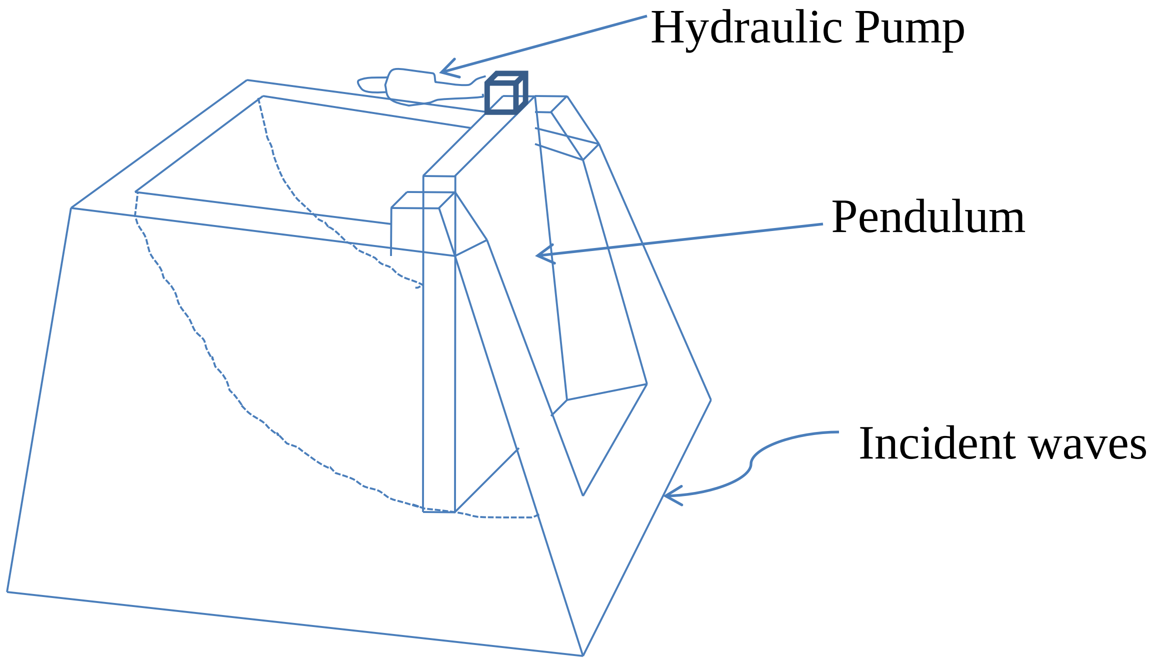


Fig: Schematic of a Pendulor

The pendulum or oscillating flap acts up on directly by the wave water. This device was under test in the year 1999, Japan by Watable *et al*. Plans are executed in Sri Lanka for development of power 150 - 250 KW.

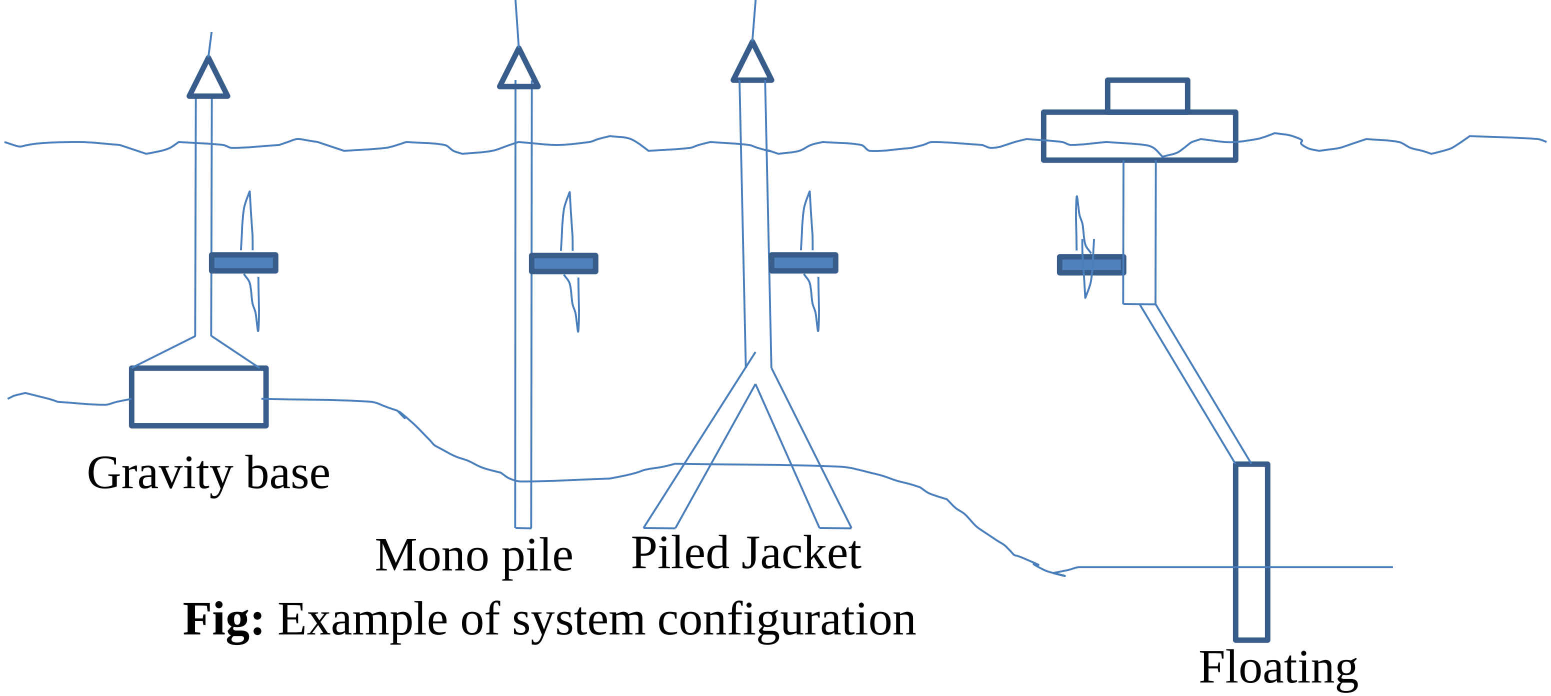


Fig: Example of system configuration

Offshore Devices:-

The extraction of energy from the wave is possible if the devices are installed at or near water surface of the sea. In most of the cases, the main element is the oscillating body that either floats or submerged near the surface. The conversion of oscillating motion of body into mechanical energy has been done by mechanical devices like hydraulic pumps or rams which are incorporated into the floating body. Some of the examples are Swedish Hose Pump.

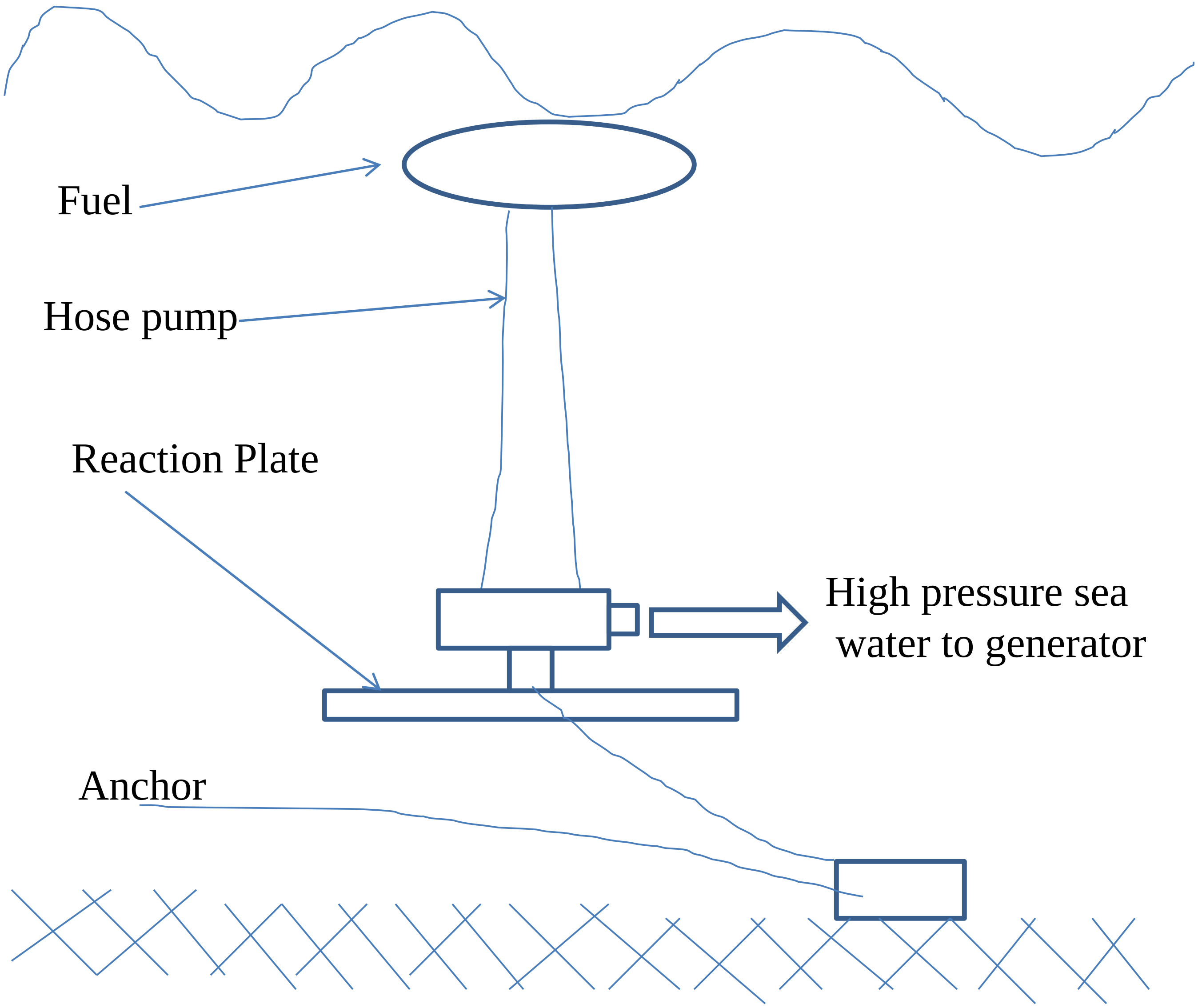


Figure: Hose Pump

Ocean Thermal Energy Conversion (OTEC):-

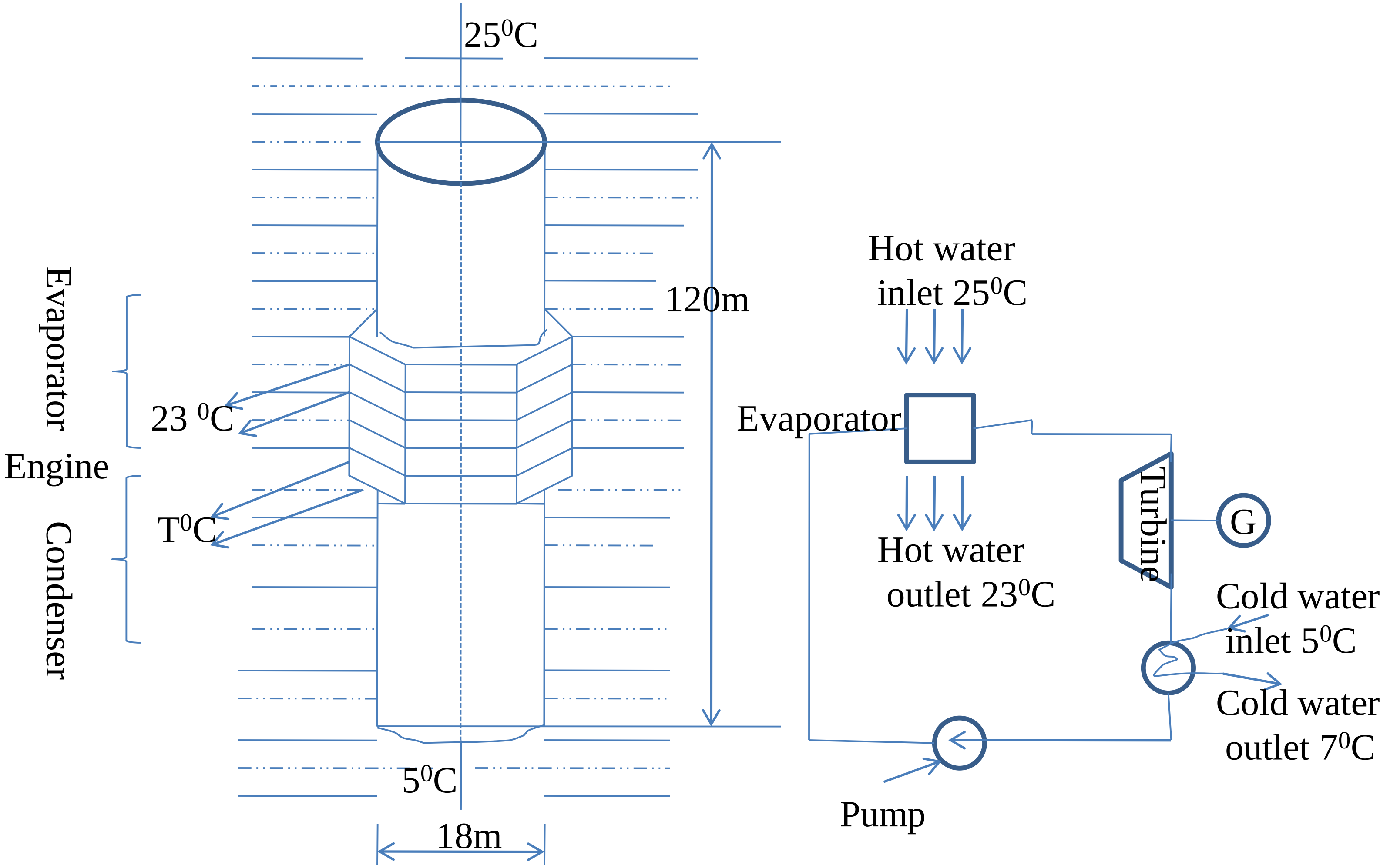


Fig: A closed Rankine cycle power plant in an ocean thermal energy power plant

* A concept first proposed by the French engineer Jacques Arsene d' Arsonval in 1880s.

OTEC generates electricity using open or closed Rankine cycle from the temperature differential between the warm surface of ocean (heated by solar radiation) and cold water at dipper surface. This system uses a secondary working fluid (refrigerant) such as ammonia. Heat transferred from the warm ocean water to the working fluid through a heat exchanger vaporizes the working fluid. The vapor then expands under moderate pressure in turbine which is connected to the generator and thereby producing electricity. Cold sea water is pumped up from the ocean depth to a second heat exchanger provides cooling to the condenser. The working fluid, the refrigerant remains within the closed circuit.

Some of the researchers have already started working on an open-cycle OTEC systems which employs water vapours as working fluid. The sea water enters into a vacuum forming patial amount of vapour. This vapour is led to the low pressure turbine (which is connected to the generator) for expansion process to produce power. Cold sea water is used to condense the steam and a vacuum pump maintains the proper system pressure.

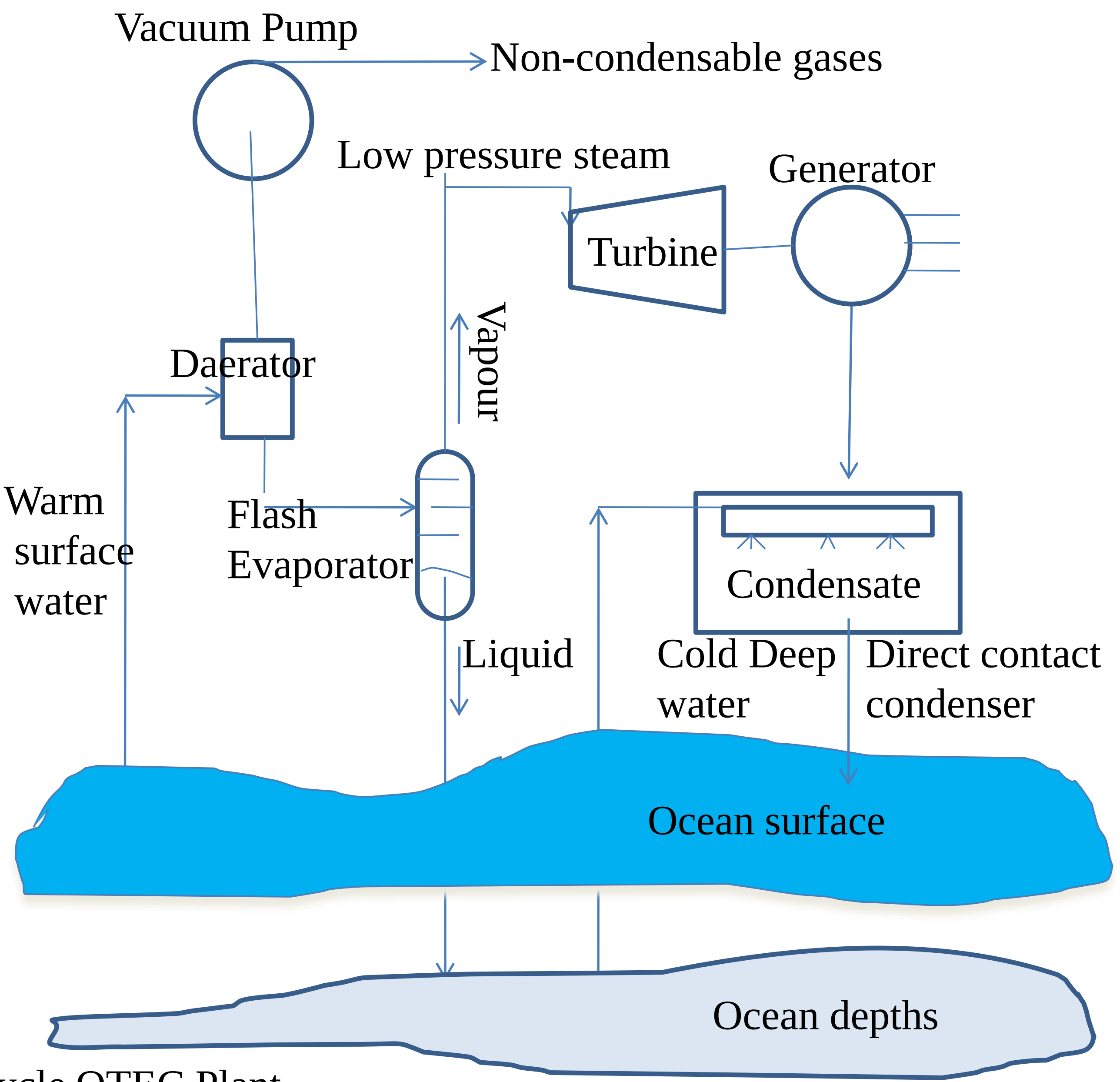


Fig: Open cycle OTEC Plant

Limitations:-

OTEC plant set up for power generation is relatively expensive . Therefore it seems little chance for replacement of power generation in future.

Photovoltaics:

* The use of solar power in the form of electricity is called phototvoltaics. The photovoltaic process converts solar radiation into electricity through a solar cell.
* Photovoltaic systems are available in the range of milliwatts to megawatts.
* Photovoltaic modules may include mono-crystalline silicon, Polycrystalline silicon, amorphous silicon and cadmium telluride and copper indium gallium selenide/ sulfide; out of these commonly used modules are polycrystalline silicon solar cells or thin film amorphous silicon cells.
* Mono-crystalline silicon is used for space applications or automobile vehicles.
* Photovoltaic has gathered third position among the renewable energy sources of their global use after hydro and wind power.

Solar Thermal Energy(STE):-

* The solar thermal energy produces power from thermal devices (collector) by convection process. There are three types of collectors based on temperatures i.e. low, medium and high temperatures.
* Low temperature collectors are used for residential heating purposes like swimming pools and for drying.
* Medium temperature collectors are advance flat plate collectors where temperature range is around 100^0C or more for residential or commercial heating.
* High temperature collectors are usually employed for solar power generation. STE is much more efficient than photovoltaics especially for heat applications.

BIOMASS ENERGY
&
PHOTOSYNTHESIS

Biomass and Conversion of Energy

*   Biomass includes all the living or dead organic materials like wastes and residues. The animal and plant wastes and their residues are regarded as biomass. In addition to this the products originate from the conversion processes like paper, cellulose, organic residues for food industry and organic wastes from houses and industries are in this category.

Origin of Bio-mass: -

*   Animals feed on plants and plants grew up through the photosynthesis process using solar energy. Thus photosynthesis process is primarily responsible for generation of biomass energy. A small portion of solar radiation is captured and stored in plants during photosynthesis process. Therefore biomass energy is an indirect form of solar energy.

*   To use biomass energy, the initial biomass may be transformed by chemical or biological processes to produce more convenient intermediate bio-fuels such as

methane, producer gas, ethanol and charcoal. On combustion it reacts with oxygen to release heat.

* In nature bio-mass is formed by the process of photosynthesis of inorganic materials. With the help of the solar radiation in the visible region (0.4-0.8 μm), the coloured material molecules (mainly chlorophyll) split water in organic cells (photolysis). The originating hydrogen along with carbon dioxide forms the biomass. During this process molecular oxygen is released into the air. The production of bio-mass can be understood by the following equation.

$$\underset{\text{(From soil of water)}}{\mathbf{H_2O} + b.\ \mathbf{NO_2} + c.\ \mathbf{SO_4} + d.\ \mathbf{PO_4}} + \underset{\text{(From air)}}{\mathbf{CO_2}} + \underset{\text{(From Sun)}}{(8\text{-}10)\ \mathbf{h\nu}} \xrightarrow{\text{Chlorophyl}} \underset{\text{Biomass}}{\mathbf{C_kH_mO_n}} + \mathbf{H_2O} + \underset{\text{Water Vapour}}{\mathbf{O_2}}$$

+ Other material products

where *b*, *c*, *d* are various small quantities (ppm)

h is a Planck's constant = 6.625×10^{-34} JS

ν is frequency = C/λ (s-1)

C is the speed of light = 2.99×10^{8} m/sec.

The left hand side of the equation contains CO_2 from the air with large number of trace elements like nitrogen, phosphorous, sulphur, etc. are taken from the soil. These are the fertilizers taken by the plant. These elements are very small in quantity and hence neglected on the right of the equation. For chlorophyll the plant requires 8 to 10 photons (*hν*) of solar energy . The above molecular equation which is responsible for formation of biomass can be written as:

$$12\,\mathbf{H_2O} + 6\,\mathbf{CO_2} + 2.8\text{ MJ} \xrightarrow{\text{Chlorophyl}} \mathbf{C_6H_{12}O_6} + 6\,\mathbf{O_2} + 6\,H_2\mathbf{O}$$

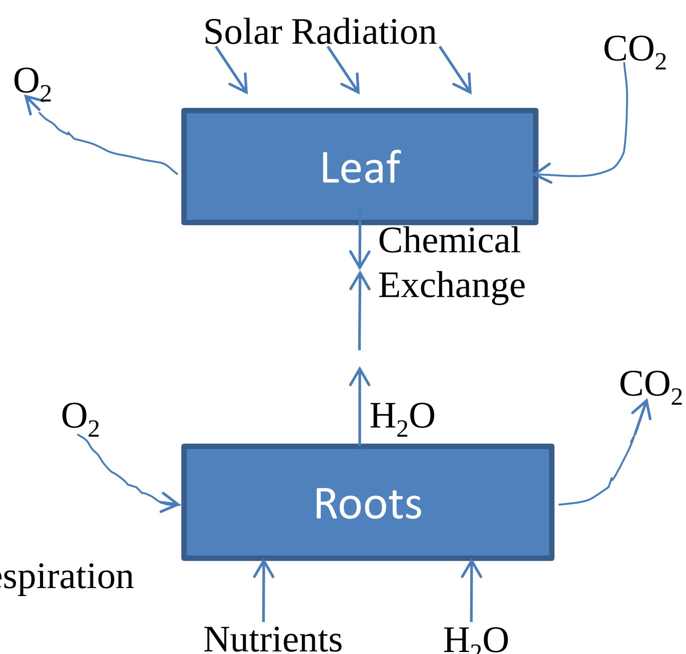


Fig: Photosynthesis and respiration processes in the plant

Manifestation of Biomass:-

Biomass manifests itself in various forms which are generally present in the organism simultaneously. These are shown in the table below.

Table: Manifestation forms of biomass and their annual Production.

Manifestations of biomass	**Worldwide annual Production**	
	% ge	Billion t/a
Cellulose	65	100
Hemi-cellulose	17	27
Lignin	17	27
Starch, Sugar, Fat, Protein, Chlorophyll	1	0.13
Total	100	155.28

Cellulose is the most common substance in all forms of biomass. It is polysaccharide which contains a chain of glucose molecules ($C_6H_{12}O_5$) which are held together in hydrogen bonds in the crystal bundle. Cellulose is not soluble in water and other molecule solvents but reacts with alkaline and acidic solutions to hydrate cellulose, which through formation of acids at higher temperature, can be converted to glucose.

Hemi-cellulose is a polysaccharide which made not only of a glucose molecule chain, but also of other sugars (C_5 and C_6 sugar molecules). About 20 to 40% of the lumber type plants contain in it.

Lignin is formed in the plants through the storage of lignified plant cell Membrane. It is soluble in soda lye (caustic soda solution) and calcium bisulphate but not in water. Lignin offers considerable resistance to the mechanical and enzymatic digestion of cellulose. About 30% of lumber plants contain the wood material it.

Other materials like starch, sugar, fat, protein, chlorophyll contain very little amount of contribution for biomass production.

Potential of Biomass:-

The worldwide existing biomass estimates to be about $2x10^{12}$ t = $30x10^{21}$ J = 1000 billion tons of coal equivalent (land area only). Out of these estimates, about $8x10^{11}$ = $8x10^{11}$ t/a are used for carbon fixation. The amount of wood is estimated to be 50 to 90%. The annual growth rate of forest (storage for biomass) also decides the amount of use of biomass and this has been estimated around 1.5 x 10^{11} t = 3 x 10^{21} J/a = 100 billion tons COE/annum. This amount to be 10% of the total biomass estimates.

Table:12.2 Distribution of biomass Production in the Earth's Surface (Lith 1975).

Biomass Source	**Area in 10^6 km^2**	**Net primary productivity, g/m^3 a**	**Net primary productivity in biom. 10^9 t/a**	**Calorific value in MJ/kg**	**Annual energy equivalent KWh/m^2 10^9 MWh**		**Percentage gain in solar energy in %.**
Forest	50	1290	64	18.0	6.5	322	0.55
Forest land	7	600	4	16.7	3.33	23	0.30
Shrub	26	90	2.4	18.8	0.5	12	0.04
Grassland	24	600	15	17.6	2.9	70	0.30
Desert	24	1	-0	16.7	0	0	0
Culture land	14	650	9	17.2	3.1	44	0.30
Fresh water	4	1250	5	18.0	6.3	25	0.50
Total land	149	669	100	18.0	6.3	25	0.50
Ocean	361	155	55	18.8	0.8	303	0.07
Earth	510	305	155	18.4	1.6	799	0.14

The net primary production of biomass from the world's forest comprises about 7% of total production of the overall world's land area. Considering the existing land/ water distribution, 60% of the total world's biomass production falls in northern hemisphere and 40% in southern hemisphere.

The efficiency of biomass production can be defined as the ratio between the calorific value of mass and necessary solar energy for the formation of biomass. Forests and fresh water show a large gain from solar radiation, about 0.5% tropical forests attain a value of about 0.8%. The maximum achievable values of some of the biomass are:

1. Sugarcane (4.8%), 2. Maize (3.2%), 3. Sugar beat (white) (5.4%).

It is always to be taken care of that only a part of the biomass energy can be harvested. About 50% of the biomass (roots, leaves, etc) cannot be converted into energy. But it is also counted that *the theoretical potential of biomass energy availability is four to six times the world's energy consumption presently.*

Energy Conversion Process:-

The conversion of biomass either in the form of heat or solid, liquid or gas form of energy fuels. Using these individual elements in a particular process chain, a number of bio-conversion processes can be defined which is represented below.

Table: the elements of bio-conversion systems that may be used for a number of Bio-processes Conversion chain (Nairobi Conference, 1981).

Forms of Biomass →	*Method of Bio-conversion* →	*End Product* →	*Region of Application*
1. Terrestrial Primary biomass	5. Physical conversion	8. Solid bio-fuel	14. Agriculture
2. Aquatic Primary biomass	6. Thermo-chemical methods	9. Liquid bio-fuel	15. Industry
3. Plant and animal waste	7. Biological conversion	10. Gaseous bio-fuel	16. Commercial
4. Residues		11. Electricity	17. Transport
		12. Mechanical energy	18. Domestic
		13. Heat	

Raw materials in all these processes is biomass, that is available in nature either in land or in water beds, but all is available in the form of residues or waste. Biomass waste materials cannot be used as food or for wood production like rice husk, saw dust and animal waste, etc. The biomass waste material (like straws, twigs, stem pieces may also be used for bio-conversion). These waste materials are also used for fertilizer on the earth.

From the table, it is observed that there are four forms of biomass that gets converted into useful energy forms by several processes of biomass energy conversion into useful products.

Table: Bio-conversion process, Raw material, End-product and Conversion Efficiencies.

Process	Raw material	End product	An efficiencies (%)
Physical processes			
Mechanical Compression	Wood waste, straw, saw dust	Pellets, briquettes	90
Extraction	Euphobia lathyris	Oil	20
Thermo-chemical processes			
Combustion	Wood	Steam, heat	70
Combustion	Wood	Steam, electricity	20
Gasification	Wood	Hot Producer gas	80
Gasification	Wood	Cooler producer gas	70
Gasification	Wood	Medium Joule value gas	70
Liquefaction			
1. Chemical reduction	Wood	Oil	30
2. Pyrolysis	Wood	Methanol	60
3. Synthesis	Wood	LPG	40

Biological Processes			
Fermentation	Sugar plants, Corn	Ethanol	30
(Alcohol Production)	Dung, algae		
Fermentation		Biogas	50
(Biogas production)	Agricultural waste		
Composting		Heat	50

Physical Methods of Bioconversion:-

Mechanical compression of combustible materials:-

The simplest form of physical conversion of biomass is through compression of combustible material. Its density is increased by reducing the volume by compression through the processes *called briquetting, cobs or pelletization*. The end products are called *briquettes, cobs or pelletization*.

The mechanical compression of combustible materials simultaneously leads to drying of the product. There is not any uniform standardization of the end products exist. Generally the compressed biomass or pellets contain 15-18% of moisture.

Some characteristics parameters of compressed products are shown in the table below. The whole mechanical conversion of biomass includes *collection, processing, drying etc.; which requires total energy of 10 to 15% of the respective calorific values*. So the net conversion efficiency of biomass compression process lies between 85% and 90%.

Table: Parameters of compressed biomass (Wieneke 1983)

Product	**Preparation**	**Pressing Plant**	**Dia of edge length,** ***mm***	**Pressing density** ***kg/m³***	**Bulk density** ***kg/m³***	**Specific energy requirement** ***kWh/t***
Pellets	Chopping and powdering	Grooved pressed	6 - 12	1100 - 1400	450 - 750	30 - 90
Cobs	Chopping, pressing and powdering with hammer	Grooved pressed	15 - 35	900 - 1200	403 - 600	30 - 80
Milling	Milling	Grooved and piston press	40 - 80	450 - 850	300 - 450	25 - 70

Extraction of oil from plant products:-

The extraction of energy source from biomass consists of *hot press or cold press*, *steam extraction or acid reduction* etc. Some plants produce acid free hydrocarbons like *cellulose and lignin*. The acid free hydrocarbons can be converted into oil which can be treated as an oil. Vegetable oils are mainly edible oils along with their use in paints, soaps and cosmetic articles.

* In Europe, the main investigation on rapeseed oil have been made. The following outcomes are obtained:

(1) Rapeseed oil is a suitable power source for diesel engine and its efficiency is almost similar.

(2) A mixture of rapeseed oil and diesel fuel in the ratio 1:1, leads to resinification and carbon deposition in the engine.

(3) Emulsion of 40% oil, 40% diesel, 19% water and 1% gives good combustion in the engine and almost no deposition. However there are small problems like cold start of the engine due to higher viscosity.

* Bio-fuel development in India is the extraction of oil from Jatropha plant seeds. This bio-fuel contains 40% oil which is the quality of a rich oil. This oil has served as a replacement of bio-diesel for long decades in India. It can be used directly after extraction in generators and diesel engines. It has the potential to provide economic benefits at the local level since with proper management, it has the potential to grow in dry marginal non-agricultural lands.

* One of the most productive oil plants in African soil is the palm oil. After simple treatment this oil has capability to produce low viscosity oil which can be used as diesel fuel. The advantages of using palm oil are: (1) it does not require any distillation, (ii) it shows small volumes (no water), (iii) continuous harvesting is possible.

* Another African extracted oil named as African milk bush which grows very fast and can be harvested several times a year.

* In the forest of South America, the famous Copaiba tree is available from which oil is extracted and used directly as fuel without any processing. The test values for the

yield lie between 40 to 60 l/a per tree.

Thermo-Chemical Conversion Processes:-

In thermo-chemical processes, the biomass is either converted into heat through the process of oxidation or it is converted into a secondary form like producer gas by some chemical processing. One can roughly distinguish three different classes of thermo-chemical reactions:

(1) Combustion, (2) Gasification, and (3) Liquefaction.

These three processes may run parallel or one after another.

A. Combustion:-

One of the thermo-chemical method of bioconversion is combustion. *The main biomass which has been used over the years for combustion is wood*. Now 50% of the world are using wood for combustion. Especially in developing countries wood, dung and agricultural wastes e.g. straw, stem etc. are burned.

In the combustion process of biomass ($C_kH_mO_n$), the products produced are carbon dioxide, water vapor and ash. If it comes in contact with sulphur, then SO_2 is formed. Amount of energy (calorific value) released is equivalent to the burning of dryness fraction (x) portion of mass of fuel and rest (1-x) fraction is utilized for water evaporation process. The calorific value of moist biomass can therefore can be written as:

$$H_u = (1-x)H_{CDS} - x2441\,\text{KJ/kg}$$

where

H_{CDS} = calorific value of completely dry substance

x = dryness fraction.

About 40 to 60% moisture is present in the fresh wood. The moisture content in the fresh wood can be defined as:

$$X = \frac{m_{H_2O}}{m_{biomass}} = \frac{m_{H_2O}}{m_{H_2O} + m_{ODS}}$$

The *humidity(u) of wood* is defined as:

$$u = \frac{m_{H_2O}}{m_{CDS}} = \frac{X}{1-X}$$

Table: Calorific values of dry and moist biomasses:-

Dry biomass		Moist biomass		
Material	Calorific Value, H_{CDS} (MJ/kg)	Fuel	Calorific Value, H_u (MJ/kg)	Humidity (%)
Ash Wood	18.6	Fresh Wood	6 - 8	40 - 60
Beech Wood	18.8	Air-dried Wood	14 - 16	10 - 20
Oakwood	18.3	Straw	11 - 18	15 - 18
Pine Wood	20.2	Waste	5 - 8	25 - 38
Waste Paper	17.0	Sludge	0	> 90
Sugarcane	15.0			
Algae	15.0			
Leaf Wood	18.0			
Vegetable Oils	39.0			
Heating oil	43.0			

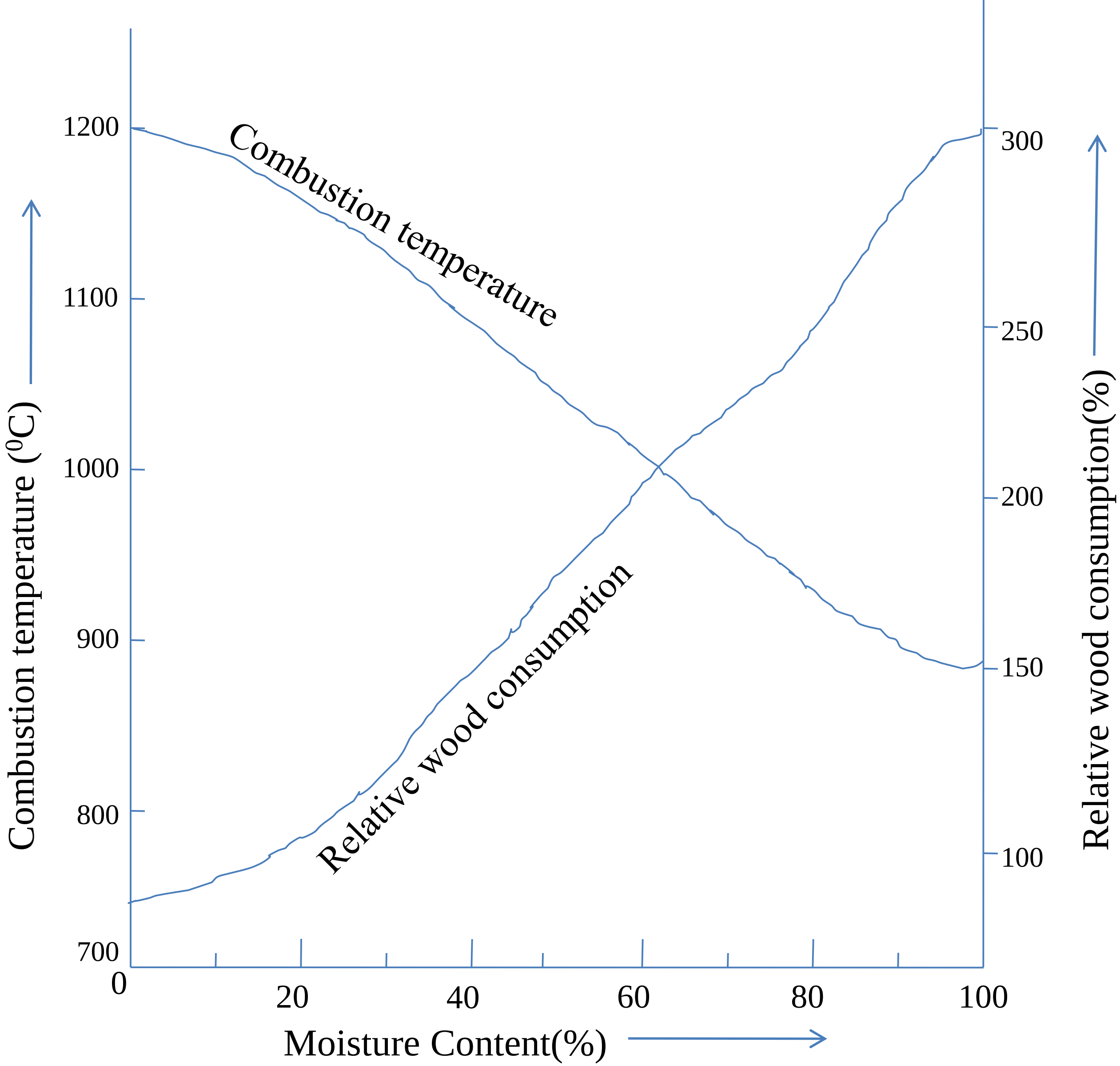


Fig: Combustion temperature and relative wood consumption as a function of moisture content (ECO 1980)

The combustion temperature decreases with increasing moisture content and the relative wood Consumption increases for generating the same amount of heat energy.

For many combustion process, the wood containing moisture is heated in a *pre-combustion chamber* so that moisture is removed from the fuel. The heated fuel is burnt in *second combustion chamber*.

B. Biomass Gasification:-

The complete and controlled combustion of biomass produces carbon dioxide, hydrogen, carbon monoxide and traces of methane along with dust, tar and steam vapor. *If the combustion is partial* (fuel-air supply is not as per the stochiometric), the products of combustion contains *carbon monoxide, hydrogen, and other elements is known as producer gas.* This producer gas is combustible. The equipment used to produce producer gas through the process of biomass gasification is known as gasifier. The steam required for gasification process is obtained from wet biomass during the first stage of combustion chamber.

Depending on the relative movement of the feedstock (biomass and air), three different kinds of gasifiers are used: (1) Updraft gasifier (the air moves upward through the biomass), (2) Downdraft gasifier (the air moves downward), and (3) Cross-draft gasifier (feed of air and biomass are perpendicular to each other).

Table: Advantage and disadvantage of various Gasifiers.

S. N.	Gasifier Type	Advantages	Disadvantages
1	Updraft feed ↑	1. Small Pressure drop, 2. Good thermal efficiency, 3. Little tendency towards slag formation	1. Great sensitivity to tar and moisture and moisture content of fuel, 2. Relatively long time required for start up of I.C. engine, 3. Poor reaction capability with heavy gas load.
2.	Downdraft feed ↓	1. Flexible adaptation of gas production to load, 2. Low sensitivity to charcoal dust and tar content of fuel.	1. Design tends to be tall, 2. Not feasible for very small particle size of fuel.
3.	Cross-draft fuel →, air ↑	1. Short design height, 2. Very fast response time to load, 3. Flexible gas production.	1. Very high sensitivity to slag formation, 2. High pressure drop

Almost all gasifiers fall under these three categories. The selection of gasifier depends upon the following factors:

(1) Fuel, (2) its final available form, (3) its size, (4) moisture content and (5) ash content.

There are four zones in each of the gasifier. These are: (1) Drying zone, (2) Pyrolysis zone, (3) Reduction zone, and (4) Combustion zone.

Drying Zone: Drying of wet biomass takes place.

Pyrolysis Zone: The products like Carbon dioxide and Acetic acid are produced.

Reduction Zone: Carbon monoxide and hydrogen are produced.

$$C + CO_2 = 2CO - 164.9 \quad \text{MJ/kg mole}$$
$$C + H_2O = CO + H_2 + 42 \text{ MJ/kg mole}$$
$$C + 2H_2 = CH_4 + 75 \text{ MJ/kg mole}$$
$$CO_2 + H_2 = CO + H_2O - 42.3 \text{ MJ/kg mole}$$

Combustion Zone: Steam and carbon-dioxide are formed.

$$C + O_2 = CO_2 + 393 \quad \text{MJ/kg mole}$$
$$2H_2 + O_2 = 2H_2O - 242 \text{ MJ/kg mole}$$

On an average 1 kg of biomass produces 2.5 m^3 of producer gas at S.T.P. with consum-ption of 1.5 m^3 of air (Reed *et al*.). For complete combustion of wood 4.5 m^3 of air is required. For example to calculate the conversion efficiency (η_{Gas}) of wood gasifier; the calorific value of producer gas and dry wood are assumed as 5.4 MJ/m^3 and 19.8MJ/kg respectively. $$\eta_{Gas} = \frac{2.5 \times 5.4}{1 \times 19.80} = 68\%$$

Application:-

Producer gas can be used for many applications like:

(a) Direct heating,

(b) Shaft Power, and

(c) Chemical synthesis into methanol.

C. LIQUEFACTION OF BIOMASS

The liquefaction of gas takes place through three different processes:

1. Liquefaction through chemical reduction with the help of gasification medium.
2. Liquefaction through pyrolysis without any gasification medium.
3. Liquefaction through methanol synthesis and pre-gasification.

1. Liquefaction through Chemical Reduction:-

By introduction of carbon monoxide at high temperatures (250^0C to 400^0 C) and high pressure (140-280 bar), and in the presence of an adequate alkali catalyzer, biomass can be liquefied directly. One such catalyzer is $NaHCO_3$. The cellulose in appropriate reduction to form an acidic substance and CO is reduced to CO_2. The cellulose must form a solution in 85% water. CO is obtained from the biomass in the form of producer gas (gasification) containing H_2 also. By hydrolysis, H_2 leads to hydrolysis and eventually to liquefaction.

2. Pyrolysis:-

Pyrolysis is the destructive distillation or degasification of biomass that is subjected to thermal splitting in the absence of air/oxygen. This is the reverse process of gasification where heat is supplied externally to biomass contained in cylinders, fluidized beds or drum reactors at temperatures between 300-1000^{0}C. The products of pyrolysis with calorific value are:

* Gas: Pyrolysis gas (10-15 MJ/m^3)
* Liquid: Pyrolysis oil (23-30 MJ/kg)
* Solid: Coke: (20-30 MJ/kg)

The efficiency of the *pyrolysis* process depends upon the following factors:

(i) Composition and size of the biomass

(ii) Pyrolysis temperature

(iii) Heating rate

(iv) Duration of biomass in reactor

The main product from pyrolysis is wood only. The destructive distillation of wood produces pyrolysis oil or bio oil. The properties of the pyrolysis oil are closer to the diesel oil or thermal oil.

Pyrolysis of Wood

↓

Up to 150^0C → Removal of free and bound water (little amount of formation of acetic acid, amino acids, carbon monoxide)

↓

Up to 270^0C → Increasing amount of reaction water, methyl alcohol, acetic acid, CO, CO_2

↓

Up to 280^0C → Spontaneous exothermic reaction (8-10% of heat content of wood), formation of large amount of gas and distillates, acetic acid, methanol, tar, hydrogen, methane and ethylene.

↓

Up to 380^0C → Increase in temperature without any energy input, gas and distillates decrease.

Pyrolysis of biomass, domestic or municipal waste and non-biological waste products like automobile tyres, has been of interest from the point of view of the following:

* Manufacturing of pyrolysis oil as a liquid fuel
* Production of basic raw materials.

Pyrolysis has not been a commercial success because of the following:

- Bad quality of pyrolysis oil,
- High water content
- Highly viscous fluid
- Corrosion of containers due to high acidic contents
- Partly soluble in water.

3. Liquefaction through synthesis of Methanol:-

Lowest quality of fuel, methanol is produced catalytically from the suitable mixture of synthetic gas (CO and H_2 mixtures). Methanol (CH_3OH) is used as a fuel in certain engines of vehicles.

$$CO + H_2 \xrightarrow{Catalysis} CH_3OH + 91\ MJ/mol\ (\text{heat of evolution})$$

The various processes of methanol production can be categorized as follows:

1. Low pressure (50 - 60 bar)
2. Average pressure (100 – 150 bar)

} at temperature range: 230^0C to 260^0C.

3. High pressure (275 – 360 bar) → at temperature of 300 and 400^0C

Catalyst used: Cu, Zn, Cr and their oxides. In comparison with petrol, methanol has the following disadvantages:

1. Low calorific value of 19.7 MJ/kg in contrast to petrol has 45.5 MJ/kg,
2. Cold start under 10^0 C is not possible,
3. Poisonous and corrosive.

Production of methanol requires H_2 and CO which can be obtained by gasification of wood. Gasification requires H_2 : CO = 2:1 for synthesis of methanol. Gas mixture is often reacted with steam in presence of catalyst to promote a shift to increase hydrogen content.

$$CO + H_2O \longrightarrow H_2 + CO_2$$

CO_2 and H_2S present in producer gas are removed prior to methanol reactor. Yields of methanol from woody biomass are expected to be the range 480-568 litres/ton.

Biological Methods for Biomass Conversion:-

The biological method of conversion or the biochemical method of conversion takes place at low temperature with the help of single cell micro-organisms known as microbes. For this reason these methods are called microbiological methods. The microbiological reduction of carbon and water containing biomass usually takes place in the absence of air in an aqueous environment. The microbiological reduction of organic matter is also known as fermentation. Presently two methods are of most important from the point of view of technology and energy gain.

1. The fermentation of biomass of methane (biogas) production, and
2. The fermentation of biomass for ethanol production.

The detail discussion of these methods will be done later on this section.

Aerobic and Anaerobic Digestion:-

When the moist biomass comes in contact with air, it automatically decays with the help of aerobic micro-organisms. As a result C and H oxides into CO_2 and H_2O with simultaneous release of heat at temperature of $70\text{-}90^0C$. In the carbon dioxide cycle, the aerobic bacteria plays an important role. The bacteria releases CO_2 and thus mineralize the bounded carbon in the organic substance.

In anaerobic digestion the organic material is allowed to decay in absence of oxygen. The different types of bacteria make a number of exchange processes resulting the digestion of biomass and conversion into a mixture of methane and carbon dioxide. The energy obtained is much higher than of a low temperature decaying process.

There three steps in the production of methane. These are:

1. Acid production (hydrolysis) →Where the bonds are broken and acid is formed.
2. Acid reduction
3. Methane production → is formed from anaerobic bacteria.

Raw Products	Conversion	Final Products
Biomass (all rotating materials, e.g. food waste plant materials)	Preparation of the output Mineralization Fermentation 1. Acid formation (from fats and cellulose proteins) 2. Acid reduction (e.g. acetic acid, CO_2, H_2, H_2O Heat	1. Biomass CH_4 (50– 60%) CO_2 (30-40%) N H H_2S 2. Organic residues: lignin and cellulose Slurry as fertilizer.

Fig: Simple scheme of an anaerobic digestion (Meinhold,980)

Step – I: (Acid production and hydrolysis):

In this hydrolysis process, the biomass like protein, fat and carbohydrates are broken through the influence of water. The polymers (large molecules) are reduced to monomers (basic molecules). The reaction is accelerated through enzymes, which are separated from bacteria. The resulting products are: Fat, Protein, Carbohydrates, Fatty acids, Amino acids, Sugar. These products are fermented by the fermentation bacteria (bacteria which are active in this step) leading to the formation of the following products:

1. H_2, H_2O, CO_2, NH_3
2. Acetic acid (CH_3COOH)
3. Alcohol and low organic acids.

Step-II (Acid Reduction):

In the second step, the alcohol and the low organic acids are fermented into the following products through the action of acetogenic bacteria. (i) H_2O, (ii) CO_2, (iii) H, (iv) Acetic acid (CH_3COOH)

The final product of fermentation process is the acetic acid.

Step-III (Methane Production):

The acetic acid produced in the first and second step is converted into methane and CO_2 (biogas) through the effect of methanographic bacteria. At the end the residual

waste is rich in nitrogen and can be used as a good fertilizer. In each step of the anaerobic digestion, a variety of bacteria are formed which cause the decaying of the organic material and which are specialized for the reduction of intermediate products.

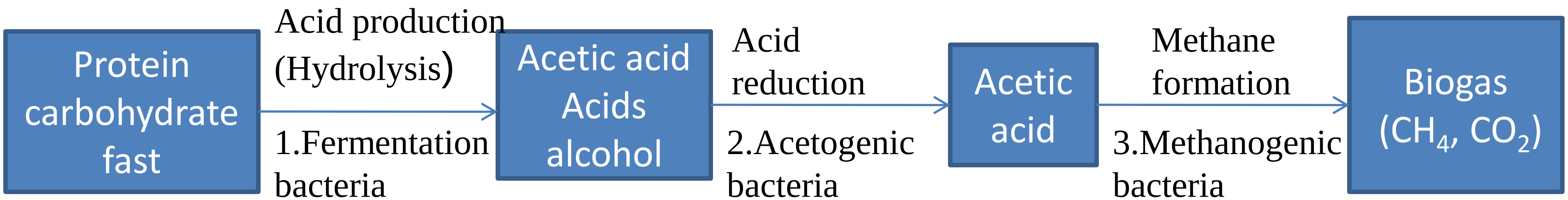


Fig: Sequence of methane production from aerobic digestion of organic waste

Influencing parameters: -

The amount of biogas produces through anaerobic digestion of organic waste and also the methane content in it depends upon the following parameters:

1. Kind of substrate, 2. Dry matter content, 3. Temperature, 4. Digestion period,
5. Mode of operation, 6. PH value.

Description of biogas Digesters:-

There are various types of digesters according to the need of the situation. But there are two basic types of distinguishable digesters according to the loading used.

1. Batch type digester
2. Continuous flow digester.

A batch type digester is a simple digester in which organic material is filled in a closed container and allowed to be digested an aerobically over a period of two to six months time depending upon the feed material and other parameters like temperature, pressure etc.

Advantage: This type of digester is very simple to run and requires very less attention. It is easy to start and emptying out. Maximum efficiency of digestion depends upon the carefully loading and waste of biomass.

Limitation: It has the problem of handling the waste material.

A typical miniature digester with a tank of 10 liter is shown in the figure below. The batch digesters are suitable for fibrous waste and difficult to digest. According to the availability of the waste, this is more suitable for irregular availability of waste. For continuous waste supply, batch digester can be used. With increase of digestion time.

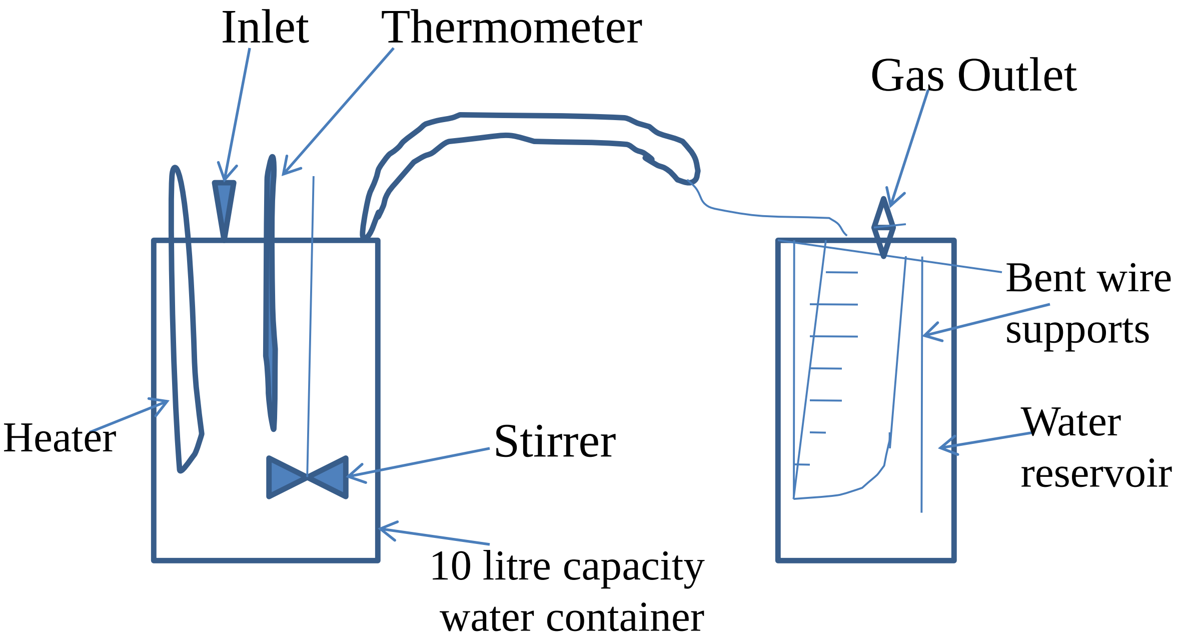


Fig: Experimental batch methane digester (Borda, 1979)

If several batch digesters are used in series, with each at a different stage in the digestion cycle, a continuous gas flow is obtained which is shown in the cycle. The digesters would be started up at regular intervals, so that the continuous gas flow is

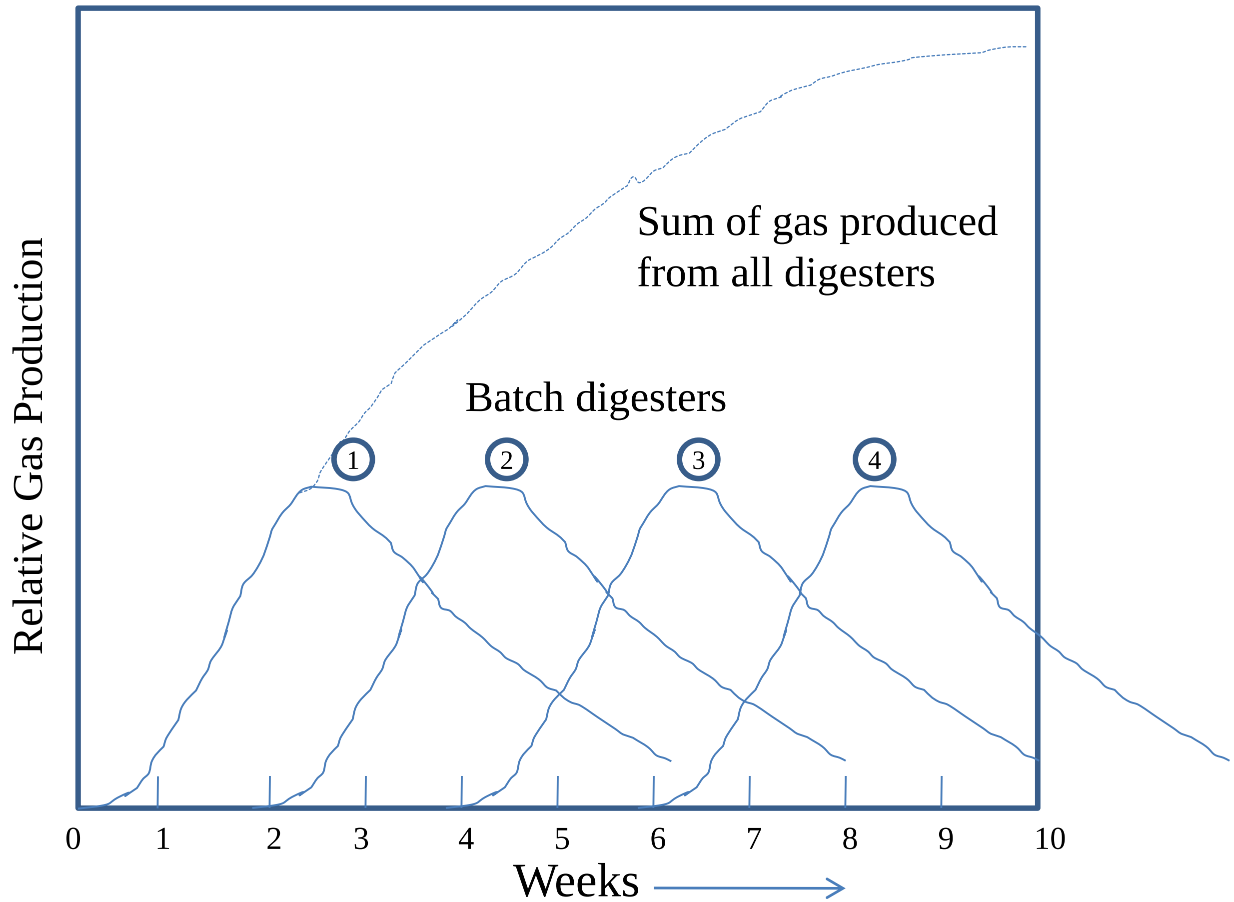


Fig: A continuous flow of biogas from four batch digesters with a staggered operation

maintained.

* Indian Institute of Science (IISc) Bangalore has developed a digester but that shows some heat los problem.
* Indian Institute of Technology (IIT) Delhi have made attempts to utilize solar energy systems which could be integrated with flouting or fixed dome designs for maintaining higher slurry temperature. They have produced biogas from rated value 0.3 $m^3/day/m^3$ digester volume to 0.37-0.52 $m^3/day/m^3$ (Bansal *et al*, 1985).

Biogas from agro industrial residues:

The agro-industrial residues can be conventionally converted into biomass production with suitable mixed digesters. The Commonwealth Scientific and Industrial Research Organization (CSIRO) in Australia tested various fruit processing waste in 23 m^3 pilot digester. This is completely mixed through biogas recirculation.

1. *Thermophilic Digestion:-*

   Most of the biogas digesters produce biogas due to action of bacteria known as mesophilic bacteria. These type of bacteria needs 35^0C but biogas can also be produced due to some of the other bacterias which need temperature around of 50^0 C.

The advantages of this thermophilic digestion includes:-

1. Shorter retention times,
2. Increased digestion efficiency,
3. and increased destruction of pathogens.

The disadvantages include:-

1. Greater sensitivity to temperature variation,
2. the need for better mixing,
3. and the additional energy needed for digester heating.

2. Anaerobic Contact Reactors:-

In this digester the feed enter near the top and is drawn off at the bottom. The liquid flows through a setting tank where the sludge containing methane forming micro-organisms settles out and is returned to the digester.

3. *Anaerobic Filter Reactors:-*

It consists of a chamber filled with a packing medium; The methane forming bacteria form a film on the large surface and are not carried out of the digester with the effluent. For this reason, these digesters are also known as fixed film or retained film digesters. The fluid enters at the bottom and flows up through the packing medium; as the organisms in the liquid pass over the bacterial film, they are converted to biogas.

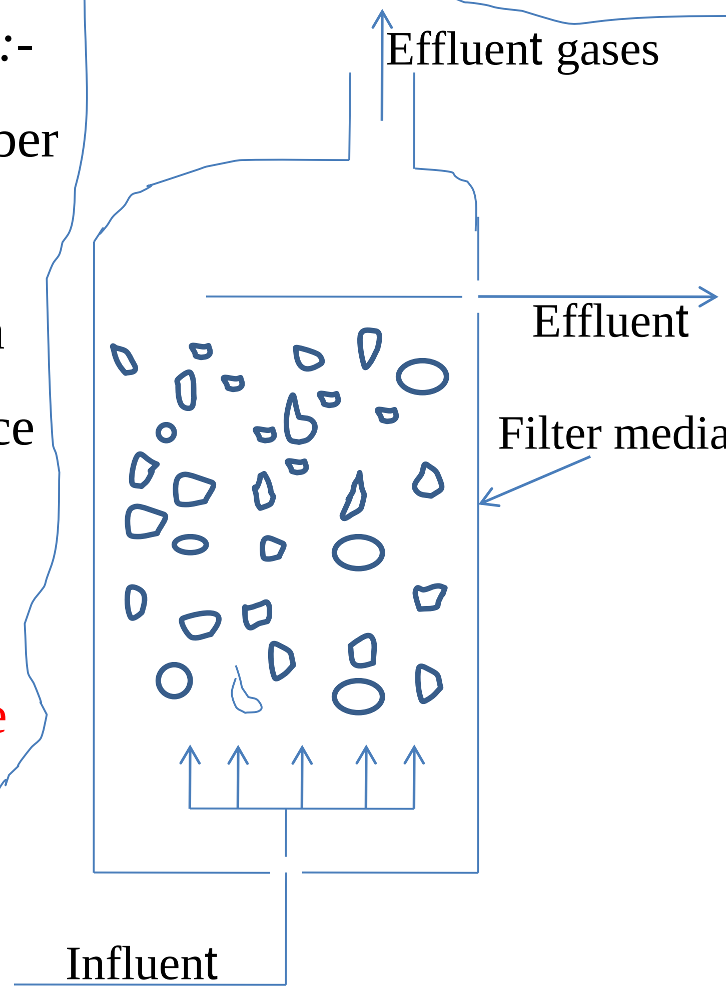


Fig: Anaerobic Filter Reactor

4. Up-flow Anaerobic Sludge Blanket Reactor (UASB):- It was developed in Netherland. It is similar to the anaerobic filter. USAB reactor does not contain packing medium. The methane forming bacteria are concentrated in the dense granules of the sludge blanket. The upward movement of the gas bubbles keeps the sludge fully mixed. The bacteria are retained in the reactor for very long periods through the operation of gas collection devices resembling inverted funnels. They allow the gas to escape, but encourage the setting of the suspended solids which contain the bacteria. Very high gas production rates have been reported with USAB process.

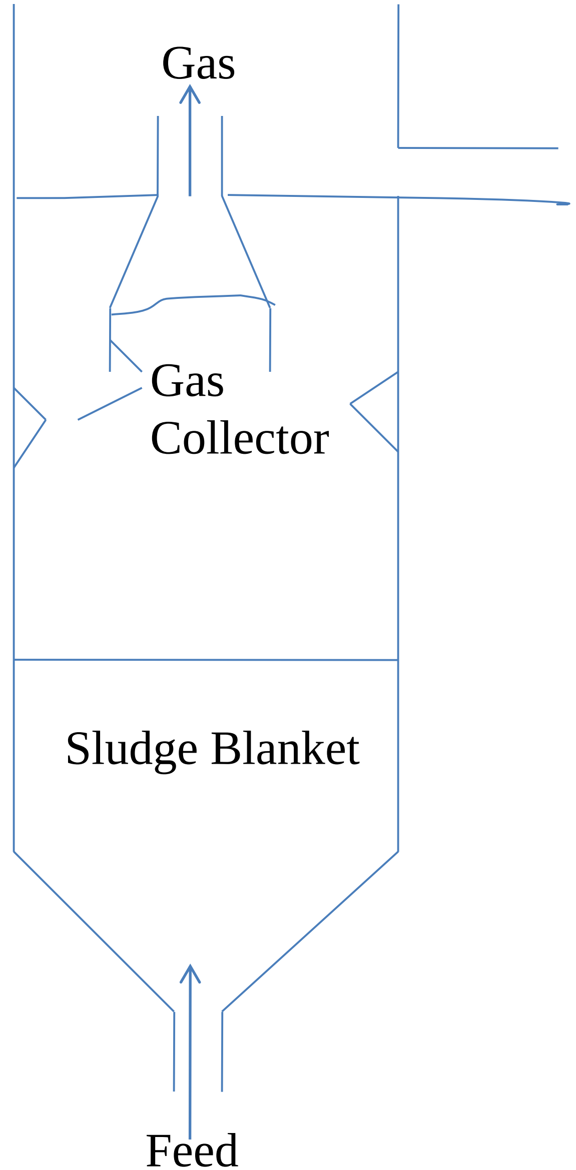


Fig: Upflow anaerobic sludge digester

5. Fixed-flow Fixed-film Reactors:-

This Down-flow Stationary Fixed Film (DSFF) reactors developed by the research council of CANADA. Here the feed enters at the top and the effluent passes out at the bottom. These reactors use a bio-film formed on support materials arranged in vertical channels. These channels must be relatively large to avoid filling up with and the total surface area is thus relatively small compared to other fixed reactors. However, operation of the rector in the down-flow mode avoids the accumulation of suspended solids which is often a problem with up-flow anaerobic filters. Gas production from the DSFF units in the Canada has extended 50 m^3/day/m^3 digester volume in some cases.

Biogas from Human Residue:-

Biogas from sewage:-

In 1949's and 1950's, anaerobic digestion system were used to produce heat energy or electric power in sewage treatment in US municipalities as well as several other countries. But it was abandoned due to the cost of energy production is higher than the Govt. supply. Biogas is used in several states to fuel engines and to produce electricity. Biogas provides low pressure steam for Chicago plant and boiler fuel for a steam power plant in Los Angels. Waste heat from biogas is supplied to New York Plant for running purposes.

Biogas heat may be utilized for generation of steam which will be utilized to run the turbine to produce electricity.

* About 600,000 ft^3 of biogas is produced from daily sewage treatment plant in New Delhi. About 50,000 families are using as cooking gas for their use.

Biogas from Night Soil:-

Human excreta (waste) from the human body is known as night soil. These can be used in biogas plants to produce electricity. These type power production is quite popular in India, Nepal and China. The study has been found that night soil from 40 to 60 people are enough to produce cooking gas for one family.

Stirring Equipment:-

It is desirable that the digesters are thoroughly mixed to:-

1. Avoid the formation of sink layers on the floor of the fermenter,
2. Avoid the formation of scum on the uppermost surface of the substrate resulting in the cooking of the system,
3. Maintain a uniform temperature,
4. Maintain a uniform food stuff to the bacteria.

Usually mechanical stirring equipment is used for the mixing of the substrate. Other equipments like circulation pump, gas compression, valve gear are also used for

Stirring.

Production of Ethanol (C_2H_5OH):-

Ethanol production is based on the principle of anaerobic fermentation of sugar solutions with the help of microorganism present in the yeast. This process is known as alcoholic fermentation. There are three types of biomass used for ethanol production in order of increasing complexity.

1. Sugar containing biomass,
2. Starch containing biomass,
3. Cellulose containing biomass.

Table: Inputs for Ethanol production

Sugar containing	Starch containing	Cellulose containing
Sugarcane	Maize	Wood
Sugar beat	Corn	Straw
Sugar millet	Potato	
Fodder beat (mangold)	Cassana	

Ethanol production from various crops.

Crop	Annual production tons/ha	Sugar/starch content % weight	Ethanol %	Ethanol tons/ha	Production l/ha
Sugar beat	34 - 51	15	8	2.7 – 4.1	3375 - 5125
Wheat	3.6 – 6.3	60	32	1.2 – 2.1	1520 - 2625
Sugarcane	56 - 70	12.5	6	3.1 – 4.9	3875 - 6125
Wood	5 - 6		15	0.75 – 0.9	940 - 1125

Ethanol production from starch and cellulose biomass must be converted into sugar before fermentation. Conversion of sugar into alcohol takes place according to the following chemical reactions.

$$\text{Sugar} \xrightarrow{\text{Yeast}} \text{Ethanol} + CO_2$$

$$C_6H_{12}O_6 \longrightarrow 2C_2H_5OH + 2CO_2$$

$$100\text{ kg} \longrightarrow 51\text{ kg} + 49\text{ kg}$$

The following types of sugars can be easily differentiated between

Glucose = grape sugar ($C_6H_{12}O_6$)

Fructose = fruit sugar ($C_6H_{12}O_6$) and

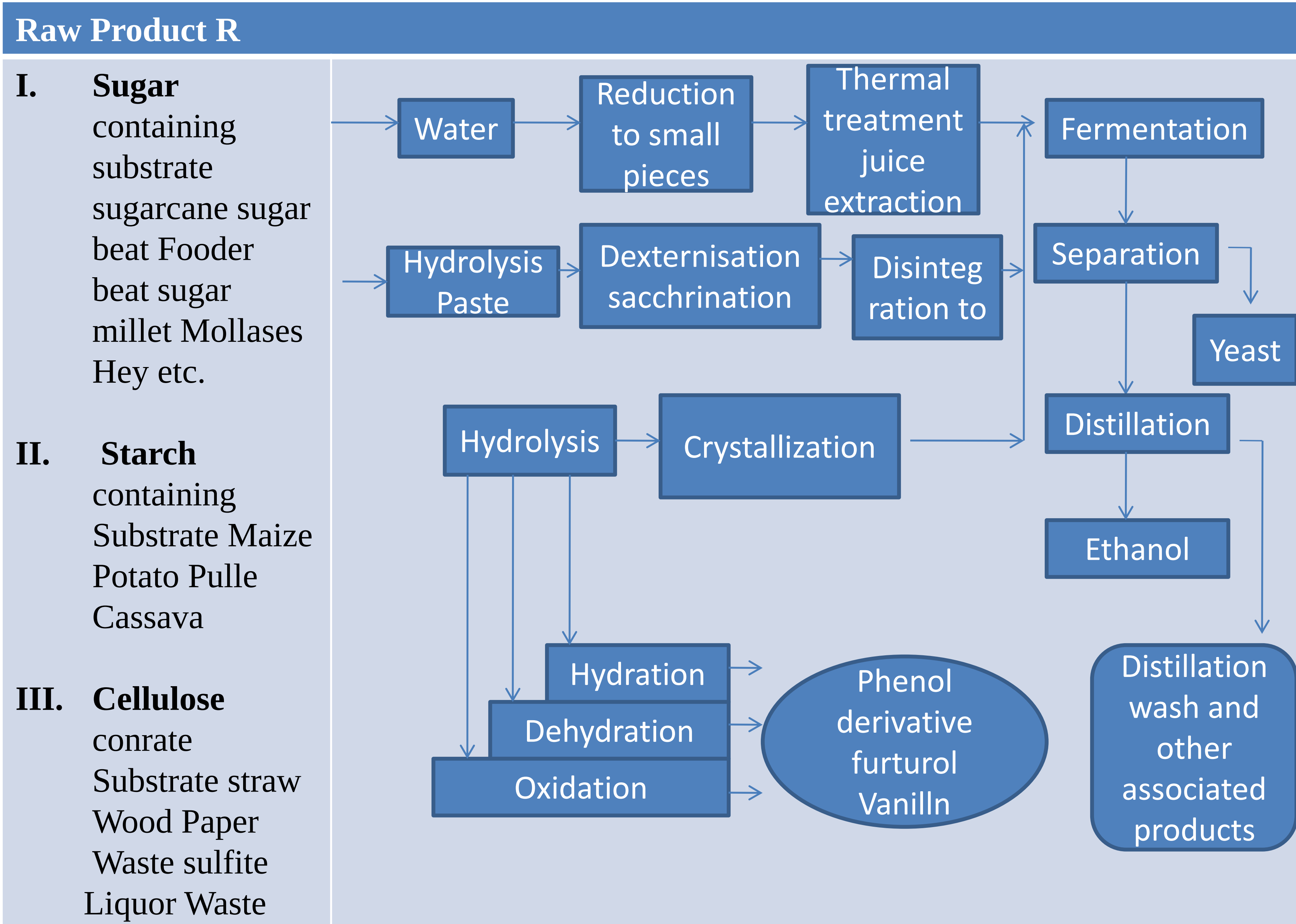
Sucrose = Beat sugar, cane sugar ($C_{12}H_{22}O_{11}$)

Starch ($C_6H_{10}O_5$) is converted to sugar through hydrolysis and then fermented to ethanol. The following chemical reaction takes place.

$$\text{Starch } (C_6H_{10}O_5) + \text{Water } (H_2O) \rightarrow \text{Glucose } (C_6H_{12}O_6)$$

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2$$

Fig: Schematic of ethanol production



The Fermentation Process:-

The rate of alcohol production depends upon the following factors.

1. *Sugar content:* (generally, 10 – 18% w.r.t. mass. Higher values will slow down the fermentation process.)
2. *Fermenting temperature:* (30 – 40^{0}C. The reaction being exothermic. At higher temperature, there is danger of foam formation and therefore loss of efficiency.)
3. *pH value :* (pH value of 4.0 or higher is required because yeast lives in the range of 3.0 to 6.0.)
4. *Yeast concentration:* (In stationary condition, 40 – 60 gram of yeast used for 1 litre of substrate. Aerobic process takes place. For fermentation process, air is allowed to flow through the fermenter to ensure the presence of yeast.)
5. *Fermentation time:* (Simple fermentation process requires 36 to 48 hours. However new technology requires 1 to 5 hours.) .

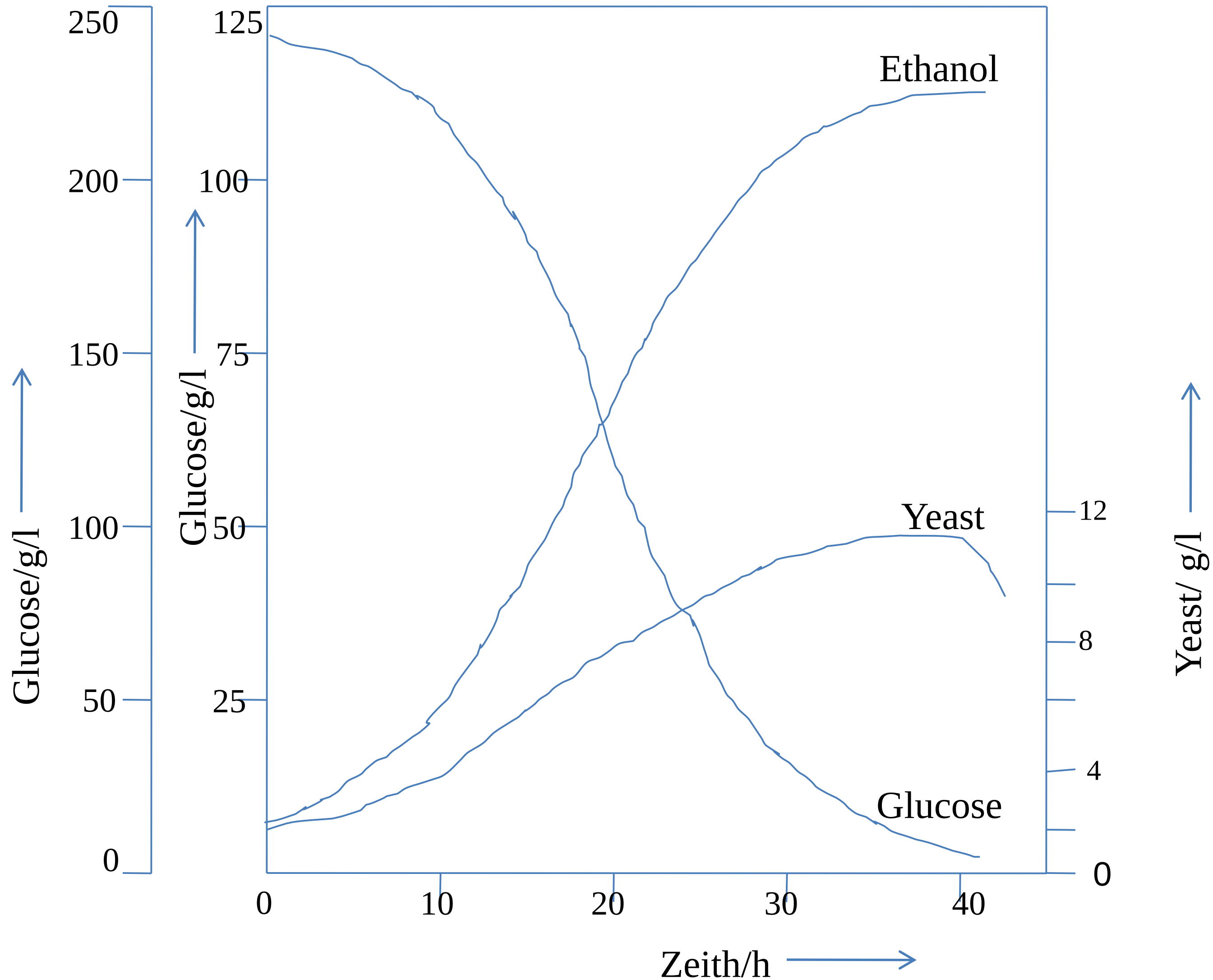


Fig: Reaction time for fermentation in a batch process (Menrad *et al*., 1982)

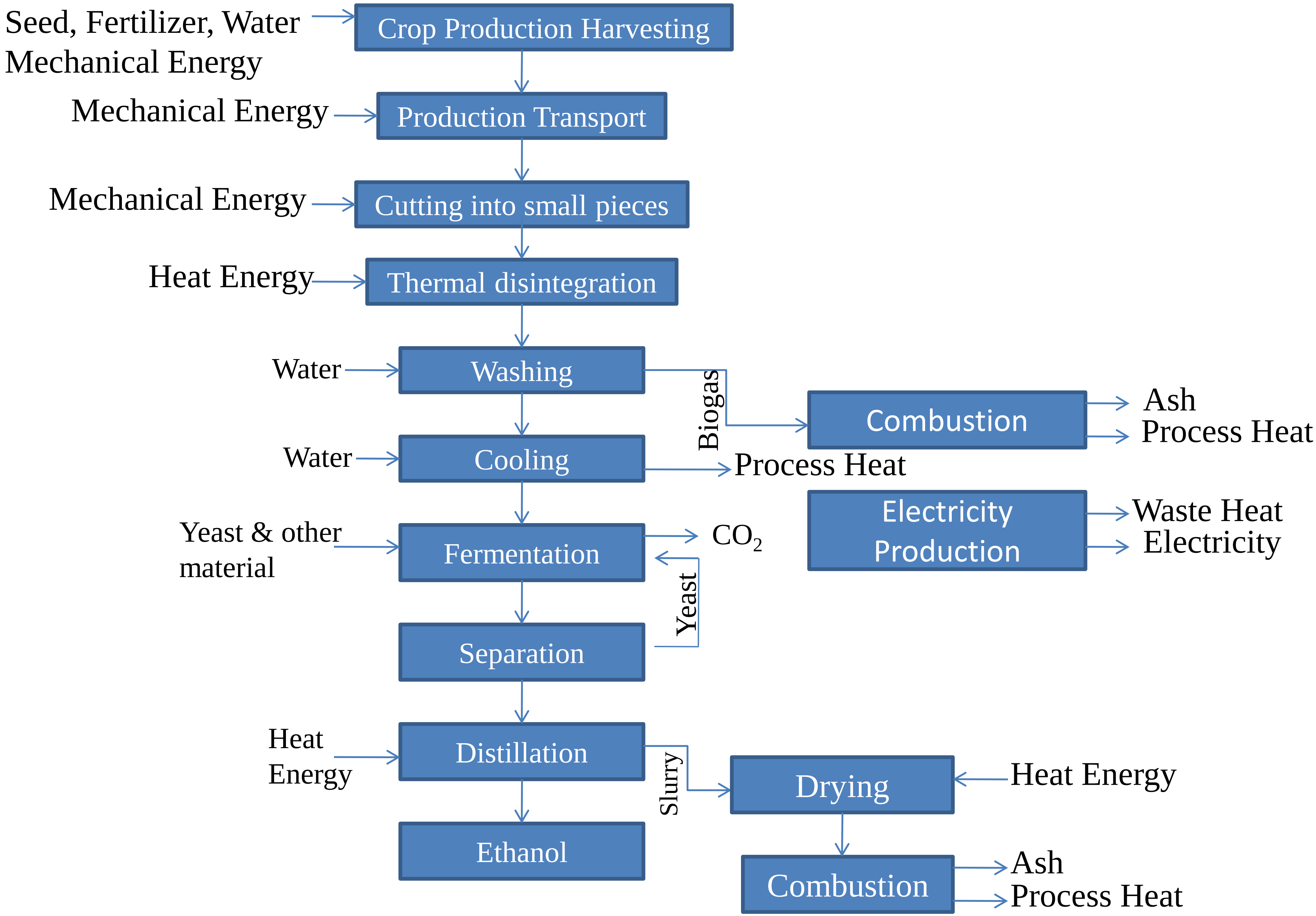


Fig: Block diagram of ethanol production from sugarcane

* At the end of the distillation, slurry remains as a waste, which is mixture of water, organic material and minerals. This slurry can be used either as fodder or as fertilizer. This slurry can also be used in biogas plants for biogas production. The slurry has been combusted and the heat produced is used for manufacturing process.

Characteristics of Ethanol:-

* The calorific value of ethanol is quite lower than that of petrol.
* Since the ethanol has a lower stochiometric ratio, the calorific value of air/fuel mix is nearly same.
* The boiling point of ethanol is same as that of petrol.
* Lower volatile nature of ethanol leads to a bad engine start in cold.

Continued……………………………………………..

Its main disadvantages are:-

(1) It is dispersed and land-intensive source.

(2) It is often low energy density.

(3) It is also labour intensive and cost of collecting large quantities for commercial application is significant.

(4) Capacity is determined by availability of bio-mass and not suitable for varying loads.

(5) It is not feasible to set up at all locations.

Biomass Conversion Process:-

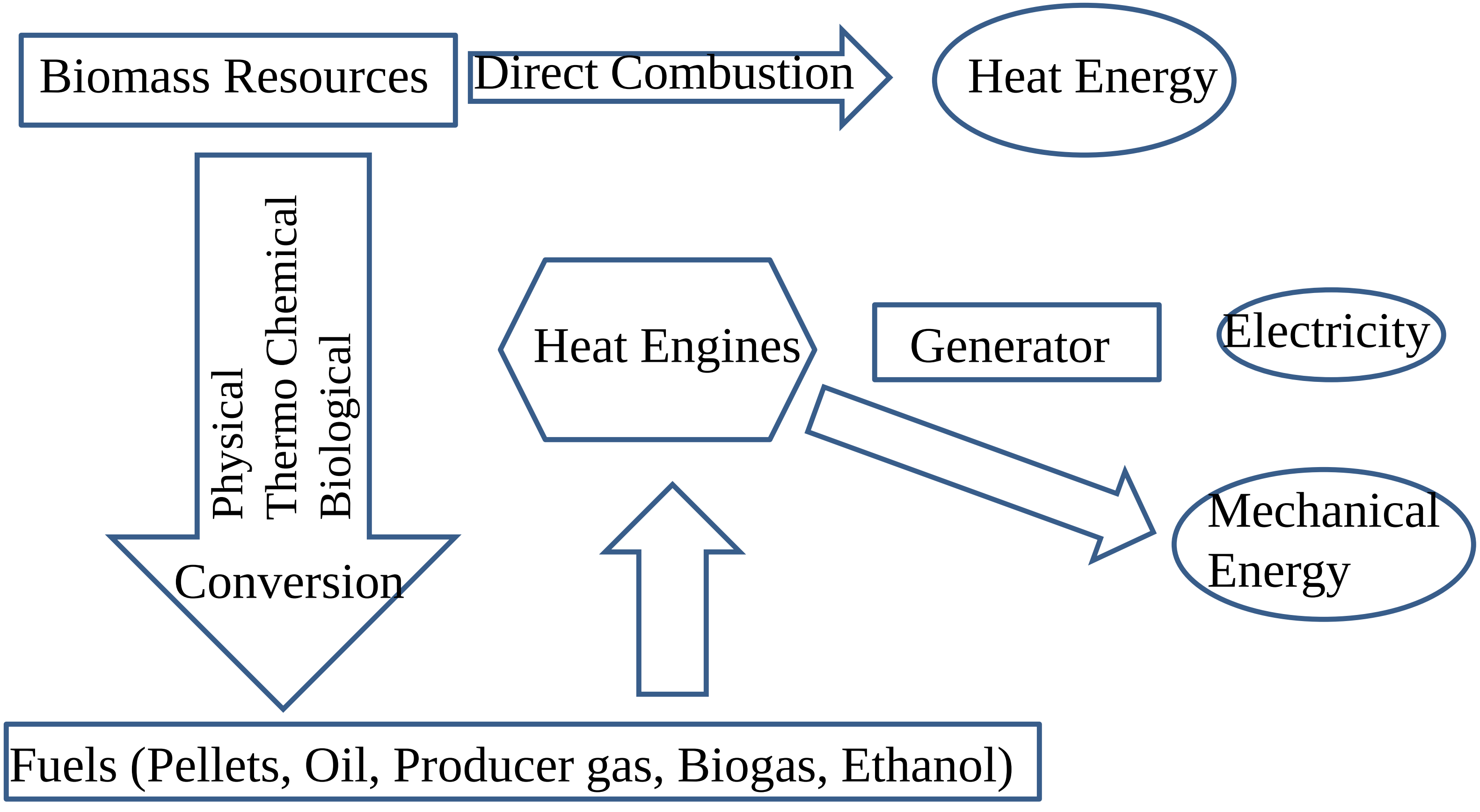


Fig: Biomass energy conversion Process

To be continued…………..

SOLAR RADIATION

TERRESTRIAL RADIATION:

The radiation from the sun corresponds to black body radiation at a temperature of T_s = 5762^{0}K. Taking the diameter (D_s) of the sun as 1.39x10^6 km and using Stefan-Boltzmann law, the solar radiation can be calculated as follows.

$$I_s A_s = A_s \sigma T_s^4 = \pi D_s^2 \sigma T_s^4 \;..................(1)$$

where I_s is the rate of the sun's radiant energy per unit area of its outer surface, which has an area A_s (m^2) and temperature T_s (K). The Stefan-Boltzmann constant, σ=5.67x10^{-8} Wm^{-2}k^{-4}, one gets

$$I_s A_s = 3.8\text{x}10^{26} \text{ watt and } I_s = 62.5\text{x}10^6 \text{ w/m}^2 .$$

The distance between earth and sun is one astronomical unit (AU = 1.5x10^8 km). The value of incident radiation on the earth's atmosphere is equal to

$$I_0 = I_s (D_s/D)^2 \sigma (T_s)^4 = 1.341 \text{ kw/m}^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

This value is called solar constant. With little variation the actual average of solar constant is 1367 w/m^2. The daily variations to the value of solar constant can be calculated using the formula as:

$$I_0 = I_s\ (1 + 0.0334\ \cos x\ ) \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

The value of solar constant I_s is maximum 1399 w/m^2 on December to a minimum of 1310 w/m^2 on June 21.

where x is 0.9856^0 N – 2.72^0

I_0 is the average solar constant 1367 w/m^2.

The intensity of solar radiation varies with respect to wavelength. The relation between wavelength and temperature is

$$\lambda_{max}T = 2897.8\ (\mu m.K)\ \ldots\ldots\ldots\ldots\ldots (4)$$

Ninety-nine percent of the solar radiation lies in between the wavelength of 0.276 and 4.96 μm. About 90 percent of solar radiation lies in the wavelength region between 0.3 and 1.6 μm.

Solar Radiation through atmosphere:

Outside the earth's atmosphere, the air mass is zero. The longer the path of solar radiation through the earth higher will be air mass. For estimating efficiencies of the solar systems, one usually takes sky conditions of AM =1.5 i.e. the radiation has to travel 1.5 times more through the atmosphere in comparison to the normal incidence.

Solar radiation without any scattering suffers considerable losses at all wavelength regions while passing through earth's atmosphere. For certain wavelengths, the atmosphere is completely opaque and it is not allowed to reach earth. The solar radiation received on the earth without any scattering in the atmosphere is known as beam or direct radiation. *The solar radiation received on earth from the sun with multiple scattering is known as diffused or sky radiation.*

Sun Surface angles:-

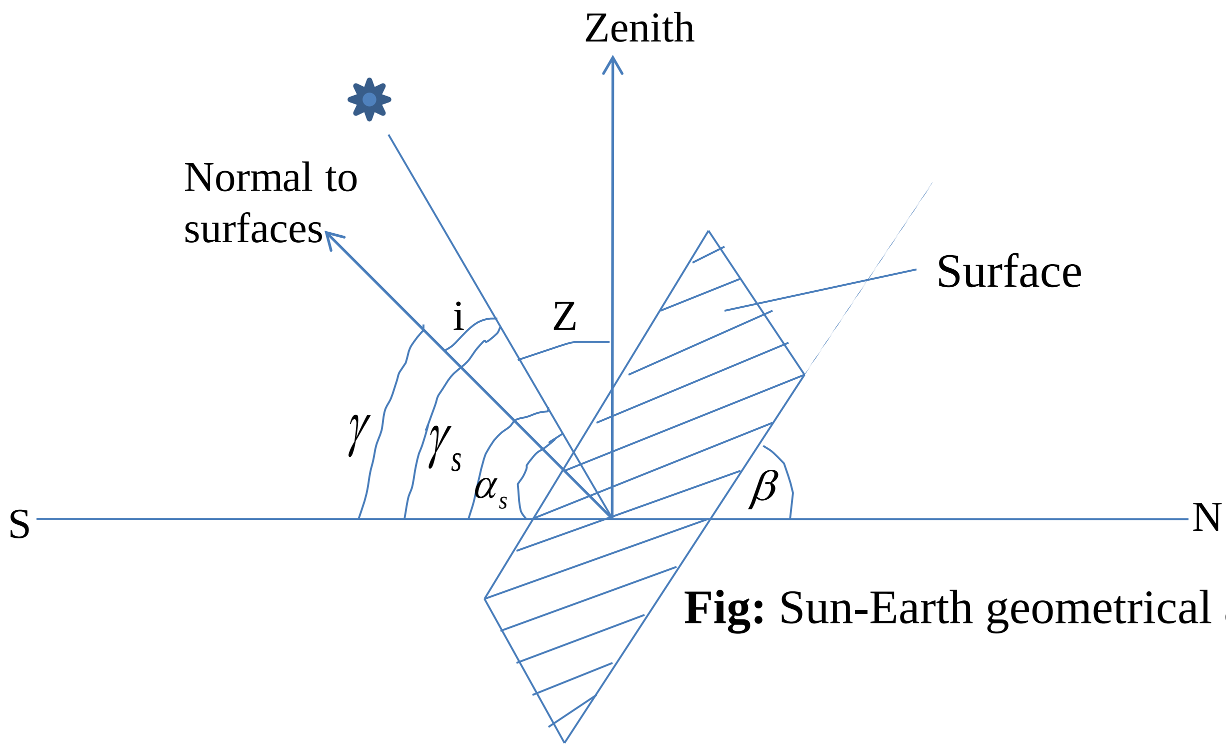


Fig: Sun-Earth geometrical angles

β = Inclination angle of a surface to the horizontal

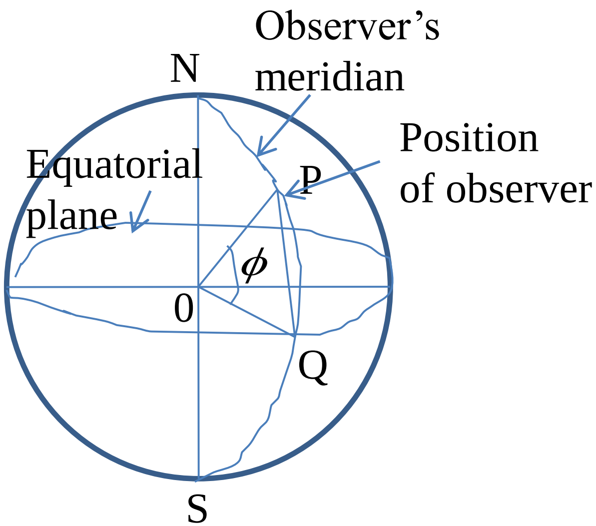
i = angle of incidence.

α_s = solar altitude angle: East of south negative and west of south positive.

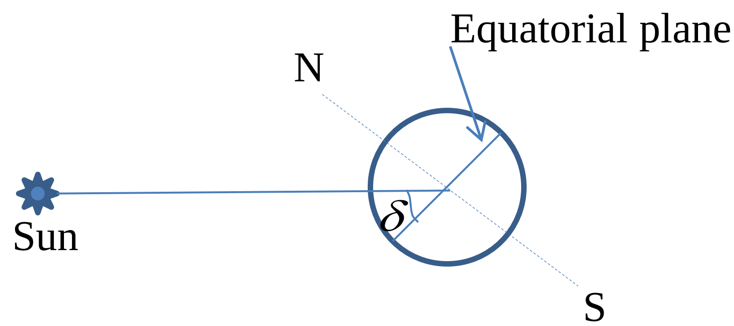
γ_s = solar azimuth angle: East of south negative and west of south positive.

Z = zenith angle.

γ = surface azimuth.



(a) Latitude



(b) Declination angle, δ

(a) Latitude angle (ϕ):-

The latitude of a location on the earth's surface is the angle made by a radial line joining the given location to the centre of the earth with its projection on the equator plane. It is positive for northern hemisphere and negative for southern hemisphere.

(b) Declination(δ):-

It is defined as the angular displacement of the sun from the plane of the earth's equator. It is positive when measured above the equatorial plane or in the northern hemisphere. The declination , δ can be approximately determined from the equation

$$\delta = 23.45 \times \sin\left[\frac{360}{365}(284+n)\right] \text{degrees..............(5)}$$

where '*n*' is the day of the year counted from first January.

© *Hour angle (ω):-*

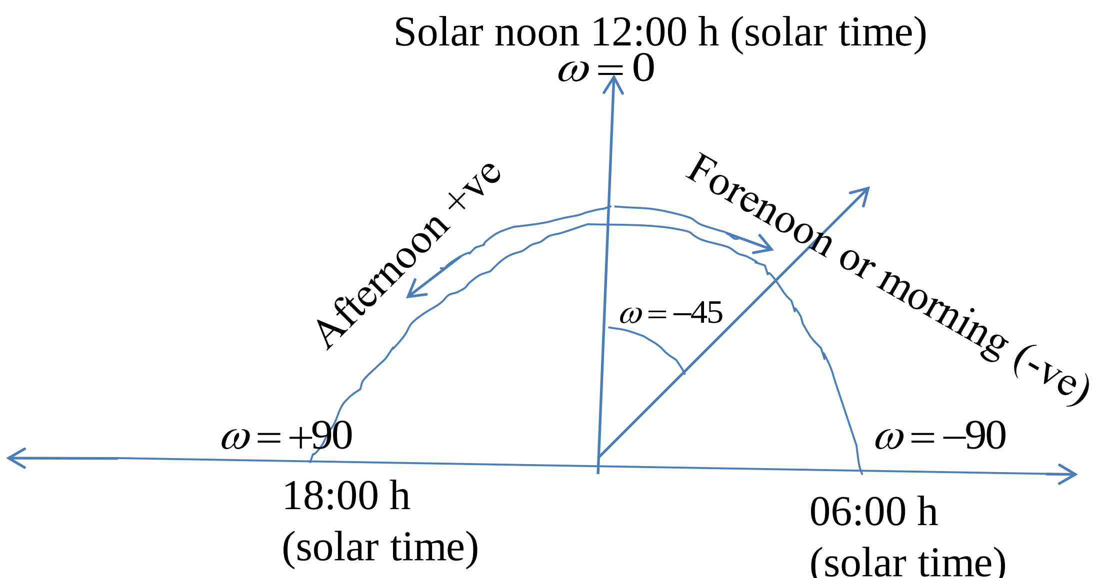


Fig: Hour angle

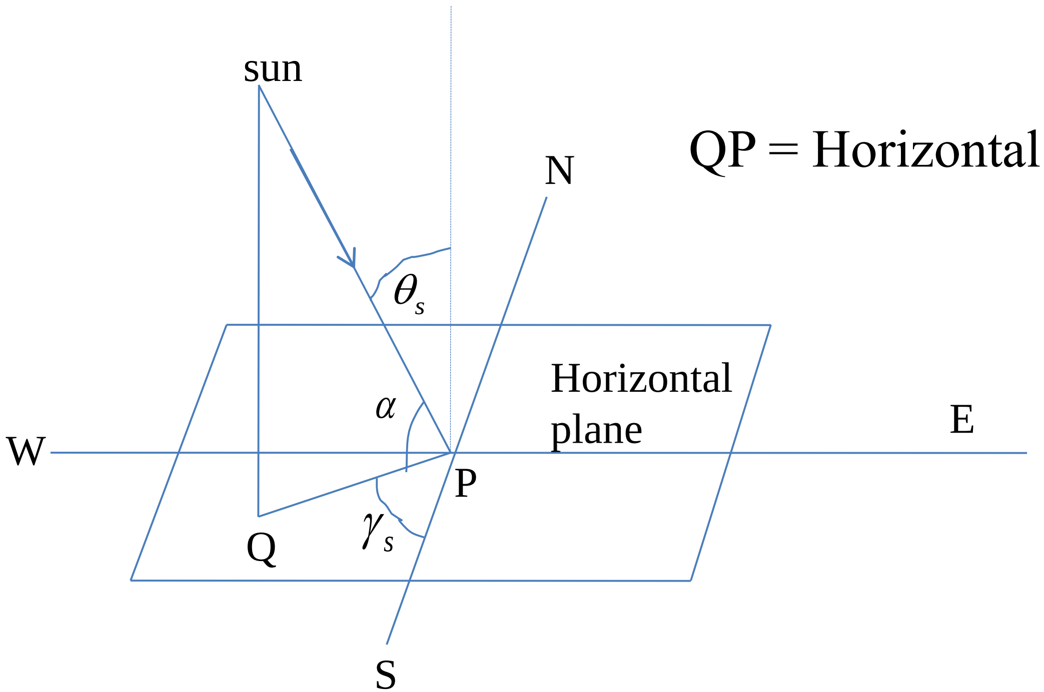
The hour angle at any moment is the angle through which the earth must turn to bring the meridian of the observer directly in line with the sun's rays. In other words, at any moment, it is the angular displacement of the sun towards east or west of local meridian (due to rotation of earth on its axis).

It can be calculated as: $\omega = [\text{Solar time} - 12:00](\text{hours}) \times 15 \text{ degrees}$............(6)

(d) Inclination Angle (altitude), (α) :-

The angle between sun's ray and its projection on a horizontal surface is known as the inclination angle.

(e) Zenith angle(θ_s):- It is the angle between the sun's ray and the perpendicular (normal) to the horizontal plane.



QP = Horizontal projection of sun's ray.

Fig: Solar altitude angle, solar azimuth angle and zenith angle.

(f) Solar azimuth angle (γ_s):-

It is the angle on a horizontal plane, between the line due south and the projection of sun's ray on the horizontal plane. It is taken as positive when measured from south towards west.

(g) Slope (tilt angle), (β):-

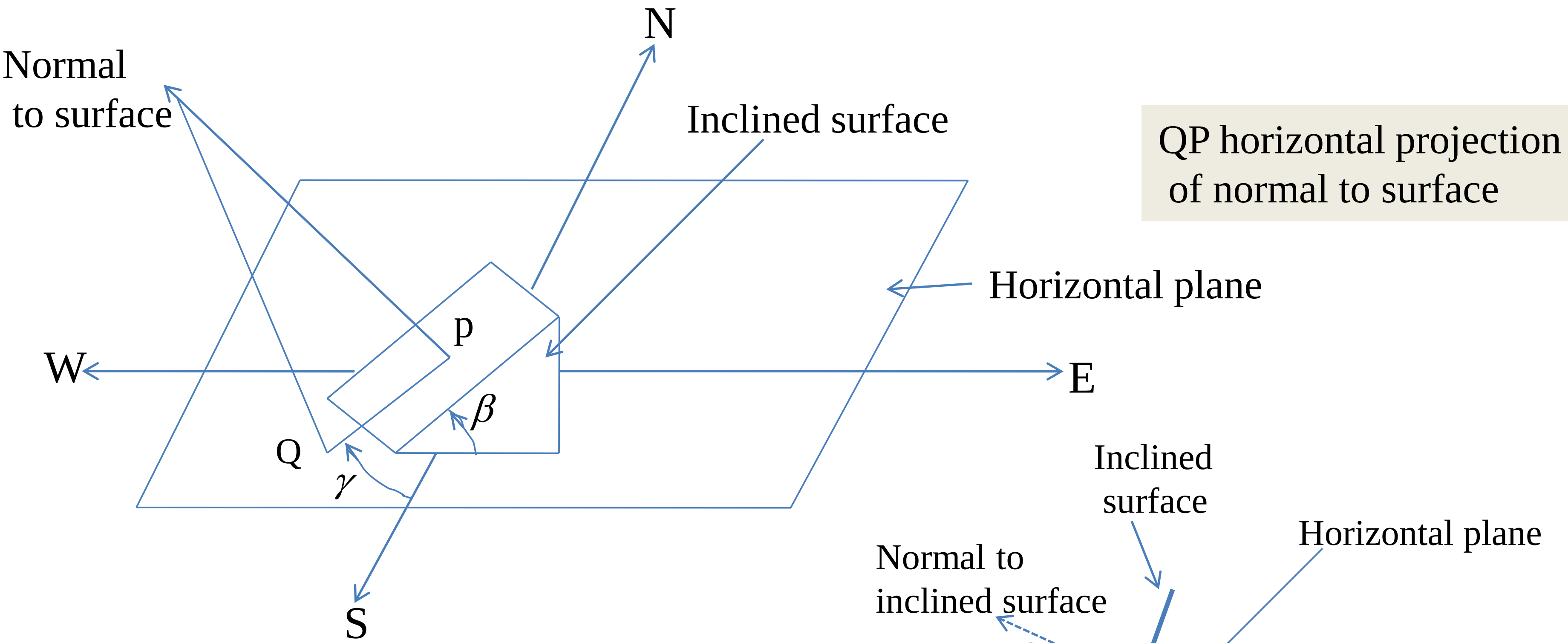
It is the angle between the inclined plane surface, between (collector), under consideration and the horizontal. It is taken to be positive for the surface sloping towards west.

(h) Surface Azimuth angle (γ) :-

It is the angle in the horizontal plane, between the line due south and the horizontal projection of the normal to the inclined plane surface (collector). It is taken as positive when measured from south towards west.

(i) Angle of incidence (θ_z):- It is the angle between the sun's ray incident on the plane surface (collector) and normal to that surface.

Fig: Surface azimuth angle and slope (tilt angle)



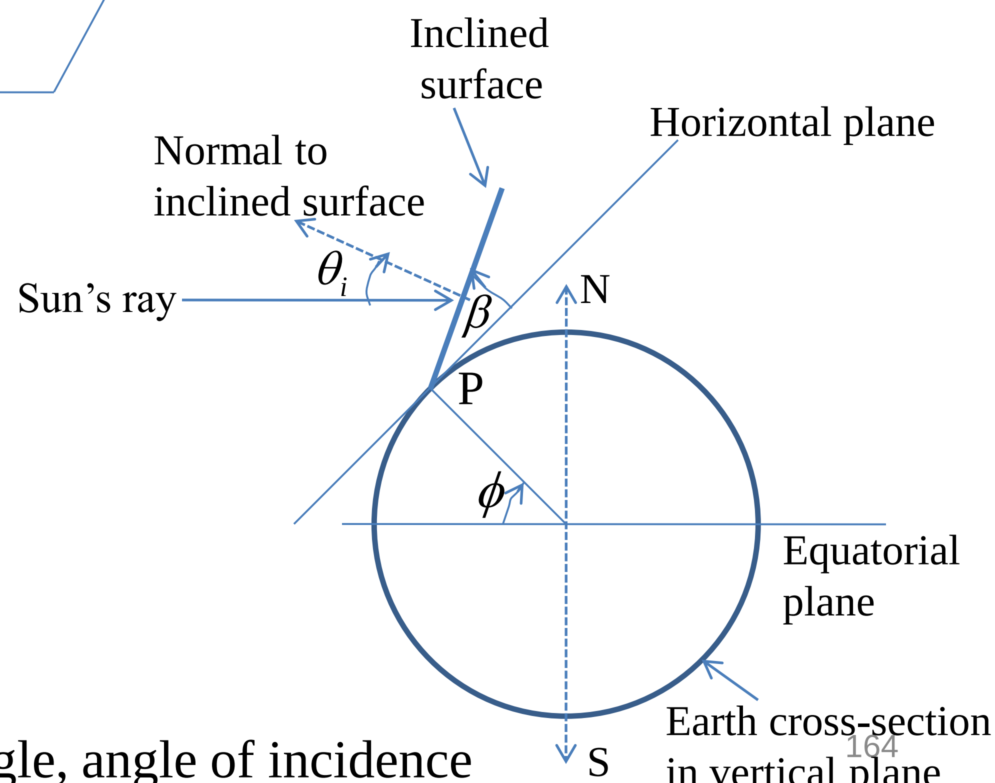


Fig: Angle of latitude, tilt angle, angle of incidence

All these angles are shown in the above figures. The angle of incidence can be expressed as:

$$\cos\theta_i = (\cos\phi\cos\beta + \sin\phi\sin\beta\cos\gamma)\cos\delta\cos\omega + \cos\delta\sin\omega\sin\beta\sin\gamma$$
$$+ \sin\delta(\sin\varphi\cos\beta - \cos\phi\sin\beta\cos\gamma)\ldots\ldots\ldots\ldots\ldots(7)$$

Special Cases:-

(i) For a surface facing due south, $\gamma = 0$

$$\cos\theta_i = \cos(\phi - \beta)\cos\delta\cos\omega + \sin\delta\sin(\phi - \beta)\ldots\ldots\ldots\ldots(8)$$

(ii) For horizontal surface, $\beta = 0, \theta_i = \theta_z$ (Zenith angle)

$$\cos\theta_z = \cos\phi\cos\delta\cos\omega + \sin\delta\sin\phi\ldots\ldots\ldots\ldots(9)$$

(i) For a vertical surface facing due south, $\gamma = 0, \beta = 90^0$

$$\cos\theta_i = -\sin\delta\cos\phi + \cos\delta\cos\omega\sin\phi\ldots\ldots\ldots\ldots(10)$$

Solar Day Length:-

At sunrise, the sun’s rays are parallel the horizontal surface. Hence the angle of incidence, $\theta_i = \theta_z = 90^0$, the corresponding hour angle, ω_i from Eq.(9) is:

$$\cos\theta_i = 0 = \cos\phi\cos\delta\cos\omega_i + \sin\delta\sin\phi$$

$$\Rightarrow \omega_i = \cos^{-1}\left(-\tan\phi\tan\delta\right)\ldots\ldots\ldots\ldots\ldots\ldots\ldots(11)$$

The angle between sunrise and sunset is given by

$$2\omega_i = 2\cos^{-1}\left(-\tan\phi\tan\delta\right)\ldots\ldots\ldots\ldots\ldots\ldots\ldots(12)$$

Again, 15^0 of hour angle is equivalent to one-hour duration ($380^0/24$), the duration of sunshine hours, t_d or daylight hours is given by

$$t_d = \left(\frac{2}{15}\right)\cos^{-1}\left(-\tan\phi\tan\beta\right)\ldots\ldots\ldots\ldots\ldots\ldots(13)$$

The hour angle, ω_i at sunrise(or sunset) for horizontal (collector) surface is given by Eq.(11). It is negative to sunrise and positive to sunset. The hour angle at sunrise as seen by the observer on an inclined plane facing south (i.e. $\gamma = 0$.) will also be given

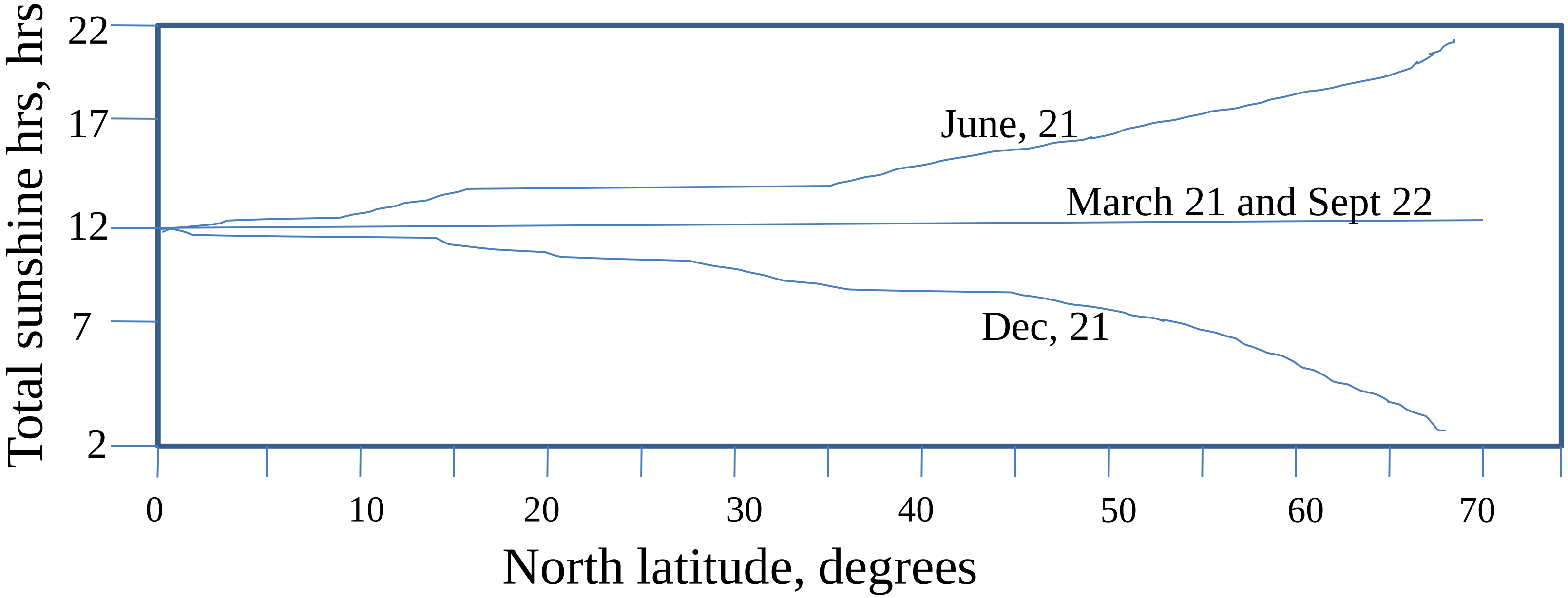


Fig: *Variation of sunshine hours, t_d with latitude, on certain days of the year.*

by the Eq.(11). If the day under consideration lies between September 22 and March, 21 and the location is in the northern hemisphere. However if the day under consideration lies between March 21 and September 22, the hour angle at sunrise or sunset would be smaller in magnitude than the value given by in Eq.(11).

and would be obtained by substituting $\theta_i = 90$ in Eq.(8). Thus

$$\omega_i = \cos^{-1}\left[\tan\left(\phi - \beta\right)\tan\delta\right] \quad \text{.........................(14)}$$

Radiation Balance:-

The solar radiation reaches on the earth surface depends upon the following factors:

(1) Reflection of the extra terrestrial atmosphere and on the earth's surface

(2) Scattering on the earth's atmosphere.

(3) Absorption in the atmosphere.

The reflection from the earth or atmosphere averages approximately 28% and this part goes to space in the form of short-wave radiation which is not available for use. The remaining part comes to earth in the form of celestial radiation with some amount lost due to multiple scattering as shown in the diagram. The incident radiation on the earth's surface consists of the following components:

(i) Direct radiation:- Some part of the radiation after reaching the earth directly gets absorbed and scattered.

(ii) Diffused celestial radiation: - This radiation reaches the earth after multiple scattering by earth's atmosphere. Summation of both these components yields global solar radiation.

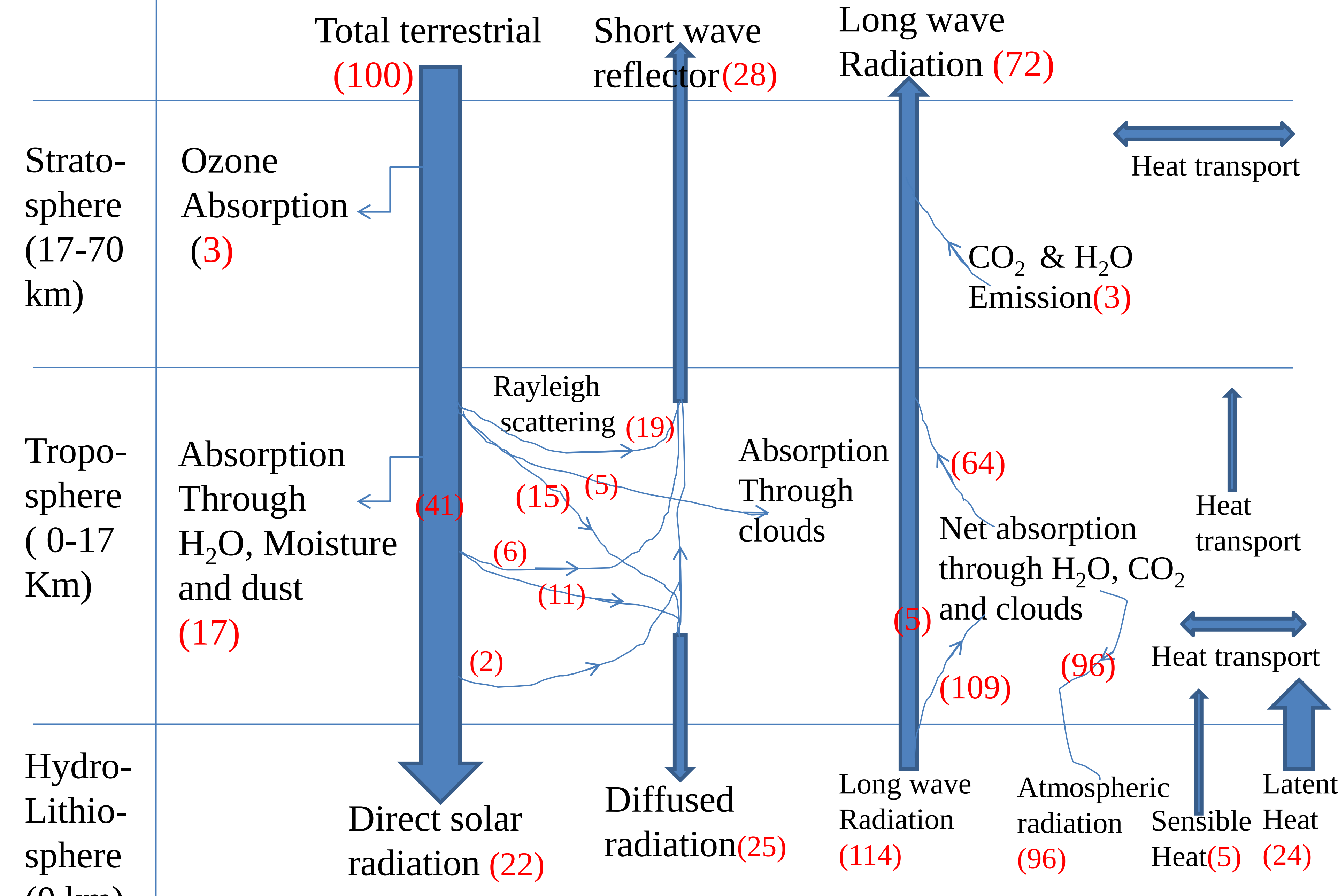


Fig: Radiation balance of the earth atmosphere system. It is seen that only 47% of the extra terrestrial radiation reaches the earth as direct or diffused radiation.

The atmosphere also radiates energy to the earth and its intensity is higher than that of global radiation. This radiation is included in the region of long-wavelength radiation to the atmosphere. The earth also radiates back long-wavelength radiation to the atmosph-ere and part of which gets absorbed (shown in the block diagram).

Table: Radiation balance on a receiving surface on earth.

No.	Incident radiation components	Symbol	No	Reflected radiation components	Symbol
1.	Direct solar radiation	I_D	5.	Reflected direct solar radiation	I_{DR}
2.	Sky radiation	I_d	6.	Reflected diffused sky radiation	I_{dr}
3.	$\sum 1+2$: Global radiation	I_G	7.	$\sum 5+6$: Reflected total radiation	I_{GR}
4.	Atmosphere radiation	I_g	8.	Reflected atmospheric radiation	I_{AR}
			9.	Radiation from the receiving surface	I_E
			10.	$\sum 8+9$:Total re-radiation from the receiving surface	I_R

Rate of useful energy, $Q = (I_D) + I_d + I_g - (I_{DR} + I_{dr} + I_{AR} + I_E)$

The Generalized Transmission Law:-

The radiation balance of earth's system fluctuates w.r.t. time and location. The global radiation which is the sole interest by the researchers, is affected by the wavelength of the scattering and absorptive radiation phenomena in the atmosphere. These are termed as *extinction* in meteorology. The radiation reaching the earth's surface can be calculated as:

$$dI_{\lambda} = -I_{0\lambda} a\, d_s \qquad \mathrm{W/m^2}$$

where

dI_{λ} is the radiation of the remaining wavelength after the incident radiation of the same wavelength $I_{0\lambda}$ has travelled through distance d_s of the atmosphere (w/m^2),

d_s is the distance travelled by the solar radiation in the atmosphere (m),

a is extinction coefficient (m^{-1}).

Integrating the above equation over the entire length of the atmosphere (m) yields the general transmission law for radiation passage through the atmosphere, i.e.

$$I = I_0 \exp(-a\,m) \qquad \text{W/m}^2$$

Where

I = radiation received on the earth, I_0 = extra-terrestrial radiation, m = air mass.

The transmission factor of the atmosphere

$$\tau_G = \frac{I}{I_G} = \exp(-a\,m)$$

The extinction coefficient (a) depends upon the transmission coefficient which consists of three factors.

$$\tau_G = \tau_{RS}\tau_{MS}\tau_{AB}$$

Where

τ_{RS} = transmission factor corresponding to Rayleigh scattering.

τ_{MS} = transmission factor due to Mie scattering

τ_{AB} = transmission factor due to absorption.

From the figure given below, the optical path length (m) can be calculated as:

$$\mathrm{m} = \frac{H}{\sin \alpha_s} = \frac{H}{\cos Z}(m)$$

H = height of the atmosphere
α_s = solar altitude

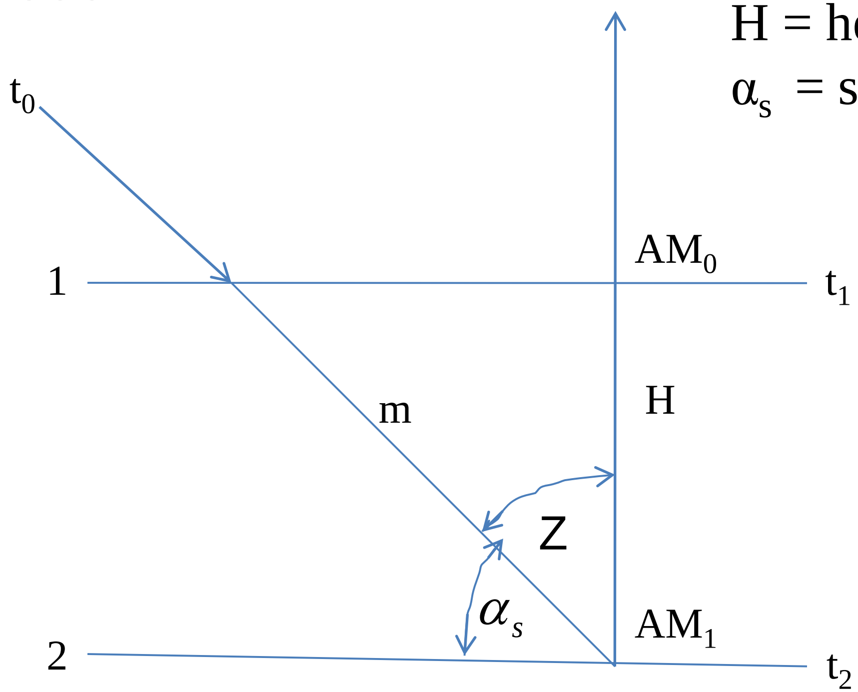


Fig: Penetration of solar radiation through an ideal plane atmosphere of constant density.

Instead of H, one can use only, $\mathrm{m} = \frac{1}{\sin \alpha_s} = \frac{1}{\cos Z}$

Scattering by the atmosphere:-

The scattering of radiation by the atmosphere can be divided into two categories:

(i) Rayleigh scattering in molecules (φ)

(ii) Mie scattering in aerosols.

The Rayleigh scattering takes place in particles, whose diameter is much smaller than the wavelength of the incident radiation. These particles scatter the *short wavelength of radiation* strongly. The scattered radiation is given by the expression:

$$I_{RS} = \frac{2\pi^2}{N\lambda^4}\left(n^2 - I\right)^2\left(1/\cos^2\varphi\right)I_0 \ \ \text{W/m}^3$$

Where

I_{RS} = scattered radiation from a scattering volume (W/m^3).

N = number of molecules in the irradiated volume of air ($1/m^3$).

λ = wavelength (m), φ = angle of scattering (degree), n = refractive index,

I_0 = extra-terrestrial radiation (solar constant).

The integration of Rayleigh scattering equation in all possible values of the Scattering angle φ, we get Rayleigh coefficient as:

$$a_1 = \frac{8\pi^3}{3N\lambda^4}(n^2 - I)\left(\frac{1}{m}\right)$$

Since the scattered coefficient is proportional to λ^4, it is evident that short wave length of radiation will be much more scattered than long wavelength of radiation. For an ideal Rayleigh atmosphere, the general transmission law can be expressed as:

$$I_a = I_0 \exp(-a_1\, m) \qquad \text{W/m}^2$$

Where,

I_a = Transmission from ideal Rayleigh atmosphere (W/m^2),

I_0 = Extra-terrestrial radiation (W/m^2),

a_1 = Rayleigh scattering coefficient,

m = Air mass (m).

The transmission factor of the atmosphere corresponding to the Rayleigh scattering coefficient (a_1) can be obtained as: $\tau_{RS} = \exp(- a_1\, m)$, where ‘a’ being air mass.

Mie scattering takes place from particles whose diameter is close to the wavelength of radiation. The particles like dust or dust laden water vapor or air molecules. Mie scattering depends heavily on the amount of aerosols present in the air, so it depends upon the path length of the atmosphere. The type and composition of aerosol differ w.r.t. place and time.

According to meteorology, four regions where aerosol varies quantitatively:

(i) High mountains,

(ii) Flat land

(iii) Big cities

(iv) Industrial areas.

Absorption of Solar Radiation:-

The solar radiation is absorbed in the water vapor, ozone, oxygen and carbon dioxide present in the upper layer of the atmosphere then it comes to lower aerosol layer where the radiation is absorbed by the stable parts of the atmosphere. The absorption in water vapour, oxygen and carbon dioxide is usually described by the overall transmission coefficient τ_{AB}.

Direct Solar Radiation:-

The combined loss of solar radiation due to scattering and absorption through transmission in the atmosphere is defined by a physical parameter called *turbidity factor* (T_r).

$$T_r = 1 + \frac{\ln(\tau_{MS}) + \ln(\tau_{AB})}{\ln(\tau_{RS})}$$

The total transmission factor τ_G can now be written as:

$$\tau_G = \exp(-T_r \ m)$$

Using in terms of optical path length (m= 1/sin α_s), $\tau_G = \exp\left(-\frac{T_r}{\sin \alpha_s}\right)$

The direct solar radiation (I_D) on a plane surface in the normal direction is, therefore,

$$I_D = I_0 \exp\left(-\frac{T_r}{\sin \alpha_s}\right) \quad \text{w/m}^2$$

For an inclined surface angle β,

$$I_{\beta D} = I_0 \exp\left(-\frac{T_r}{\sin \alpha_s}\right) \cos i \quad \text{w/m}^2$$

Where α_s is the solar altitude angle and *i* is incident angle of radiation in degrees.

Diffused Sky Radiation: -

Like direct solar radiation diffused solar radiation also varies from place to place. The diffused radiation dominates over the regions like federal Republic of Germany whereas the direct radiation dominates the regions like India. For the measurement of diffused radiation, one may approximate the following formula on a horizontal plane surface.

$$I_{dh} = \frac{1}{3}(I - I_D)\sin \alpha_s$$

Global Radiation:-

The summation of direct solar radiation and diffused celestial radiation is known as global radiation. In addition to that the surface also receives small amount of the re-radiation from the atmosphere and the reflection from the objects and surface. The summation of all the components of radiations received from the neighboring objects is known as total radiation. For surfaces with extreme inclinations only, one should take the reflected radiation from the neighboring objects into account. This may be approximated as:

$$I_{R\beta} = \rho_E I_{Gh} \sin^2 \frac{\beta}{2}$$

where ρ_E is the reflectivity of the earth surface,

I_{Gh} is the global solar radiation on horizontal surface,

β is the inclination angle of the surface.

Like direct and diffused radiation, the global solar radiation also varies with space and time.

Measurement of Solar Radiation:-

The measurement of solar radiation is performed with the help of sunshine recorders, Pyranometres and Pyrheliometers.

Pyranometer: -

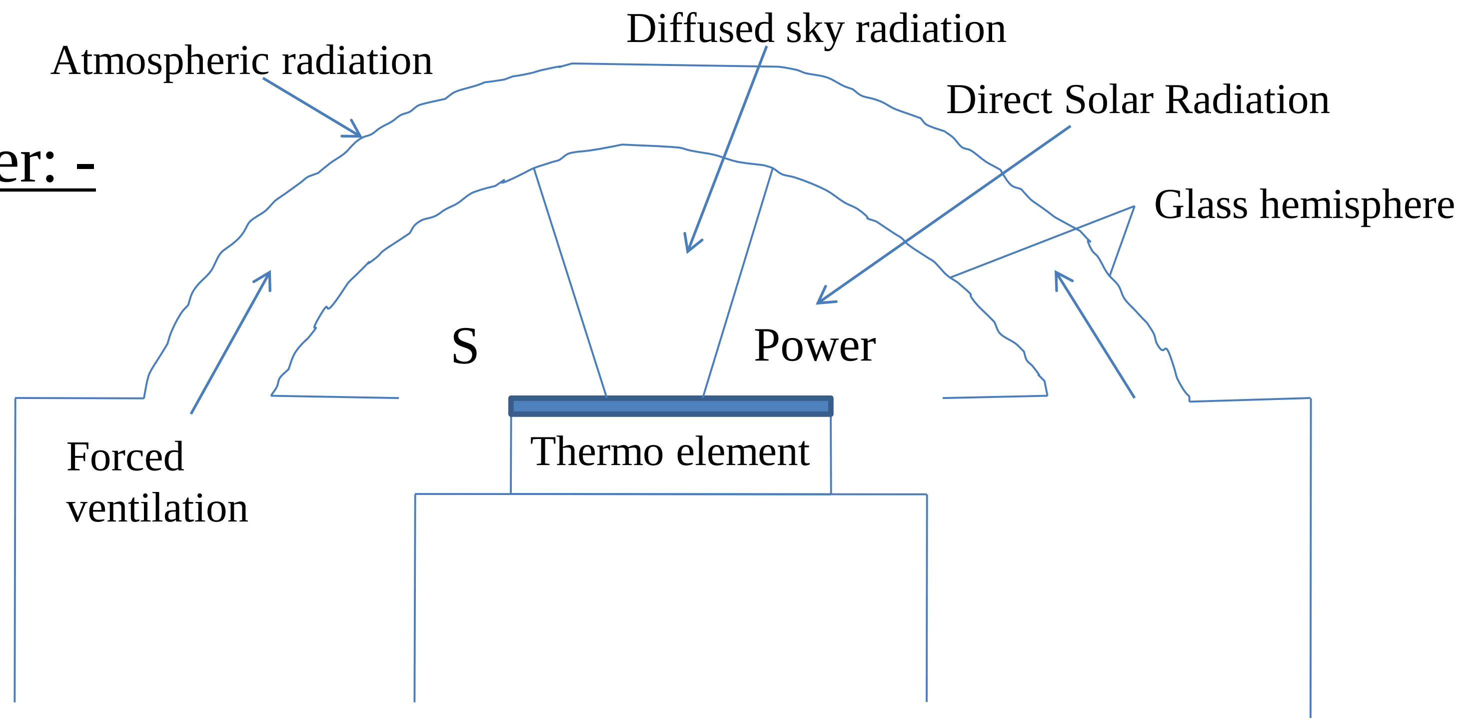


Fig: Schematic diagram of Pyranometer for the measurement of global solar radiation.

A precision pyranometer is designed to respond all wavelengths of radiation and hence measures accurately the total power in the incident spectrum. It contains a thermopile whose sensitive surface consists of circular, blackened, hot junctions exposed to the sun.

The cold junction being completely shaded. The temperature difference between the hot and cold junctions is the function of radiation falling on the sensitive surface. The sensing element is covered with two concentric hemispherical glass domes to protect from rain and wind. A radiation shield surrounding the outer dome and coplanar with the sensing element, prevents direct solar radiation from the base of the heating element.

Pyrheliometer: -

The long collimator tube collects the beam radiation whose field of view is limited to a solid angle of 5.5^0. The diaphragms are present inside the tube. The inside of the tube is blackened to absorb any radiation incident at angles outside the collection solid angle. At the base of the tube a wire wound thermopile having a sensitivity of approximately 8 $\mu V/W/m^2$ and an output impendence of approximately 200Ω is provided. The tube is sealed with dry air to eliminate absorption of beam radiation within the tube by water vapour.

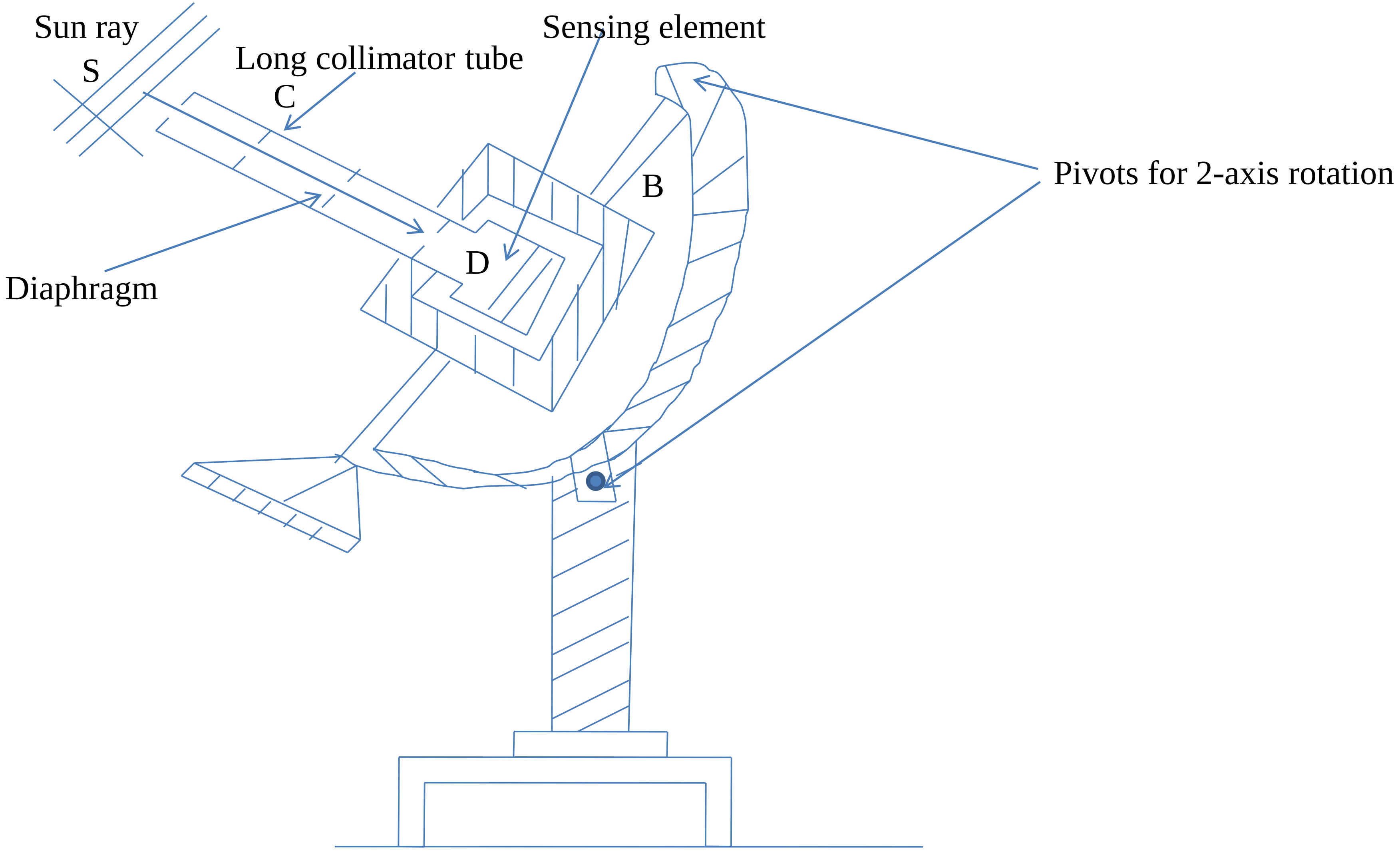


Fig: Schematic of a Pyrheliometer

Sunshine recorder:-

The instrument measures the duration in hours of bright sunshine during the course of a day. It consists of a glass sphere (about 10 cm in diameter) mounted on its axis parallel to that of the earth within a spherical section (bowl). The bowl and glass sphere are arranged in such a way That the sun's ray are Focused sharply at a spot on a card held in a groove in the bowl. As the sun moves, the focused bright

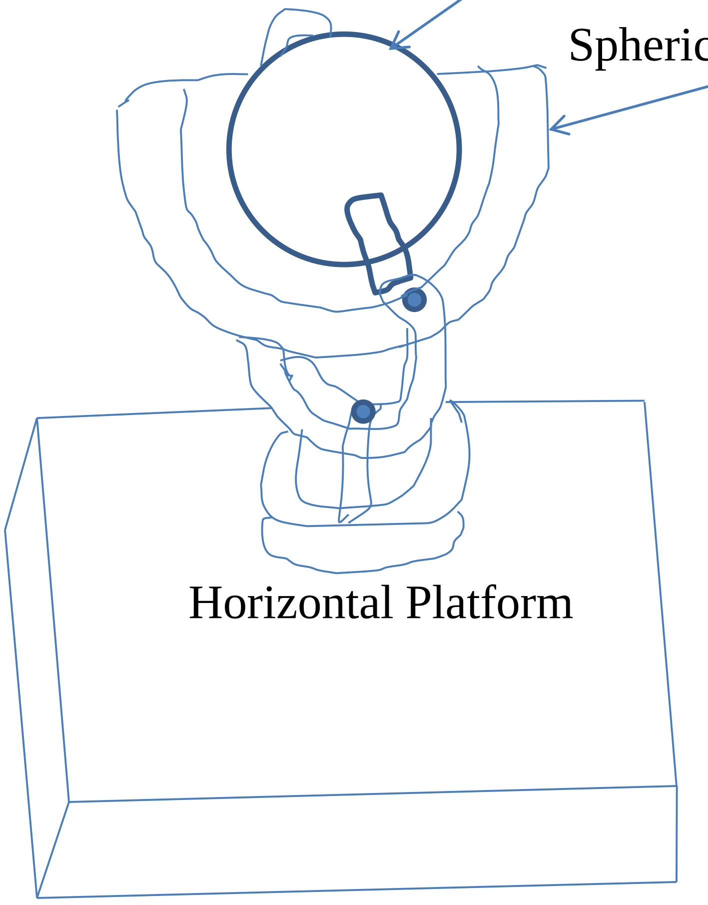


Fig: Sunshine recorder

sunshine burns a path along this paper. The length of the trace thus obtained on the paper is the measure of the duration of the bright sunshine.

Solar Collectors:-

Solar power has low density (1kW/m^2 to 0.1kW/m^2) per unit area. Hence large amount of solar power collection needs larger area. The solar collector being the first unit in the solar thermal system, collects heat from solar radiation then transfers to the transport fluid efficiently. The transport fluid utilizes the heat for necessary purposes.

Classification:

Solar Collectors

- Non-concentrating type (Flat-plate collector)
  - (a) Liquid flat plate collector
  - (b) Flat-plate air heating collector
- Concentrating type
  - Focus type
    - Line focus (one axis tracking)
      - (a) Cylindrical parabolic concentrator
      - (b) Fixed mirror solar concentrator
      - © Linear Fresnel lens collector
  - Non-focus type
    - (a) Modified flat-plate collector
    - (b) Compound-parabolic Concentrating(CPC) type

Point focus (two-axis tracking)
(a) Pentaboloidal dish collector.
(b) Hemispherical bowl mirror conc.
(c) Circular Fresnel lens cone.
(d) Central Tower receiver.

(**Fig:** Types of Solar Collector)

Concentrating type	Non-concentrating type (Flat Plate Type)
(1) In concentrating type solar collectors, solar radiation is converged from a large area into smaller area using optical means. Beam radiation has a unique direction which travels in a straight line, can be converged by reflection or refraction techniques. On the other hand diffused radiation does not have unique direction, can not obey optical principles. Thus diffused radiation does not converge to a single point. Thus concentrating type solar collectors utilizes beam radiation and partly diffused radiation coming directly over the observer.	(1) Non-concentrating (flat plate) type solar collectors absorb both beam type and diffused radiation.

(2) Complex in construction.	(2) The flat plate collector is simple in construction and does not require sun tracking.
(3) It does not sustain harsh atmospheric conditions.	(3) Since it requires outdoor installation, the outside atmospheric harsh conditions are likely to sustain.
(4) It requires high maintenance.	(4) It requires little maintenance.
(5) It attains high temperature due to presence of optical concentration.	(5) Due to absence of optical concentration, the heat loss is more. So it attains low temperature.

Performance Indices:-

The following performance indices are measured in a solar collector.

(1) *Collector efficiency:*- It is defined as the ratio of the energy actually absorbed and transferred to the heat-transport fluid by the collector (useful energy) to the energy incident on the collector.

(2) *Concentration ratio*:- It is defined as the ratio of the area of the aperture of the system to the area of the receiver. The aperture of the system is the projected area of the collector facing (normal) to the beam.

(3) *Temperature range*: It is the range of temperature to which the heat transport fluid is heated up by the collector.

There are three types of solar collectors based on the temperature ranges.

(i) Low temperature Systems(<150^0C):

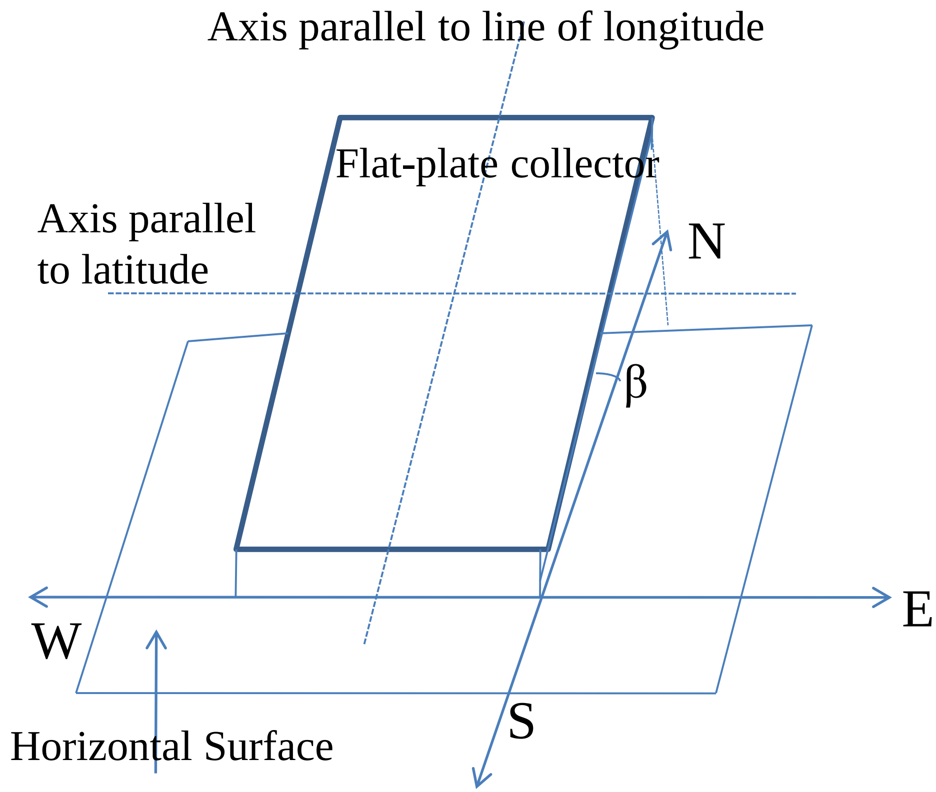
(ii) Medium-temperature Systems(150-400^0C):

(iii) High-temperature Systems(400-1000^0C):

FLAT-PLATE COLLECTORS:-

The flat-plate collector is located in a position such that its length is aligned with longitude and is suitably tilted towards south to have maximum collection.

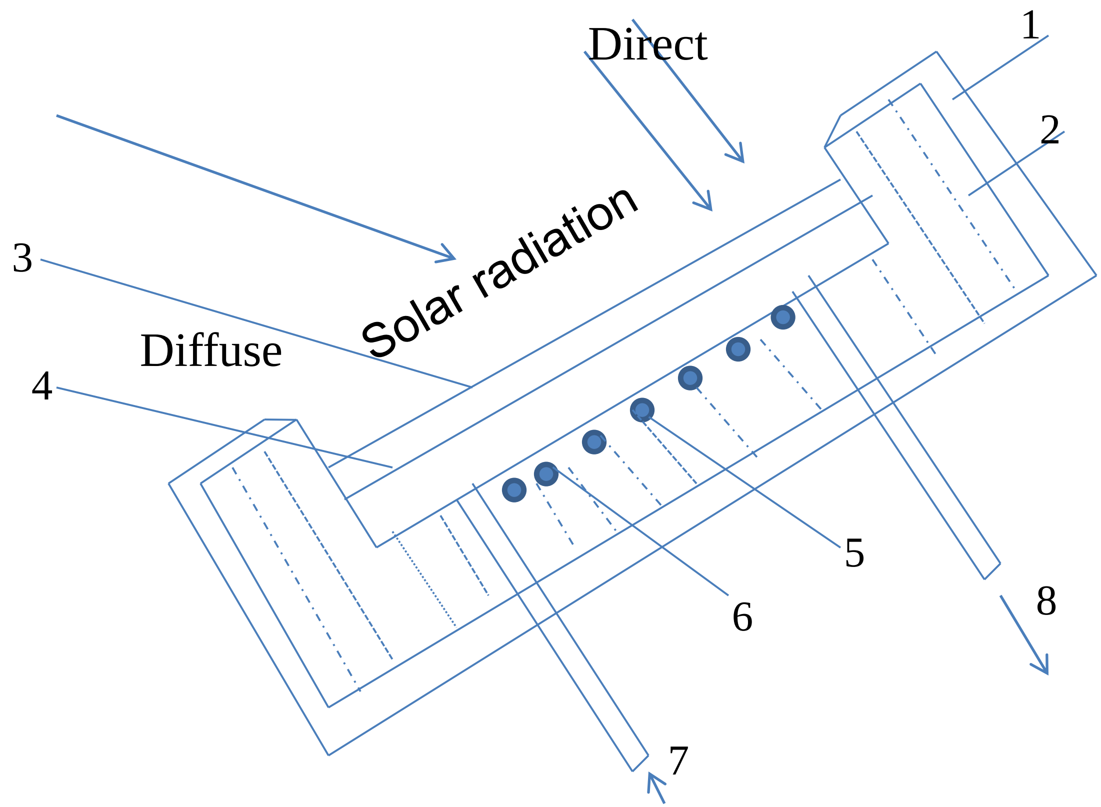
The schematics of flat plate collectors are shown in the figure (a) and (b). It consists of a black coated plate made of metal or plastic, which absorbs all the solar radiation incident on it and converts into heat. This plate is known as the absorber. Fluid channels are welded below the absorber for carrying a heat transfer fluid generally water. This transport fluid transports the heat from the absorber into the utilisation purposes.



Fig(a): Positioning of flat-plate collector**.**

To reduce the heat losses, the back side and sides of the collector (below the absorber) are covered with insulation. The front above of the absorber is covered with one or two transparent glass sheets. The whole thing is sealed in a box or some sort of casing.

Different types of absorber designs are shown in figure © where liquid as the transport medium of heat. The working of the collector basically depends upon the



Fig(b): Schematic of a flat plate solar energy collector

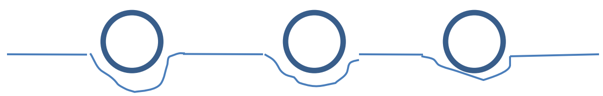
1. Case
2. Insulation
3. Transparent cover (e.g. glass, tedlar etc)
4. Transparent cover (e.g. IR-reflecting glass cover
5. Absorber (black or selectively coated)
6. Fluid channel for collecting heat (air, water or any other fluid can flow through them)
7. Inlet for the heat transfer fluid
8. Outlet for the heat transfer fluid.

greenhouse effects. Flat plate collectors can convert solar radiation into heat upto maximum 100^{0}C. Air heating solar collectors are mostly used for agricultural drying and space heating applications. The basic advantages are low sensitivity to leakage, less corrosion and no need for additional heat exchanger. The main disadvantage is the requirement of larger surface area for heat transfer and higher flow rate.

(A) Tube in black plate

(B) Tubes bonded on upper surface of the plate

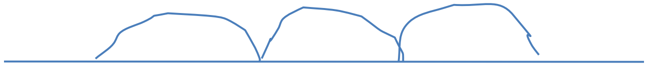
(C) Tubes bonded on upper surface of the plate



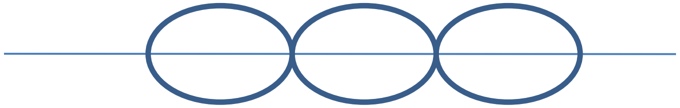
(D) Tubes fitted in grooved plate

(E) Different modes of alignment

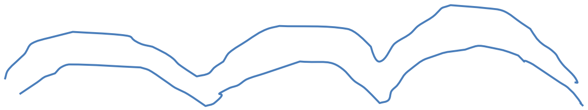
(F) Rectangular tubes bonded to plates.



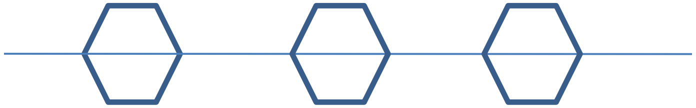
(G) Corrugated sheet on a flat plate.



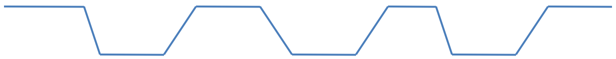
(H) Corrugated sheets riveted together.



(I) Corrugated sheets fastened together



(J) Rollbond aluminium collector.



(K) Thompson system

(L) Rollbond aluminium collector

Fig©: different types of absorber designs with liquid as the transport medium.

Flat Plate Collector Efficiency:-

The instantaneous collection efficiency of a flat plate solar collector is defined as:

$$\eta_i = \frac{\text{Useful heat gain}}{\text{Solar Radiation incident on the Collector}} = \frac{Q_u}{I_{G\beta}}$$

Where $I_{G\beta} = Q_u + Q_c + Q_R + Q_c$

If A_c, τ and ρ are the collector area in m^2, transmissivity and reflectivity; the useful energy is given by: $Q_u = \tau I_{G\beta}\ (1-\rho)A_c - Q_L$ (W)

For an absorber, $(1-\rho) = \alpha$. So, $Q_u = \tau I_{G\beta}\alpha A_c - Q_L$ (W).

The heat losses Q_L are composed of convection and radiation parts. So Q_L can be represented as: $Q_L = Q_c + Q_R = U\ A_c\ (t_c - t_s)$ (W)

Where U = Overall heat transfer coefficient of the observer ($W/m^2\ {}^0C$).

t_c = Temperature of the collector's absorber (${}^0C$).

t_s = Temperature of the ambient (${}^0C$).

The reflected radiation from the absorber is given by: $Q_R = \tau I_{G\beta} A_c\ \rho$ (W) .

So, $Q_u = \tau I_{G\beta}\alpha A_c - U\ A_c\ (t_c - t_s)$ (W).

HOT WATER TREATMENT

Solar Pond:-

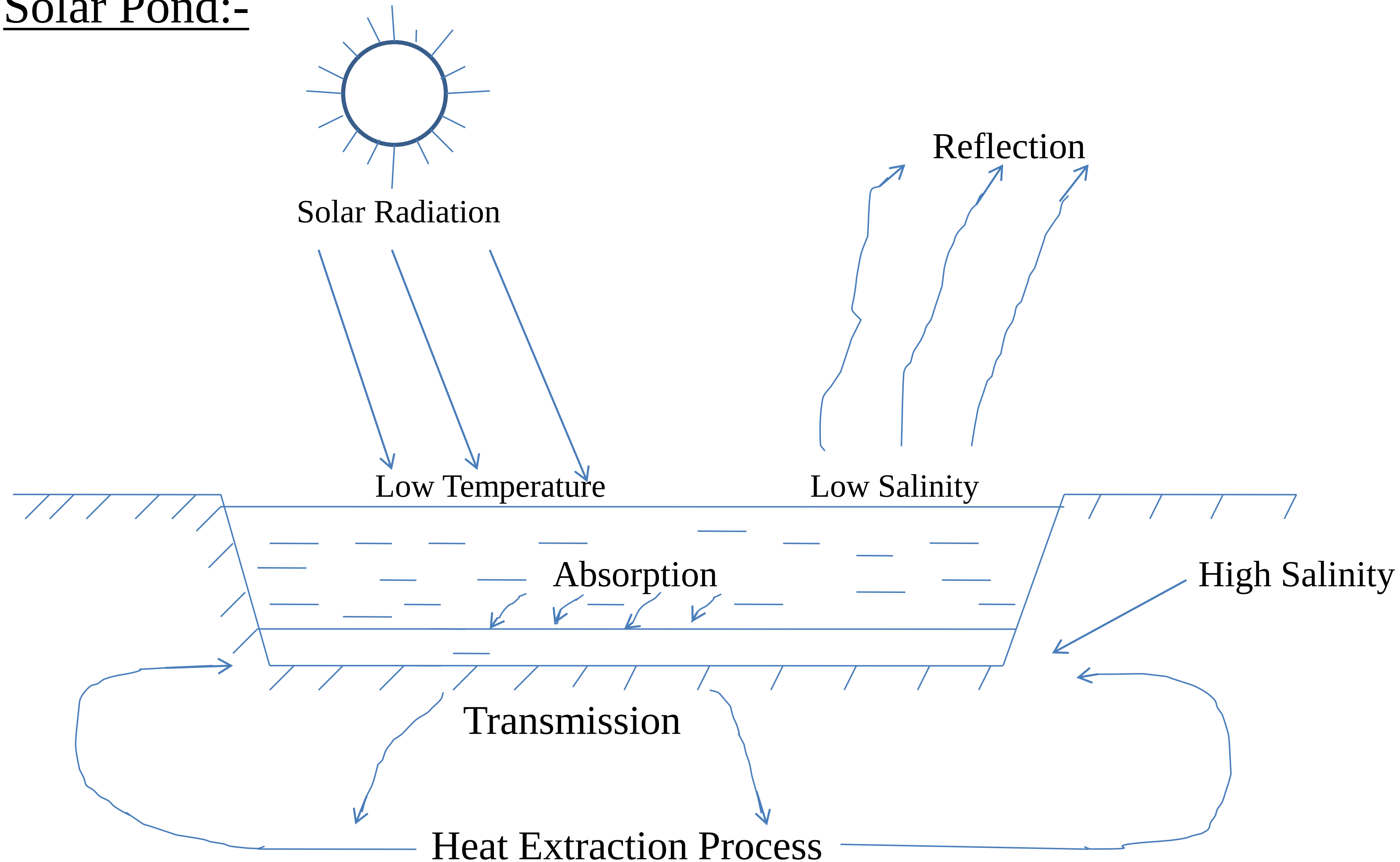


Fig: Schematic of Solar Pond

Principle of operation:-

The figure shown above is a schematic of a solar pond. The depth of the solar pond varies between 1m and 2m. The lowest layer is designed to have high salinity (260 kg/m NaCl) and it is decreased progressively in a vertical direction until it becomes equal to that of fresh water at the top. The distinct zones can be identified in an operating pond as:

(1) Constant layer (high salinity layer at the bottom)

(2) Intermediate non-convective layer.

(3) Top, or surface layer of 20 cm thickness of uniform density.

Solar radiation is absorbed around 50% on the top surface and the remaining short-wavelength component of radiation penetrates into the into the depth of the pond. Around half of the penetrated radiation is absorbed in the intermediate layer and rest 25% is absorbed by the bottom layer. Since the salt water is denser than the fresh water, it has high capacity of heat content. The bottom layer thus get heated and the heat is extracted from the pond by a heat exchanger.

Solar Photovoltaics:-

Solar photovoltaic is the method of generating by conversion of solar radiation in to direct electrical energy using semi-conductors that exhibit photovoltaic effect. The device which is used for conversion is known as solar photovoltaic cell or a solar cell. Photovoltaic power generation employs solar panels composed of a number of solar cells containing photovoltaic material. The materials presently used are: mono-crystalline silicon, poly-crystalline silicon, amorphous silicon, and cadmium telluride and copper indium gallium selenide/sulpide.

The solar time can be calculated from the local time by using the following equation:

$$\text{Solar time} = \text{Local time} + (\lambda_0 - \lambda) \times 0.4 - \left(7.66 \sin x + 9.87 \sin[2x + 24.99^0 + 3.83^0 \sin x]\right) \qquad \text{.........................(7)}$$

Where λ_0 is the standard meridian of the time zone and λ is local meridian. The Meridians are taken as negative towards east and positive towards west. In India, standa-rd meridian correspond to Allahabad, i.e. 82.5^0 east. The value of x in equation (3) is given by

$$x = 0.9856^0, N - 2.72^0 \ \text{(deg)} \qquad \text{...................(8)}$$

It is now possible to calculate the position of the sun in the sky given by two angles, Namely solar azimuth angle and solar altitude angle. These are

$$\sin \alpha_s = \sin \delta . \sin \phi + \cos \delta \cos \phi \cos \omega \qquad \text{...............(9)}$$

$$\cos \gamma_s = \frac{(\sin \delta \sin \phi - \sin \delta)}{(\cos \omega . \cos \phi)} \qquad \text{...................(10)}$$