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RESEARCH ARTICLE

COMPUTER BASED ANALYSIS OF HIGH-EFFICIENCY SOLAR CONCENTRATOR

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ABSTRACT

In this paper I a study is carried out on tracking modes I and II for compound parabolic concentrator and cylindrical parabolic concentrator type across the different latitudes of India for different times of day. Since the solar irradiation level is different for different latitudes and the total amount of energy received at ground level from the sun at the zenith depends on the distance to the sun and thus on the time of year. The comparison between different cities which fall at different latitudes for various time using solar concentrators is done using MATLAB programming with respect to the solar flux and other solar parameters and analyzing using graphical output from the program was done. The importance of this thesis is that it will help in deciding the type of geometry to be used for receiving maximum radiation and flux for given solar concentrator system.

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INTRODUCTION

Solar energy is a source of heat and light. This energy is harnessed using a range of ever evolving technologies such as solar heating, solar photovoltaic's, solar thermal energy etc. It is an important source of renewable energy and its technologies are broadly characterized as either passive solar or active solar depending on the way they capture and distribute solar energy or convert it into solar power.

Active Solar techniques include the use of photovoltaic systems, concentrated solar power and solar water heating to harness the energy.

Passive Solar techniques include orienting a building to the sun, selecting materials with favourable thermal mass or light dispersing properties, and designing spaces that naturally circulate air.

Classification of methods for Solar Energy Utilization

I. Direct Methods
1. Thermal
2. Photovoltaic

II. Indirect Methods
1. Hydro power
2. Wind Energy
3. Wave Energy
4. Ocean Thermal energy
5. Tidal Energy
6. Geothermal Energy

1.1 The promise of solar energy

Solar energy is emerging as one of the most promising sustainable energy sources. The entire world can theoretically be supplied with its current needs for electricity from solar power stations covering only 1% (Pilkington, 1996) of the semi-arid or arid lands on earth. The SI unit for the measure of irradiance (radioactive flux) is (W/m^2). At the mean distance between Earth and sun of 150 million kilometers, the flux of the solar radiation reaching the Earth's atmosphere is 1367 W/m^2 (World Meteorological Organization, 1982). This quantity is named as Solar Constant.

The total amount of energy received at ground level from the sun at the zenith depends on the distance to the sun and thus on the time of year. It is about 3.3% higher than average in January and 3.3% lower in July. If the extraterrestrial solar radiation is 1367 W/m^2 (the value when the earth-sun distance is 1 astronomical unit), then the direct sunlight at the earth's surface when the sun is at the zenith is about 1050 W/m^2, but the total amount of solar radiation (direct and indirect from the atmosphere) hitting the ground is around 1120 W/m^2. In terms of energy, sunlight at the earth's surface is around 52 to 55 percent infrared (above 700 nm), 42 to 43 percent visible (400 to 700 nm), and 3 to 5 percent ultraviolet (below 400 nm). At

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the top of the atmosphere, sunlight is about 30% more intense, having about 8% ultraviolet (UV).

1.2 Sun: source of energy

The sun is a sphere of intensely hot gases. The solar energy strikes our planet a mere 8min and 20 sec after leaving the giant furnace, the sun which is 1.5×10^{11} km away. The sun has an effective blackbody temperature of 5762□ K. The temperature in the central region is much higher and it is estimated at 8×10^6 to 40×10^6 □K. In effect the sun is a continuous fusion reactor in which hydrogen is turned into helium. The sun’s total energy output is 3.8×10^{20} MW which is equal to 63 MW/m^2 (Solar Thermal Collectors And Applications) of the sun’s surface. This energy radiates outwards in all directions. Only a tiny fraction, 1.7×10^{14} kW (Richard B Bannerot et al., 1982) of the total radiation emitted is intercepted by the earth. However, even with this small fraction it is estimated that 30 min of solar radiation falling on earth is equal to the world energy demand for one year.

The solar energy potential in India is immense due to its convenient location near the Equator. India receives nearly 3000 hours of sun shine every year (REN21 2012), which is equivalent to 5000 trillion kWh of energy. India can generate over 1,900 billion units of solar power annually.

Table 1.1. Global Solar Potential (Total Primary Energy Consumption Energy Information Administration Retrieved, 2013)

Global Solar Potential	Maximum Power (TW) annually
Solar	23000
Total surface solar	8500
Desert solar	7650
World Energy Consumption	16

1.3 Solar technology

There are *two* ways to produce electricity from the sun. First is by using the concentrating solar thermal system. This is done by focusing the heat from the sun to produce steam. The steam will drove a generator to produce electricity. This type of configuration is normally employed in solar power plants. The other way of generating electricity is through a photovoltaic (PV) cell. This technology will convert the sunlight directly into electricity. This technique is now being widely installed in the residential house and at remote places. It is also contributing to the significant increase in the development of Building Integrated Photovoltaic (BIPV) system (A).

Factors affecting performance of solar concentrators

1.4 Solar concentrating Colle-Ctors

Solar energy collectors are special kind of heat exchangers that transform solar radiation energy to internal energy of the transport medium. The major component of any solar system is the solar collector. This is a device which absorbs the incoming solar radiation, converts it into heat, and transfers this heat to a fluid (usually air, water, or oil) flowing through the collector. The solar energy thus collected is carried from the circulating fluid either directly to the hot water or space conditioning equipment or to a thermal energy storage tank from which can be drawn for use at night or cloudy days.

There are a large number of solar collector designs that have shown to be functional. There designs are classified in two general types of solar collectors:

- **Flat-Plate Collectors** – The absorbing surface is approximately as large as the overall collector area that intercepts the sun's rays. Then the incident beam radiation which falls over whole surface is giving its heat energy to the thermic fluid or directly converted into electricity.

- **Concentrating Collectors** – Large areas of mirrors or lenses focus the sunlight onto a smaller absorber where the trapped heat (thermal) energy by fluid is sent to other processing unit for generating electricity.

A non-concentrating / flat plate collector has the same area for intercepting and for absorbing solar radiation, whereas a sun-tracking concentrating solar collector usually has concave reflecting surfaces to intercept and focus the sun’s beam radiation to a smaller receiving area, thereby increasing the radiation flux.

1.5 Solar concentrator techno-logies

Solar concentrator involves a number of collectors which are classified according to their design.

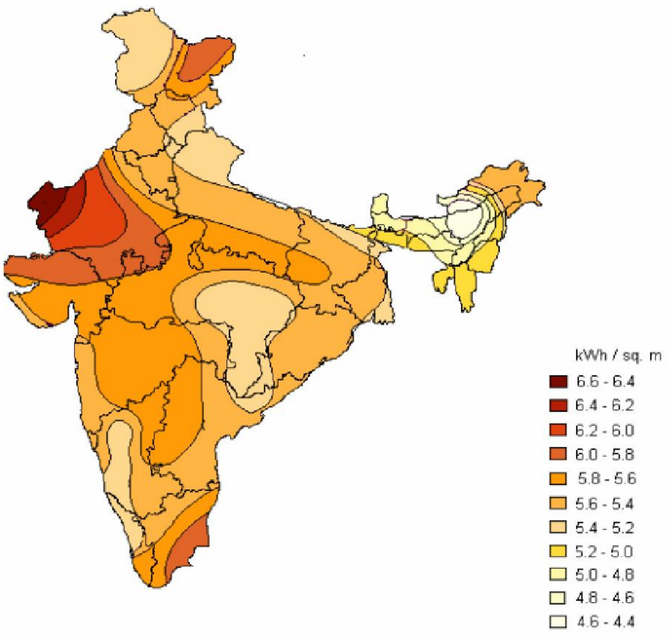

Fig 1.1. Solar irradiance (Sukhatme, ?)

There are many parameters involve for choosing the best one for a particular location.

1. Parabolic Trough
2. Enclosed Trough
3. Dish Stirlings

4. Concentrating Linear Fresnel Reflector
5. Solar Power Tower

1.6 Solar constant

Solar constant, is a measure of solar flux density, is the amount of incoming solar electromagnetic energy per unit area that would be incident on a plane perpendicular to the rays, at a distance of one astronomical unit (AU) (roughly the mean distance from the Sun to the Earth). The "solar constant" includes all types of solar radiation, not just the visible light. Its average value was thought to be approximately 1.366 kW/m² (19).

The sun provides 99.98% of the energy for our planet (the rest is geothermal) and it is responsible, directly or indirectly, for the existence of life on Earth. The sun is a star that consists of 71 % Hydrogen, 27 % Helium and 2% solid matter. Near the sun's core the temperature is approximately 16 million degrees and at its outer layer (the Photosphere) it is about 5,770° K. The energy emitted by the sun is approximately 63 MW for every m² of its surface.

The earth is neither a perfect sphere nor its orbit. The earth moves around the sun in an elliptical orbit having a very small eccentricity and with the sun at one of the foci. Consequently the distance between the earth and sun varies a little through the year. Because of this variation the extraterrestrial flux also varies.

The value of extraterrestrial flux on any day can be calculated from the equation.

$$I'sc = Isc\left(1 + 0.033 \cos \frac{360□}{365}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1.1)$$

Where, I'sc = Extraterrestrial radiation flux and Isc = Solar constant (1367 W/m^2) n = Day of the year

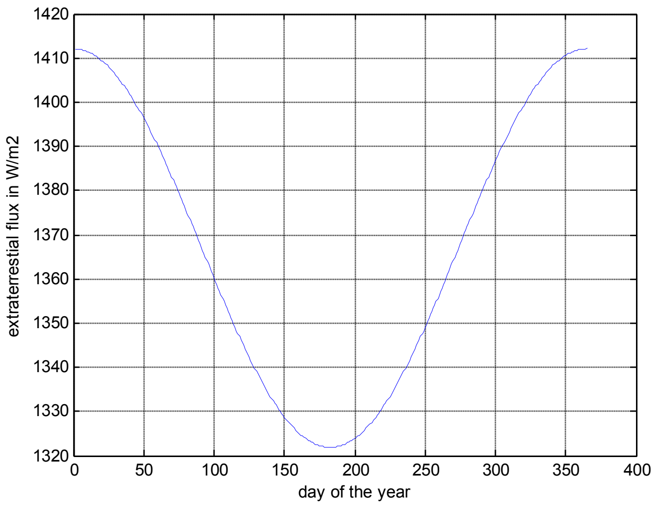

Fig 1.1. Extraterrestrial radiation flux (Eq 1.1) output based on MATLAB programming

Zenith angle Θ_z is the angle made by the sun's rays with the normal to a horizontal surface. A Pyranometer is an instrument which measures either global or diffuse radiation falling on a horizontal surface over a hemispherical field. It basically measures the solar radiation flux.

ϴ is the angle between an incident beam of flux $I_{bn.}$ Latitude ϕ of a location is the angle made by the radial line joining the location to the centre of earth with the projection of the line on the equatorial plane (vary from + 90^o to – 90^o).

Air Mass (AM) is often used as a measure of the distance travelled by beam radiation through the atmosphere before it reaches a location on the earth's surface. It is defined as the ratio of mass of the atmosphere through which the beam radiation passes to the mass it would pass through if the sun is directly overhead (i.e. at its zenith).

Slope □ is the angle made by the plane surface with the horizontal. It can vary from 0° to 180□. The surface azimuth angle □ is the angle made in the horizontal plane between the horizontal line due south and the projection of the normal to the surface on the horizontal plane. It can vary from – 180□ to + 180□.

Declination angle δ is the angle made by the line joining the centre of earth with the projection of this line on the equatorial plane.

$$\delta \text{ (in degrees)} = 23.45 \sin\left(\frac{360}{365}(284+n)\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1.2)$$

Where n is the day of the year. Its graphical output is obtained via MATLAB programming and is shown in Fig 1.2

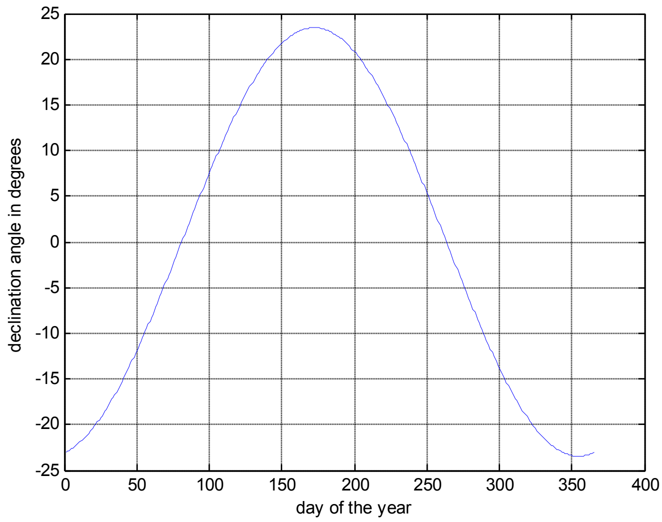

Fig 1.2. Declination angle of earth (output based on MATLAB programming)

Hour angle ω is the angular measure of time and is equivalent to 15□ per hour. It is also varies from – 180□ to + 180□. It can be shown that

$$\cos\theta = \sin\phi\,(\sin\delta\cos\beta + \cos\delta\cos\gamma\cos\omega\sin\beta) + \cos\phi\,(\cos\delta\cos\omega\cos\beta - \sin\delta\cos\gamma\sin\beta) + \cos\delta\sin\gamma\sin\omega\sin\beta \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1.3)$$

Special cases of Eq 3.3 are discussed below

Vertical surface β = 90□,

$\cos\theta = \sin\phi\cos\delta\cos\gamma\cos\omega - \cos\phi\sin\delta\cos\gamma + \cos\delta\sin\gamma\sin\omega$ …………………..(1.4)

Horizontal surface β = 0□

$\cos\theta = \sin\phi\sin\delta + \cos\phi\cos\delta\cos\omega$ ……………….(1.5)

I Orientation and Tracking Modes

A cylindrical parabolic collector is oriented with its focal axis pointed either in the east west (E-W) direction or the north-south (N-S) direction. In the east – west orientation the focal axis is horizontal, while in the north – south orientation the focal axis may be is horizontal or inclined. The various tracking modes which can be adopted are as follows.

Mode I
$\beta = (\phi - \delta)$ for γ = 0□
And $\beta = (\delta - \phi)$ for γ = 180□

Mode II
$\tan(\phi - \beta) = (\tan\delta / \cos\omega)$ for γ = 0□
$\tan(\phi + \beta) = (\tan\delta / \cos\omega)$ for γ = 180□

1.7 Solar radiation on tilted surfaces

Tilting a solar concentrator is very much useful to get the maximum absorbed flux during sunshine hours. The total absorbed flux depends on the beam radiation, diffuse radiation and reflected radiation.

Beam Radiation: The ratio of the beam radiation flux falling on a tilted surface to that falling on a horizontal surface is called the tilt factor for beam radiation and it is denoted by r_b. For a tilted surface facing south (i.e. γ = 0□)

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

while for a horizontal surface
$\cos\theta_z = \sin\phi\sin\delta + \cos\phi\cos\delta\cos\omega$
Hence, $r_b = \frac{□□□\ □}{□□□\ □□}$ (1.6)

2 Thermal analysis of con-centrating collectors

An energy balance on the absorber yields the following equation under steady state conditions.

$Q_u = A_aS - Q_l$ ………………..(2.1)
where,

Similarly, it is convenient from the point of view of analysis to express the heat lost from the collector in terms of an overall loss coefficient defined as

$Q_l = U_l A_p (T_{pm} - Ta)$ ………………..(2.2)

where

U_l = Overall loss coefficient
A_p = Area of the absorber surface
T_{pm} = Average temperature of the absorber surface
T_a = Temperature of surrounding air (assumed to be same on all sides of the collector)

Combining the above equations, we get

$Q_u = A_a (S - \frac{□□}{□} (T_{pm} - Ta))$ (2.3)

Where

C = (A_a/A_p) is the concentration ratio.

2.1 Design of solar concentrator

For the past four decades, there have been a lot of developments involving the designs of the solar concentrators. This paper presents some of the distinguish designs which have shown significant contribution to the solar technology.
(3.24a)

They are:

a) Flat Plate with plane reflectors
(3.26a)
b) Cylindrical parabolic Collector
(3.26b)
c) Compound Parabolic Concentrator (CPC)
(3.24b)
d) Collector with fixed circular concentrator and moving receiver
e) Fresnel Lens Concentrating Collector
f) Paraboloid dish concentrating Collector

2.2 Case study for calculating solar flux

For cylindrical parabolic concentrator at Jaipur (26.9° N, 75.8°E) on a particular day of the year (i.e. June 10 , *n* =161), for the given value of beam radiation which would fall on one square metre of aperture plane of this collector during sunshine hours i.e. between 8:30 to 18:30 IST. Cos of zenith angle, tilt factor and incident beam flux normal to the aperture was calculated for tracking mode I and the results were then compared with other cities (or latitudes) of the India.

Solution:

1. Using the equation for calculating declination angle for the day of June 10, $n = 161$

$\boldsymbol{\delta}$ (in degrees) $= 23.45 \sin\left(\frac{360}{365}(284 + n)\right)$

Where *n* is the day of the year.

Q_u = Rate of useful heat gain
A_a = Effective area of aperture of the concentrator
S = Solar beam radiation per unit effective aperture area absorbed in the absorber
Q_l = Rate of heat loss from the absorber

Therefore,
$\boldsymbol{\delta} = 23.45 \sin\left(\frac{360}{365}(284 + 61)\right) = 23.012°$
cos of zenith angle is calculated from Eq 1.2

$\cos \theta_z = \sin \phi \sin \delta + \cos \phi \cos \delta \cos \omega$

$\cos \theta_z = \sin 26.9° \sin 23.012° + \cos 26.9° \cos 23.012° \cos 22.5°$ $\cos \theta_z = 0.134$

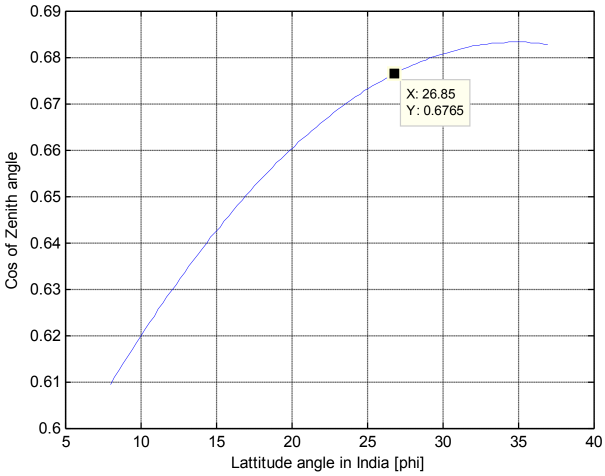

Fig 2.1. The graphical output of cos of zenith angle (for Jaipur 26.9°N) at 12:30 hrs IST as obtained using MATLAB Programming

The table for corresponding cos of zenith angle for various locations of India for tracking mode I is shown in Table 2.1

Table 2.1. Cos of zenith angle for various latitudes of India for tracking mode I

S.No	Time (IST)	Lat (16.12°)	Cos of Zenith angle (θ_z)	Lat (24.53°)	Cos of Zenith angle (θ_z)
1	08:30		0.985		0.992
2	10:30		0.925		0.935
3	12:30		0.682		0.672
4	14:30		0.224		0.271
5	16:30		– 0.229		– 0.158
6	18:30		– 0.593		– 0.502

$\cos \theta = \sin^2 \delta + \cos^2 \delta \cos \omega = \sin^2 26.9° + \cos^2 26.9° \cos 22.5°$
$\cos \theta = 0.1627$

Tilt factor for any cos of zenith angle can be obtained using the formula given below

$$r_b = \frac{\cos \theta}{\cos \theta_z}$$

The table for corresponding tilt factor versus various locations of India for tracking mode I of above discussion is shown in Table 2.2

Table 2.2. Tilt factor versus various latitudes of India for tracking mode I

S.No.	Time (IST)	Lat (16.12°)	Tilt factor (R_b)	Lat (24.53°)	Tilt factor (R_b)
1	08:30		1.008		1.000
2	10:30		1.011		0.999
3	12:30		1.034		0.994
4	14:30		1.176		0.969
5	16:30		0.745		1.084
6	18:30		0.875		1.034

Incident beam flux normally on aperture plane = $I_b r_b$

The table for corresponding incident beam flux for various locations of India for tracking mode I of above discussion is shown in Table 2.3

Table 2.3. Incident beam flux normally on aperture plane for various latitudes of India for tracking mode I

S.No	Time (IST)	Incident Beam Radiation (I_b) W/m^2	Lat (16.12°)	Incident Beam flux normal to aperture ($I_b r_b$) W/m^2	Lat (24.53°)	Incident Beam flux normal to aperture ($I_b r_b$) W/m^2
1	08:30	333		335.5		333.1
2	10:30	495		500.4		494.8
3	12:30	523		540.6		520.3
4	14:30	445		523.4		431.6
5	16:30	220		196.4		226.5
6	18:30	118		103.3		122.1

The graphical output for corresponding incident beam flux versus various latitude and tracking mode I of India is shown in Fig. 2.2

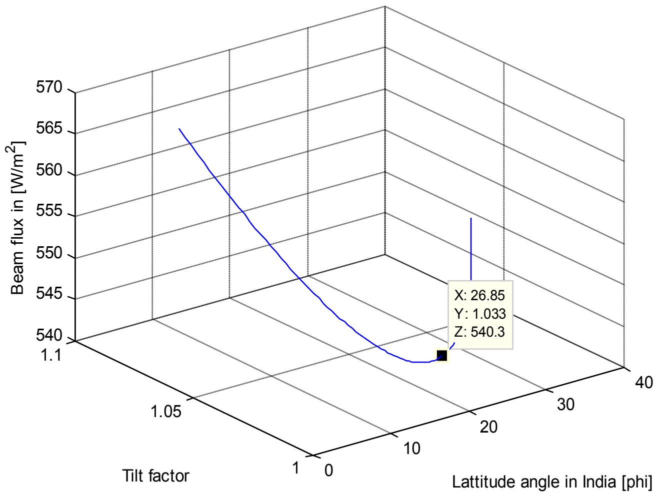

Fig 2.2. Solar flux absorbed by cylindrical parabolic collector at Jaipur (26.9°) as obtained by MATLAB Programming

3 RESULTS AND COMPARISONS

Table 4.1 and its corresponding MATLAB program output suggests that while considering the four cities in India Jodhpur will give the best results for global solar radiation (Hg = 26740 kJ/m^2 –day) among the four cities. The fact is due to that the Jodhpur has high constant value of *a* and *b*.

Also the Jodhpur area (Rajasthan) receives the maximum solar beam radiation due to its best geographical location (low humidity Zone). The irradiance level of solar energy as shown by the fig 3.1 directly indicates that the effect of low humidity gives a direct conclusion of installing solar concentrators in Rajasthan due to high thermal atmosphere throughout the year.

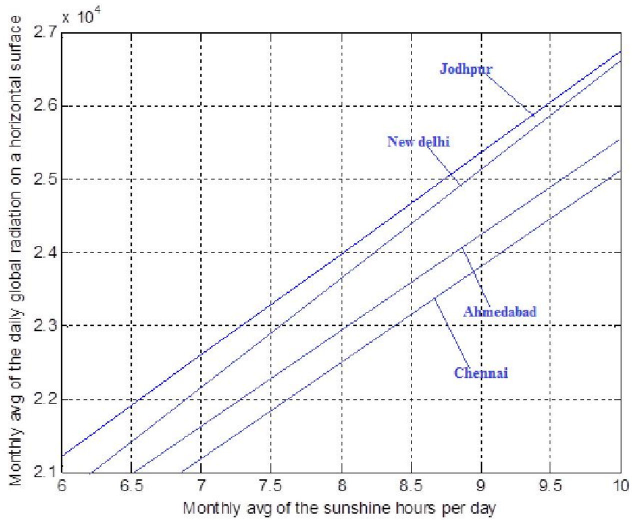

Fig 3.1. Comparison of Global solar radiation (Hg) for various cities

From Table 2.1 for tracking mode I and Eq 1.6 we know that the cos of zenith angle is inversely proportional to tilt factor. If the cos of zenith angle is maximum then there must be less tilt factor to absorb that incident solar beam. The cos of zenith angle is maximum in the evening and gradually decreases to zero and then goes negative in the region of Indian latitude. This is due to the earth declination and hour angle that depends on it. The maximum cos of zenith angle is obtained during the morning. Since the beam radiation is highest in noon only and at that time cos of zenith angle is 0.682 only but the absorbed beam flux is not maximum at that time. Even the sun is directly over head but due to hour angle and declination of earth the incident beam radiation is not maximum in the morning. When beam radiation is maximum we can get the maximum solar flux on the concentrator by taking suitable tilt factor.

3.1 Recommendations for futu- re work to achieve better performance and efficiency

Mainly we can improve the efficiency of solar concentrators by using advanced technologies, good materials, better tracking systems and detailed survey based on use of various solar sensors before installing solar concentrator systems etc. Firstly we can improve results by using good quality materials for solar concentrator which can result in better absorption and less reflection of solar radiation. At present we use *glass mirrors* (generally considered to be the baseline reflector material for solar thermal electric applications). Glass mirrors have high specular reflectance (typically 91%), long lifetimes, durability in the field, and (usually) modest degradation of reflectivity over the concentrator lifetime. Drawbacks of glass include weight, fragility, and expense. Relative to glass, polymer mirrors have advantages of being flexible, lightweight, and less expensive, but they have lower durability and shorter lifetimes than glass mirrors. The use of *polymer mirrors* materials will provide improved results relative to glass. Polymer mirrors have advantages of being flexible, lightweight, and less expensive, but they have lower durability and shorter lifetimes than glass mirrors. Recent improvements have been made in the performance and durability of silvered-polymer reflector materials

Also by using luminescent solar concentrators (LSCs) we can increase the concentration of solar concentrators. A Luminescent solar concentrator (LSC) is a device for concentrating radiation, non-ionizing solar radiation in particular, to produce electricity. Luminescent solar concentrators operate on the principle of collecting radiation over a large area, converting it by luminescence (commonly specifically by fluorescence) and directing the generated radiation into a relatively small output target.

LSCs concentrate light by absorbing and re-emitting it at lower frequency within the confines of a transparent slab of material. They can not only collect direct sunlight, but on cloudy days, can collect diffuse light as well.

Survey of a particular region and latitude with respect to sunny day and solar flux will be helpful in selecting the site for solar concentrator systems. Then testing it for various tracking modes will help in deciding which is best for particular latitude using different formulas given in the thesis.

Following key aspects are very useful and recommended for future work for reduction in costs for construction and maintenance of solar concentrators:

(1) Use of Immobile Primary Conc. (PCs)
(2) Conventional Heat Storage System
(3)Using Advanced Technology to Trap Solar Energy like Light-Sensitive Nano particles
Gallium Arsenide

4 Conclusion

In this paper I have focused my study on tracking modes I and II for compound parabolic concentrator and cylindrical parabolic concentrator type across the different latitudes of India for different times of day.

Firstly the main factors which result in maximum incident beam flux normally to aperture on plane are declination angle (δ), latitudes (ϕ), hour angle (ω), tilt factor (r_b), incident beam radiation (I_b) and cos of zenith angle (θ_z). when we are considering our study on tracking mode I

Now if we keep latitude constant for a particular day of the year we can get the varied results for incident beam flux normal to the aperture for different latitude across the country. From which we have found the maximum Incident beam flux normal to aperture is 676.1 W/m^2 at 8.4° latitude for n = 161.

Similarly for tracking mode II if we keep latitude constant for a particular day of the year we can get the varied results for absorbed solar flux normal to the aperture for different latitude across the country. From which we have found the maximum absorbed solar flux normal to aperture is 393 W/m^2 at 37° latitude when taking n = 125. The things which are necessary for getting maximum absorbed solar flux are: minimum tilt factor and the maximum incident beam radiation during sun at zenith. By varying tilt factor we can get maximum absorbed solar flux throughout the day and therefore this scheme is more economical. With suitable tracking mechanism and improved materials (least absorption or maximum reflection) the desired results can be obtained. Solar concentrators have emerged in recent years as a way to intensify the amount of sunlight hitting solar cells, which are the most expensive part of solar panels to make solar power more affordable.

List of symbols

kWh Kilowatt-hours
η_{optics}Optical efficiency of concentrator
$\eta_{receiver}$ Solar receiver efficiency
I Solar flux in W/m^2
I_{sc}Solar constant in W/m^2
I'_{sc}Extraterrestrial solar flux in W/m^2
I_{bn} Incident beam radiation on concentrator
αAbsorptivity of concentrator
α_a Solar altitude angle
ϕ Latitude angle in degrees
Θ_z Cos of zenith angle or angle of incidence
ϵ Emissivity
*C*Concentrated
*Θ*Angle between an incident beam of flux I_{bn}
□Angle made by the plane surface with the horizontal (Slope)
$□_s$Surface azimuth angle corresponding to sunrise and sunset
δDeclination angle of earth
ωHour angle (equivalent to 15□ per hour)
ω_sHour angle corresponding to sunrise and sunset
H_gMonthly average of the daily global radiation on horizontal surface at a location (kJ/m^2-day)
H_cMonthly average of the daily global radiation on a horizontal surface at the same location on a clear day (kJ/m^2-day)
H_dMonthly average daily diffuse radiation on a horizontal surface (kJ/m^2-day)
r_bTilt factor for beam radiation
SMonthly average of the sunshine hours per day at the location (h)
*a,b*Constants obtained by fitting data (varies between values 0.1 to 0.7)
Q_lRate of heat loss from the absorber
U_lOverall loss coefficient
A_{con}Surface area of concentrator
nNumber of days of the year
T_HHeat source temperature in degrees
T°Heat sink room temperature in degrees
T_{pm}Average temperature of the absorber plate
T_aTemperature of surrounding air or ambient temperature
A_aEffective area of aperture of the concentrator
A_pArea of the absorber plate

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