

**Estimation of enhanced solar energy availability for single axis tracking and polar axis mounted collectors with double booster mirrors****Rajvir Satyen Bhanuchandra***

e-mail: sbrajvir@gmail.com

JJT University

Rajasthan INDIA

Dr S.T.Rajan

Sustainable Technologies Consultant

213, "Jayashree", Swapna Srushti Society.

Near Top 3 Cinema, Talaja Road. Bhavnagar Gujarat

364 002 INDIA

e-mail:sodankur21@gmail.com

ABSTRACT : This paper estimates and compares the enhancements of solar energy incident under clear sky conditions on the apertures of two solar collector systems with two booster mirrors on Eastern and Western sides and without them and which are mounted on polar axis and track solar azimuth angle, for three significant days of a year and for three select locations near to and far from the Tropic of Cancer, in India. The objectives of the work are to study the trend of increase in solar energy availability due to polar mounted booster mirrors over a year, to incentivize the integration of a cheap and passive single axis solar azimuth tracker with solar thermal or photovoltaic collectors and to promote their wider use. A simpler technique of optical analysis for a complex system is presented here.

Key words: single axis tracking, solar PV, solar thermal, booster mirrors, solar collector

I. INTRODUCTION

In the last few decades, rapid progress has been made relating to solar thermal systems where conventional flat plate collectors have given way to now ubiquitous vacuum tube collectors and as regards wind turbines sizes of individual turbines have gone up from a few hundred kW rating to multiple MW. Compared to these developments progress of micro solar thermal devices like solar box cookers or solar paraboloidal dish type concentrators have stagnated and their use is limited to hobbyists or a few thousand well-to-do households or few hundred organizations where solar cookers are subsidized by the government. Till now they have not reached the level of being marketed on their own merits or without government subsidies and they are not as popular and as essential as other gadgets of daily household use. The main reason has been that they have remained as technically dumb units unlike other domestic utilities such as washing machines, ovens, electric irons or water purifiers which have some embedded "intelligence" via electronic controls which minimize the need for frequent human intervention.

Some sort of "semi-intelligence" may be realized if at least one axis sun tracking can be introduced in box or concentrating solar cookers, or solar PV panels, preferably without requiring external electrical power supplies. Earlier attempts were made in this direction using gravity driven systems by Scheffler [1,2,3].

II. SYSTEM DESCRIPTION

The system analyzed comprises of a solar thermal or photovoltaic collector with two booster mirrors inclined at 120° with respect to collector aperture plane and mounted on a polar axis as shown in Fig 1. This implies that the axis of rotation of the collector is inclined at an angle $\beta = \lambda$, the latitude of the collector's site. The width of each mirror is equal to the width of aperture. The lengths of the collector and mirrors are equal and long enough such that the optical effects at their ends could be ignored. It is assumed that a cheap single axis sun tracker unit is available and is integrated with the system to track the solar azimuth angle throughout a "working day" the duration of which may be set by the user. We shall designate such a polar axis mounted solar azimuth tracking mirror boosted collector as PAMSATMBC.

Nomenclature A_C = Area of collector aperture [m^2] A_M = Area of mirror (set equal to A_a) [m^2] E_D = Solar beam radiation energy incident on total collector aperture area [W] E_{DMC} = Amount of solar beam radiation energy intercepted by booster mirror and reflected completely on to the collector aperture [W] E_{DMCT} = Total beam radiant energy reflected on to collector by two booster mirrors [W]

E_{DCT} = Total beam radiant energy incident on polar axis oriented and solar azimuth tracking collector that has two booster mirrors tilted at 120^0 with reference to collector aperture plane [W]
 E_{DCTH} = Total beam radiant energy incident on polar axis oriented and solar azimuth tracking collector that has two booster mirrors tilted at 120^0 with reference to collector aperture plane, in the particular case of horizontal collector with two booster mirrors and when solar radiation under clear sky condition is incident normally on the collector[W] N_C = Normal to the collector plane
 S = Incident solar ray vector
 I_D = Intensity of solar beam radiation incident on collector under clear sky condition ; a function of latitude, longitude, day of the year and time of a day [$W m^{-2}$]
 I_{DC} = Normal component of I_D incident on collector under clear sky conditions
 I_M = the solar beam radiation intercepted by mirror under clear sky conditions
 CP = Collector Plane
 HP = Horizontal Plane
 V_p = Any plane perpendicular to polar axis and passing through collector
 α = Solar altitude
 β = Tilt angle of collector
 λ = latitude λ (for polar axis mounting of collector)
 θ = Angle between N_C and S (can be + or – depending on latitude and day)
 $\theta = 90^\circ - (\lambda + \alpha)$ if $(\lambda + \alpha) < 90^\circ$
 $\theta = (\lambda + \alpha) - 90^\circ$ if $(\lambda + \alpha) > 90^\circ$
 $\theta = |(\lambda + \alpha) - 90^\circ|$ in general

System optics

For PAMSATMBC, when the sun faces the polar axis mounted collector directly on an Equinox day the concentration factor for the system would be 2 throughout the day as may be derived from a simple optical analysis . This would be the maximum and occurs twice in a year. A length to width ratio of 10 may be chosen to minimize the end loss effects which , if one wishes, could be reduced by using one or two additional booster mirrors at both the ends. For any other day and at any other instant of sun shine, that component of the incident solar ray projected on to the plane which is vertical to polar axis (V_p) would be available either for direct absorption by the collector or for absorption by the collector after reflection by booster mirrors. That component of incident radiation which lies along polar axis would miss both the collector and the mirrors and hence are not useful. When there is a booster mirror at the top end of collector, part of the tangential component of incident radiation may be available which is being small, is ignored in present studies.

Computing solar position

The solar azimuth and solar altitude angles for select Indian locations spread wide across Indian subcontinent and for select days (consecutive solstice and equinox days during year 2014-2015) were computed using an online calculator available at <http://www.nrel.gov/midc/solpos> (accessed on 21st Mar 2015). For studying the trend of variation and for approximate computation, in the first instance, 30 minute time intervals were chosen. Location specific data are shown in Table 1.

Table 1.Location specific data for three Indian cities

Place	Lat ^o N	Long ^o E	Alt. m,a.s.l
Ahmedabad	23.03	72.58	53
Kanyakumari	8.08	77.57	0
Leh, J & K	34.15	77.58	3409

Solar beam radiation

The terrestrial solar beam radiation at any given place at a height above sea level h , day of the year and time of the day under clear sky condition is given by [4,5]

$$I_D = 1.353 [(1 - 0.14h) 0.7^{(AM^{0.678})} + 0.14h]$$

and the global radiation is given by

$$I_G = 1.1 I_D$$

The effects of day of the year and the time of the day are reflected in the air mass AM value which is defined as the ratio of path length travelled by sun ray to the depth of the atmosphere.

In a single axis tracking polar axis mounted solar collector the optical analysis may be carried out in two stages, as relating to (1) solar collector only (2) booster mirrors

I. Solar collector optics

The solar collector optics is as shown in Fig 2 and Fig 3. The normal component of obliquely incident solar radiation gets mostly absorbed after incidental thermal and optical losses. The tangential component of obliquely incident solar radiation misses the collector and escapes into atmosphere.

Normal component of solar beam radiation incident on collector

$$I_{DC} = I \cos\theta \quad (1)$$

Total solar beam radiation energy incident on collector aperture area.

$$I_{DCT} = I A_C \cos\theta$$

Total global radiation (beam + diffuse) energy incident on the collector aperture area

$$I_{GT} = 1.1 I A_C \cos\theta \quad (2)$$

The $\sin\theta$ component which is tangential to the collector aperture is missed by it and hence not useful. Since the booster mirror axis is also parallel to the collector axis, this tangential component will be missed by the booster mirror too and hence will not be reflected onto collector.

II. Booster mirror optics

The normal component of obliquely incident solar radiation gets mostly reflected onto the collector after incidental thermal and optical losses. The tangential component of obliquely incident solar radiation misses the mirror and escapes into atmosphere.

Normal component of solar beam radiation incident on mirror

$$I_M = I_D \cos\theta \quad (3)$$

To understand and compute the solar beam radiation energy incident on mirror, one may imagine that the collector aperture plane has been rotated by 120° about polar axis and with respect to original collector aperture plane. Subsequently the original energy incident on the rotated plane would be reduced proportionate to the projected area of the rotated plane. Thus amount of solar beam radiation energy intercepted by one booster mirror and reflected completely on to the collector aperture (because of chosen angle of 120° between the mirror and collector)

$$I_{DMC} = I_M \cos 60^\circ$$

II. Booster mirror optics

The normal component of obliquely incident solar radiation gets mostly reflected onto the collector after incidental thermal and optical losses. The tangential component of obliquely incident solar radiation misses the mirror and escapes into atmosphere.

Normal component of solar beam radiation incident on mirror

$$I_M = I_D \cos\theta \quad (3)$$

To understand and compute the solar beam radiation energy incident on mirror, one may imagine that the collector aperture plane has been rotated by 120° about polar axis and with respect to original collector aperture plane. Subsequently the original energy incident on the rotated plane would be reduced proportionate to the projected area of the rotated plane. Thus amount of solar beam radiation energy intercepted by one booster mirror and reflected completely on to the collector aperture (because of chosen angle of 120° between the mirror and collector)

$$I_{DMC} = I_M \cos 60^\circ \quad (4)$$

III. Optics of mirror boosted collector system

Total reflected radiation on collector area, due to one mirror, using eqn (2) and eqn (3), is

$$E_{DMC} = A_c I \cos\theta \cos 60^\circ \quad (5)$$

Total beam radiant energy reflected on to collector by two booster mirrors is

$$E_{DMCT} = 2 E_{DMC} = A_c I \cos\theta \cos 60^\circ \quad (6)$$

Thus the sum of solar radiant energy directly incident on collector, those reflected by booster mirrors, and including the diffuse radiation (taken as $0.1 I_D$) on to a solar collector that is mounted on a polar oriented axis and tracking solar azimuth angle under clear sky conditions is given by equations (2) & (6) as

$$E_{DCT} = 1.1 I A_c \cos\theta + 2 A_c I_M \cos 60^\circ = 1.1 I A_c \cos\theta + 2 A_c I \cos\theta \cos 60^\circ$$

In terms of basic parameters

$$E_{DCT} = 2.1 I A_c \cos |(\lambda + \alpha) - 90^\circ| \quad (7)$$

In the special case of horizontal collector

($\beta = 0$, $\lambda = 0$ and $\alpha = 90^\circ$ in equation (6))

$$E_{DCTH} = 2.1 I A_c \quad (8)$$

(as is to be expected and thus verified)

III. RESULTS AND DISCUSSIONS

The summary of the results of computations are indicated in Table 2. The entries are for solar energy radiation available on unit area of collectors.

From the computed estimates of enhancement of solar radiation availability at the apertures of polar axis mounted and single axis tracking collectors located at three different places of India nearly at the same longitude but at different latitudes spread over the Indian mainland, summarized in Table 2, Fig 4 and Fig 5 the following may be inferred.

- (1) As one moves away from Equator, the enhancements become more and more until the Tropic of cancer and thereafter becomes marginally less and less.
- (2) For a given place the enhancement increases from their least values in winter and peaks in summer.
- (3) Over a year and over the Indian subcontinent the enhancements range from 29% to 66%.
- (4) During summer, though Leh is farther from equator and at a high altitude, receives more radiation than Kanyakumari or Ahmedabad. During winter the trend is reversed as is to be expected.
- (5) Over the year Ahmedabad receives more radiation during late afternoon than other two places.
- (6) The difference in radiation availabilities between summer solstice and winter solstice is much larger than the difference in availabilities between summer solstice and summer equinox.
- (7) Both the systems considered here are polar axis mounted and single axis tracking. If radiation availability to two mirrors boosted system is compared with that available to solar azimuth tracking horizontal collector with a South facing mirror (such as a solar box cooker), or with fixed and polar axis mounted collector (such as solar hot water or solar PV system) then enhancements are bound to be still higher underlining the desirability of polar axis mounting and single axis tracking features.

Narasimha Rao [6] analysed the effects of providing a single adjustable mirror booster that is South facing and hinged on a box type solar cooker. The mirror is hinged on one side and points toward the south. The total energy incident on the cooker

aperture was calculated for a latitude of 18°N (Warangal City) and for five different five different days in a year. They analysed the effects of mirror adjustment considering only beam radiation to assess the energy boost. Their calculated results for one place compared the options of intermittent adjustment, continuous adjustment and fixed orientation of the mirror for three significant days. Only beam radiation was considered in the calculations. In the present study three different locations and three significant days of the year are considered. Further instead of a single south facing booster mirror, in our case East and North facing dual mirrors are considered and instead of horizontal installation of a collector a polar axis mounted and tracking collector is considered.

IV. CONCLUSION

The enhanced values of solar radiation availability at the apertures of solar thermal and solar photovoltaic collectors highlight the importance of incorporating a simple and affordable single axis sun tracker to deliver higher energy per day. The actual energy that is absorbed and delivered to loads would depend on the efficiencies of individual collectors. The enhancement would benefit solar investor in two ways, namely reducing the size of solar collector and reducing the land area for installation for delivering the same energy.

REFERENCES

- [1] http://www.solare-bruecke.org/index.php?option=com_content&view=article&id=6&Itemid=6&lang=en (accessed on 15th Feb 2015)
- [2] Suhail Zaki Farooqui A gravity based tracking system for boxtype solar cookers, *Solar Energy* 92 (2013) 62–68
- [3] Rajvir S.B and S.T.Rajan, *Using Hagen Poiseuille Flow Device as a Hydraulic Timer for very Simple Low Speed Applications*, *International Journal of Futuric Trends in Engineering and Technology*, Vol 1, Issue VI, July 2014
- [4] Honsberg C., Bowden S., Photovoltaics DROM, Properties of Sunlight, <http://pvcdrom.pveducation.org/index> accessed on 1st Apr 2015
- [5] A. B. Meinel and M. P. Meinel, *Applied Solar Energy-- An Introduction*. Addison-Wesley, Reading, Mass. (1977), pp 46
- [6] A. V. Narasimha Rao et al.,(1988), MIRROR BOOSTERS FOR SOLAR COOKERS—I, *Energy Convers.. Mgmt* Vol. 28, No. 3, pp. 265-269

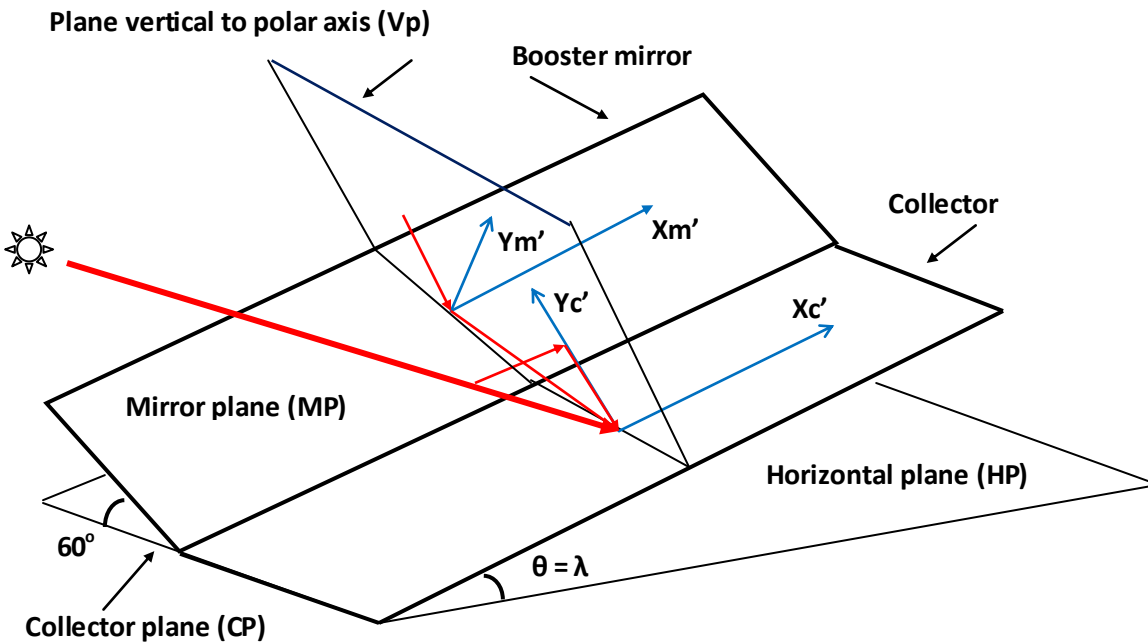


Fig 1. Polar axis mounted solar collector with two mirrors

Note: One mirror not shown for clarity of figure but which works symmetrically opposite to the mirror shown in figure. X_m' , Y_m' and X_c' , Y_c' are local coordinates specific to mirror and collector respectively and along which incident radiation is resolved.

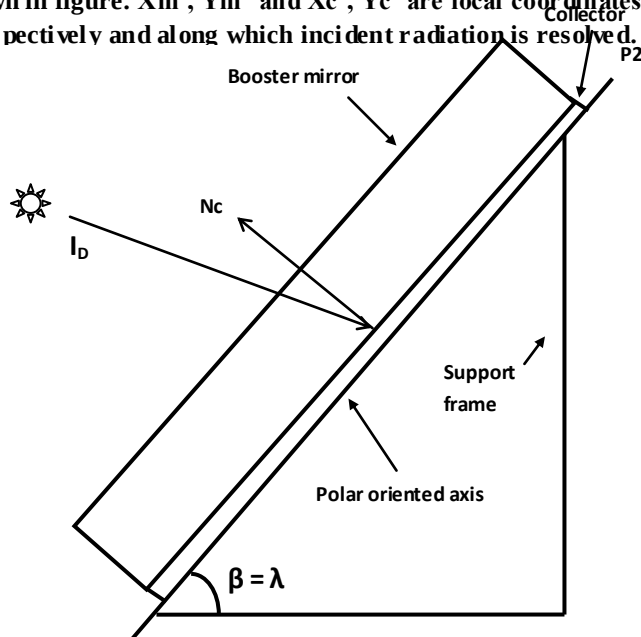


Fig 2. Scheme of polar axis mounted solar collector with double booster mirrors (only the farther mirror shown for clarity)

I_d

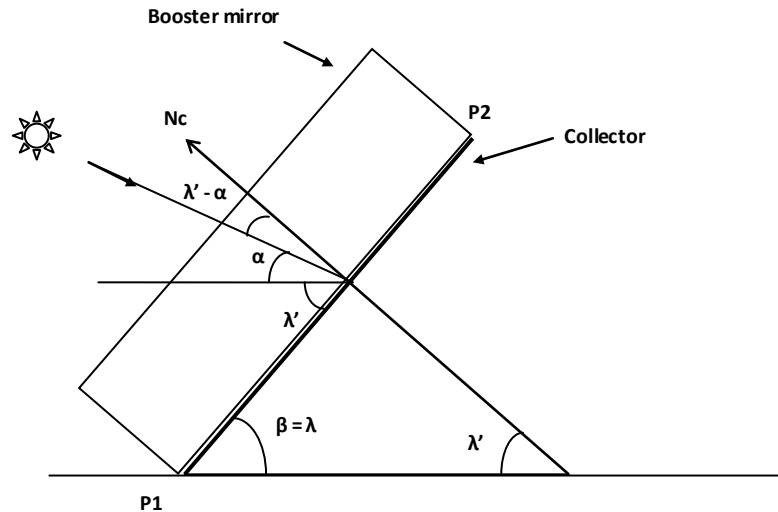


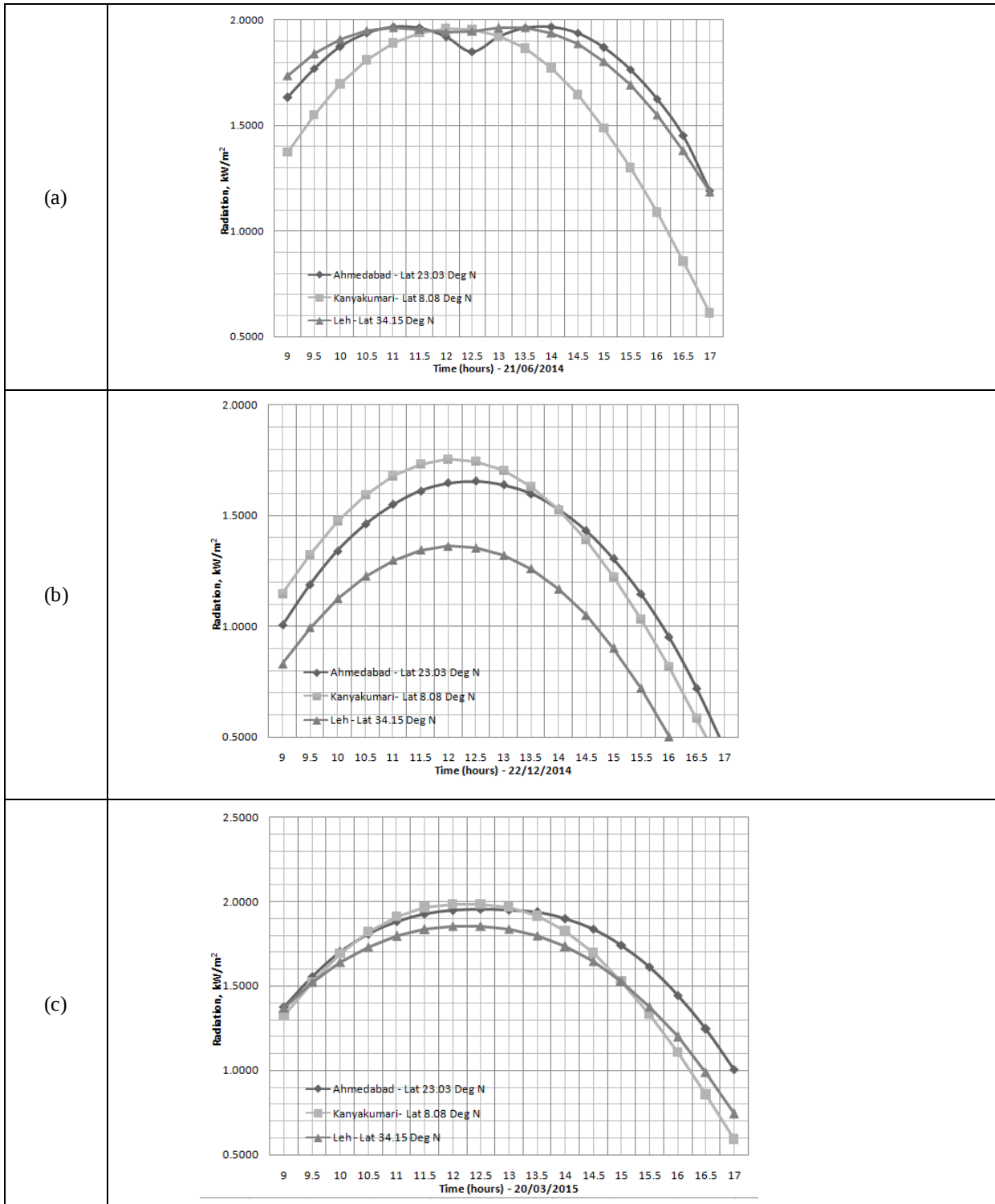
Fig 3. Optics of polar axis (P1-P2) mounted solar collector (Only one mirror shown for clarity)

Table 2. Estimation and comparison of enhanced overall solar radiation availability [kW/m²] to two-mirrors-boosted collector system with that available to a system without booster mirrors both systems being polar axis mounted and single axis (solar azimuth) tracking under clear sky conditions, assuming the working day to be from 9:00 am to 5:00 pm

Day →	21 st Jun 2014		22 nd Dec 2014		20 th Mar 2015	
Place	I _C	I _{MBS}	I _C	I _{MBS}	I _C	I _{MBS}
Kanyakumari	8.96	13.35	8.45	11.34	8.99	13.51
% increase		49		34		50
Ahmedabad	9.28	15.30	7.79	11.11	8.90	14.41
% increase		65		43		62
Leh, J & K	9.21	15.30	6.51	8.36	8.50	13.23
% increase		66		29		56

Note

I_C Total Solar radiant energy (Global = beam+diffuse) available to collector only [kW/m²]
I_{MBS} Total Solar radiant energy available to mirrors- boosted collector [kW/m²]



**Fig 4. Comparison of solar radiation availabilities at Ahmedabad, Kanyakumari and Leh on a given day
(a) 21st June 2014 (b) 22nd Dec 2014 and (c) 20th Mar 2015**

