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SHAPE ADOPTIVE SOLAR COLLECTOR: DESIGN METHODOLOGY

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Abstract — *This thesis work describes the design methodology, simulation, and validation of a mathematical model (optical) for a Shape adoptive solar collector. Function of the model is to simulate the optical dynamics of a Collector system for heating water.*

Complete design methodology of Shape adoptive solar collector is shown. This design consists of design of bracket, shaft and ball bearing. Need of each elements belongs to collector is also described. Torque and step angle required to track the sun is calculated and it is given to shaft by means of steeper motor.

Optical analysis of Shape adoptive solar collector has been done Here all analysis is concerned for Trichy. Tilt angle of all reflectors at different time for the 15^{th} of April are simulated and represented in terms of graph. It has been noticed that for all reflectors which are placed left side of receiver tilt angle increases with time and vice-versa. Inclination of reflector with their position are also simulated and has been noticed that inclination goes on slightly increasing with their position from extreme left side to extreme right side for a given angle of incidence of radiation. Optical efficiency for maximum reflection with receiver diameter is also simulated and it is found after certain value of receiver diameter optical efficiency value approaches to constant value that results optimum diameter of receiver for maximum reflection.

Keywords- *Solar collector; Optical; Design; Reflector; Inclination; Steeper motor; Optical efficiency*

I. INTRODUCTION

Concentrated Solar Power (CSP) may play a major role in the future energy mix, especially in countries with a very high annual global direct irradiation, where it seems to be a more cost-effective technology than photovoltaic for electricity generation or other process work. Nevertheless, it is still not a mature technology, even though 354MW were installed in Mojave Desert during the 1980s and 1990s.There are many possible configurations for CSP, such as parabolic dish, linear Fresnel, parabolic trough and central receiver. A typical linear Fresnel reflector consists of long narrow flat mirror elements fixed on a horizontal base. Each mirror element is tilted at an angle such that all incident solar rays falling on them are reflected to a common focus. The absorber is placed on the focus to absorb the concentrated radiation. The absorber is generally a tube or a series of tubes which contains a heat transfer fluid. Fresnel reflecting concentrator has several advantages, (i) it is useful for medium-temperature range (100–250˚C) applications (ii) it is fabricated with narrow flat mirrors or flat facets made up of constituent materials for its fabrication as well as replacement are readily available in the market; (iii) the planar configuration and the air gap between the adjacent mirrors result in very small wind loading on the concentrator. Because of this, it can be mounted on rather simple cost-effective supporting structure.

In this study, a theoretical analysis is carried out to investigate the optical performance of Shape adoptive solar collector with a cylindrical receiver. This system consists of flat facet reflection field, and metal tube absorber. Facets are horizontally placed by maintaining a suitable gap between each other and one central receiver is placed at a certain height. Working fluid is taken as water circulating in absorber. Each reflector has separate tracking mechanism (Stepper motor) and allowed to rotate independently as per angle of incidences of radiation. Reflectors acquires the desired shape for maximum reflection in each time, hence this Collector system is called as Shape adoptive solar collector.

The objective of the work presented in this thesis is to design and simulate the performance of a Shape adoptive Solar Collector with Flat reflectors using optical modeling. Results from the theoretical model are validated with data gathered from a published paper (experimental). In this thesis, complete design of collector has been carried out and an optical model has been developed by using MATLAB programming. Same designed Collector and their derived model has been simulated for location as Trichy and performances are observed.

From optical model, optical efficiency, optimum inclination of each reflector with respect to receiver line at each time throughout a day and optimum receiver diameter are obtained for Trichy and curves are drawn and interpreted.

II. DESIGN OF SHAPE ADOPTIVE SOLAR COLLECTOR

2. Introduction

This chapter illustrates a methodology for design of entire elements being involved in Shape adoptive collector and their construction details. At last of this chapter a table showing summary of design data is also included. Various elements like facet, bracket, shaft and bearing to be designed and stepper motor for required torque and step angle also to be selected.

2.1. Facet

Surface of flat reflector is generally called as a facet shown below in figure 1. It is required to reflect the solar radiation incident over it to the receiver as much as possible. Its dimension is been taken arbitrarily as per the past data. Material as aluminum is chosen but it can be replaced by flat mirror also for better reflection.

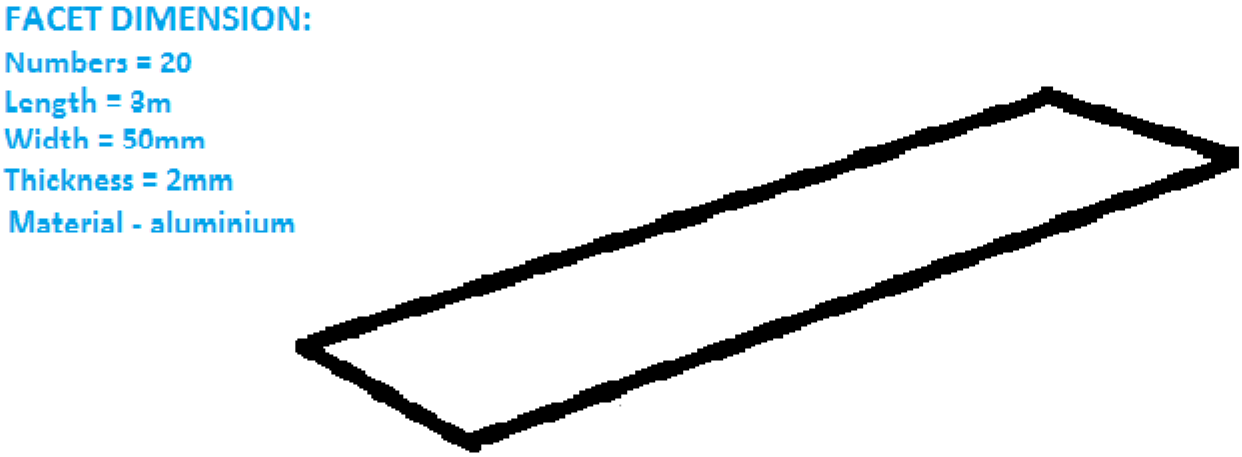

Figure 1.Facet

2.2. Bracket

Bracket is needed to place the facet over it. L-type of bracket is selected as shown in figure 2. Its length, width and thickness have been taken as per facet requirement and height is determined and shown below. Facet is fastened with bracket by help of screws and nuts.

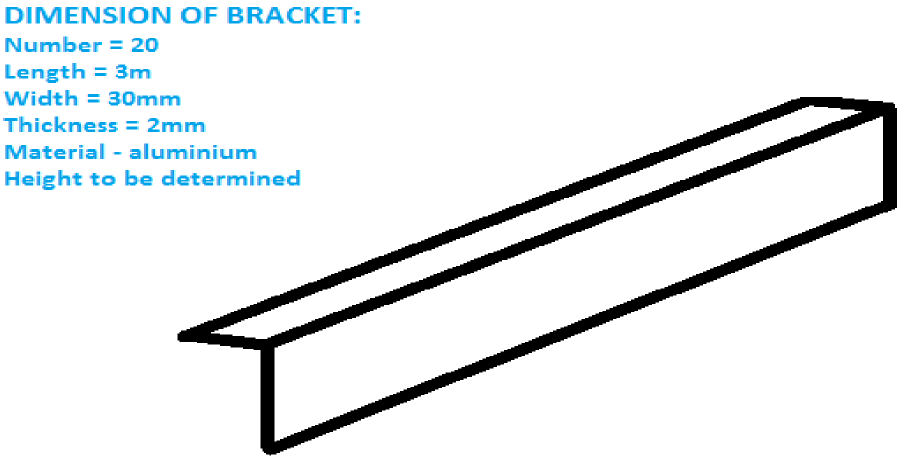

Figure 2.Bracket

Given
Material: Aluminum
Density of aluminum = 2700 kg/m^3
Modulus of elasticity (E) = 69 GPa
Length (L) = 3 m
Width (w) = 30 mm
Thickness = 2 mm
Mass loaded on the bracket (m) = (m) = $\rho \times v = 2700 \times (3 \times 50 \times 10^{-3} \times 2 \times 10^{-3}) = 0.81$ kg
Hence weight = 0.81×9.81 = 7.95 N
Weight per unit length (W/L) = 7.95/3 = 2.65 N/m
Here bracket is assumed as a simply supported beam with uniform loading.
Hence maximum deflection may take place at middle of bracket.
Maximum deflection,

$$\delta = \frac{5WL^4}{384EI}$$

Let us assume maximum deflection is 0.3mm

Hence $\frac{5WL^4}{384EI} = 0.3 \times 10^{-3}$

$EI = 9311.84\ Nm^2$
$I = 1.35\times10^{-7}\ m^4$
But $I = bH^3/12$
$1.35\times10^{-7} = (2\times10^{-3})\ h^3/12$
H = 93 mm
Maximum bending moment = $WL^2/8 = 2.98$ Nm
Bending stress can be calculated as
$\sigma = My/I = 2.98\times0.0466\times10^7/1.35 = 1.03$ MPa

2.3. Shaft

Shaft is required for rotating the facet-bracket assembly. It rests on bearing from both side and powered with stepper motor connected from one side of it. Material is selected as aluminium because of its properties like light weight, relatively cheaper and wide availability.

Given
Material – Al
For Al
$G = 25.5\times10^9$ Pa
$S_{ut} = 110\times10^6$ Pa
$\tau_{max} = 0.18S_{ut} = 20$ MPa
$\sigma t_{max} = 0.36S_{ut} = 40$ MPa
l = 3.1 m
$\theta = 0.9$ to 1.8 deg
Mass loaded on shaft = mass of bracket + mass of facet
Mass of bracket = $[(3\times30\times10^{-3}\times2\times10^{-3}) + (3\times9.3\times10^{-2}\times2\times10^{-3})] \times2.7\times10^3 = 1.9926$ Kg
Mass of facet = 0.81Kg
Hence weight on shaft = (1.9926+0.81) ×9.8 = 28 N
Now Maximum bending moment = 14 × 1.55 = 21.7 Nm
Since shaft is subjected to bending moment only
From flexural formula
$M/I = \sigma/Y$
21.7/ (0.049D^4) = (40×〖10〗^6×2)/D
D = 17mm
But when deflection will be given to shaft, it subjects under torsional moment also
Hence from torsional formula
$T/J = G\beta/l$
If $\beta = 0.9$deg
T = 1.1 Nm
$\beta = 1.2$
T = 1.41 Nm
$\beta = 1.8$deg
T = 2.11 Nm

2.4. Bearing

Bearing is required to provide support to the shaft from both end as well as smooth rotation. Single row deep groove ball bearing is taken into account.

Given
Single row deep grove ball bearing
Material – Al
Total radial load on bearing = shaft load + bracket load +facet load
Shaft load = [(π× (8.5×10-3)2×3.1)] ×2700 = 1.89 Kg
Other load (bracket+ facet) = 2.8 Kg
Hence total radial load = 1.89 +2.8 = 4.7 Kg
Total radial weight = 4.7×9.81 = 46 N

Since there will be two bearings of each shaft
Hence radial weight on each bearing (W_r) = 23 N
Let axial weight (W_a) = 8 N
Speed of shaft
Let us assume each day shaft deflects from 20deg (initial position) to 160deg (final Position) and takes 6hr.to complete this deflection.
So rev per min is 7×10^{-3}
$N = 7\times10^{-3}$ rev/min
Life of bearing for intermittent and light weight operation
L_h = 1200 hrs (Taken from data book)
Life in rev. is
$L = 60\times N\times L_h = 60\times7\times10^{-3}\times1200$
L = 488 rev
Radial load factor and axial load factor(X&Y)
$W_a/W_r = 8/23 = 0.3478$
$W_a/Co = 0.5$
From data book table
X = 0.56
Y = 1.0
Rotation factor (V) = 1 (for inner race rotating)
Dynamic equivalent load (W)
$W = XVW_r + YW_a$
$W = (0.56\times1\times23) + (1\times8)$
W = 21 N
Basic dynamic load capacity(C)
$C = W\,(L/10^6)^{1/3} = 21(488/10^6)^{1/3}$
C =1.7 N
Based on basic dynamic load capacity suitable bearing as per requirement may be selected from manufacturer catalogue.

2.5. Motor selection

Each reflector needs to be rotate intermittently to track the sun. This rotation has to be provided by stepper motor. Selection of Suitable Stepper motor is essential to fulfill the demand of desired amount of torque and steps.
Given
Stepper motor
Step angle = 1.2 deg
Output torque required = 1.41 Nm
Turn rate = 5.42×10^{-3} steps/sec
By matching such specification with commercially available motor, motor can be chosen.

2.6. Summary of design

When all the elements designed above assembles together that appears like a structure (reflector) as shown in figure 3. All the data related to their design are tabulated in table 1.

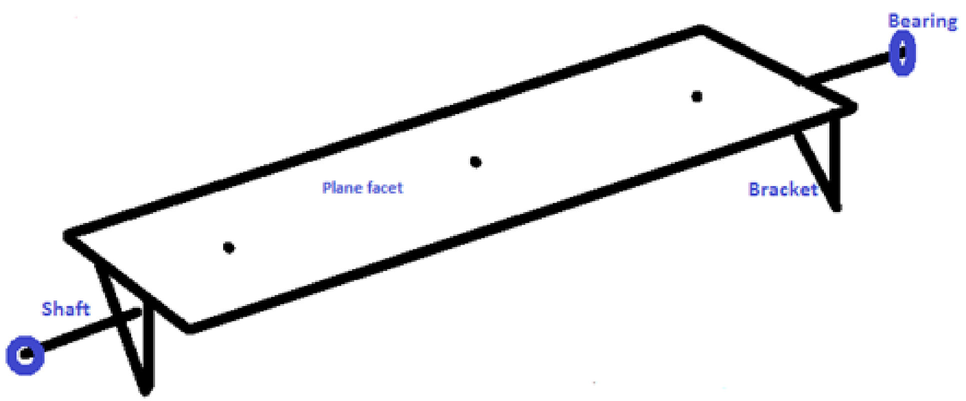

Figure 3.Construction of reflector

Table 1.Design data summary

COMPONENTS	NUMBERS	MATERIAL	DIMENSIONS
Facet	20	Aluminum	L = 3 m, w = 50 mm B = 2 mm
Bracket	20	Aluminium	L = 3 m, w = 30 mm B = 2 mm, H= 93 mm
Shaft	20	Aluminium	L = 3.1 m, D = 17 mm
Bearing	40	Aluminium	d_o = 20 mm, d_i = 18mm, C = 1.7 N
Stepper motor	20		β = 0.9 deg , T = 1.1 Nm

III. OPTICAL ANALYSIS

3. Introduction

This chapter illustrates optical analysis of Shape adoptive solar collector. Here all analysis is concerned for Trichy. The outcome of this analysis includes variation of angle of incidences (zenith angle) of solar radiation with time, optimum inclination of each reflector at each time with respect to receiver line for maximum reflection, optical efficiency and corresponding optimum receiver diameter of receiver for maximum reflection.

3.1. Optical modeling

The main objective of the optical model is to calculate the solar radiation that leaves the reflector field and reaches to absorption pipe. The calculated solar radiation is an input parameter for thermal model. The model also calculates all the optical parameters of the primary collector system such as reflector inclination, Optical efficiency, Optical losses etc. Mat lab is used to solve optical model whose input and output parameters are like dimension of reflector, properties of reflector (absorbtivity, reflectivity etc.), Insolation intensity, emissivity of receiver etc.

3.1.1. Variation of Angle of incidences of radiation with time

Angle of incidence or zenith angle can be defined as angle subtended by radiation with normal to the plane. In figure 4, Variation of incidence angle of radiation with time is shown. It is drawn for Trichy for the day of 15^{th} April. Before going to optical analysis it is necessary to know about the variation of angle of incidences with time of a place where Collector is supposed to be installed. Inclination of each reflector with time to be simulated based on these angles of incidences.

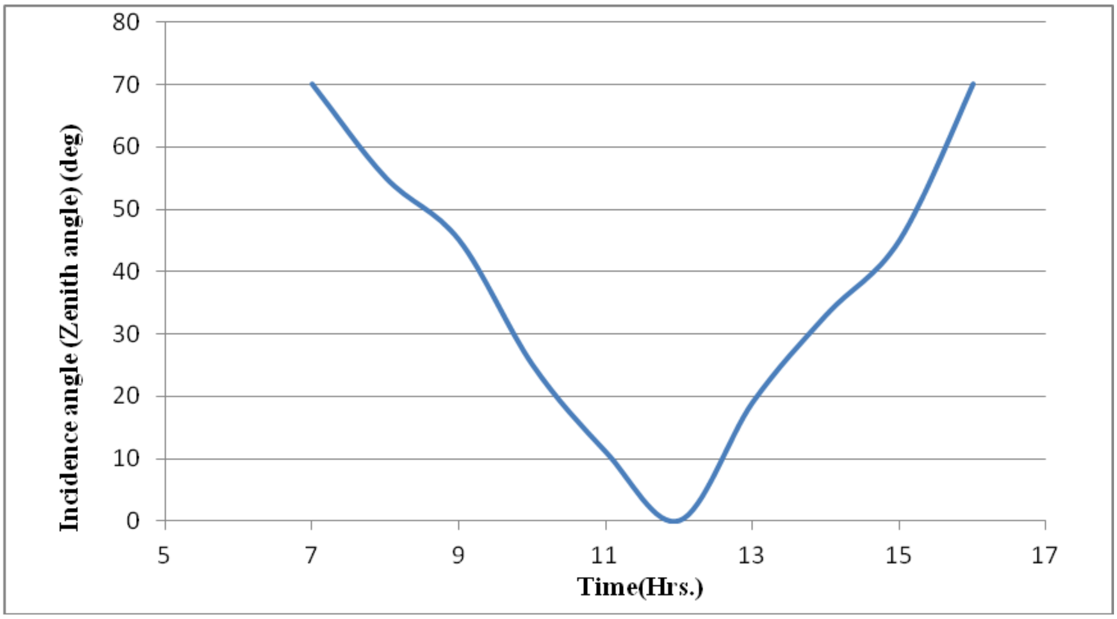

Figure 4.Variation of Zenith angle with time for Trichy on 15th April

3.1.2. Optimum inclination of reflectors

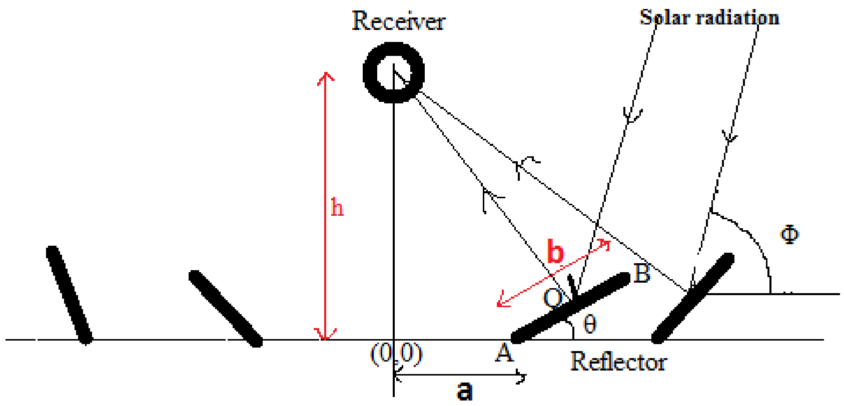

Figure5. Schematic of ray tracing for optimum inclination of reflector

In order to maximize the reflections to receiver optimum inclination of each reflector is done for different angle of incidences. A sketch of ray tracing for optimum inclination is shown in figure5. Twenty reflectors are taken into consideration, ten each side of receiver. For each reflector there will be different inclination for each angle of incidences. Reflectors are kept 2mm apart of each other.

At any instant let angle of incidence of solar radiation is Φ for which optimum angle of inclination is θ for a reflector AB aparted by distance 'a' from centre as shown in figure5.

Co-ordinates of A = (a, 0)

Co-ordinates of Q = (a + b/2cosθ, b/2sinθ)

Equation of AB

$y = \tan\theta\ (x-a)$ .... (1)

Equation of ray

$y - b/2\sin\theta = \tan\Phi\ (x-a-b/2\cos\theta)$ . .. . (2)

Angle of reflection

$\Phi' = \theta - \Phi + 90$ .... (3)

Slope of reflected rays

$\theta' = 2\Phi' + \Phi$ .... (4)

Equation of reflected rays

$y - b/2\sin\theta = \tan(2\Phi' + \Phi)(x-a-b/2\cos\theta)$ .... (5)

This reflected rays cuts the y-axis

i.e.; x = 0

Now equation (5) reduces to

$y = b/2\sin\theta - \tan(2\Phi' + \Phi)(a + b/2\cos\theta)$ .... (6)

Thus equation (6) gives point of reflection at centre of receiver.

i.e. $YR = b/2\sin\theta - \tan(2\Phi' + \Phi)(a + b/2\cos\theta)$ .... (7)

If value of YR matches to height of receiver 'h' then it shows optimum inclination of a particular reflector at given angle of incidence.

3.1.3. Optical efficiency of Collector

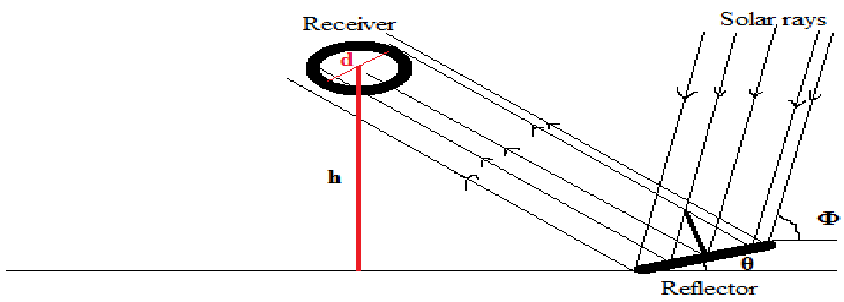

Figure 6.Schematic of ray-reflector-receiver interaction

A mathematical model is obtained to get optical efficiency of collector. A schematic of ray-reflector-receiver interaction is shown in figure6.It is assumed that reflectors are oriented in such a way that (optimum inclination) maximum number of radiation reflects to receiver. Receiver is kept at a particular height 'h' having diameter'd'.

From figure6.It is clear that maximum number of rays either touches or intersects to receiver. Only some of rays go away to receiver. Number of rays going away to receiver to be counted from given number of rays incidented over the reflector.

Equation of reflected line

$y - b/2\sin\theta = \tan(2\Phi' + \Phi)(x-a-b/2\cos\theta)$ .... (1)

Cross-section of cylindrical receiver is circle and equation of circle with centre (0, h) and radius 'r' is

$(x-0)^2 + (y-h)^2 = r^2$ .... (2)

Solving equation of circle and reflected line together, there will be a quadratic equation as follows

$Ax^2 + Bx + C = 0$ .... (3)

Where

m = Slope of reflected line

$A = 1 + m^2$

$B = 2my - 2hm - 2m^2x$

$C = m^2x^2 + y^2 + h^2 - r^2 - 2mxy - 2hy + 2hmx$

Condition of rays focused to receiver

$D = B^2 - 4AC$

If D >0 ......Ray cuts the absorber

D = 0 ..... Ray touches the absorber

D <0 ......Ray do not touches the absorber

Absorbed intensity by absorber

$IA = \alpha\rho I_o$

Optical efficiency of collector

$\eta = (\sum IA)/(NIo)$ .... (4)

IV. RESULTS AND DISCUSSION

4. Introduction

Optical model and thermal model for surface adoptive solar collector has been developed in previous chapter. In this chapter results and interpretations based on simulation and modeling has been shown and described.

4.1. Simulation results of optical modeling

In Table2. Tilt angle of the all reflectors of collector at different times are shown. For each reflector at each time, the tilt angle is simulated by the optical model. The input of model has been given for location as Trichy of 15th of April .the reflectors far from line of the receiver pipe are more inclined than the reflectors more centered in collector, due to relative position between reflector, receiver pipe and sun.

Table2. Tilt angle of each reflector at different time

Local time (Hrs.)	Ref 1 (Deg)	Ref 2 (Deg)	Ref 3 (Deg)	Ref 4 (Deg)	Ref 5 (Deg)	Ref 6 (Deg)	Ref 7 (Deg)	Ref 8 (Deg)	Ref 9 (Deg)	Ref 10 (Deg)
8:00	50.4	48.8	47	45	42.8	40.4	37.8	35.03	32.08	29.08
10:00	33.7	32.1	30.3	28.35	26.2	23.8	21.2	18.4	15.54	12.54
12:00	22.6	21	19.2	17.2	15	12.7	10.1	7.3	4.5	1.54
14:00	-0.2	-1.8	-3.5	-5.4	-7.5	-9.9	-12.4	-15.1	-18	-20.93
16:00	-12.6	-14.1	-15.8	-17.8	-19.9	-22.2	-24.8	-27.5	-30.4	-33.42

Local time (Hrs.)	Ref 11 (Deg)	Ref 12 (Deg)	Ref 13 (Deg)	Ref 14 (Deg)	Ref 15 (Deg)	Ref 16 (Deg)	Ref 17 (Deg)	Ref 18 (Deg)	Ref 19 (Deg)	Ref 20 (Deg)

8:00	-25.99	-23.1	-20.3	-17.6	-15.1	-12.8	-10.6	-8.6	-6.8	-5.3
10:00	-9.47	-6.55	-3.7	-1	1.6	3.95	6	8.1	9.7	11.5
12:00	1.54	4.5	7.3	10.1	12.7	15	17.2	19.2	21	22.6
14:00	18.04	20	24	26.7	29.3	31.7	33.9	35.9	37.8	39.2
16:00	36.59	39.6	42.5	45.3	48	50.4	52.6	54.5	56.3	57.9

Inclinations of reflectors are simulated from -90˚ to +90˚with x-axis. In figure7.Variation of inclination of reflectors with respect to time is shown. Two curves are presented, one of them showing pattern of variation of tilt angles for reflectors which are placed left side of receiver where as other representing same for reflectors situated right side of receiver line. Variations are same for both side of receiver line except take place reversely. It is because target of focus for left side of reflectors is right side and vice-versa. All inclinations of reflectors are simulated with positive x-axis regardless of their position.

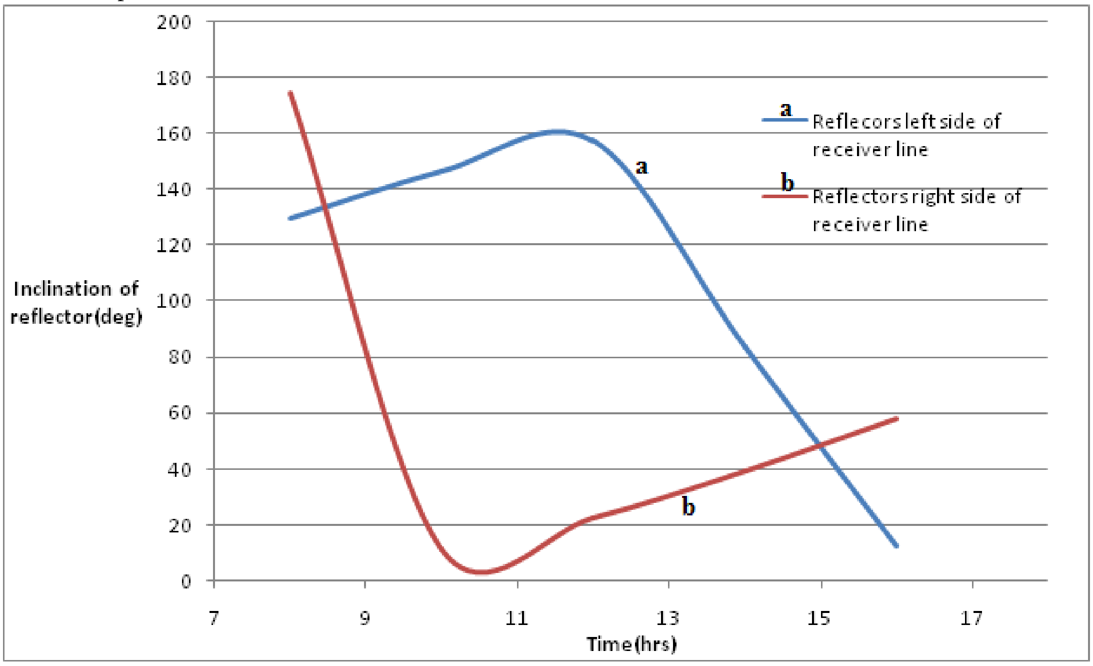

Figure 7.Variation of reflectors inclination with time

In figure8.Inclination of reflectors with respect to their position is shown. Usually the reflectors far from line of the receiver pipe are more inclined than the reflectors more centered in collector, due to relative position between reflector, receiver pipe and sun. But in below graph it is slightly increasing from reflector1 to reflecor20 because all inclinations are considered from one side of axis (positive x-axis).

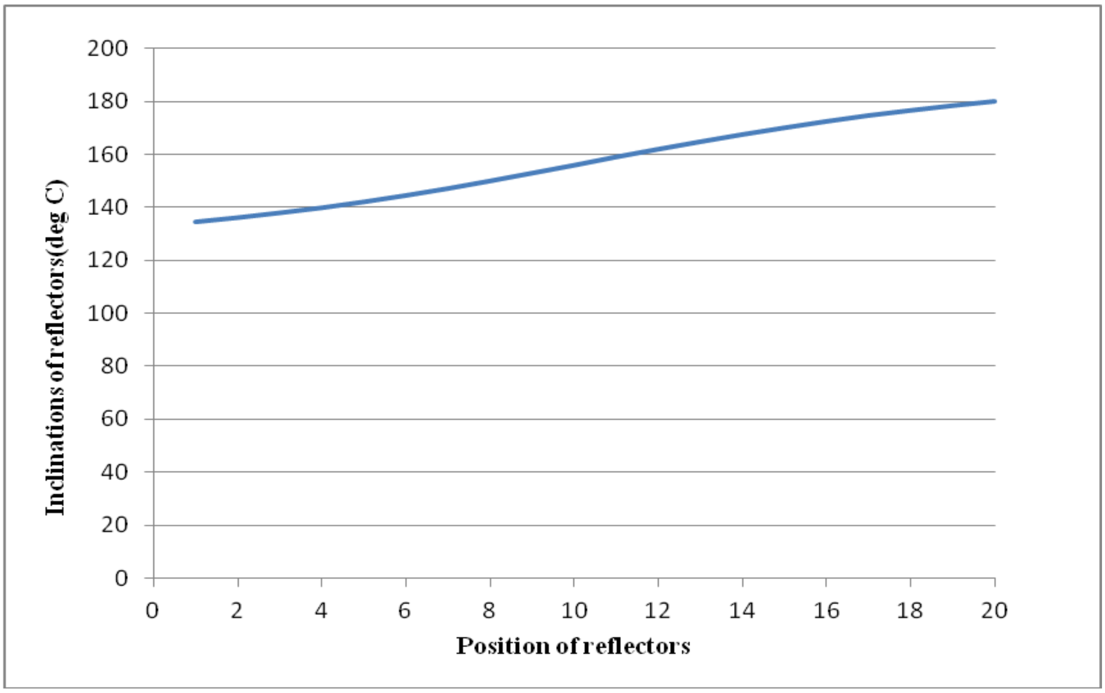

Figure 8.Variation of inclination of reflectors with their position for a given time

In figure9.Graph of optical efficiency of collector with diameter of receiver is shown. Optical efficiency at each receiver diameter is simulated from optical model. This graph plays a vital role to determine optimum diameter of receiver for maximum efficiency of collector. In curve it can be easily seen that after certain value of receiver diameter optical efficiency approaches a constant value. Hence the value of diameter where graph pattern turns to straight line is optimum value of diameter of receiver.

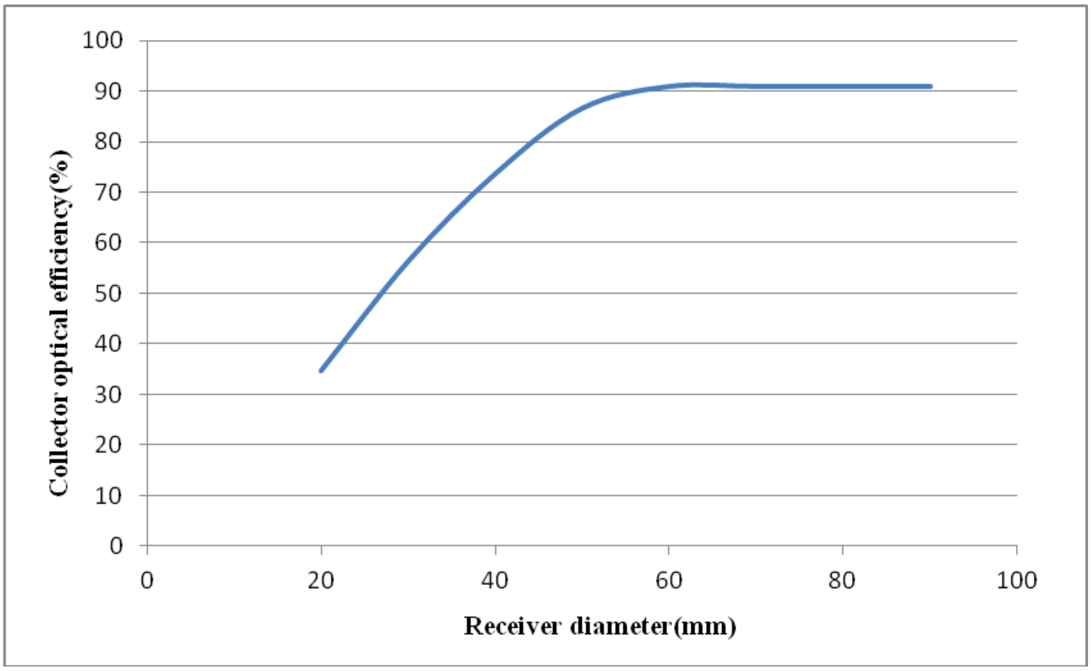

Figure 9.Effect of receiver diameter on optical efficiency of collector"

V. CONCLUSION

Complete methodology of design of Shape adoptive solar collector is presented. This design consists of design of bracket, shaft and ball bearing. In each design aluminium as a material is considered and their properties are taken into account. Need of each elements belongs to collector is also described. Torque and step angle required for steeper motor is calculated .A summary of design data is reported as well.

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Optical efficiency for maximum reflection with receiver diameter is also simulated and it is found after certain value of receiver diameter optical efficiency value approaches to constant value that results optimum diameter of receiver for maximum reflection.

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