Design, Simulation and Manufacturing of an Integrated Composite Material Parabolic Trough Solar Collector

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Abstract— Design, simulation, and manufacturing process of an integrated thermal photovoltaic closed parabolic collector (ITPVCPC) using composite material is presented in this paper. The design includes two flanges for supporting photovoltaic panels. Two cases of troughs were designed and studied, one with glass cover over the aperture area and another without it in order to investigate the structure rigidity and solar ray collection in the absorber tube. Three-dimensional modelling and structural finite element analysis (FEA) based simulation was done for the design. In the simulation, the ITPVCPC structure was subjected to the upper limits of wind pressure and temperature-rise loadings similar to the real working conditions. Optical analysis was done for the trough to study the effect of structure deformation on solar ray collection. The glass covered ITPVCPC showed higher structure deformation than the one without glass. Glass fiber with polyester resin was used in the manufacture of ITPVCPC for its low price compared to other composite materials. The study shows that glass fiber (with polyester matrix) is an ideal composite material for ITPVCPC for its high rigidity, low cost, and ease of manufacture. This design is successfully implemented and is the source of thermal and electrical power for a solar desalination system installed in Jeddah, Saudi Arabia.

Keywords: Finite element analysis (FEA), concentrating solar power (CSP), hand-layup method, glass fiber reinforced polymer (GFRP)

I. INTRODUCTION

Fossil fuels such as petroleum oil, coal and natural gas are used as a primary energy source in developed nations. These carbon rich fuels release CO2 to the environment which has a negative effect on the atmosphere. It alters the radiation-balance of the earth and promotes global warming [1]. This has forced the consumers to think of alternate sources which would be cheap at least in the long run. Due to awareness of pollution and economics of fuel, the focus is now shifted to solar and other clean energy sources. Parabolic trough technology is currently the lowest-cost concentrating solar power (CSP) technology for electricity production [2]. Parabolic trough collector (PTC) uses a highly reflective surface to focus incident solar rays on a heat collector element (HCE) also called receiver tube. The receiver tube is placed at the point of convergence (focal point of parabola). The tube contains a working fluid that absorbs solar heat and gets heated up to temperatures of 350o C or more. It is enveloped by an evacuated (vacuumed) glass tube to reduce convective heat loss to the surrounding. The collector has a disadvantage of smaller angle of view. Therefore, to maximize the solar heat gain, a tracking mechanism is used to align it with respect to the changing position of the sun. Collector is being considered for a lot of applications like Enhanced Oil Recovery (EOR) [3], water disinfection in third world countries [4], desalination [5], refrigeration and cooling [6], heating applications [7] etc. Many innovative approaches to reduce the cost and increase the efficiency of collector were adopted in recent times. With an aperture of 7.5 m and length 247 m the Ultimate Trough (UT) in 2013 became the largest collector ever built and operated [8]. This collector made of steel is deployed in California and is expected to reduce the solar field cost by 20 to 25%. A composite collector was manufactured in 1994 using fiberglass and dead load corresponding to 145 km/h wind velocity was applied [9]. The deflection at the center using a dial gauge was measured as 1.2 mm. In the same year mild steel was used for collector manufacture and deflection upon static loading using sand bags was measured as 0.01 mm [10]. A 7 mm thick fiberglass collector was manufactured in 2006 and tested using sand bags as static load [11]. The deflection using 72 kg loading was 0.95 mm at the center using dial gauge. Calculation intensive Monte Carlo ray tracing methodology is very common for optical analysis and has been used by Z.D. Cheng et al [12] and Wang Fuqiang et al [13] for PTC performance analysis. This paper proposes a mathematical model for evaluation of solar ray collection for a PTC which is directly linked to input thermal energy for the collector. An important factor for parabolic trough design is that it should not distort, primarily under wind loads, and should withstand the heat generated due to the sun. The simulation includes the study of deflection in the collector structure subjected to wind pressure and thermal loads. Optical analysis using mathematical formulation for solar ray collection is done for evaluating the effect of deflection in the design. Then a manufacturing methodology of hand-layup is presented and implemented for the current design.

Nomenclature

F	Focal length of parabola	*Greek symbols*	
H	Height of parabola	**n**	Poisson's ratio
Y	y-axis of parabola	κ	Conductivity
X	x-axis of parabola	α	Coefficient of thermal expansion
S	Length of parabola arc	ρ	Density
W	Width of parabola		
L	Length of the parabolic trough / receiver tube	*Acronyms*	
		collector	Parabolic trough collector
D	Receiver tube outer diameter	*CAD*	Computer aided design
S4RT	A 4-node thermally coupled thin or thick shell	*CSP*	Concentrated solar power
		CFRP	Carbon fiber reinforced polymer
U	Spatial displacement at nodes	*GFRP*	Glass fiber reinforced polymer or Eglass
C	Geometric concentration ratio	*FEA*	Finite element analysis
E1	Young's modulus in fiber direction	*ASCE*	American Society of Civil Engineers
E2 and E3	Young's modulus in transverse direction	*BC*	Boundary condition
		HCE	Heat collector element
G	Shear modulus	*PV*	Photovoltaic

II. DESIGN

Integrated Thermal Photovoltaic Closed Parabolic Collector (ITPVCPC) is a parabolic solar collector which is made of composite material and has provision for photovoltaics (PV) to be integrated with the body. In a solar power plant, the tracking mechanism requires electrical energy, therefore to make this design to work as a standalone system, PV panels are thus included. The trough along with integrated flat sides and flanges is made of glass fiber with polyester matrix material. The trough length is 2150 mm and the length of the parabolic arc is 1965.5 mm. The trough has two extensions on in the form of flanges to accommodate solar PV panels. The PV panels are 500 mm in width, 1000 mm in length and 25 mm in thickness.

The focal length is required to be shorter than the parabolic height to accommodate for the glass cover. The receiver tube placed at the parabolic focus is required to have adequate clearance between itself and the glass cover. The other components of the PTC are dimensioned accordingly so that they can be manufactured with ease when the design goes to the production stage. CAD modeling is done implementing the above design key points to make a comprehensive design and to visualize the exact details.

A. Parabola design

The position of the focus is a controlling factor for the current design. If the focal length (f) is more than the parabola height (h), then it will go beyond the extremities of the parabolic shape. If the focal length is less than the parabola height, then it will fall inside the parabolic shape.

In this design the trough aperture is required to accommodate a glass cover. Therefore, the focal length is required to be less than the parabola height (Fig.1). The closed parabolic trough will reduce convective heat loss from the absorber tube to the ambient air medium [14]. The glass cover will offer structural rigidity and will allow easy cleaning and maintenance without disturbing or damaging the reflector surface.

The equations of parabola involved in the design are:

$$y = \frac{x^2}{4f} \tag{1}$$

$$s = \left[\frac{w}{2}\sqrt{\left(\frac{4h}{w}\right)^2 + 1}\right] + 2f\ln\left[\frac{4h}{w} + \sqrt{\left(\frac{4h}{w}\right) + 1}\right] \tag{2}$$

$$h = \frac{w^2}{16f} \tag{3}$$

Where y is the y-axis (along parabolic axis), x is the x-axis, f is the focal length, s is the length of arc, h is the height of parabola, and w is the width. Given s, x and y, the equations are solved for w, f, and h. The values of the unknown parameters are obtained by iteration and are given in table 1.

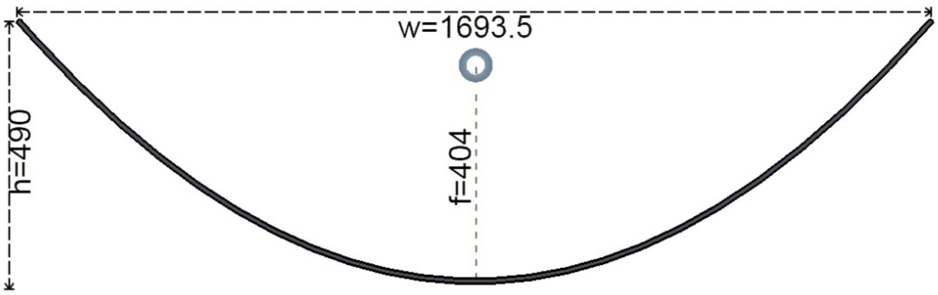

Fig 1 Key dimensions for the parabola (mm)

B. Dimensions of the collector components

It is required to have an adequate clearance between the focal point and the aperture plane which would accommodate the glass cover. The dimensions were chosen after considering the diameter of the absorber tube to be placed at the focal point (table 1). In addition, PV panels are to be accommodated on the wings of the trough (Fig.2). They would serve as the power source for solar tracking mechanism and other electric equipment in the complete system. Five ribs are placed equidistant from each other for the sole purpose of providing structural stiffness.

TABLE I Dimensions of the parabola

Description	Dimension (mm)
Focal length (f)	404
Width (w)	1693.5
Height (h)	490
Trough length (l)	2150
Length of parabolic arc (s)	1965.5
Distance between height and focal length	86
Absorber tube outer diameter (d)	42
Solar panel width	500
Ribs cross section	50 x 25

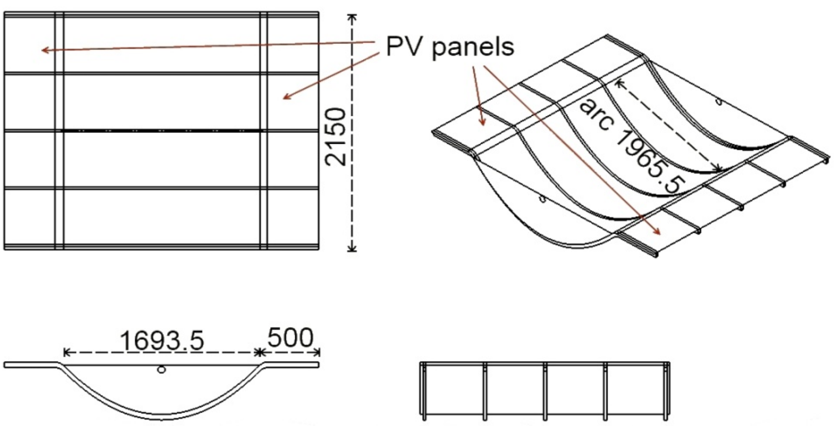

Fig 2 Parabolic trough collector (mm)

C. Geometric concentration ratio

It is the ratio between the collector aperture area and the total area of the absorber tube [15]. In this design the geometric concentration ratio (C) is 12.83, this PTC is suitable for applications like desalination, heat driven cooling and refrigeration, irrigation water pumping and space heating [16] [17].

$$C = \frac{Collector\ Aperture\ Area}{Total\ Area\ of\ Absorber\ Tube}$$

$$C = \frac{w*l}{\pi*d*l} = \frac{w}{\pi*d} \qquad (4)$$

Where w is the width of the parabola, l is the length of the trough and d is the outer diameter of the receiver tube.

D. CAD modeling of the collector unit

The parabolic trough collector is modeled in Dassault Systèmes SolidWorks® [18] software. The various components are the parabolic trough, vertical side panels for absorber tube support, ribs for trough support and shape, and flange panels for photovoltaics (Fig.3). This model is imported in Abaqus® [19] and used for finite element simulation with little or no modification. The complete assembly of PTC with mounting frame and tracking mechanism is shown in figure 4.

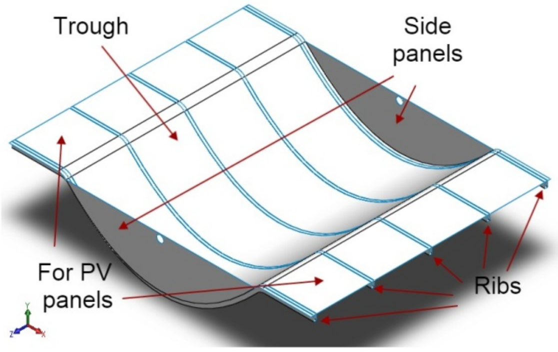

Fig 3 Collector design model

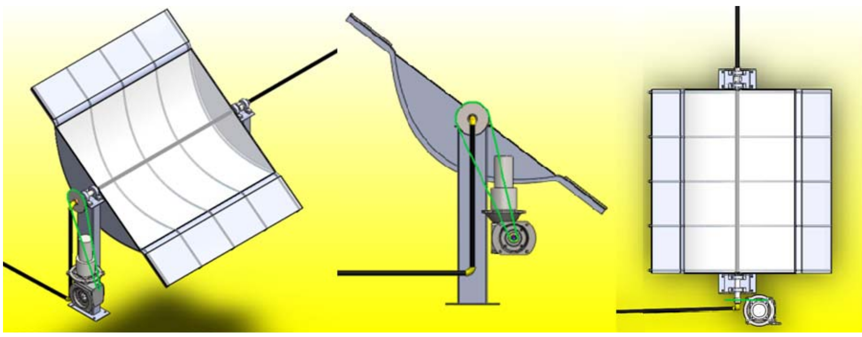

Fig 4 Complete collector assembly- isometric, side and top view (left to right)

III. MATERIAL SELECTION

The criteria for selection of materials include durability, rigidity, high strength under reasonable external loads, ease of availability and manufacture, and cost effectiveness. Composite material is one of the most advanced and major material used in modern engineering. It is a combination of two or more different materials in order to take advantage of positive properties of each constitutive material [20]. It has high strength to weight ratio (specific strength) [21], stiffness to weight ratio (specific stiffness) [22], and high resistance to heat [23] and corrosion due to chemicals. The most common composite materials used for industrial applications are carbon fiber reinforced polymer (CFRP) and glass fiber reinforced polymer (CFRP).

A. Glass fiber reinforced polymer (GFRP)

Glass fiber, carbon fiber and their hybrid is finding a variety of applications in automobile industry [24] and building construction [25]. Glass fiber being the cheaper material is used in almost all industries where structural optimization and weight reduction could lead to energy saving and cost reduction. In this paper the whole structure including the trough, the supporting ribs, flange panels for mounting of PV panels are designed with glass fiber (with polyester matrix) material. Configuration of the GFRP plies used in the design is

[0°,90°,0°,90°,+/-45°,90°,0°,90°,0°]. Each ply of glass fiber was assigned a thickness of 0.23 mm (initial sampling in the lab), therefore making the total thickness of the material 2.3 mm.

The stiffness matrix of the GFRP laminate used in the design was calculated using cash register method [26]. This is useful for determining accurate material stiffness for finite element (FE) simulation.

$$A_{GFRP} = \begin{bmatrix} 12.2 & 1.9 & 0 \\ 1.9 & 12.2 & 0 \\ 0 & 0 & 2.98 \end{bmatrix} GPa$$

B. Glass properties

A 4 mm glass sheet was attached to the collector aperture to close the trough completely. It reduces convective heat loss and could contribute to rigidity of the structure [14]. The properties of the glass used for FE simulation are given in table 2. It protects the inner lying reflective trough surface and absorber tube from dust as well (Fig.5).

TABLE II Physical properties of glass [27]

Property	Value
Density (ρ)	25 kg/m^3
Young's Modulus (E)	70000 MPa
Poisson's ratio (**n**)	0.23
Coefficient of thermal expansion (α)	9x10^{-6} K^{-1}
Conductivity (κ)	1 W/mK

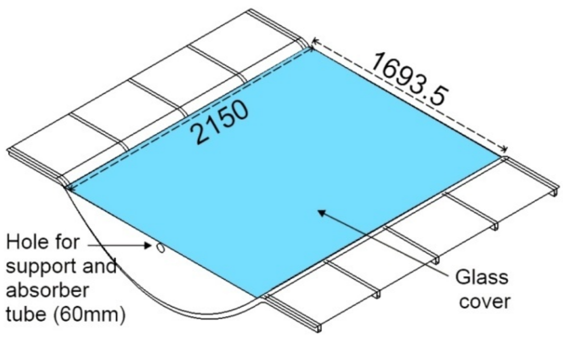

Fig 5 Glass-cover (mm)

IV. FINITE ELEMENT ANALYSIS SIMULATION

FE analysis is done prior to manufacturing of the ITPVCPC so that the structural robustness can be analysed. Shell elements representing equivalent single layer for composites in 3-d domain has been studied by E. Carrera [28] and implemented in FE analysis by J. Reinoso et al [29] with high accuracy. Therefore shell elements being computationally efficient are used for the analysis model. One trough with glass cover and one without glass cover is analysed for deflection due to thermal and pressure loads.

A. Temperature-displacement analysis boundary conditions

Hand layup [30] is a simple and predominant composite material manufacturing process. Subsequent layers of individual plies are laid in specific orientation angles and then processed to form the material. Abaqus® software has the capability to simulate this process. Three dimensional CAD model of the collector is imported into the FE software utilising its cross platform model recognition capability. Glass fiber (with polyester matrix) layup is designed and assigned to the shell profile of the collector. The material properties of GFRP are given in table 3.

TABLE III Material properties of GFRP

Material	Value
Young's Modulus E1	38600 MPa
E2 and E3	8270 MPa
Poisson ratio (**n**)	0.26
Shear Modulus (G)	4140 MPa
Density (ρ)	2500 kg/m^3

Orientation of the plies is [0°,90°,0°,90°,+/-45°,90°,0°,90°,0°] and the total thickness of the 10 ply laminate is 2.3 mm. The collector was constraint to zero degree of movement at the side panel holes (Fig.6). Uniform pressure of $5*10^{-4}$ MPa is applied normal to the trough surface as prescribed in the American Society of Civil Engineers (ASCE) guidelines [31].

Thermal boundary condition was applied according to the hottest working conditions to which the collector could be exposed (table 4). Material properties corresponding to thermal behavior like conductivity and thermal expansion coefficient were also assigned.

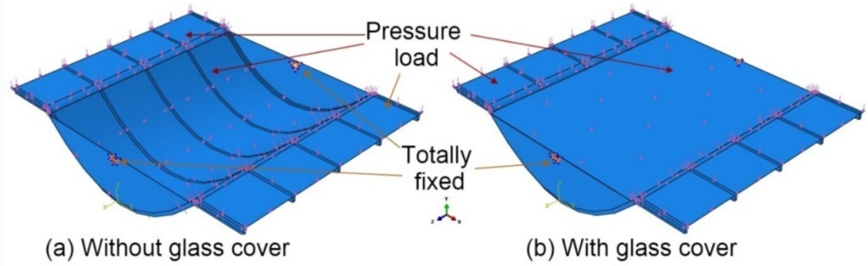

Fig 6 Boundary conditions acting on the collector profile

TABLE IV Boundary conditions

Parameter	Value
Initial Ambient temperature	30 °C
Maximum Temperature achieved by the material	80 °C
Normal uniform pressure	0.0005 MPa

B. Mesh generation

The whole collector profile was assigned quad-shaped elements - S4RT, that represent 4-node thermally coupled thin or thick shell. Parabolic trough sheet and rib elements were assigned global-seed size 15. The mesh around the high stress concentration region was assigned a global-seed size 5 (Fig.7). The glass cover was assigned global seed size of 25 since further reducing the seed size doesn't affect the stress distribution on it. All the mesh refinement is done to meet the convergence condition where the results are not affected with further refinement of the mesh.

The aspect ratio (AR) is the ratio of the shortest to the longest side in a mesh cell. It should be equal to 1 for ideal results [32]. In the meshed collector without glass the total elements produced were 41510 and the trough with glass cover had 57516 elements. The average AR in both cases was 1.1 which is close to ideal case.

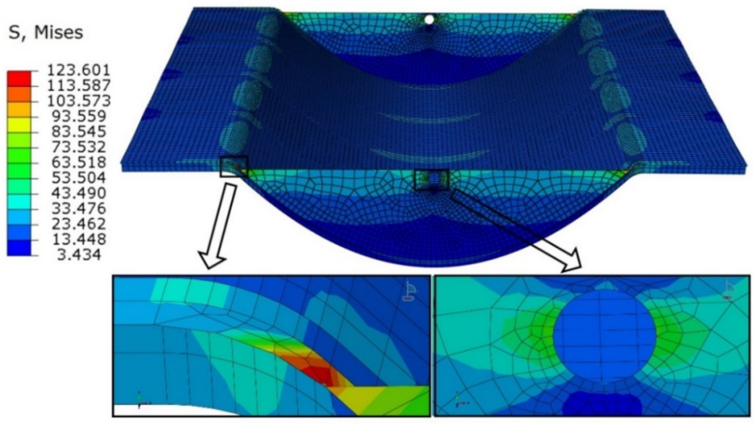

Fig 7 Mesh generation and stress distribution (MPa)

V. SIMULATION RESULTS

Simulations for the two cases were run for coupled temperature-displacement analysis. The figures 8 to 10 show the deflection visualization in which the red color and blue color represents maximum and minimum deflection, respectively. A deflection of 10 mm is obtained in flanges of the trough without glass cover (fig.8). This area is not responsible for solar ray reflection, thus it doesn't affect the efficiency of the trough. In the glass covered trough maximum deflection of 17.2 mm is obtained in the glass region, and 7.2 mm in the trough region (fig.9

and 10). Again these deflections doesn't affect the optical efficiency of the trough. The effect of deflection in the parabolic trough region is studied in section 6.

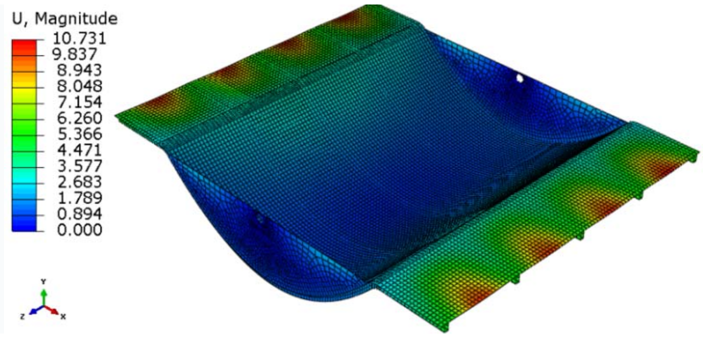

Fig 8 Deflection in collector without glass cover (mm)

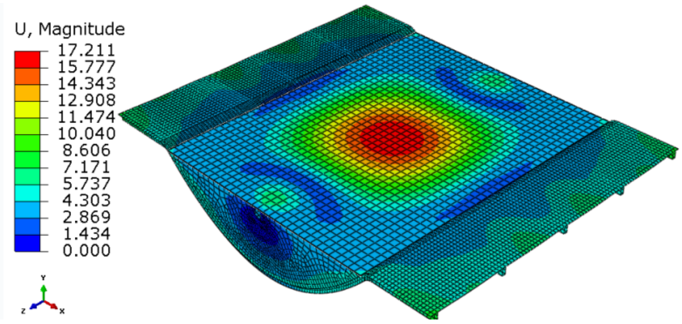

Fig 9 Deflection in collector with glass cover (mm)

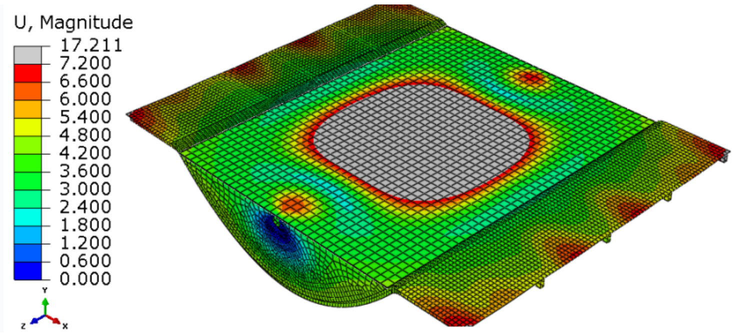

Fig 10 Deflection in the solar panel region of the collector with glass cover (mm)

The area of importance is the trough region, excluding the side panels, flanges for PVs and the glass. This area is responsible for the reflection of sunlight on to the receiver tube. Therefore, there should be minimum deflection in this area. Maximum deflections for main trough components are presented in table 5. The maximum deflections in each region are reasonable enough to be accepted in the manufacturing design model without further stiffening.

TABLE V Deflection of the collector under uniform pressure and temperature BC

Trough without glass	Maximum Deflection (mm)	Trough with glass	Maximum deflection (mm)
Trough region	2.98	Trough region	3.56
Side panel	1.6	Side panel	4.02
Solar panel	10.731	Solar panel	7.2
		Glass	17.21

VI. OPTICAL ANALYSIS

Parabola has a unique property that the rays falling parallel to the vertical axis always pass through the focus after reflection from the parabolic curve. An analytical method was developed by D. Chemisana et al for measuring optical performance of two-axis Fresnel reflective concentrators in 2013 [33]. Maccari et al developed a complex profile-meter using helium-neon laser beam, a digital camera and image processing software to locate the coordinates of PTC [34]. The previous optical analysis methodology involve complex and intricate calculations compared to the proposed geometrical analysis. In this methodology, the analysis relies on the coordinate information of the deformed parabola after structural analysis. The structural analysis could be experimental or finite element based.

In the current design the absorber tube with diameter 42 mm is located at the focus of the parabola to collect the reflected sunlight (Fig.11). If the parabola is in perfect shape, then all the incident rays fall on the focus.

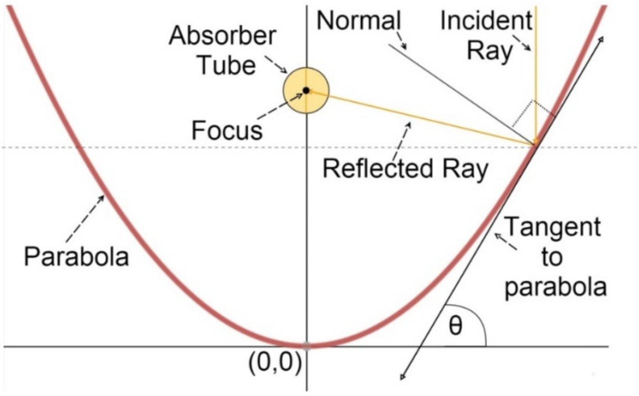

Fig 11 Parabolic profile optical parameters

The FE simulation resulted in the deflection of the trough area along with other components due the action of pressure and temperature boundary conditions. The information of this deflected region is obtained through software interface and is the key for determining the optical performance of the collector under loaded condition (Fig.12).

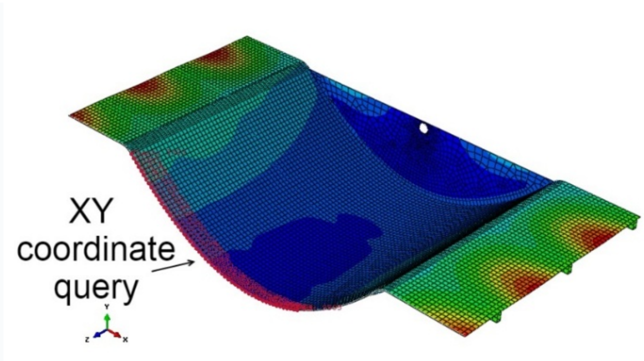

Fig 12 Path of XY coordinates along the section of the deformed trough

A. Mathematical ray tracing model

The coordinates were obtained from the FE software query module and then plotted. A corresponding second order trend line with close fitting of the coordinates was obtained. A mathematical relation was developed involving the equation of deformed parabola (eq. 5), the tangent to the parabolic curve (equation 6 to 8), normal slope (equation 9), reflected-ray slope (equation 10), and reflected-ray coordinate equation (equation 11 and 12). The purpose of this mathematical model is to find the Y-intercept of the reflected ray (Fig.11). In the un-deformed parabola it should be at the focus, located at Y = 404 mm in the current design.

The equation of trend line obtained from close fitting of deformed parabola coordinates is:

$$y = 0.0006{x_1}^2 + 3e^{-5}x_1 - 0.5866 \quad (5)$$

Then the slope of the above deformed parabola equation was obtained.

$$y' = 0.0012x_1 + 3e^{-5} \quad (6)$$

Or

$$tan\theta = 0.0012x_1 + 3e^{-5} \quad (7)$$

Or

$$\theta = tan^{-1}(0.0012x_1 + 3e^{-5}) \quad (8)$$

Then the slope of the normal to the tangent is given as:

$N' = -\frac{1}{Slope\ of\ curve} = \frac{1}{tan\theta}$ (9)

The slope of the reflected ray is given as:

$R' = \tan{(90 + 2\theta)}$ (10)

The equation of the reflected ray is obtained from which we can get the value of Y intercept.

$y - y_1 = \tan(90 + 2\theta) * (x - x_1)$ (11)

Or

$y = \tan(90 + 2\theta) * (x - x_1) + y_1$ (12)

1) Deformed collector trend line

The X-Y coordinates of the original and deformed trough section is plotted and the trend line (Fig.13) is obtained for the deformed troughs to implement the mathematical model.

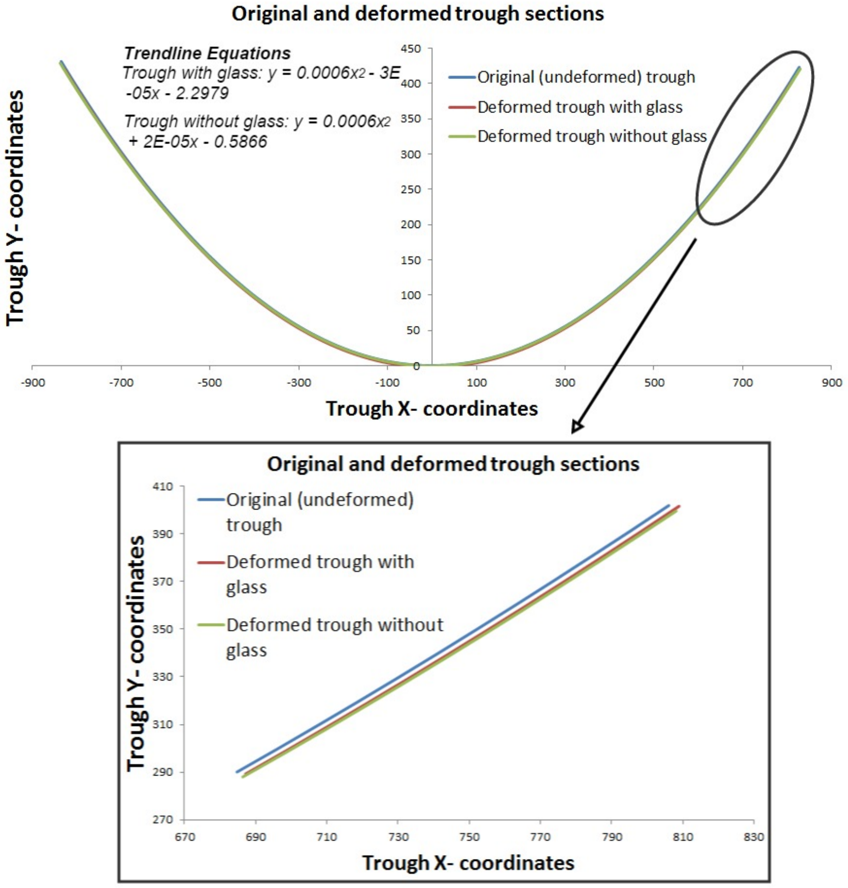

Fig 13 Trough-section plot of collector with and without glass cover and original (un-deformed) trough

2) Deviation from the focus

The Y-intercept was obtained for the two deformed trough cases using the mathematical model for ray tracing. The focus is located at Y = 404 mm, the difference between the focus and Y-intercept is shown in figure 14. The half region plot or the first quadrant is sufficient for analysis since the parabola is symmetric along the Y-axis. The blue series represents the reflected rays of the trough with glass cover falling on the Y-axis. The red series represents the reflected rays of the trough without glass cover falling on the Y-axis.

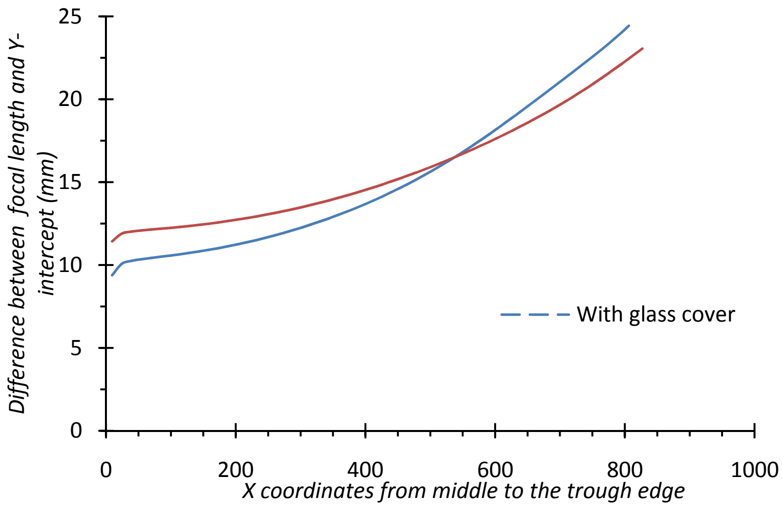

Fig 14 Deviation of the reflected ray from the focal point along Y-axis

The absorber tube being 42 mm in diameter has 21 mm radius. Under full loading condition, 11.1% of rays fall out of absorber tube region in the PTC without glass cover, and 16.3% of rays fall out of the absorber tube region in the PTC with glass cover. The absorber tube diameter could be made 25 mm to make all the rays fall on it, but since it is not desirable to sacrifice the optical concentration ratio, 21 mm radius is good for this design. It can be further supported by the fact that it is not windy all the time and these values are for maximum pressure and temperature boundary conditions. The focal deviation in the glass covered collector is more than the open collector. However, the benefits of the glass covered collector cannot be overlooked and it is thus adopted for the manufacturing phase.

VII. MANUFACTURING METHOD

The first step in manufacturing of any part using hand layup technique is preparation of the mold. After making a CAD drawing for reference (Fig.15), a base structure was prepared using acrylic and steel rods for support. Three pieces of parabolic profile acrylic sheet (20 mm thick) were made using laser cutting. They were joined and held together using three steel tubes and two planks made of acrylic (for PV panels). A recess between the sheets was made to accommodate galvanized steel sheet (0.5 mm) so that an exact negative profile of the actual parabolic trough can be obtained. The trough region of the mold was then reinforced by fixing thin acrylic sheet below it and then filling it with industrial foam (Fig.16). The gaps in the mold were then covered using automotive filler, and smoothed out by sand paper.

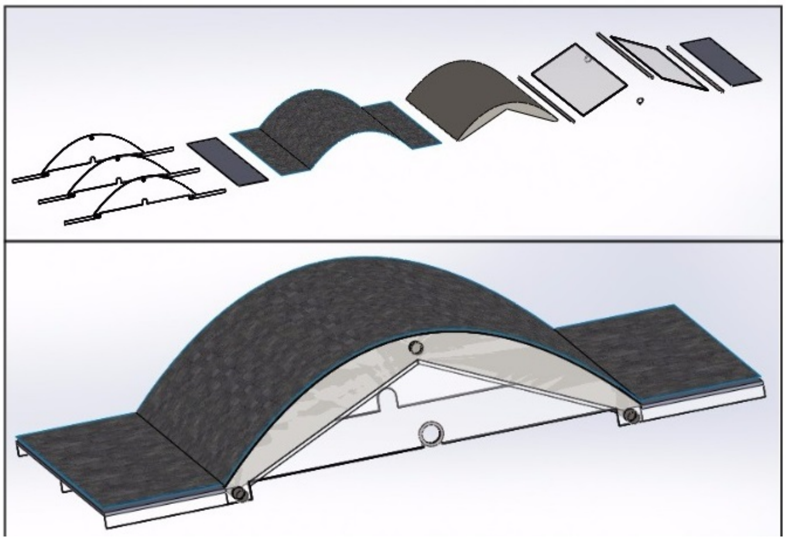

Fig 15 Mold exploded view and assembled view

Fig 16 Mold preparation

After the mold was manufactured, it was treated with mold release agent, and then a thin gel coat of poly vinyl alcohol (PVA) was applied to the surface of the mold. When the gel coat was set, 5 layers of glass fiber and polyester resin were applied. Then 5 ribs made of rigid foam were placed equidistant along the trough and the remaining 5 layers of glass fiber were placed over it. Then vacuum bagging was done to make the layers compact and remove the excess resin. Vacuum bagging equipment - breather fabric, vacuum bag, mastic sealant (yellow colored), and vacuum pump is visible in figure 17. The reflector material used is a 3M® [35] polymeric mirror film bonded to a stainless steel sheet of 0.5 mm thickness. The stainless steel standard sheet size is 1000 mm x 2000 mm which was cut and joined to match the trough size.

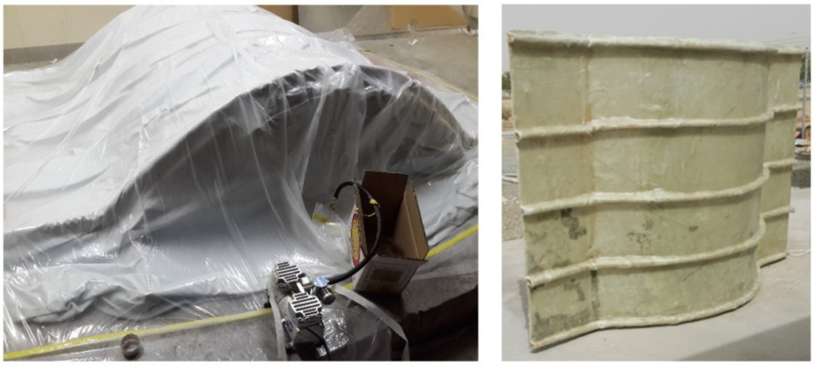

Fig 17 Vacuum bagging setup (left) and completed composite structure (right)

A complete setup of six ITPVCPC installed at site is shown in figure 18. Two sets composed of three collectors each are installed in series. They are offset from each other to allow for a tracking mechanism to be installed in between. The absorber tubes are connected in series throughout the six collectors. This unit of collectors produces both thermal and electrical energy and is a part of a complete solar desalination system located in Jeddah, Saudi Arabia. The tracking mechanism, and the blower of the humidification unit of desalination system is supported by the electricity provided by the PV panels. The energy drawn from the collectors allows the unit to produce 500 liters of fresh water per day under clear sky condition. Further testing is being conducted.

Fig 18 Set of six ITPVCPC collectors installed at site

VIII. CONCLUSION

The parabolic trough is designed to accommodate a clear glass cover over the aperture. It will help in retaining the heat and raising the temperature of the absorber tube, also it would be easier to clean and the trough reflector surface would be protected from abrasions due to sand, dust, hail etc. The optical analysis shows that the loss in sunlight collection is reasonable under maximum pressure and temperature boundary conditions. The trough section made of glass fiber (with polyester matrix) is just 2.3 mm in thickness and the ribs are very light (Rigid foam), this makes a very light and economical design. The whole trough was easily manufactured using the hand layup technique after preparing a suitable mold. A single mold can be reused for producing many troughs with minor or no repair. The mathematical model of ray tracing can be used for optical analysis of any other parabolic trough using deformed XY coordinates. The study shows that glass fiber (with polyester matrix) can be used as a cheap and light replacement for conventional material like steel, especially for integrated thermal photovoltaic closed parabolic collector (ITPVCPC). This innovative design of the hybrid collectors can be used as a standalone power generation unit, and thus it has a significant application in remote areas to generate both thermal and electrical power.

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