



Design, manufacturing and experimentation of compounded parabolic collector

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Abstract

Design and performance result of a CPC (Compounded Parabolic Concentrator) water heating system is presented. The system consists of 10 evacuated glass tubes (absorbers), CPC for each tube and manifolds. Calculations are done to calculate the acceptance angle for heating 60 lit/hr water up to 80°C. Fabrication is done using suitable manufacturing processes and leak test of welded joints is done. Results are obtained using Pt100 sensor for CPC system and compared with the ETC system for 5 hours. Rise of 10 % is observed when CPC is used.

Keywords: solar collector, CPC, acceptance angle, solar radiation

Introduction

Solar thermal energy systems are considered as the most economical choice among all renewable energy systems. Different types of solar collector are used depending upon the level of temperature application. Flat Plate Collectors are used for low temperature applications. For medium temperature applications, i.e. applications in the temperature range between 100°C -250°C, it has become imperative to concentrate the solar radiations. Various methods are available for concentrating the solar radiations like compound parabolic concentrator, parabolic trough concentrator, fixed reflector-moving receiver, fixed receiver-moving reflector, Fresnel lens and central receiver, etc. [1].

We have restricted our study to concentrate the solar radiation utilizing compound parabolic concentrators. These non-imaging concentrators have the capability of reflecting the entire radiations incident on the aperture over ranges of incident angles within the acceptance angle of the concentrators. Compound Parabolic Concentrators are special types of solar collector fabricated in the shape of two meeting parabolas. It is considered among the collectors having the highest possible concentration ratio. It belongs to the non-imaging family. As it has large aperture area, only intermittent tracking is required [2].

Qiang Wang *et al.* have studied six symmetric compound parabolic solar concentrators (CPCs) with all-glass evacuated solar tubes (EST) as the receiver and a comparative study on their optical performance is performed based on theoretical analysis and ray-tracing simulations. We have selected the design of compound parabolic collector based on an 'ice-cream absorber' for our design calculations [3].

Description of CPC

Compound parabolic collector consists two halves of parabolas and a receiver situated along their line of symmetry.

Fig.1 shows the geometry of CPC, in which there are two parabolas intersecting each other. The angle between the two parabolas is called as acceptance of CPC. Acceptance angle is very important to determine the geometry of CPC [1].

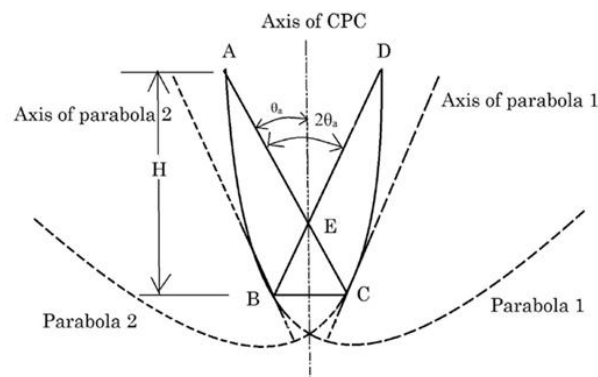


Fig 1: Geometry of CPC

As shown in Fig. 2, any point S on the reflector of CPC can be described in two parameters: φ (formed by lines from the negative y-axis and OR) and $\rho = RS$ (the line tangent to the absorber tube at R). Thus, in the suggested coordinate system as shown in Fig.2, the (right) reflector of CPC constructed based on a tubular absorber is expressed by [3]:

$$\begin{cases} x = r \sin \varphi - \rho \cos \varphi \\ y = -r \cos \varphi - \rho \sin \varphi \end{cases} \quad (1)$$

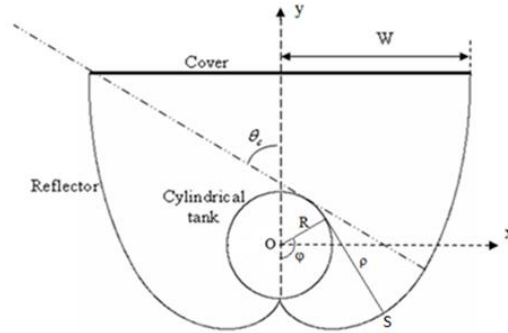


Fig 2: Geometry of a tubular absorber ideal solar concentrator

As shown in Fig.3, lines AB and AC are tangent to the inner tube of the EST, and the distance from the lowest point (A) of the “ice-cream” to the centre (O) of inner tube is just equal to R in order to accommodate the vacuum space of the EST [3].

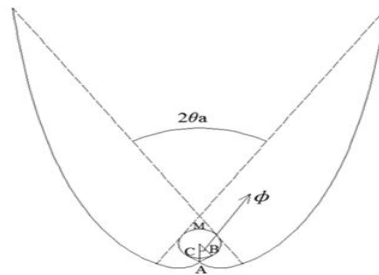


Fig 3: Designed based on an “ice-cream” absorber

The ρ in Equation (1) is expressed by:

$$\rho/r = \begin{cases} \varphi & 0 \leq \varphi \leq 0.5\pi + \theta_a \\ \frac{0.5\pi + \theta_a + \varphi - \cos(\varphi - \theta_a)}{1 + \sin(\varphi - \theta_a)} & 0.5\pi + \theta_a < \varphi \leq 1.5\pi - \theta_a \end{cases} \quad (2)$$

For involute, $0 \leq \varphi \leq 0.5\pi + \theta_a$ and

For parabola, $0.5\pi + \theta_a < \varphi \leq 1.5\pi - \theta_a$.

Design of CPC

In design of CPC, our aim is to find the acceptance angle of CPC. By substituting the value of acceptance angle of CPC in equations of parabolas and involutes we can find out the profile of CPC, which is used to manufacture reflector of CPC.

Air temperature = 300 K

Assume the cover has temperature of 302 K. To estimate the wind heat transfer coefficient, it is necessary to find the Reynolds number for an air temperature that is the average of the cover and the ambient temperatures, 301 K:

Reynolds number

$$Re = \frac{\rho_a V_a D_{co}}{\mu_a} = \frac{1.225 * 1 * 0.058}{2.9970921 * 10^{-5}}$$

$$Re = 2370.631186$$

Nusselt number and wind heat transfer coefficient:
For $1000 < Re < 50000$,

$$Nu = 0.30Re^{0.6} = 0.30 * 2370.631186^{0.6}$$

$$Nu = 31.7716413$$

Also
$$Nu = \frac{h_{wo} D_{co}}{k}$$

$$h_{wo} = \frac{31.7716413 * 0.2612}{0.058}$$

$$h_{wo} = 14.38488449 \text{ W/m}^2 \text{ } ^\circ\text{C}$$

Sky temperature:

According to Berdahl and Martin ^[2],

$$T_{sky} = T_a [0.711 + 0.0056T_{dp} + 0.000073T_{dp}^2 + 0.013\cos(15t)]^{1/4} \quad (4)$$

$$T_{sky} = 298 [0.711 + 0.0056 * 9.4 + 0.000073 * 9.4^2 + 0.013\cos(15 * 12)]^{1/4}$$

$$T_{sky} = 277.71K$$

Heat transfer due to wind convection and radiation on outer cover:

It is the heat loss between air and outer surface of the cover tube. It is the addition of heat loss due to convection and radiation, which is expressed as ^[2]:

$$Q_{loss} = \pi D_{co} L h_{wo} (T_{co} - T_a) + \varepsilon_c \pi D_{co} L \sigma (T_{co}^4 - T_{sky}^4) \quad (5)$$

Substituting h_w in the equation, given with 1.8m length provides the first estimate of the loss:

$$Q_{loss} = \pi * 0.058 * 1.8 * 14.38488449 (302 - 300) + 0.88 * \pi * 0.058 * 1.8 * 5.67 * 10^{-8} (302^4 - 277.71^4)$$

$$Q_{loss} = 48.22490339W$$

The inside cover temperature:

By using Q_{loss} from eq. (5) we have to calculate temperature of inner surface of cover tube by using equation of heat loss between inner surface of cover tube and outer surface of absorber tube. It is calculated as ^[2]:

$$T_{ci} = T_{co} + Q_{loss} * \frac{\ln(D_{co}/D_{ci})}{2\pi k_c L} \quad (6)$$

$$T_{ci} = 302 + 48.22490339 * \frac{\ln(0.058/0.0548)}{2\pi * 1.2 * 1.8}$$

$$T_{ci} = 302.2016625K$$

Heat transfer due to conduction and radiation between receiver and inside cover:

We have to substitute calculated temperature of inner surface of cover tube in the give equation of heat loss between receiver and inside cover. It is expressed as ^[2]:

$$Q_{loss} = \frac{2\pi k_{eff}L}{\ln\left(\frac{D_{ci}}{D_r}\right)} * (T_r - T_{ci}) + \frac{\pi D_r L \sigma (T_r^4 - T_{ci}^4)}{\frac{1}{\varepsilon_r} + \frac{1 - \varepsilon_c}{\varepsilon_c} \ln\left(\frac{D_r}{D_{ci}}\right)} \quad (7)$$

Space between receiver and cover tube is evacuated, therefore $k_{eff} = 0$.

$$Q_{loss} = 0 + \frac{\pi * 0.047 * 1.8 * 5.67 * 10^{-8} * (473^4 - 302.2016625^4)}{\frac{1}{0.08} + \frac{1 - 0.88}{0.88} \left(\frac{0.047}{0.0548}\right)}$$

$$Q_{loss} = 49.82338895W$$

Since 49.82338895 is not equal to 48.22490339 (the difference is 1.59848556), our initial guess of the outside cover temperature was quite high. A second guess of the outside cover temperature of 302.5K has an error of -1.6799 W. Linear interpolation to find the temperature where the error is zero yields a cover temperature of 302.25K. With this new cover temperature the loss calculated from Equations (5) and (7) are virtually identical and equal to 49.82 W.

$$Q_{loss} = 49.82 W$$

Heat loss coefficient [1]:

$$U_L = \frac{Q_{loss}}{A_r(T_r - T_a)} \quad (8)$$

$$U_L = \frac{49.82}{\pi * 0.047 * 1.8(473 - 300)}$$

$$U_L = 1.083521128 W/m^2$$

Heat transfer coefficient inside the tube calculation:

Velocity of water:

$$V_w = \frac{\dot{m}}{\rho_w A_{ri}} = \frac{0.00166666}{1000 * \pi/4 * 0.0483^2}$$

$$V_w = 9.096296109 * 10^{-4} m/s$$

Reynold's number

$$Re = \frac{V_w D_{ri}}{\vartheta_w} = \frac{9.096 * 10^{-4} * 0.0438}{0.326 * 10^{-6}}$$

$$Re = 122.2140397$$

Nusselt number:

For $Re < 2000$, $Nu = 3.66$

$$Nu = \frac{h_{fi} D_{ri}}{k_w}$$

$$\therefore h_{fi} = \frac{3.66 * 0.6753}{0.0438}$$

$$h_{fi} = 56.42917808 \text{ W/m}^2\text{K}$$

Collector efficiency factor

Collector efficiency factor represents the ratio of the actual useful energy gain to the useful gain that would result if the collector absorbing surface had been at the local fluid temperature. It is expressed as [2]:

$$F' = \frac{\frac{1}{U_L}}{\frac{1}{U_L} + \frac{D_o}{h_{fi}D_i} + \frac{D_o}{2k} \ln\left(\frac{D_o}{D_i}\right)} \tag{9}$$

$$F' = \frac{\frac{1}{1.08}}{\frac{1}{1.08} + \frac{0.047}{56.429 * 0.0438} + \frac{0.047}{2 * 1.2} \ln\left(\frac{0.047}{0.0438}\right)}$$

$$F' = 0.9783773641$$

Heat removal efficiency factor

Heat removal efficiency factor is defined as a quantity that relates the actual useful energy gain of a collector to the useful gain if the whole collector surface were at the fluid inlet temperature. It is expressed as [1]:

$$F_R = \frac{\dot{m}C_p}{A_r U_L} \left[1 - \exp\left(-\frac{A_r U_L F'}{\dot{m}C_p}\right) \right] \tag{10}$$

$$F_R = \frac{0.01 * 4.187 * 10^3}{\pi * 0.047 * 1.8 * 1.08} \left[1 - \exp\left(-\frac{\pi * 0.047 * 1.8 * 1.08 * 0.978}{0.01 * 4.187 * 10^3}\right) \right]$$

$$F_R = 0.975092905$$

Yearly radiation data for calculation of beam radiation

Table 8.1: Average yearly Radiation Data

Month	Global Radiation	Diffused Radiation
January	548.8828	391.3333
February	614.1705	361.4364
March	630.2775	365.5333
April	680.1282	385.3221
May	726.984	409.821
June	537.9925902	379.132807
October	543.7554529	400.5749965
November	573.566667	380.1684685
December	521.6861389	233.2805433

Beam Radiation (I_b) = Global Radiation (I_g) – Diffused Radiation (I_d)

Beam Radiation (I_b) = 597.493761 – 367.4002906 = 230.0934704

Beam Radiation (I_b) = 230.0934704 W/m²

Diffused Radiation (I_d) = 367.4002906 W/m²

Useful heat gain rate

The amount of heat gained by fluid inside absorber tube per unit time is known as useful heat gain rate. The equation of useful heat

gain rate is expressed as [1]:

$$Q_u = \dot{m} C_p (T_{fo} - T_{fi}) \quad (11)$$

$$Q_u = 0.00166666 * 4.187 * 10^3 (80 - 25)$$

$$Q_u = 383.8083333 \text{ W}$$

Absorbed radiation per unit area of collector aperture:

Absorbed radiation per unit area of collector aperture is the amount of solar radiation falling on the absorber per area of collector aperture. It is expressed as [4]:

$$S = \rho_{CPC}^{ni} \alpha_r \tau_r (I_{b,CPC} + I_{d,CPC}) CR \quad (12)$$

$$I_{b,CPC} = F I_b \cos \theta_a$$

F is a control function. It has a value of 1 if the beam radiation is incident on the CPC and zero if it is not.

$$\therefore I_{b,CPC} = 230.09 \cos \theta_a$$

$$I_{d,CPC} = \frac{I_d}{C} = \frac{367.4}{1/\sin \theta_a}$$

$$\therefore I_{d,CPC} = 367.4 \sin \theta_a$$

$$\rho_{CPC} = 0.865, \alpha_r = 0.93 \text{ and } \tau_r = 0.913$$

Substituting values in equation

(12),

$$S = 0.865^{ni} * 0.93 * 0.913 (230.09 \cos \theta_a + 367.4 \sin \theta_a) * \frac{1}{\sin \theta_a}$$

$$S = 0.865^{ni} * 0.84909 (230.09 \cos \theta_a + 367.4 \sin \theta_a) * \frac{1}{\sin \theta_a}$$

Average number of reflections

Average number of reflections is the average of the number of times the ray is reflected by the reflector. It is expressed as [4]:

$$ni = \frac{1}{2} (1 + \sin \theta_a) * \left(\frac{\cos \theta_a}{(\sin \theta_a)^2} + \ln \frac{(1 + \sin \theta_a)(1 + \cos \theta_a)}{\sin \theta_a (\cos \theta_a + \sqrt{2(1 + \sin \theta_a)})} - \frac{\sqrt{2} \cos \theta_a}{(1 + \sin \theta_a)^{3/2}} \right) - \frac{(1 - \sin \theta_a)(1 + 2 \sin \theta_a)}{2(\sin \theta_a)^2} \quad (13)$$

Substituting obtained values in the equation of useful heat gain rate,

$$Q_u = F_R A_a \left[S - \frac{A_r}{A_a} U_L (T_{fi} - T_a) \right] \quad (14)$$

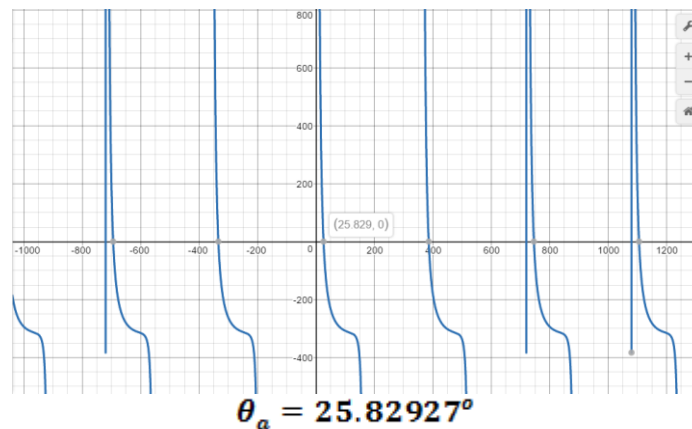
$$\therefore 383.8 = 0.975 * C * A_r \left(0.865^{ni} * 0.849 (230.09 \cos \theta_a + 367.4 \sin \theta_a) * \frac{1}{\sin \theta_a} - \frac{1}{C} * 1.08 (25 - 27) \right)$$

$$\begin{aligned} \therefore 383.8 &= 0.975 * \frac{1}{\sin \theta_a} * \pi * 0.047 \\ &\quad * 1.8 \left(0.865^{ni} * \frac{0.849(230.09 \cos \theta_a + 367.4 \sin \theta_a)}{\sin \theta_a} - \sin \theta_a * 1.08(25 - 27) \right) \\ \therefore 383.8 &= \frac{0.259}{\sin \theta_a} \left(\frac{0.865^{ni}(195.37 \cos \theta_a + 311.956 \sin \theta_a)}{\sin \theta_a} + 2.167 \sin \theta_a \right) \\ \therefore \frac{0.259}{\sin \theta_a} \left(\frac{0.865^{ni}(195.37 \cos \theta_a + 311.956 \sin \theta_a)}{\sin \theta_a} + 2.167 \sin \theta_a \right) - 383.8 &= 0 \end{aligned}$$

Consider,

$$y = \frac{0.259}{\sin \theta_a} \left(\frac{0.865^{ni}(195.37 \cos \theta_a + 311.956 \sin \theta_a)}{\sin \theta_a} + 2.167 \sin \theta_a \right) - 383.8$$

Solving by graphical method,



Equations of CPC

After calculations, we get an acceptance angle,

$$\theta_a = 25.82927^\circ$$

By substituting the value of acceptance angle in eq. (1) and eq. (2), we get following equations of CPC:
Equations of right hand side involute:

$$\begin{aligned} x &= 23.5 \sin \varphi - 23.5(\varphi + 0.09703533551) \cos \varphi \\ y &= -23.5 \cos \varphi - 23.5(\varphi + 0.09703533551) \sin \varphi \end{aligned}$$

Equations of right hand side parabola

$$\begin{aligned} x &= 23.5 \sin \varphi - 23.5 \left(\frac{2.215672803 + \varphi - \cos(\varphi - 0.4508058049)}{1 + \sin(\varphi - 0.4508058049)} \right) \cos \varphi \\ y &= -23.5 \cos \varphi - 23.5 \left(\frac{2.215672803 + \varphi - \cos(\varphi - 0.4508058049)}{1 + \sin(\varphi - 0.4508058049)} \right) \sin \varphi \end{aligned}$$

Equations of left hand side involute

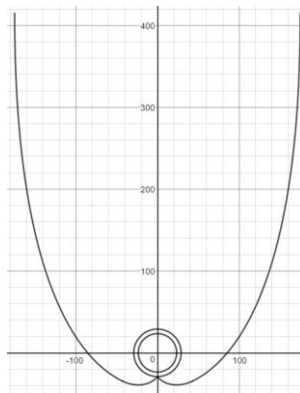
$$\begin{aligned} x &= 23.5 \sin \varphi - 23.5(\varphi - 0.09703533551) \cos \varphi \\ y &= -23.5 \cos \varphi - 23.5(\varphi - 0.09703533551) \sin \varphi \end{aligned}$$

Equations of left hand side parabola

$$x = 23.5\sin\varphi - 23.5 \left(\frac{-2.215672803 + \varphi - \cos(\varphi + 0.4508058049)}{1 - \sin(\varphi + 0.4508058049)} \right) \cos\varphi$$

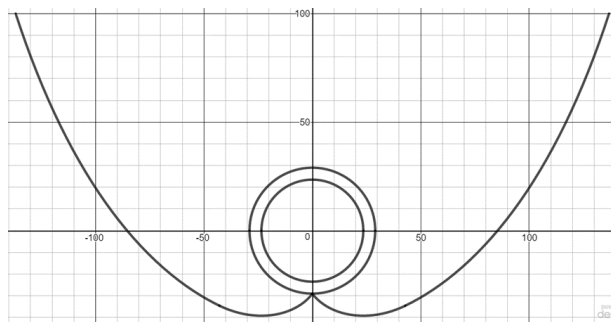
$$y = -23.5\cos\varphi - 23.5 \left(\frac{-2.215672803 + \varphi - \cos(\varphi + 0.4508058049)}{1 - \sin(\varphi + 0.4508058049)} \right) \sin\varphi$$

Plot of full CPC using above equations



Height/Depth of full CPC (H)	443.197mm
Width of full CPC (W)	349.36622mm
Concentration ratio	2.366097425

Truncated CPC



Height/Depth of truncated CPC (H_t)	139.2mm
Width of truncated CPC (W_t)	272mm
Concentration ratio	1.842133



Fig 4.8: CPC Panel

Fabrication

Manifold

The Manifold is a structure made by joining hollow square section of M.S. Sheet with the opening provisions for insertion of tubes and for inlet and outlet as per the drawing. First step is to cut the metal sheet of M.S. in the required size. Then punching operation is done with specific pitch using vertical punching machine. This sheet is then bent into rectangular shape using vertical bending machine and joined using welding process. Once manifold is papered insulation is done to prevent heat losses.

First step of insulation is cutting a GI sheet of required dimensions. Then punching operation is done with specific pitch. The sheet is then bent into rectangular shape slightly larger than the manifold. After insertion of gaskets, the assembly is kept vertical and puff is poured into it. To ensure that no puff contents enter the manifold, it is properly sealed. After solidification manifold is insulated.

Compounded parabolic concentrator

Compounded parabolic concentrator is made of aluminium sheet. It is made by bending process using die of compound parabolic shape with the specified design.

Stand

Stand is a rigid support structure for the assembly of manifolds and tubes. Stand is made of M.S material and assembled using nuts and bolts.

Base Manifold

Base manifold is made by using MS sheet of required dimensions. Punching is done using hydraulic bending machine with pitch similar to the manifold. Then it is bended in required shape.

Testing

1. Leak proof test is carried out on the welded joints of the manifold. Compressed air is filled in it with proper sealing on each openings and water is sprayed on the joints. If bubble appears, it is defective.
2. Assembly of the system is done. Water is provided to the system. Temperature is measured using Pt100 sensor. Inlet water temperature is 24°C. After 5 hrs outlet temperature of ETC as well as CPC is measured. The output temperature of ETC is 50°C and that of CPC is 55°C. An increase of 10% is observed when CPC is used.

Conclusion

1. After studying various types of CPC design, best CPC design i.e. design based on ice- cream absorber is selected. Acceptance angle of 25.829 is calculated. The Equations of CPCs are obtained using calculated acceptance angle and plotted graphically.
2. By truncating height of Full CPC by 68%, concentration ratio was reduced by only 22%. Hence height is reduced without significant change in concentration ratio.
3. Results are obtained using Pt100 sensor for CPC system and compared with ETC system. For ETC and CPC water was heated up to 50°C and 55°C respectively in 5 hrs. Rise of 10% is observed when CPC is used.

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