Optical and thermal performance of a three-dimensional compound parabolic concentrator for spherical absorber

S SENTHILKUMAR^{1*}, K PERUMAL² and P S S SRINIVASAN³

^{1*}Department of Basic Sciences, Kongu Polytechnic College, Perundurai, Erode 638 052

²Department of Physics, SRMV College of Arts and Science, Coimbatore 641 020

³K S R College of Technology, Tiruchengode 637 209

e-mail: shansenthils@yahoo.com

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Abstract. For medium range temperature applications, focusing type collectors like Compound Parabolic Concentrator (CPC) are most commonly used. Considerable research work has been carried out to improve the performance of the two-dimensional compound parabolic concentrator (2D CPC). The three-dimensional compound parabolic concentrator (3D CPC) was found to be more efficient than 2D CPC because of the higher concentration ratio. In the present work a 3D CPC was fabricated with a half acceptance angle of 4° for a spherical absorber of radius 100 mm. UV stabilized aluminized polyester foil having high reflectivity (0.85) was pasted on the reflector for a total height of 441 mm and an aperture width of 540 mm. The optical efficiency was estimated theoretically and compared with the experimental value. Experimentally determined values of optical and thermal efficiencies were in good agreement with theoretically predicted value. The experimental results shown that the optical efficiency obtained from the 3D CPC (0.626) was significantly higher than that of the 2D CPC (0.570) of similar dimensions. Since the optical efficiency of the 3D CPC was increased, the thermal efficiency of the collector was also increased. In addition to that, time constant of the concentrator was also calculated. The time constant of the 3D CPC (431 s) was fairly high when compared with the 2D CPC (110 s). An attempt was made to generate low pressure steam using 3D CPC in the in situ steam generation mode. The efficiency of the steam generation was about 38%, which was one of the possible applications of 3D CPC module.

Keywords. Solar concentrator; 3D CPC; optical and thermal efficiency of CPC.

1. Introduction

Depleting fossil fuel reserves, pollutant emissions due to the use of fossil fuels and increased cost of conventional fuels have forced the scientific and engineering community to focus more

*For correspondence

and revive interest on renewable, solar energy utilization options. Flat plate collectors have been widely used for applications that demand below 90°C and large amount of research efforts are already made. For medium temperature range (90–300°C) applications, concentrating type collectors are suitable, which are under investigation. The compound parabolic concentrator (CPC) have moderate concentration ratio and require only intermediate tracking at regular intervals. 3D CPC do not demand high technology continuous tracking systems. Despite such advantages, only limited studies are made in 3D CPC.

The first design of CPC was described by Winston (1974). The design and constructional details are reported in Duffie & Beckman (1974); Meinel & Meinel (1979). The major advantage of 2D CPC is, they can receive radiation arriving with large angular spread and yet concentrate it on to linear receivers of small transverse width. The effect of mirror errors and receiver misalignments of the 2D CPC were discussed by Rabl *et al* (1979). The varieties of 2D CPCs in terms of their most general characteristics, namely concentration, acceptance angle, sensitivity to mirror errors, size of the reflector area and average number of reflections are compared by Rabl (1976), he also established a simple analytical technique for calculating the average number of reflections that is useful for computing optical losses for 2D CPC. The possible extension of 2D CPC to 3D CPC is reported by Rabl (1976) and also he pointed out that a 3D CPC offers a higher concentration over a 2D CPC. In the present work, 3D CPC was fabricated for half-acceptance angle of 4° to achieve higher concentration ratio. The 3D CPC profile was fabricated using analytical equations proposed by Rabl (1976). The 3D CPC was simulated for the same data using Pro-E software. The dimensions (aperture width and height) of the fabricated model were compared with the simulated model, it was found to be equal. The present work also focuses on the optical and thermal performances of 3D CPC.

2. Experimental procedure

An experimental setup has been developed to analyse the optical and thermal performance of a 3D CPC. A reflector profile is designed and fabricated for a half acceptance angle 4° proposed by Rabl (1976) for a spherical absorber of radius 100 mm. Rabl (1976) pointed out that top portion of reflector area can be truncated without seriously reducing the concentration. Based on Rabl (1976) 69% of the top portion of the reflector is truncated and only 31% is taken for construction. The final reflector profile designed has a total height of 441 mm and an aperture width of 540 mm. The UV stabilized aluminized polyester foil of high reflectivity (0.85) is carefully pasted over the metal sheet. The absorber is a sphere having 200 mm outer diameter and 197 mm inner diameter. Copper tube with 8 mm outer diameter and 6 mm inner diameter is connected to the top and bottom of the absorber. Finally, the top of the reflector was covered with transparent glass (transmissivity – 0.9) of thickness 3 mm.

The collector assembly was placed in a location where there was access to sunlight and throughout the experiment the collector was kept with its absorber to track the sun continuously so as to maximize the useful solar energy. The collector was incorporated in the fluid loop and operated in the open loop mode. In the performance study of the 3D CPC, water was used as a heat transfer fluid. Figure 1 shows the experimental set-up.

The temperatures were measured using Resistance Temperature Detector (RTD). The RTD PT(100), which measures the temperature in the range of – 50 to 100°C. The inlet, outlet and ambient temperatures were measured using RTD's and an 8 – channel data logger DAS 8000. The flow rate of the fluid in the fluid loop was measured using a graduated jar and a stop

Figure 1. Experimental set-up.

watch, because the flow-meter in the fluid loop was not effective at low flow rate. To measure the intensity of direct solar radiation at normal incidence, Pyrheliometer was used. A wind velocity meter was also used to find the wind velocity. The experimental values were analysed using ANOVA software and the error was found to be 6%.

3. Optical performance

Optical efficiency is estimated theoretically from parameters of materials used in the constructions and also determined experimentally.

3.1 Theoretical estimation of optical efficiency

The CPC with top glass cover and glass around the absorber (Rachel & Jayaraman 2002) is given as

$$\eta_o = \tau_a \tau_e \rho_m^{\langle n \rangle} \alpha P f_{ref}. \quad (1)$$

Where τ_a is the transmittance of the aperture cover, τ_e is the transmittance of the glass envelope around the absorber, ρ_m is the reflectance of the reflector material, $\langle n \rangle$ is the average number of reflections, α is the absorptance of the material coated on the absorber, P is the optical loss due to the gap width and f_{ref} is the multiple reflections between the absorber tube and glass envelope. The receiver thermal losses of 3D CPC are primarily radiative and the absorber area is small, it may not be necessary to have convection suppressing cover (Magal 1975). Since there was no envelope to the absorber, the equation (1) for the 3D CPC without the glass envelope to the absorber reduces to

$$\eta_o = \tau_a \rho_m^{\langle n \rangle} \alpha. \quad (2)$$

Table 1. Experimental readings to calculate optical efficiency.

S. No.	T_A (°C)	T_I (°C)	T_O (°C)	M_o (Kg/s)	I_B (Wm ⁻²)	η_o
1.	30.5	29.1	32.8	6.666E-03	710	0.630
2.	31.3	30.3	33.9	6.666E-03	725	0.613
3.	31.4	30.2	34.0	7.142E-03	790	0.647
4.	32.5	31.1	34.7	7.142E-03	775	0.613
5.	32.2	31.2	34.9	6.666E-03	710	0.630

The transmittance of the aperture cover was determined using a pyranometer and the average value was found to be 0.90. The reflectance of the aluminized polyester foil used was tested using a sensitive reflectance meter and the average reflectance of the reflector material was found to be 0.85. The average number of reflections (Winston 1975) was 1.4 for a half acceptance angle 4°. Dull black paint of absorptance (0.90) was used for the spherical copper absorber. Thus the theoretically estimated optical efficiency using all the values of optical parameters was 0.645.

3.2 Experimental determination of optical efficiency

The collector was incorporated in the fluid loop with water as the heat transfer fluid. The open loop operation was found to be more convenient because it was easy to maintain stable conditions and high flow rates for long periods. The flow rate was kept sufficiently large and constant such that $0 \leq (T_{av} - T_a) \leq 1^\circ$, where T_{av} is the average of inlet and outlet water temperatures and T_a is the ambient temperature. The optical efficiency was computed from the observed data along the lines similar to those described by Rabl (1980) and Balasubramanian & Sankarasubramanian (1988)

$$\eta_o = (m^\circ C_w (T_o - T_i) / I_b A), \quad (3)$$

where m° is the mass flow rate of fluid, C_w is the specific heat capacity of water, T_o is the outlet temperature, T_i is the inlet temperature, A is the aperture area (0.226 m²) and I_b is the beam component of solar radiation. The experiments are carried out on a number of clear sunny days. A set of experimental data for a day was given in table 1, to calculate the optical efficiency.

Under steady state conditions the optical efficiency computed from the observed data was found to be 0.626. Optical efficiency of 3D CPC was compared with a 2D CPC of almost similar dimensions reported earlier (Rachel & Jayaraman 2002) as shown in figure 2. Optical efficiency was also determined from the instantaneous efficiency measurement.

4. Thermal performance

One of the important parameter of interest in the testing of concentrator is the time constant, which is a measure of the heat capacity of concentrator. For better functioning of a concentrator at higher temperature with reasonably high efficiency, the overall heat loss coefficient should be made as low as possible. This heat loss coefficient could be determined by two ways.

- (i) From the slope of the instantaneous efficiency curve
- (ii) From thermal loss rate at zero solar irradiance.

Figure 2. Comparison of optical efficiency of 2D and 3D CPCs.

The experimental determination of heat loss coefficient by two methods and instantaneous efficiency of the concentrator are explained in detail in the following sections.

4.1 Time constant

The time constant is defined as the time required for a fluid to leave a concentrator to attain change through 0.632 of the total change from its initial to its ultimate steady value after a step change in incident radiation or inlet fluid temperature (ASHRAE 1977). Two methods have been proposed in (Pott & Cooper 1976), among which, the shading off the collector after the inlet and outlet temperatures had reached the steady state and continuously recording the outlet temperature was found to be most suitable.

The time constant of our concentrator module was determined according to the above recommendations as follows: The 3D CPC module was incorporated with fluid loop. The fluid loop was fabricated keeping in view of the guidelines suggested in (ASHRAE 1977) and (Hill & Streed 1976). The concentrator was allowed to attain steady state condition around noon time. The solar radiation was abruptly shut off by shading the concentrator, and the variation of the outlet temperature with time has been recorded. The time constant 't' was calculated using the relation.

$$(T_{o,t} - T_i)/(T_{o,i} - T_i) = 1/e = 0.368, \quad (4)$$

where $T_{o,t}$ is the outlet temperature at time t, $T_{o,i}$ is the outlet temperature when the solar radiation is interrupted and T_i inlet temperature of the concentrator which remains constant throughout the experiments. The flow rate was maintained to be steady throughout the experiment. The cooling curve of our 3D CPC module, with time constant of 431 seconds was shown in figure 3.

The determined value of time constant of a 3D CPC is fairly high (431 s) when compared (figure 4) with the value of time constant of a 2D CPC (110 s) of similar dimensions reported (Rachel & Jayaraman 2002).

Figure 3. Cooling curve of CPC.

4.2 Thermal loss rate at zero solar irradiance

The heat loss co-efficient was calculated from the thermal loss rate determination during the night and from the instantaneous efficiency studies during the day time. The useful heat collected by the CPC under steady state condition is given by Rachel & Jayaraman (2002)

$$q_u^\circ = q_a^\circ - q_i^\circ,$$

where q_u° is the rate of useful heat gain of the collector, q_a° is the rate of heat absorbed from the solar radiation and q_i° is the rate of heat incident,

$$m^\circ C_w (T_o - T_i) = I_b A_c F' \eta_o - A_c F' U_L (T_{av} - T_a).$$

In the absence of solar radiation $I_b = 0$

$$A_c F' U_L (T_{av} - T_a) = m^\circ C_w (T_i - T_o). \quad (5)$$

Figure 4. Comparison of time constant of 2D and 3D CPCs.

Figure 5. Thermal loss rate curve.

The heat loss measurement experiment was carried out during the night. Online heaters were used to heat the inlet water. The inlet, outlet, ambient temperatures and the mass flow rate were recorded. The experiment was repeated for various inlet temperatures.

From the steady state values of m° , T_o and T_i , the loss rate $A_c F' U_L (T_{av} - T_a)$ was calculated using the equation (5). These calculated values are plotted against excess temperature $[T_{av} - T_a]$ as shown in figure 5.

The slope of the curve gives $F' U_L$ for that aperture area. The straight line fit to data yields $F' U_L = 3.27 \text{ W/m}^2\text{°C}$.

4.3 Instantaneous efficiency

The performance of any collector designed for operation in the intermediate temperatures is determined by the fact that how efficiently it works as the operating temperature increases. The instantaneous efficiency of the CPC is given by (Rachel & Jayaraman 2002)

$$\eta_i = F'[\eta_o - U_L(T_{av} - T_a)/I_b], \quad (6)$$

decreases for higher values of operating temperature. When $(T_{av} - T_a)$ increases the second factor in equation becomes more and more significant. The collector is incorporated in the fluid loop and operated in the open loop mode for its performance study at different operating temperatures. To start with particular inlet temperature, 40°C is maintained for the whole period of observation using one of the online heaters arrangements. The over head tank itself contains 15 liters of water. The top cover of over head tank was removed and the over head tank was kept open to atmosphere during these experiments. The experiment was carried out on clear sunny days. The inlet, outlet and ambient temperatures, solar beam radiation readings and the wind velocity were recorded. The thermal performance curves are as shown in figure 6.

A graph drawn between time and beam radiation is shown in figures 7 and 8 represents the graph between time and the wind velocity. As the aperture of the collector was covered with a glass envelope, no considerable variations were observed due to the wind velocity even up to 2.5 ms^{-1} .

Under the steady state conditions, the overall efficiency of the collector was calculated using the relation (ASHRAE 1977),

$$\eta_i = m^\circ C_w (T_o - T_i) / I_b A. \quad (7)$$

Figure 6. Thermal performance curve of CPC.

Figure 7. Time Vs beam radiation.

The experimental data points are fit into a straight line by the least square fitting method. A graph (figure 9) drawn between instantaneous efficiency (η_i) and $\Delta T/I_b$, where $\Delta T = [T_{av} - T_a]$ and I_b is the beam radiation measured using a pyrheliometer.

Figure 8. Time Vs wind velocity.

Figure 9. Instantaneous efficiency curve.

The Y – intercept (figure 9) gives the optical efficiency (0.622) of the 3D CPC and the slope of the instantaneous curve gives the heat loss co-efficient ($3.16 \text{ W/m}^2\text{°C}$). The 3D CPC gives an average efficiency 0.582 over a period of day as shown in figure 10.

5. In situ steam generation

The fabricated 3D CPC absorber assembly was slightly modified (condenser unit attached at the outlet of the absorber assembly) to generate low pressure steam. For the performance study of *in situ* steam generation of 3D CPC, the absorber assembly (capacity - 3.5 liters) was filled with a measured quantity of water. Solar beam radiation, wind velocity, outlet temperature, ambient temperature and the volume of steam condensate in the measuring jar were recorded at an interval of 5 minutes on many clear sunny days. The experiment was carried out for duration of about ± 3 hours around solar noon.

It was observed that the temperature of water was risen to 80°C in a time period of 70 minutes (the warm up period depends on the intensity of solar irradiance during the experiment). As the temperature reaches 75 to 80°C some quantity of hot water was suddenly ejected from the output end (this quantity got collected in the measuring jar). As the output temperature

Figure 10. Time Vs instantaneous efficiency.

Table 2. Summary of results for steam generation.

S. No.	Duration of steam generation (mts)	Mass of water condensate (lts)	Incident solar radiation (Wm^{-2})	Average thermal efficiency η_i
1.	150	0.160	500	0.355
2.	160	0.260	710	0.380
3.	178	0.295	710	0.389
4.	185	0.320	750	0.384
5.	200	0.350	780	0.373

reaches 98°C a steady output of steam started coming out and was escaping to the atmosphere. Invariably such steam was accompanied by a spray of hot water droplets. During the interval for the output temperature to rise from about 80 to 98°C , intermittent hot water ejections were found to take place a few times. The experiments are carried out on a number of days, and the readings are tabulated (table 2).

The instantaneous efficiency η_i was compiled from the relation (Rachel & Jayaraman 2002),

$$\eta_i = m^{\circ\circ}[C_w(T_o - T_i^1) + L]/I_b At, \quad (8)$$

where $m^{\circ\circ}$ is the mass of the condensate for t second, T_i^1 is the initial temperature of the water, T_o is the output temperature and L is the latent heat of vaporization of water at 100°C . After the warm up time the inlet and outlet temperatures were almost same, so the equation (8) reduces to,

$$\eta_i = m^{\circ\circ}L/I_b At. \quad (9)$$

The efficiency of the steam generation was about 38%, calculated using the relation (9) taking into account of the total quantity of steam generated.

6. Conclusions

Performance of 3D CPC was carried out in the present investigation, which resulted in the following conclusions.

- Experimentally determined values of optical efficiency (0.626) are in good agreement with theoretically predicted value (0.645). And the optical efficiency determined from the instantaneous curve (0.622) was in good agreement with both the experimentally determined value and the theoretically predicted value. These values of optical efficiency of the 3D CPC are significantly higher than that of the 2D CPCs of similar dimensions (figure 2). Thus 3D CPC can provide a better optical performance than that of a 2D CPC.
- The 3D CPC provides high optical efficiency, which in turn increases the thermal efficiency of the collector. Hence the average efficiency over a period of day is found to be 0.582, which is fairly high.
- The value of heat loss co-efficient of 3D CPC at zero solar irradiance $3.27 \text{ W/m}^2\text{C}$ is in good agreement with the value of heat loss coefficient obtained from the instantaneous efficiency curve $3.16 \text{ W/m}^2\text{C}$. But this heat loss coefficient is slightly higher when compared with the 2D CPC ($2.72 \text{ W/m}^2\text{C}$ at zero solar irradiance and $2.52 \text{ W/m}^2\text{C}$

from the instantaneous efficiency curve) of similar dimensions (Rachel & Jayaraman 2002) and it can be reduced by giving selective coating to the absorber.

- The time constant of the 3D CPC (431 s) is fairly high when compared (figure 4) with the 2D CPC (110 s) of similar dimensions (Rachel & Jayaraman 2002), which also clearly indicates the good heat capacity of the 3D CPC.
- This type of 3D CPC module can be operated as stand-alone solar low pressure steam generator with the efficiency of steam generation nearly 40%. By giving selective coating to the absorber, the efficiency of the steam generation can be increased.
- Further, this type of 3D CPC can be used for steam cooking, oil and water heating in many industrial applications.

List of symbols

A	Area, m ²
CPC	Compound Parabolic Concentrator
C_w	Specific heat capacity of water, Jkg ⁻¹ K ⁻¹
F	Heat transfer factor, dimensionless
f_{ref}	Multiple reflections, dimensionless
I	Solar irradiance, Wm ⁻²
$\dot{m}$	Mass flow rate, kg s ⁻¹
$\dot{m}^o$	Mass of the water condensate, kg s ⁻¹
$\langle n \rangle$	Average number of reflections
P	Optical loss due to the gap width
L	Latent heat of vaporization, J
t	Time, s
T	Temperature, °C
U_L	Heat loss co-efficient, Wm ⁻² °C

Greeks

θ	Angle, degree
θ_a	Half-acceptance angle, degree
η	Efficiency, dimensionless
ρ_m	Reflectance, dimensionless
α	Absorptance, dimensionless
ΔT	Temperature difference, °C
τ	Transmittance, dimensionless

Subscripts

a	Aperture, Ambient
b	Beam
e	Envelope
i	Inlet, Instantaneous
o	Outlet, Optical
av	Average of inlet and outlet temperature

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