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Enhancement of Optical Performance of a Three Dimensional Compound Parabolic Concentrator

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Abstract:- A three Dimensional Compound Parabolic Concentrator (3-D CPC) has been developed to collect solar energy and to achieve the highest possible concentration. The significant research work describes the methodology to bring out the performance of 3-D CPC reflector profile that is designed and fabricated for a half acceptance angle of 4º in support of a spherical absorber with radius 100 mm. In the present work, two types of absorber coating materials are used in 3-D CPC modules, one with a commercially available ordinary Black paint (3-D CPC IA) and another with a Black-Nickel-Tin (3-D CPC IB). The optical efficiencies of 3-D CPCs have been projected hypothetically and comparisons have made among the experimental values. The study examines the values of optical efficiencies that are experimentally determined are in good agreement with the values that are predicted theoretically. Optical performance of 3-D CPC IB has been enhanced by selective coating to the absorber.

Keywords:- *3-D CPC; Optical Efficiency; Black Nickel–Tin; Solar Energy.*

I. INTRODUCTION

Focusing collector is a tool to gather solar energy by means of high intensity of solar radiation on the energy absorbing surface. Such collectors usually employ optical system in the form of reflectors or refractors. Focusing collectors like Compound Parabolic Concentrators (CPC) are most common for applications with medium temperature. In 1974, CPC was first designed and determined by Winston [1]. The design and constructional details are reported in [2, 3]. The most important benefit of 2-D CPC is, they can receive radiation reaching the destination with large angular spread and so far concentrate it on to linear receivers of small transverse width. The end result of mirror errors and receiver misalignments of 2-D CPC were explained [4]. The varieties of 2-D CPCs expressed their greater part in terms of general characteristics, namely concentration, acceptance angle, sensitivity to mirror errors, size of the reflector area and average number of reflections were compared [5], moreover generate an easy analytical technique to work out the average number of reflections that make use of calculating optical losses for 2-D CPC. The feasible extensions of 2-D CPC to 3-D CPC were described and indicated that 3-D CPC propose a high concentration more than 2-D CPC [6]. A wide-ranging theoretical estimation of 2-D and 3-D ray tracing techniques has been taken in the recent study to work out the optical efficiency of the novel Elliptical–Hyperboloid Concentrators (EHC) [7]. An optical efficiency of 63% has been established for a 2-D model of the EHC with the dimensions as followed: aperture length 1m, height 0.85 m, receiver diameter 0.182 m and concentration ratio of 8X. The reflectivity of EHC has been considered as 0.94. As a result of the three-dimensional nature of EHC, the optical efficiency has been enhanced to 78% based on 3-D ray trace geometry. The limitation placed on 2D indicates that the CPC has to include rays in the output whose angle exceed the critical angle that are causing waste of concentration [8]. This waste concentration can be regained by the use of 3D structures which are practically necessary. Through the proper assembling of the 3-D CPCs, the minimal diffused element that present can be captured [9]. A new methodology (approximate development method) has been used to design 3-D CPC [10].

II. EXPERIMENTAL PROCEDURE

In the present work, two types of absorber coating materials have been used to the absorbers in the 3-D CPC modules fabricated for half-acceptance angle of 4º to achieve higher concentration ratio by approximate development method. Figure.1 shows the experimental set-up of 3-D CPC modules. The absorber is a spherical ball with 200 mm outer diameter and 197 mm inner diameter. To enhance the optical performance of the 3-D CPC modules, one of the absorber is coated with a commercially available ordinary Black paint (3-D CPC IA) and another absorber coated with Black Nickel-Tin (3-D CPC IB). The absorber for 3-D CPC IA is coated with dull black paint having absorptivity (**α**) 0.90 and 3-D CPC IB is coated with Black Nickel –Tin having absorptivity (**α**) 0.92. In the study of the 3-D CPCs, water is used as a heat transfer fluid. The temperatures have been measured by using Resistance Temperature Detector (RTD) in which the RTD (PT100) measures the temperature in the range of - 50 to 100˚C. The inlet, outlet and atmospheric temperatures were calculated using RTDs. This kind of concentrator operates simply on the beam component of solar radiation despite the fact that beam radiation has been calculated by means of a pyrheliometer. The flow rate of the fluid has been measured by using a graduated jar and a stopwatch. A stable head tank has been employed by an online heater to endow with various inlet temperatures to provide a constant flow of water. Moreover a wind velocity meter has been used to find the wind velocity.

Fig 1:- Experimental Set-Up

III. THEORETICAL ESTIMATION OF OPTICAL EFFICIENCY OF 3-D CPCs

The optical efficiency of 3-D CPC with top glass cover and glass envelope around the absorber [11] is given as,

$$\eta_o = \tau_a \, \tau_e \, \rho_m^{<n>} \, \alpha \, P \, f_{ref} \qquad (1)$$

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; <n> 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 average number of reflections was 1.4 for a half acceptance angle 4° [12]. To avoid conduction losses between the absorber and reflector, the cusp is removed and made flat. In view of the fact that, the receiver thermal losses of 3-D CPC are primarily radiative and the absorber area is undersized, the convection suppressing cover is not essential for 3-D CPC modules [13]. The top view of 3-D CPC IA is shown in Figure.2. Necessary modifications in the expression (Eq.1) for η_o were made for various CPC modules and are presented in Table 1 along with the estimated values of optical efficiencies.

Fig 2:- Top view of 3-D CPC IA

Module	*Absorber coating*	*Expression for* η_o	*Estimated optical efficiency*
3-D CPC IA*	Black paint	$\rho_m^{<n>} \alpha$	0.716
3-D CPC IA#	Black paint	$\tau_a \rho_m^{<n>} \alpha$	0.645
3-D CPC IB *	Black Nickel - Tin	$\rho_m^{<n>} \alpha$	0.732
3-D CPC IB #	Black Nickel - Tin	$\tau_a \rho_m^{<n>} \alpha$	0.659

Table 1:- Theoretical estimation of optical efficiency (η_o)
* Without glass cover, # with glass cover

IV. EXPERIMENTAL DETERMINATION OF OPTICAL EFFICIENCY

The collector has been incorporated with water as heat transfer medium in the fluid loop. The open loop operation that has been established was more convenient since it was effortless to uphold stable conditions and elevated flow rates for longer periods. The flow rate was set aside sufficiently large and stable such that $0 \le (T_{av} - T_a) \le 1^o$, where T_{av} is the average of inlet and outlet water temperatures and T_a is the ambient temperature. The inlet, outlet and atmospheric temperatures have been measured using RTD's and the beam radiation has been calculated using pyrheliometer. The observation has been taken from 9.00 am to 4.00 pm on several clear sunny days, at 2 minutes interval. For every different configuration of 3-D CPC modules steady state conditions has been obtained for 5 to 10 minutes around noon time on several days. The optical efficiency has been computed from the observed data [14, 15]. Based on this, the optical efficiency was computed as,

$$\eta_0 = m^\circ \, C_W \, (T_o - T_i) \, / \, I_b \, A \qquad (2)$$

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 and I_b is direct (beam) component of solar irradiance. The experiments were carried out on a number of clear sunny days. The sample readings taken during steady state conditions for 3-D CPC IA and 3-D CPC IB have been presented in Table.2 and Table.3. The experimentally determined optical efficiencies of various CPCs have been shown in Table 4.

S.NO	T_A (°C)	T_I (°C)	T_O (°C)	M° (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
mean						0.626

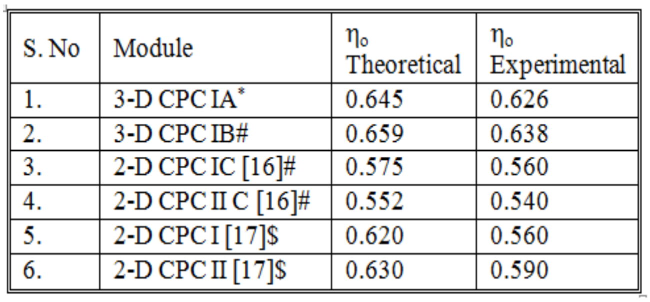
Table 2:- Experimental investigation of optical efficiency of 3-D CPC IA

S.NO	T_A (°C)	T_I (°C)	T_O (°C)	M° (KG/S)	I_B (WM^{-2})	η_o
1.	31.5	30.2	34.2	5.932E-03	690	0.636
2.	31.8	30.5	34.5	6.672E-03	770	0.641
3.	32.0	30.8	34.9	6.672E-03	780	0.649
4.	32.3	31.0	35.2	5.932E-03	730	0.632
5.	32.5	31.2	35.5	5.965E-03	750	0.633
Mean						0.638

Table 3:- Experimental investigation of optical efficiency of 3-D CPC IB

V. SUMMARY AND CONCLUSIONS

From Table 4, the theoretically estimated optical efficiency values are in good agreement with experimental optical efficiency values. It clearly shows that, the experimentally determined optical efficiency values of 3-D CPCs are higher than the 2-D CPC values that are reported earlier. Further, the optical efficiency values of 3-D CPC IB are higher than that of 3-D CPC IA and 2-D CPC due to the selective coating given to that absorber. The scope for the improvement in the present work gives the prior idea about the enhancement of thermal performance of 3-D CPC IB which in turn enhances the overall efficiency of the 3-D CPCs.



S. No	Module	η_o Theoretical	η_o Experimental
1.	3-D CPC IA*	0.645	0.626
2.	3-D CPC IB#	0.659	0.638
3.	2-D CPC IC [16]#	0.575	0.560
4.	2-D CPC II C [16]#	0.552	0.540
5.	2-D CPC I [17]$	0.620	0.560
6.	2-D CPC II [17]$	0.630	0.590

Table 4:- Optical efficiencies of various CPCs
*Black paint, #Black Nickel – Tin, $ NALSUN

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