Construction and performance analysis of a three dimensional compound parabolic concentrator for a spherical absorber

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Received 01 May 2006; revised 30 March 2007; accepted 02 April 2007

Three-dimensional compound parabolic concentrator (3-D CPC) was found to be more efficient than 2-D CPC because of higher concentration ratio. A 3-D CPC was fabricated with a half acceptance angle of 4° for a spherical absorber (radius 100 mm). UV stabilized aluminized polyester foil having high reflectivity was pasted on the reflector for a total height of 441 mm and an aperture width of 540 mm. Theoretical value (0.645) of optical efficiency compared well with experimental value (0.626). Experimental values of optical and thermal efficiencies were in good agreement with theoretical values. Optical efficiency from 3-D CPC was found significantly higher than that of 2-D CPC of similar dimensions. Time constant of 3-D CPC (431 sec) was fairly high as compared with 2-D CPC (110 sec). An attempt was made to generate low-pressure steam in in-situ steam generation mode, which was one of the possible applications of 3-D CPC module.

Keywords: 3-D CPC, Optical and thermal efficiency of CPC, Solar concentrator

Introduction

Flat plate collectors have been widely used for applications below 90°C. For medium temperature range (90-300°C), compound parabolic concentrator (CPC) type collectors are suitable. A 2-D CPC can receive radiation arriving with large angular spread and yet concentrate it on to linear receivers of small transverse width. Varieties of 2-D CPC’s in terms of concentration, acceptance angle, sensitivity to mirror errors, size of reflector area and average number of reflections have been compared. A 3-D CPC has been found to offer a higher concentration over a 2-D CPC. Besides, CPC’s also employed in photovoltaic-clad building facades.

In present work, an attempt is made to fabricate a 3-D CPC for half-acceptance angle of 4° to achieve higher concentration ratio and it also focuses on optical and thermal performance.

Experimental Details

A 3-D CPC reflector (Figs 1 & 2) is designed and fabricated for a half acceptance angle (4°) for a spherical absorber (outer diam 200 mm, inner diam 196 mm). Top portion (69 %) of the reflector is truncated and remaining (31 %) is taken for construction. Final reflector designed has a total height of 441 mm and an aperture width of 540 mm. UV stabilized aluminized polyester foil of high reflectivity is carefully pasted over the metal sheet. Copper tube (outer diam 8 mm, inner diam 6 mm) is connected to the top and bottom of absorber. Reflector top is covered with transparent glass (thickness, 3 mm). Collector assembly was placed in a location having access to sunlight and throughout the experiment collector was kept with its absorber to track the sun continuously so as to maximize solar energy. Collector was incorporated in fluid loop and operated in open loop mode. In 3-D CPC, water was used as a heat transfer fluid.

Inlet, outlet and ambient temperatures (-50 to 100°C) were measured using Resistance Temperature Detector (RTD, PT100) and 8-channel data logger DAS 8000. This type of concentrator operates only on the beam component of solar radiation; beam radiation was measured using a pyrheliometer. Flow rate of the fluid was measured using a graduated jar and a stopwatch. To provide a constant flow of water, a
constant head tank is employed with an online heater to provide various inlet temperatures. A wind velocity meter was also used to find the wind velocity.

**Results and Discussion**

**Optical Performance**

*Theoretical Estimation of Optical Efficiency (OE)*

CPC with top glass cover and glass around the absorber is given as

\[ \eta_o = \tau_a \tau_e \rho_m <n> \alpha P f_{ref} \]  \( \cdots (1) \)

where, \( \tau_a \), transmittance of aperture cover; \( \tau_e \), transmittance of glass envelope around absorber; \( \rho_m \), reflectance of reflector material; \( <n> \), average number of reflections; \( \alpha \), absorptance of material coated on absorber; \( P \), optical loss due to gap width; and \( f_{ref} \), multiple reflections between absorber tube and glass envelope. The receiver thermal losses of 3-D CPC are
primarily radiative and absorber area is small, it may not be necessary to have convection suppressing cover\(^9\).

Since there was no envelope to absorber, Eq (1) for 3-D CPC without the glass envelope to absorber reduces to

\[
\eta_\text{a} = \tau_a \rho_m^{C_{\text{air}}} \alpha \quad \text{...(2)}
\]

Transmittance of aperture cover was determined by pyranometer and average value was found to be 0.90. Reflectance of aluminized polyester foil was tested using a sensitive reflectance meter and average reflectance of reflector material was found to be 0.85. Average number of reflections\(^{10}\) was 1.4 for a half acceptance angle 4°. Dull black paint of absorptance (0.90) coating was used for spherical copper absorber. Thus, theoretical OE using all values of optical parameters was 0.645.

**Experimental Determination of Optical Efficiency**

Open loop operation was found to be more convenient because it was easy to maintain stable conditions and high flow rates for long periods. 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. OE was computed from the observed data as\(^{11,12}\)

\[
\eta_\text{a} = \left( m^\circ \cdot C_w \cdot (T_o - T_i) / I_b \cdot A \right) \quad \text{...(3)}
\]

where, \(m^\circ\), mass flow rate of fluid; \(C_w\), specific heat capacity of water; \(T_o\), outlet temperature; \(T_i\), inlet temperature; \(A\), aperture area; and \(I_b\), beam component of solar radiation. The experiments are carried out on a number of clear sunny days. Under steady state conditions, OE computed from the observed data was found to be 0.626. OE was also determined from the instantaneous efficiency measurement.

**Thermal Performance**

Time constant is a measure of the heat capacity of concentrator. For better functioning of a concentrator at higher temperature with reasonably high efficiency, overall heat loss coefficient should be made as low as possible and could be determined in two ways: i) From the slope of instantaneous efficiency curve; and ii) From thermal loss rate at zero solar irradiance.

**Time Constant**

Time constant is the time required for a fluid leaving 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\(^{13}\). Out of two methods\(^{14}\), shading off the collector after inlet and outlet temperatures had reached the steady state and continuously recording the outlet temperature was found to be most suitable.

To determine time constant, 3-D CPC module was incorporated with fabricated fluid loop\(^{13,15}\). Concentrator was allowed to attain steady state condition around noon. Solar radiation was abruptly shut off by shading concentrator, and variation of outlet temperature with time was recorded. Time constant (\(t\)) is calculated as

\[
(T_{o,t} - T_i) / (T_{o,i} - T_i) = 1 / e = 0.368 \quad \text{...(4)}
\]

where, \(T_{o,t}\), outlet temperature at time \(t\); \(T_{o,i}\), outlet temperature when the solar radiation is interrupted; and \(T_i\), inlet temperature of the concentrator which remains constant throughout the experiments. Flow rate was maintained to be steady throughout the experiment. Value of \(t\) (Fig. 3) of a 3-D CPC is fairly high (431 sec)

![Fig. 3— Cooling curve of CPC](image-url)
as compared with the same for 2-D CPC (110 sec) of similar dimensions reported.16

**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 instantaneous efficiency studies during day. The useful heat collected by CPC under steady state condition is given by

\[ q_u = q_a - q_L \]  \hspace{1cm} \text{(5)}

where, \( q_u \) = rate of useful heat gain of the collector, \( q_a \) = rate of heat absorber absorbed from the solar radiation, and \( q_L \) = rate of heat incident.

In the absence of solar radiation (\( I_b = 0 \)), Eq. (5) becomes,

\[ q_u = -q_L \]  \hspace{1cm} \text{(7)}

Hence Eq. (6) can be modified for this condition as

\[ A_c F' U_L (T_{av} - T_a) = m^C_w (T_i - T_o) \]  \hspace{1cm} \text{(8)}

This relation is used for the determination of \( F' U_L \) values. 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 steady state values of \( m^\circ, T_o \), and \( T_i \), the loss rate \( A_c F' U_L (T_{av} - T_a) \) was calculated using Eq. (8). These values are plotted (Fig. 4) against excess temperature \([T_{av} - T_a]\) and \( F' U_L (3.27 \text{ W/m}^2\text{°C}) \) is obtained.

**Instantaneous Efficiency**

Instantaneous efficiency (\( \eta_i \)) of the CPC is given by

\[ \eta_i = \left[ (\eta_o - U_L (T_{av} - T_a)) / I_b \right] \]  \hspace{1cm} \text{(9)}

Collector is incorporated in fluid loop and operated in the open loop mode for its performance study at different temperatures. To start with particular inlet temperature (40°C) is maintained for the whole period (110 sec) using one of the online heaters. Overhead tank itself contains 15 l of water and kept open to atmosphere during these experiments. The experiment was carried out on clear sunny days. Inlet, outlet and ambient temperatures (Fig. 5), solar beam radiation readings (Fig. 6) and wind velocity (Fig. 7) were recorded. As the aperture of collector was covered with a glass envelope, no considerable variations were observed due to wind velocity even up to 2.5 ms\(^{-1}\). Under steady state conditions, overall efficiency of collector was calculated as

\[ \eta_i = m^\circ C_w (T_o - T_i) / I_b A \]  \hspace{1cm} \text{(10)}

A graph (Fig. 8) was drawn between \( \eta_i \) and \( \Delta T / I_b \), where \( \Delta T = [T_{av} - T_a] \) and \( I_b \) is the beam radiation measured using a pyrheliometer. The Y – intercept
Fig. 5— Thermal performance curve of CPC

Time, h

Fig. 6— Time vs beam radiation

Time, h

Fig. 7— Time vs wind velocity

Time, h
(Fig. 8) gives OE (0.622) of 3-D CPC and the slope of instantaneous curve gives the heat loss co-efficient (3.16 W/m²°C).

**In-situ Steam Generation**

Fabricated 3-D CPC absorber assembly was slightly modified (condenser unit attached at the outlet of the absorber assembly) to generate low-pressure steam. Absorber assembly (capacity, 3.5 l) was filled with a measured quantity of water. Solar beam radiation, wind velocity, outlet temperature, ambient temperature and the volume of steam condensate in measuring jar were recorded at an interval of 5 min on many clear sunny days. The experiment was carried out for 3 h around solar noon. Temperature of water rose to 80 °C in 70 min (warm up period depends on intensity of solar irradiance during experiment). As temperature reaches 75-80 °C, some quantity of hot water was suddenly ejected from the output end and it was collected in measuring jar.

The efficiency of steam generation (38%) was calculated using Eq. (12) taking into account of the total quantity of steam generated.

### Conclusions

Performance of 3-D CPC indicated that values are in good agreement with theoretically predicted value (0.645). OE determined from the instantaneous curve (0.622) was also in good agreement experimentally determined and theoretically predicted. OE values of 3-D CPC are significantly higher than that of 2-D CPC’s of similar dimensions. This provides high OE, which in turn increases the efficiency of the collector. The value of heat loss coefficient (3.27 W/m²°C) of this collector at zero solar irradiance is in good agreement with the value of heat loss coefficient (3.16 W/m²°C) obtained from instantaneous efficiency curve. But this heat loss coefficient is slightly higher when compared with 2-D CPC of similar dimensions and it can be reduced by giving selective coating to the absorber. Time constant of the 3-D CPC is fairly high when compared with 2-D CPC of similar dimensions, which also clearly indicates the good heat capacity of 3-D CPC. The 3-D 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 steam generation can be increased. The 3-D CPC can be used for steam cooking, oil and water heating in many industrial applications.

\[
\eta_i = m^{°°} \frac{C_w (T_o - T_i) + L}{I_b A t} \quad \text{...(11)}
\]

where, \(m^{°°}\) = mass of the condensate for t sec, \(T_i\) = initial temperature of water, \(T_o\) = output temperature, and \(L\) = latent heat of vaporization of water at 100 °C. After warm up time, inlet and outlet temperatures were almost same, so Eq. (11) reduces to,

\[
\eta_i = \frac{m^{°°} L}{I_b A t} \quad \text{...(12)}
\]
Nomenclature

**Greek symbols**

- \( \theta \) Angle, degree
- \( \theta_a \) Half-acceptance angle, degree
- \( \eta \) Efficiency, dimensionless
- \( \rho_m \) Reflectance, dimensionless
- \( \alpha \) Absorptance, dimensionless
- \( \Delta T \) Temperature difference, °C
- \( \tau \) Transmittance, dimensionless

**Subscripts**

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

References