Performance Investigation of Cavity Absorber for Parabolic Dish Solar Concentrator

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Abstract

The conventional flat surface short cylinder absorber produces an energy efficiency of 45-55% in the 16-square meter solar parabolic dish collector. A cavity absorber with circumferential fins is proposed for the in the place of conventional flat surface absorber. The thermal performance of cavity absorber using embedded fins is carried for a flow rate of 100, 150 and 200 litres per hour (LPH). The average wall temperature of the cavity absorber is obtained around 69°C - 110°C. The experiments are conducted in steady state condition, and the average thermal efficiency of the cavity absorber using the circular fins at 100, 150 and 200 LPH are found to be 56.2%, 58.4%, and 64.2% respectively. This proposed absorber is observed with around 4.6% more efficiency with the flat surfaced receiver. The results are concluded that the circumferential fins in the cavity absorber increase the thermal performance of the absorber.

Keywords: Parabolic dish collector, Cavity absorber, Circumferential Fins. Heat transfer fluid, Phase change material.
1. Introduction

The solar absorber is the main component in concentrated solar system. Heat losses are high in such absorbers due to higher operating temperatures. The radiation and convection heat losses are dominant. Cavity absorber allows the total absorption through total internal reflection of concentrated solar rays. The uniform distribution of heat occurs by the large internal surface of the absorber cavity.

An experimental study carried out on the flux distribution for 20 square-meter fuzzy focal cavity absorber. The heat losses and thermal performance of the modified cavity absorber is performed under various wind condition and resulted that the average thermal efficiency of modified cavity absorber is found to be 74% for the flow rate of 250 l/hr [1].

A performance study carried out of 8 square-meter parabolic dish collector (PDC) with storage tank instead of an absorber in the focus. It is concluded that the average power and efficiency concerning water boiling was found to be 1.30 kW and 21.62% respectively, with a mean beam solar radiation input of 742 W/m² [2]. The performance of 16 square-meter PDC is designed and investigated with a conventional circular absorber. Absorber plate temperature varied from 138°C to 235°C, while the maximum steam temperature of 107°C was achieved at the outlet of the boiler. The overall efficiency of 57.41% was achieved with an absolute temperature of 188°C [3].

The fin heat transfer based concentrated solar collector was built by Arunasalam et al. [4] using Fresnel lens. The performance study of 16 m² square-meter PDC with the efficiency of 45-58%. The usage of PCM increases the thermal efficiency of PDC to 60 to 68% [5]. The impact of the aperture size, inlet/outlet configuration of the different solar absorber and the rim angle of the parabolic dish investigated numerically. The results show that the rim angle of the parabolic dish has no impact on the thermal behaviour of the absorber and the suitable configurations of the absorber inlet and outlet [6].

The numerical investigation on modified cavity absorber of spherical geometry and also carried out the numerical study on the modified cavity absorber with two stage concentrations using a cone, CPC, and Trumpet reflectors. It is concluded that among the three absorbers were the preferred absorber for a fuzzy focal dish collector system [7-9]. Formed simpler correlations to predict convection losses from cavity absorbers. Numerical study of three different cavity geometrics, one of which is a small-scale experimental model absorber, while the order two are full-scale absorbers used in the ANU 20 square-meter and 400 square-meter dishes were carried out [10].

A parametric study of several relevant parameters in natural convection heat loss from open cavity absorber in a solar parabolic application with varying aperture diameter to cavity diameter ratio. Study on effect of varying inclination
angle of the absorber from -90 to 90 was also carried out [11].

A numerical study on heat losses from conical and dome shaped absorbers of solar parabolic dish system assuming flat square mirrors arranged on the dish as a reflector.

It is concluded that convection and emission losses increase with working temperature. It observed that the dome absorber is appropriate for higher working temperatures [12]. The temperature distribution on the solar parabolic dish absorber is determined and expressed the performance [13-17]. The performance of cavity absorber was investigated by various researchers and the effect of circumferential fins inside the absorber is aimed in this work. The enhanced effects are reported in this work.

2. Materials and Methods

The 16 m² parabolic dish collector is built by Thermax Ltd, Pune, India. The glass reflectivity is 0.92. Figure 1 illustrates the photographic view of the experimental setup, schematics of an experimental setup and the fin configuration of the cavity absorber without the back cover. The absorber is tested on sunny days in Chennai climate. This work involves an experimental investigation of the cavity absorber through outdoor testing and the comparison of energy efficiency with the conventional cavity absorber.

The absorber is kept at a focal distance of 2.5 m. The concentrated direct radiation on the absorber surface is transferred to HTF through the attached fins (mild steel). The capacity of the cavity absorber is 5 liters. The radii of the fins are 103 mm, 97 mm, 84 mm, 63 mm, 33 mm respectively that is embedded to cavity absorber with the thickness of 5mm.
The experiment is conducted for three different flow rates 100, 150, 200 LPH respectively at an interval of 10 mins. The time taken to attain steady state is inversely proportional to the flow rate of the fluid. Based on the experimental results, steady state is obtained faster at 100 LPH than 150 LPH and 200 LPH.

The steady state is attained at the outlet temperature of the absorber around 100°C. The thermal efficiency of the receiver is calculated based on the measurements of average absorber wall temperature, ambient temperature and water at inlet/outlet temperatures by K-type thermocouples (accuracy of ±1%), beam solar radiation by shaded ring pyranometer (accuracy of ±3%) and wind speed using cup type anemometer (accuracy of ±1%), cavity temperature and efficiency of the system.

The thermal performance of the PDC can be characterized by an estimation of
the stagnation temperature and performance test at constant solar energy input with the equal period of time interval. The solar radiation, wind speed and ambient temperature are observed using pyranometer, anemometer and K-type thermocouples respectively. The stagnation test is often the preliminary test to compare the characteristics between the different plates.

An energy balance on the absorber plate yields the following equation:

\[ Q_s = A_s S - Q_i \]  \hspace{1cm} (1)

Where \( S \) is the incident solar flux and \( Q_i \) is the total rate of heat losses. At stagnation condition, \( Q_u = 0 \), this is done by focusing the reflector on to the absorber plate when there is no water flowing through the absorber [18]. This gives us the maximum temperature that the absorber plate can achieve. After stagnation test is completed, the reflector is defocused, the plate is allowed to cool down and then the pump is started to fill the circuit with water. The water then flows into the absorber, which already has the reflector focusing radiation on it. Readings are then taken at regular time intervals. As can be observed, the sun’s rays fall on the parabolic dish. The absorber is fixed at the focal point to absorb the concentrated direct solar radiation and transforms it to HTF as thermal energy. The thermal efficiency of the cavity absorber is evaluated by calculating the convection and radiation losses from the absorber. For perfect insulation of the absorber which conduction heat losses is neglected. The instantaneous efficiency of the PDC can be expressed as under steady state condition,

\[ \eta = \frac{m_i C_p (T_o - T_i)}{I_s A_s \eta_{op}} \]  \hspace{1cm} (2)

Where \( m_i \) is the mass flow rate of water (kg s\(^{-1}\)), \( C_p \) is the specific heat of water (J kg\(^{-1}\) k\(^{-1}\)), (\( T_o - T_i \)) is the temperature difference of HTF in the absorber inlet and outlet. The overall efficiency of the system is evaluated by the given expression as,

\[ \eta_{op} = \frac{Q_u}{Q_{in}} = \frac{m_i C_p (T_o - T_i)}{I_s A_s \eta_{op}} \]  \hspace{1cm} (3)

Where \( Q_u \) is useful heat gain by water (kJ), \( Q_{in} \) is input energy of the absorber (kJ) and it is calculated by using the optical efficiency of the collector (\( \eta_{op} \)) can be expressed as,

\[ \eta_{op} = \tau \alpha \rho \left( 1 - \frac{T_o}{T_s} \right) \]  \hspace{1cm} (4)

Where \( \tau \) is transmissivity of a collector, \( \alpha \) is absorptivity of a collector, \( \rho \) is reflectivity of the collector, \( T_a \) is ambient temperature (°C), \( T_s \) is surface temperature of the collector (°C). The total heat loss (W) of the absorber is
evaluated by calculating convection and radiation losses of expression as

\[ Q_i = h_i A_s \Delta T + \varepsilon \sigma A_s \left( T_s^4 - T_a^4 \right) \]  \hspace{1cm} (5)

Where the convection loss is calculated by the sum of natural convection loss \((h_{nc})\) and forced convection loss due to surroundings wind velocity, \(k\) is thermal conductivity (Wm\(^{-2}\)K\(^{-1}\)), \(D\) is the diameter of the absorber (m) and \(Nu\) is the Nusselt number of natural and forced convection.

\[ h_i = \frac{Nu_{nc} k}{D} + \frac{Nu_{fc} k}{D} \]  \hspace{1cm} (6)

\[ Nu_{nc} = 0.10(Gr Pr)^{0.333} \]  \hspace{1cm} (7)

\[ Nu_{fc} = 0.10(Re Pr)^{0.333} \]  \hspace{1cm} (8)

Where \(Pr\) is Prandtl Number, \(Gr\) is Grashoffs Number and \(Re\) is Reynolds Number is calculated the expression as,

\[ Gr = g \beta D^2 \Delta T \gamma^2 \]  \hspace{1cm} (9)

\[ Re = \frac{\nu D}{\gamma} \]  \hspace{1cm} (10)

Where \(g\) is the gravitational force (m s\(^{-2}\)), \(\beta\) is coefficient of thermal expansion (K\(^{-1}\)), \(D\) is diameter of absorber (m), \(\Delta T\) is temperature difference between wall temperature and ambient temperature (K), \(\gamma\) is kinematic viscosity of HTF (m\(^{-2}\) s) and \(\nu\) is wind speed (m s\(^{-1}\)).

### 3. Results and Discussion

Experimental performance of 16 square-meter solar PDC with cavity absorber using embedded fins to the disc of aperture diameter 400 mm with mass flow rates of 100, 150 and 200 LPH is conducted. The graphs were plotted for various flow rates with respective to time, temperature, beam radiation, average wall temperature, efficiency, the inlet and outlet temperature of the water tank, inlet and outlet temperature of the absorber. By obtaining summarized results, the effect of temperatures with solar irradiance and the thermal behavior of cavity absorber discussed.

In Figure 2 shows initially the cavity absorber holds no solar radiation and the temperature difference is maximum at 12.20hrs, 12.40hrs and 13.10hrs and beam radiation is peaked at 11.50hrs. The water attains steady temperature quicker than 150 LPH and 200 LPH. **Temperature Difference Across the Absorber**

The time taken to attain steady state is inversely proportional to the flow rate of the fluid. Based on the experimental results, steady state is obtained faster at
100 LPH than 150 LPH and 200 LPH. The steady state is attained at the inlet and outlet temperature of the absorber at 100, 150, 200 LPH are 100°C and 104°C, 113°C and 116°C, 97°C and 114°C respectively.

By the result obtained for thermal efficiency process at different mass flow rates, various parameters have been calculated such as average temperature, beam radiation, cavity temperature and efficiency of the system. Figure 2-4 shows the temperature difference of HTF and incident radiation during the outdoor testing. The water at 100 LPH attains steady temperature quicker than 150 LPH and 200 LPH.

Figure 2: Temperature Gain by Water for 100 LPH Mass Flow Rate

Figure 3: Temperature Gain by Water for 150 LPH Mass Flow Rate
Figure 4: Temperature Gain by Water for 200 LPH mass Flow Rate

**Absorber Surface Temperature**

The graph is plotted in between time and the absorber wall average temperature in Figure 5-7. Initially, the cavity absorber holds no solar radiation. The average temperature is maximum when the beam radiation is maximum. The average temperature of 144°C is highest at 13.40 hours, and the beam radiation is highest at 12.50 hrs.

Figure 5: Average Wall Temperature of the Absorber for 100 LPH
The maximum receiver wall temperature is observed around 156-161°C when the flow rate varied between 100 and 200 LPH. This surface temperature results in not only useful heat to the water but also convection and radiation heat losses.

**Absorber Inlet and Outlet Temperature**

Figures 8-10 are plotted between the inlet temperature and outlet temperature of the absorber. The inlet and outlet temperature of absorber gradually increases with the increase in time as the radiation is focused towards the absorber.
Figure 8: Inlet and Outlet Temperature of Absorber for 100 LPH

Figure 9: Inlet and Outlet Temperature of Absorber for 150 LPH

Figure 10: Inlet and Outlet Temperature of Absorber for 200 LPH
The inlet and outlet temperature attains steady state after 15.00 hours when the inlet temperature is at 90°C and outlet temperature is at 101°C for the water flow rate of 100 LPH. The steady state is attained that the outlet temperature is constant. The similar test conditions for the fluid flow rate of 150 LPH attained the boiling point when the inlet temperature is 95°C as shown in Figure 9.

The inlet and outlet temperature of cavity absorber gradually increases with the increase in time as the radiation is focused towards the absorber. The inlet and outlet temperature attains steady state after 15.00 hours when the inlet temperature is at 89°C and outlet temperature is at 101°C at the flow rate of 200 LPH.

**Absorber Efficiency**

Figures 11 shows the energy efficiency over the selected mass flow rate of water. As the beam radiation increases the efficiency of the absorber also increases. The maximum efficiency of the absorber is 56% at 12.20 hours for 100 LPH.

At the time of the maximum efficiency the beam radiation is 0.545 MJ/m². The highest efficiency of the absorber is 58.4% at 12.00 hrs for a mass flow rate of 150 LPH. At the time of the maximum efficiency the beam radiation is 0.49 MJ/m².

The maximum efficiency of the absorber is 62.4% at 13.00 hrs for a mass flow rate of 200 LPH. At the time of the maximum efficiency the beam radiation is 0.522 MJ/m². The thermal performance of the finned absorber was studied and the results are useful in the design of efficient solar absorber for concentrated collectors.

The uncertainty of energy efficiency is determined through root mean square method as 1.02%. This uncertainty shows that the measurement errors are within a significant level.

### 4. Conclusions

In this study, a cavity absorber using embedded fins has investigated to study the thermal performance on a parabolic dish collector. The linear fins are used in the solar receiver and the average energy efficiency is around 55% during the water heating experiments.

The modification of the absorber with circumferential fins into a cavity absorber using circumferential fins was investigated at various HTF mass flow rates. The average thermal efficiency of the cavity absorber using the fins at 100, 150, 200 LPH is 54.2%, 58.4%, and 64.2% respectively during the water heating experiment.

The increase in mass flow rate increases the absorber efficiency. Using the fins
in the absorber increases the average thermal efficiency of the absorber by 3.6 - 4.6%. The proposed absorber produces more thermal output under the similar solar radiations using the same parabolic dish collector.

The cavity absorber is proved with enhanced thermal performance and one of the better option for the conventional flat surface absorber. The cavity absorber will be studied with the heat transfer enhancement techniques to improve the rate of heat absorption further.

References


