Experimental Investigations of Stagnation Temperature and Overall Heat Transfer Coefficient of Flat Receiver for Solar Parabolic Dish Concentrator System

Susant Kumar Sahu, Vadivukkarasan M, Dharamsoth Suman, Devineni Ramanjaneyulu, Gurugubelli Raja Rao Naidu, Reddi Sudarshan, Arjun Singh K and Sendhil Kumar Natarajan*

Department of Mechanical Engineering, National Institute of Technology Puducherry, Karaikal - 609 609, U.T. of Puducherry, INDIA.
*Corresponding Author: Assistant Professor and Head
Email: drsendhil1980iitmuk@gmail.com, sendhil80@nitpy.ac.in

Abstract. The parabolic dish concentrator is one of the most efficient technologies to convert direct beam radiation into thermal energy for steam and power generation. The parabolic dish concentrates direct beam radiation from the sun on to a receiver at the focal point. The receiver plays a major role to transform the reflected solar radiation into thermal energy. The conversion efficiency of the dish is severely influenced by imperfection of the dish collector such as the contour of parabola, size of the facets aligned, positioning of the receiver and tracking of the system. These imperfections are mainly involved in the design, manufacturing, construction and operation of a parabolic dish collector. To overcome this imperfection, secondary reflector are normally deployed at the focal region of the receiver. The function of the secondary reflector reradiates the deviated rays from the primary concentrator onto the receiver. In this aspect, flat receiver is initially fabricated to evaluate the performance of the flat receiver without secondary reflector. In this paper, the experimental investigations on flat receiver for 12.6 m² area of solar parabolic dish concentrator system to estimate the receiver temperature and overall heat transfer coefficient of the flat receiver. In order to estimate this, rectangular box type aluminium receiver is fabricated and placed at the focal point of 2.42 m from the base of the dish. The aperture area of dish concentrator system is 12.6 m² area and it consists of 12 petals and in each petals 128 flat mirrors of size 7.5 cm × 7.5 cm with reflectivity of 0.95 are pasted on 1.2 mm thickness MS plate to form a parabolic dish concentrator. The azimuth and elevation manual tracking arrangements are made to track the dish continuously for different orientation of the sun. K-type thermocouples are used to measure the temperatures of the top and bottom of the receiver. To measure the maximum temperature of the receiver, experiments are carried out for stagnation conditions (without heat retrieval from the receiver). Experiments are carried out on 5th, 6th and 7th March 2018 from 10.00 am to 3.00 pm. For different direct beam solar radiation, the top and bottom temperatures, ambient temperatures are measured. The maximum temperature of 399°C is achieved at the bottom surface of the flat receiver for the beam radiation of 955 W/m², and the corresponding top surface temperature of 58°C is achieved for the same flux. Based on the measured bottom surfaces temperatures, the overall heat transfer coefficient of bottom surface are estimated as 145.56 W/m² K. Based on this study, further heat transfer analysis will be carried out for the developed flat receiver.
1. Introduction

The demand for energy is increasing day by day due to more incoming of the man – made energy consuming inventions. Due to this, the existing energy scenario is alarmed to use renewable energy sources. Among the renewable energy sources, solar energy plays a prominent role to satisfy the energy demand. There are lot of solar energy technologies are available to harvest the energy from the sun efficiently. Nowadays, concentrating solar power (CSP) technologies are extensively used for thermal and electric power generation. In this CSP technologies, parabolic dish, parabolic trough, central receiver and compact linear Fresnel reflector are being used. Among these CSP technologies, parabolic dish concentrator system attracts more researchers due to its modularity (size can be varied depends on the requirement). Parabolic dish concentrator system is one of the technologies that capture the thermal energy from the sun with more efficiency by concentrating the direct beam radiation on to a focal point of the parabolic dish, where the receiver is mounted. The conversion efficiency of the dish system is highly influenced by the imperfection of the dish collector such as the contour of parabola, size of the facets aligned, positioning of the receiver and tracking of the system. These imperfections are mainly due to the design, manufacturing, construction and operation of a parabolic dish collector. Many research work have been carried out in the area of solar parabolic dish concentrator, receivers, tracking system. In this aspect, Sendhil and Reddy [1,2] numerical investigated the natural convective heat loss from three different shape of the receivers; cavity, semi cavity and modified cavity receiver for fuzzy (imperfect) focal solar dish concentrator system. It was concluded that modified cavity receiver gives less convective heat loss compared to other receivers. Separate convective heat transfer correlations were also proposed for the modified cavity receiver of with insulation and without insulation. Shuang – Ying Wu et al [3] evaluated the overall thermal to electric conversion performance of parabolic dish with alkali metal thermal to electric converter (AMTEC) thermal power system. It was found that thermal to electric conversion of 20.6% with a power output of 18.54 kW. Based on that, it was indicated that, parabolic dish systems exhibits great potential and competitiveness among other CSP systems. Shuang –Ying Wu et al [4] presented the comprehensive review of performance of the cavity receiver in a parabolic dish thermal system. The convection heat loss mechanism, different shapes of the cavity receiver, cavity heat loss prediction with wind effect were reviewed. It was suggested that, more detailed study of cavity receiver for parabolic dish concentrator is necessary for more quantitative information. Huairui Li et al [5] analytically predicted the optical performance of solar parabolic dish concentrator with a cavity and flat receiver. Gaussian distribution was considered at the receiver to predict the optical efficiency of the dish.

Weidong Huang et al [6] presented the analytic function to calculate the intercept factor of solar parabolic dish concentrator with sphere receiver. It was indicated that solar parabolic dish concentrator with sphere receiver gives thermal efficiency of 20% more than parabolic trough and central receiver system. Hamza Hijazi et al [7] designed a low-cost parabolic solar dish concentrator of three diameters of 5 m, 10 m and 20 m with a common focal length to dish diameter (f/d) ratio of 0.3. It was conclued that, dish diameter of 5m with a rectangular ribs frame of 40mm×8mm cross-sectional area and for diameter of 10 m with a rib frame of 90mm × 8mm cross-sectional area rectangular beams satisfied the factor of safety with minimum cost. Hafez et al. [8] carried out a feasibility study to investigate the possibility of solar dish technologies in various regions. Solar factors such as solar radiation, aperture size, the focal length of the parabola, the diameter of the focal point, the aperture area of receiver and dish concentration ratio were considered and finally concluded the optimal efficiency of the collector depends mainly on rim angle, receiver diameter and the concentration ratio of the parabolic dish. Andrea Giorsti and Ennio Macchi [9] discussed the simulation tool for thermodynamic and economic assessment of coupling of parabolic dish concentrator with air micro gas turbine engine to mitigate the

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technological issues and investment cost. It was also mentioned that the thermal receiver and ceramic turbine for hybrid mode needs to be addressed. Joe Coventry and Charles Andraka [10] reviewed the power generation, central storage and hybridisation options based on the dish. Ka Lok Lee et al [11] numerically investigated the combined natural and forced convective heat loss from the cylindrical cavity receiver. The effects of aspect ratio and wind speed (head-on) on combined convective heat loss were investigated. It was found that for aspect ratio greater than unity and wind speed of about 4 m/s, the combined natural and forced convective heat loss is independent of the aspect ratio. It was also mentioned that, for wind speed of 10 m/s, the combined heat loss drops by 74% when the aspect ratio is increased from 0.5 to 3.

Kentaro Kanatani et al [12] developed a model of helically coiled tube solar cavity receiver for cross linear concentrating system. The parameters such as outlet temperature, maximum temperature of the receiver, receiver efficiency, pumping power were investigated. It was mentioned that absorptivity of the receiver slightly influence the receiver outlet temperature. Song Yang et al [13] proposed the method of forced air circulation system both in clockwise and anticlockwise mode to suppress the convective heat loss across the aperture of the dish concentrator. It was observed that, anticlockwise mode gives better performance than clockwise. Loni et al [14] experimentally investigated the thermal performance of cylinder cavity receiver circulated with two types of nanofluids of Al₂O₃/Thermal oil, SiO₂/Thermal oil and pure thermal oil. It was observed that, Al₂O₃/thermal oil nanofluids gives lower heat loss coefficient than others. Jiabin Fang et al [15] investigated the effect of surface properties such as radiative and optical on the thermal performance of the water-steam cavity receiver. Yabin Jin et al [16] performed coupled simulations of Monte Carlo Ray Tracing and Finite volume method on 2-D solar cavity filled with air-carbon mixtures to overcome the non-uniform temperature distributions. Loni et al [17] numerically and experimentally investigated the thermal performance of two types of cavity receiver (cubical and cylindrical) for dish concentrator system. It was observed that, cubical cavity receiver gives better heat gain than cylindrical cavity receiver for dish system. Based on the above literature review, it is observed that very few researchers investigated the flat receiver for solar parabolic dish concentrator. In this paper, experimental investigation is carried out on flat receiver to estimate its stagnation (maximum) temperature and overall heat transfer coefficient for different direct beam radiations. Real time experiments are carried out on 5th, 6th and 7th March 2018 from 10.00 am to 3.00 pm. for different direct beam solar radiation to measure the top and bottom surface temperatures.

2. Experimental Setup
A 12.6 m² aperture area of dish concentrator is designed and constructed at terrace of the science block, National Institute of Technology Puducherry, Karaikal (10.92° N, 79.83° E). The developed parabolic dish consists of 12 petals and in each petal 128 flat mirrors of size 7.5 cm × 7.5 cm with reflectivity of 0.95 are pasted on 1.2 mm thickness MS plate to form a parabolic dish concentrator. The manual azimuth tracking and elevation tracking arrangements are made to track the sun continuously from east to west. A 0.5 HP AC motor with pulley belt drive of 1: 10 and a gear box drive of 1:60 and worm and worm wheel drive of 1:40 is used for elevation tracking. A separate worm and worm wheel of 1:20 is used for azimuthal tracking. A center support with supporting three legs is used to hold the entire dish collector system. The specification of the solar parabolic dish is given in Table 1.

| Description                          | Dimensions |
|--------------------------------------|------------|
| Aperture area of dish (Aₚ)           | 12.56 m²   |
| Diameter of dish (Dₚ)                | 4 m        |
| Radius of Dish (Rₚ)                  | 2 m        |
| Rim angle of the Dish (ψ)            | 45°        |
A rectangular box type aluminium receiver is fabricated and painted with black color to increase its absorptivity. The receiver of dimension of 18 cm × 15 cm × 7.5 cm is placed at the focal point of 2.42 m from the base of the dish. The three K-type thermocouples are used to measure the bottom flat surface and top flat surfaces of the rectangular box type aluminium receiver and also ambient temperature. The copper tubing coil is placed inside the rectangular box with two openings on the sides. From the two openings, copper tubes are connected to circulate the cold water. In order to estimate the maximum surface temperature of the receiver, the solar parabolic dish is operated under various solar beam radiation without circulating the water through rectangular aluminium receiver. i.e without heat retrieval. Solar beam radiations are measured by using a pyrheliometer (DR02-10) by Hukseflux thermal sensors. Agilent 3470A data acquisition system consisting of 20 channels is used to measure temperature of the top, bottom surface and ambient temperatures. The photograph of the solar parabolic dish concentrator with flat rectangular aluminium receiver is shown in Figure 1.

3. Results and Discussion
To measure the maximum temperature of the receiver, experiments are carried out for stagnation conditions (without heat retrieval from the receiver). Experiments are carried out on 5th, 6th and 7th March 2018 from 10.00 am to 3.00 pm for different direct beam solar radiation. The top, bottom temperatures of the flat rectangular aluminium receiver, and ambient temperatures are measured for every half an hour. The variations of the beam radiation on, ambient temperature, top and bottom surfaces temperatures with time for three days is shown in Fig.2,3 and 4.

|                |                |
|----------------|----------------|
| Focal Length   | 2.42 m         |
| Depth of the dish (h) | 0.415 m       |
| Receiver Dimensions | 18 cm × 15 cm × 7.5 cm |

Figure 1. Photograph of the solar parabolic dish concentrator with flat receiver.
Figure 2(a). Variation of beam radiation with time on 5th March 2018

Figure 2(b). Variation of ambient temperature, top and bottom surfaces temperatures with time on 5th March 2018
Figure 3(a). Variation of beam radiation with time on 6th March 2018

Figure 3(b). Variation of ambient temperature, top and bottom surfaces temperatures with time on 6th March 2018
Figure 4(a). Variation of beam radiation with time on 7th March 2018

Figure 4(b). Variation of ambient temperature, top and bottom surfaces temperatures with time on 7th March 2018
From the Figure 2 (a) and (b), it is very clear that, the peak beam radiation of 865 W/m² occurs at 1:15 pm on 5th March 2018. The corresponding bottom surface, top surfaces and ambient temperatures are 302°C, 44°C and 28°C. Similarly from Figure 3(a) and (b), on 6th March 2018, the peak beam radiation of 955 W/m² occurs at 10:45 am and 11:30 am. The corresponding bottom surface, top surfaces and ambient temperatures are 399°C & 353°C, 58°C & 62°C, 26°C & 25°C. Similarly from Figure 4 (a) and (b), the peak beam radiation of 775 W/m² occurs at 1:00 pm on 7th March 2018. The corresponding bottom surface, top surfaces and ambient temperatures are 300°C, 110°C, and 29°C. It is also evident that, the maximum bottom surface temperature of the developed rectangular aluminum receiver is 399°C and the same time, the top surface temperature is 58°C for the beam radiation of 955 W/m². Separately, overall heat transfer coefficient is calculated for all the three days (5th, 6th, and 7th March 2018) based on bottom surface and top surface and ambient temperatures. The overall heat transfer coefficient (U_L) is calculated as per the Eq. 1.

\[ U_L = \frac{A_p S \alpha \rho}{A_r (T_{st} - T_a)} \]  
Eq.(1)

Where, 
\( A_p \) = Aperture area of the concentrator (m²)  
\( A_r \) = Aperture area of receiver (m²)  
\( T_{st} \) = Stagnation temperature (K)  
\( T_a \) = Ambient temperature (K)  
\( S \) = Direct beam radiation (W/m²)  
\( \alpha \) = Absorptivity of the concentrator  
\( \rho \) = Reflectivity of the concentrator

It is observed that, the overall heat transfer coefficient of 113.62 W/m² K is obtained for the corresponding highest bottom surface temperature. The average overall heat transfer coefficient for rectangular aluminium receiver is 134.32 W/m² K. The overall heat transfer coefficient for rectangular aluminium receiver on 5th, 6th and 7th March 2018 is given in Table 2.

**Table 2. Overall Heat Transfer Coefficient for flat rectangular aluminum receiver on 5th, 6th and 7th March 2018**

| Time     | Direct Beam Radiation (W/m²) | Overall Heat Loss Coefficient (W/m² K) | Time     | Direct Beam Radiation (W/m²) | Overall Heat Loss Coefficient (W/m² K) | Time     | Direct Beam Radiation (W/m²) | Overall Heat Loss Coefficient (W/m² K) |
|----------|------------------------------|----------------------------------------|----------|------------------------------|----------------------------------------|----------|------------------------------|----------------------------------------|
| 10:30 AM | 820                          | 136.63                                 | 10:30 AM | 892                          | 111.64                                 | 10:30 AM | 640                          | 108.41                                 |
| 10:45 AM | 838                          | 136.89                                 | 10:45 AM | 955                          | 106.19                                 | 10:45 AM | 613                          | 99.98                                  |
| 11:00 AM | 802                          | 100.13                                 | 11:00 AM | 928                          | 109.35                                 | 11:00 AM | 631                          | 149.99                                 |
| 11:15 AM | 784                          | 103.63                                 | 11:15 AM | 946                          | 124.13                                 | 11:15 AM | 667                          | 108.66                                 |
| 11:30 AM | 757                          | 105.60                                 | 11:30 AM | 955                          | 120.73                                 | 11:30 AM | 640                          | 126.43                                 |
| 11:45 AM | 820                          | 126.76                                 | 11:45 AM | 919                          | 132.76                                 | 11:45 AM | 721                          | 121.20                                 |
| 12:00 PM | 838                          | 132.27                                 | 12:00 PM | 901                          | 143.95                                 | 12:00 PM | 694                          | 105.20                                 |
| 12:15 PM | 811                          | 128.17                                 | 12:15 PM | 910                          | 141.21                                 | 12:15 PM | 679                          | 162.23                                 |
| 12:30 PM | 802                          | 128.03                                 | 12:30 PM | 910                          | 155.89                                 | 12:30 PM | 730                          | 130.29                                 |
| 12:45 PM | 829                          | 128.44                                 | 12:45 PM | 928                          | 141.97                                 | 12:45 PM | 631                          | 118.30                                 |
| 1:00 PM  | 820                          | 146.91                                 | 01:00 PM | 919                          | 150.53                                 | 01:00 PM | 676                          | 118.25                                 |
| 1:15 PM  | 865                          | 130.56                                 | 01:15 PM | 919                          | 142.13                                 | 01:15 PM | 703                          | 115.84                                 |
| 1:30 PM  | 838                          | 187.03                                 | 01:30 PM | 928                          | 134.09                                 | 01:30 PM | 775                          | 124.34                                 |
| 1:45 PM  | 856                          | 140.70                                 | 01:45 PM | 919                          | 134.23                                 | 01:45 PM | 757                          | 153.10                                 |
| 2:00 PM  | 829                          | 157.65                                 | 02:00 PM | 910                          | 125.92                                 | 02:00 PM | 748                          | 122.58                                 |
4. Conclusion
A 12.6 m² solar parabolic dish concentrator with flat rectangular aluminium receiver is designed and developed. The stagnation temperature were measured for the developed flat receiver. The maximum bottom surface temperature of 399°C was obtained for beam radiation of 955 W/m² at stagnation conditions. The corresponding overall heat transfer coefficient was estimated as 113.62 W/m²K. The average overall heat transfer coefficient of 134.8 W/m²K was obtained for the flat rectangular aluminium receiver under stagnation conditions. Further heat transfer analysis will be carried out for the developed receiver with variable flow conditions.

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