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Experimental performance investigation of modified cavity receiver with fuzzy focal solar dish concentrator

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ABSTRACT

In this paper, thermal performance analysis of 20 m^2 prototype fuzzy focal solar dish collector is presented. The focal image characteristics of the solar dish are determined to propose the suitable design of absorber/receiver. First, theoretical thermal performance analysis of the fuzzy focal solar parabolic dish concentrator with modified cavity receiver is carried out for different operating conditions. Based on the theoretical performance analysis, the total heat loss (conduction, convection and radiation heat losses) from the modified cavity receiver is estimated. It is observed that the maximum theoretical efficiencies of solar dish collector are found to be as 79.2% for no wind conditions and 78.2% and 77.8% for side-on and head-on winds speed of 5 m/s respectively. Latter, real time analysis of parabolic dish collector with modified cavity receiver is carried out in terms of stagnation test, time constant test and daily performance test. From stagnation test, the overall heat loss coefficient is found to be 356 W/m^2 K. The time constant test is carried out to determine the influence of sudden change in solar radiation at steady state conditions. The daily performance tests are conducted for different flow rates. It is found that the efficiency of the collector increases with the increase of volume flow rates. The average thermal efficiencies of the parabolic dish collector for the volume flow rate of 100 L/h and 250 L/h are found to be 69% and 74% for the average beam radiation (I_{bn}) of 532 W/m^2 and 641 W/m^2 respectively.

1. Introduction

Parabolic dish collector is one of the most efficient systems for producing high temperature heat. Solar parabolic dish collector consists of three components viz., concentrator, cavity receiver/absorber and support structure with tracking arrangements. The performance of solar dish collector depends on accuracy and reliability of these components. The flux distribution at the focal region of solar dish concentrators plays a key role in the design of cavity receiver configuration. This can be predicted by means of optical analysis or direct measurement. The optical analysis can be accomplished either by analytical method [1–3] or ray tracing technique [4–7]. Several researchers investigated the flux distribution for different configuration of receivers. In this regard, Wen et al. [1] compared different analytical methods for computing the flux distribution at the focal plane of a paraboloidal solar concentrator and concluded that type of method selected depends on the maturity of design and data available. Sharma et al. [2] developed an integral relationship to evaluate the solar flux distribution on receivers of flat and cylindrical shapes. Jeter [3] presented a procedure for calculating the distribution of concentrated flux in paraboloidal solar collector based on the concepts of flux integral and radiant intensity. Traditionally, ray tracing technique is applied for flux distribution analysis at focal plane/receiver of the concentrating solar collector. Schubnell [4] investigated the influence of sunshape on the maximum overall efficiency of an optically accurate parabolic dish cavity receiver. Jones and Wang [5] computed the flux distribution on a cylindrical receiver of paraboloidal dish concentrator using geometric optics method. The parameters such as concentrator surface errors, pointing offset errors and finite sunshape were considered in the geometric optics method. Johnston [6] predicted the focal region characterization of a 20 m^2 point focus dish concentrator using a ray trace algorithm (COMPREC) and compared with the measured values. Shuai et al. [7] predicted the performance of solar dish concentrator/cavity receiver system using Monte-Carlo ray-tracing and optical properties. The effects of sunshape and surface slope error have also been studied. Johnston [8] used videographic flux mapping technique to characterize the

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focal flux distribution of the 400 m^2 solar concentrator. The surface slope error was estimated using ray trace analysis and compared with the videographic flux mapping. Pottler et al. [9] discussed the analysis of high precision photogrammetric tool for large concentrators to measure three dimensional (3-D) coordinates of concentrator support points and mirror surfaces. The analysis of flux distribution at the focal region is one of the major tasks for receiver design configuration. As the focal image width increases, parabolic dish collector requires larger size receiver and it becomes significant source of heat losses from the receiver. Among various modes of heat losses from receiver, natural convection and radiation heat losses contribute a significant fraction of total heat loss.

In order to improve the overall system efficiency, the heat loss characteristics of the receiver needs to be studied extensively. Harris and Lenz [10] studied the thermal performance of solar concentrator with various shapes of cavity receiver systems and suggested that the deviation in concentrator rim angle and cavity geometry cause large variations in power profiles produced inside the cavity receiver. Kaushika and Reddy [11] presented thermal performance characteristics and optimization of cavity receiver of a low cost solar parabolic dish and concluded that the conventional cavity receivers are inadequate for fuzzy focal dish concentrator. Taumoefolau et al. [12] investigated the natural convection heat loss from an electrically heated cavity receiver for different inclinations with temperature ranging from 450 to 650 °C. Reddy and Sendhil [13] investigated 3-D numerical analysis to estimate the natural convection heat loss from modified cavity receiver of fuzzy focal solar dish concentrator. Prakash et al. [14] carried out the experimental and numerical studies of convection and radiation heat losses from a cylindrical cavity receiver under steady state conditions and it was found that the convective heat loss increases with receiver mean temperature and decreases with receiver inclination. Nepveu et al. [15] presented a thermal model of the energy conversion for the 10 kW Eurodish dish/Stirling unit. A nodal method was used to calculate the heat losses from the cavity. The thermal model was compared with the experimental measurements. Wu et al. [16] carried out an extensive review on the convection heat loss from a cavity receiver for the parabolic dish system. It was suggested that a detailed study of the effect on cavity receiver convection heat loss would be necessary to provide more quantitative information.

The present work is focused on design and performance analysis of modified cavity receiver for a 20 m^2 fuzzy focal solar dish concentrator. In this analysis, optical, thermal (theoretical) and experimental investigations are carried out. The main objective of optical analysis is to predict the flux distribution at focal plane by considering the optical imperfection of the reflected ray's cone. Separate theoretical thermal analysis is also carried out to study the thermal efficiency of the receiver by considering wind effect for different receiver inclinations. Experimental investigations are also carried out to identify the receiver effectiveness by performing the stagnation test, time constant test and daily performance test.

2. Focal flux distribution of 20 m^2 fuzzy focal solar dish collector

2.1. Configuration of solar dish

A prototype of 20 m^2 fuzzy focal solar parabolic dish system is developed at Indian Institute of Technology Madras (IIT Madras), Chennai (13.06°N, 80.28°E) India for low and medium temperature application. An imperfect solar dish concentrator is referred as fuzzy focal solar dish concentrator. The imperfection of dish results in spreading the focal image size and casting fuzzy focal image. The imperfection of the dish is represented in terms of dispersion angle (δ_A). The circular image size (D_i) in the focal plane of a solar parabolic dish concentrator is given [17] by:

$$D_i = \frac{4f \tan \delta_A}{(1 + \cos \psi)\cos \psi} \quad (1)$$

where, $\delta_A = \omega_o + \Delta\omega$ for fuzzy focal dish; $\delta_A = \omega_o$ for a perfect optical disherrors.

The amount of imperfection of the 20 m^2 fuzzy focal solar dish at IIT Madras is predicted as 1.7° dispersion angle (δ_A) and the corresponding image diameter is measured as 0.305 m at the focal plane. The photograph of the 20 m^2 solar parabolic dish collector system developed at IIT Madras is shown in Fig. 1.

2.2. Flux distribution at the focal plane

An analytical model is developed to determine the flux distribution at focal region of a fuzzy focal solar dish concentrator. In this model, the central cones reflected from the two opposite halves of the dish intercept and disperse apart. The solar radiation reflected from each element of the dish would generate an elliptical image in the focal plane [11]. The flux mapping due to each hemisphere of the dish would be the superposition of numerous elliptical images of numerous orientations & sizes [1,11]. The outer portion of the image has intensity that gradually diminishes to zero beyond semi major axis of ellipses. As one moves away from the focal point there is variation in intensity due to decrease in the number of ellipses contributing at a point.

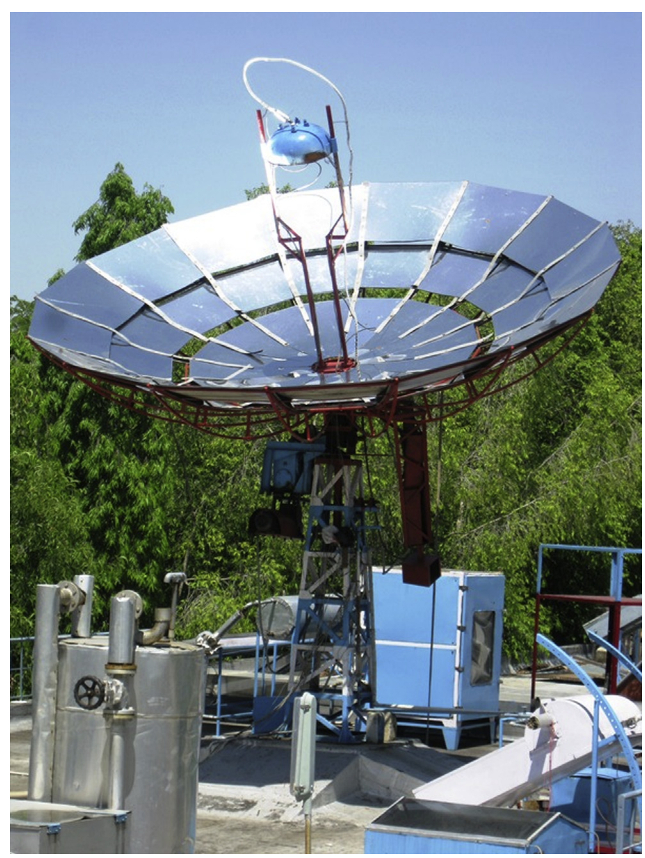

Fig. 1. A prototype of 20 m^2 solar parabolic dish collector system developed at IIT Madras.