International Journal of Thermal Sciences 125 (2018) 324–341

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

Heat loss investigation of 125kW$_{th}$ solar LFR pilot plant with parabolic secondary evacuated receiver for performance improvement

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ARTICLE INFO

Keywords:
Solar energy
Linear Fresnel Collector
Secondary reflector
Constant flux
Variable flux
Non-uniform flux
Wind velocity
Wind direction

ABSTRACT

Numerical investigation is carried out on the secondary reflector system of the pilot solar linear Fresnel reflector module of 154 m^2 in Vallipuram, Tamil Nadu. Initially, optical investigation on the design of the Linear Fresnel Collector module and the secondary reflector system is carried out. The optimized flux thus obtained is applied as a boundary condition to the thermal loss analysis. Investigation of the total heat losses (convective, radiative and conductive) with three different boundary conditions namely, the constant flux, variable flux and non-uniform flux distribution is carried out. The heat loss study has been carried out when the absorber is under non-evacuated and evacuated state. The study has been carried out with the DNI ranging between 250 W/m^2 and 1000 W/m^2. Uncoated and selectively coated absorbers with the emissivity of 0.01–1 are analyzed. Comprehensive analysis on the influence of wind flow on the receiver system is carried out. The variation of wind velocity from the ground level is incorporated in the forced convection. Investigation on the effect of the wind speed (0 m/s–10 m/s) and the wind direction (0°–90°) on this second stage reflector system is analyzed. The deviation between the different flux boundary conditions is comprehensively analyzed under different DNI and wind conditions. The variable flux distribution shows less deviation of about 15% from the non-uniform flux distribution for the DNI of 1000 W/m^2 and is found to be less than 5% for 500 W/m^2 under evacuated conditions. To avoid the computational complications in applying non-uniform flux boundary conditions to the absorber for DNI greater than 500 W/m^2, variable boundary flux condition can be applied as an equivalent flux condition by augmenting 15% non-uniform error percentage to the final heat loss value.

1. Introduction

Solar energy utilization from the clean and plentiful renewable solar energy is aided by solar to thermal conversion and solar to electric power conversion. The energy thus obtained with proper installation, maintenance and storage is highly reliable, environment-friendly and becomes an alternate of irrenewable fossil fuels [1]. Based on the necessity of energy output, thermal collectors are to be chosen and installed. Flat plate collectors and evacuated tube collectors [2] are preferred for the low-temperature application (100 °C), while linear collectors such as parabolic trough, linear Fresnel are used for medium temperature application (300 °C) [3,4]. Point focusing collectors such as central receivers are used for very high-temperature application (500 °C) [5,6]. Our area of interest is on solar linear Fresnel collector system which pledges simple design and construction, stability and easy maintenance [7,8]. The solar rays are reflected by thin, curved strips of mirrors on the receiver system comprising of single or multiple tubes. For multi-tube receiver system, the tubes are placed inside the cavity to prevent the convective heat losses and for single tube receiver system; reflectors are to provide uniform distribution of flux along the circumference of the absorber tubes in addition to prevent the convective heat losses [9,10]. The receiver cavity or the secondary reflector of the profile such as a trapezoid, V-shape, compound parabolic, involute etc. are studied [11–13].

Literature reviewed in our work details the peer's research on non-uniform distribution on the receiver tubes for different thermal collectors and the performance of the collectors in the presence of wind. Analyses have been carried out on the thermal performance of the receiver system assuming isothermal conditions [14] and uniform flux distribution [15] on the multiple/single tubes are studied. But in actual conditions, the flux is highly non-uniform [16] The bottom portion of the absorber receives rays reflected from the primary thin mirror strips while the upper portion receives the direct sun rays in absence of cavity/secondary reflector. In the presence of reflectors, the rays re-reflected from the secondary falls on the absorber thus increasing the intercept factor. The distribution of flux on the upper part of the

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https://doi.org/10.1016/j.ijthermalsci.2017.11.006
Received 21 June 2017; Received in revised form 10 November 2017; Accepted 10 November 2017
1290-0729/

absorber tube is highly dependent on the secondary profile, hence making the scope for the research. The thermal performance of a conical solar collector with concentric absorber tubes was investigated [17]. Experimental and numerical investigation on forced convection was carried on the dual axis tracking conical solar collector. Non-uniform solar flux caused by the conical shape of the collector was applied as the boundary condition along the length of the absorber. The efficiency of the system was higher because of the increased rate of concentrated solar flux despite the increased heat loss. Heat loss coefficient and the gain factors inversely varied with the volumetric flow rate. The heat loss analyses were performed on 250 kW parabolic trough collector located in Shiraz, Iran [18]. Experimental and numerical studies were performed on the absorber tubes under three different conditions; lost vacuum and broken glass tube.40% higher heat loss was observed in a tube with lost vacuum and 3–5% of the thermal performance deterioration was found. Numerical simulations claimed 12–16% reduction in thermal performance for a broken glass tube. A numerical study was performed by combining the solar ray trace and the finite element method and analyzed the heat transfer and thermal stress in a parabolic trough collector system with fluid [19]. The profile of the solar flux on the tube was determined from the solar ray trace and the distributions of the stress intensity and the thermal deformations of the receiver were numerically studied. The circumferential temperature difference was found to increase with the DNI and inversely increased with the temperature and heat transfer fluid inlet velocity. Calculations on stress distributions and deformations of the receiver were performed, with one end of the absorber allowed to expand. The absorber tube had greater displacement than the glass tube along its length. Analysis for hydrodynamically and thermally fully developed heat transfer in a circular tube with variable circumferential heat flux was done and the temperature variations along the axial and radial direction were predicted [20]. The effects of radial heat flux variation were much greater for turbulent flow compared to the laminar flow.

Numerical study on heat loss from a non-evacuated receiver of parabolic trough collectors [21]. Two cases were considered for study: one with uniform temperature and the other with non-uniform temperature distribution obtained by solving the energy balance equations along the cross-section of the receiver tube, considering the sun as a point source. Temperature distribution was found to fit the sinusoidal step function. The critical value of the ratio of receiver tube outer radius to the glass tube inner radius for minimum heat loss was dependent on receiver diameter and is found to decrease with the increasing receiver diameter. The value of critical RR (radius ratio defined as the ratio of the inner radius of the glass tube to the outer radius of the receiver pipe) for particular receiver diameter was found to be independent of the wind velocity. Non-uniform distribution of a receiver tube with fully developed turbulent flow and the heat transfer with Reynolds number 2 × 10ˆ4 to 2 × 10ˆ5, Prandtl number of 1.5 and Grashof number of 10ˆ9 to 10ˆ12 showed significant differences in the velocity field, temperature distribution, flow resistance and heat transfer between uniform and non-uniform flux distribution [22]. It was found that the friction factor was high at a solar elevation of 0° and 30° for uniform distribution compared to the non-uniform distribution. But at higher elevation angles of 60°–90° it was compared to be lower than non-uniform distribution. The performance of the parabolic trough collector with non-uniform distribution on the receiver was analyzed [23,24]. Higher relevance in the thermal performance was obtained from the non-uniform model.

Combined 3D optical and 2D thermal model of solar trough system with vacuum tube receiver based on energy balance, which can be applied to calculate the heat loss of solar trough system were carried out [25]. The convection in the axial direction was ignored. The model was validated with the experimental data of different models. The model showed 0.61% and 0.82% root mean square errors of the predicted efficiency. One-dimensional analysis on the PTC by segmenting the receiver and the envelope and applied the mass and the energy balance equations for each segment were performed [26]. Radiation heat transfer between the absorber and the glass envelope, conduction heat transfer of the support frame were considered in the analysis. Two-dimensional study on the solar parabolic trough collector by Engineering Equation Solver on the evacuated tube with the heat transfer fluid in the no-wind and wind condition were analyzed for heat loss [27]. Numerical heat transfer model analysis was carried out by discretizing the receiver into several segments both in the axial and the azimuthal directions [28]. Ray tracing analysis was carried out to determine the non-uniform flux distribution and these were coupled with the energy balance model. Modified cavity receiver of parabolic dish collector for different wind direction and wind speeds were investigated [29]. Convective heat losses from the cavity for different orientation and configuration were analyzed to obtain a Nusselt number correlation for determining the heat losses for higher temperature. Numerical and experimental analysis to study the influence of the wind and its direction on the cavity receiver of a solar power tower [30,31]. Similarity approach was implemented and the results were transferred to the receiver at atmospheric conditions. Influence of wind was found to increase with the increase in the inclination angle of the receiver from the horizontal position.

Analytical, numerical and experimental investigation of convective heat losses were performed on three different configurations of cavity receivers [32]. Wind flow of 2 m/s were made to flow on the cavity receivers with conical, cylindrical and spherical shapes with a similar aperture covered with glass pane. Minimum heat loss was proclaimed from the conical receiver with the temperature range between 363 K and 423 K. The two-dimensional analysis presented that the maximum force of 506.1 N/m was observed at 60° inclination of the trough. The Nusselt number was found to be constant for positive angles and varied for the negative angles of the collector's orientation.

The present work focusses on analyzing the parabolic receiver system with uniform, non-uniform and variable flux distribution. Two stages of investigation have been carried out. First, optical analysis of the pilot plant installed in Vallipuram has been carried out. Optimising the optical efficiency of the receiver with a new parabolic profile and the design parameters [33], heat flux along the circumference of the absorber are attained. These data are imbibed to the thermal study with the above-mentioned boundary conditions. The total heat loss for different DNI and emissivity are studied with the non-evacuated/evacuated absorber tubes. Realistic thermal conditions of the parabolic receiver system for different wind velocity and direction are estimated considering the variation of wind velocity with height from the ground level. An insight on the performance of the receiver under these varied boundary conditions can hence be obtained for the future work.

2. Description of solar LFR module with parabolic receiver system

The Linear Fresnel Reflector module, developed and installed in Vallipuram (12.65°N, 79.74°E), Tamil Nadu has 125 kWth capacity and with output stream of 50 bar pressure and 350–400 °C temperature and is shown in Fig. 1. The plant of 154 m^2 consists of single axis tracking twelve primary mirrors focusing the solar rays to the second stage of the reflector and the evacuated absorber. Schematic of the LFR module with the parabolic receiver system in Vallipuram is presented in Fig. 2. The receiver system comprising of the evacuated absorber is optimized to the parabolic profile for maximum optical efficiency and is improvised for uniform flux distribution along the circumference of the absorber to avoid hot spots, which is formed by prolonged exposure to the reflected solar rays at a particular spot in the absorber [33]. The absorber is selectively coated with sputtered cermet coating to reduce the emissive losses and hence increase the absorptivity. Modeling sequence of the LFR module starts from our previous work:designing a slightly parabolic curvature primary mirrors (each primary mirror has different curvature and is compared to circular curvature mirrors), tilt angle of the primary mirrors (tilted to defocus the rays to avoid hot