International Journal of Thermal Sciences 80 (2014) 48–57

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

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

Estimation of convective and radiative heat losses from an inverted trapezoidal cavity receiver of solar linear Fresnel reflector system

K.S. Reddy*, K. Ravi Kumar

Heat Transfer and Thermal Power Laboratory, Department of Mechanical Engineering, Indian Institute of Technology Madras, Chennai 600036, India

ARTICLE INFO

Article history:
Received 25 May 2013
Received in revised form
25 January 2014
Accepted 25 January 2014
Available online 4 March 2014

Keywords:
Solar energy
Linear Fresnel reflector
Cavity receiver
Heat loss
Aspect ratio

ABSTRACT

Solar linear Fresnel reflector (LFR) system is simple in design and cost effective technology for medium temperature (400 °C) applications. In this article, convective and radiative heat losses from the inverted trapezoidal cavity receiver for solar linear Fresnel reflector are estimated using a two dimensional (2-D) numerical model. The 2-D numerical simulation of trapezoidal cavity receiver is carried out by considering the receiver surface as isothermal conditions. The heat loss analysis is carried out for various receiver geometric and operating parameters viz. thickness of the insulation (t_{ins}), aspect ratio (A_s), cavity depth (D_c), cavity width (w), operating temperature (T_r), cavity cover emissivities (ε_{cc}), and wind speed (V_w). Based on the numerical simulation of the receiver, an optimum configuration of trapezoidal cavity receiver is obtained with $t_{ins} = 300$ mm, $D_c = 300$ mm and $A_s = 2$. The total heat losses varies from 663.47 W/m to 1046.3 W/m for w of 300 mm–800 mm at $T_r = 500$ °C, $\varepsilon_{cc} = 0.5$, $V_w = 2.5$ m/s. The effect of cavity cover emissivity on total heat losses is found to be less significant when compared to that of other cavity parameters. The optimum receiver configuration of the inverted trapezoidal cavity receiver can be used in solar LFR system with minimum heat losses.

1. Introduction

Medium and high temperature heat can be produced by using concentrating solar technologies. Based on the reflector configurations, the solar concentrating technologies may be classified as: linear Fresnel reflector, parabolic trough, parabolic dish and power tower. Among these, the linear Fresnel reflector (LFR) system is simple in design and cost effective system for medium temperature (100 °C–400 °C) applications. The performance of LFR system significantly depends on the receiver design. The earlier research work on LFR collector has been reported in the following order. The design and performance investigation of LFR has been reported first and followed by heat loss analyses from the cavity receiver for LFR collector. Negi et al. [1] presented the optical design and performance characteristics of a LFR with a flat vertical absorber. The analysis was carried out to study the effect of absorber height, concentrator aperture diameter and receiver width on performance of the system. Sootha and Negi [2] studied the optical designs and solar flux concentrating characteristics of a linear Fresnel reflector solar concentrator with tubular absorber. The development and performance of LFR with different sets of mirrors have been carried out by Singh et al. [3]. Mills and Morrison [4] evaluated the compact linear Fresnel reflector (CLFR) system for large scale solar thermal power plants. Alternative versions of the basic CLFR concept have been evaluated in terms of receiver and reflector field configurations. Reynolds et al. [5] developed heat loss and hydrodynamic models for CLFR system to predict output steam conditions and pressure drop across the receiver tubes for given input and environment conditions. Pye et al. [6] developed correlations for unsteady heat losses from the CLFR receiver system and compared with the steady state conditions.

Dey [7] carried out an analysis to maximize the heat transfer between the absorbing surface and receiver tubes. Reynolds et al. [8] studied the heat loss characteristics of trapezoidal cavity receiver for linear Fresnel reflector system. The heat losses from the receiver and the flow visualization technique to capture the flow patterns within the cavity have been described. Mills et al. [9] proposed the CLFR system for feed water heating of 35 MW_e coal fired power plant. Eck et al. [10] analyzed the thermal mass of receiver tubes for horizontal linear Fresnel collectors. The highest thermal mass was found out in the superheating section due to the lowest heat transfer coefficient at the inner surface of the absorber tube. Mills and Morrison [11] analyzed the performance and cost of the CLFR power plants for large scale solar thermal power

* Corresponding author. Tel.: +91 44 22574702; fax: +91 44 22574652.
E-mail addresses: ksreddy@iitm.ac.in, dr_k_s_reddy@yahoo.co.in (K.S. Reddy).

http://dx.doi.org/10.1016/j.ijthermalsci.2014.01.022
1290-0729/

generation. The flux distribution of LFR system was analyzed by Reddy and Reddy [12]. Based on the flux distribution analysis, the receiver size was optimized for maximum energy capture and the concentration ratio of the system was determined.

The design of receiver significantly influences the overall performance of the system. The convective and radiative heat transfer in the cavity has been studied by earlier researchers. Natarajan et al. [13] investigated the natural convection in the trapezoidal cavity with uniformly and non-uniformly heated bottom wall. Basak et al. [14] simulated the natural convection within the trapezoidal enclosures for uniformly heated bottom wall, linearly heated vertical walls and insulated top wall. Reddy and Kumar [15] studied the combined natural convection and surface radiation heat transfer in a cavity receiver for the solar parabolic dish collector. The influence of various parameters such as operating temperature, emissivity of the surface, orientation and the geometry on total heat loss has been investigated. Reddy and Kumar [16] investigated convection and surface radiation heat losses from the cavity receiver with different secondary reflectors. Facao and Oliveira [17] analyzed the natural convection inside the cavity receiver and optimized the cavity geometric parameter such as cavity depth and insulation thickness. Sahoo et al. [18] carried out the numerical and experimental analysis of heat losses from the trapezoidal cavity receiver for linear Fresnel reflector. The heat losses are found out for two different external heat transfer coefficient with Boussinesq approximation. Reddy and Kumar [19] and Natarajan et al. [20] analyzed the convective and radiative heat losses from the inverted trapezoidal cavity receiver for the LFR.

Most of the above studies dealt with natural convection and radiation heat transfer separately in the cavity but only few studies are available for combined natural convective and radiative heat losses from the trapezoidal cavity with simplified form. In all the above studies, heat losses from the cavity receiver had been analyzed by considering the heat transfer coefficient at the cavity wall surface. Also, most of the studies carried out based on Boussinesq approximation. The novelties of this article are to evolve optimum configuration of the receiver based on the combined convective and radiative heat losses from the inverted trapezoidal cavity receiver with non-Boussinesq approximation and actual convective & radiative boundary conditions. Therefore, the present article contributes to design an optimum receiver configuration and determines the convective and radiative heat losses accurately.

2. Modeling of solar linear Fresnel reflector power system

The linear Fresnel reflector system comprises of array of long parallel curved/flat mirrors/reflectors and focal cavity receiver. The reflectors are equipped with single axis tracking to focus the solar radiation onto the focal cavity receiver. The schematic of LFR with inverted trapezoidal cavity receiver is shown in Fig. 1. The receiver is placed at the middle of the module at focal distance to absorb maximum solar radiation. The receiver consists of bank of black coated parallel high-pressure boiler grade tubes encased in an insulated inverted trapezoidal stainless steel cavity. The cavity aperture is covered with transparent cover to allow concentrated solar radiation and to reduce heat losses from the cavity. The top and side surfaces of trapezoidal cavity are covered with ceramic insulation blanket encased in metallic cover to minimize the heat losses (mild steel). The parallel receiver tubes are coated black selective coating and placed very closely in the cavity to absorb the maximum concentrated solar radiation.

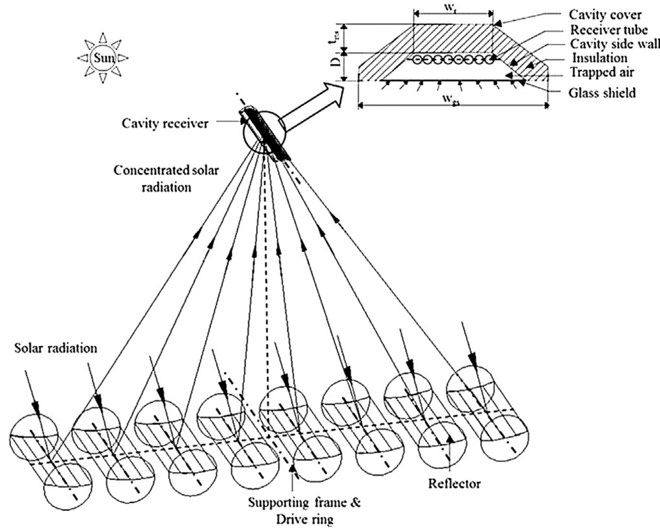

Fig. 1. Schematic of linear Fresnel reflector system.

The 2-D numerical simulations have been carried out to investigate the convective and radiative heat losses from the inverted trapezoidal cavity receiver for different receiver geometric and operating parameters. In order to analyze the heat losses from LFR cavity receiver 2-D numerical simulation is sufficient because LFR system is linear along the Z direction. In the present numerical modeling, it is assumed that the receiver tube surfaces equivalent to flat surfaces for the analysis and the cavity depth is considered from center of the receiver tubes to glass shield. The heat loss analyses are carried out for various receiver geometric and operating parameters viz. thickness of the insulation (50 mm–300 mm), aspect ratio (ratio of receiver width to receiver aperture, 1–3), cavity depth (100 mm–400 mm), cavity width (300 mm–800 mm), cavity cover emissivities (0–1), operating temperature (100 °C–500 °C) and wind speed (0 m/s–20 m/s) to arrive an optimum receiver configuration. The range of cavity (receiver) width from 300 mm to 800 mm is considered in order to accommodate the different solar field size and capacity. The thermo-physical properties of the cavity receiver are illustrated in Table 1.

2.1. Governing equations

The flow and heat transfer simulations in the cavity receiver are carried out by solving mass, momentum and energy equation simultaneously. The continuity, momentum and energy equations are given as [21]:

Continuity equation

$$\nabla\cdot(\rho V) = 0 \tag{1}$$

Momentum equation

$$V\cdot\nabla V = -\frac{\nabla P}{\rho} + \upsilon\nabla^2 V + X \tag{2}$$

Table 1
Thermo-physical properties of inverted trapezoidal cavity receiver.

Property	Cavity absorber	Insulation	Glass shield
Material	Steel	Ceramic wool	Borosilicate
Density (kg m^{-3})	8030	60	2230
Specific heat (J kg^{-1} °C^{-1})	502.48	670	837.36
Thermal conductivity (W m^{-1} °C^{-1})	16.27	0.04	1.46
Transmissivity	–	–	0.92 [8]
Absorptivity	–	–	0.034 [8]