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Heat loss analysis from a trapezoidal cavity receiver in LFR system using conduction-radiation model

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ABSTRACT

Linear Fresnel Reflector systems are medium temperature (100–400 °C) application systems where heat flux from the sun is concentrated on absorber tubes housed in a trapezoidal cavity by an array of mirrors. The absorber tubes carry working fluid inside them. Several earlier works have considered convective and radiative heat transfer from these trapezoidal cavities in LFR systems. It has also been shown that the convective heat transfer constitutes up to 15% of the total heat losses which is significant. On the other hand, it is seen that the flow velocities are negligible due to stratification of isotherms with hot air trapped on top of the cavity which suggests that convection should be negligible. In the present work, it is shown that the heat transfer which is considered as convective is actually, only conduction through (almost) static air inside the cavity. Due to the above-mentioned reason, in the present work, only conduction-radiation problem is considered in the cavity which is far easier to solve due to the absence of complex Navier-Stokes equations. The comparison of heat transfer results obtained using conduction-radiation model and those obtained using convection-radiation model show that the difference between the two results is negligible. Moreover, new correlations are developed with fewer parameters to capture the underlying physics of the heat loss mechanism in such cavities.

1. Introduction

Linear Fresnel reflector (LFR) systems are medium temperature (100–400 °C) solar thermal devices; where an array of parallel mirrors called Heliostats concentrate sun rays to parallel pipes carrying suitable working fluid as shown in Fig. 1. LFR systems are not efficient as compared to other solar thermal energy conversion systems such as Parabolic Trough Collector (PTC) and Parabolic Dish Reflector (PDR) (Zhu et al., 2014). However; these systems are cost effective compared to other systems due to its ease of use and simple construction. Compact Linear Fresnel Reflector (CLFR) systems were developed in 1993 which eliminated huge space requirement of LFR system.

It uses multiple absorbers. This arrangement avoids the shadow of one array of mirrors falling over the next reflectors. The main parts of a CLFR system are mirrors, receiver, process and instrumentation system, and tracking system (Ministry of New & Renewable Energy, and Government of India, 2014). The concept of the CLFR for large sclae of solar thermal electricity generation was first introduced by Mills and Morrison (2000). In this study the authors discussed the reduction of the tower height and the elimination of the blocking and the shading while the ground coverage is maximised. In additon to this, they concluded that the small reflector size, low structural cost, fixed receiver position and non-cylindrical reciever results in improved performance of the CLFR sysytem.

The most important part of the receiver is the absorber tubes which carry the thermal fluid. It is an array of pipes usually made up of stainless steel with sufficient gap between them so that they do not crush each other during the thermal expansion. The receiver is placed at 7–15 m above ground at the focus of the concentrating reflectors. The tubes are placed at the top of the inside of an insulating casing. It is an iron casing surrounding heat insulator on the sidewalls and top. The receiver is commonly filled with air. The bottom of the casing is covered with low iron window glass (Ministry of New & Renewable Energy, and Government of India, 2014). Here the cavity is open to heat transfer via glass, unlike the other power generating systems (coal, nuclear, etc.) using boilers.

Many researchers have simulated heat transfer in cavity receivers for convective, conductive and radiative heat losses and optimized the design to minimize the losses. Pye et al. (2003) have shown that in cavity receiver radiation dominates the internal heat transfer since the absorber is at quite a high temperature compared to other surfaces of the cavity. They have used discrete transfer radiation model (DTRM) to simulate radiation inside the cavity. The authors conclude that, the heat from the absorber is transferred to other parts by radiation, conduction,

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Nomenclature

A	area (m^2)
a	absorption coefficient
Bi	Biot number
D	depth of the cavity (m)
F	view factor
g	gravity ($m\,s^{-2}$)
Gr	Grashof number
I	radiation intensity ($W\,m^{-2}\,sr^{-1}$)
J	radiosity ($W\,m^{-2}$)
k	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
n	refractive index
$\hat{n}$	normal vector
N_{RC}	radiation-conduction parameter
Nu	Nusselt number
p	pressure ($N\,m^{-2}$)
Q_r	radiative heat flux
r	position vector
Ra	Rayleigh number
s	direction vector
T	temperature (K)
u	velocity in X direction ($m\,s^{-1}$)
v	velocity in Y direction ($m\,s^{-1}$)
W	bottom width of the cavity (m)

Greek symbols

α	thermal diffusivity ($m^2\,s^{-1}$)
β	thermal expansion coefficient (K^{-1})
ε	emissivity
θ	angle of the cavity (degree)
ρ	density ($kg\,m^{-3}$)
σ	Stephan-Boltzmann Constant ($W\,m^{-2}\,K^{-4}$)
φ	phase angle (radian)
Ω	solid angle (radian)
ν	kinematic viscosity ($m^2\,s^{-1}$)

Subscripts

b	black body
C	cold
comb	combined radiation and convection
conv	convection
ext	external
H	hot
int	internal
R	reradiating
r	ratio
rad	radiation
ur	convection when radiation is present
λ	wavelength

Acronyms

DO	discrete ordinate
DTRM	discreet transfer radiation model
S2S	surface to surface
SIMPLE	Semi-Implicit Method for Pressure-Linked Equations

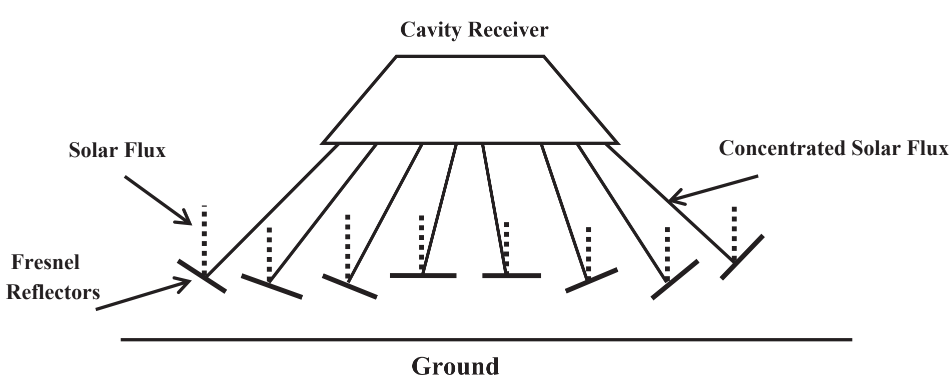

Fig. 1. Schematic diagram of an LFR system.

and convection. Moreover, in this study it has also been shown that, the top space of the cavity is almost stratified so that only conduction is present and at the bottom part convection is present (although flow velocities are very small) due to the higher temperature at the centre of the glass. Reynolds et al. (2004) shown that around 91% of the heat loss to the atmosphere is through the glass cover. The authors investigated that the 2/3rd of the cavity in the top is thermally stratified and the remaining part of the cavity has counter-rotating flows on either side of the symmetry plane. Even though their flow pattern is in excellent agreement with the CFD simulated model, the CFD model under predicted the losses by more than 40%. Their explanation was that it is because of the uncertainties in measurement. Moreover, they simulated the heat losses from the cavity using Fluent 5.0 and compared the result with the experimental data.

Singh et al. (2010) compared various models with combinations of shapes and coatings for the absorber and have shown that shape of absorber does not have much influence in the heat transfer coefficient of the absorber. However, the selective coating offered 20–30% less heat transfer coefficient compared to the ordinary black paint. The double glass cover of the cavity provided a 10–15% lower heat transfer coefficients for different absorber temperature. Moreover, the correlation between heat transfer coefficient and absorber temperature has also been carried out by Singh et al. (2010). In addition to this, the authors investigated the values analytically by using Balaji and Venkateshan's correlation (1994) and using these correlations for heat transfer coefficient between parallel plates.

Facão and Oliveira (2011) included the lower halves of pipes in their CFD model as it is more accurate compared to the flat plate assumption. The influence of depth of the cavity and thickness of insulation on loss has been analysed by Facão and Oliveira (2011). Moreover, they compared the heat transfer coefficients obtained with the other available literature and found that their values are closer to the experimental values. In addition to this, the authors tried different thicknesses of insulation and depth of cavities using a trial and error method to find out heat transfer coefficient and then found the best thickness and depth which minimizes heat transfer.