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Three-dimensional analysis and numerical optimization of combined natural convection and radiation heat loss in solar cavity receiver with plate fins insert

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ABSTRACT

The numerical study and optimization of combined laminar natural convection and surface radiation heat transfer in solar cavity receiver with plate fins is presented in this paper. Minimizing heat loss in cavity receivers is seen as an effective way to enhance the thermal performance and the use of plate fins has been proposed as a low cost means to minimize heat loss. Firstly, the influence of operating temperature, emissivity of the surface, orientation and the geometric parameters on the total heat loss from the receiver was investigated. It was observed that convective heat loss is largely affected by the angle of inclination of the receiver, the presence of fins and the number of fins in the receiver. As for the radiation heat loss it was observed that it is mainly influenced by the properties of the cavity receiver surface. The radiation heat loss was found to be constant at all the angles of the receiver. Significant reduction in natural convection heat loss from the cavity receiver was accomplished by using the plate fins whereas radiation heat loss was marginally reduced by about 5%. Secondly, the optimization was conducted to obtain the optimal fin geometry and lastly, the overall thermal efficiency of the receiver was presented at different operating temperatures. The overall cavity efficiency marginally increased by approximately 2% with the insertion of fin plates although the convective heat loss was suppressed by about 20%. This is due to the fact that radiation heat loss dominates at high operating temperatures compared to convective heat loss.

1. Introduction

The total energy loss of solar receivers plays an important role in the light-heat conversion. It is comprised of conduction heat loss through the cavity receiver housing, convection and radiation heat losses to the ambient through the aperture. However, most of the heat loss is mainly through natural convection and surface radiation since the cavity receiver is insulated and as such it is very important to understand the behavior of this type of heat transfer mechanisms.

Research of heat transfer and flow in the cavity receivers can greatly contribute to the estimation of the thermal performance and optimization of the design [1–3]. A literature review indicates that numerous studies have been conducted on natural convection heat loss in open cavities [4–11].

Some numerical and experimental investigations on combined natural convection and radiation heat transfer in cavities have been carried out by researchers. With regards to numerical studies, Lin et al. [12] numerically investigated the steady turbulent free convection in a two-dimensional open square cavity with and without surface radiation. Balaji and Venkateshan [13] presented results of a numerical study for natural convection and radiation heat transfer and observed that the results that included radiation were more realistic. Singh and Venkateshan [14] reported numerical results of a study of natural convection and surface radiation heat transfer for a two-dimensional open cavity using air as the fluid medium. They observed that surface radiation altered the flow patterns and the thermal performance significantly.

Hinojosa et al. [15] conducted a numerical analysis of both natural convection and radiation heat transfer in a titled 2D open cavity. They observed that cavity receiver inclination angle significantly influences the convective Nusselt number and not the radiation Nusselt number. Hinojosa et al. [16] used the Boussinesq approximation in the numerical study of natural convection and surface thermal radiation in an open cavity. Reddy

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Nomenclature

Alphabetical symbols

A	surface area, m^2
D	cavity diameter, m
d	aperture diameter, m
C_p	specific heat capacity, J/(kg K)
h_c	convective heat transfer coefficient, W/(m^2 K)
h_R	radiative heat transfer coefficient, W/(m^2 K)
H	plate fin height, m
H/W	dimensionless plate fin height
J	Joules
J	radiosity
K	Kelvin
F	view factor
F	flux, W/m^2
k	thermal conductivity, W/(m K)
kg	kilogram
m	meter
N	number of fins
N	number of surfaces
Nu	Nusselt number
P	power, W
p	pressure, Pa
Pr	Prandtl number
Pa	Pascal
q	energy flux, W/m^2
Q	heat loss, W
Ra	Raleigh number
S	fin space, m
t	plate fin thickness, m
t/W	dimensionless plate fin thickness
T	temperature, K
T_s	surface temperature, K
$\mathbf{V}$	velocity vector, m/s
W	Watt
$\mathbf{X}$	mass force vector, N/kg

Greek symbols

α	absorptance
φ	receiver inclination angle, degree
ρ	density of air, kg/m^3
μ	dynamic viscosity, kg/(m s)
ε	emissivity
σ	Stefan–Boltzmann constant, W/m^2 K^4
η	efficiency
λ	standard deviation

Subscript

c	convection
eff	effectiveness
R	radiation
s	surface
∞	ambient

Abbreviation

S2S	Surface-to-Surface
CFD	computational fluid dynamics

and Sendhil Kumar [17] reported numerical results of natural convection and radiation heat transfer in a modified cavity receiver. Using asymptotic computational fluid dynamics approach Sendhil Kumar [18] numerically investigated combined natural convection and radiation heat loss from a modified cavity receiver.

Gonzalez et al. [19] presented numerical results for natural convection and radiation heat transfer with variable properties and large temperature differences in a square cavity receiver. They observed that the radiation heat transfer is more important than convective heat transfer at larger temperature gradients.

In terms of experimental studies, Ramesh and Merzkirch [20] experimentally studied the interaction of natural convection and surface radiation heat transfer on side-vented open cavities. They presented results highlighting the effect of interaction and concluded that the surface emissivity had a huge effect on temperature and flow patterns. Tan et al. [21] conducted experiments to investigate the heat loss of semi-spherical cavity with fluid inlet temperatures from 348 K to 423 K.

Minimizing heat loss is seen as an effective way to enhance the thermal performance of cavity receivers. Some research have been conducted on the reduction of heat loss from cavity receivers. However, fewer studies have been done on cavity enhancement, performance and optimization. And most of these studies used the Boussinesq approximation in the analysis. Kribus et al. [22] designed and demonstrated the operation of the multistage receiver under elevated temperatures, which separated the aperture into different stages depending to the irradiation distribution. This was aimed at reducing heat losses and they achieved exit temperatures of up to 1000 °C.

Hahm et al. [23] compared the performance of a single cavity receiver with solar cavity receiver combined with a fabricated cone concentrator. They observed large amounts of heat rejection with smaller exit aperture size for the cone concentrator. On the other hand thermal losses increased with larger exit aperture size of the cavity and therefore optimum cone geometry is essential. Le Roux et al. [24] optimally sized a modified cavity receiver for maximum power using the second law of thermodynamics.

Karni et al. [25] designed a volumetric solar receiver, nicknamed Porcupine. They demonstrated the capability of the Porcupine to endure concentrated solar flux of up to 4 MW/m^2 and producing exit working fluid temperatures of up to 940 °C. Chen et al. [26] designed a novel linear cavity absorber and investigated its thermal performance. They observed that this cavity absorber performed better under medium temperatures. Reddy and Kumar [17] compared the thermal performance of the cavity receiver with extended reflectors of different geometries (CPC, cone and trumpet). They observed better performance from the trumpet one compared to the other ones. A glass covered cavity receiver was presented by Cui et al. [27]. The aim of using the glass cover was to separate the ambient air from the inner cavity receiver thus reducing both the natural convection and radiation heat loss.

Most of the earlier studies used 2D numerical model and the Boussinesq approximation. However, at higher temperature the Boussisneq approximation does not provide accurate results. In this study, a 3D numerical model of a modified cavity receiver with fin plates has been developed and investigated for combined laminar natural convection and surface radiation heat loss using the non-Boussinesq method. The effect of surface emissivity, operating temperature, orientation and the geometric parameters on the total heat loss from the receiver was investigated. The optimization was conducted to obtain the optimal fin geometry and the overall thermal efficiency of the receiver was presented at different operating temperatures. In this paper, the analysis is based on parabolic