Renewable Energy 74 (2015) 95–105

Contents lists available at ScienceDirect

Renewable Energy

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

Numerical modelling and optimisation of natural convection heat loss suppression in a solar cavity receiver with plate fins

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ARTICLE INFO

Article history:
Received 1 February 2014
Accepted 24 July 2014
Available online 20 August 2014

Keywords:
Parabolic dish
Cavity receiver
Natural convection
Plate fin
Rayleigh number

ABSTRACT

This study details the numerical modelling and optimization of natural convection heat suppression in a solar cavity receiver with plate fins. The use of plate fins attached to the inner aperture surface is presented as a possible low cost means of suppressing natural convection heat loss in a cavity receiver. In the first part of the study a three-dimensional numerical model that captures the heat transfer and flow processes in the cavity receiver is analyzed, and the possibilities of optimization were then established. The model is laminar in the range of Rayleigh number, inclination angle, plate height and thickness considered. In the second part of the study, the geometric parameters considered were optimized using optimization programme with search algorithm. The results indicate that significant reduction on the natural convection heat loss can be achieved from cavity receivers by using plate fins, and an optimal plate fins configuration exit for minimal natural convection heat loss for a given range of Rayleigh number. Reduction of up to a maximum of 20% at 0° receiver inclination was observed. The results obtained provide a novel approach for improving design of cavity receiver for optimal performance.

1. Introduction

The use of concentrating solar thermal technology has great potential for generating power. The parabolic dish-receiver assembly is one such promising system among several others. It normally consists of a reflector in the form of a parabolic dish with a downward facing receiver at the focus of the dish. These systems are continuously subjected to changes in environmental conditions such as wind, solar insolation, and ambient temperature. These environmental variations coupled with changes in receiver inclination angle affect the overall receiver performance leading to energy loss. A cavity receiver is preferred in such a system to maximize the absorption of the concentrated flux. The total energy loss of solar receivers which includes conduction through the receiver insulation, convection and radiation through the aperture opening to the ambient environment plays a dominant role in the light–heat conversion. Heat loss through radiation heat is dependent on the temperature, emissivity/absorptivity and the shape factors of the receiver walls, while conduction heat loss is dependent on the receiver wall temperature and the material of the insulation used. Natural convection through the receiver aperture contributes a significant fraction of the energy loss and hence it is essential to effectively minimise it in order to improve the system efficiency.

Research of flow and heat transfer for cavity receivers can greatly help to estimate the thermal performance and optimise the design of the receivers [1–3]. With cavity receivers radiation and conduction can readily be determined analytically. However, this is not the case for natural convection. The complexity of geometry, temperature and velocity fields in and around the receiver makes it difficult to use existing analytical models for predicting convective heat loss. Therefore, many significant investigations have been conducted on natural convection heat transfer in open cavities. For instance, Le Quere et al. [4] investigated heat loss characteristics of two different sized cubical cavities. They considered variations in receiver operating temperature and angle, in their study. They found convection heat loss to be strongly dependent on the cavity inclination. Harris and Lenz [5] presented a study performed by Koenig and Marvin that empirically derived a correlation for convective heat loss from cylindrical cavity type receivers, including the effects of variation in operating temperature and

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http://dx.doi.org/10.1016/j.renene.2014.07.047
0960-1481/

Nomenclature

Alphabetical symbols

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	plate fin height, m
H/W	dimensionless plate fin height
K	Kelvin
J	Joules
k	thermal conductivity, W/(m K)
kg	kilogram
m	metre
N	number of fins
Nu	Nusselt number
P	pressure, Pa
Pr	Prandtl number
Pa	Pascal
Q	heat loss, W
Ra	Rayleigh 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

φ	receiver inclination angle, °
ρ	density of air, kg/m^3
μ	dynamic viscosity, kg/(m s)
ε	fin effectiveness

Subscript

c	convection
s	surface
∞	ambient

Abbreviation

ANU	Australia National University
CFD	Computational Fluid Dynamics
CPC	Compound Parabolic Concentrator

angle. An analytical model for convective heat loss for an open cubical cavity receiver was presented by Clausing [6]. The Clausing model was developed for a central receiver operating at much higher temperatures.

Siangsukone and Lovegrove [7] presented work on modelling and simulation of the Australia National University (ANU) 400 m^2 paraboloidal dish concentrator system with a direct steam generating cavity receiver and the steam line. Taumoefolau and Lovegrove [8] presented an experimental investigation based on an isothermal electrically heated model cavity receiver. Kumar and Reddy [9] presented a two-dimensional model to estimate the approximate natural convection heat loss from the modified cavity receiver of a fuzzy focal solar dish concentrator. Both insulation conditions and no insulation conditions are used for estimation of heat loss. The analysis of the receiver carried out was based on the assumption of the uniform and maximum solar flux distribution in the central plane of the receiver. Kumar and Reddy [10] performed a comparative study to predict the natural convection heat loss from the cavity, modified cavity and semi-cavity receivers. Reddy and Kumar [11] presented a numerical study of combined laminar natural convection and surface radiation heat transfer in a modified cavity receiver of solar parabolic dish collector. A comparison of 2-dimensional and 3-dimensional natural convection heat loss from a modified cavity receiver was carried out by Reddy and Kumar [12]. Prakash et al. [13] have reported experimental and numerical studies of the steady state convection heat losses occurring from a downward-facing cylindrical cavity receiver. From all the data points Nusselt number correlations as a function of receiver aperture diameter were proposed for the natural convection heat losses. Wu et al. [14] performed a three-dimensional numerical study of a heat-pipe receiver to investigate the influence of aperture size and position on natural convection heat loss taking into account the effects air property variation with temperature. Le Roux et al. [15] used the second law of thermodynamics to optimally size a modified cavity receiver under steady-state so that the parabolic dish system can have maximum net power.

Minimizing natural convection is seen as an effective method to improve the thermal efficiency of cavity receivers. Some investigations have been reported on the heat loss reduction of the cavity receiver. Kribus et al. [16] designed and demonstrated the operation of the multistage receiver under elevated temperatures, which divided the aperture into separate stages according to the irradiation distribution, to achieve high working temperature and thermal efficiency. Karni et al. [17] 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 exist working fluid temperatures of up to 940 °C. Reddy and Kumar [18] analyzed the heat transfer behaviour of the modified cavity receiver with cone, CPC and trumpet reflector. The results showed that the trumpet one had the better performance than other ones. Fuqing Cui et al. [19] presented a cavity receiver with quartz glass cover for the dish concentrating system. They proposed the use of a quartz glass cover to separate the receiver cavity from the ambient air and its selective coating layer to intercept the infrared radiation emitted from the inner-surface of the cavity receiver, which greatly reduced the natural convection and surface radiation heat losses.

Heat transfer rate through the enclosures can be controlled by means of fin's configuration and literature is available [20–40]. In this study, a cavity receiver with plate fins attached to the inner aperture surface is presented as a possible low cost means of suppressing natural convection heat loss in a cavity receiver. This numerical study employs air as the working fluid, and laminar natural convection heat transfer from cavity receiver with plate fins attached to the inner aperture surface has been investigated for a range of Rayleigh number, inclination angle, fin height and thickness. Furthermore, visualisation results, such as fluid flow and temperature contours have also been presented to gain an insight into the suppression of natural convection. In addition a numerical optimisation tool is used to select the best plate fin geometric configuration that improves the cavity receiver performance at minimum natural convection heat loss. This study presents a novel approach of suppressing natural convection heat loss in a cavity