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The optical efficiency of three different geometries of a small scale cavity receiver for concentrated solar applications

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HIGHLIGHTS

- The effect of the receiver shape on the optical efficiency was investigated.
- The relation between the cavity shape and its proposed absorption ratio has been found by different numerical correlations.
- The effect of the receiver position on optical efficiency was investigated.
- The effect of the receiver absorption ratio on optical efficiency of was investigated.

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ABSTRACT

The demand for energy is continually increasing day after day; but at the same time, investigations around the world into sustainable sources of power are growing in number. Concentrated Solar Power (CSP) can act as an efficient low cost energy conversion system to produce electricity which could lead to reducing the continuous demand on conventional fossil fuels. Most of the literature concerning CSP concentrates on the heat losses and their relationship to the receivers' geometries; where these receivers are evaluated according to their thermal efficiency. The majority of the literature has often neglected heat gain enhancement by the receivers' geometries, which helps to increase the heat transfer to the working fluid. This work concentrates on the optical efficiency as well as the heat flux distribution of three different geometries. The cylindrical, conical and spherical geometries of a cavity receiver are considered with the objective of analysing their optical and thermal behaviour optically and thermally, using the ray tracing method and a Computational Fluid Dynamic (CFD) model. The results showed that the conical shape of the receiver gathered, as well as absorbed, a higher amount of reflected flux energy than the other shapes, with about 91% and 82% for 75% and 85% absorption ratios respectively. The cavity receiver shapes and their absorption ratio are key parameters which affect the focal point location; thereby there is an optimum distance for each design depending on these two parameters. The results of the simulated work are validated using the experimental work found in the literature. Overall, in order to evaluate the heat balance, 3-D thermal analysis was employed using Fluent 15 and the amount of heat losses for the three shapes was determined. It was observed that the conical shape receiver experienced a lower heat loss. To ensure more confidence in the results, the thermal outcomes were validated against experimental works in the literature and they demonstrated good agreement.

1. Introduction

Solar radiation is collected by different types of Concentrating Solar Collectors (CSC) and focused into thermal receivers in order to be converted to the thermal energy of Concentrated Solar Power (CSP). With the existing energy demand and environmental dilemmas the technology of solar energy has an essential role [1]. The Heat Transfer Fluid (HTF) is pumped to the thermal receiver to carry the thermal energy in order to drive one of the power cycles such as the Rankine cycle, the Organic Rankine cycle, the Stirling cycle and the Brayton cycle [2]. The CSP with the Brayton Cycle (BC) has the potential to offer higher efficiency, lower cost and pressure losses compared to other cycles [3,4].

Thermal analysis of different types of receiver was investigated: central [5–7], trough [8–12] and volumetric types [13–16]. Furthermore, for the cavity receiver types' heat losses analysis

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Nomenclature

A	area (m^2)
Aa	aperture area (m^2)
Cp	specific heat (J/kg K)
d	diameter (m)
ε	surface emissivity
f	focal
F	view factor
g	gravity (kg)
Gr	Grashof number
h	height of receiver (m), heat transfer coefficient
J	radiosity
k	thermal conductivity (W/m K)
L	characteristic length (m)
m	mass flow rate of fluid
Nu	Nusselt number
Pr	Prandtl number
ρ	density (kg/m^3)
Q	heat
Ra	Rayleigh number
u	velocity component in x-direction (m/s)
T	temperature (K)
t	time (s)
μ	viscosity (kg/m s)
η_o	optical efficiency
ϕ	receiver inclination angle (deg)
x	coordinate
ST	energy source

Subscripts

1	compressor inlet
2	recuperator inlet of high pressure air
3	receiver inlet
4	turbine inlet
5	recuperator Inlet of low pressure air
6	recuperator exit
Amb	ambient
Ap	aperture
Cav	cavity
Cond	conduction
Conv	convection
i	coordinate
f	fluid
natu	natural
Rad	radiation
Ref	reflector
Rec	receiver
Sur	surface area
T	total
W	wall or cavity internal surface
WI	with insulation

and their connection with receiver geometries, dimensions and positions were investigated for different applications [17–24]. Among the literature [17–24], the most relevant have been chosen and will be discussed in the next paragraph.

Harris and Lenz [17] assessed the thermal performance of five different geometries of cavity receivers (cylindrical, heteroconical, spherical, elliptical and conical) with a parabolic concentrator. Their results showed that the losses of the cavity receiver are about 12% of the input energy to the aperture of the receiver and there is a small effect from the cavity geometry on the overall efficiency. Reddy et al. [20] studied the effect of different factors such as the emissivity, inclination, insulation thickness and operating temperature on natural and forced convection and radiation heat losses of a modified hemispherical cavity receiver. Regarding the effect of the receiver inclination, they found that the minimum natural convection heat loss occurs when the open side of the receiver faces downwards, i.e. at 90°. Also, a correlation for the Nusselt number for radiation and the convection heat transfer losses' calculation has been proposed. Roux et al. [21] analyzed theoretically a modified cavity receiver combined with a parabolic dish concentrator used in a small scale CSP-BC system. Many design parameters were studied, including the tube diameter, tube length of the thermal receiver, rim angle, inclination receiver, concentration ratio and mass flow rate. The results showed that the channel length is affected by the wind factor, rim angle and concentration ratio and that the thermal receiver design has a significant effect on the net power output of the system. Prakash [22] studied the natural convection heat losses of different diameters of a cylindrical cavity receiver based on CFD simulations. The model included flow inside a helical coil with air as an HTF. The results showed that the increase in the convection losses is due to the increase in the mean temperature of the HTF and to the opening ratio as well; while a decrease in the convection loss is due to the increase in the receiver inclination.

However, there is still some ongoing research regarding the optical characterisation for other kinds of receivers in the literature. For example, a single and double elliptical pipe receiver was studied by Abdullahi et al. [25]. They analyzed a Compound Parabolic Concentrator (CPC) with this type of receiver in different configurations. The results showed that the optical efficiency of a horizontal and vertical double receiver is greater than the single receiver by 15% and 17%, respectively. Roux et al. [26] evaluated optically a tubular receiver in terms of different variables such as; concentrator shape, reflectivity, diameter, rim angle. They also studied different receiver factors such as; aperture area, material and tube diameter, working fluid mass flow rate, inlet temperature through the receiver with the aim of finding the receiver's surface temperature and its efficiency. The results revealed that the optimum area ratio depends directly on both optical and tracking errors. They concluded that the receiver efficiency can be raised up by increasing the dish reflectivity and also by increasing the precision of both the optics and dish surface. Furthermore, enlarging the receiver tube and decreasing the mass flow rate decreases the efficiency of the collector because of the high receiver surface temperature. Qiu et al. [27] numerically and experimentally investigated the performance of a cylindrical cavity receiver with its helical tube using five lamps of Xe-arc light source with splitter placed at the bottom of the receiver to distribute the received flux. Their experimental results showed that with a 300 kW/m^2 average flux and 5 m^3/h of air volume flow rate, the air outlet temperature can reach up to 800 °C. Also, deviation between theoretical and the experimental results ranged between 2.5% and 8%. A model of multi-cavity receiver for high concentrated flux was analyzed by Fleming et al. [28]. The study was carried out on a simple model designed with all the necessary parameters for analysing its thermal efficiency by applying an optimal value and distribution of flux. Based on their results, they concluded that there is high potential of achieving more than 90% thermal efficiency from the receiver at absorptivity greater than 99.8% and heat transfer coefficient of the working fluid ranging 250–500 $W/m^2/K$. Algarue et al. [29] investigated the effects of concentration ratio on three types of reflective concentrator solar collectors as well as two types of refractive concentrator solar collectors using OptisWorks®. Their results showed that optical efficiency for all collectors is about