Energy Conversion and Management 149 (2017) 293–302

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Effects of geometric parameters on thermal performance for a cylindrical solar receiver using a 3D numerical model

Chongzhe Zou [a], Yanping Zhang [a,c,*], Huayi Feng [c], Quentin Falcoz [b,c], Pierre Neveu [b,c], Wei Gao [a], Cheng Zhang [a]

[a] *School of Energy and Power Engineering, Huazhong University of Science and Technology, Wuhan, China*
[b] *PROMES-CNRS Laboratory, 7 rue du Four Solaire, 66120 Font-Romeu-Odeillo-via, France*
[c] *China-EU, Institute for Clean and Renewable Energy, Huazhong University of Science and Technology, Wuhan, China*

ARTICLE INFO

Article history:
Received 20 March 2017
Received in revised form 27 June 2017
Accepted 30 June 2017

Keywords:
CSP technology
Cylinder cavity receiver
3-D modeling
Geometric parameters
Thermal performance

ABSTRACT

The geometric parameters of a cavity receiver play critical roles in solar energy conversion and heat transfer. However, the effects of geometric parameters on thermal performance have not been studied sufficiently, especially for a cylinder cavity receiver with a 3D numerical model. In the present study, the effects of aperture diameter and cavity length are numerically simulated using the finite element method by ANSYS 17.0. The combined convection and radiation loss is taken into consideration in the simulation process. A simulation validation is also proposed with a comparison between the numerical simulation result and published data from the theoretical model. Good agreement has been achieved. The combined heat loss increases considerably with an increase in aperture diameter from 184 mm to 300 mm. Attending to the number of loops and the corresponding cavity length, a maximum thermal efficiency is achieved with five loops at a 480 mm cavity length. This paper provides a successful example of the design of a cylinder cavity receiver.

1. Introduction

Central receiver systems can achieve solar concentration ratios exceeding 1000 suns using CSP (Concentrating Solar Power) technology, thereby supplying solar process heat at high temperatures [1]. Significant improvement in terms of solar-to-electricity conversion can be made by supplying high-temperature fluid to the thermoelectric generator [2]. One of the key components of such a solar-to-electricity conversion cycle is the solar receiver, in which the concentrated solar thermal energy is absorbed and transferred to the heat transfer medium. Two types of solar receivers have been widely investigated; these are the volumetric receiver and cavity receiver. In cavity receivers, the heat loss mechanism can drastically reduce thermal performance and consequently, economic viability [3]. The thermal performance of the receiver directly influences the thermal efficiency of the whole power generation system. Thus, a careful study of solar receivers is necessary to determine innovative cavity designs for the better thermal performance and greater economical effectiveness of the CSP system.

In preliminary stage of cavity receiver, most researchers focused on convection heat loss. Clausing [4] proposed an analytical model for investigating the convection heat loss of a cubical cavity receiver, which indicated that the convective loss from cavity receivers is appreciable. Le Quere et al. [5] investigated the thermally driven laminar natural convection in an open cubical cavity with isothermal side surfaces, finding that flow and temperature fields within the cavity are determined mainly by local heat transfer events. Stine and McDonald [6] presented a Nusselt number correlation for a cylindrical cavity receiver considering the effects of operating temperature, the inclination of the receiver and the aperture size. Finally, Paitoonsurikarn and Lovegrove [7] investigated natural convection heat loss considering the effect of factors like cavity geometry and inclination.

New technique of scientific study, such as computational fluid dynamics (CFD) helped researchers to obtain better understanding of the convection loss mechanism. Kumar et al. [8] proposed a 2-D-model for estimating natural convection heat loss, finding that maximum convection heat loss occurs at a 0° inclination. Wu et al. [9] performed a 3D numerical study to determine the influence of aperture characteristics on the natural convection heat loss of a heat-pipe receiver. Their study revealed that both tilt angle and aperture position influence natural convection heat loss.

---

* Corresponding author at: School of Energy and Power Engineering, Huazhong University of Science and Technology, Wuhan, China.

E-mail address: zyp2817@hust.edu.cn (Y. Zhang).

http://dx.doi.org/10.1016/j.enconman.2017.06.088
0196-8904/

Nomenclature

A_{mirror}	dish area (m^2)
c_p	special heat capacity of cavity air (J/kg K)
d_{cav}	cavity inner diameter (m)
d_{ap}	aperture diameter (m)
I	direct normal irradiance ($W/m^{2)}$
h	heat transfer coefficient (W/m^2 K)
p	pressure of cavity air (Pa)
Q_{conv}	convection heat loss (W)
Q_{in}	energy entering the receiver (W)
Q_{rad}	radiation heat loss (W)
Q_{loss}	combined heat losses (W)
T	air temperature (K)
$\mathbf{V}$	the velocity vector of air (m/s)
$\mathbf{X}$	the mass force vector

Greek symbols

ρ	density of air (kg/m^3)
μ	dynamic viscosity of air (kg/m s)
η_t	thermal efficiency
τ_i	mirror interception factor
ρ_r	reflectivity of mirror
τ_s	transmissivity of the cover glass

To verify the results of these theoretical and numerical studies, many researchers carried out experimental studies of convection heat loss. Yusuaki et al. [10] studied natural convection in a hemisphere heated from below, identifying a correlation between the heat transfer rate and the Rayleigh number on a hemispherical surface. Taumoefolau et al. [11] investigated natural convection losses from cavity receivers, using inclinations that saw the cavities anywhere from facing up to facing straight down, with test temperatures ranging from 450 °C to 650 °C. This study provided the closest prediction of both the numerical and experimental results, as compared with Clausing's [12] model. Testing a novel receiver in the Sandia National Laboratories solar furnace. Hogan et al. [13] discovered that for larger apertures, convection heat losses are exaggerated. They also suggested that these losses could be better characterized.

More recent, studies have endeavored to numerically and experimentally analyze the total heat transfer mechanism inside a receiver, focusing on the combination of radiation heat transfer and convection. Ngo et al. [14] developed a numerical model using the plate fins cavity receiver, finding that natural convection heat loss and radiation heat loss were reduced by 20% and 5%, respectively. Qiu et al. [15] numerically studied a helical tube cavity receiver with a 7 kW man-made light as the heat source. The experiment showed that the outlet temperature increased to 800 °C under a 300 kW/m^2 average flux, and the thermal efficiency increased 8% by decreasing the inner radius 2 mm. Zhang et al. [16] researched the effects of input power and flow rate on the total heat loss of a 100 kWt molten salt receiver, finding that the effects on the efficiency were small.

Researchers have also begun to pay attention to geometrical influences on the solar cavity receiver. Detailed studies have been carried out using diverse shapes of cavity receivers. Prakash et al. [17] numerically analyzed natural convection occurring within cubical, spherical and hemispherical geometries with equal heat transfer area. It was observed that a hemispherical open cavity has the greatest natural convection loss. Tu et al. [18] proposed a 3-D numerical model to investigate the effect of depth on the thermal performance of an irregularly shaped steam receiver, finding that a suitable cavity depth is equal to 2 m for this studied cavity receiver. Gil et al. [19] used a finite differences model to optimize thermal efficiency regarding aperture diameter and receiver absorptivity. The results indicated that the optimal aperture height depends on the minimum focal distance. To optimize the location of the focal points, Prezenak et al. [20] constructed a flat dish receiver model with pipes wiggling across it. The CFD and MCRT simulation results indicated that a distance of 76 cm and a fluid flow velocity of 0.6 m/s are optimal value for maximizing the heat transfer. Shirvan et al. [21] numerically investigated the influence of a porous solar cavity receiver on natural convection and surface radiation. The result suggested that the total heat transfer rate increases with an increase of the Rayleigh number, Darcy number, inclination angle and wall surface emissivity. Loni et al. [22] constructed a square prismatic tubular cavity receiver model, revealing that methanol and R11 provide the greatest and smallest thermal efficiencies within the range of turbine inlet temperature considered.

Geometric parameters have been carefully studied using diverse shapes of cavity solar receivers including the hemispherical cavity, the rectangular cavity, and some other irregularly shaped cavities, but the cylindrical cavity with a helical pipe inside of it has yet to be considered. Furthermore, only a few theoretical and experimental studies about geometric parameters' effects on the heat transfer of cylindrical receivers have been completed. Compared to the irregularly shaped cavity presented by Tu et al. [18], a cylindrical cavity is more convenient to manufacture. When compared with a cubical cavity, spherical cavity, or semi-spherical cavity, a cylindrical cavity has no obvious advantage in optical efficiency, according to Daabo et al. [28]. No matter how complicated a cavity shape is, it comprises several kinds of basic shapes. Therefore, it makes sense to study the cavity in its basic shapes, such as that of a cylinder. Hussain et al. [23] performed an experiment to analyze the heat losses of a cylindrical cavity receiver without a helical pipe inside, using a Fresnel lens to focus the solar beam as the direct heat source of a Stirling engine. The results showed that the aperture ratio (AR = d/D) and aperture position (AP = H/D) were most suitable when they equaled 0.5 and 0.53, respectively. Zou et al. [24] proposed a theoretical model of a cylindrical cavity receiver with a helical pipe inside. With the assist of thermal equation solution software (EES), three critical geometric parameters were individually optimized. Loni et al. [25] also theoretically analyzed the geometric parameters of a cylindrical cavity receiver model, including the receiver aperture area, receiver tube diameter, and cavity receiver depth. An optimum thermal efficiency emerged when the depth of the cavity was between 0.5D and 2D.

While researchers such as Wu et al. [9], have investigated the cylindrical cavity, they have overlooked geometric effects on the cylindrical cavity. Other studies have paid attention to such geometric effects on receivers while neglecting the importance of the cylindrical shape; these studies include those of Prakash et al. [17] and N. Tu et al. [18], but they don't focus on cylinder cavity. Yet in order to implement an efficient CSP system, the high quality design of the cavity receiver is necessary. An initial design and optimization of the cylindrical receiver using a theoretical model was proposed by Zou et al. [24]. To avoid the excessive costs associated with the experimental testing of a number of