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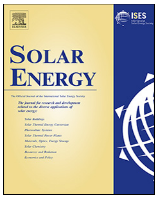

Reducing convective heat losses in solar dish cavity receivers through a modified air-curtain system

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ABSTRACT

Here we propose a forced air circulation system to reduce the convective heat loss across the aperture of a dish concentrator. The function of the proposed system was validated with computational fluid dynamics (CFD) simulations. Compared to a concentrator without such a system, the modified solar dish cavity receiver could clearly reduce the convective heat loss and its fluctuation in the receiver. In the best case studied, the convective heat losses could be suppressed by up to 58%. In addition, two types of air circulation modes (clockwise and anticlockwise) were compared, showing that the anticlockwise mode yields better performance.

1. Introduction

The receiver of a concentrating solar thermal (CST) system transforms intensive irradiation into high-temperature heat for generating electricity or driving thermochemical reactions (Blanco and Santigosa, 2016). The higher the temperature of the heat, the higher is its exergy and usefulness for the thermodynamic cycles. But at the same time, the total heat losses of the CST will increase, which will decrease the cavity efficiency. The heat losses are dominated by radiation and convection. The structure of the receiver will not only affect these losses, but also the reflection losses of the incoming solar radiation. Often a cavity type of receiver is used in solar tower or dish systems, which significantly reduces both reflected sunlight and emission losses from the absorber surface. As the aperture needs to let concentrated sunlight to pass across, its size cannot be indefinitely reduced to minimize the heat and reflection losses. Some trade-off rules are therefore usually applied, e.g. the size of the aperture is set to the diameter of the maximal circle within which at least 90% of the incident rays can enter the cavity (Yang et al., 2018).

Convective losses form a major loss component, but they are very difficult to measure or simulate. Past research in this field include assessing the effects of geometry, scale, temperature, inclination, buoyant or wind forces, etc., on convective heat exchange in the cavity receiver using theoretical, numerical (CFD), experimental and combined approaches (Baïri et al., 2014; Wu et al., 2010). One of the first studies on forced convection research in a cavity structure already originates from the 1960s (Fox, 1965) Clausing (1981) has illustrated the physics of convective heat losses from a cubical cavity receiver and established a correlation between the parameters of the geometrical structures, gravity, temperature, inclination angle, and the Nusselt number. Hogan (1994) developed a numerical model for calculating the heat losses from solar reflux receivers, including estimations on the shares of each loss mechanism. Leibfried and Ortjohann (1995) studied convective losses of a spherical and a hemispherical cavity over a range of title angles, and presented to well-validated algorithms the convective heat losses. McDonald (19950 executed a series of trials on exploring heat loss mechanisms from an open cavity with and without the effect of wind. Reddy and Kumar (2009); Reddy et al. (2016) modified the cavity receiver of a solar dish concentrator by coupling it with a CPC to reduce heat losses, and also studied the impacts of wind speed and direction on convective heat losses. Paitoonsurikarn and Lovegrove (2002); Paitoonsurikarn and Lovegrove (2006) and Taumoefolau et al. (2004) reported on simulations and experiments on convective losses from cavity receivers with small sizes relevant to solar dish systems. Two important conclusions can be drawn from the studies above: Though the infrared radiation is the dominant mechanism of the total heat loss, convective losses can be of the same magnitude in some specific conditions depending on the receiver orientation and temperature; Convective heat losses are the only loss mechanism that significantly depends on the receiver orientation and inclination of the cavity. For solar dish configurations with tracking systems, the influence of the convective losses could therefore be an uncertainty factor for the design process. Therefore, better understanding of the mechanisms of convective loss in enclosures would be important, but also to find effective

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Nomenclature

CFD	computational fluid dynamics
CST	concentrating solar thermal
FVM	finite volume method
k	turbulent kinetic energy
PJ	pressure jump
PV	photovoltaic cell
q	radial flux/heat flux
$\bar{q}$	average heat loss
T	temperature
T^{*}	normalized temperature $\left(\frac{T-T_{\min}}{T_{\max}-T_{\min}}\right)$
v	velocity of air flow
V^{*}	normalized velocity $\left(\frac{v-v_{\min}}{v_{\max}-v_{\min}}\right)$
σ	standard deviation
ε	dissipation rate
η	efficiency
θ	inclination

Subscripts

cav	cavity
conv	convective
ds	differential element of section area in air channel
fan	fan configuration
input	input

solutions to avoid its fluctuation as this would impact the overall thermal performance of the CST system.

Previous studies include suggestions on modified solar dish cavity receivers to reduce the convection heat losses, e.g. combining cone, CPC, and trumpet reflectors (Reddy and Kumar, 2009) with plate fins attached to the inner aperture surface (Ngo et al., 2015). However, the outcomes have been modest and the suppression of convective losses was limited. Another commonly proposed option with quartz glass cover (Cui et al., 2013) could considerably reduce natural convection and IR losses from the inner part, but would also partially intercept the incident sunlight as well.

In this paper a modified design of the cavity receiver is proposed to reduce the convective heat losses, based on a special forced-air circulation system. The idea was inspired by air-curtain technology used in cooling and refrigeration industries (Foster et al., 2007). Actually, a kind of air-curtain concept was used by Zhang et al. (2015) in a solar dish system for reducing heat losses. Hughes et al. (2016) reported that optimal designs of air-curtain systems depend on the velocity and direction of the air jet as well as on the inclination of the cavity. Flesch et al. (2016) took into account the wind effects in evaluating the merits of air-curtain for a solar tower receiver. In this paper we propose a modified version of the air-curtain configuration for a dish cavity receiver. It contains a special air channel with an inserted fan instead of a conventional air nozzle. This helps to form a closed forced-air circulation system and reduce the convective losses, which increased the receiver performance considerably. We introduced improvements to the dish receiver using the modified air-curtain, also making use of previous methodologies for analyzing forced-air circulation processes (Kolb, 2012; Tan et al., 2009). We presented here the new concept and a thermal analysis based on CFD simulations to verify the improved performance in a range of different inclination conditions. Improvements were obtained both in absolute scale and reducing the fluctuations of convective heat losses through the opening of the receiver.

2. Methodology

The basic analysis tool used here is a CFD model employing the Fluent 17.0® and ICEM® software. We used as basis the cavity receiver/reactor model by the Australian National University (ANU), which was modified and validated for our specific case (Paitoonsurikarn and Lovegrove, 2006; Taumoefolau et al., 2004). ICEM® was employed in the modeling and meshing work. Grid dependency was investigated and the final computational grid used consisted of approximately 3×10^{6} unstructured cells. The 3D CFD calculation of the convection through the aperture of the cavity receiver was simulated with Fluent 17.0®. The SIMPLE scheme was applied to couple the pressure-velocity fields based on the finite volume method (FVM).

The ANU's original receiver model was simplified and geometrically considered as an ideal cylinder with a hollowed cylindrical cavity zoom (Paitoonsurikarn and Lovegrove, 2002; Taumoefolau et al., 2004). The modified receiver incorporated a U-shaped channel for air circulation (Fig. 1). The air channel in Fig. 1 consists of four flat rectangle enclosures connected with four quarter circular passages creating a loop. To allow comparison to reference cases, we used the original ANU parameters as basis for the new design (Table 1). For simulating the free atmosphere around the receiver, a large enclosure of at least 10-times the receiver size was used around the receiver for guaranteeing that the influence from the finite boundaries is minimized.

The physical model is based on the Navier-Stokes equations, which are suitable for describing turbulent flow of an incompressible viscous liquid with constant properties. The governing equations used follow the Reynolds averaged Navier-Stokes (RANS) approach (Mavriplis, 1995). Enhanced Wall Treatment (EWT) is applied here to obtain the

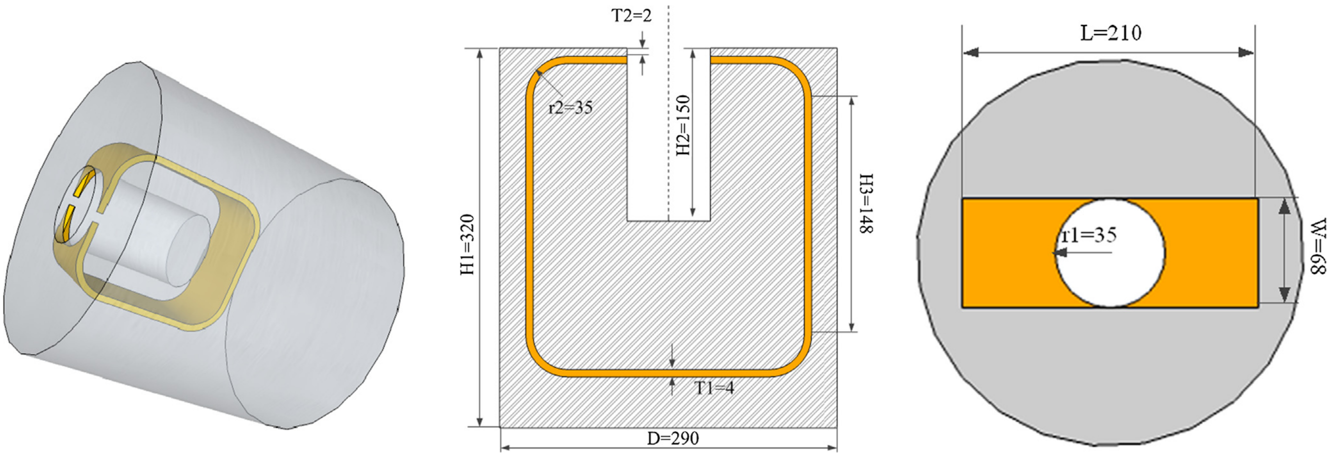

Fig. 1. The sketch of modified model receiver with a special air channel (left: 3D model, middle: cross-section, right: plane). All units are in mm.