Solar Energy 149 (2017) 20–31

Contents lists available at ScienceDirect

Solar Energy

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

An investigation into the effect of aspect ratio on the heat loss from a solar cavity receiver

Ka Lok Lee *, Mehdi Jafarian, Farzin Ghanadi, Maziar Arjomandi, Graham J. Nathan

School of Mechanical Engineering, The University of Adelaide, SA 5005, Australia

ARTICLE INFO

Article history:
Received 9 September 2016
Received in revised form 28 March 2017
Accepted 31 March 2017

Keywords:
Solar receiver
Solar thermal power
Heat loss
Concentrated solar thermal radiation
Aspect ratio
Wind

ABSTRACT

The effect of aspect ratio and head-on wind speed on the force and natural (combined) convective heat loss and area-averaged convective heat flux from a cylindrical solar cavity receiver has been assessed using three dimensional computational fluid dynamics (CFD) simulations. The cavity assessment was performed with one end of the cavity open and the other end closed, assuming an uniform internal wall temperature (i.e. the cavity walls were heated). The numerical analysis shows that there are ranges of wind speeds for which the combined convective heat losses are lower than the natural convective heat loss from the cavity and that this range depends on the aspect ratio of the cavity. In addition, the effect of wind speed on the area-averaged flux of convective heat loss from a heated cavity is smaller for long aspect ratios than for short ones, which indicates that the overall efficiency of the solar cavity receiver increases with the aspect ratio for all conditions tested in this study.

1. Introduction

Solar thermal power is expected to play an important role in the mix of power generators of the future owing to the foreseeable development of low-cost thermal energy storage system, relative to electrical energy storage system (Kolb et al., 2011). Solar thermal power plants typically use a receiver to transfer the energy of the highly concentrated solar radiation to an internal fluid which is then used for power generation. Recent research has sought to develop systems to achieve higher operating temperatures than what is available from the state-of-the-art, which lead to a higher power generation efficiency, larger solar power plants and an anticipated lower cost (Ávila-Marín, 2011; IEA-ETSAP and IRENA, 2013; Lovegrove et al., 2012; Price, 2003; Segal and Epstein, 2003; Steinfeld and Schubnell, 1993). One of the challenges to be overcome to enable higher temperatures of the solar receiver is to decrease the heat losses from the solar receiver, since heat loss increases with temperature. However, the underlying mechanisms that control the heat losses from a receiver are highly complex and remain poorly understood. Hence, there is a need to further increase the understanding of the mechanisms of heat loss from solar receivers.

One of the geometric configurations being developed for solar thermal systems is a cavity receiver. Previous studies have shown that cavity-type receiver configurations are the most suitable configuration for high temperature receivers, owing to their lower radiation losses, which is significant given the trend in research to increase the temperature of the solar thermal system (Collado, 2008; Segal and Epstein, 2003). However, an increase in the operating temperature will also increase the heat losses from the receiver (Ho and Iverson, 2014). Hence, to achieve high operating temperatures, there is a need to lower heat losses. One advantage of external receivers is the relatively low surface area compared with cavity receivers. However, in addition to their high radiative losses, both external receivers and very short cavity receivers have high convective heat losses, particularly in windy conditions. Furthermore, their heat losses are very complex, since they include conductive heat loss through insulated walls as well as radiative and convective heat losses through the aperture. Conductive and radiative heat losses can be estimated analytically using a typical wall temperature of the cavity, emissivity and absorptivity, shape factors and the properties of the insulation material (Holman, 1997; Mills, 1999). However, convective heat losses are more difficult to estimate due to the complexity of the temperature and flow fields in and around the cavity. In addition, convective heat losses include both natural convection, which is driven by buoyancy, and forced convection, which is driven by any wind currents. Therefore, the primary objective of the present work is to assess the convective heat loss mechanisms from a fully open heated cavity.

Natural convective heat losses from heated solar cavities were first studied by Clausing (1981). He concluded that convective heat

* Corresponding author.
E-mail address: ka.lee@adelaide.edu.au (K.L. Lee).

http://dx.doi.org/10.1016/j.solener.2017.03.089
0038-092X/

loss is governed by two factors: (1) the transfer of energy and mass across the aperture and (2) the transfer of heat to the air inside the cavity. Due to the high internal wall temperatures, the density of air inside the receiver or near to its internal surfaces is lower than that of the ambient air because of the high temperature of the internal walls, which are exposed to concentrated solar radiation. Depending on the configuration, this leads to natural circulation of the air inside the cavity receiver, resulting in natural convective heat loss. They also found that, for certain receiver configurations, hot air is trapped in the upper part of the receiver, dividing the volume within the receiver into a convective (non-stagnant) and a stagnant zone. The boundary between the two zones lies approximately at the horizontal plane, passing through the highest end point of the aperture and is sometimes also referred to as a shear layer (Clausing, 1981, 1983). Similarly, Quere et al. (1981) evaluated the convective heat loss from a cubical cavity with one face open and isothermal conditions numerically. They observed that the convective heat loss is strongly dependent on the inclination (tilt angle φ) of the cavity, which is defined as the angle between the horizontal plane and the normal direction of the aperture, as shown in Fig. 1. Ma (1993) presented detailed experimental data for combined convective heat loss from a cylindrical receiver. He showed that wind directions parallel to the aperture (side-on wind) have a greater impact on the convective heat loss than those normal to the aperture (head-on wind). Other studies (Leibfried and Ortjohann, 1995; Paitoonsurikarn and Lovegrove, 2003) found that some wind can even have reduce the convective heat losses, depending on its speed and direction, together with the cavity geometry. Paitoonsurikarn and Lovegrove (2006) also investigated the effects of various angles of incident wind on the flow field inside the cavity and on the convective heat losses for a parabolic dish structure. They showed that the magnitude of heat loss for side-on wind is higher than head-on wind, similar to the experimental observations of Ma (1993). In contrast, the study by Prakash et al. (2009) found that a head-on wind generates convective heat losses from a cylindrical cavity receiver than the side-on wind for the wind speeds of 1 m/s and 3 m/s. Xiao et al. (2012) investigated the effects of wind incident angle and receiver inclination on the combined free-forced convective heat loss from a solar cavity receiver. They showed that the combined convective heat loss decreases with an increase in inclination for low wind speeds. However, this rate of decrease reduces as the wind speed increases, while the convective heat loss does not vary much with the tilt angle of the cavity for high wind speeds.

The literature shows that, while the effects of wind on the heat loss from the solar cavity have been studied extensively, the effects of geometry on the combined convective heat loss from solar cavity receivers is not well known. There are studies on the effect of wind direction on the heat loss (Flesch et al., 2014; Xiao et al., 2012). Previous studies have also shown that forced convective heat loss could result in an increment of up to 2.5 times the heat loss from a cavity relative to the minimum convective heat loss for the same wind speed (Xiao et al., 2012; Yu et al., 2012). Head on and side on wind are the most commonly used wind directions for this type of simulation. It has also been shown that wind with a direction parallel to the aperture may possibly has a reduction effect on the heat loss as it inhibits hot air from leaving the cavity (Flesch et al., 2014; McIntosh et al., 2014; Prakash et al., 2009). Nevertheless, there are conflicting results in a number of investigation (Ma, 1993; Paitoonsurikarn and Lovegrove, 2006; Prakash et al., 2009) regarding the effects of head-on and side-on wind on the combined convective heat loss from the heated cavity, which is possibly due to the different cavity configurations, temperatures of the walls and wind conditions used in the respective studies. Furthermore, it has been found that the larger the aspect ratio of the cavity, the smaller the mean air flow speed inside the cavity (Rockwell and Naudascher, 1978; Tam and Block, 1978).

The aforementioned discussion shows that, while the effects of wind on the heat loss from a solar cavity have been studied extensively for head-on and side-on wind directions, the effect of the cavity geometry on the combined convective heat loss from solar cavity receivers is not well understood. Furthermore, the effect of aspect ratio on solar cavity receivers in terms of its combined convective heat loss is also not well known. Therefore, the principle objective of this work is to assess the effects of aspect ratio of a cavity on its combined convective heat loss for various wind speeds.

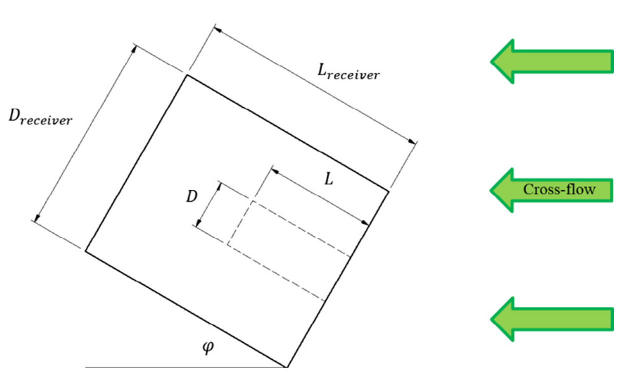

Fig. 1. Schematic diagram of the configuration chosen for investigation, with a fully open cylindrical solar cavity receiver in the presence of a uniform cross-flow.

2. Methodology and model validation

A fully open cylindrical cavity receiver, as shown schematically in Fig. 1, was chosen for the present study. The experimental data on the heat losses from the smaller cylindrical cavity receivers used in solar dish systems (Ma, 1993; McDonald, 1995; Prakash et al., 2009; Taumoefolau and Lovegrove, 2002) was chosen for validation in the absence of any publically available larger scale data. Comparing those experimental studies, Taumoefolau and Lovegrove's study was chosen for this project, as the effect of the cavity's aspect ratio on its convective heat loss is the focus of this study. Since the effect of tilt angle of solar cavity and wind direction have already been assessed numerically (Flesch et al., 2014; Wu et al., 2011; Xiao et al., 2012). This work is not repeated. Instead only one tilt angle and wind direction was employed.

Validation of the model was performed through comparison of the model predictions with the experimental data reported by Taumoefolau et al. (2004). In this experiment, a simple cylindrical solar cavity receiver was used with an outer diameter $D_{receiver}$ of 280 mm, an outer length $L_{receiver}$ of 320 mm, an inner diameter D of 70 mm and inner length L of 155 mm. The comparison was undertaken for tilt angles φ from 0° to90°. Of these, a tilt angle of 15° was chosen as a reference case, since it is within the suitable range for large solar towers (Wei et al., 2010a,b). The modelled small-scale cavity receiver has an inner cavity length where L is 155 mm, similar to the experimental study undertaken by Taumoefolau et al. (2004). For the present work, L was varied from 35 mm to 210 mm with increments of 35 mm to alter the aspect ratios (the ratio of cavity length to the cavity diameter), from 0.5 to 3 with increments of 0.5. Furthermore, a parametric analysis of the effects of changing the head on wind velocities (2, 4, 7 and 10 m/s) was also performed.

An isothermal boundary of 400 °C for the inner cavity walls was chosen, following the approach of previous numerical studies (Paitoonsurikarn et al., 2004; Wu et al., 2011; Xiao et al., 2012). This avoids the challenge of addressing the complex coupling