Solar Energy 165 (2018) 178–188

Contents lists available at ScienceDirect

Solar Energy

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

# Experimental investigation of the effects of wind speed and yaw angle on heat losses from a heated cavity

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ARTICLE INFO

*Keywords:*
Solar receiver
Solar thermal power
Heat loss
Concentrated solar thermal
Temperature distribution
Wind

ABSTRACT

An experimental investigation of the effects of wind speed (0–12 m/s) and yaw angle (0°–90°) on the convective heat losses from a cylindrical cavity heated with a uniform wall temperature, is presented. The cavity is heated with 16 individually controlled copper surface elements, so that both the heat losses and the heat flux distribution can be measured and subjected to a controlled convective environment in the open section of a wind tunnel. It was found that the convective heat losses through the aperture are ~4 times greater for the head-on wind case than for the side-on wind case, when the inverse of Richardson number ($1/Ri$) > 77 (wind speed > 12 m/s). For the no-wind condition, ≈85% of the heat was lost from the lower half of the surface of the cavity, while for $1/Ri > 43$ (wind speed > 9 m/s), the heat loss was more uniformly distributed over the surface of the cavity. For head-on-wind conditions and for $1/Ri > 19$ (wind speeds > 6 m/s), the convective heat losses are ~2 times greater than for side-wind conditions. The correlations between the mixed (natural and forced) convective heat losses, Nusselt number and Richardson number are also reported.

## 1. Introduction

Solar thermal power is expected to play an important role in the mix of power generators of the future owing to the growing development of thermal energy storage technology, which has a low-cost relative to electrical energy storage counterparts (Kolb et al., 2011; Philibert, 2010; Tanaka, 2010). Solar thermal power plants typically use a receiver to transfer the energy of the highly concentrated solar radiation to a heat transfer medium, such as fluid, which is then transferred to storage and then to the working fluid of a power cycle. Recent research has sought to develop systems to achieve higher operating temperatures than are commercially, since higher temperatures will enable a higher power generation efficiency, larger solar power plants and an anticipated further reduction in cost (Ávila-Marín, 2011; IEA-ETSAP and IRENA, 2013; Jafarian et al., 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 losses also increase with the 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.

Solar cavity receivers are one class of geometric configurations being developed for solar thermal systems. Previous studies have shown that cavity receivers are the most suitable configuration for high temperature receivers, owing to their radiation losses being lower than for surround-field or billboard receivers. This is significant because of the above-mentioned trend in research to develop solar thermal system to operate at higher temperatures (Collado, 2008; Segal and Epstein, 2003). The mechanisms controlling heat losses from a solar receiver are complex, comprising both radiative and convective components through the walls and aperture, which are linked by conductive heat transfer through insulated walls. 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, the convective heat losses are more difficult to estimate due to the complexity of both the temperature and flow fields inside and around the cavity. Importantly, convective losses can be expected to be significant in windy sites because cavity receivers are typically mounted on a tower, where wind speed is higher than on the ground due to the shape of the atmospheric boundary layer. However, these effects are yet to be assessed systematically and very little experimental data are available in the literature. Therefore, the primary objective of the present work is to advance understanding of the convective heat loss mechanisms from

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https://doi.org/10.1016/j.solener.2018.03.023
Received 14 November 2017; Received in revised form 4 March 2018; Accepted 9 March 2018
0038-092X/

**Nomenclature**

*Symbols*

| | |
|---|---|
| A | area ($m^2$) |
| $\beta$ | coefficient of thermal expansion ($^\circ C^{-1}$) |
| $D$ | diameter (m) |
| $\varepsilon$ | emissivity coefficient of the internal wall surface |
| $g$ | gravity ($m/s^2$) |
| $Gr$ | Grashof number $= \frac{g\beta(T_{wall} - T_a)D_{cav}^3}{\nu^2}$ |
| $h_c$ | convective heat transfer coefficient though the aperture ($W/(m^2\,K)$) |
| $k$ | thermal conductivity of air at reference temperature (W/(m K)) |
| $L$ | length (m) |
| $\overline{Nu}$ | mean Nusselt number $= \frac{h_c D_{cav}}{k_{ref}}$ |
| $Q$ | heat loss (W) |
| $R$ | Ratio |
| $Re$ | Reynolds number $= \frac{VD_{cav}}{\nu}$ |
| $Ri$ | Richardson number $= \frac{Gr}{Re^2} = \frac{g\beta(T_{wall} - T_a)D_{cav}}{V^2}$ |
| $T$ | temperature (°C) |
| $V$ | wind speed (m/s) |
| $\nu$ | kinematic viscosity of air at reference temperature kg/(sm) |
| $\alpha$ | yaw angle or incoming wind direction (°) |
| $\varphi$ | tilt angle of the cavity (°) |

*Subscript*

| | |
|---|---|
| a | ambient |
| as | aspect |
| ap | aperture |
| cav | cavity |
| conv | convection |
| rad | radiation |
| ref | reference |
| tot | total |
| w | wall |

a solar cavity receiver as a function of wind direction and speed.

Convective heat losses from heated solar cavities were first studied by Clausing (1981), who found that the convective flow pattern in a heated cavity receiver can be divided into two zones, which are the stagnant and the convective zones. The stagnant zone means that, the air in that region move very slow due to the trapped hot air in the upper part of the cavity. On the other hand, air moves quickly in the lower part of the cavity when compared to the air in the stagnant zone. Therefore the heat transfer coefficient is higher in the convective zone than the stagnant zone. Ma (1993) was the first to present detailed experimental data for combined convective heat loss from a hot heat transfer fluid (Syltherm@ 800, Dow Coming) within a heated cylindrical receiver to a temperature of ~277 °C and a wind speed up of to 8.9 m/s. He reported that wind directions normal to the axis (side-on wind) have a greater impact on the convective heat loss than those parallel to the axis (head-on wind). More recently, Flesch et al. (2015) reported that, for some conditions, the minimum convective heat losses can occur at an intermediate wind speed, so that a low wind speed can reduce the losses to below that of natural convection. A low temperature cavity is placed in a cold wind tunnel to have a similar Reynolds number of a large scale solar cavity receiver. A similar experimental approach was used in the present study with a much wider range of temperatures. This study also found that a side-on wind has a greater impact on the heat loss than does a head-on wind. In the following year, a CFD simulation was performed, and it reported similar findings to those measured experimentally (Jafarian et al., 2013). However, the results from the CFD model are about 20–25% lower than the experiment, which may be due to the fact that the boundary conditions of the CFD model are difference to the experiment, such as wall temperature and hence heat fluxes. Also worth noting, is that the effect of side-on wind is stronger than head-on wind only for cases tilt angle larger than 30°. Therefor the tilt angle may also be one of the parameters when assessing the effect of yaw angle. In contrast, the study by Prakash et al. (2009) found that a head-on wind generates greater convective heat losses from a cylindrical cavity receiver than does a side-on wind. Another recent study found that there is no simple rule to describe the influence of wind yaw angle reliably (Wu et al., 2015). However, a reduction in the effect of yaw angle on convective losses was measured at wind speeds of ~5.7 m/s, relative to a lower wind speed. This apparently contradictory mix of information shows that the effect of yaw angle on the convective heat loss from a solar cavity receiver is not fully understood. The summary of the tested key parameters, methods and findings for previously measured combinations of forced and free convective heat loss from the heated cavities are shown in Tables 1 and 2. Importantly, for each of these measurements, only the total heat loss from the system is reported. Other details about the flow are not available.

The convective heat losses from cavity receivers have also been investigated numerically, both for natural convection (Paitoonsurikarn and Lovegrove, 2002; Paitoonsurikarn et al., 2011; Wu et al., 2011) and for mixed convection (Flesch et al., 2014; Hu et al., 2017; Lee et al., 2017; Paitoonsurikarn and Lovegrove, 2003; Xiao et al., 2012). Despite their value, these numerical studies have only been partially validated due to the lack of experimental data. As can be seen from Table 1, the provision of only single value of total convective heat loss is insufficient for reliable model validation.

**Table 1**
List of key operating conditions and measured parameters for the experimental studies combined forced and free convective heat loss from heated cavities.

| Studies | Wall temperature $T_w$ (°C) | Wind speed $V$ (m/s) | Diameter of cavity $D_{cav}$ (m) | Diameter of aperture $D_{ap}$ (m) | $R_{as}$ | $R_{ap}$ | $Re$ | $\frac{1}{Ri}$ | Tilt angle $\varphi$ (°) | Yaw angle $\alpha$ (°) | Blockage ratio |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Ma (1993) | 277 | 0, 2.7, 3.6 and 8.9 | 0.66 | 0.46 | 1.05 | 0.70 | $2.08 \times 10^5$ | 0–20.1 | 0, 30, 60 and 90 | 0 and 90 | 36% |
| Prakash et al. (2009) | 75 | 0, 1 and 3 | 0.33 | 0.33 | 1.52 | 1.00 | $5.04 \times 10^4$ | 0–16.2 | 0, 30, 45, 60 and 90 | 0 and 90 | 22% |
| Wu et al. (2015) | 39–128 | 1.15, 1.84, 2.94 and 5.69 | 0.105 | 0.105 | 1.82 | 1.00 | $3.18 \times 10^4$ | 0–101 | 0, 15, 30, 45, 60, 75 and 90 | 0, 15, 30, 45, 60, 75 and 90 | 58% |
| Flesch et al. (2015) | 60.4 | 0, 1, 3, 5 and 7 | 0.66 | 0.36 | 1.11 | 0.55 | $5.20 \times 10^5$ | 0–7.02 | 0, 30, 60 and 90 | 0, 30, 60, 90, 135 and 180 | N/A |
| Present | 100, 150, 200, 300 and 400 | 0, 3, 4, 6, 9 and 12 | 0.3 | 0.15 | 1.50 | 0.50 | $8.78 \times 10^4$ | 0–204 | 15 | 0, 22.5, 45, 77.5 and 90 | 4.1% |