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Experimental Investigation of the Effects of Wind Speed, Aperture Ratio and Tilt Angle on the Convective Heat Losses from a Solar Cavity Receiver

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Abstract

The present study is the first experimental investigation for the combined influences of wind speed, aperture ratio and tilt angle on the convective heat losses from a heated cavity. A complex inter-dependence was found between wind speed, aperture ratio and convective heat losses, which can vary by up to 75%. Varying the tilt angle from 15° - 45° was found to have a relatively small effect on heat losses compared with the wind speed and aperture ratio.

Introduction

Over the last three decades, resulting in a marked increase in their deployment for power generation and in the development of novel approaches to utilise thermal energy for industrial processes [1, 2]. The highly concentrated solar radiation, from a solar field, is collected by a solar receiver, which uses a heat transfer medium to efficiently absorb the radiation. The heat losses from a receiver comprise both radiative and convective component, which are highly complex so that the underlying mechanisms remain poorly understood. In particular, the heat loss from a solar cavity receiver is influenced by the cavity aspect ratio, aperture ratio, wind speed, yaw angle, tilt angle, mean temperature and temperature distribution. However, little information is available about these effects. A systematic investigation of the effect of wind speed, aperture ratio and the tilt angle is reported in the present study.

The influence of tilt angle on the natural convection heat loss from a solar cavity receiver was investigated experimentally [3] and the concept of stagnant and convective zones was introduced. They also found that the tilt angle has a significant influence on the size of the stagnant and convective zones and the heat transfer rate in the convective zone is much higher than the stagnant zones. Ma [4] experimentally investigated the effect of wind speed on the convective heat loss using a heated cavity receiver in a wind tunnel. The internal surface of the cavity was heated with a heat transfer fluid, whose temperature change was used to measure the heat losses. They found that the trend of increasing convective heat with wind speed for a side-on wind is independent of the receiver tilt angle. However, for head-on winds, the heat loss is a function of the receiver tilt angle. The influence of head-on wind and side-on wind on cavity receivers with different inclination angles in the range of 0-90° has been analysed numerically by Flesch, Stadler [5]. They claimed that wind has only a small influence on the convective heat losses from a horizontal cavity receiver. Conversely, in most cases, the losses from cavity receivers increase significantly at high inclination angles. The ratio of the aperture diameter to that of the cavity (aperture ratio) has a strong influence on the re-radiation and convection losses from the cavity [6-8]. They claimed that that the convective heat loss increases with wind speed and aperture area. Further work is therefore required to better understand the interactions between wind speed and aperture area on the heat loss from a solar cavity receiver.

Most previous experiments of heat transfer were performed with only a single temperature controller for the entire internal surface. This makes it impossible to achieve a truly uniform internal temperature distribution because the heat transfer across the entire surface is controlled to a single temperature set-point, even though the surface temperature varies spatially. As a result, it is difficult to reliably validate numerical models with existing data, since they require invoking the assumption of a uniform internal wall temperature [5, 8-12], even though this assumption is known to be incorrect. Therefore, there is a need for new experimental data that more accurately reproduces a uniform internal wall temperature. In addition, the interactions between tilt angle and aperture ratio under conditions with wind have not been assessed experimentally, either on the total losses or on the heat losses from different sections of the cavity.

In light of the above gaps in understanding and in available data, the principal objective of the present investigation is to provide direct measurements of the influence of wind speed, aperture ratio and tilt angle on the mixed convection heat losses from a solar cavity receiver with uniform internal wall temperature.

Methodology

The experimental arrangement used in the study is shown in Figure 1. An electrically heated cavity was placed within the open section of the wind tunnel at University of Adelaide's Thebarton laboratory. The key dimensions of the cavity are shown in Figure 1b) and the tested conditions are shown in Table 1. The surface of the cavity was lined with 16 segments of heating elements that are individually controlled, as shown in Figure 1 and Figure 2. The internal walls of the cavity are made from copper, because of its high thermal conductivity and a safe operating temperature. Therefore the internal temperature of each surface is reasonable to be assumed as a uniform for each small segment. These are arranged to comprise 6 annular rings of 12 heaters, each covering a 180° arc along the length of the chamber to measure separately the upper and lower half, together with another 4 circumferential rings on the back wall. The temperatures of each segment are measured and each heater is controlled with a feedback controller, which controls the set-point temperature to the desired value and records the power required to do so.

The steady-state power required to maintain the system at the set point temperature was measured, with the sum of these corresponding the total heat loss from the system. The different contributions to convective and radiative heat losses from the receiver were identified in a series of steps. Firstly the radiative heat loss was determined, being independent of the cavity's orientation. This was performed with the cavity oriented vertically downward (tilt= 90°), because this position minimises the convective heat loss. The total heat losses from the cavity were then measured both with the aperture of the cavity being opened and closed. The power loss for the case with the aperture closed, Q_{wall} corresponds to the wall losses. Then, the aperture was opened and the total power loss, Q_{total} was recorded again. The difference between the cases with the

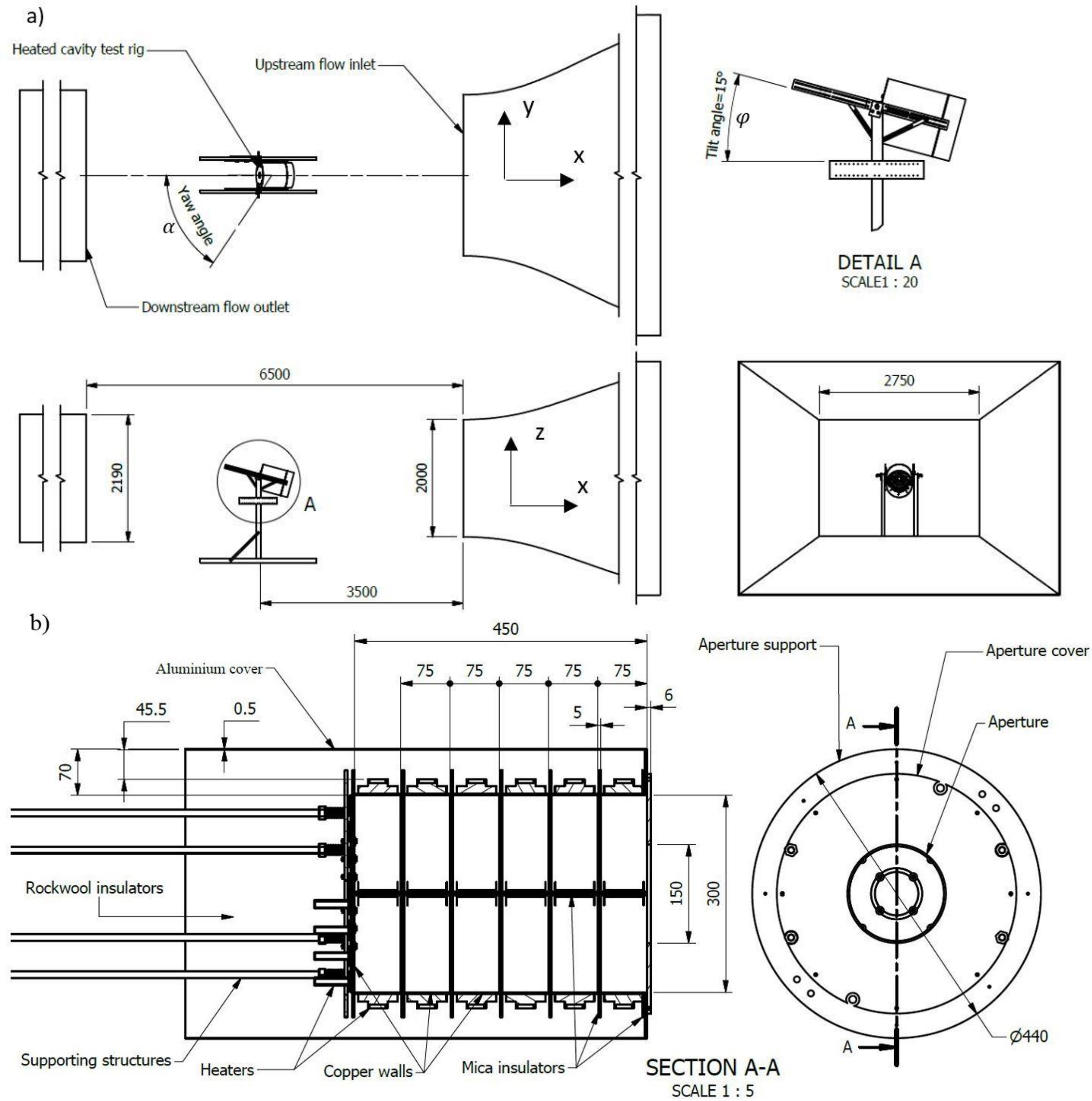

Figure 1 Schematic diagram of a) the heated cavity in the Thebarton wind tunnel and b) the dimensions of the receiver.

aperture opened and closed presents the heat loss though the aperture ,Q_{ap} calculated as follow:

$$Q_{ap} = Q_{total} - Q_{wall} = Q_{rad} + Q_{conv} \,. \tag{1}$$

The radiative component of heat loss though the aperture is Q_{rad}. A Medtherm 64 series was used to measure the direct radiative heat loss though the aperture [13]. The convective heat loss thought the aperture Q_{conv}, was then determined by subtraction. A cross check was performed using the different proportionality constant for radiation, which scales with T^4, while convection scales with T following previous work [14]. The details of this method is shown in [15]. The Richardson number Ri was used to characterise the effect of geometry and wind speed on the relative roles of the buoyancy and inertia forces. The cavity was aligned head-on to the wind for this dimensionless study as wind has the greatest impact on the heat losses for this orientation. The Ri is the ratio of the buoyancy term to the flow shear term, and can also be expressed in terms of the Grashof and Reynolds numbers, as shown in equation 2.

$$Ri = \frac{\text{buoyancy term}}{\text{flow shear term}} = \frac{Gr}{Re^2} = \frac{g\beta(T_w - T_a)D_{cav}}{V^2} \tag{2}$$

Here g is the acceleration due to gravity, β is the thermal expansion coefficient. T_w is the wall temperature and T_a is the ambient temperature. D_{cav} is the internal diameter of the cavity. Typically, a heated surface is dominated by natural convection for Ri < 0.1, and by forced convection for Ri > 10, while both are important for 0.1 < Ri < 10 (Garbrecht, 2017).

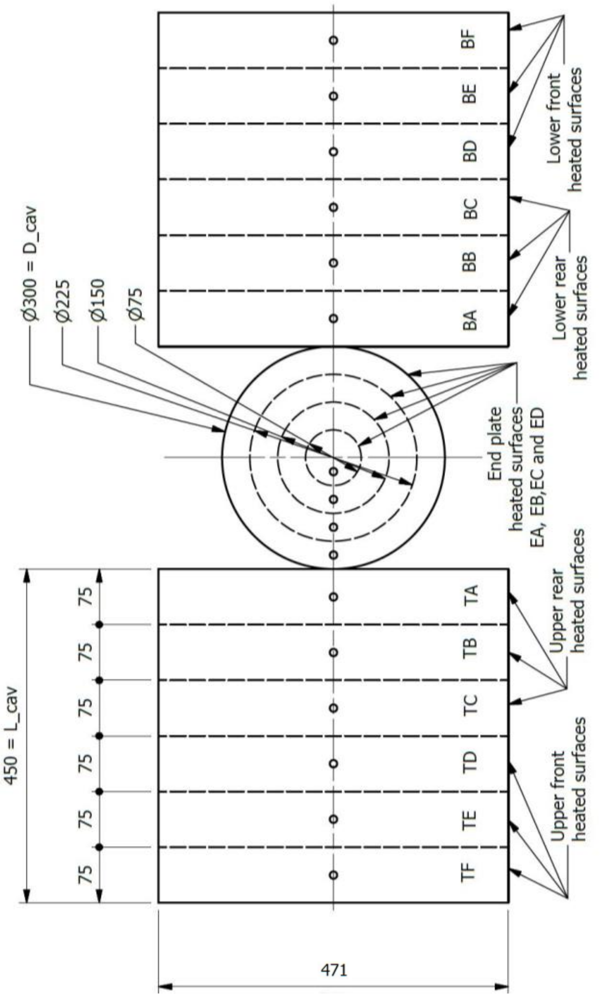

Figure 2 Schematic diagram of the simplified configuration of the internal copper wall surface of the heated cavity (shown unrolled view). The thermocouples are shown as small circles.

Velocity (V, m/s)	**Yaw angle (α°)**	**Tilt angle (φ°)**
0,3,6 and 9	0	15, 30 and 45
Temperature of the wall (T_w, °C)	**Aspect ratio ($\frac{L_{cav}}{D_{cav}}$)**	**Aperture ratio ($\frac{D_{ap}}{D_{cav}}$)**
300	1.5	0.00, 0.33, 0.50, 0.75, 1.00

Table 1 List of experimental conditions

Results and Discussion

The effects of the aperture ratio and wind speed on the convective heat losses for the 2 values of the tilt angles is shown in Figure 3. For the no wind condition, the convective heat losses increase with the D_{ap}/D_{cav}, while the influence is more complex in the presence of a wind. There is a general trend of the convective heat losses being lower with higher tilt angle (as expected), although there is an exception for highest value of wind speed (V = 9 m/s). For $1/Ri$ = 8.5 (V = 4m/s), the tilt angle on the convective heat losses and the convective heat losses are also almost independent of D_{ap}/D_{cav}, although it has a weak local minimum for 0.5 <D_{ap}/D_{cav} < 0.75. For higher values of $1/Ri$ = 43 (V = 9m/s), the convective heat loss decreases with the aperture ratio for both tilt angles, except the case V=9 m/s, φ = 30° and D_{ap}/D_{cav} =1.

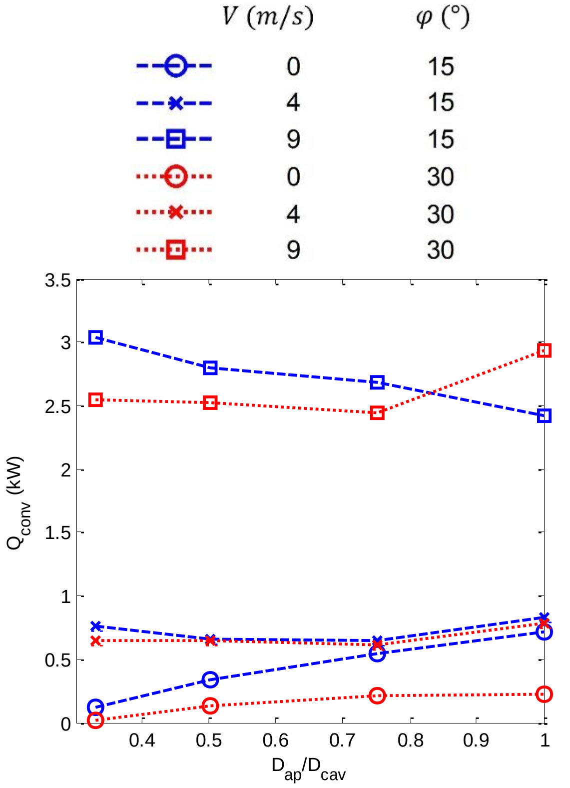

Figure 3 Dependence of the convective heat losses through the aperture on tilt angle, wind speed and inverse Richardson number for a series of aperture ratio. Conditions: wall temperature of 300°C, yaw angle of 0°and aspect ratio of 1.5.

The dependence of the relative convective heat losses through the aperture, $Q_V/Q_{V=0}$ on inverse Richardson number and wind speed is presented in Figure 4 for various values of D_{ap}/D_{cav}. The difference between the forced convection and natural convection case increases as wind speed. For D_{ap}/D_{cav} =0.33, the corresponding increase is about 25. That is, the influence of wind speed on the convective heat loss is very high for D_{ap}/D_{cav} =0.33. It is because the natural convective heat loss is low for cavity with a low D_{ap}/D_{cav}. However convective heat losses are similar for all of the tested D_{ap}/D_{cav} at high wind speed Ri > 19.

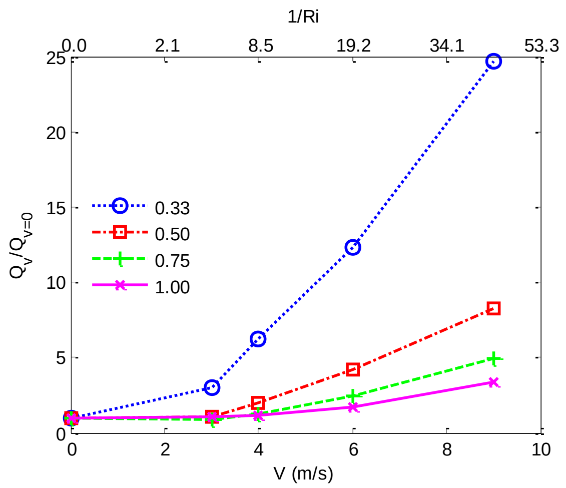

Figure 4 Dependence of the relative convective heat losses through the aperture with wind speed for various values of aperture ratio.

Conditions: wall temperature of 300°C, tilt angle of 15°, yaw angle of 0°and aspect ratio of 1.5. The relative convective heat loss $Q_V/Q_{V=0}$ is the ratio between the convective heat loss for a given wind speed and no wind condition.

The heat loss at a given tilt angle normalised by that at 15° with the same wind speed is presented in Figure 6. For the no wind speed condition, the heat loss from the 30° and 45° case are 83% and 77% of that of the 15° case respectively, which is as expected. However, $Q_\varphi/Q_{\varphi=15°}$ exhibits a maximum for wind speed $1/Ri$ = 8 to 19 (V = 4 to 6 m/s). The normalised heat loss for the 30° case is always below that for unity for these cases. The maximum normalised heat loss of the 45° case is more than the 30° case and it is also above 100%, which was not expected. That is, increasing tilt angle above 30° has a negative effect on the overall heat loss. This will be compounded in practice, because the wind speed at the receiver increase with the tilt angle, since the tower height increases with tilt angle.

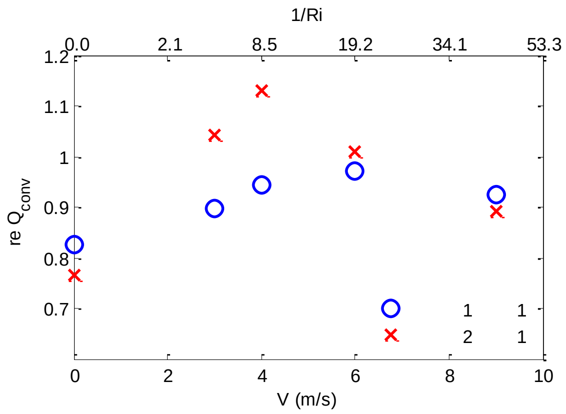

Figure 5 Normalised heat loss from the various sections of the heated cavity plotted for various wind speeds and tilt angle. Conditions: temperature = 300°C, yaw = 0°, aperture ratio = 0.75 and aspect ratio = 1.5.

Conclusions

Introducing a lip at the aperture plane, by decreasing D_{ap}/D_{cav}, acts to inhibit the natural convective losses (at zero wind speed) by up of to a factor of 5, but increases the forced convection losses by a factor of up to 30%. More specifically, for tilt angle = 15° and $1/Ri$ < 4. 8 (V < 3 m/s), the convective heat losses increase with aperture ratio, although this behaviour reverses for $1/Ri$ > 19 (V > 6 m/s). For the cases with a larger tilt angle of ~30°, the effect of aperture ratio on convective heat loss is small.

The effect of tilt angle on the total heat loss from the system was found to be relatively small comparing with aperture ratio. For φ = 30°, the heat loss increases from 0 m/s to a local maximum at $1/Ri$ ≈19 (V ≈6 m/s). However, it is always below that from 15° case for all tested wind speeds. Conversely, the heat loss for the 45° case is more than that from the 15° case for 4.8 < $1/Ri$ < 19 (3 < V < 9 m/s). This shows that there is a slight advantage with respect to heat loss in keeping the tilt angle of a solar cavity below 30°.

Overall the configuration with a tilt angle of 30° has the minimum convective heat loss. Increasing tilt angle from 30 to 45° does not reduce the convective heat loss from the heated cavity for all cases, which is contrary to expectation based on previous work. In addition, although the aperture ratio does influence the convective heat loss, its influence is less than 15% over the range 0.33 < D_{ap}/D_{cav} < 1 for a tilt angle of 30°and wind speed above 3 m/s. These data highlight the need to consider convective losses in optimising the size, shape and orientation of a cavity receiver, and for more detailed measurements of the flow-field with the cavity to better understand the mechanisms that drive these heat losses.

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