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# The influence of wind speed, aperture ratio and tilt angle on the heat losses from a finely controlled heated cavity for a solar receiver

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ABSTRACT

The first systematic experimental study of the combined influences of wind speed (0–9 m/s), aperture ratio (0.33–1) and tilt angle (15°–45°) on the mixed (free and forced) convective heat losses from a heated cavity, is presented. The cylindrical cavity is heated by 16 individually temperature-controlled heating elements in the open section of a wind tunnel. Heat flux distribution and total heat losses from the cavity were measured. A complex inter-dependence was found between aperture ratio, wind speed and convective heat losses. In particular, the total heat losses can vary by up to ~75% by varying the aperture ratio from 0.33 to 0.75, for no wind condition, but the effect of aperture ratio is decreased as wind speed is increased. The tilt angle was found to have a small effect on the heat losses relative to the aperture ratio and wind speed. Nevertheless, the average minimum mixed heat loss for various wind speeds occurs for a tilt angle of between 15° and 30° for a downward tilting solar tower system.


## 1. Introduction

The ongoing development of solar tower thermal energy technology has been driven recently by the low cost of thermal energy storage relative to their electrical energy storage counterparts [1–3]. Nevertheless, to capitalise on this, there is an ongoing need to continue to lower the cost of the entire system. One opportunity is to reduce the heat losses, which become increasingly significant with the ongoing drive toward higher operating temperatures to increase the thermal efficiency of the power block [4–9]. However, the heat losses from a receiver comprise both radiative and convective component, which are highly complex, so that the underlying mechanisms remain poorly understood, especially it has been difficult to generalise the findings of mix convection. In particular, the heat losses from a solar cavity receiver are influenced by several parameters, including the cavity aspect ratio, the aperture ratio, the wind speed, the yaw angle, the tilt angle, the mean temperature and temperature distribution. However, little information is available about these effects. Our previous experimental study reported on the interaction between temperate, yaw angle and wind speed [10,11], but a systematic investigation of the effect of wind speed, aperture ratio and tilt angle yet to be reported. Therefore, the present investigation aims to meet this need.

The influence of tilt angle on the natural convection heat loss from a solar cavity receiver was first reported via experiments by Clausing [29,30], who introduced the concept of stagnant and convective zones. In the stagnant zone, the air inside the cavity is nearly stationary, and the convective heat transfer coefficients are low. However, in the convective zone, the air moves at higher velocity resulting in a much higher heat transfer rate. They also found that the tilt angle has a significant influence on the size of the stagnant and convective zones. The larger the tilt angle, the larger the stagnant zone. Ma [12] experimentally investigated the effect of wind speed on the mixed 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. It was found that the trend of increasing mixed 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

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**Nomenclature**

*Symbols*

| | |
|---|---|
| A | Area ($m^2$) |
| $\beta$ | Coefficient of thermal expansion (°$C^{-1}$) |
| $D$ | 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 through the aperture ($W/(m^2K)$) |
| $k$ | Thermal conductivity of air at reference temperature (W/(m. K)) |
| $L$ | Length (m) |
| $Nu$ | 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/(s.m) |
| $\alpha$ | 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 |

analysed numerically by Flesch et al. [13]. They claimed that wind has only a small influence on the mixed convective heat losses from a horizontal cavity receiver. Conversely, in most cases, the losses from cavity receivers increase significantly at high inclination angles. However, the heat losses were found to reduce with increasing wind speed in some cases, although this effect is highly geometry dependent and only occurs for some cavity configurations. This highlights the need for more understanding of the convective losses from cavity receivers.

The ratio of the aperture diameter to that of the cavity has a strong influence on the re-radiation and convection losses from the cavity [9,14–18]. The effect of the aperture size on the convective heat loss from a heated cavity was first reported by Clausing et al., [14,15]; who found that both size and configuration are critical parameters. However, this study only considered natural convection, at zero wind velocity. Steinfeld and Schubnell [9] investigated the effect of the aperture size and operating temperature on the radiative losses from a solar cavity receiver on its heat losses for solar dish system. Kim et al. [16] measured the heat loss from a cavity receiver from a solar power tower system with four aperture configurations, with no cavity, open cavity (aperture ratio = 1), small centre cavity (aperture ratio = 0.5) and small lower cavity (aperture ratio = 0.5 with an aperture opening from the lowest end of the cavity). They claimed that the mixed convective heat loss increases with wind speed and aperture area but is not related to the aperture position or the distance between the aperture and the heated surface. However, the distance between the aperture and the heated surface (aspect ratio) was short, and only one aspect ratio was tested in that study. A recent study claimed that the variation of heat losses from a different section of the internal surface of cavities with a larger aperture is lower than that of a smaller aperture [19]. However, this study only shows the variation of heat losses in term of the maximum heat loss for that condition. Therefore, further work is required to better understand the interactions between wind speed and aperture area on the heat loss from a solar cavity receiver.

A low number of heating elements was used in most of the previous experimental study to heat the entire internal surface of the cavity receivers. This leads to a broad temperature distribution within the cavity, with the temperatures of the cavities far from being uniform. Nevertheless, this assumption was made for most of the previous numerical studies [13,18,20–24], even though is known to be incorrect. To reliably validate numerical simulation models, new experimental data is required for more accurate data to reproduce the uniform internal wall temperature cases. Also, 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. The details of the compassion between the experimental method of the present and the previous studies [12,25–27] are shown in the previous study from our group [10].

In light of the available data and presented gaps in understanding, the principal objective of the current study is to deliver experimental data of the effect of aperture ratio, tilt angle and wind speed, on the mixed convection heat losses from a heated cavity as a solar receiver with uniform internal wall temperature. In addition, this work aims to resolve the following questions: 1) whether mixed convective heat loss increases or decrease with tilt angle for various wind speed; 2) how the aperture ratio influences the mixed convective heat; and 3) how wind speed, tilt angle and aperture ratio influence the heat flux distribution within a heated cavity with uniform temperature. This investigation is the first experimental study for the effect of aperture ratio on the convective heat losses from a fine temperature-controlled cavity. In this study heat loss distribution from various sections of the cavity are also presented. The first experimental data for the convective heat losses distribution from a solar cavity receiver can be used for numerical model validation. The validated numerical model can be used to develop a new solar cavity design for the concentrated solar system.

## 2. Methodology

The key features of the present experiment are provided in this section, while the basic experimental principle can be found in our previous study [10]. Fig. 1a) presents the experimental arrangement used in the study. The key dimensions of the cavity are shown in Fig. 1b). A systematic study of the influence on the heat losses was assessed for variations of wind speed V = 0, 3, 4, 6, and 9 m/s, aperture ratio $R_{ap} = 0.33$, 0.50, 0.75 and 1.00, and tilt angle $\varphi = 15°$, 30° and 45°. This leads to 75 tests in total with 15 of them are closed aperture ($R_{ap} = 0$), and the other 60 are opened ($R_{ap} \neq 0$).

Sixteen segments of heating elements are lined on the outer side of the cavity. The power of each heater is individually controlled

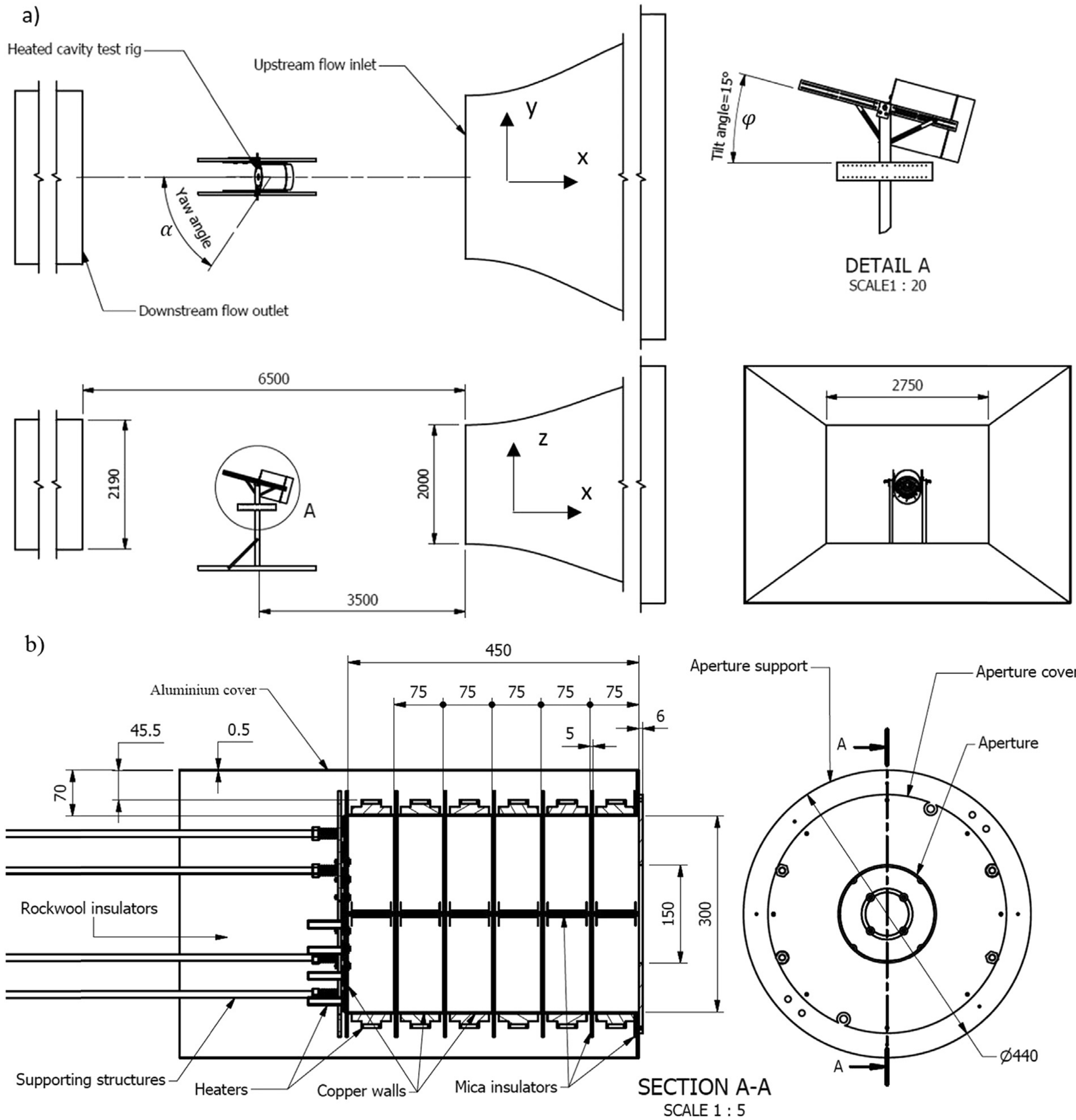


**Fig. 1.** Schematic diagram of a) the heated cavity in the Thebarton wind tunnel and b) the dimensions of the receiver.

and measured, as shown in Figs. 1 and 2. Heat flux distribution can also be obtained within the cavity for each test using the individual controlled heating elements on each copper surface. The cavity temperature was fixed to 300 °C. It is worth noting that this temperature is lower than that of real commercial receivers. However, this study focuses mainly on the influence of wind speed, aperture ratio and tilt angle rather than the absolute temperature. Grashof and Richardson numbers should also be used to assess and generalise the results for different temperatures and receiver size. These two non-dimensional numbers are shown to work well for different temperatures [10], and the range of Richardson analysed here well cover the range of that for a real receiver, which features a higher cavity temperature and size. However, careful validation should be taken for a case which has different conditions.

The Richardson number $Ri$ and Nusselt number $\overline{Nu}$ were used to characterise the effect of wind speed and geometry on the relative roles of the inertia and buoyancy forces as well as heat losses [10].

The main uncertainties in the experiments are summarised below, and the details are shown in the previous study [11]. The maximum uncertainty of the power output from each heater is ±25 W (~3.1% of its maximum power), which includes that from the power and temperature measurement (±0.5 °C) and their effect on the feedback control system. Although the total maximum uncertainty is ~± 400 W (±3.1% of the maximum power), the average error should be much less than ± 3.1% of the maximum power. This is because the random error is reduced by using the 16 results from the heaters. In addition, the uncertainty of the incoming wind speed is estimated to be ±0.2 m/s.

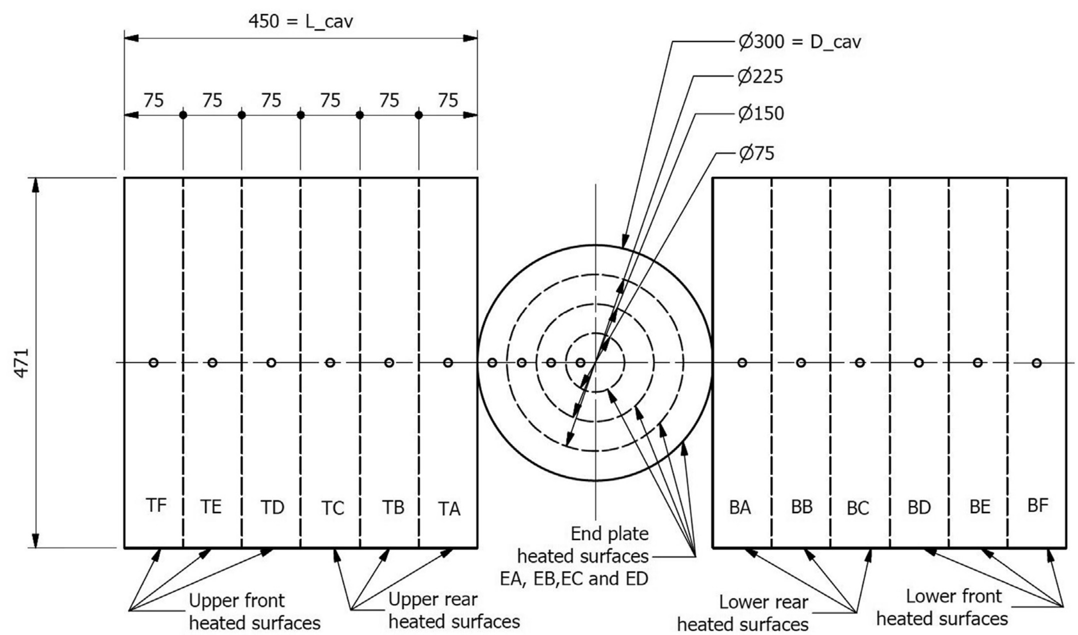


**Fig. 2.** Schematic diagram of the simplified configuration of the internal copper wall surface of the heated cavity (shown unrolled view). The thermocouples are shown as small circles.

## 3. Results and discussion

### 3.1. Absolute convective heat loss

The variation of the convective heat losses through the aperture with wind speed is presented in Fig. 3 for various values aperture ratios, but for a constant wall temperature of 300 °C, the tilt angle of 15°, yaw angle of 0° and the length-to-diameter cavity ratio of 1.5. This case was chosen as a reference case because of its relevance to practical conditions and to match the conditions reported by Lee et al. [10]. The convective heat losses increase with an increase in $1/Ri$ and $V$, for all the aperture ratios $D_{ap}/D_{cav}$ considered here.

However, the dependence is non-linear. The effect of wind speed is weak for $1/Ri < 8.5$ ($V < 4$ m/s), and strong for $1/Ri > 8.5$ ($V > 4$ m/s). The effect of $D_{ap}/D_{cav}$ is weaker but is also non-linear. In the low range $1/Ri < 4.8$ (i.e. $V < 3\ m/s$), an increase in $D_{ap}/D_{cav}$ increases the convective heat losses. Conversely, for high wind speed cases ($1/Ri > 19$ and $V > 6$ m/s), an increase in $D_{ap}/D_{cav}$ leads to a decrease in the convective heat losses for $3 < V < 4$ m/s ($4.8 < 1/Ri < 8.5$).

Fig. 4 presents the corresponding dependence of the convective heat losses through the aperture on $1/Ri$ and $V$ for series of $D_{ap}/D_{cav}$, but for the case of a tilt angle of 30° with the other conditions unchanged. It can be seen that the general trends are the same as for the tilt angle of 15° (Fig. 3). However, the effect of aperture ratio on the convective heat loss is even less than for the case of a tilt angle = 15°. In particular, the effect of the aperture ratio is negligible for the higher wind speeds, where $1/Ri > 4.8$ (V > 3 m/s) and $D_{ap}/D_{cav} < 0.75$. Also, the local minimum in the convective heat losses at moderate wind speeds is not observed for

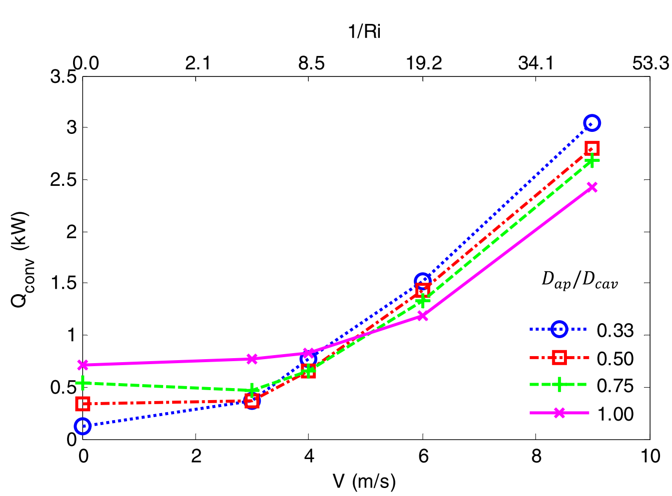


**Fig. 3.** Dependence of the convective heat losses through the aperture on wind speed and inverse Richardson number for a series of aperture ratio. Conditions: wall temperature of 300 °C, tilt angle of 15°, yaw angle of 0° and aspect ratio of 1.5.

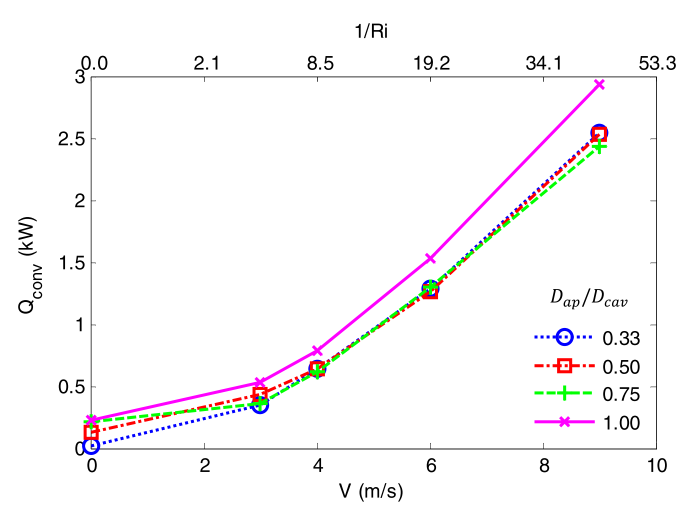


**Fig. 4.** Dependence of the convective heat losses through the aperture on wind speed and inverse Richardson number for a series of aperture ratio. Conditions: wall temperature of 300 °C, tilt angle of 30°, yaw angle of 0° and aspect ratio of 1.5.

this orientation. Instead, the slope is weaker, but still positive, throughout the low wind-speed regime.

Fig. 5 presents the effects of the aperture ratio and wind speed on the convective heat losses for the 2 values of the tilt angle. 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 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 the highest value of wind speed ($V = 9$ m/s). For $1/Ri = 8.5$ ($V = 4$ m/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 $1/Ri = 43$ ($V = 9$ m/s), the convective heat loss decreases with the aperture ratio for both tilt angles, except the case $V = 9$ m/s, $\varphi = 30°$ and $D_{ap}/D_{cav} = 1$.

### 3.2. Relative convective heat loss

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 Fig. 6 for various values of $D_{ap}/D_{cav}$. It can be seen that the difference between the forced convection and natural convection case increases as V departs from unity. 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 significant for $D_{ap}/D_{cav} = 0.33$. It is worth noting from Fig. 3 that for this case, the absolute increase in $Q_v$ is only about 30% at the high wind speed, while it features the smallest value of the convective heat loss for $V = 0$ m/s. That is, the use of a small aperture greatly reduces the natural convective losses in comparison with a larger aperture, but also slightly increases the forced convective losses at high wind speed.

The dependence of the relative convective heat losses through the aperture $Q_{R_{ap}}/Q_{R_{ap=1}}$ on $D_{ap}/D_{cav}$ is presented in Fig. 7 for various values of wind speed. It can be seen that the trend is opposite for high and low values of $1/Ri$. For $1/Ri > 19$ ($V > 6$ m/s), the relative convective heat loss increases by about 25% as $D_{ap}/D_{cav}$ is decreased from 1 to 0.33. For $1/Ri < 4.8$ ($V < 3$ m/s), the convective losses decrease strongly with a decrease in $D_{ap}/D_{cav}$. This is the regime in which natural convection is dominant so that a small aperture inhibits the escape of hot air through the aperture. The case for $1/Ri = 8.5$ ($V = 4$ m/s), shows that the transition between these two regimes is complex, with $Q_{R_{ap}}/Q_{R_{ap=1}}$ first

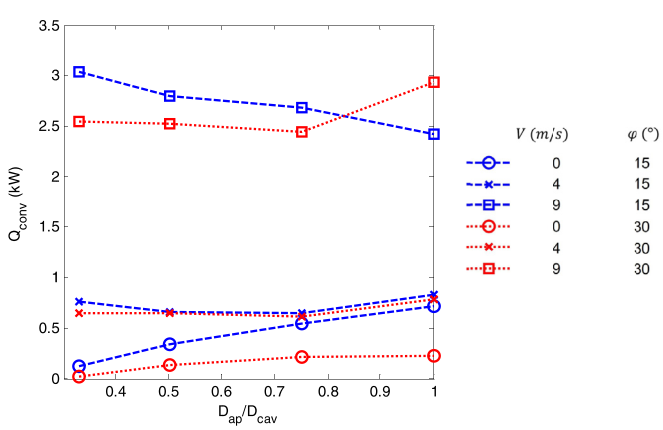


**Fig. 5.** Dependence of the convective heat losses through the aperture on tilt angle, wind speed and inverse Richardson number for a series of aperture ratio. Conditions: wall temperature of 300 °C, yaw angle of 0° and aspect ratio of 1.5.

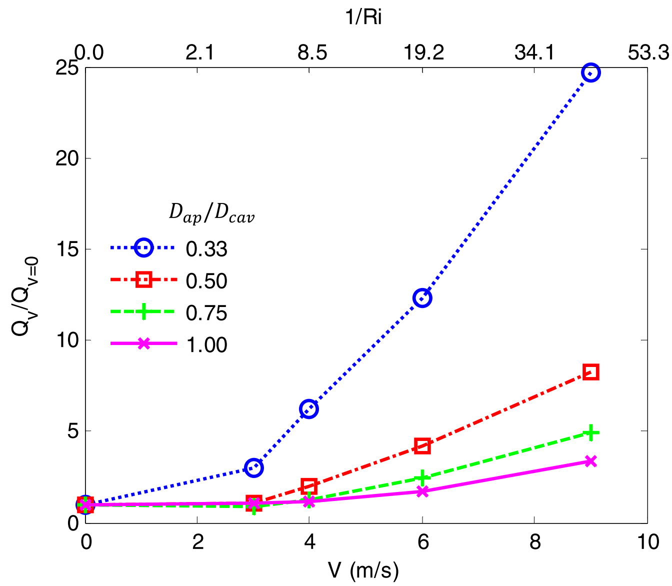


**Fig. 6.** Dependence of the relative convective heat losses through the aperture with wind speed for various values of aperture ratio. Conditions: wall temperature of 300 °C, tilt angle of 15°, yaw angle of 0° and aspect ratio of 1.5. The relative convective heat loss $Q_V/Q_{V=0}$ is the ratio between the convective heat loss for a given wind speed and no wind condition.

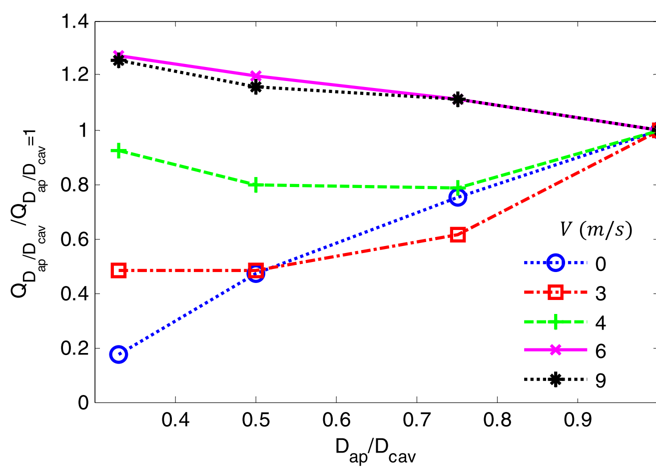


**Fig. 7.** Dependence of the relative convective heat losses through the aperture with aperture ratio for various values of wind speeds. Conditions: wall temperature of 300 °C, tilt angle of 15°, yaw angle of 0° and aspect ratio of 1.5. The relative convective heat loss $\mathbf{Q}_{D_{ap}/D_{cav}}/\mathbf{Q}_{D_{ap}/D_{cav}=1}$ is the ratio between the convective heat loss for a given $\boldsymbol{D_{ap}/D_{cav}}$ and $\boldsymbol{D_{ap}/D_{cav}} = 1$.

decreasing by 20% and then increasing back to near unity with a decrease in $D_{ap}/D_{cav}$.

The experiment has been compared with data from our previous works [10,11]. Also, the comparison of the influence of tilt angle has been published in many other works [21,23,28]. Therefore, the present work is focus on other parameters. A comparison of the effect of the aperture ratio is presented in Fig. 8. The results from the present study match with those from a previous numerical study for a large aperture ratio ($D_{ap}/D_{cav} > 0.75$). For $\varphi = 30°$, the results from both studies also agree with each other well. However, for $\varphi = 15°$ and $D_{ap}/D_{cav} < 0.75$, the relative heat loss of the previous numerical study is ~10% lower than the experiment. Overall, a good agreement was found.

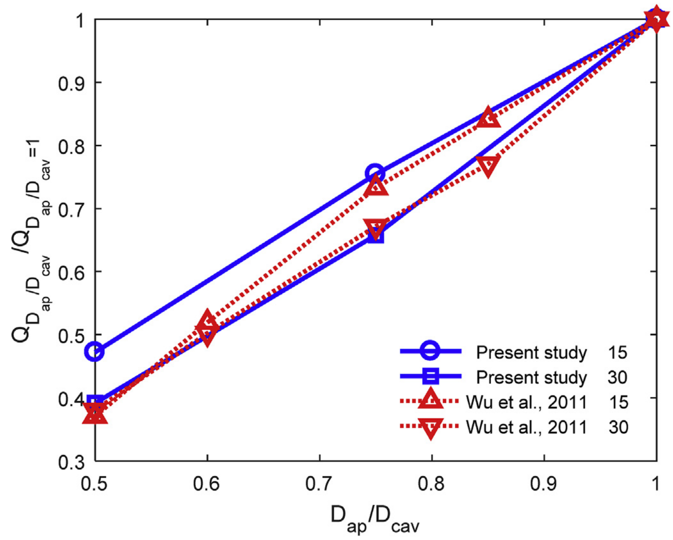


**Fig. 8.** Comparison of the relative convective heat losses through the aperture with aperture ratio for various values of wind speeds. Conditions: wall temperature of 300 °C, tilt angle of 15 & 30°, yaw angle of 0°and aspect ratio of 1.5. The relative convective heat loss $\boldsymbol{Q_{D_{ap}/D_{cav}}}$ $/\boldsymbol{Q_{D_{ap}/D_{cav}=1}}$ is the ratio between the convective heat loss for a given $\boldsymbol{D_{ap}/D_{cav}}$ and $\boldsymbol{D_{ap}/D_{cav}} = 1$.

### 3.3. Heat losses distribution

#### 3.3.1. Effect of wind speed and aperture ratio

The distribution of the total heat loss from the various surface heated elements in the cavity is presented as a function of aperture ratios for three values of wind speed in Fig. 9, and the value is shown in Table 2.

For the no wind condition, increasing $D_{ap}/D_{cav}$ from 0.33 to 0.5, increases the heat losses preferentially from the lower elements (~85% of the total incensement), especially from the lower rear section where they are increased by more than 100%, although the total heat loss is only increased by approximately 40%. In contrast, increasing $D_{ap}/D_{cav}$ from 0.5 to 1.0 causes the average heat losses to increase by approximately 90% for the upper elements, while average increment of heat loss from the lower elements increases by only are approximately 35%.

For $1/Ri < 4.8$ ($V < 3$ m/s), the heat loss from each heater element is similar as $D_{ap}/D_{cav}$ is increased from 0.33 to 0.5. As $D_{ap}/D_{cav}$ is increased from 0.5 to 1.0, the factional heat loss from the lower elements decreases from 68 to 56%, while that from the upper elements increases from 23 to 31%. It is also worth noting that the heat losses from the lower elements are always more than 50% of the total losses.

For $1/Ri < 43$ ($V < 9$ m/s), the heat losses from the lower elements are less than 50% of the total losses, which is different from the low wind speed cases. In addition, the heat loss from each heater element is similar for $D_{ap}/D_{cav}$ between 0.33 and 1.0. This is because the losses are forced-convection dominated.

The fractional distribution of heat loss from various section of the heated cavity for various wind speeds and aperture ratios is shown in Fig. 10. For the zero and low wind speed conditions ($V <$ 3 m/s, $1/Ri < 4.8$), about 60% of the total heat losses are lost from the lower section of the heated cavity for all the aperture ratios tested here. And about 43% of the heat losses are from the lower front section of the heated cavity for $D_{ap}/D_{cav} = 0.33$ and 0.5, but only about 36% are from the $D_{ap}/D_{cav} = 0.75$. This is because increasing in aperture ratio reduce the size of the stagnant zone region, resulting in more heat loss from the upper section.

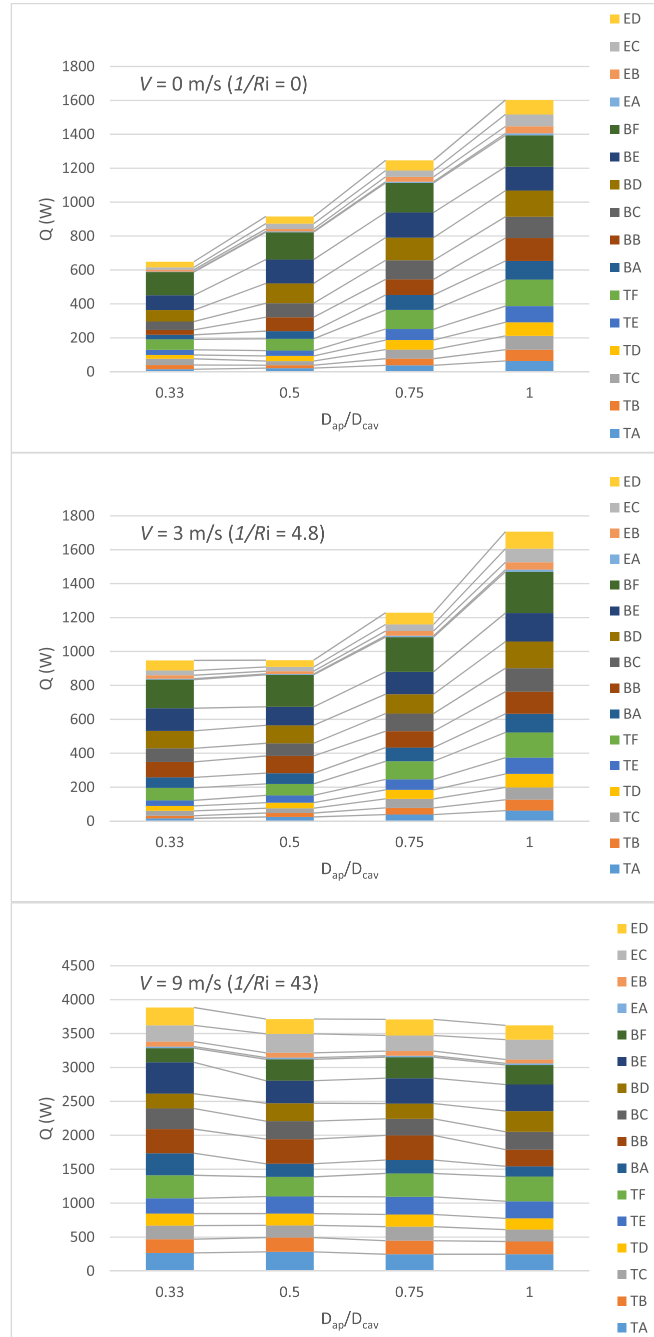


**Fig. 9.** Distribution of the total heat loss from each heater element in the cavity surface as a function of aperture ratio for various wind speeds. Conditions: temperature = 300 °C, yaw = 0°, tilt = 15° and aspect ratio = 1.5.

The heat lost from the lower section of the cavity is about 47% of the total heat losses for all the tested aperture ratios and $V = 9$ m/s ($1/Ri = 43$). Although the fractional distribution of heat loss is much more uniform for the high wind speed conditions, for the low wind speed cases, the fraction of heat losses from the upper section increases with the aperture ratio. That is although the wind speed has a strong influence on the fractional distribution of the heat loss for low aperture ratios (0.33 and 0.5), its effect is weakened by increasing $D_{ap}/D_{cav}$.

**Table 1**
List of experimental conditions.

| Velocity ($V$, m/s) | Yaw angle ($\alpha^\circ$) | Tilt angle ($\varphi^\circ$) | Temperature of the wall ($T_w$, $^\circ C$) | Aspect ratio ($\frac{L_{cav}}{D_{cav}}$) | Aperture ratio ($\frac{D_{ap}}{D_{cav}}$) |
|---|---|---|---|---|---|
| 0, 3, 4, 6 and 9 | 0 | 15, 30 and 45 | 300 | 1.5 | 0.00, 0.33, 0.50, 0.75, 1.00 |

**Table 2**
List of heat loss from each heating element in the cavity surface for various wind speeds and aperture ratio. Conditions: temperature = 300 °C, yaw = 0°, tilt = 15° and aspect ratio = 1.5.

| Heat losses (W) | | | | |
|---|---|---|---|---|
| Heater code | Wind speed (m/s) | | | |
| | 0 | | | |
| | Aperture ratio | | | |
| | 0.3 | 0.5 | 0.8 | 1.0 |
| TA | 14.7 | 20.9 | 37.6 | 63.8 |
| TB | 25.2 | 17.9 | 39.3 | 66.2 |
| TC | 36.6 | 23.9 | 53.8 | 81.1 |
| TD | 22.7 | 30.5 | 56.1 | 80.7 |
| TE | 30.0 | 31.3 | 64.8 | 95.5 |
| TF | 61.6 | 69.6 | 112.9 | 156.1 |
| BA | 27.1 | 45.5 | 88.0 | 109.4 |
| BB | 28.9 | 81.7 | 92.4 | 135.7 |
| BC | 49.0 | 83.0 | 111.9 | 125.2 |
| BD | 67.7 | 116.8 | 133.7 | 154.0 |
| BE | 87.3 | 140.6 | 148.4 | 139.9 |
| BF | 136.6 | 161.1 | 174.5 | 186.2 |
| EA | 3.0 | 4.5 | 7.1 | 11.2 |
| EB | 10.6 | 14.1 | 28.8 | 41.7 |
| EC | 15.1 | 31.3 | 37.4 | 70.2 |
| ED | 32.4 | 42.8 | 60.1 | 85.5 |
| Total | 648.6 | 915.4 | 1246.7 | 1602.6 |
| Heater code | Wind speed (m/s) | | | |
| | 3 | | | |
| | Aperture ratio | | | |
| | 0.3 | 0.5 | 0.8 | 1.0 |
| TA | 16.1 | 24.5 | 38.5 | 61.8 |
| TB | 15.3 | 22.8 | 39.0 | 64.3 |
| TC | 29.3 | 28.6 | 53.2 | 72.4 |
| TD | 28.9 | 33.0 | 53.7 | 79.2 |
| TE | 32.2 | 42.6 | 61.4 | 95.8 |
| TF | 74.1 | 67.9 | 106.7 | 149.3 |
| BA | 61.8 | 63.2 | 81.1 | 109.6 |
| BB | 91.2 | 101.9 | 96.3 | 130.7 |
| BC | 80.0 | 74.0 | 104.1 | 138.4 |
| BD | 103.1 | 106.3 | 114.5 | 157.1 |
| BE | 133.7 | 108.9 | 131.6 | 168.1 |
| BF | 168.2 | 188.8 | 205.1 | 243.6 |
| EA | 5.5 | 5.3 | 7.6 | 12.0 |
| EB | 20.6 | 16.5 | 28.0 | 43.4 |
| EC | 27.8 | 24.6 | 38.9 | 80.7 |
| ED | 59.6 | 39.8 | 69.3 | 100.0 |
| Total | 947.4 | 948.4 | 1228.9 | 1706.5 |
| Heater code | Wind speed (m/s) | | | |
| | 9 | | | |
| | Aperture ratio | | | |
| | 0.3 | 0.5 | 0.8 | 1.0 |
| TA | 266.4 | 282.0 | 247.8 | 247.6 |
| TB | 201.7 | 210.8 | 199.2 | 187.6 |
| TC | 200.7 | 180.2 | 206.5 | 175.6 |
| TD | 177.3 | 173.9 | 180.3 | 165.0 |
| TE | 224.7 | 251.5 | 259.9 | 252.5 |
| TF | 339.7 | 289.6 | 344.9 | 363.5 |
| BA | 325.0 | 193.3 | 197.9 | 151.9 |
| BB | 356.0 | 363.0 | 363.3 | 244.8 |
| BC | 304.1 | 265.1 | 244.0 | 264.2 |
| BD | 217.5 | 263.5 | 224.8 | 304.8 |
| BE | 463.0 | 332.6 | 374.1 | 391.2 |
| BF | 208.8 | 315.7 | 308.9 | 287.8 |
| EA | 22.6 | 24.5 | 21.3 | 23.9 |
| EB | 74.2 | 70.0 | 68.4 | 55.7 |
| EC | 239.6 | 280.0 | 230.6 | 294.3 |
| ED | 263.0 | 218.0 | 237.3 | 210.2 |
| Total | 3884.5 | 3713.8 | 3709.2 | 3620.5 |

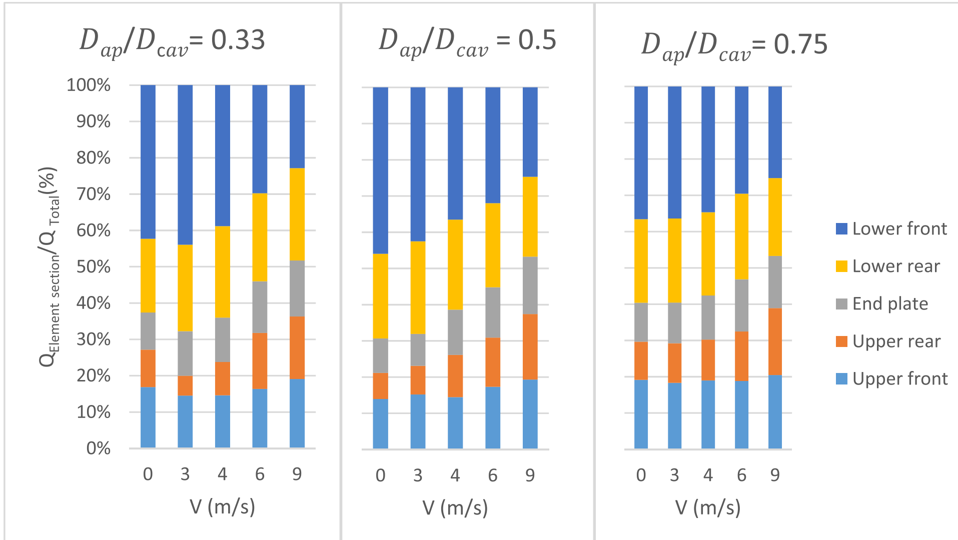


**Fig. 10.** Fractional distribution of the total heat loss from each heater element section in the cavity surface cavity surface plotted as a function of wind speeds for various aperture ratio. Conditions: temperature = 300 °C, yaw = 0°, tilt = 15° and aspect ratio = 1.5.

*3.3.2. Effect of wind speed and tilt angle*

The absolute distribution of heat loss from each section of the heated cavity is shown in Fig. 11 for various wind speeds and tilt angles. For a given value of wind speed, the total heat loss decreases with an increase in the tilt angle for almost all the cases investigated. However, there exists some combinations of wind speed and tilt angle for which the heat losses increase with the tilt angle. For the zero and low wind speed conditions, the percentage of heat loss from the front sections of the heated cavity is increased with the tilt angle. This is because an increase in the tilt angle causes an increase in the size of the stagnant zone near to the back of the cavity. This, in turn, decreases the natural convective heat losses from the rear sections. Hence, although the absolute heat losses from the front sections are similar, the fractional heat losses from the front sections increase with the tilt angle. For the highest wind speed ($V = 9m/s 1/Ri > 43$), the effect of tilt angle on the heat loss distribution of various sections of the heated cavity is minimal with a change of <1.5% for any given rear section and <3.3% for any given front sections.

Fig. 12 presents the heat loss at a given tilt angle normalised by that at 15° with the same wind speed. 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, $Q_{\varphi}/Q_{\varphi=15^{\circ}}$ exhibits a maximum for wind speed $1/Ri = 8$ to 19 ($V = 4$–6 m/s). The normalised heat loss for the 30° case is always below that for 100% 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° does not have much positive effect on the overall heat loss, and this is also compounded in practice with reasonable tower height.

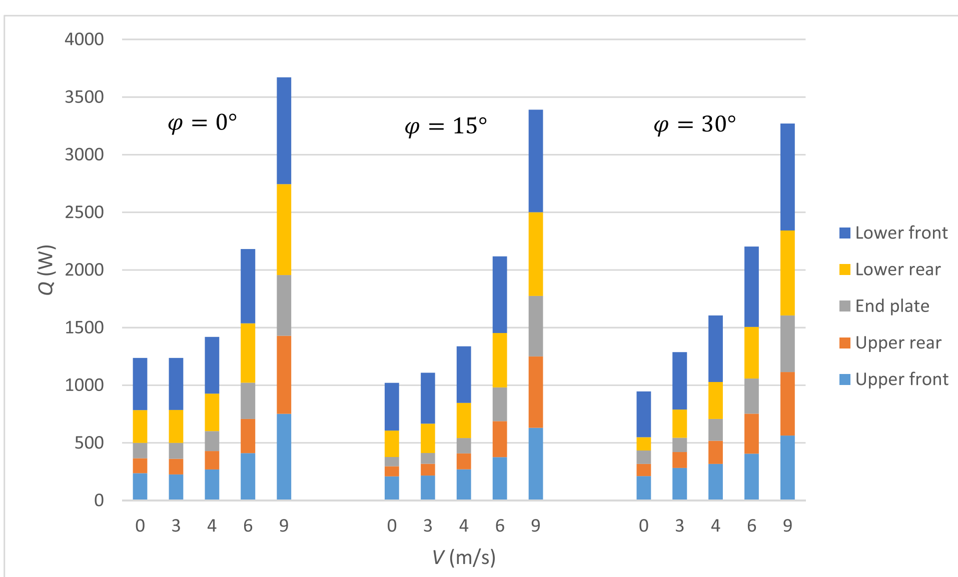


**Fig. 11.** Distribution of the total heat loss from the various sections of the heated cavity plotted as a function of wind speed for three value of tilt angle. Conditions: temperature = 300 °C, yaw = 0°, aperture ratio = 0.75 and aspect ratio = 1.5.

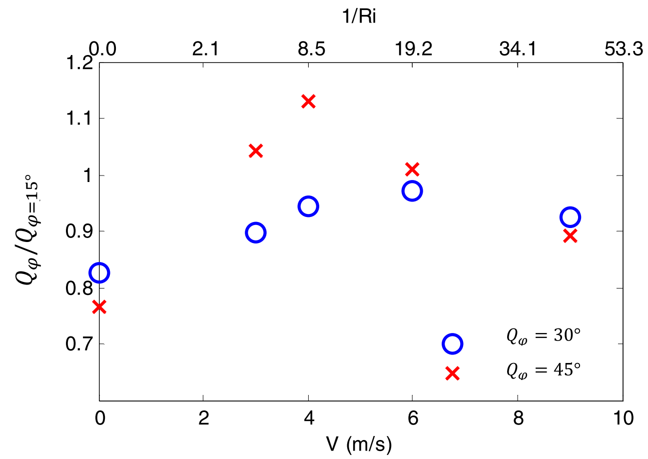


**Fig. 12.** Normalised heat loss from the various sections of the heated cavity plotted for various wind speeds and tilt angle. Conditions: temperature = 300 °C, yaw = 0°, aperture ratio = 0.75 and aspect ratio = 1.5.

## 4. Conclusions

In summary, the dependence of convective heat loss on wind speed, tilt angle and the aperture ratio is complex and coupled, despite a general trend of increasing heat loss with wind speed as expected. 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.

For $1/Ri > 8.5$ ($V > 4$ m/s), the total heat losses are independent of $D_{ap}/D_{cav}$ for a given value of $1/Ri$ to within 10%. On the other hand, for $1/Ri < 4.8$ ($V < 3$ m/s) the total heat loss can vary by up to about 75% by increasing the aperture ratio from 0.33 to 0.75.

For $1/Ri < 4.8$ ($V < 3$ m/s), about 60% of the total heat is lost from the lower section of the heated cavity for the 3 tested aperture ratios. Furthermore, approximately 43% of the heat is lost from the lower front section of the heated cavity for values of the aperture ratio of 0.33 and 0.5, while this only approximately 36% for the case with aperture ratio = 0.75. This difference is attributed to the decreased size of the stagnant zone at the rear of the cavity. Similarly, the increased uniformity in heat losses with an increase in wind speed is attributed to a decreased significance of the stagnant zone. The same is true for the increased fraction of heat losses from the upper section with an increase in $D_{ap}/D_{cav}$.

The effect of the tilt angle on the total heat loss from the system was found to be relatively small. For $\varphi = 30°$, the heat loss increases from 0 m/s to a local maximum at $1/Ri \approx 19$ ($V \approx 6$ 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 indicates that it is beneficial in terms of heat loss to maintain the tilt angle of a solar cavity below 30°.

Overall, for a downward tilted solar tower cavity receiver system, the configuration with a tilt angle of ~30° has the minimum average of mixed convective heat loss for the various wind speeds. 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. Also, 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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## References

[1] G.J. Kolb, C.K. Ho, T.R. Mancini, J.A. Gary, Power Tower Technology Roadmap and Cost Reduction Plan, Technical Report No. SAND2011-2419, Sandia National Laboratories, Livermore, CA, 2011.
[2] C. Philibert, Technology Roadmap: Concentrating Solar Power, OECD/IEA, 2010.
[3] N. Tanaka, Technology Road Map, Concentrating Solar Power, International Energy Agency, 2010.
[4] A.L. Ávila-Marín, Volumetric receivers in solar thermal power plants with central receiver system technology: a review, Sol. Energy 85 (5) (2011) 891–910.
[5] IEA-ETSAP, IRENA, Concentrating Solar Power Technology Brief, 2013.
[6] K. Lovegrove, M. Watt, R. Passey, G. Pollock, J. Wyder, J. Dowse, Realising the Potential of Concentrating Solar Power in Australia: Summary for Stakeholders, Australian Solar Institute Pty, Limited, 2012.
[7] H. Price, Assessment of Parabolic Trough and Power Tower Solar Technology Cost and Performance Forecasts, Sargent & Lundy LLC Consulting Group, National Renewable Energy Laboratory, Golden, Colorado, 2003.
[8] A. Segal, M. Epstein, Optimized working temperatures of a solar central receiver, Sol. Energy 75 (6) (2003) 503–510.
[9] A. Steinfeld, M. Schubnell, Optimum aperture size and operating temperature of a solar cavity-receiver, Sol. Energy 50 (1) (1993) 19–25.
[10] K.L. Lee, A. Chinnici, M. Jafarian, M. Arjomandi, B. Dally, G. Nathan, Experimental investigation of the effects of wind speed and yaw angle on heat losses from a heated cavity, Sol. Energy 165 (2018) 178–188.
[11] K.L. Lee, A. Chinnici, M. Jafarian, M. Arjomandi, B. Dally, G. Nathan, The Influence of Wall Temperature Distribution on the Mixed Convective Losses from a Heated Cavity, Applied thermal engineering, 2019.
[12] R.Y. Ma, Wind Effects on Convective Heat Loss from a Cavity Receiver for a Parabolic Concentrating Solar Collector, Sandia National Laboratories, 1993.
[13] R. Flesch, H. Stadler, R. Uhlig, R. Pitz-Paal, Numerical analysis of the influence of inclination angle and wind on the heat losses of cavity receivers for solar thermal power towers, Sol. Energy 110 (2014) 427–437.
[14] A. Clausing, L. Lister, J. Waldvogel, Combined convection from isothermal cubical cavities with a variety of side-facing apertures, Int. J. Heat Mass Transf. 32 (8) (1989) 1561–1566.
[15] A. Clausing, J. Waldvogel, L. Lister, Natural convection from isothermal cubical cavities with a variety of side-facing apertures, J. Heat Transf. 109 (2) (1987) 407–412.
[16] J.K. Kim, H.K. Yoon, Y.H. Kang, Experimental study on heat loss from cavity receiver for solar power tower, in: Proceedings of ISES World Congress 2007, Vol. I–V, Springer, 2009, pp. 1719–1723.
[17] S.-Y. Wu, L. Xiao, Y. Cao, Y.-R. Li, Convection heat loss from cavity receiver in parabolic dish solar thermal power system: a review, Sol. Energy 84 (8) (2010) 1342–1355.
[18] S.-Y. Wu, L. Xiao, Y.-R. Li, Effect of aperture position and size on natural convection heat loss of a solar heat-pipe receiver, Appl. Therm. Eng. 31 (14) (2011) 2787–2796.
[19] S. Siegrist, H. Stadler, B. Hoffschmidt, Wind tunnel measurements of forced convective heat loss from multi-megawatt cavities of solar central receiver systems, Sol. Energy 169 (2018) 607–615.
[20] T. Hu, P. Jia, Y. Wang, Y. Hao, Numerical simulation on convective thermal loss of a cavity receiver in a solar tower power plant, Sol. Energy 150 (2017) 202–211.
[21] K.L. Lee, M. Jafarian, F. Ghanadi, M. Arjomandi, G.J. Nathan, An investigation into the effect of aspect ratio on the heat loss from a solar cavity receiver, Sol. Energy 149 (2017) 20–31.
[22] S. Paitoonsurikarn, T. Taumoefolau, K. Lovegrove, Estimation of convection loss from paraboloidal dish cavity receivers, in: Proceedings of 42nd Conference of the Australia and New Zealand Solar Energy Society, ANZSES, Perth, Australia, 2004.
[23] T. Taumoefolau, S. Paitoonsurikarn, G. Hughes, K. Lovegrove, Experimental investigation of natural convection heat loss from a model solar concentrator cavity receiver, J. Sol. Energy Eng. 126 (2) (2004) 801–807.
[24] L. Xiao, S.-Y. Wu, Y.-R. Li, Numerical study on combined free-forced

convection heat loss of solar cavity receiver under wind environments, Int. J. Therm. Sci. 60 (2012) 182–194.

[25] R. Flesch, H. Stadler, R. Uhlig, B. Hoffschmidt, On the influence of wind on cavity receivers for solar power towers: an experimental analysis, Appl. Therm. Eng. 87 (2015) 724–735.

[26] M. Prakash, S. Kedare, J. Nayak, Investigations on heat losses from a solar cavity receiver, Sol. Energy 83 (2) (2009) 157–170.

[27] S.-Y. Wu, Z.-G. Shen, L. Xiao, D.-L. Li, Experimental study on combined convective heat loss of a fully open cylindrical cavity under wind conditions, Int. J. Heat Mass Transf. 83 (2015) 509–521.

[28] S. Paitoonsurikarn, K. Lovegrove, Numerical investigation of natural convection loss in cavity-type solar receivers, in: Proceedings of Solar, 2002.

[29] A. Clausing, An analysis of convective losses from cavity solar central receivers, Sol. Energy 27 (4) (1981) 295–300.

[30] A. Clausing, Convective losses from cavity solar receivers—comparisons between analytical predictions and experimental results, J. Sol. Energy Eng. 105 (1) (1983) 29–33.