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The influence of wall temperature distribution on the mixed convective losses from a heated cavity

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Abstract

An experimental investigation is presented of the effects of wind speed (0 - 9 m/s), yaw angle (0° and 90°), and tilt angle (15° and -90°) on the mixed convective heat losses from a cylindrical cavity heated with different internal wall temperature distributions. The internal wall comprised 16 individually controlled heating elements to allow the distribution of the surface temperature to be well controlled, while the air flow was controlled with a wind tunnel. It is found that temperature distribution has a strong influence on the convective heat losses, with a joint dependence on the wind speed and its direction. For the no-wind and side-on wind conditions, the measured range of the heat losses varied by up to 50% with a change in the wall temperature distribution. However, for high head-on wind speeds, this variation reduced down to ~20%. In addition, the heat losses from downward tilted were ~3 times larger than the upward facing heated cavity for high wind speeds (typical of tower-mounted and beam-down configurations, respectively). Also, the measured heat losses were found to be only slightly dependent on wind speed and direction in contrast with the downward tilted cases.

Keywords

Solar Cavity Receiver; Wind; Concentrated Solar Thermal; Convective Heat Loss

Nomenclature

Symbols			
A	Area (m^2)	V	Wind speed (m/s)
β	Coefficient of thermal expansion (°C^{-1})	v	Kinematic viscosity of air at reference temperature kg/(s.m)
D	Diameter (m)	α	Yaw angle or incoming wind direction (°)
ε	Emissivity coefficient of the internal wall surface	φ	Tilt angle of the cavity (°)
g	Gravity (m/s^2)		
Gr	Grashof number = $\frac{g\beta(T_{wall}-T_a)D_{cav}^3}{v^2}$	**Subscript**	
h_c	Convective heat transfer coefficient through the aperture (W/(m^2K))	a	Ambient
k	Thermal conductivity of air at reference temperature (W/(m. K))	as	Aspect
L	Length (m)	ap	Aperture
Nu	Nusselt number = $\frac{h_c\, D_{cav}}{k_{ref}}$	cav	Cavity
Q	Heat loss (W)	conv	Convection
R	Ratio	rad	Radiation
Re	Reynolds number = $\frac{VD_{cav}}{v}$	ref	Reference
Ri	Richardson number = $\frac{Gr}{Re^2}=\frac{g\beta(T_{wall}-T_a)D_{cav}}{V^2}$	tot	total
T	Temperature (°C)	w	Wall

1 Introduction

Despite the development of Concentrated Solar Thermal technologies has progressed, the understanding of the influence of wall temperature distribution and wind speed on the heat losses from a heated cavity remains limited. 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 (ASTRI 2017; Chinnici, A et al. 2016; Chinnici, Alfonso et al. 2015; Chinnici, A, Nathan & Dally 2018a, 2018b; Kolb et al. 2011; Philibert 2010; Tanaka 2010). 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. Pre-commercial solar cavity receivers have been operated at temperatures on the order of 1000 °C during short-term trials, which offers potential to achieve higher thermal efficiency than is presently possible (Ávila-Marín, 2011; IEA-ETSAP and IRENA, 2013; Lovegrove et al., 2012; Price, 2003; Segal and Epstein, 2003; Steinfeld and Schubnell, 1993). However, these temperatures result in a significant increase in the heat losses (radiative and convective) from the receiver relative to commercial systems. However, while it is desirable to identify ways to decrease these losses, this is difficult to do because the underlying mechanisms controlling them are still not well understood, especially it has been difficult to generalize the findings of mix convection. Therefore, further research is required to deepen the understanding of the mechanisms influencing heat losses in solar receivers and, in particular, in solar cavity receivers. More specifically, new measurements are needed of the influence of the controlling parameters of receiver geometry (cavity aspect ratio, aperture ratio), wind speed and direction (yaw angle), cavity orientation (tilt angle), operating temperature, and wall temperature distribution. The overall objective is to meet this need.

A detailed review of previous experimental and numerical studies of the influence of these parameters on the heat losses from solar cavity receivers was reported by Ho and Iverson (2014) and Wu et al. (2010). The updated review, the relation to the present and the comparison between the experimental method use in different studies have been presented in the earlier study from our group by Lee et al. (2018a), hence only some important reviews are highlighted in the present study. The studies by Ho and Iverson (2014), Wu et al. (2010) and Lee et al. (2018a) highlighted the role of wind speed and its direction and their strong influence on the mixed, natural and forced convective heat losses from a cavity receiver (Mokhtar, Marwan et al. 2014); (Clausing 1983; Flesch et al. 2015; Ho & Iverson 2014; Lee et al. 2018a; Ma 1993; Taumoefolau et al. 2004; Wu et al. 2015). They also highlighted the strong coupling between the heat losses and the geometrical features of the receiver, namely aperture and aspect ratios (Ho & Iverson 2014; Lee et al. 2018b; Wu et al. 2010). In our previous work (Lee et al. 2018a, 2018b), we have systematically assessed the influence of wind speed, yaw angle, aperture ratio, tilt angle and cavity temperature on the convective heat losses from a heated cavity facing downward, for the case of a uniform temperature distribution over the surface of the cavity. These recent data provide further insights into the complex heat loss phenomenon from cavity receivers while also confirming trends from earlier works. However, the majority of presently available data, under well-defined conditions, only consider solar cavity receivers with a uniform wall temperature distribution. Although this approach simplifies the validation of engineering models, in reality, solar receivers are generally characterised by a varied heat flux along the walls of the cavity at different times of the day. Therefore, there is a need to better understand the influence of wall temperature distribution on the heat losses for a range of conditions of relevance to operation. Hence, the overall objective of the present investigation is to assess the effects of the joint dependencies between temperature distribution and wind speed on the heat losses through the aperture of a heated cavity receiver.

Understanding of the convective heat losses from cavity receivers has been advanced by the numerical studies, some of which have investigated the influence of the temperature distribution (uniform and non-uniform) on the radiation heat losses (Asselineau, Abbassi & Pye 2014; Gil et al. 2015; Sánchez-González, Rodríguez-Sánchez & Santana 2016; Steinfeld & Schubnell 1993). However, the absolute validity of these assessments is not yet known because no data has previously been available with which to validate them (Flesch et al. 2014; Hu et al. 2017; Lee et al. 2017; Paitoonsurikarn & Lovegrove 2003; Paitoonsurikarn, S & Lovegrove 2002; Paitoonsurikarn, Sawat et al. 2011; Wu, Xiao & Li 2011; Xiao, Wu & Li 2012). Furthermore, most previous numerical analyses on convective heat losses have been performed for a uniform wall temperature distribution, probably largely due to a lack of experimental data for model validation (Ho & Iverson 2014; Stalin Maria Jebamalai 2016). Therefore, the present investigation also aims to provide an experimental dataset of convective heat losses from a cavity receiver with uniform and non-uniform temperature distribution, under controlled conditions, to advance the development of the numerical tools needed for optimisation and scale-up.

Advancing understanding requires spanning a range of conditions, including orientation due to the dependence of natural convection on orientation. In addition, despite its lower popularity relative to the tower-mounted receiver due to disadvantages of an extra surface and anticipated higher cost (Kolb et al. 2011; Li, Dai & Wang 2015), the beam-down cavity solar receivers have continued to receive interest due to some (at least partly) compensating advantages. These include a lower wind speed and higher functionality (Leonardi 2012; Mokhtar, M 2011; Segal & Epstein 2008; Wei et al. 2013). Recent studies, utilising new solar field design have also reported good performance for beam-down applications (Li, Dai & Wang 2015; Mokhtar, Marwan et al. 2014). One of the perceived disadvantages of the beam-down configuration is the perceived high natural convective heat loss due to buoyancy (Holman 1997). On the other hand, a beam-up configuration offers the advantages of a beam down without the disadvantages of the secondary reflector, but at the additional cost of a taller tower. Hence all are worthy of further consideration. However, no experimental measurements are available that directly compare the convective heat losses from an upward facing heated cavity a downward facing cavity or a downward tilted heated cavity. For these reasons, we also aim to compare the effect of wind on the heat losses from a downward tilted and an upward facing receiver.

In light of the aforementioned gaps, the key aim of the present investigation is to provide direct measurements of the influence of temperature distribution, tilt angle and wind speed on the mixed convective heat losses from a solar cavity receiver. In particular, the research aims to investigate; i) the effects of the temperature distribution on the convective heat losses as a function of wind speed and direction; ii) the convective heat losses for an upward facing cavity and a downward tilted one (15°) and its effect on the cavity's thermal performance. This investigation is the first experimental study for the effect of temperature distribution on the convective heat losses from a heated cavity. In this study, the effects of wind speed and cavity direction on the heat losses are also presented for various temperature distribution. This is also the first experimental study to investigate and compare the heat losses from the cavity receivers between 2 concentred solar technologies. The first experimental data for the convective heat losses from a solar cavity receiver with various temperature distribution can be used for numerical model validation, which simulate a cavity receiver heated by various solar flux distribution. This is much more realise realistic than a cavity which assume uniform temperature for the entire internal surface. The validated numerical model can be used to develop a new solar cavity design for the concentrated solar system. The general finding about heat loss from heated cavity from this work can also be applied to other engineering applications.

2 Methodology

The details of the experimental arrangement used in the study have been published previously by Lee et al. (2018a) so that only a brief overview is shown here. The experimental arrangement has also been reported previously so that it reproduced in the supplement here (Figure S1). A cavity was electrically heated and located within the open section of the University of Adelaide's wind tunnel to generate negligible blockage. The external dimensions of the cavity have a maximum projected area (~0.249 m^2) of ~4.1% of the wind tunnel, which has a cross-sectional dimension of area 2.75 m × 2.19 m. This is approximately 330 times larger than the projected area of the aperture, which is approximately 0.018 m^2). Air was used as the working fluid and the velocity in the tunnel was measured using a multi-hole pressure probe from the Turbulent Flow Instrumentation. K-type thermocouples are used to measure the temperature and recorded by Datataker DT85. The temperatures were feedback controlled using Matlab and Simulink. The power of the heaters are controlled by the output from the Simulink to the Arduino, then a DMX lighting system power controllers. Additional details of the instrumentation used in this work can be found in one of our previous works (Lee et al. 2018). Figure S1b presents the key dimensions of the cavity, which has an inner diameter $D_{cav} = 0.3m$. The details of the method of recording the power and its errors are reported by Lee et al. (2018a).

The influence temperature distribution on the heat losses was assessed systematically. The tested conditions are shown in Table 1. This leads to a total of 112 combinations of wind speed, tilt angle, yaw angle and temperature distribution. In particular, 56 combinations for the case with the open aperture (to measure the convective and radiative heat losses), and 56 cases for the aperture closed (to measure the heat loss through the walls). The data was recorded for each heaters every time steps. However, to reduce the number of data, only the total steady state power from each condition is presented in here. The powers required for each heater to maintain the set point temperature are summed to be the total heat loss from the system for that condition. Each condition required between 20 to 60 minutes to reach a steady state condition. Here, 'steady-state condition' is intended when the following conditions are satisfied for 300 seconds: 1) the variation of each measured temperature is below ±0.5°C; and 2) the variation of total heat loss is less than ±5% of the total power required for that condition if the total heat loss is above 2kW or ±100W if the power is below 2kW. The mean total heat losses from the system at the steady state condition are used for this investigation.

Normalised heat loss for the no wind case $Q/Q_{V=0}$ was used to characterise the effect of wind on the heat loss through the aperture. This is defined as the total heat loss through the aperture relative to that for the no wind condition for various temperature distribution, as shown in Table 1 and Table 2. The total heat losses through the aperture for no wind condition is the combination of convective and radiative heat loss at zero wind speed.

Another normalised heat loss for the uniform temperature case $Q/Q_{T=uniform}$ was used to assess the effect of temperature distribution on the heat loss through the aperture. $Q/Q_{T=uniform}$ is defined as the total heat losses through the aperture over the total heat losses through the aperture for the 300°C uniform temperature case for various wind speeds. These were performed with the average temperature of the cavity was kept constant at 300°C. Notice this, the temperatures of the heated cavity in this study are lower than the real commercial receivers. However, this study focus on the temperature distribution more than the absolute temperature. Grashof number and Richardson number should also be used to generalise the result to assess the result for other temperature and receiver size. These two non-dimensional numbers are shown to work well for varying temperature (Lee et al. 2018a), but it should be carefully validated before they are applied to a case which has different conditions.

The air properties, such as thermal expansion, density and kinematic viscosity, were calculated at a reference temperature T_{ref}, which is defined as

$$T_{ref} = \frac{T_w}{2} + \frac{T_a}{2}. \tag{1}$$

Here T_w is the internal wall temperature and T_a is the ambient temperature.

The main uncertainties in the instrumentation/ uncertainty term and measured data are summarised in Table 3 (in the Supplement section), the details are reported by Lee et al. (2018a). The maximum uncertainty of the power output from each heater is ±25W (~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 ~± 400W (± 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 ($\frac{\sqrt{16\times\pm25^2}}{16\times800} \sim \pm0.8\%$). In addition, the uncertainty of the incoming wind speed is estimated to be ±0.2m/s.

Table 1: List of experimental conditions

Velocity V (m/s)	Yaw angle α (°)	Tilt angle φ (°)	Temperature of the wall T_w (°C)	Aspect ratio ($\frac{L_{cav}}{D_{cav}}$)	Aperture ratio ($\frac{D_{ap}}{D_{cav}}$)
0,3,6 and 9	0	15	5 various distributions	1.5	0.0 and 0.5

0,3,6 and 9	90	15	4 various distributions	1.5	0.0 and 0.5
0,3,6 and 9	0	-90	3 various distributions	1.5	0.0 and 0.5
0	0	90	100, 200, 300 and 400	1.5	0.0 and 0.5
0	0	15	100, 200, 300 and 400	1.5	0.0 and 0.5
0	0	-90	100, 200, 300 and 400	1.5	0.0 and 0.5

The list of set point temperature for each heater position for various temperature distribution is given in Table 2, while the position can be found in the supplement Figure S2. The temperatures were firstly estimated analytically as a starting point, then the final set point temperatures were chosen based on trial and error in the experiment. This is because it is very complex to analytically estimate the temperature for various temperature distribution and wind conditions. In this study, the range of temperatures is designed to be as wide as possible with the limitation of keeping the maximum variation of the average temperature to be $\pm 10°C$ for the various wind conditions. Although the maximum variation of the average temperature was set at $\pm 10°C$, 90% of the cases are less than $\pm 5°C$ and 80% of the cases are less than $\pm 3°C$. The 10, 5 and 3 $°C$ of error will give a maximum of 3.7%, 1.9% and 1.1% of error in power respectively. The cases with the large temperature difference are the cases with low wind speed and the hotter position away from the aperture. This is because the heat transfer between the hot air near the back of the cavity and ambient air is very low for the low wind speed condition.

Table 2 list of setpoint temperature of each heater position for various conditions

Temperature of the internal walls (°C)		Wall position																
Temperature distribution		TA	TB	TC	TD	TE	TF	BA	BB	BC	BD	BE	BF	EA	EB	EC	ED	Average
Head-on $\alpha = 0°$ $\varphi = 15°$	Uniform	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300
	Upper hotter	340	350	360	375	390	400	260	250	240	225	210	200	300	300	300	300	300
	Lower hotter	260	250	240	225	210	200	340	350	360	375	390	400	300	300	300	300	300
	Front hotter	275	250	250	300	350	400	250	225	250	300	350	400	300	300	300	300	300
	Rear hotter	350	400	325	275	250	225	350	400	325	275	225	200	300	300	300	300	300
Side-on $\alpha = 90°$ $\varphi = 15°$	Uniform	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300
	Upper hotter	340	350	360	375	390	400	260	250	240	225	210	200	300	300	300	300	300
	Front hotter	275	250	250	300	350	400	250	225	250	300	350	400	300	300	300	300	300
	Rear hotter	350	400	325	275	250	225	350	400	325	275	225	200	300	300	300	300	300
Beam-down $\alpha = N/A$ $\varphi = -90°$	Uniform	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300
	Front /near aperture hotter	250	250	250	300	350	400	250	250	250	300	350	400	300	300	300	300	300
	Rear /near back wall hotter	325	400	325	275	250	225	325	400	325	275	250	225	300	300	300	300	300

3 Results and discussion

3.1 Head-on wind

The effect of wind speed in the head-on direction, together with that of wall temperature distribution on the convective heat losses through the aperture of a heated cavity is presented in Figure 1. For low wind speed conditions ($Ri < 4.8,\ V < 3$m/s), the cases featuring the 'lower section hotter' and 'front section hotter', have a higher convective heat loss than the other cases, including that of the uniform distribution. The higher losses of the 'lower section hotter' case, can be deduced to be associated with the added role of natural convection, that is of buoyancy. The higher loss from the 'front section hotter' case suggest that close the proximity of the hotter part of the wall to the aperture facilitates increased egress of the hot air than for the reference case. Similarly, for high wind speed condition ($Ri > 19,\ V > 6$m/s), the 'front section hotter' case has the highest measured value of the convective heat loss among all the cases investigated. On the other hand, the 'lower section hotter' case features the lowest convective heat loss for high wind speeds. This suggests that a greater fraction of the power lost from the lower section is transferred under these conditions to maintain the temperature of the upper and rear sections. Further evidence for this can be found from our previous study (Lee et al. 2017), which identified a strong flow recirculation transporting the hot air from the lower section toward the rear and the upper section before it leaves the cavity. This flow pattern reduces that heat lost from the other surfaces, and hence the power required to maintain the set point temperature of the lower temperature surface. Therefore, the qualitative trends from the CFD (Lee et al. 2017) are consistent with the measured trend that the 'lower section hotter' case has the lowest convective heat loss behaviour of the cases assessed here for high wind speed condition.

The dependence of the convective heat losses, normalised by the case for no wind on wind speed is presented in Figure 2 for the same conditions as those reported in Figure 1. It can be seen that varying the wall temperature distribution causes up to 50% change in the total natural convection. The 'upper section hotter' case has the lowest convective heat loss where natural convection dominates. For $V > 3$ m/s, the heat transfer moves to the mixed convection regime which greatly reduces this range to < 20%. Consistent with this trend, the 'lower section hotter' case has the highest loss for the lower wind speed case and lowest loss for high wind speed. However, the 'upper section hotter' case has the lowest average convective heat loss in the range of wind speeds investigated. For the cases with $V > 6$ m/s the heat loss plateaus and tends to become independent of the temperature distribution, which also implies that it tends toward that of the uniform temperature distribution case. That is, the shape of the temperature distribution becomes relatively unimportant in the inertia-dominated regime.

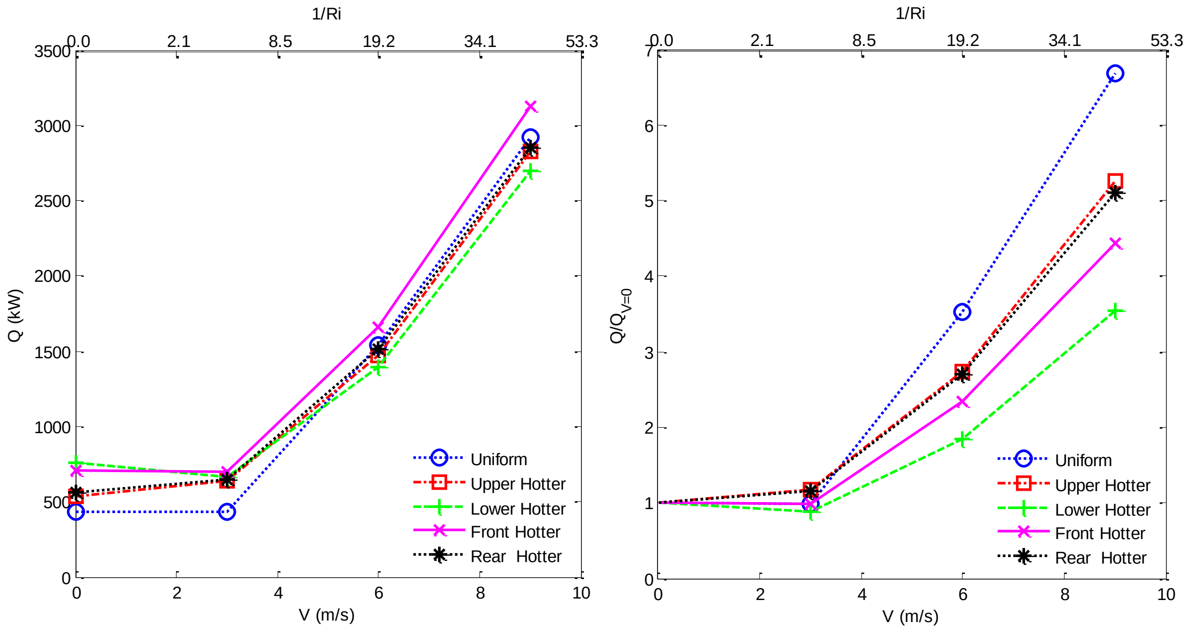

Figure 1 Dependence of the heat losses through the aperture on wind speed for a series of wall temperature distributions. Conditions: tilt angle of 15°, yaw angle of 0°, aperture ratio of 0.5 and aspect ratio of 1.5.

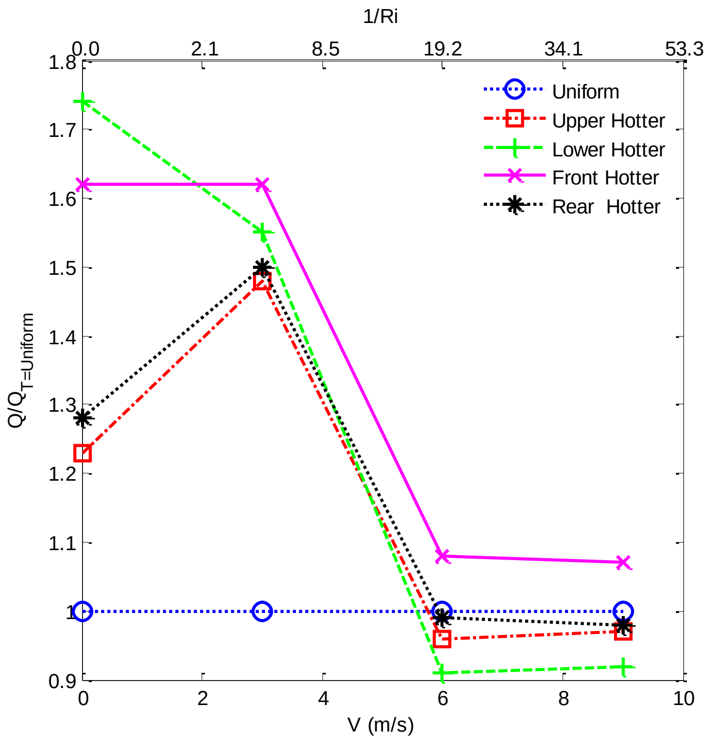

Figure 2 Dependence of the normalised heat losses through the aperture in wind speed for a series of wall temperature distributions. Conditions: tilt angle of 15°, yaw angle of 0°, aperture ratio of 0.5 and aspect ratio of 1.5.

3.2 Side-on wind

The influence of wind speed on the convective heat losses through the aperture for the side-on direction is presented in Figure 3 for several types of wall temperature distribution. The 'front section hotter' case has the highest convective heat loss for most of the cases, similar to the head-on wind cases. However, the 'rear section hotter' cases feature the lowest convective heat loss, which is different from the head-on wind cases. This can be attributed to the fact that the relatively cold wind does not penetrate as far into the cavity for the transverse direction as for the head-on direction. This deduction is reasonable for this configuration in which the cavity has an aspect ratio of 1.5 and an aperture ratio of 0.5 so that the distance between the aperture and the back section is 3 times that of the aperture diameter. Hence the 'rear section hotter' case is likely to have the lowest heat loss for those configurations in which a relatively quiescent zone is established at the rear of the chamber.

Figure 4 presents the same data as Figure 3, except that convective heat losses is normalised by the reference case of uniform wall temperature. This highlights the importance of wind speed on the effect of temperature distribution on the normalised convective heat loss. The 'rear section hotter' case has ~40% less convective heat losses than does the distribution with the highest convective loss for all wind speeds assessed here.

Figure 4 also shows that the convective heat losses, which occur in the low wind speed range (0$< V < 6\, m/s, 0 < Ri < 19$) are less than the natural convection. This trend can be attributed to the generation by a side-on wind of a natural "aerodynamic seal" or "air curtain", which helps to mitigate the heat loss from the cavity. However, for $V > 6$ m/s, the momentum of the transverse flow becomes so strong that it drives a mixing process between the cold wind and hot air inside the cavity that dominates of the "air curtain". Therefore, the convective heat loss increases strongly with the wind speed, for $V\ > 6m/s$.

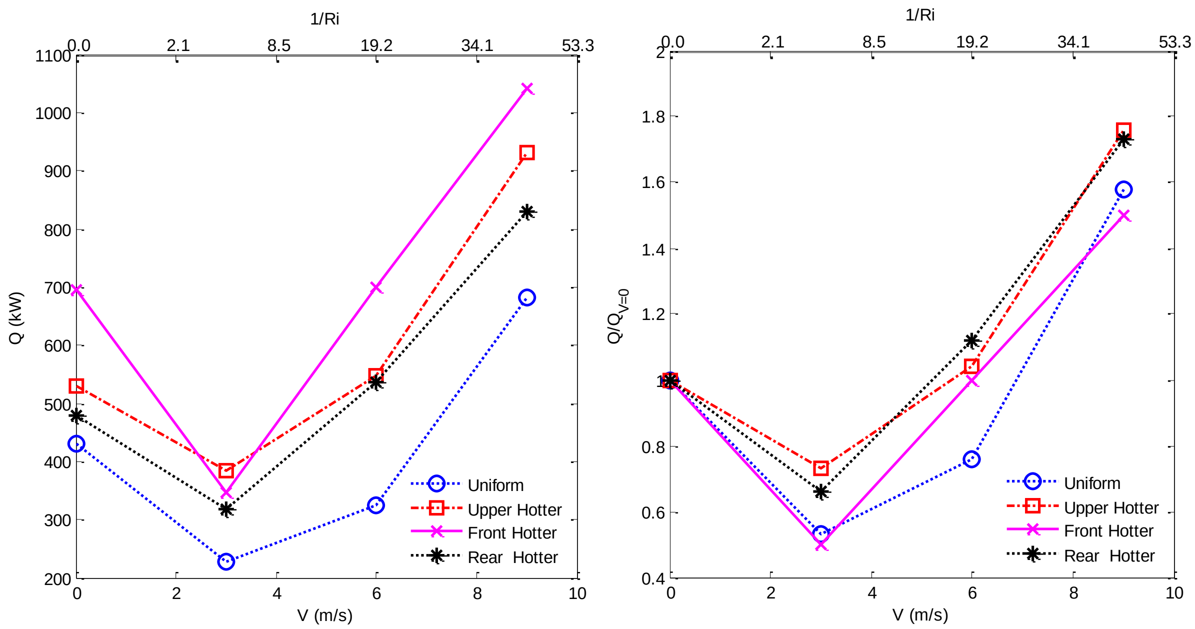

Figure 3 Dependence of the heat losses through the aperture on wind speed for a series of wall temperature distributions. Conditions: tilt angle of 15°, yaw angle of 90°, aperture ratio of 0.5 and aspect ratio of 1.5.

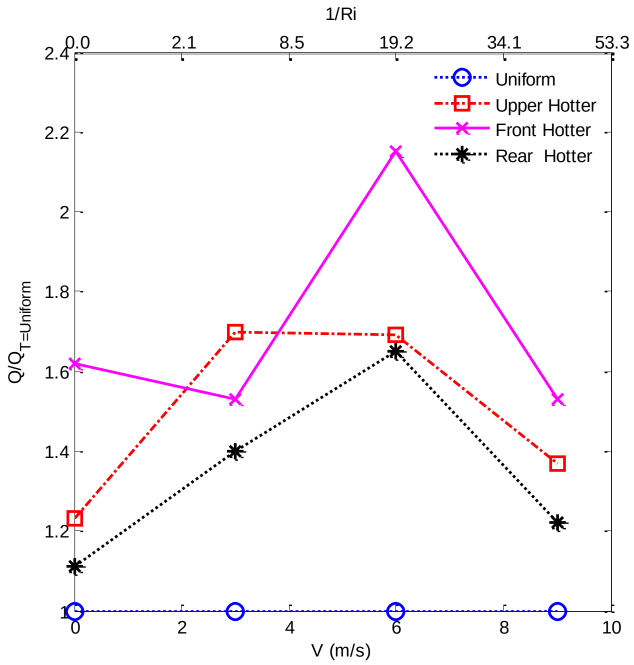

Figure 4 Dependence of the normalised heat losses through the aperture on wind speed for a series of wall temperature distributions. Conditions: tilt angle of 15°, yaw angle of 90°, aperture ratio of 0.5 and aspect ratio of 1.5.

3.3 Upward facing cavity

The influence of wind speed on the convective heat losses through the aperture of an upward facing heated cavity is presented in Figure 5 for three different wall temperature distribution. The convective heat loss through the aperture increases non-linearly with the wind speed, and the case with the hotter surface near to the aperture has the highest heat losses through the aperture, which is consistent with the other cases. The heat losses through the aperture for the 'near aperture hotter' cases are approximately 150W higher than the 'back wall hotter' cases for all tested wind conditions. It is noteworthy that the wind speed has a particularly strong influence for the upward facing cavity. The convective power losses increase by approximately 50% when the wind speed is increased from 0 to 3 m/s (Ri from 0 to 4.8). For the high wind speed condition ($Ri > 43, V > 9m/s$), the heat losses are ~ 5 times greater than the natural convection cases. The upward facing solar cavity receiver is also likely to place closer to the ground than the tower mounted case, where it is less windy than the downward facing cavity, which will further reduce the convective heat loss. In addition, the influence of wind is likely to be easier to mitigate by shielding for an upward facing cavity than a tilted one, since the wind direction is always normal to the cavity axis for the vertical orientation but varies in three dimensions for the tilted case.

In contrast to Figure 3 in which the side-on wind was found to initially decrease convective losses for the tilted receiver, this reduction does not occur for the vertical orientation although the wind direction is also perpendicular to the aperture. This is consistent with the vertical orientation avoiding the strong adverse mechanism of the near horizontal orientations in which natural convection establishes a strong recirculation through the aperture.

Figure 6 presents for the vertical orientation the convective heat losses for the three temperature distributions normalised by the case with the uniform wall temperature. The shape of the temperature distribution can be seen to change the total convective heat losses by up to ~ 60%, which is more significant than the tilted cases. However, the impact of the shape of the temperature distribution decreases with an increase in wind speed to less than 20% for high wind speed condition ($Ri > 43, V > 9\ m/s$). The total convective heat losses converge with an increase in wind speed to a value that approaches the uniform temperature distribution case. This gives further evidence that both the orientation and temperature distribution become unimportant at sufficiently high wind speeds aligned normal to the cavity axis.

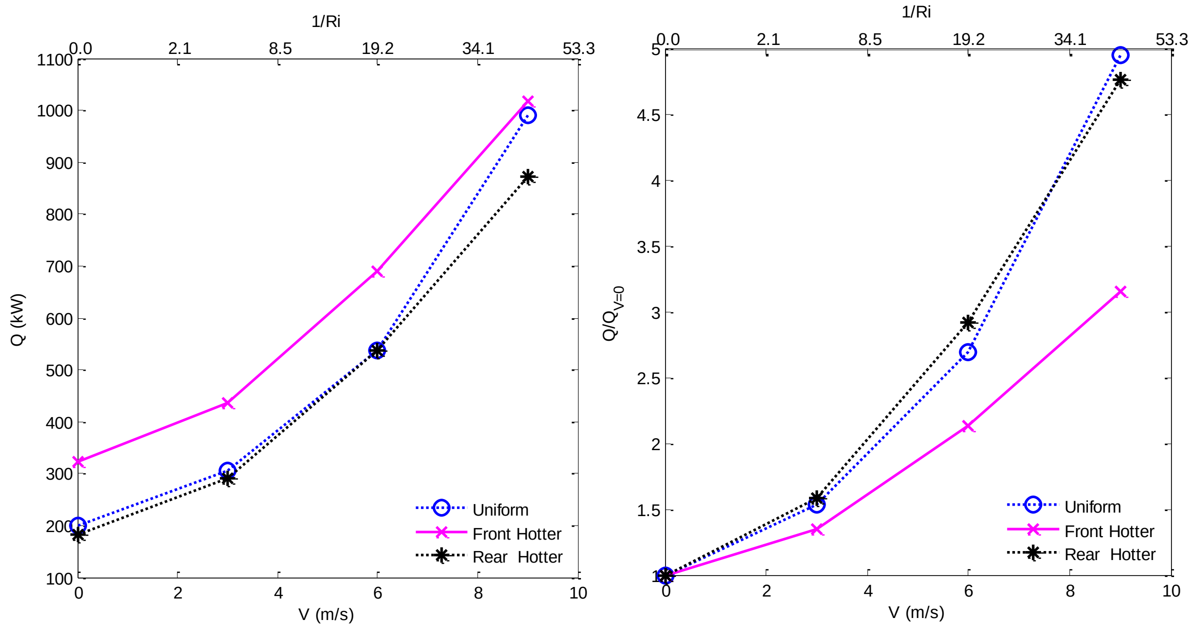

Figure 5 Dependence of the heat losses and normalised heat loss wind speed through the aperture on wind speed for a series of wall temperature distributions. Conditions: tilt angle of -90°, yaw angle of 0°, aperture ratio of 0.5 and aspect ratio of 1.5.

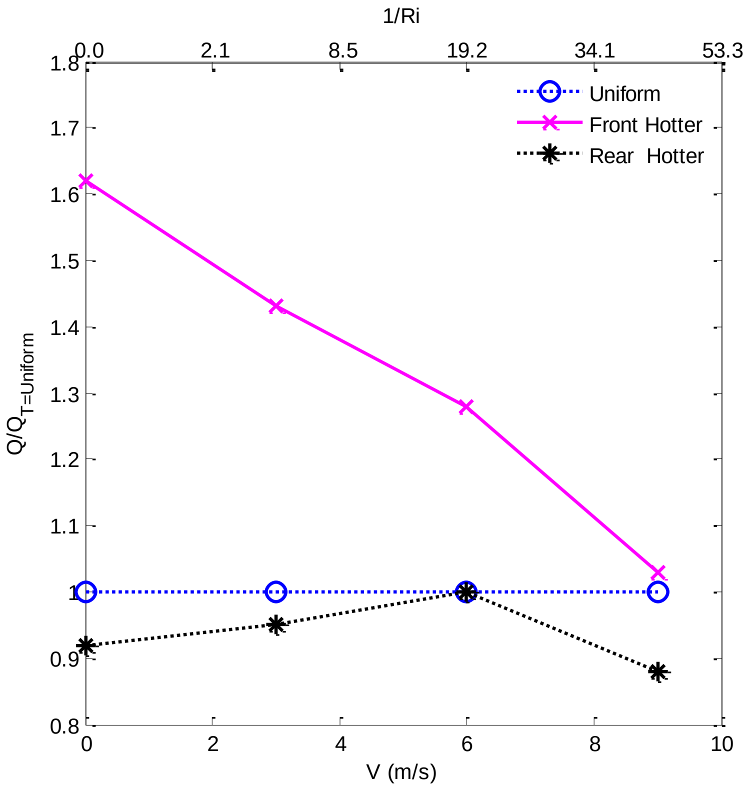

Figure 6 Dependence of the normalised heat losses through the aperture on wind speed for a series of wall temperature distributions. Conditions: tilt angle of -90°, yaw angle of 0°, aperture ratio of 0.5 and aspect ratio of 1.5.

3.4 Temperature and tilt angle

The combined effects of temperature and tilt angle of a heated cavity on convective heat losses through the aperture of a heated cavity are present in Figure 7, incorporating both the beam up ($\varphi = 90°$) and beam down ($\varphi = -90°$) cases. It can be seen that the beam-up has the lowest convection losses as expected, being only 30-40% that of the beam-down. Also the heat loss through the aperture increase non-linearly with temperature. This effect, which is observed fir all of the tested tilt angles cases, appears to be related to the influence of radiation heat loss, which has a fourth order dependence on temperature. Worth noting is that the heat loss from the aperture has a complex dependence on tilt angle. The heat losses from the 15° tilted cavity are higher than both the 90°and -90° cases. This indicates that there is at least one tilt angle which will have the highest convective heat loss, although further work in required to determine this. However, this angle is likely to also depend on the cavity dimensions. That is, the heat loss from the $\varphi = -90°$ case may not necessarily be less than the 15° for all geometries, but is expected to depend on the geometry of the cavity, such as aspect ratio and aperture ratio (Bilgen & Oztop 2005). However, the trend is independent temperature , because the same trend can be observed in Figure 7a for all tested temperatures.

a)

b)

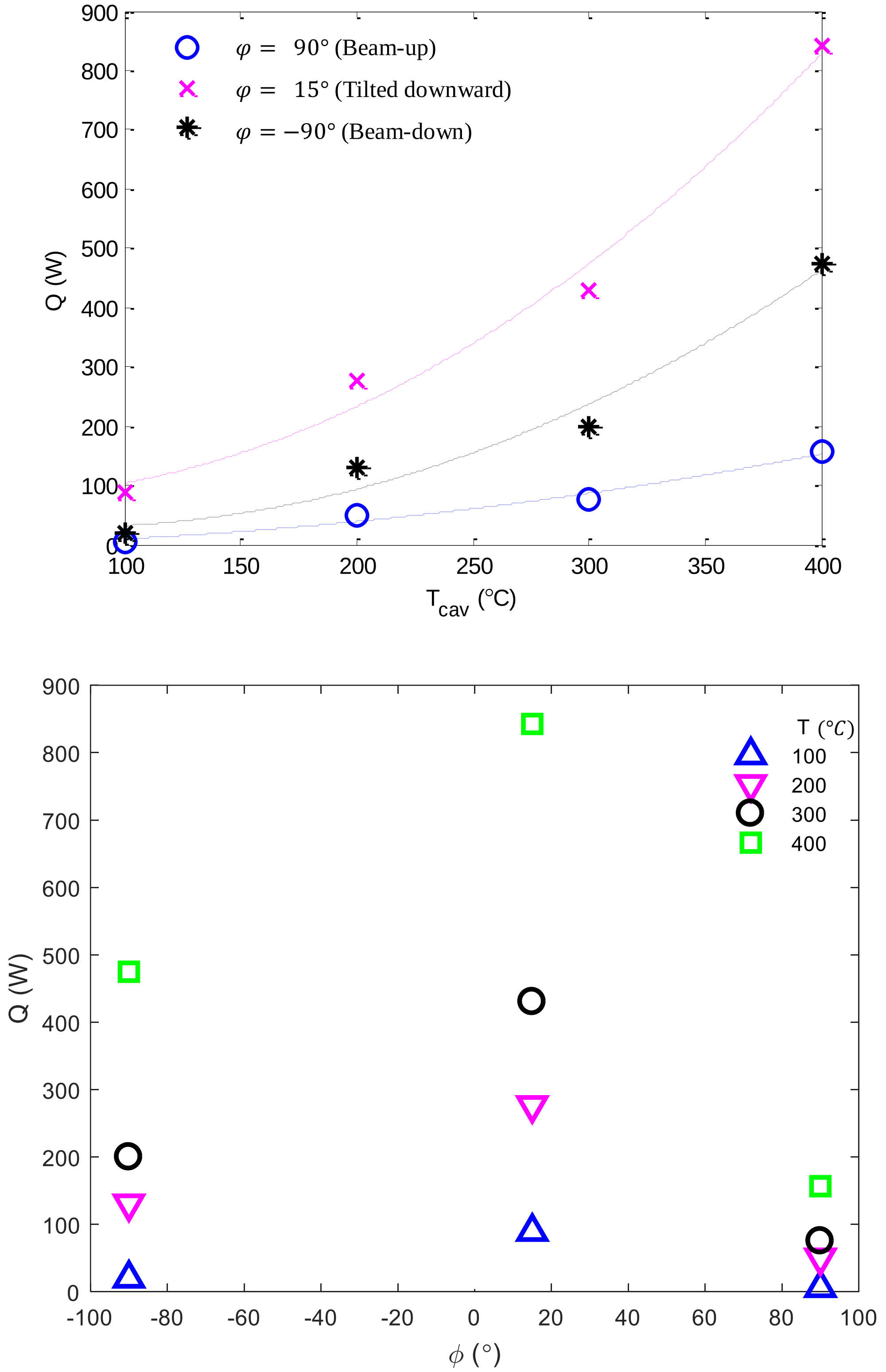

Figure 7 Dependence of the heat losses through the aperture of a heated cavity on temperature and tilt angle. Conditions: no wind, aperture ratio of 0.5 and aspect ratio of 1.5.

The effect of wind speed on normalised heat losses by natural convection for the beam-down case, for various wind directions and the tilt angles is presented in Figure 8. The natural convection of the 'beam-down' was chosen to be the reference case because it has the lowest heat losses. The figure shows that the 'downward tilted cavity with side-on wind' case has a very similar trend with the 'beam-down' case for wind speed $Ri > 4.8$. This is because, for both cases, the air/ wind flows parallel to the aperture plane. Therefore the flow pattern is expected to be similar for all wind speeds. For these 2 conditions, the increase in heat losses at high wind speed ($Ri < 43$) is up to 4.5 times the value of the natural convection of the 'beam-down' case. However, the influence of wind speed on heat losses through the aperture is very high for the head-on wind speed cases, to reach up to 12 times that of the reference case. This highlights the potential benefits of being able to mitigate convective heat loss from for head-on wind directions.

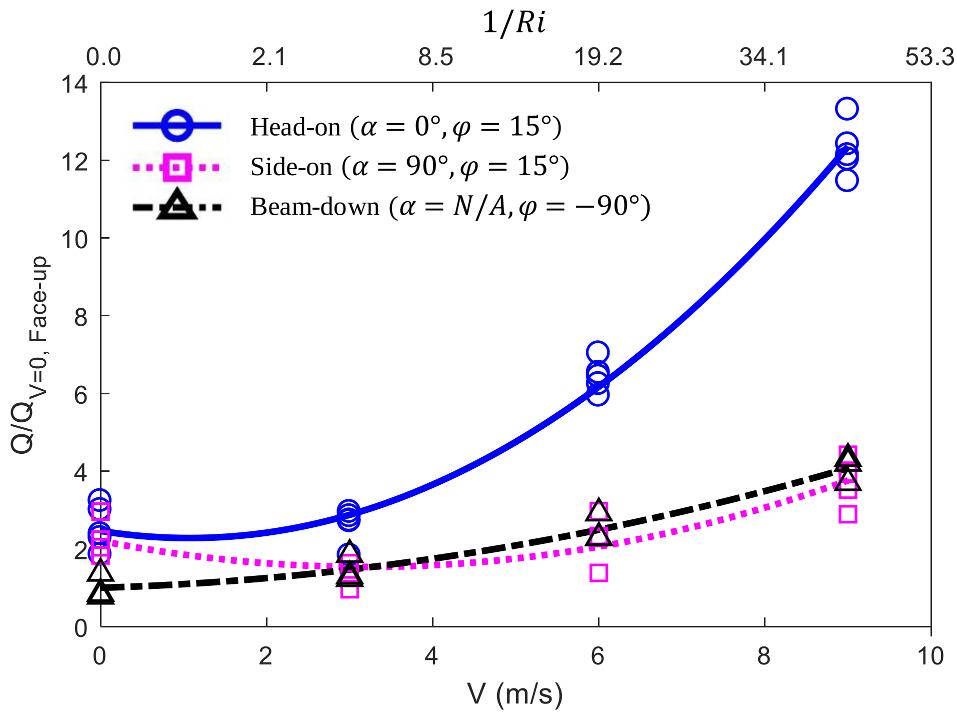

Figure 8 Dependence of the normalised heat losses by natural convection of the 'beam-down' case on wind speed for a series of tilt and yaw angles. Conditions: aperture ratio of 0.5 and aspect ratio of 1.5.

The dependence of the inverse of Richardson number on the Nusselt number is presented in Figure 9 for three orientation. It can be seen that the data all collapse very wall for the head-on case and quite well for the beam-up case, but is much more complex for the side-on orientation. A strong local minimum in the heat losses at $1/Ri{\sim}5$ is clearly observed for of the side-on direction and a very weak minimum is present for a few cases in the head-on direction. This shows that a low velocity cross-flow can inhibit the buoyancy-driven transport of gas through the aperture when the cavity is tilted slightly downward. However, for an upward facing cavity, there is no stagnant zone so that a slight wind does not inhibit buoyancy for this case. Worth noting is that the heat losses from the head-on wind speed case does not vary much between the first 2 data points. Insufficient data are available to identify whether or not a local minimum or maximum is present between $0 < Ri < 5$. In addition, it is also noted that, for high wind speed the heat losses from the head-on cases are about 4 times larger than the side-on cases, agreeing with our earlier study (Lee et al. 2018a). The data also suggests that there may be a local minimum at $1/Ri\sim1.25$ for the head-on cases. Figure 9a also shows that, Nu has near linear dependency relationship with $1/Ri$ for $1/Ri > 10$ for the head-on case, hence this behaviour is also expected $1/Ri > 40$ for the side-on cases.

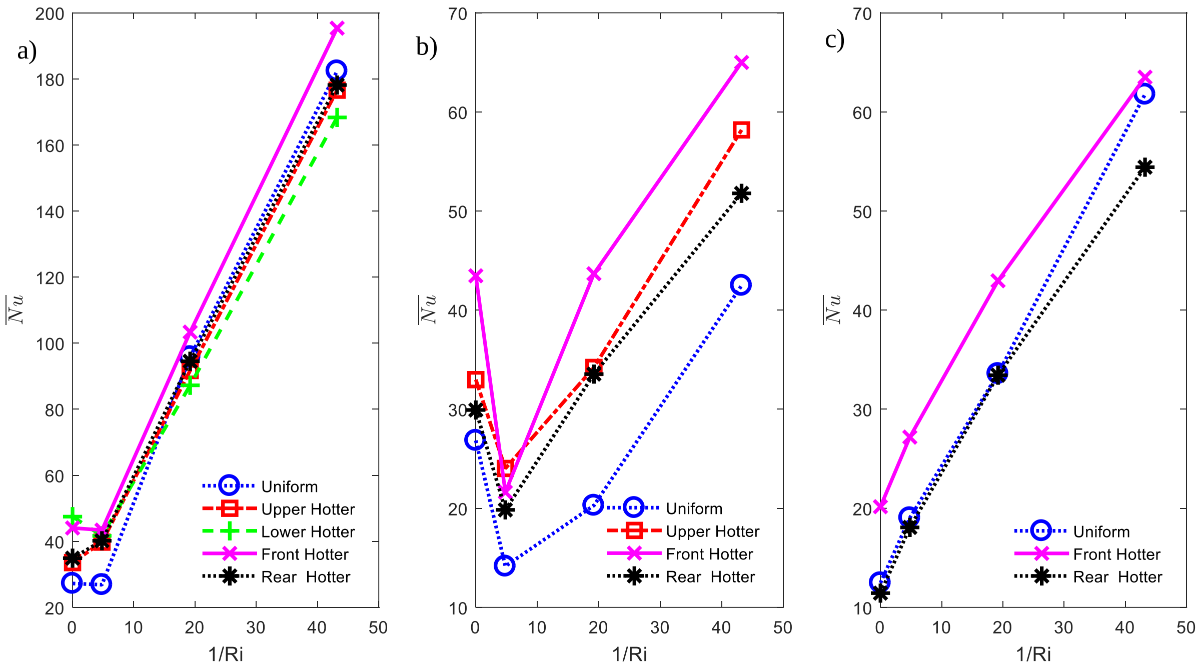

Figure 9 Dependence of the Nusselt number of a heated cavity on the inverse of Richardson number for a series of wall temperature distributions. Conditions: aperture ratio of 0.5, aspect ratio of 1.5, a) head-on ($\alpha = 0°$ and $\varphi = 15°$), b) side-on ($\alpha = 90°$ and $\varphi = 15°$) and c) beam-down ($\alpha = N/A$ and $\varphi = -90°$).

4 Conclusions

The dependence of convective heat loss on wind speed, yaw angle, tilt angle and temperature distribution from a cavity receiver of various geometrical parameters were investigated experimentally in this study. Results point to a complex and joint relationship between the heat loss and the various operating parameters. It is found that there is no heat flux profile that exhibits the best or worst convective heat flux for all orientation. In general, the heat losses from a downward tilted solar cavity receiver ($\varphi = 15°$) tend to be minimised with the upper or rear surface to be hottest. This outcome should be further investigated with the solar optical system.

The convective losses are lowest for the beam-up orientation as expected, but the downward tilted solar cavity receiver ($\varphi = 15°$) has greater losses than the beam down, even at zero wind, which contradicts the expectation from the literature. The main reason for this difference is that the wind direction is always normal to the cavity for the beam-up and beam-down orientations, which is the orientation with the lowest convective losses. These configurations avoid the wind flowing directly into the cavity, which has the greatest connective losses. Furthermore, at high wind speeds, with corresponds to high inverse Richardson number, the heat transfer is momentum dominated, so that the heat losses are controlled by orientation relative to the wind, irrespective of the direction of gravity.

Finally, the heat loss from a beam down cavity receiver has a nearly linear dependence on $1/Ri$ throughout the range. This linear dependence shows that natural convection is not significant anywhere. For the downward tilted orientation, the relationship becomes linear for higher wind speed, where momentum dominates over natural convection. The study also suggested that there may be a local minimum of heat loss at $1/Ri{\sim}1.25$ for the head-on cases. However, this wind speed is out of the range of the wind tunnel of this study, so requires further work to confirm.

Acknowledgements

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Supplement

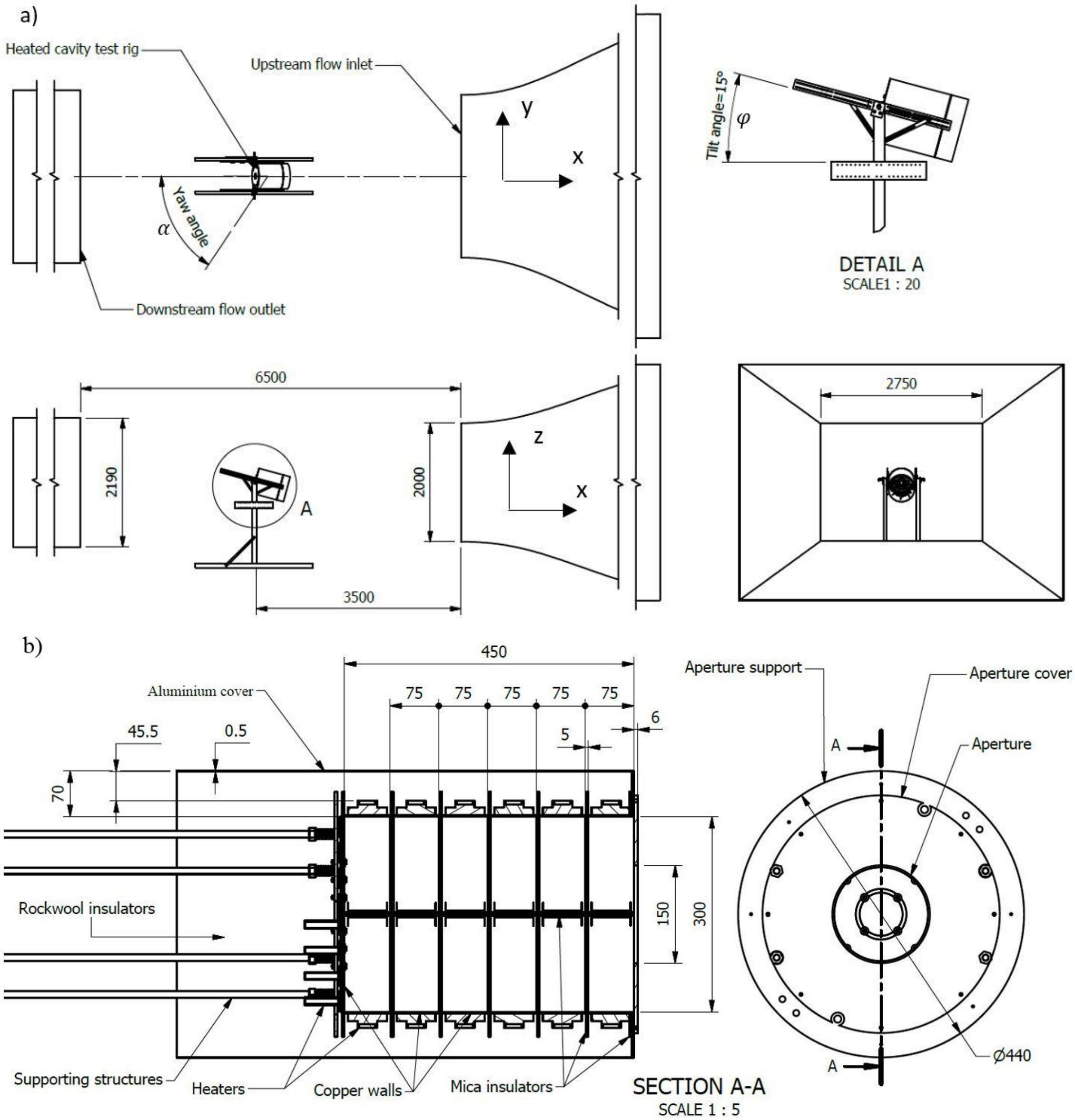

Figure S1 Schematic diagram of a) the heated cavity in the Thebarton wind tunnel and b) the dimensions of the receiver.

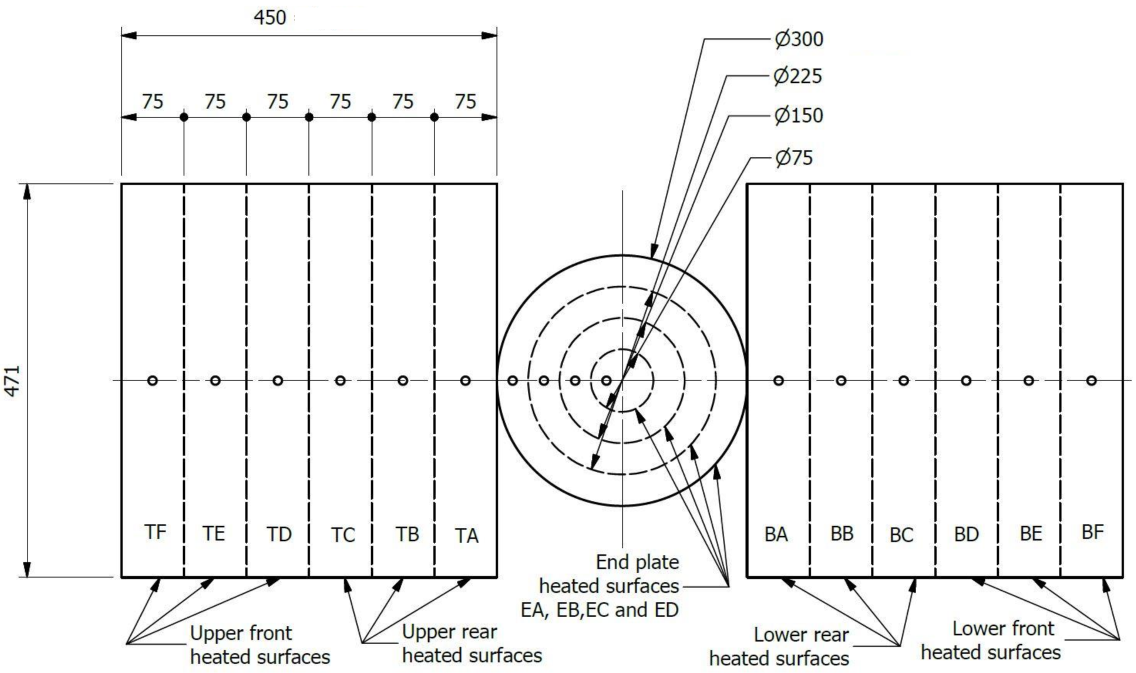

Figure S2 Schematic diagram of the simplified configuration of the internal copper wall surface of the heated cavity (shown unrolled view). The thermocouples are shown as small circles. Please notice that, for the cavity facing upward cases (tilt angle = -90°), upper heaters are the downstream heaters and lower heaters are the upstream heaters.

Table 3 List of instrumentation/ uncertainty term

Instrumentation/ uncertainty term	Accuracy/ uncertainty
K-type thermocouple	$\pm 2.2°C$ / $\pm 0.7\%$
Datataker DT85	$\pm 0.01\%$
Arduino with DMX output	$\pm 0.2\%$
Lighting system power controllers	$\pm 1.5\%$
Steady state temperature	$\pm 0.5°C$ / $\pm 0.2\%$
Steady state power	$\pm 0.5\%$

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