Impact of dish structure on the convective heat loss from a parabolic dish solar cavity receiver

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Abstract

Parabolic dish cavity receivers achieve higher operating temperatures by using higher concentration ratios from larger dish structures, which in turn incur greater costs. Many studies have focused on understanding the heat loss from the cavity receiver in order to accurately predict the technical and hence economic performance of these systems. However, there is a lack of work on the influence of the dish structure on the wind and its subsequent effect on convective heat loss from the receiver. Hence, this work investigated the heat losses from a coupled dish-cavity receiver system. Convective heat losses from a cavity receiver (with a coupled dish) were determined numerically using computational fluid dynamics (CFD) for various wind directions and dish-receiver orientations. The heat losses were assessed considering wind velocities from 0 to 20 m/s, together with a range of wind incidence angles and dish tilt angles.

The results show that the dish orientation in the flow field has a significant impact on the convective heat loss. It was found that at wind velocities less than 3m/s, the convective heat loss was lower than the natural convection heat loss (at 0 m/s). Further, the results indicate a significant reduction in heat loss (of between 15% to 40 % for winds between 3 m/s to 20 m/s) when including the presence of dish structure, compared to its absence. This finding highlights the need to consider the dish structure in the determination of thermal performance of these systems in order to avoid over design and excessive cost.

1. Introduction

The performance of parabolic dish system (PDS) Concentrating Solar Power (CSP) systems is sensitive to heat losses from the cavity receiver, particularly at high temperatures. The associated heat losses from the cavity receiver need to be better understood in order to improve the thermal performance and the accurate design of dish systems. PDS CSPs are often installed in open environments where wind can influence their thermal performance and reduce their cost effectiveness (Lupfert et al., 2001). Heat is lost to air inside the cavity by radiation and convection, as well as by conduction through the insulation. The dominant parameters governing the radiation losses are the cavity wall temperature, the shape factor, emissivity and absorptivity, while the conduction losses are dependent on the receiver temperature and the insulation material (Shuang et al., 2010). Analytical techniques presented by Holman (1997) can be used to estimate the radiation and conduction heat losses from a cavity receiver, however, determination of convection heat losses from the receiver is much more complicated, as it is strongly influenced by the surrounding air flow conditions.

There have been numerous experimental and analytical studies of convection heat loss from cavity receivers. These studies were performed to determine natural and forced convection from cavity receivers of different shapes including cubical (Le Quere et al., 1981a, 1981b; Clausing 1981,1983; Clausing et al., 1987; Leibfried and Ortjohann,1995), rectangular (Hess and Henze, 1984; Mohamad, 1995; Sezai and Mohamad, 1998; Hinojosa et al., 2006), hemispherical (Yausuaki et al., 1994; Khubeiz et al., 2002; Sendhil and Kumar, 2007; Reddy and Kumar, 2008) and cylindrical cavities (Koening and Marvin, 1981; Stine and Mcdonald, 1989; Lovegrove et al., 2003; Paitoonsurikarn and Lovegrove, 2003; Paitoonsurkarn et al., 2004; Prakash et al., 2009).

In the case of natural convection, heat loss from the receiver is dependent on the receiver's tilt angle. Thus, many of these studies investigated heat loss from cavity receiver treating it as a separate entity decoupled from reflector dish. That said, Paitoonsurikarn and Lovegrove (2006) and Christo (2012) investigated the effect of the dish structure on the wind near the cavity receiver without exploring its effect on the heat loss effect from receiver. However, with wind, the dish structure does affect the local air velocity near the receiver and subsequently the heat loss from receiver at higher velocities (Uzair et al., 2014, 2015)

Despite the work done in the area, there is still a strong need to understand the heat losses from the receiver when it is coupled to the reflector dish, in order to facilitate more accurate thermal analysis and design of parabolic dish based CSP systems.

2. Numerical Model

For this work, a three dimensional steady state computational fluid dynamics (CFD) analysis was performed to examine the behaviour of wind flow around a parabolic dish and cavity receiver. The geometry chosen was that of the Australian National University's (ANU) 20 m^2 dish and frustum shaped receiver. The parabolic dish has an aperture diameter (D) of 5 m and a nominal aperture area of 20 m^2, a focal length of 1.84 m and a rim angle of approximately 70°. The orientation and dimensions of the frustum shaped cavity receiver are shown in Figure 1a. Previously, some numerical and experimental studies had been performed to assess the thermal characteristics of the receiver of this specific dish, however only a few numerical studies of the flow fields have been published (Paitoonsurikarn and Lovegroove, 2006).

To model the open environment in which the system operates, the computational domain around the dish receiver system was modelled as shown in Figure 1b. The domain extends 15D upstream to allow the flow to become fully developed, 21D downstream to capture all the affected parameters and 6D in the lateral direction to avoid any shear effects of the walls on the flow field near dish.

Simulations of the wind flow over the entire parabolic dish system were performed using the ANSYS CFX 15.0.7. The Shear Stress Transport (SST) two-equation eddy-viscosity turbulence model was selected for the simulation. The SST model is one of the most accurate two-equation models for separation prediction and has successfully been used to predict the wind flow over parabolic troughs (Paetzold et al., 2014) to capture the effect of natural and forced convection. To simplify the simulation a uniform inlet velocity profile was used. An ambient temperature of 25°C was chosen in all cases. The internal cavity walls for the receiver were considered to be isothermal at a temperature of 600°C, and the outer walls were assumed to be adiabatic. In order to accommodate the buoyancy flow, the fluid properties were varied across the domain as a function of temperature with the assumption that the pressure does not change significantly in the flow domain.

This simulation was performed to investigate two heat loss conditions: the natural convection heat losses with no wind, and mixed convection heat losses with different free stream wind velocities, various dish tilt (elevation) angles (θ) and wind incidence angles (φ).

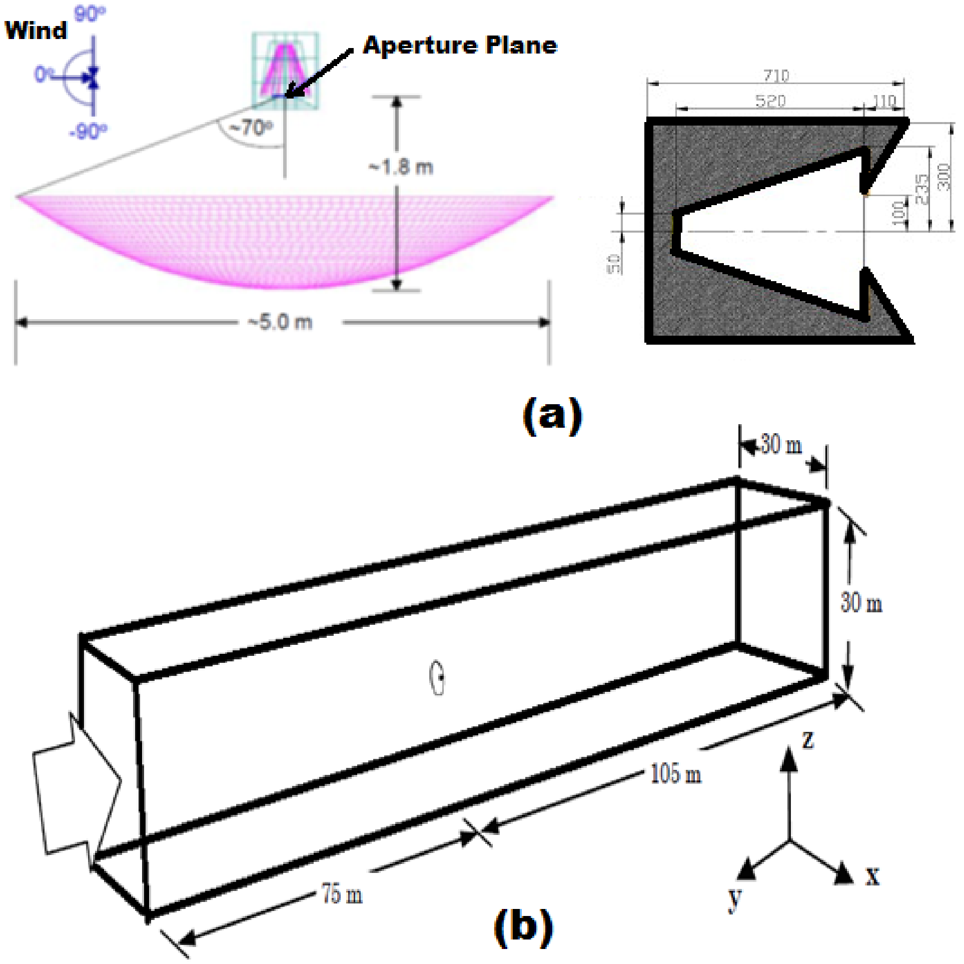

Figure 1: (a) Orientation and dimension of cavity receiver (b) Domain Size

3. Results and Discussion

Detailed three dimensional numerical simulations were performed to investigate the impact of flow behaviour around the cavity receiver on the convective heat losses with and without the dish structure being present. Subsequently, the variation of heat loss from the cavity receiver was studied at various free stream wind flow ranges, from 0 m/s (free convection) to 20 m/s (forced convection).

The natural convection heat losses from the cavity receiver, with no wind condition, were simulated over a range of tilt angles and the results shown in Figure 2. The results obtained were in reasonably good agreement with previous correlations, also in Figure 2. These include the modified Stine & McDonald equation (Leibfried and Ortjohann, 1995), Taumoefoliau (2004), Paitoonsurikarn (2006) and Koening & Marvin models (1981). From these results, it is clear that convective heat loss is strongly dependent on the tilt angle of cavity receiver. The minimum heat transfer occurs when the cavity receiver is facing vertically downward and the symmetrical geometry prevents the establishment of convection currents. The increasing heat loss with tilt angle is as a result of the strengthening convection caused by the raised lip of the cavity releasing the heated air.

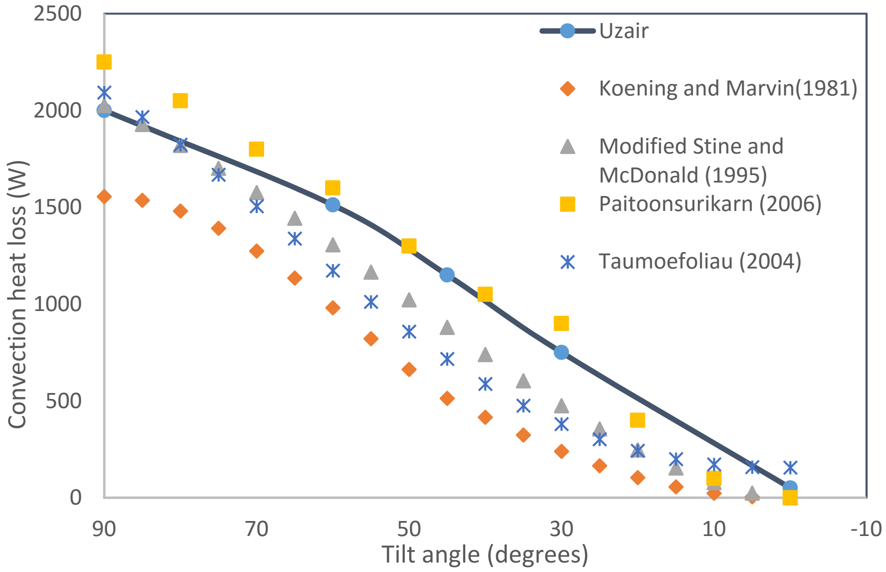

Figure 2: Comparison of numerical simulation with other correlations

Following on from this, the mixed and forced convection heat loss from the cavity receiver, with and without dish structure being present, were investigated. Figure 3 shows the results of this comparison with the wind impinging directly on the back side of dish (φ = -90°). From this it can be seen that at low wind speeds, the dish structure has no impact on the heat losses. However above 3 m/s the presence of dish structure provides a blockage to the horizontal movement of air. This means the receiver sits in the wake of the dish, and so the heat loss is driven principally by natural convection, whereas not accounting for the dish leads to a forced convection condition, implying the heat loss is much greater than would occur in reality (i.e. with the dish present).

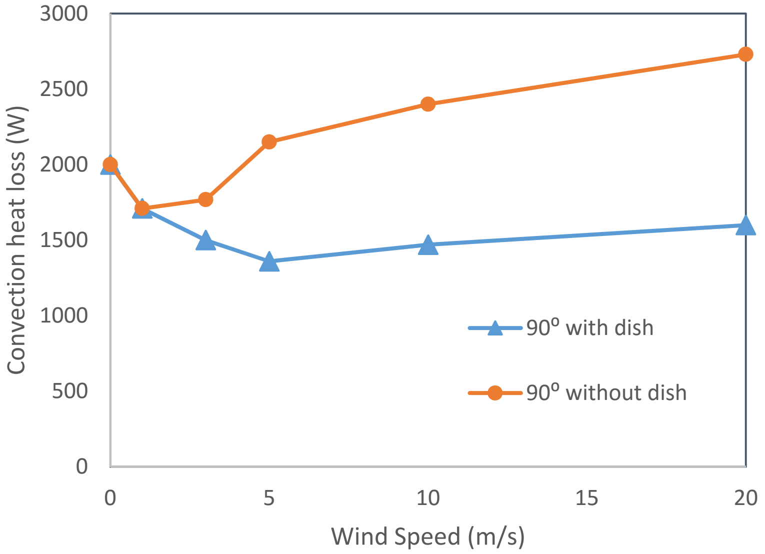

Figure 3: Comparison of heat losses from cavity receiver at -90° tilt angle

Figure 4 shows the velocity contours and illustrates a typical wake profile generated by the dish, it can be seen that the local velocity reduces significantly in the region where the cavity is installed. This reduced local velocity decreases the strength of the convective heat transfer. An experimental validation of some of these conditions has been previously published by the authors (Uzair, et al 2015).

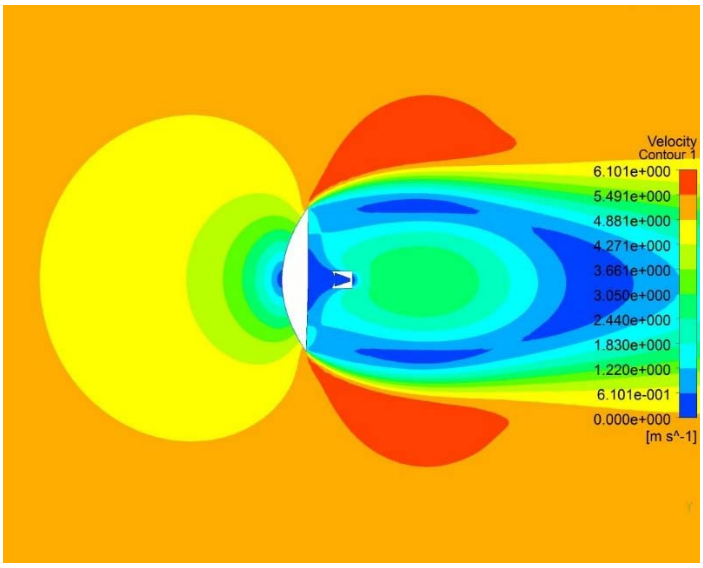

Figure 4: Velocity contours near the dish for a free stream velocity of 5m/s

The effect of the dish is further highlighted in Figure 5, where the difference between the predicted heat loss from the cavity with and without the dish is compared. This difference constitutes the error in estimating heat losses without considering the dish, and amounts to 15% at a wind speed of 3 m/s and increases to 40% at 20 m/s (Figure 5). Hence, it shows that considering the heat loss from the receiver in isolation from the flow around the dish can lead to spurious results under some conditions.

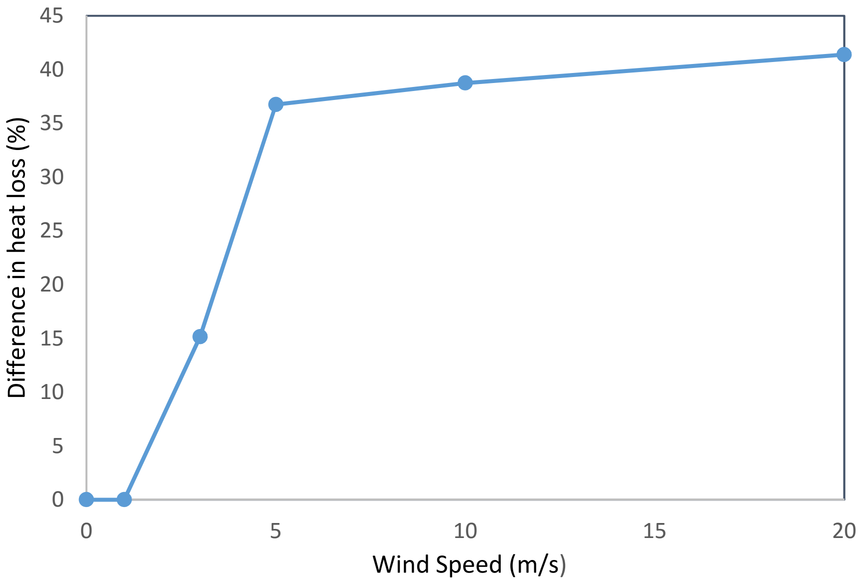

Figure 5: Percentage difference in heat loss due to the presence of the dish (tilt angle- 90°)

In essence, the presence of the dish structure significantly impacts the heat loss for the real scenario when the system is tracking the sun. The dish structure effectively reduces the wind speed near the cavity receiver when the receiver is in the wind shadow of the dish, and subsequently the convective heat transfer decreases. To illustrate this point three different cases, parallel flow ($\varphi = 0°$), wind directly impinging on the reflective surface ($\varphi = 90°$) and wind impinging on the rear of the dish (φ =-90°), were selected to investigate the effect of the dish structure on the heat transfer from the receiver at varying dish elevation angles (θ).

For the parallel or side-on flow condition shown in Figure 6, the bulk flow is parallel to the receiver opening and so the dish structure does not affect the local air flow around the receiver. As such, the heat loss increases above 3 m/s, for all tilt angles, whereas at lower wind velocities (less than 3 m/s) the air movement near the receiver is insufficient to influence the heat loss from cavity receiver, so the flow is principally driven by natural convection. Furthermore, at higher wind speeds, the heat loss at all tilt angles are similar, indicating the dominance of the forced convection over natural convection. However, what is interesting to note is the initial decrease in heat loss that occurs at low wind speeds (above 0m/s). This suggests that at low wind speeds the wind acts as an air curtain that suppresses convective losses from the receiver.

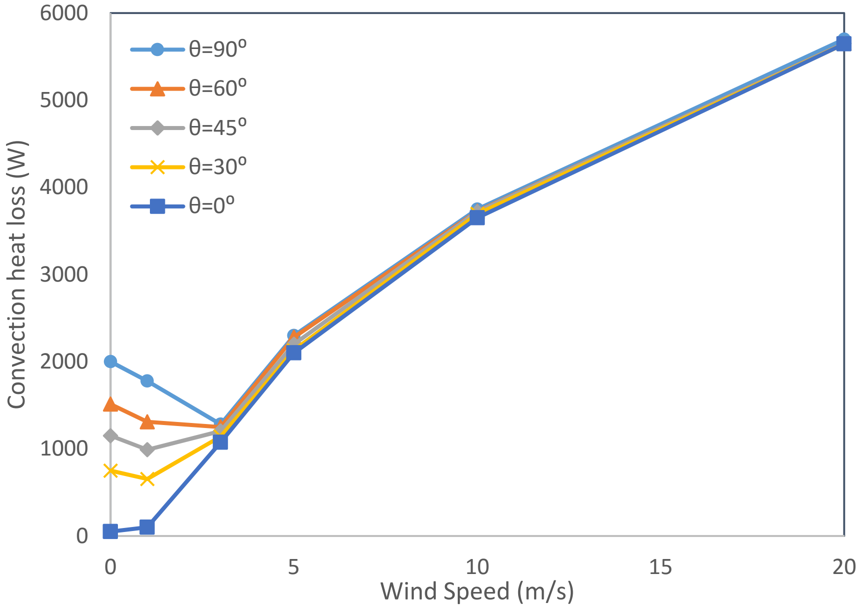

Figure 6: Flow parallel to the cavity receiver aperture plane (φ =0°)

Now if we consider the case where the wind approaches the reflective (front) surface of the dish (φ = 90°) (Figure 7) it can be seen that for no wind, the convection heat loss values are identical those seen with parallel flow (Figure 6). Also, with an angle of tilt of 0° (cavity/dish vertical), the heat loss values are again identical to those seen in the parallel flow scenario (Figure 6). This is due to the dish in this orientation having no effect on the air flow around the receiver.

Also, in Figure 7, it can be seen that as the wind speed increases above 3 m/s the magnitude of the heat loss is significantly lower than those observed in Figure 6. This is due to the dish structure providing an impediment to the flow, thus creating a region of stagnant low velocity air near the cavity receiver. The presence of the stagnation region generated by the dish reduces the convective heat losses, relative to those where the receiver is exposed to the free stream wind alone, as is the case for a tilt angle (θ) of 0°.

Exploring these observations further, when varying the tilt angle of the dish through the range 90° (cavity centreline parallel to the ground) to 45° it is found that as the wind speed increases, the magnitude of the convective heat loss initially decreases at lower velocities and then increases at higher wind velocities. In this range of tilt angles the dish acts as a blockage and slows the air motion around the receiver. However as the angle is reduced further , in the range of 30° to 0°, the blockage is less severe, and the flow over the dish becomes more uniform without any major flow separation. Under these conditions, the receiver location is such that the shape of the dish has less impact the local flow around it and so as the wind speed increases, the magnitude of the convective heat losses also increases.

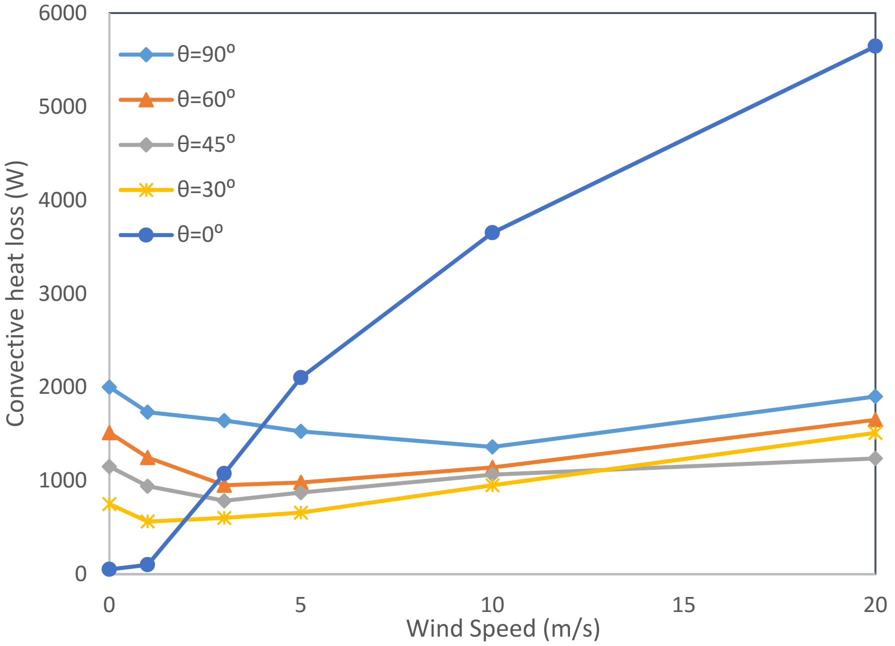

Figure 7: Flow approaching the reflective (front) surface of dish (φ =90°)

Finally, Figure 8 shows the case when the wind flow impinges on the rear surface of the dish (φ= -90°). As before, for the condition of no wind, the convection heat loss values are identical those seen in the parallel flow (Figure 6). Similarly, with an angle of tilt of 0° (cavity/dish facing vertically), the heat loss values are identical those seen in the parallel flow over the whole wind speed range (Figure 6). This is due to the disk in this orientation having no effect on the air flow around the receiver.

However, when the wind does impinge on the dish’s rear surface, the dish constitutes a bluff body between the cavity receiver and the oncoming wind, where the receiver is positioned in the wake of the dish. Comparing these results to those in Figure 7, the heat loss trends are similar to those with the wind impinging on the front face, where the dish causes a partial stagnation zone around the receiver. It would seem that whether the receiver is in the wake, or stagnation zone, the effect of the wind speed on the magnitude of the convective heat loss is similar. Hence, as the wind speed drops the heat loss for all tilt angles converge towards the natural convection values at zero wind speed, as seen in Figure 8.

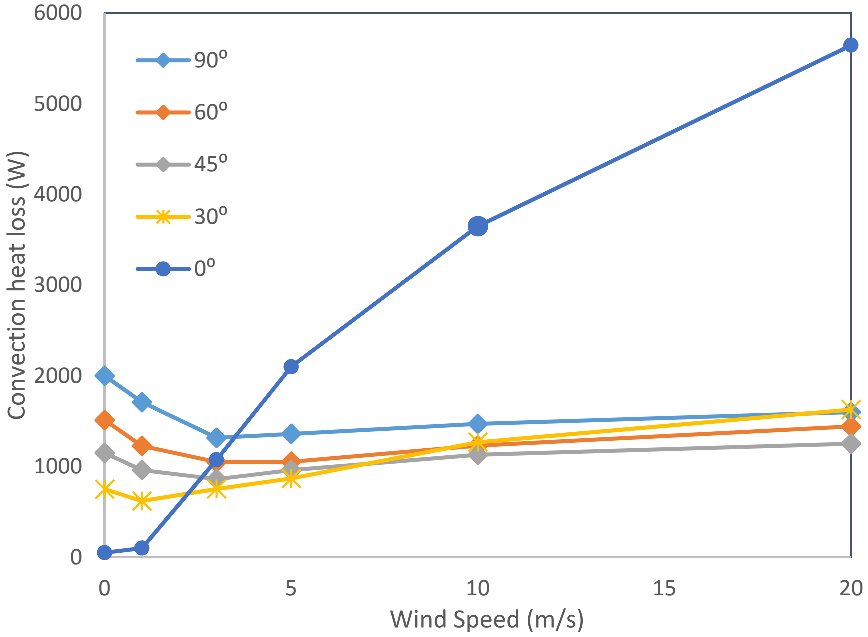

Figure 8: Flow impinging on the rear of dish (φ =-90°)

4. Conclusion

This work presented a comprehensive study investigation of the impact of dish structure on the convective heat losses from a coupled cavity receiver and dish over a range of wind speeds, wind incidence and tilt angles. For the different operating conditions, it was observed there was a critical wind velocity, between 3 m/s and 5 m/s (depending on incidence and orientation), above which forced convection dominates. Below this critical speed, the heat loss is dominated by natural convection and the presence of the dish has little effect on the heat losses. Above the critical speed, the forced convection heat loss is highly influenced by the dish, with respect to its angle of tilt and attitude toward the wind. However, the most significant outcome of this work is that it shows that evaluating a cavity receiver without considering the presence of the dish could lead to errors in the heat loss analysis of up to 40% which result in increased cost or poor system performance.

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