Numerical Investigation to Determine the Optimized Solar Cavity Shape

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ARTICLE INFO

Article history:
Received: 19 August 2020
Revised: 22 October 2020
Accepted: 2 November 2020

Keywords:
Convective heat loss
Numerical simulation
Parabolic dish receiver
Cavity receiver

ABSTRACT

To optimize the output of parabolic receiver-dish systems, a proper selection and designing of receiver is essential. The performance of the system greatly depend on convective heat losses In this study, the experimentally validated numerical study is performed on different commonly used receivers(Conical, cylindrical and rectangular shapes with and with frustum opening) to find the most efficient shape of cavity receiver. The simulation was carried out using different operating tilt angles ranges from 0° to 90° with cavity receiver walls at a temperature of 600°C. The decision is based on the natural convection through different geometries. Among all types of geometries, the conical shaped cavity performed very effectively. The conical shaped is further examined to investigate the effect of aspect ratios on the performance of the system. With higher aspect ratio, the heat flux in the upper zone of the cavity receivers is found to be very low making it worst operating scenario.

1. INTRODUCTION

The development of any country is mainly dependent on the energy sector. A rough figure of 1.5 billion world population does not have the electricity supply to meet their basic requirements [1, 2]. In order to meet the requirement, renewable energy especially solar energy plays a vital role. In the recent few years, due to rapid advancements in the solar conversion techniques, concentrating solar power (CSP) systems are capturing the most of the market share of renewable resource. By concentrating the sun light on the receiver, the CSP systems are capable to achieve the high temperature and thus high quality energy [3]. Among all CSP systems, the parabolic dish systems are one of the promising technologies to produce power [4, 5] and have been used in different other purposes like desalination and chemical processes [6-9].

The complete parabolic dish system is mainly comprises of (i) reflector (truncated paraboloid), (ii) supporting structure, (iii) tracking arrangements, and (iv) receiver. The concentrated solar radiation reflected form the reflector shape are absorbed in the receiver installed at the focal point. The main purpose of the receiver is to transform the solar energy into thermal/chemical energy. Due to high value of temperature attained at the receiver by the concentrated solar energy, the heat is lost in all three modes i.e. conduction, convection and radiation. There are well established techniques available [10, 11] to determine the conduction and radiation heat loss, however due to tracking of the system, the fluid and heat transfer behavior changes by changing the orientation of the receiver. Hence the convective heat loss from the cavity receiver plays a major role to design a parabolic dish system [12]. Therefore, there is a need to investigate the effect of natural convection extensively. A variety of receivers have been studied to enhance the overall performance of the parabolic dish system [13-21]. However, the established correlations are for particular cavity receiver. The literature showed that numerous works had been done on cubical, rectangular, cylindrical and hemispherical shapes of cavity receiver. Since then different efforts are utilized to achieve higher efficiency along with high operating temperatures so that maximum solar power can be utilized. Consequently, generation of electricity can become more affordable in comparison with fossil fuels. The convective loss is changed due to the dimensions of cavity and along with the temperature of wall [22]. This study is further followed by Clausing [23], in which he proposed that two distinct regions are present inside cavity and the losses are mainly dependent upon heat and energy transfer with heat air trapped inside cavity but he used only two shapes, cylindrical and hemispherical. The convection heat losses were determined using heated cavity [24]. Later, four types of geometries of cavity have been numerically investigated

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by Paitoonsurikarn [19] and correlations were developed.. Electrically heated models with cylindrical shape were examined and their convective heat losses were investigated as a function of applied heat input, cavity temperature and inclination angle [25, 26].

Mostly, studies are concerned with the convective heat losses with different shapes of isolated cavity. However, there is a need to have numerical investigation on different shapes of cavities at different tilt angles and to compare them all together in order to find out the most effective shape of cavity with lesser convective heat losses among others. The improvement can be done by modifying the ratio of aperture and cavity-receiver diameters. In this study, the numerical study is performed on different type of receivers in order to select a good receiver. This study investigates the results to select a best cavity receiver to improve the performance of the system based on the convective heat losses.

2. METHODOLOGY

For steady state numerical investigation, computational fluid dynamics CFD analysis were carried out on ANSYS 16.0, CFX Solver. The inlet velocity of 0 m/s in x, y and z direction was selected for natural convection. Ambient temperature of 298K and relative pressure 101325 Pascal were selected for initialization in all cases. The internal walls of the cavity receiver were considered to be isothermal at a temperature of 873 K or 600°C while the outer walls were assumed to be adiabatic, so that no heat can enter or move outside the body. Air (Ideal Gas) having buoyancy reference density 1.16761 kg/m^3, and Turbulence Prandtl number 0.7 was selected with molar mass 28.96 (kg kmol^-1) and Specific heat capacity 1.0044E+03 (J kg^-1 K^-1). In order to accommodate the buoyancy flow in the flow field, the properties of fluid were varied as a function of temperature across the domain with the assumption that the domain has approximately constant pressure. The gravity was taken as -9.818 m/s^2 in y-direction (downward). K-Omega SST (Shear Stress Transport) model was opted in turbulence model category for the simulations as the y-plus value for all the cases was found to be in acceptable range for this turbulent model. SST (shear stress transport) utilizes two equation turbulence model of eddy equation. It is satisfied model for prediction of separation near wall. At outlet relative pressure was chosen as 0 Pascal. The convergence criteria in most of the simulations used is the thresholds for the continuity equation, and the x-, y-, and z- momentum equations were set equally at $1x10^{-4}$, whereas the thresholds for the energy equation and the eddy viscosity transport equation were set at a smaller value of $1x10^{-6}$ due to the fact their residual were relatively less than those of the others.

The selection of domain size and the mesh sensitivity analysis was done after careful investigation to avoid any thermal stratification. The selected domain is shown in Figure 1. To illustrate the operation of our model system in an open environment, the domain selected was of cylindrical shape having radius of 6m and length 12.71 m.

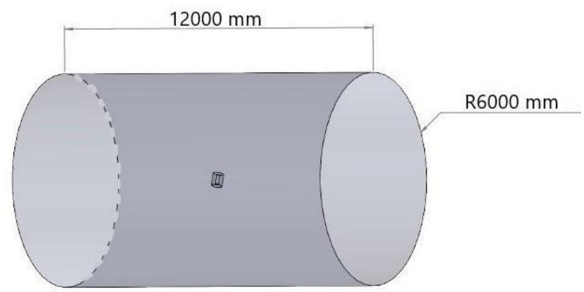
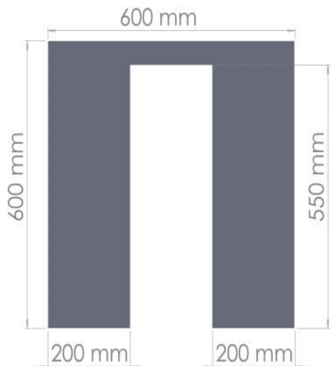


Fig. 1: Three dimensional domain (Cylindrical).

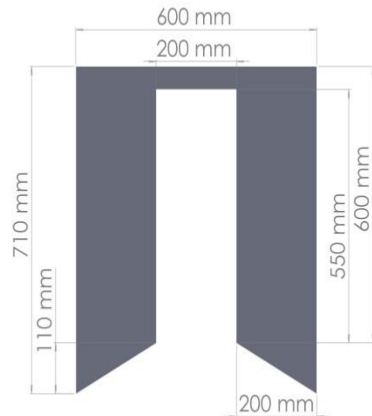
Seven different shapes of cavity (Figure 2) are considered with different changes in the aperture of cavity receivers. First cavity is conical shape with large opening at the aperture. Second cavity is extended conical shape which has large opening from the face and is conical from inside and cylindrical from outside. Third shape is conical shape with small opening which is also conical from inside and cylindrical from outside. Fourth cavity is cylindrical shape cavity which is of cylindrical shape from inside and outside both. Fifth cavity is the modification fourth type cavity with frustum shape included in it. Sixth cavity is rectangular shape cavity which is rectangular from inside and cylindrical from outside. Seventh type cavity is the modification of the sixth type cavity with frustum shape included in it. All the shapes of cavity are kept at different tilt angles from 0° to 90°

3. VALIDITY OF SIMULATION:

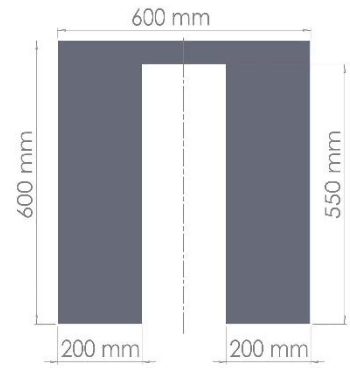
The simulations were performed on the frustum shaped cavity receiver at different attack angles of dish which is relative to the wind direction, ranges 0° to 90°. The above mentioned numerical setup was adopted and the obtained results were compared with Paitoonsurikarn [19] model and Uzair et al. [27] model and the results came out to be similar trend of reduction of convective heat losses and thus our numerical setup is validated (Figure 3).



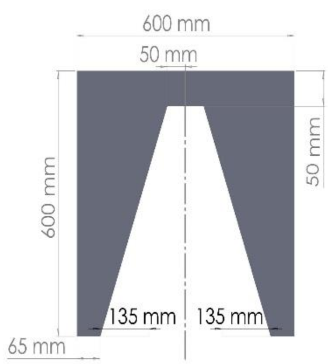
Rectangular shaped Cavity



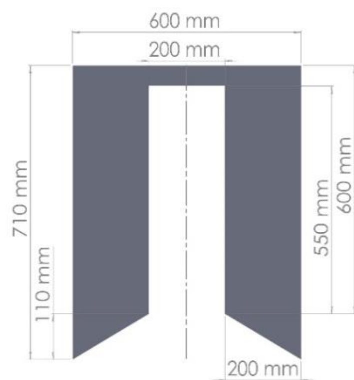
Rectangular frustum Shaped Cavity



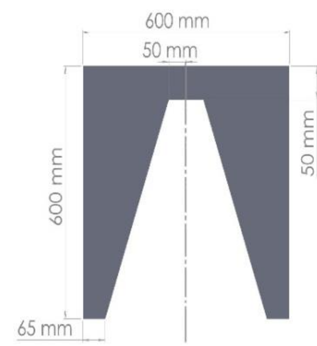
Cylindrical Shaped Cavity



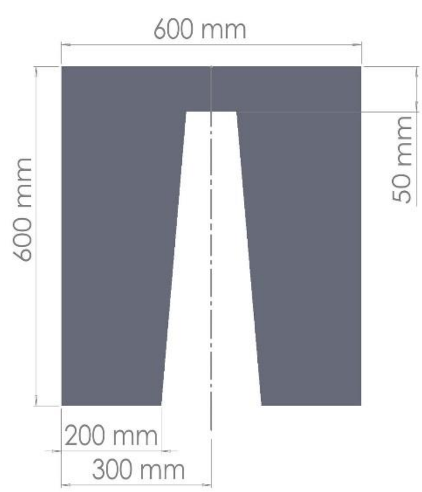
Conical Shaped with Large Opening Cavity



Cylindrical Frustum Shaped Cavity



Extended Conical Shape Cavity



Conical Shaped with Small Opening Cavity

Fig. 2: Shapes of cavity used in the study.

4. DISCUSSION AND RESULTS:

From Figure 3, it is clear that the convective heat loss from cavity receiver is dependent on the tilt angle. As the face of cavity receiver turns down, the convective heat loss decreases dramatically. The maximum convective heat loss occurs with the cavity facing on the side plane. As the air enters the cavity's aperture from its lower half and leaves the cavity by sweeping from the interior from its upper half as a hot pattern in the upward direction and as the distance from the exit of cavity increases, temperature decreases due to hot air mixing with cool ambient air in the surrounding. Due to the stagnation conditions that have been applied in numerical setup at the inlet of the domain of flow field, the temperature gradient that has been formed between the cavity wall and its surroundings, a thermo-siphon is created due to which convection heat transfer occurs, causing loss of heat from the walls of cavity receiver aperture. In the results, the average wall heat flux of the interior of cavity is monitored and the converged value is used to find the losses of heat in different shapes of cavities. The simulation was performed at different tilt angles (0°, 30°, 45°, 60° and 90°). In order to show an idea, only two cases are shown here i.e. when the cavity is facing down and when the cavity is facing sideway. Figure 4 shows the velocity and temperature contours of all the selected cavities when face of cavity receiver is facing sideway. At this tilt angle, the cavity having conical shape with small opening showed the minimum heat loss compared with other cavity receivers. From Figure 5, the velocity and temperature contours of selected cavity receivers can be seen.

At 0 degree, as the bottom of the cavity wall heats up, the air intact with it also heats up, and due to the natural tendency of thermosiphon, hot air rises and cold air takes its place. As hot air rises up, some part of it is caught with the top wall of the cavity receiver, and the remaining leaves the cavity and rises up. Thus, a stagnation zone is created near wall of the cavity and hence its temperature rises. While, a continuous flow of air upwards, from the cavity takes place, strong stagnation zones are created above, below and behind the outer walls of cavity, having constant temperature as no heat transfer takes place at those locations. Consequently, the maximum heat transfer happens when the cavity receiver is horizontally facing the inlet due to less hot air trapped and small stagnation zones inside cavity in all the cases of 0° (Figure 4a- 4g). In addition, the local circulation exists below the lower lip.

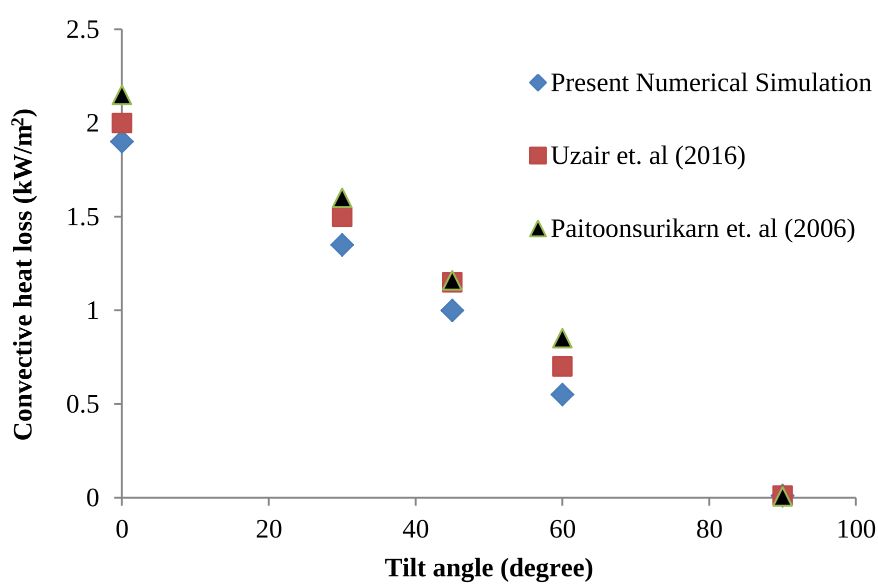
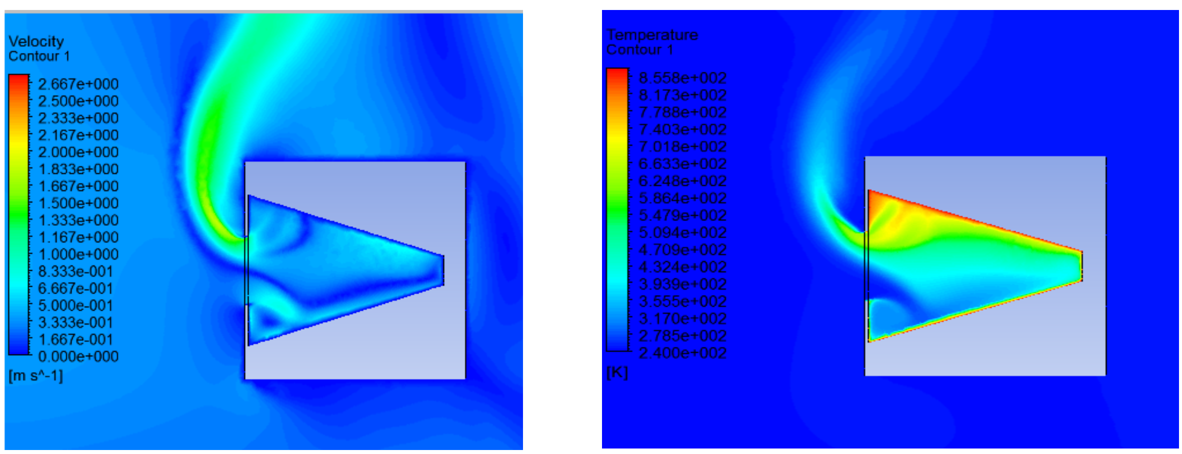


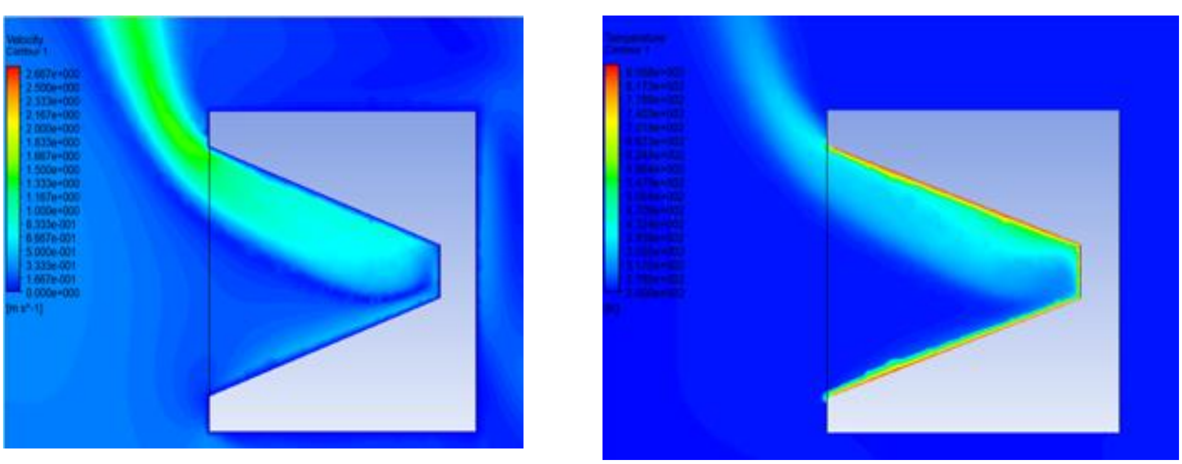
Fig. 3: Validation of numerical simulations with other correlations.

At 90 degrees , when the inner walls of cavity heated at 873K thermosiphon started creating in the middle of interior of cavity due to temperature variations due to which the symmetrical circulation inside the cavity can be observed which means almost whole fraction of air is trapped inside the cavity, and only minute portion of air manages to escape from both sides of the cavity, temperature inside the cavity reaches its maximum value and heat loss due to convection reaches its minimum value, a large stagnation zone is present at top of the outer wall of cavity while stagnation zones at left and right of the outer wall of cavity are also present but are not intact with the wall instead they are certain distance apart which results from the different wall temperature boundary condition on each cavity wall inside the cavity. Figure 5 is clearly showing; the bottom wall temperature is not as hot as those of other walls. Therefore, the air in the interior of cavity receiver is heated and rises along the side wall. After it approaches the bottom wall, it is slightly cooled down and descends along the center channel of the cavity. In figure 5(a), the cavity with large conical area from inside and a stoppage at bottom hot air traps at that particular which makes it has less convective heat losses as compared to figure 5 (b) in which the bottom has no stoppage. In figure 5 (c), L/D ratio decreases to less than 1 which shows that less air trapped inside cavity thus the convective heat losses increases. When L/D ratio changes to equal to 1 as shown in figure 5 (d), convective heat losses further increases due to greater amount of heat leaving the cavity which shows Extended conical shape cavity with L/D ratio greater than 1 (figure 5c) has the lesser convective heat loss among others of same shape but different L/D Ratio. In figure 5c, due to smaller conical area inside cavity greater amount of air trapped than others shape of cavity inside cavity, which shows less heat loss in the conical shape cavity with small opening at 90°. While the temperature contours of figures 5d-5g showing greater amount of temperature just near the walls in the upper part in very smaller area which shows they have greater heat losses than the conical shape cavity with small opening.

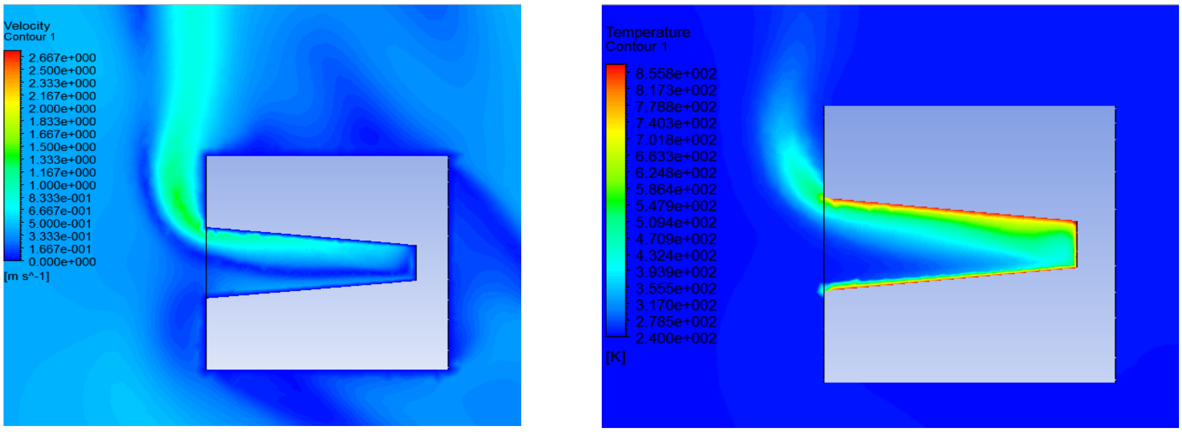
Thus, by inspecting the above results of the simulations, it was found out that the air velocity in the interior of the cavity receiver decreases as distance increases from the opening of the cavity and the heat loss by convection increases as the area inside the cavity increases, thus the cavity with minimum area has minimum heat loss by convection.



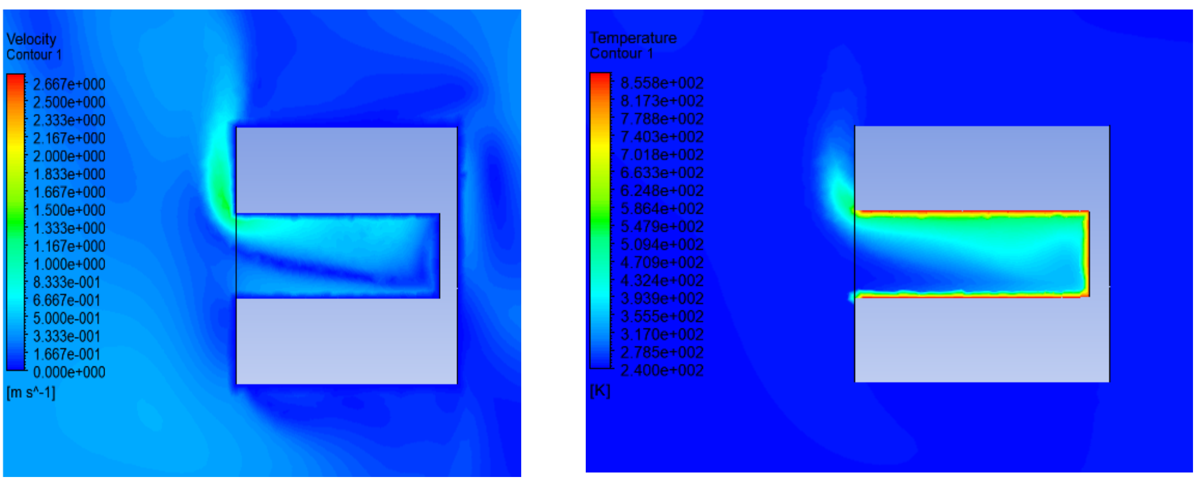
(a) Conical Shape with Large Opening cavity receiver.



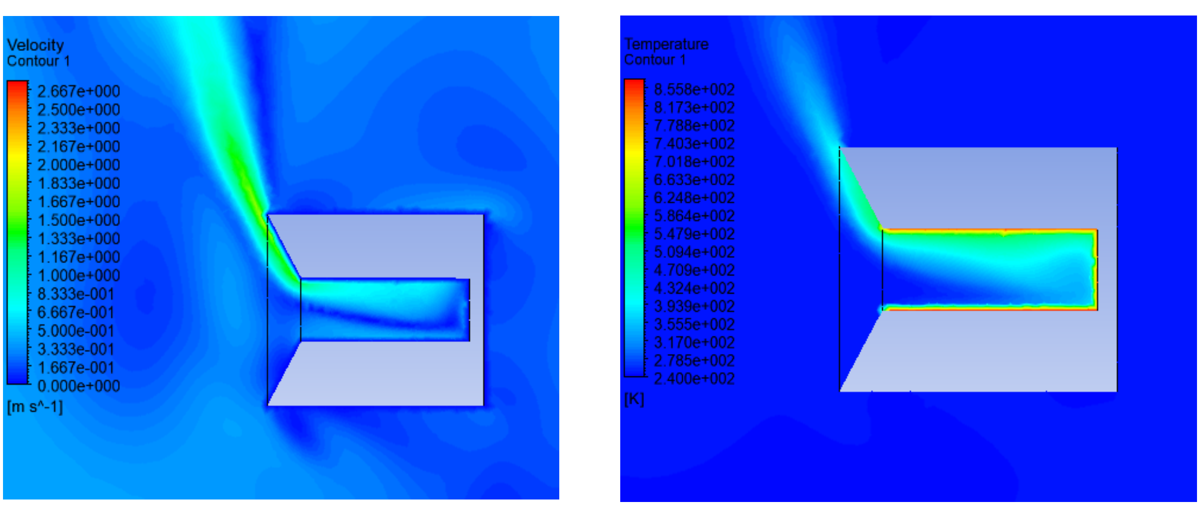
(b) Extended Conical Shape cavity receiver.



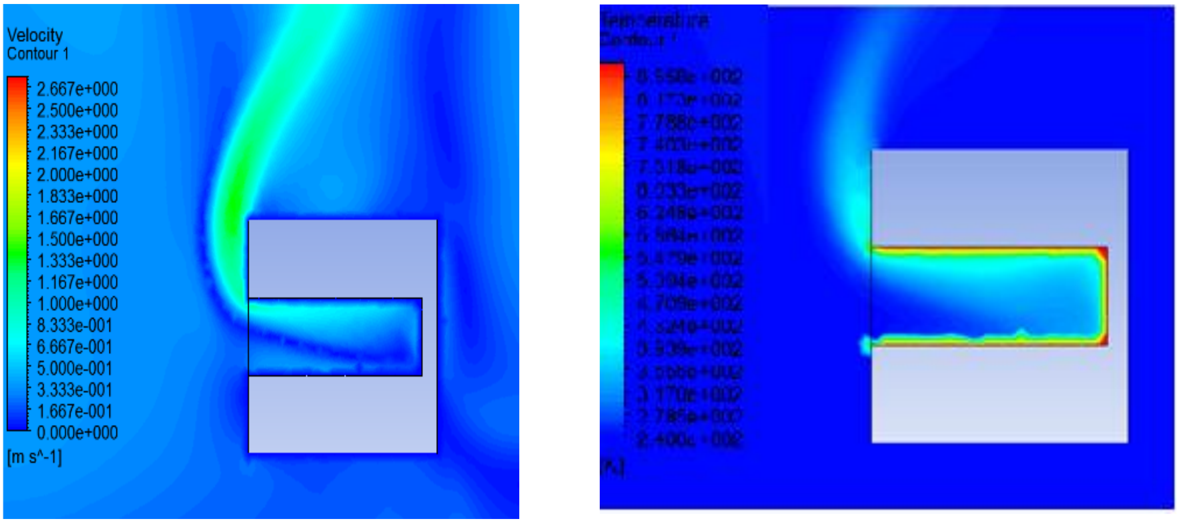
(c) Conical Shape with Small Opening cavity receiver.



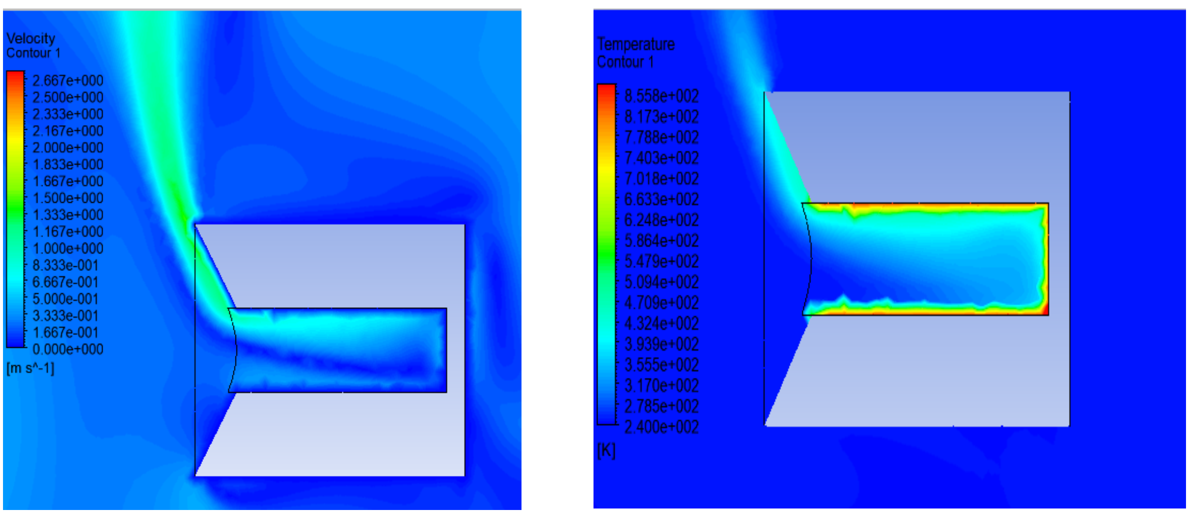
(d) Cylindrical Shape cavity receiver.



(e) Cylindrical Frustum Shape cavity receiver.



(f) Rectangular Shape cavity receiver.

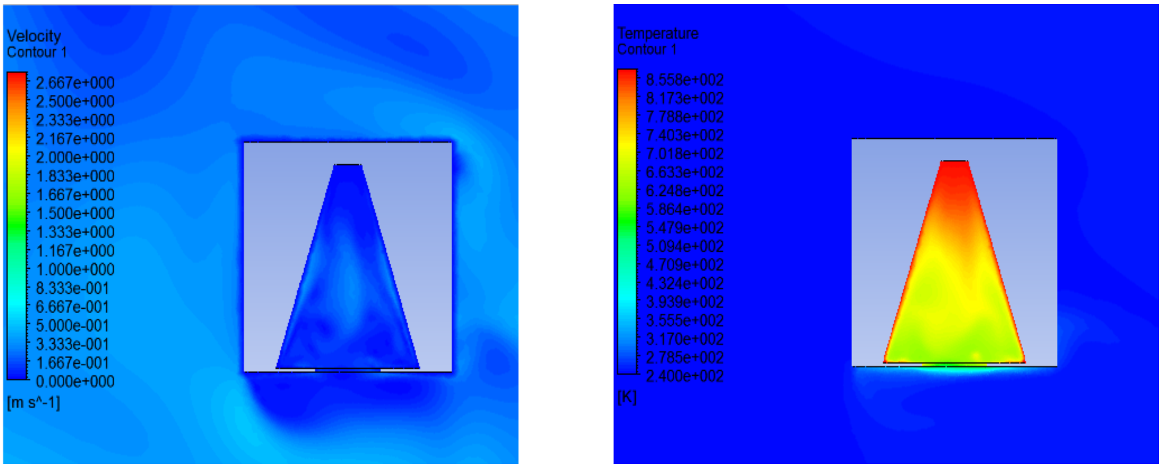


(g) Rectangular Frustum Shape cavity receiver.

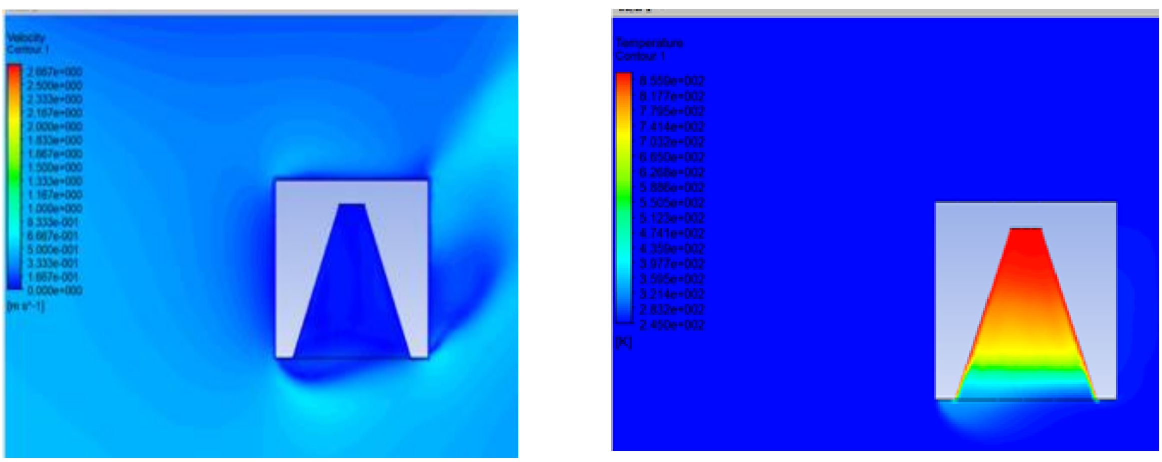
Fig. 4: Velocity and Temperature contours of selected cavity receivers at 0°.

Further, convective heat losses were also calculated from different cavity receivers at different tilt angles ranges from 0° to 90° in order to find the optimal cavity receiver shape at different tilt angles. Figure 6 is clearly showing the heat losses from extended conical shape cavity were greater than other shapes. It is also clear that convective heat losses decreased as the tilt angle changed from 0° to 90° which is the angle when the cavity is vertically downward. From figure 6, it is clear that the convective heat losses of conical shape with small opening cavity were the lowest among others at all tilt angles from 0° to 90° and hence have the highest efficiency. So, the fewer amounts of convective losses of heat at natural convection conical shape with small cavity must be chosen. This is in the good agreement with the observation made from the velocity and temperature contour plots as shown above which indicates that there is relatively small amount of the uprising plume.

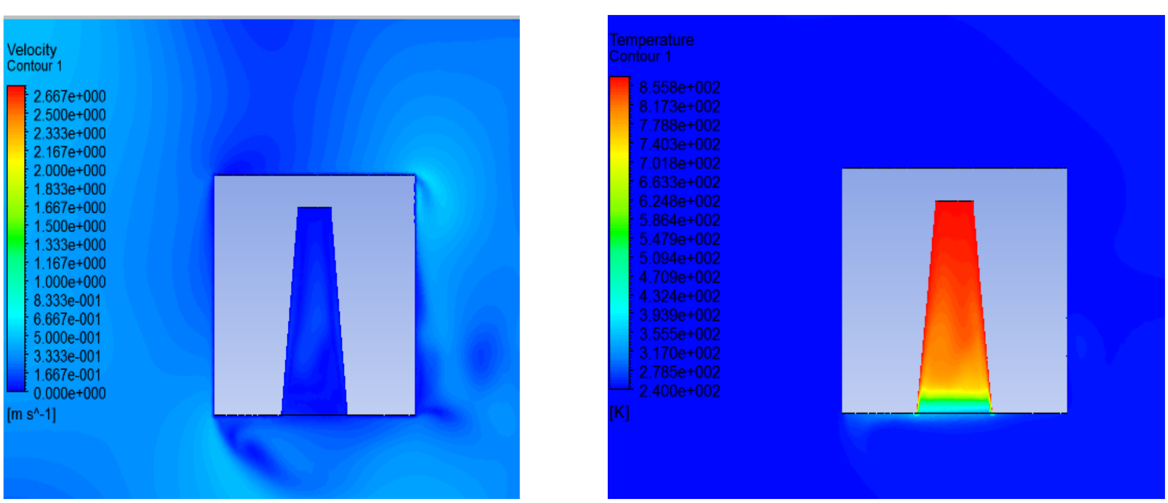
VELOCITY CONTOURS **TEMPERATURE CONTOURS**



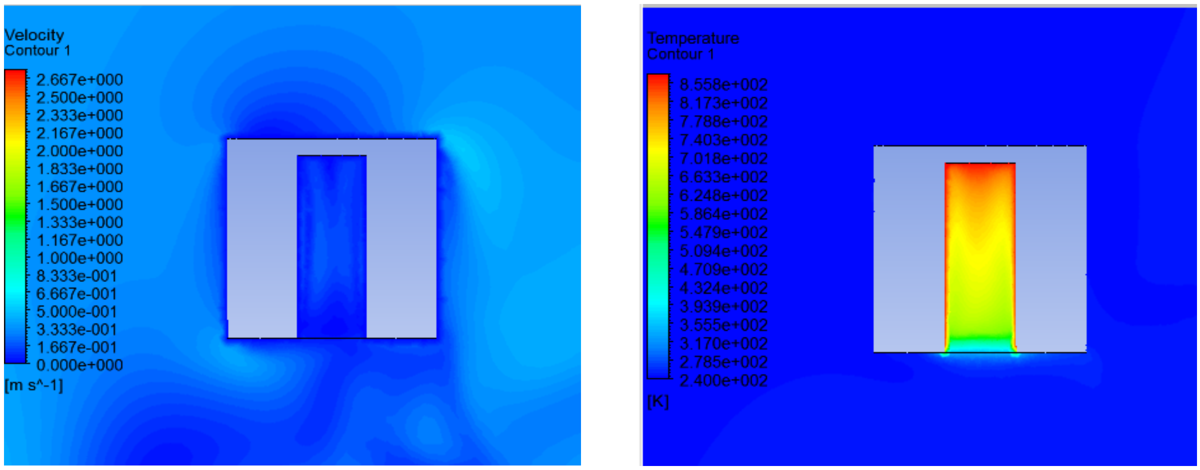
(a) Conical Shape with Large Opening cavity receiver.



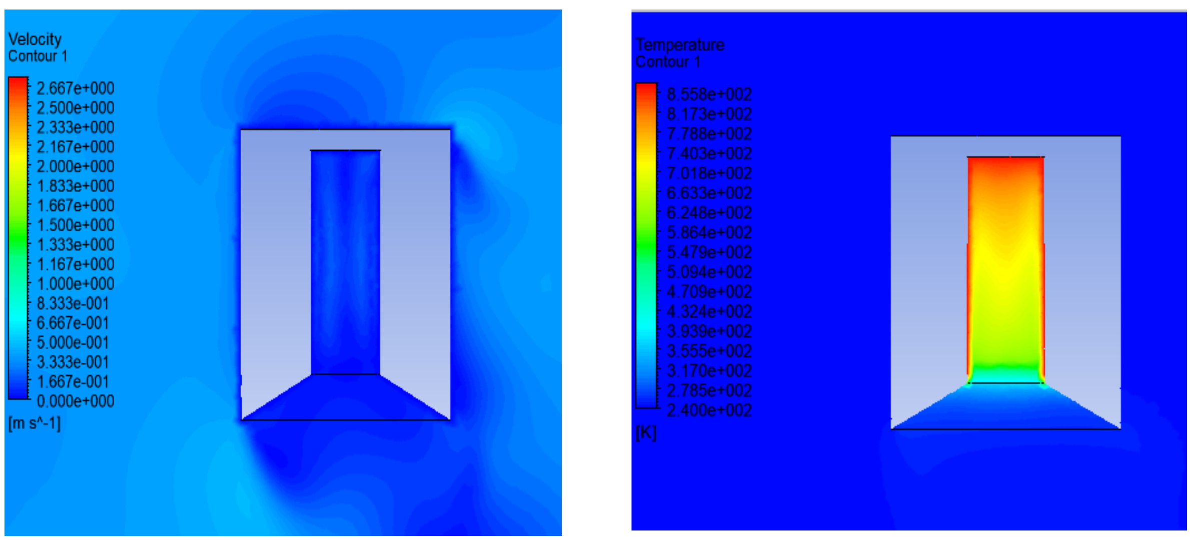
(b) Extended Conical Shape cavity receiver.



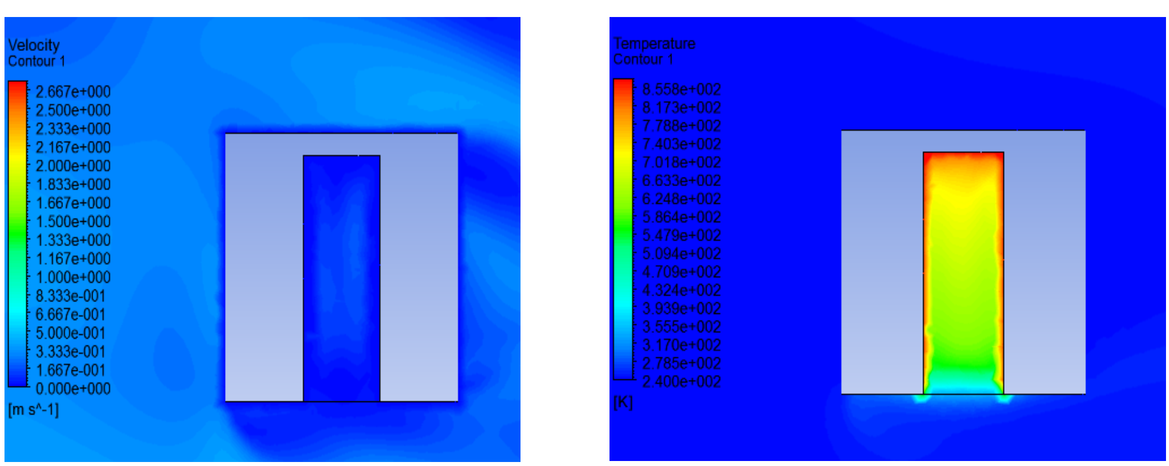
(c) Conical Shape with Small Opening.



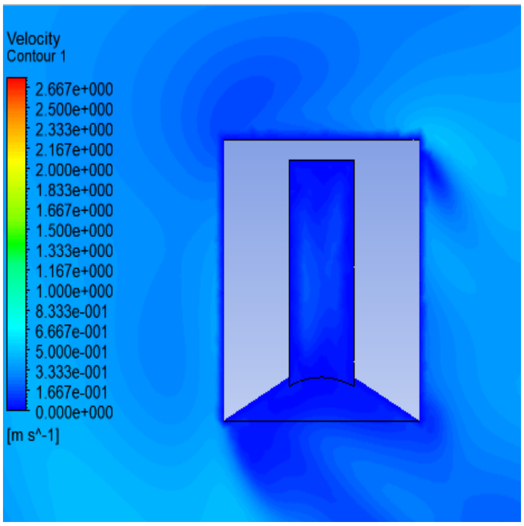
(d) Cylindrical Shape cavity receiver.

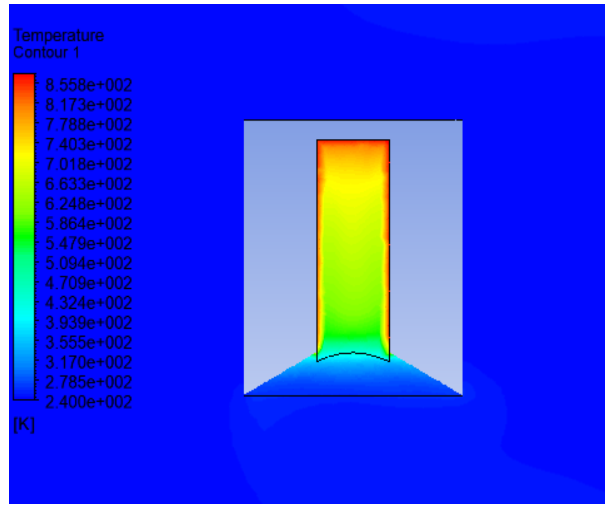


(e) Cylindrical Frustum Shape cavity receiver.



(f) Rectangular Shape cavity receiver.





(g) Rectangular Frustum Shape cavity receiver.

Fig. 5: Velocity and Temperature contours of selected cavity receivers at 90°.

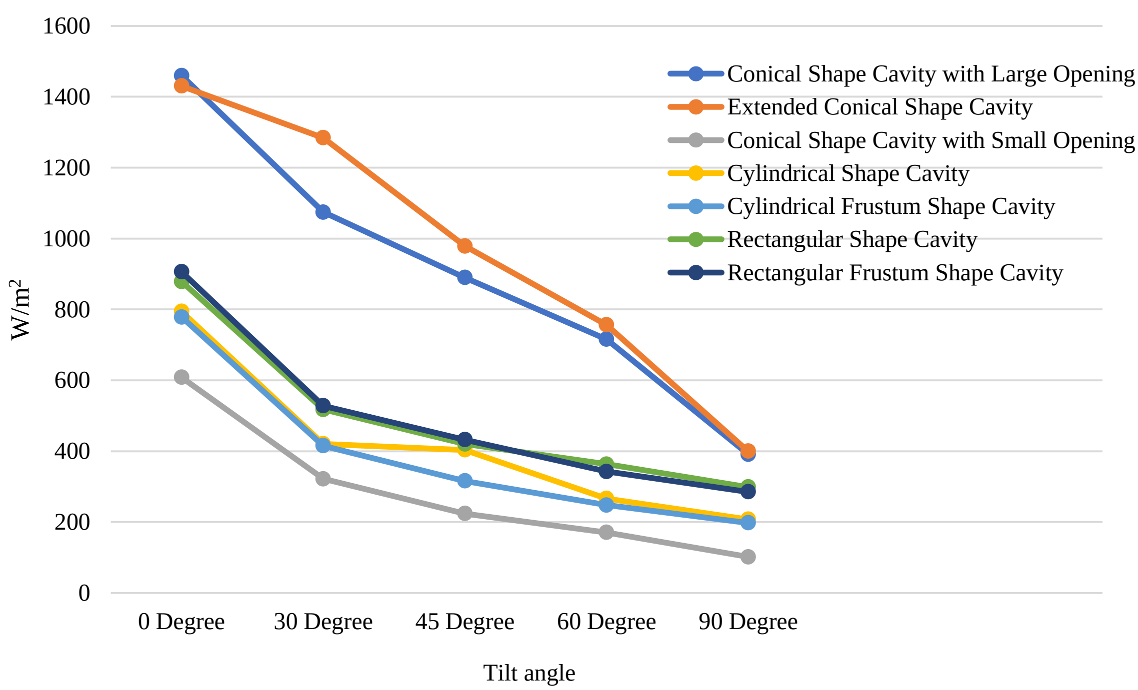


Fig. 6: Convective Heat Losses at different tilt angles.

5. CONCLUSION

This study focused to investigate the optimal shape of cavity receiver in order to improve the output of parabolic-dish system. The main investigation was based on the convective heat losses form the different cavity receivers. The results showed that the conical shaped cavity receiver performed efficiently. The losses in the form of convective heat were very low compared with other shaped cavities. The conical shaped was further examined to investigate the effect of aspect ratios. With higher aspect ratio, the heat flux in the upper zone of the cavity receivers was found to be very low making it worst operating scenario. So, it is recommended to use conical shaped cavity receiver with L/D ratio less than 1. These numerical results could be helpful starting point to design and optimize the solar parabolic dish concentrators systems.

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