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Effect of Converging Duct on Solar Chimney

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ABSTRACT

Solar chimney is very useful in terms of improving indoor thermal comfort. There are not many studies or simulation that have been done for a converging duct of solar chimney A CFD model of a solar chimney is simulated in this study using ANSYS Workbench 19.2 to find out the effect of convergent of the solar chimney to the velocity in the solar chimney and the air changes per hour in the developed numerical model. Solar chimney is mainly used in hot climate as a passive solar cooling system that can regulate the temperature and increases ventilation. The data needed to simulate the numerical model is taken from previous study. Using fluid flow (CFX) a 2D CFD steady state is simulated by 10 mm of thickness for the model. Four openings were set up to let air leave and enter the cabin. There were four configurations of bottom-top ratio were studied, 1:1, 1:0.8, 1:0.75 and 1:0.5. The 1:0.5 ratio gives the highest outlet velocity while the 1:1 ratio have the highest air changes per hour. Converging the solar chimney bring the solar chimney performance down.

1. Introduction

Indoor thermal comfort is a very important aspect in the operational of a building. Good indoor thermal comfort helps to increase productivity and at the same time avoids undesirable health issues to the occupants [1]. The most important parameters determining indoor thermal comfort are the indoor temperature and indoor air circulation [2]. These two parameters often controlled by air-conditioning system which consume massive amount of electrical energy thus increase the operational cost of the building. One of the inexpensive ways to regulates the indoor temperature and indoor air circulation is through the installation of solar chimney. A solar chimney is a passive solar heating and cooling system that make use of the solar heat energy to regulate the temperature of a building as well as providing ventilation. Among the early design that applied similar concept to the solar chimney is the Trombe wall [3]. The similarity between these two is both designs utilize the

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solar heat energy to heat the wall surface to initiate natural convection on the inner surface which will further allow air to be vented out from the indoor space.

Considerable number of researches have been made on solar chimney design and performance. In general, solar chimney has been proved to be more practical for the cooling purpose instead of heating [4,5]. The full depended of solar chimney towards the solar heat energy make it very suitable for a tropical country like Malaysia where relatively high sun irradiation is available throughout the year [6]. Gan [4] has conducted a comparison between the performance of solar chimney and the Trombe wall for the purpose of space cooling. The work utilizes the computational fluid dynamics technique to predict the ventilation rate inside the Trombe wall. It has been reported that, solar chimney is more preferable than Trombe walls for passive ventilation. Thanks to the less cost extensive of computational fluid dynamics in comparison with the experimental approach, it has been utilized by numbers of researches to evaluate effects of various parameters on the performance of solar chimney such as height, inclination angle, width and depth of solar chimney [7–15]. In the work of Bassiouny and Korah [16], both experimental and numerical approach have been conducted. The work focuses on the effect of chimney inclination angle on air change per hour and indoor flow pattern. The analytical results showed an optimum air flow rate value was achieved when the chimney inclination is between 45° and 70°. Thus, the performance of solar chimney can be further improved by altering the geometrical parameters of the solar chimney duct.

In terms of height, inclination angle, width and depth of solar chimney there are many studies have been conducted but there are not many studies that have been conducted for a diverging or converging solar chimney. The present study aims to find the effect of converging duct of solar chimney in terms of u-velocity vector, velocity profile at the outlet of solar chimney, vorticity and air changes per hour (ACH).

2. Methodology

2.1 Computational Domain

Figure 1 illustrates a physical domain schematic with an attached inclined L-length chimney that have width and angle, θ. The domain is considered to have an open side window 1 m and from the floor it is 1 m high. The dimensions considered were 3 m height by 3 m wide for this domain, and the chimney was considered 1 m long and the air gap was taken as 0.35 m. Table 1 shows all the variables that have been used for this study.

Table 1
All case study bottom-top ratio

Case	Bottom-Top Ratio
Case A	1:1
Case B	1:0.8
Case C	1:0.75
Case D	1:0.5

The domain modelled contains only fluid domain that is air at 25 °C as the material. The reference pressure for the air is at 1 atm. The air enters the open window and leaves through the solar chimney. Buoyancy model is turn on referring at 25 °C and gravity is put on at y-direction. The air inside the domain is considered laminar with thermal energy and thermal radiation activated.

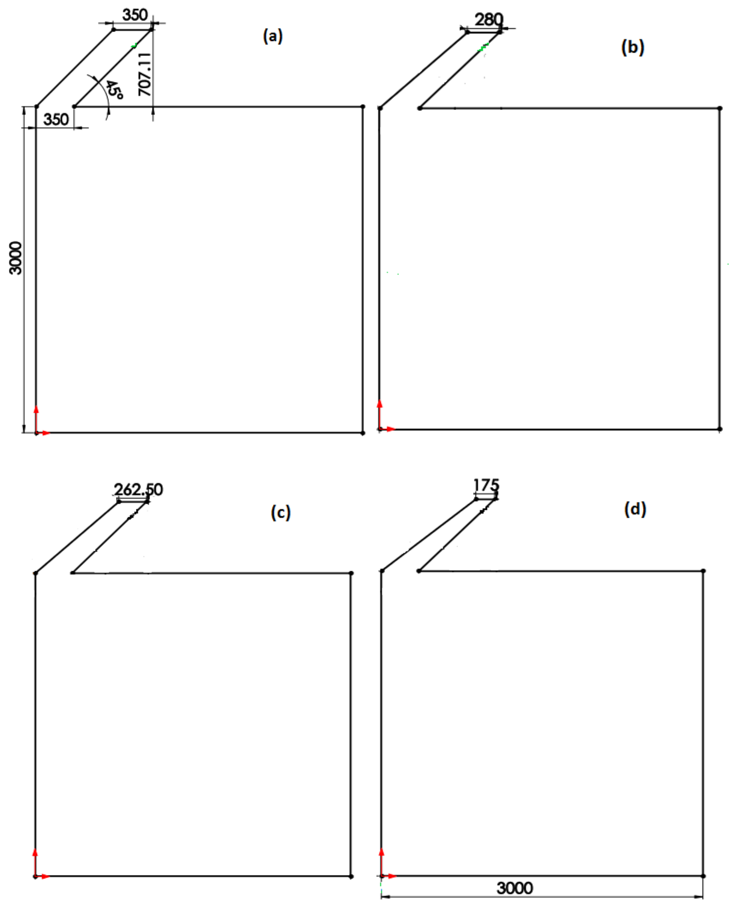

Fig. 1. Configuration for the study (a) Case A, (b) Case B, (c) Case C, (d) Case D

2.2 Computational Setup

Figure 2 and Table 2 shows details on boundary condition to be applied for the simulation. The model considered is two-dimensional model with front and the back surface set as symmetry boundary condition. The solar chimney drives element to create a breeze within the fluid domain naturally, air entering the chimney was considered to have the same room temperature. The exchange of energy between other room and surrounding walls has been neglected. Solar irradiance setup for the simulation is 720 W/m^2 with 306 K of outside temperature.

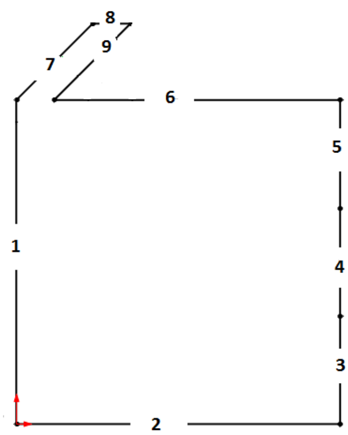

Fig. 2. Location for boundary condition

Table 2
Specification for boundary condition

Location	Surface Name	Boundary Condition
1,2,3,5,6	Wall	Wall (Room Temperature)
4	Window	Opening (Room Temperature)
7	Glazing	Glass Heat Flux (0.9 emissivity)
8	Chimney	Opening (Outlet Temperature)
9	Absorber	Absorber Heat Flux (0.95 emissivity)

The mesh size of the model is equivalent to model thickness (0.01 m) and running up to 6000 iterations with convergence criteria of 0.0001.

2.3 Performance Criteria: Air Changes Per Hour (ACH)

As a result of mechanical and passive ventilation and infiltration through the cabin, air is continually exchanged between buildings and their surroundings. For the purposes of ventilation design and heat loss calculations, the rate at which air is exchanged is an important property and is expressed in air changes per hour. If a building has a rate of air change of 1 ach, this means all of the air within the domain being replaced in an hour period. ACH is formulated by:

$$ACH = \frac{600Q}{V} \quad (1)$$

Where Q is volumetric flow rate (cubic meter per minute) and V is volume of the room (cubic meter).

2.4 Validation

To make sure the computational model and its setup are reliable the result must be compared and validated with the previous study [16]. Figure 3 shows the comparison between the simulation with theoretical and experimental results. The simulation is validated and can be seen at Tables 3, 4 and 5 where Table 3 shows the comparison of outlet velocity data, Table 4 shows comparison of the mass flow rate and Table 5 shows the grid independence study. From Tables 3, 4 and 5 this simulation can be used for this study because of the similarity of the graph pattern even though the percentage error is quite high.

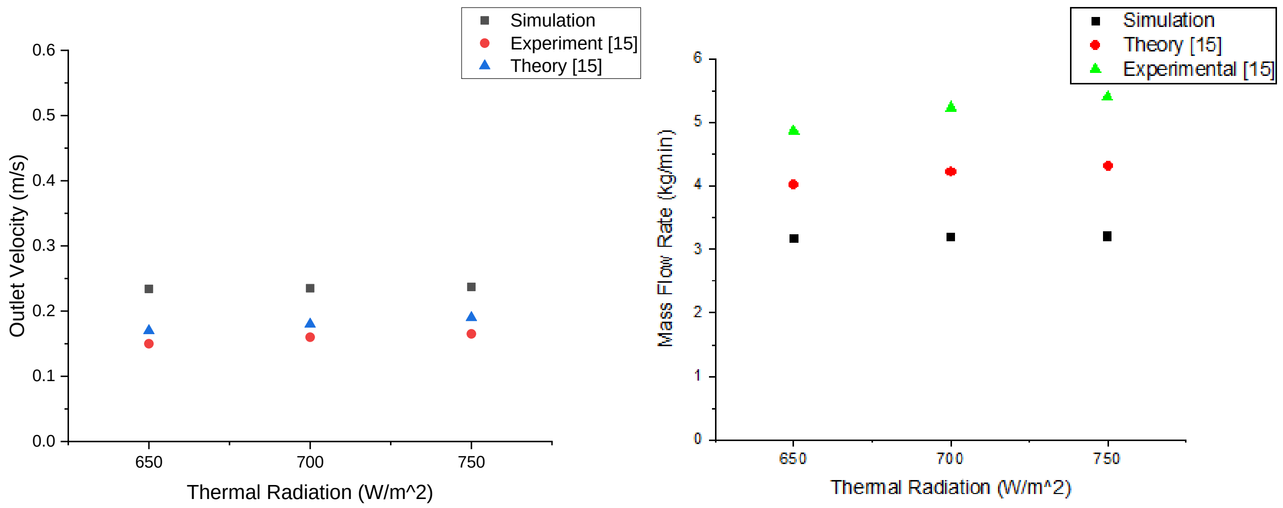

Fig. 3. Outlet Velocity and Mass Flow Rate

Table 3
Percentage of error for outlet velocity

Thermal Radiation (W/m^2)	Percentage of error for theory results (%)	Percentage of error for experiment results (%)
650	37.64	56
700	30.56	46.88
750	24.73	43.64

Table 4
Percentage of error for mass flow rate

Thermal Radiation (W/m^2)	Percentage of error for theory results	Percentage of error for experiment results
650	21.32	34.84
700	24.51	39.04
750	25.76	40.61

Table 5
Grid independence study

Mesh size (m)	Outlet Velocity (ms^{-1})	Time taken for 6000 iterations
0.1	0.35	1 hour
0.075	0.22	2 hours 15 minutes
0.05	0.155	3 hours
0.025	0.152	5 hours 30 minutes
0.01	0.15	10 hours 45 minutes

3. Results and Discussion

The simulation results of the present study will be discussed in terms of velocity contour, vorticity contour, vector plot, velocity profile together with the Air changes per hour. The results will provide physical explanation on the flow phenomenon inside the solar chimney and its intended attached space.

3.1 Velocity Contour

Figure 4 shows the u velocity component contour of four considered solar chimney configurations. The velocity contours were plot in the range of -0.27 m/s to 0.29 m/s with the positive direction of the flow is set to the right side of the computational models. In general, high u velocity component can be observed at the solar chimney area for all cases, justifying the existent of the buoyancy effect due to the surface heat flux. Lower u velocity component can be observed in the cabin area. For the Case A, strong negative u velocity component can be observed entering the cabin area from the window. The relatively high value of u velocity component indicates good penetration of outside air into the cabin area. The penetration can be observed to reduce as the ratio of the chimney outlet reduces in the Case B, C and D. Figure 4 also shows that the top right and bottom area of the cabin is subjected to very low positive u velocity suggesting the occurrence of rotational flow in the respective area. The phenomenon will be further discussed in the next section of the writing.

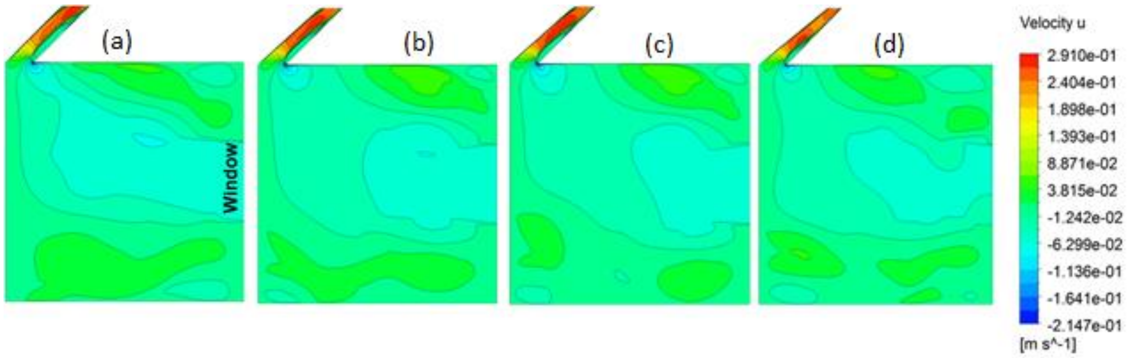

Fig. 4. Velocity Contour (a) Case A, (b) Case B, (c) Case C, (d) Case D

3.2 Velocity Vector and Vorticity Contour

Figure 5 shows the vorticity contour and vector plot of each solar chimney configurations considered in the present study. The results intended to discuss the possibility of the rotational flow occurrence has been suggested earlier in the previous section. The vorticity contour has been set to the range between 0 s^{-1} to 1 s^{-1} while the vector representing total velocity magnitude inside the computational domain. Vorticity is described as the curl of the velocity field mathematically and is therefore a measure of the fluid's local rotation. This definition makes it a quantity of vectors. Higher vorticity value indicates wind speed increasing when moving away from centre point of trough and vice versa. In general, the vorticity can be observed to be high in the top right and bottom area of the cabin.

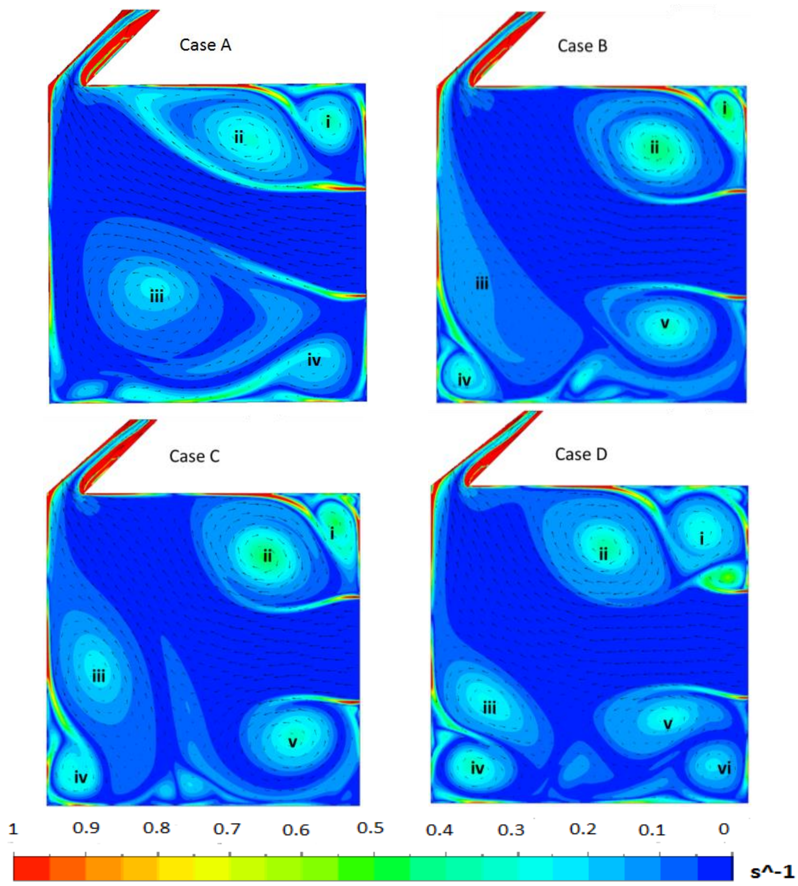

Fig. 5. Swirl point for each case

The numbers of vorticity core or swirl points can be observed to be minimum in the Case A at four points and maximum in the Case D at six points. All the points have been labels as shown in Figure 5. For the Case A, the top right area of the cabin has been dominated by the rotational flow originated at point labelled as i while the lower area is dominated by two distinguished rotational flow originated at points labelled as iii and iv. The occurrence of the rotational flow is cause by the main air flow path from the window to the solar chimney leaving the air in the areas to continuously remain in the cabin area. As the penetration of the flow from the window become weaker in the Case D, the formation of rotational flow also becoming relatively more significant. This is supported by the existence of six swirl points in the cabin area of Case D. Although the top right area is observed to have similar formation of rotational flow, the bottom area of Case D shows multiple existence of the rotational flow origin. The low vorticity values observed in the bottom cabin area indicate poorer air flow that take place in the area. Vector plots shown in Figure 5 are in line with the discussion made in the previous section on the flow penetration from the window into the cabin area.

3.3 Velocity Profile

Figure 6 shows the velocity profile captured at the solar chimney outlet for all the configurations. Total of twenty points have been extracted and plotted to represent the velocity profile. In comparison with all cases, Case A registered lowest average exit velocity at 0.2404 m/s while Case D registered the highest average exit velocity at 0.3135 m/s. At lower solar chimney outlet ratio, the velocity distribution is observed skewed towards the absorber surface. This is caused by early re-attachment of the boundary layer inside the solar chimney as can be observed in Figure 6.

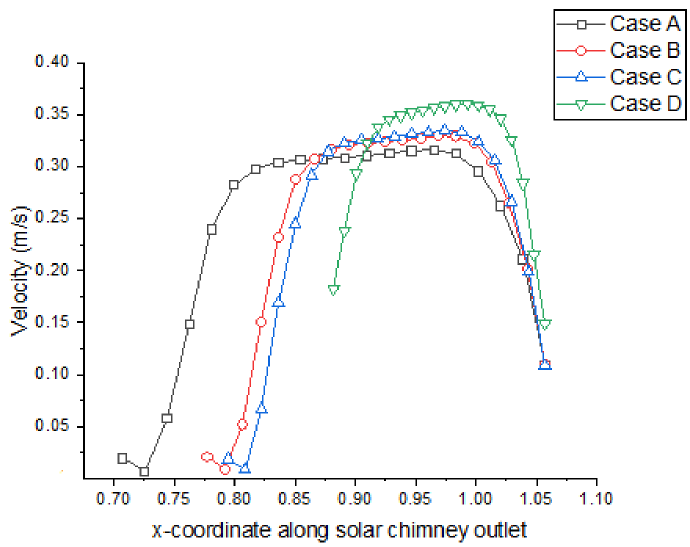

Fig. 6. Outlet Velocity

3.4 Air Changes Per Hour (ACH)

The converging effect of the solar chimney makes the velocity at the outlet increase significantly. This can be said because of the decrement area of the outlet. For Case A, Case B and Case C it has a very similar pattern and the velocity profile ended at 0.1 m/s while for Case D it ended on 0.15 m/s. Even though the average outlet velocity for the Case D ratio is the highest but the ACH for it is the lowest with 15.31. The reduction volume of air inside the solar chimney affects the mass flow rate and ACH.

From window to solar chimney airflow perspective, Case A with the highest velocity of air while Case D with the lowest velocity of air were further proven in the Table 6 below that Case A have the highest of air changes per hour (ACH) while Case D is the lowest. The low velocity inside the cabin for Case D can be seen its impact clearly in terms of mass flow rate and air changes per hour (ACH). Using air properties at 25 °C the ACH is calculated and tabulated.

Table 6
Mass Flow Rate and ACH for each case

Case	Mass Flow Rate (kg/min)	ACH
Case A	3.23605	17.73
Case B	3.17903	17.46
Case C	3.13749	17.25
Case D	2.77525	15.31

The ACH reduction can be seen clearly when the ratio is dropped from 1:0.75 to 1:0.5, Case C to Case D. Reversed flow does not happen for all case. A similar flow patterns can be seen in each simulation from windows opening to solar chimney. Case A is well ventilated and ideal for thermal comfort.

4. Conclusions

The performance of solar chimney has been assessed using a 2D model to find out the effect of converging solar chimney duct to its performance criteria, ACH. This study was limited by the design of the solar chimney that a different orientation can or cannot change the performance of the solar chimney. Data such as mass flow rate, outlet velocity and vorticity has been collected to shows more support to the solar chimney performance. The conclusions for the study are as follows:

i. Converging the solar chimney will decrease the ACH.
ii. Velocity inside the cabin will decrease slightly with decrement of bottom-top ratio.
iii. Case A with the highest ratio gives the best ACH and solar chimney performance.

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