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Performance of a solar chimney configuration to achieve equal flow rate for ventilation of three-story building

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Abstract. In energy-efficient buildings, natural ventilation using solar chimneys greatly reduces energy consumption. In this study, a solar chimney was installed in a three-story building to examine the flow rate of the floors while balancing the flow rate of each floor. To predict the flow rate, a fluid dynamics model was developed based on a computational fluid dynamics (CFD) method with a calculated model of RNG k-e, heat flux $600 \, W/m^2$. By changing design parameters, the air flow was investigated.

Keywords: Solar chimney, energy efficiency, natural ventilation, CFD

1. Introduction

Among the methods for reducing energy consumption in buildings, solar chimneys have been extensively studied by many researchers. Previous studies showed that solar chimneys could provide sufficient ventilation rate for buildings. Shi et al. [1] reported that a solar chimney can supply air at $7.42 \, ACH$ (Air changes per hour – the number of times in an hour that the air inside the room is replaced) for a two – story building in Australia. Tan and Wong [2] claimed that the solar chimneys on the roof of a three – story building in Singapore induced the maximum air speed of $0.49 \, m/s$ inside the building.

When a solar chimney is applied to a multi – story building, different forms have been proposed, such as on the roof [3] or along the wall [4, 13-14]. Its effectiveness has been reported in those studies. Using solar chimneys helped to reduce the room temperature by 0.5–3 ℃ in [14] or up to 5 ℃ in [3], to increase the air speed inside the buildings up to 0.5 m/s [14], and to maintain a daily ventilation rate of 4 times of air exchange per hour for a seven – floor office building [13].

In those previous studies, solar chimneys with constant gaps were employed. Although their effectiveness has been shown, one of their drawbacks was also reported. Both studies [3,4] showed that the induced flow rate decreased at higher floors and the maximum difference was up to 2 times. Zhou et al. [2019] reported that for a two – story building, the temperature of the upper room was higher than that of the lower one of up to 1 ℃. A similar trend was also reported by Punyasompun et al. [3] for a three – story building. Therefore, the ventilation rate and thermal comfort conditions were not equal for all floors in those studies.

To achieve similar flow rates for similar thermal comfort conditions on all floors, in the previous study [5], we tested a solar chimney connected to all three floors of a three – story building with different inlet locations and sizes but also with a constant gap of the air channel. The results showed that the

location of the air inlet (near the floor or the ceiling), the number of the inlet in each room, and the size of the inlet strongly influenced the induced flow rate through each room. However, an equal ventilation rate for all rooms has not been achieved.

In this study, the solar chimney in the previous study [5] was modified. Instead of using a constant air gap, different gaps were designed at different floors. As previous studies [3-5] reported that the higher floors had lower flow rates, it is deduced that the air gap should increase with the height of the chimney to achieve similar flow rates. Therefore, the proposed chimney configuration had larger air gaps at the higher floors. Floors are considered as a new room with empty space and no activity inside the room.
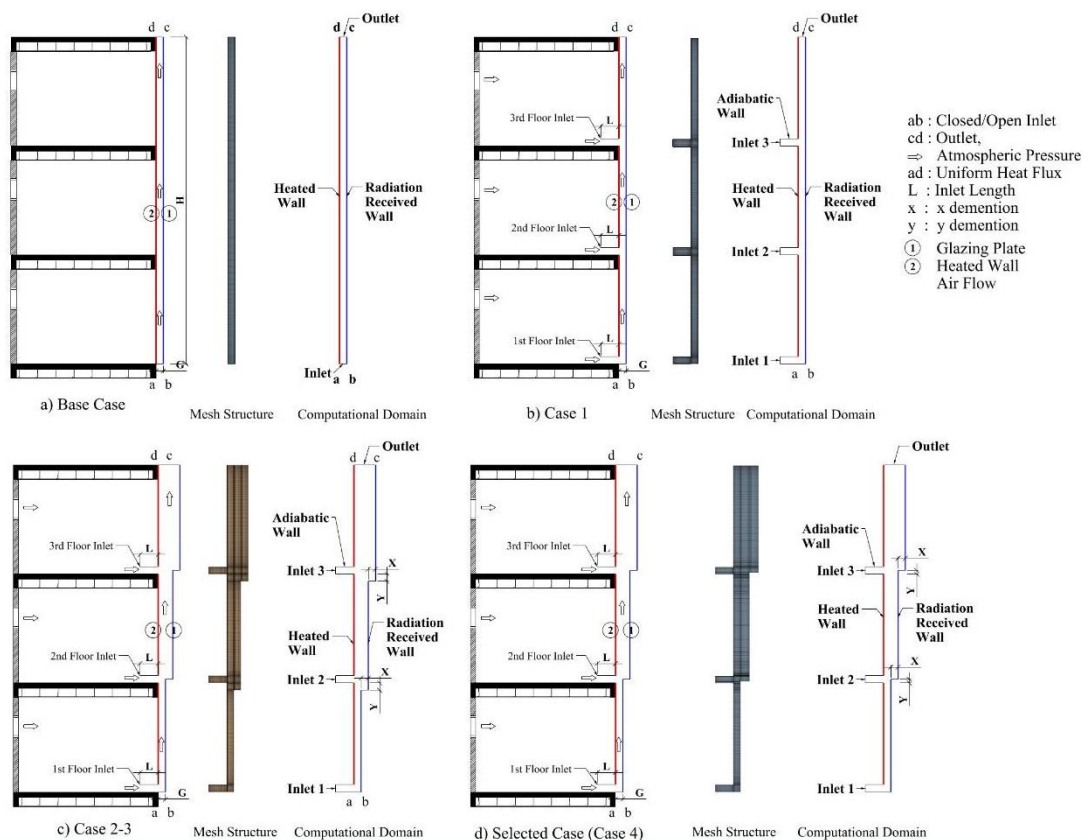

Figure 1. Schematic of a solar chimney for ventilation of a three – story building (H=9.0 m, G=0.2 m) with computational domain and mesh.

2. Problem formulation and Numerical Method

2.1. The solar chimney

The solar chimney consists of an air channel enclosed by an outer wall and a wall of the building. In this study, a solar chimney is assumed to be integrated on the right side of a three – story building, as sketched in figure 1 and tested under 4 configurations. In figure 1a, the solar chimney is vertically and measures $9m x 0.2\ m$ in the height and gap, respectively. Solar chimney's right side is a wall and the heated wall is on the left side of the chimney. The two openings are located at the bottom (inlet) and the top (outlet) of the solar chimney, respectively. Then, to examine the internal flow of the solar chimney, inlets near the floor (lower inlet) on each floor of the building were installed as depicted in figures 1b and 1c. In addition, in figure 1c, in order to investigate the variation in the inlet flow rates of the floors, the dimensions of solar chimney are changed horizontally (case 2) and longitudinally (case 3). The width of

the solar chimney on each floor is extended to size x (Case 2) and height to size y (Case 3). In all cases except the base case, the lower end of the solar chimney is closed so that the inlet flow at the floors is higher and the upper outlet is always opened to let the air flow out of the solar chimney.

2.2. Assumptions and governing equations.

For obtaining the induced air flow rate through the chimney, together with the assumption of steady flow, time – averaged flow variables can be described with the Reynolds – Averaged Navier Stokes equations [6,7]. The equations represent the conservation principles of the mass, momentum, and energy of the flow. Using the Einstein summation notation, the equations are as follows.

$$\frac{\partial u_j}{\partial x_j} = 0 \tag{1}$$

$$\frac{\partial (u_i u_j)}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} - g_i \beta (T - T_0) + \frac{\partial}{\partial x_j}\left(\nu \frac{\partial u_i}{\partial x_j} - \underline{u_i' u_j'}\right) \tag{2}$$

$$\frac{\partial (T u_j)}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\frac{\nu}{Pr}\frac{\partial T}{\partial x_j} - \underline{T' u_j'}\right) \tag{3}$$

The turbulence tress $\underline{u_i' u_j'}$ in Equation (2) and the turbulent heat flux $\underline{T' u_j'}$ in equation (3) were solved with the standard k–ω model with modification for low – Reynolds number effects by a damping coefficient for the eddy viscosity. This turbulent model was also employed in previous studies of solar chimneys [8]. For the solar chimney in figure 1, the gap – to – height ratio, G/H, is 4.25%. Gan [12] showed that for solar chimneys with very low G/H, a computational domain fitted with the air channel was sufficient. For discretizing the governing equations, equations (1), (2) and (3), Finite Volume Method was used on a structured rectangular mesh with the ANSYS Fluent CFD Code (Academic version 2020R2).

The mesh density was higher near the walls of the chimney where the gradients of the flow variables are strong as displayed in figure 1b. To check effects of the mesh resolution, we ran the preliminary numerical model for the solar chimney in the experiment by Yilmaz and Fraser [9]. The number of elements in each direction was increased gradually and the according induced flow rate was plotted in figure 2. Denser meshes resulted in a change of the flow rate below 1.0%. The equivalent required non-dimensional distance of the first grid point from the solid surfaces, or y^+ was below 1.0, which agrees with the findings by Zamora and Kaiser [8].

For the boundary conditions, atmospheric pressure was applied at the inlets of the rooms and the outlet of the solar chimney. The size $L = 0.5m$ is the distance from the inlet to the solar chimney is an adiabatic wall. At all inlets, turbulent kinetic energy and a length scale were used. As the turbulence should be low [9], it was assumed a turbulent intensity of 2.0% and a length scale of half of the inlet height, i.e. $0.1\ m$.

2.3. Validation of the numerical method

The CFD model was applied to predict the induce flow rate through the solar chimney in the experiment by Yilmaz and Fraser [9]. The solar chimney is similar to the base case (figure 2). The height and the gap of the chimney were 3.0 m and 0.1 m, respectively. In the experiment, uniform heat fluxes were applied on a surface of the air channel and the corresponding wall temperatures were in the range of 60 – 130ºC. Uniform wall temperatures were also applied in the CFD model. The predicted and measured flow rates are presented in figure 3. Difference in flow rate is negligible, less than 10%.
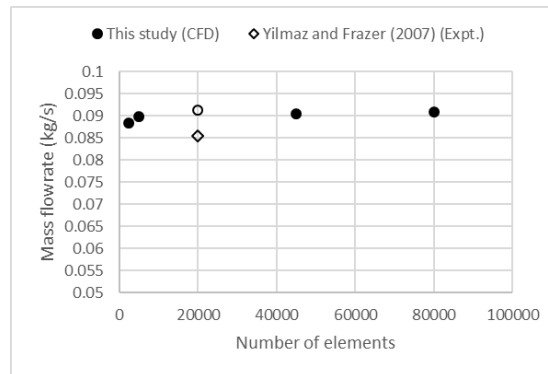
Figure 2. Variation of the flow rate versus the number of elements for simulation of the solar chimney in the experiment by Yilmaz and Fraser [9] (case of 100℃). The measured flow rate by Yilmaz and Fraser [9] was also plotted. The selected mesh is indicated with the open marker.
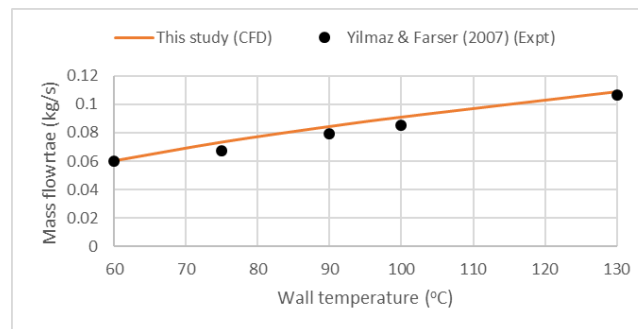

Figure 3. Comparison of the computed flowrate versus the measured data for the experiments by Yilmaz and Fraser [9].

3. Results and discussions

In this section, wind velocity and flow rate of solar chimney cases different from figure 1 are surveyed and presented. The heat flux applied to the walls is 600 W/m^2.

3.1. Base configuration (Base case)

In figure 1a, a solar chimney with 2 openings is integrated into the building, the opening below is the inlet and the top is the outlet in the air channel (figure 1a). Heated wall is placed on the left and right to the radiation received wall of a solar chimney. This configuration has been studied widely in the literature [9-11]. The temperature values in figure 7a show the temperature rising from the bottom up on both walls in the air channel while only the left wall is the heated wall. At the output of the base case, no flow reversal occurs. Air velocity increases and becomes higher when adjacent to a heated wall, as shown in figure 8a. Since there is no outlet flow reversal as shown in figure 8a, it is sufficient to use a computational domain that includes only air channels in this study.

Investigation of the mass flow rate of the base case was also studied under many effects on the variability of the width of the solar chimney as depicted in figure 4. The width of the solar chimney is changed from 0.1 to 0.4m and the result is that the flow rate increases with increasing the width of the air gap. This trend is similar to those of the experimental data of Chen et al. [10] and Burek and Habeb [11].
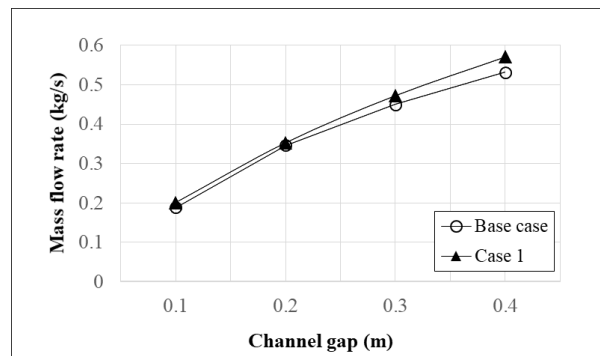
Figure 4. The induced flow rate of the Base case & case 1.

3.2.   Testing configurations (case 1-3)

Survey with changes in the width of solar chimney in the base configuration shows the trend of increasing flow rate from $0.188 \, kg/s$ in the case of $Gap = 0.1m$ to $0.53 \, kg/s$ in case of $Gap = 0.4m$. Based on the base case, a vertical solar chimney case whose inlet values lie close to the floor of each floor are studied, as depicted in figure 1b (case 1). The total flow rate at the output of case 1 shows that the lower inlet in each floor can be improved compared to the base case, about $0.01 - 0.03 \, kg/s$ as shown in figure 4e. When the gap of the solar chimney is changed, there is no big difference in the inlet traffic of the floors. The flow conservation trend is shown by the increase in the flow of inlet 1 and decrease in inlet 2 and 3 at the same time (figure 5).

Figure 5 shows that, with a constant gap, the higher floors had lower flow rate. This effect was also reported in previous studies [3,4]. It might be because the inlets at the higher floors had lower elevation difference between the inlet and the outlet of the air channel; hence weaker thermal effects and, consequently, lower induced flow rate.
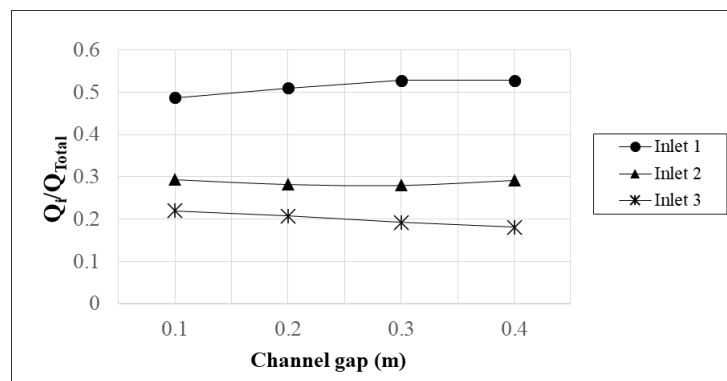

Figure 5. The induced flow rate of the case 1.

When investigating the change of channel gap in case 1, the variation in flow rate between floors is negligible. Based on this, two solar chimney models with gradual widening on each floor were computed. In case 2 (figure 1b), the model gap size remains $G = 0.2m$ on the first floor, on the second floor the dimensions are added xG and $2xG$ on the third floor where x is the variable in the computational domain, $x = 0 - 0.3m$.

From the research results of case 2, case $x = 0.0m$ is considered the case of vertical solar chimney of case 1. As the x size increases (figure 6a), outlet flow also increases gradually from $0.35 \, kg / s$ in the case x = 0m to 0.69 kg / s in the case $x = 0.3m$. The flow rates in inlet 1 tended to decrease from

$0.17\ kg\ /\ s\ (x\ =\ 0)$ to $0.24\ kg/s\ (x\ =\ 0.3m)$ and inlet 2 and inlet 3 increased the flow rate simultaneously. There is a change in the case $x\ =\ 0.3m$, the discharge in inlet 2 is higher than inlet 1, and inlet 1 continues to decrease.
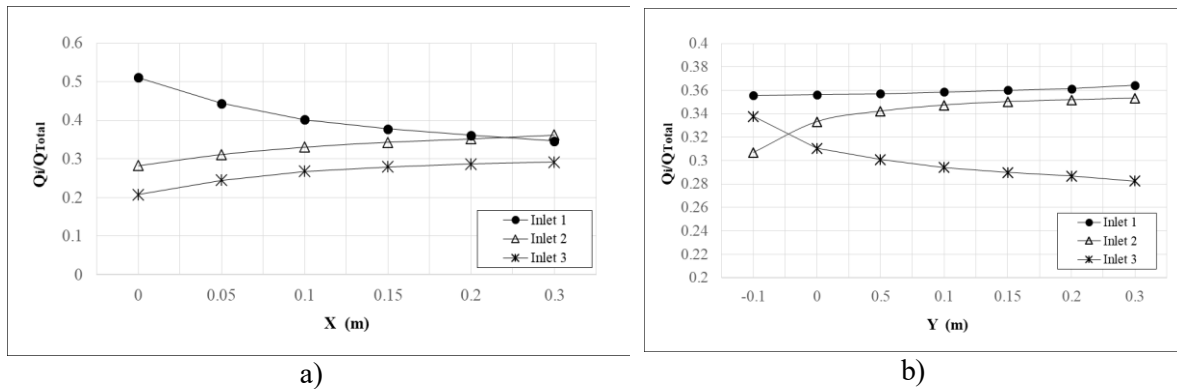

Figure 6. The induced flow rate of: a) Case 2; b) Case 3.

To evaluate the behavior of the air inside the solar chimney, three different solar chimney-sized models were compared including base case, case 1 and case 2 with dimensions $x\ =\ y\ =\ G\ =\ 0.2m$.

Survey from 3 cases of temperature and velocity (figure 7) shows a clear difference within the solar chimney. The temperature field tends to decrease gradually from inlet to outlet most clearly in the base case. The solar chimney in case 1 has a more even temperature on all 3 floors. The velocity field has a clear difference in case 1 as the velocity increases dramatically as it passes through the inlet from each layer. The velocity in case 2 tends to decrease gradually and the difference in velocity when passing through the inlet of each layer is significantly lower than that of case 1. From the study in figure 7, it can be seen that case 2 is more suitable. with the need to balance flow and velocity on each floor.
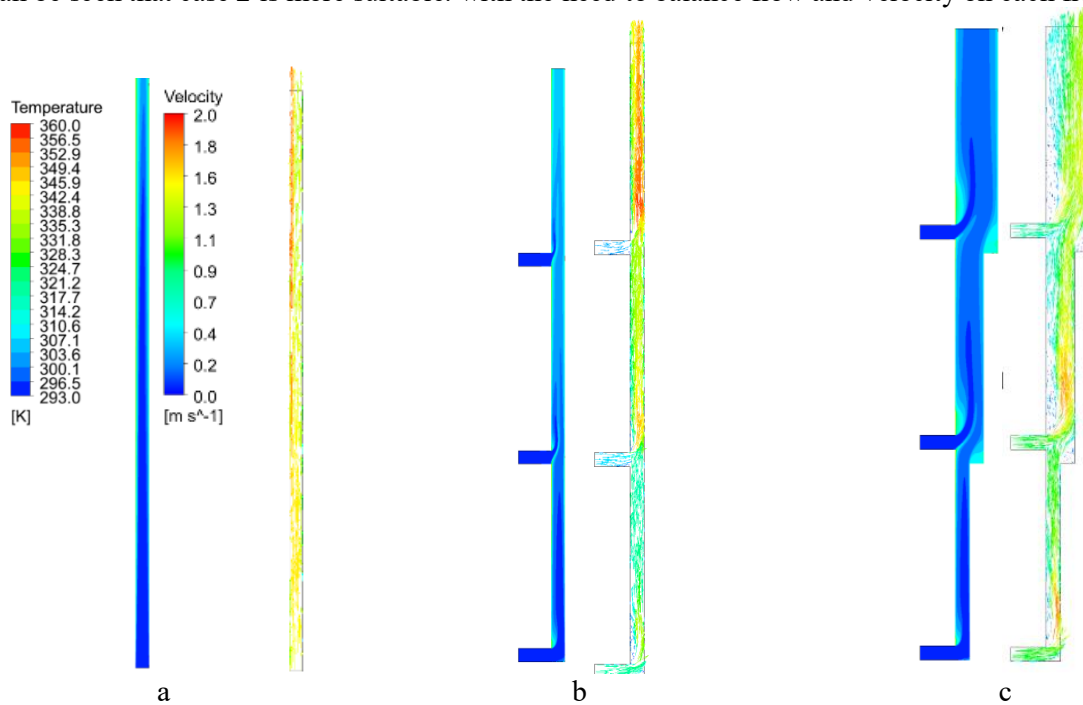

Figure 7. Temperature and flow field of: a) Base case; b) Case 1; c) Case 2.

3.3. Selected configurations

With the aim of achieving a flow balance between the floors of the building. The selected configuration (case 4) is a combination of case 2 & 3 with dimensions x and y of $x = 1.25G$ $(0.25m)$, $y = -0.25G$ $(0.05m)$. The computational domain and mesh features of the selected configuration are shown in figure 1d. Investigation of the flow rate of each floor during heat flux changes is also examined in two heated wall cases located on the left (LW) and the right (RW), as shown in figure 7.

The total output of the case with a heated wall on the left is always higher than on the right. In all 3 cases of change of heat flux, the output flow difference is less than 0.1 kg/s. The heat flux case located on the right shows that the discharge on the second floor is significantly lower than that of floors 1 and 3 and is also the lowest of the two LW and RW cases examined. In the case of LW, the flow difference between the floors is more stable than RW and tends to balance the flow more than the other cases.
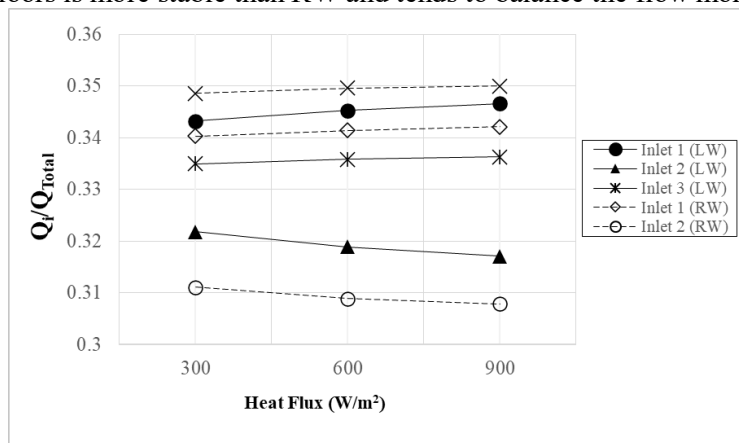

Figure 8. Heated wall induction current rate on left (LW) and right (RW) side of solar chimney

4. Conclusion

The survey results show that the optimum case (case 4) is the case with the best flow rate balance between the inner floors of the building. Survey of the discharge in each stratum using solar chimney in case 1 shows that the discharge in each stratum gradually decreases from bottom to top. Resizing x and y in case 2 and case 3 is to find the solar chimney configuration that best balances the inlet flow rate of the floors. The best configuration for natural ventilation balance surveyed is the one with dimensions x=1.25G (0.25m), y=-0.25G (0.05m). A survey of heated wall's heat flux increase and left-to-right position change is also evaluated in figure 8. Surveys show that there is still a gap in inlet flow rate for each floor but with a heated wall on the left it is more efficient when it is on the right.

This study shows the applicability of natural ventilation in sustainable architectural design. The balance of natural ventilation in the floors of the building through solar chimney positively impacts the comfort of use and wide application in multi-story projects. In the future, optimization techniques will be applied to optimize the flow balance through the resizing of solar chimneys.

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