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Ventilating aged-care center based on solar chimney: Design and theoretical analysis

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ABSTRACT

Natural ventilation is considered the first suggestion for COVID-19 prevention in buildings by the World Health Organization (WHO). Solar chimney's viability in aged care centers or similar facilities was analyzed numerically and theoretically. A new solar chimney design was proposed to reduce the cross-infection risk of COVID-19 based on an airflow path through window, ceiling vent, attic, and then chimney cavity. Solar chimney performance, quantified by the natural ventilation rate, presented power function with window area, ceiling vent area, cavity height, and solar radiation. The ceiling vent is suggested to be closer to the corridor to enhance the performance and ventilation coverage of the room. A cavity gap of 1.0 m is recommended to balance the ventilation performance and construction cost. A theoretical model was also developed for aged care centers with multiple rooms and a joint attic. Its predictions obey reasonably well with the numerical results. Solar chimney's viability in aged care center is confirmed as a 7.22 air change per hour (ACH) ventilation can be achieved even under a low solar radiation intensity of 200 W/m², where its performance fulfills the minimal ventilation requirement (i.e., 6 ACH) suggested by the WHO for airborne infection isolation rooms. This study offers a new design and a guideline for the future implementation of solar chimney in aged care centers or similar facilities.

1. Introduction

Globally, almost half (i.e., 47%) COVID-19 deaths come from aged care centers or similar facilities [1]. This is because of elders’ relatively high health risk and the inappropriate use or even the design and strategies of the ventilation systems [2,3]. Several studies [4,5] noticed that the current ventilation systems may contribute to the spread of COVID-19 if they are not correctly used. For example, those virus particles accumulated in the filters of ventilation systems may be spread to the whole building. National ventilation is the first suggestion by The World Health Organization (WHO) for the prevention of COVID-19 in the building sector [6–8], with no less than 6 air changes per hour (ACH) ventilation in the airborne infection isolation room of existing building [9], while the required value for new buildings is even higher.

As a passive natural ventilation system, solar chimney is a fast and viable solution in buildings due to its high performance, low cost, and easy installation [10,11]. However, no study was found in the literature regarding adopting solar chimney in aged care centers or similar facilities, not to mention its potential of preventing the cross-infection of COVID-19. Natural ventilation raised by solar chimney is achieved by thermal buoyancy based on solar energy. Solar chimney usually includes three parts [12,13]: (a) an absorption wall enables the solar heat absorption; (b) a glazing wall allows solar penetration; and (c) air inlet/outlet for air movement. The solar chimney performance is quantified by the airflow rate through its chimney cavity.

Previously developed theoretical models have focused on chimney cavity itself, where theoretical models for multiple chambers are less concentrated, especially for those complicated scenarios with numerous inlets and horizontal vents. It was observed that most of them have ignored the impacts from the connected chamber (i.e., the room), which results in overestimation [14]. The solar chimney is usually adopted with multiple openings (i.e., inlet and outlet), where Andersen [15] suggested improving those theoretical models to enable their prediction to those scenarios with multiple rooms. But until now, no improved theoretical model has been reported on this aspect.

Avoiding reverse/back flow is one of the principles for building ventilation system design. This is because the reverse/back flow could hamper the ventilation performance and spread the used air from one room to another. Due to the ununiform natural convection, reverse airflow was observed in previous studies [16] at
the chimney outlet with a thicker chimney cavity. Reverse airflow was also observed when the solar chimney was applied in a high-rise office building [17] or an inclined absorption wall [18]. However, it is still unclear if the reverse flow could happen at the other vents or windows when the solar chimney is applied in multi-zone buildings, which could speed up the cross-infection of COVID-19 or the similar.

It is still unknown if a solar chimney can offer enough natural ventilation under typical weather conditions to fulfill the requirement of the airborne infection isolation room suggested by WHO, namely 6 ACH. Zavala-Guillen et al. [19] obtained that a solar chimney can offer a 7.9–11.4 ACH natural ventilation for a 27 m³ room. The similar findings, together with the theoretical model, offer a guideline for the future implementation of solar chimney in aged care centers or similar facilities. The research also determined the airflow direction and rate through the chimney cavity can be described by,

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = S \]  \hspace{1cm} (2)

The equation for energy conservation is expressed as,

\[ \frac{\partial}{\partial t} \left( \rho E_p \right) + \nabla \cdot \left( \rho E_p \mathbf{u} \right) = \frac{D \bar{P}}{\Delta t} - \nabla \cdot \mathbf{Q} \]  \hspace{1cm} (3)

The boundary condition of solid obstructions of the room and chimney cavity can be described by,

\[ -k i \frac{\partial T_s}{\partial \mathbf{n}} (0, t) = \dot{q}_s^w + \dot{q}_r^w \]  \hspace{1cm} (4)

The boundary conditions of numerical domain were considered as “open”, which assumes that air is allowed to flow into or out of the numerical domain under pressure gradient [21],

\[ \zeta = \frac{\bar{P}}{\rho} + |\mathbf{u}|^2/2 \]  \hspace{1cm} (5)

where \( \zeta \) is the boundary value.

The numerical domain boundaries were set at least 0.5 m away from the sidewalks or any component of the building to ensure a smooth airflow from the ambient environment. The pressure gradient also determined the airflow direction and rate through the window. Simulation of the solar radiation was based on an integrated convective heat transfer model [22]. The above equations were solved by an open-sourced numerical tool (i.e., Fire Dynamics Simulator, FDS) [21].

2.2. Experimental validation

Its numerical simulations have been performed and validated in many previous studies [23]. Its validity for the solar chimney has also been proved by experimental data obtained by Bouchair [24] under various cavity gaps and solar radiation intensities. It can be seen from Fig. 1 that the agreement between the numerical and experimental data is reasonably good, except for the scenarios with a large cavity gap of 1.0 m. This may be due to FDS’s limitation in simulating solar radiation. With the 1.0 m cavity gap, the data trends can be predicted, but the predictions are relatively lower.
than the experimental data. So, we considered those numerical predictions conservatively when the cavity gap is relatively big. More details are not repeated here, which can refer to Refs. [23,24].

2.3. Possible designs

Several characteristics can be concluded for the typical aged care centers: (a) multiple rooms connected to a long-narrow corridor; (b) a room is usually equipped with one door and one window; and (c) typical single-storey building is adopted with attic and inclined roof. A typical aged care center with eight rooms is proposed here for the follow-up analysis, where the floor plan can be seen in Fig. 2. The situation for aged care with a different number of rooms is also applicable due to the symmetry of the airflow, which will be discussed later.

Fig. 1. Experimental validation of FDS in solar chimney applications [14]. The experimental data were obtained by Bouchair [24].
Solar chimney on the roof top acts as an "engine", where the air-flow inside those attached spaces (e.g., attic, corridor, and room) is then driven by the pressure gradient raised by the thermal buoyancy. Under the pressure gradient, the ambient air enters the room, enabling the supply of fresh air. The airflow paths shown in Fig. 2 could lead to the cross-infection of COVID-19 or similar diseases as the used air from one room could enter the corridor and then the other rooms. Therefore, the design principle of a solar chimney in aged care centers is to avoid air transferring from one room to another. Two possible designs could be adopted to ventilate the analyzed aged care center: the ventilation through the corridor (Fig. 3) or the attic (Fig. 4).

Fig. 3 shows one design with airflow through the corridor. Several disadvantages can be observed for this design based on the numerical results. First, the jet flows through the two side vents impinge on each other, which increases air resistance and hampers the natural ventilation performance. Suppose the velocity of these two jet flows is uneven under the scenario (Fig. 3(b)). In that case, it may be possible for the air from one room or the corridor to move to the other room, resulting in the cross-infection. Secondly, extra vents are needed at the top of the corridor to enable the attic airflow, complicating the retrofitting works. Finally, the used air from the rooms could contaminate the corridor which raises the risk of cross ventilation, even though the doors of those rooms are closed.

Another design was proposed here to overcome the disadvantages of the above design, as shown in Fig. 4. The used air through the room can be directed to the attic and then the chimney cavity without contaminating the corridor. As the two ceiling vents are quite far away and following the same direction, limited impingement and air resistance were observed from the numerical outputs (Fig. 4(b)). Furthermore, the top ceiling vents at the corridor top are not needed anymore. The airflow rates also evidence the advantages of the second design. Under similar designs, the airflow rate of the second design (Fig. 4) is around 0.81 m$^3$/s compared to 0.53 m$^3$/s of the first design (Fig. 3). Therefore, this study will focus on the second design (Fig. 4), namely natural ventilation through the attic.

### 2.4. Numerical scenarios

Four categories of design factors, including six design factors, were considered in this study, as shown in Table 1. The ranges of the designed values follow those of previous studies [14]. The wind environment is quite different from place to place. Therefore, to offer a benchmark assessment of solar chimney, the design of solar chimney was carried out without considering the wind [25]. The ambient air temperature was assumed at 20 °C. As the solar conditions change with location and time, and this study focuses on fluid dynamics, solar radiation was considered constant during the whole simulation. The airflow rate during the stable period represents the solar chimney performance of the scenario to enable better comparison.

### 3. Results and discussion

#### 3.1. Room configuration

Window act as a fresh air supply vent in buildings. The fresh air, denoted by those blue arrows in Fig. 4, enters the room, attic, and chimney cavity through the window, ceiling vent, and air inlet. The window area is an important design factor of the solar chimney performance. Fig. 5 shows the numerical outputs and natural ventilation rates under various window areas, which are quantified by the ACH of the room in this study, unless specified.

It can be seen from Fig. 5(a) that a bigger window can promote natural ventilation. However, its influences are limited with a continuedly increased window area. This can be reflected by its proportional relationship with $A_{\text{win}}^{0.17}$. With a big window, the ventilation performance is no longer determined by the window but by the chimney cavity, namely the pressure difference driven by the thermal buoyancy. An extreme case is an infinitely big window, the same as previous studies on a single chimney cavity only [26].
Figure 5(b-c) shows that the airflow contours are different between the side and middle rooms. The location of the side room and the middle room can be seen in Fig. 2. The ventilation coverage of the side room is relatively lower than those of the middle room. This may be due to the effects of the side walls of the chimney cavity (Fig. 5(d)). It may be similar to the case of pipe flow and air velocities are relatively lower near the pipe surface under the effect of shear stress [27]. For example, as shown in Fig. 5(d), two large vortexes were observed in the attic area above the middle room, where no large vortex was observed for the space above the side room.
room. However, it is known from the other numerical outputs that the differences between the side room and middle rooms get less pronounced with a bigger window.

All the scenarios shown in Fig. 5(a) were analyzed under 400 W/m² solar radiation intensity. All these cases can offer no less than 8.4 ACH natural ventilation, which fulfills the WHO’s suggestion of 6 ACH for airborne infection isolation rooms [9]. It proves solar chimney’s viability of enhancing natural ventilation and avoiding cross-infection of COVID-19 or similar infectious diseases.

3.2. Attic configuration

The attic is one of the considerations which differentiates this study from those previous ones. As shown in Fig. 6(a), an increasing trend was also observed for the ceiling vent area like the window. Its impacts are relatively higher than those from the window, reflected by their power exponents, such as $A_{vent}^{0.28}$ for ceiling vent compared to $A_{win}^{0.17}$ for windows. Moreover, increasing the ceiling vent area can further enhance the natural ventilation, which grows from 9.42 ACH to 11.13 ACH when the ceiling vent area rises from 1.0 to 1.8 m².

Natural ventilation is also enhanced when the ceiling vent is closer to the corridor (Fig. 6(b)). The reason is obvious: it can reduce the pressure drops, where the air can directly enter the chimney cavity with limited air resistance.

The location of the ceiling vent also affects the ventilation coverage. It was observed that the ventilation coverage inside the room is enhanced when the ceiling vent is moving horizontally to the corridor. As seen in Fig. 7(a), although a vortex is shown at the attic corner, major airflow goes along with the roof and moves directly into the chimney cavity. As shown in Fig. 7(b), the impacts from the roof are also obvious that hamper the airflow when the ceiling vent is away from the chimney cavity, evidenced by the decreased airflow velocity.

Therefore, it can be concluded that the ceiling vent is suggested to be closer to the corridor (far away from the window) as it can enhance the performance and ventilation coverage of the rooms.

3.3. Chimney configuration

Cavity gap (or cavity depth/thickness) represents the horizontal distance between the glazing and absorption walls (Fig. 3). Fig. 8(a) presents the impacts of the cavity gap on its natural ventilation performance. An increasing trend can be observed with a bigger cavity gap, but the related increasing rate turns slower when the cavity gap continues rising. This trend was also observed in our previous study on a full-size building [13], but it is different from 0.2 to 0.3 m obtained previously from the literature [28–31]. This is because those previous studies focused on the scenarios with the reduced-scale model or solar chimney connected with a single room. As the construction cost is getting higher for a big chimney cavity, the optimal range in previous studies was obtained considering a balance between its performance and construction cost. Furthermore, the analyzed full scale also affects the optimal values of the cavity gap.

Although reverse flow can be observed in a big chimney cavity, it does not affect the overall airflow path or leads to backflow. The airflow distribution of the cavity gap rises from 0.3 to 1.4 m are shown in Fig. 8(c–e). Two big vortexes can be observed when it increases to 1.4 m, but no backflow from the chimney cavity to the room was observed. It indicates a low risk of cross-infection under the situation.

Based on the above several aspects, including the airflow rates, construction cost, and reverse flow, it is suggested to limit the cavity gap up to 1.0 m for the aged care center. This is because the continually increased cavity gap will not significantly improve the ventilation performance (Fig. 8(a)). Although no backflow to the room was observed within the analyzed range of 0.3–1.4 m, a wider chimney cavity may increase the risk of backflow to the room and the follow-up cross-infection. Furthermore, a big chimney cavity is accompanied by a higher construction cost.

Fig. 8(b) presents the airflow rate through the solar chimney under various cavity heights. It was observed that a higher chimney cavity enhances the airflow rate. This is obviously due to the big absorption wall that enhances the overall thermal buoyancy. The ventilation rate is observed proportional to $h_{ce}^{0.6}$, while many previous studies have obtained similar results, such as $h_{ce}^{0.6}$ [32], $h_{ce}^{0.39}$ [33], and $h_{ce}^{2.2}$ [34].

The typical chimney configurations in this study can fulfill the WHO’s requirement of 6 ACH in the airborne infection isolation rooms, while in some cases even with a high ventilation rate of over 12 ACH.

3.4. Environment

The main environmental factor for solar chimney is the solar radiation intensity, which offers the driven force of natural ventilation. The ventilation rate rises with a higher solar radiation intensity, showing a power function, namely $q_{solar}^{0.38}$ (Fig. 9). The obtained power exponent is lower than those of previous studies,
such as $q_{solar}^{0.4015}$ [31], $q_{solar}^{0.459}$ [32], and $q_{solar}^{0.572}$ [35]. This may be due to the impacts by the attic.

The viability of solar chimney in aged care centers can be confirmed through this study. Under a low solar radiation intensity, solar chimney can still offer enough natural ventilation to fulfill WHO’s requirements. For example, even under 200 W/m² solar intensity, the solar chimney can still produce 7.22 ACH natural ventilation, which is higher than the suggested 6 ACH by the WHO. However, this does not imply that the solar chimney can replace the current mechanical ventilation system. The solar chimney is not working at night without solar radiation unless some phase change materials are adopted [36]. The relation combination may be implemented in our future works.

4. Theoretical prediction and implementation

4.1. Development of theoretical model

This section aims to develop a theoretical model that predicts the solar chimney performance (i.e., airflow rate through the solar chimney). It was assumed that the airflow through each room is
symmetric, while only one room was open to simplify the theoretical deduction, as shown in Fig. 10. During the practical calculation, the inputted areas of windows and ceiling vents are the summation of all the connected rooms.

According to the theory of mass conservation, the masses through those orifices (e.g., window, ceiling vent, and air inlet/outlet) along the airflow path are expressed by,
\[
\rho_0 V_{\text{win}} = \rho_0 V_{\text{vent}} = \rho_0 V_{\text{in}} = \rho_{\text{sc}} V_{\text{out}}
\]

The volumetric airflow rate passing through those orifices is given by,
\[
V_i = C_d A_i u_i
\]
where \(i\) represents the orifice number, such as ceiling vent, window, and air inlet and outlet.

Air velocity through the orifice is determined by the pressure gradient at its two ends,
\[
\Delta p_i = \frac{1}{2} \rho_i u_i^2
\]

Assuming the air inside each chamber is fully mixed, the pressure gradient in the chamber can be described by the static pressure,
\[
\Delta p_j = \rho g \Delta H_j
\]
where \(j\) indicates those chambers, such as room, attic, and chimney cavity.

Based on Eqs. (8) and (9), a group of equations can be obtained to describe the pressure gradients through the orifices and chambers,
\[
\sum_{n=1}^{N} \rho_i u_i^2 = 2(\rho_0 - \rho_{\text{sc}}) g H_{\text{sc}}
\]

where \(N\) represents the total number of orifices along the airflow path from the external environment to the air outlet of the chimney cavity (Fig. 10), and \(N = 4\) in this study, including (1) window, (2) ceiling vent, (3) air inlet, and (4) outlet.

Combining Eqs. (6), (7), and (10), the volume airflow rate at the air inlet can be predicted by,
\[
V_{\text{in}} = C_d A' \left[ \frac{(\rho_0 - \rho_{\text{sc}}) g H_{\text{sc}}}{\rho_0} \right]
\]

where \(A'\) is the coefficient considering the impacts of all the orifices in the airflow path; and \(C_d\) is the coefficient of discharge. A general form of \(A'\) is obtained considering a series of orifices connected to the chimney cavity,
\[
A' = \sqrt{\frac{2}{N} \sum_{n=1}^{N} A_i^{-2}}
\]

where \(A_i\) represents the area of those orifices.

The temperature rises after the airflow goes through the chimney cavity, which follows the theory of energy conservation,
\[
E = \rho C_v (T_{\text{sc}} - T_0)
\]

An approximate form is obtained following the ideal gas law [37],
\[
\rho_{\text{sc}} T_{\text{sc}} = \rho_0 T_0
\]

Based on Eqs. (11), (13) and (14), the airflow rate of the chimney cavity is obtained,
\[
V_{\text{in}} = (C_d A')^{2/3} \left( B H_{\text{sc}} \right)^{1/3}
\]
where \(B\) is the buoyancy flux,
\[
B = Eg/\left( \rho_0 C_v T_0 \right)
\]

It was observed from Eq. (15) that the same form of the equation is obtained as those in previous studies [37], where the coefficient of \(A'\) is different, which is expanded to a general form (Eq. (12)). Another difference is that a group of windows and ceiling vents was considered in this study, compared to the scenario with single vents in those previous studies [37,38].

The theoretical model shown in Eq. (15) is developed by assuming fully mixed airflow inside the chimney cavity with uniform temperature. However, the temperature distribution inside the chimney cavity is horizontally parabolic and vertically linear due to heating processes and convective heat transfer [39]. A coefficient of 0.63 was suggested if both the horizontally parabolic and vertically linear temperature profile is considered inside the chimney cavity [40].

Also, as the attic (roof) is inclined, the airflow path is also affected by this configuration. As the inclination of the attic and chimney cavity is similar, the impacts of the inclined attic can be quantified by [34].
\[ V = \left(\sin \theta\right)^{1/3} \cdot V_{in} \quad (\theta \leq 52.5^\circ) \quad (17) \]

Therefore, solar chimney performance (i.e., airflow through the chimney cavity) can be finally predicted by,

\[ V_{in} = 0.63\left(\sin \theta\right)^{1/3} \cdot \left(C_{2A}\right)^{2/3} \cdot \left(h_{in}\right)^{1/3} \quad (\theta \leq 52.5^\circ) \quad (18) \]

where the inclination angle \( \theta \) of the attic (roof) for typical buildings is usually lower than 52.5°, so the above equation is applicable to typical aged care centers; The calculation of \( A \) can refer to the Eq. (12), where the areas of window and ceiling vent are the total areas of all the rooms, namely eight rooms in this study; and \( h_{in} \) is the height (size) of the chimney cavity, but not the height from the floor.

### 4.2. Comparison and validation

The results based on theoretical and numerical analysis are compared in Fig. 11. These two groups of data fit reasonably well, which proves the viability of applying the developed theoretical model in multiple chambers and orifices.

The area of windows and ceiling vents in the theoretical model is the summation of all eight rooms in this study (Eq. (18)), which leads to reasonably good predictions. Therefore, it can be confirmed that the strategy of summating the areas of windows and ceiling vents for model inputs works to simplify the theoretical deduction and practical calculations. It should also be noted that this theoretical model applies to the typical roofs with a less than 52.5° inclination angle.

The related conclusions and developed theoretical models in this study are still applicable for those aged care centers with various rooms. There are several reasons for this: (a) when the number of the rooms is different from eight, the airflow paths in each room are relatively symmetric and similar; (b) the room volume was found with a limited impact on the solar chimney performance [14,23], so the obtained results will also be applied to those room with various sizes; and (c) for the modelling inputs of the theoretical models, the orifice areas (e.g., window and ceiling vent in this study) can be considered as the summation of all the rooms.

### 5. Conclusions

The viability of adopting solar chimney in aged care centers is confirmed through this study that fulfills the World Health Organization (WHO) requirement regarding COVID-19 prevention. Several conclusions can be addressed here:

- A new solar chimney design with an airflow path from window to room, attic and chimney cavity is suggested in aged care center or similar facilities as it can avoid contaminating the corridor or the other room;
- Solar chimney performance, quantified by the natural ventilation rate, shows power function with window area, ceiling vent area, cavity height, and solar radiation. Ceiling vent is suggested closer to corridor and far away from the window to enhance the performance and ventilation coverage of rooms;
- A cavity gap of 1.0 m is suggested to balance the ventilation performance and construction cost, which also reduce the risk of cross-infection by avoiding backflow to the room;
- A theoretical model (Eq. (18)) is developed to predict the airflow rate in typical aged care centers with attic attached to multiple rooms, where the inputted orifice areas (i.e., window and ceiling vent) are the summations of all the connected room; and
- Under typical weather conditions, solar chimney performs 6.4–14.8 air change per hour (ACH) which fulfills the requirement raised by the WHO, namely no less than 6 ACH ventilation in airborne infection isolation room; and
- Typical solar radiation is viable for adopting solar chimney in aged care center as a 7.22 air change per hour (ACH) ventilation can still be achieved even under a low solar radiation intensity of 200 W/m².

### Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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