Forced and natural ventilation of a room with a combined solar chimney and Earth - to - Air Heat Exchanger system

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Abstract. In this study, a passive ventilation and cooling technique which is widely used in sustainable building designs was investigated by a numerical simulation based on computational fluid dynamics (CFD). A system of a solar chimney (SC) and an Earth-to-Air Heat Exchanger (EAHE) is able to ensure thermal comfort in a house by generating an air flow which is induced by the thermal effect. The solar chimney drew ambient air (at 35°C) through the inlet of EAHE; the air flow was cooled by a lower temperature of the underground pipes (at 20°C) before circulating inside the house and leaving through the outlet of the solar chimney. Both the openings of the system were exposed to the atmosphere, and the atmospheric pressure was set at the inlet of the EAHE pipe and the outlet of the solar chimney. The performance of this ventilation and cooling system was analyzed under effects of design parameters, including the gap of the chimney, the diameter and length of the EAHE pipe as well as the solar heat flux applied on the wall of the air channel of the chimney. The results of the assessed parameters, such as temperature inside the house, show that the indoor temperature was reduced to 25°C and 26°C, respectively for the forced ventilation case of 0.2 m/s and natural ventilation case in the configuration with the EAHE pipe length of 11m. The coupled solar chimney and EAHE system can achieve the thermal comfort conditions for both cases of natural and forced ventilation.

Key words: solar chimney, EAHE, CFD, thermal comfort.

1. Introduction
As people have been spending more time indoors, for example about 90% in the US [1], energy consumption for HVAC systems in buildings has increased dramatically. In the USA, the energy for space cooling and heating takes 43% of the total energy consumed in buildings in 2007 [2]. That number in Australia was 42% [2].

To save energy in buildings, using renewable resources for space cooling and ventilation has been studied extensively recently [3-8]. Bansal et al. [3] proposed a solar chimney (SC) for natural ventilation of buildings. This device absorbs solar radiation and creates an air flow through its confined air channel for ventilating the connected building without fans. Furthermore, the air can be cooled prior to being supplied to the building by exchanging heat underground with an Earth – to – Air Heat Exchanger (EAHE) system [4-8]. As the soil temperature is sufficiently lower than the ambient air in summer [4,5], by bypassing the supply air through pipes buried underground, the air can be cooled.

Previous studies have shown that a coupled SC – EAHE system can achieve thermal comfort conditions for residential buildings [5,7] which are defined by the ASHRAE Standard 55 [9]. The research by Li et al. [5] demonstrated that the indoor air temperature and humidity were maintained at
21.3 – 25.1 °C and 50 – 78%, respectively. Elghamry and Hassan [6] reported that the SC – EAHE system in their experiment could reduce the air supply temperature up to 3.5 °C. The thermal comfort index PMV (Predicted Mean Vote) [9] in the study by Yu et al. [7] was within the acceptable range of ±1.0.

For thermal comfort conditions, the ASHRAE Standard 55 [9] also considers the distributions of air temperature and speed in the room. However, in those previous reports, only the average air temperature and humidity of the whole room were considered. In our previous report [10] we examined a coupled SC – EAHE system and focused on the natural ventilation flow induced by the solar chimney in the room. The results showed that an adequate ventilation rate was achieved with the proposed system. Air speed and temperature distributions inside the room were also maintained in thermal comfort ranges.

In this report, we examined the performance of the proposed coupled SC – EAHE system in our previous study [10] for the case of forced ventilation, where the air flow was forced through the system. In previous studies [5,7], the air speed and temperature only measured at one point in the room. This study considered the distributions of air speed and temperature inside the room at different elevations in the occupied zone of the room and then compared with those of the natural ventilation cases.

2. Problem formulation and numerical method

2.1. System of a solar chimney and an Earth-to-Air Heat Exchanger

As a passive cooling technique, a combination of a solar chimney and an Earth-to-Air Heat Exchanger ensures to provide a cooling air flow inside a house, as shown in figure 1a. A solar chimney is associated with the house and designed to absorb solar radiation. As the temperature of the chimney surface increases, the absorbed heat is transferred into the air in the channel of the chimney. The air inside the chimney is heated, the hot air rises, and an induced air flow is drawn through the EAHE inlet. Exploiting the potential difference between ambient and underground temperatures in hot climates, an EAHE cools the air flow during its passage through EAHE pipes. The cooling process takes place between the pipe surfaces and the air flow. On the assumption that the house is air-tight, only ambient air through the EAHE pipe circulates inside the house. Cooling the air flow before supplying into the house, a coupled SC-EAHE ensures the house is ventilated and cooled.

2.2. Numerical model

A CFD model was applied to investigate the behaviors of the air flow and heat transfer within the SC-EAHE system and the house. The setup was similar to those in previous researches [4,6,10]. A two-dimensional domain in the vertical plane was employed (figure 1b). Accordingly, the air flow and heat transfer were assumed to be steady and two-dimensional. Both modes of convection and radiation were integrated into the simulation of the heat transfer on the pipe and solar chimney surfaces. For simplicity, the process of heat conduction through the surfaces of the pipes was not directly simulated but modeled by a uniform temperature on the pipe surfaces. Similarly, a uniform heat flux was applied on the wall of...
the air channel of the chimney. The house walls were assumed to be adiabatic. A uniform vertical velocity profile was assumed to enter at the inlet of the EAHE whereas the air was assumed to leave the domain at the outlet of the solar chimney at atmospheric pressure.

Under the above assumptions, using the Reynolds – Averaged Navier Stokes equations [11,12], the problem was governed by the equations of conservation of the mass, momentum, and energy of the flow.

\[ \frac{\partial u_i}{\partial x_j} = 0 \]  
\[ \frac{\partial (u_i u_j)}{\partial x_j} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} - g_i \beta (T - T_0) + \frac{\partial}{\partial x_j} \left( \nu \frac{\partial u_i}{\partial x_j} - u_i' u_j' \right) \]  
\[ \frac{\partial (T u_i)}{\partial x_j} = \frac{\partial}{\partial x_j} \left( \nu \frac{\partial T}{\partial x_j} - T' u_j' \right) \]

In this system of equations, \( u \) and \( T \) show time-averaged components of the velocity and temperature. \( u' \) and \( T' \) are the velocity and temperature fluctuations. \( \overline{u_j u_j} \) represents the time–averaged operator. \( p, \nu, \rho, \) and \( Pr \) are respectively the pressure, air kinematic viscosity, density, and the Prandtl number. \( g \) is the gravitational acceleration and \( \beta \) is the air thermal expansion coefficient. The Boussinesq approximation was applied to Equation (2). This approximation was used for the air density variation with temperature [12,13,14]. The turbulence stress \( u_i' u_j' \) in Equation (2) and the turbulent heat flux \( T' u_j' \) in Equation (3) were solved with the low – Reynolds number \( k-\) model, which is the standard \( k-\) model with modification for low -Reynolds number effects by a damping coefficient for the eddy viscosity. This model was also employed in previous studies of solar chimneys [11,14] because it allowed to obtain the fastest convergence and the best agreement with the experiment by Burek and Habed [15].

![Figure 2](image_url)

**Figure 2.** Examination of the mesh (a) and validation of the numerical model (b)

The Finite Volume Method on a structured rectangular mesh (figure 2c) was used to discretize the governing equations, Equation (1) to (3), using Ansys Fluent CFD code. The geometric discretization focused on the proximity of the walls. High mesh densities were applied near the walls where the variation of the flow variables was strong. To respond to reliability and quality issues for the mesh generation, the variation of the induced flow rate and the air temperature at the outlet of the chimney were examined when increasing the mesh density. The flow rate and temperature at the outlet were plotted versus \( y^+ \), the maximum non – dimensional distance of the first grid point from the surfaces of the pipe and the air channel. In the mesh independence test, the value of \( y^+ \) varied from 8.5 to 4.5, which corresponded to the discretization mesh in figure 1c was finer near the wall of the chimney and EAHE pipes. The differences between the air temperature and the induced flow rate computed with \( y^+ =4.5 \) and the ones computed with \( y^+ =5.0 \) were 0.5% and 0.01%, respectively. The corresponding differences
between $y^+ = 5.0$ and $y^+ = 5.5$ were 1.55% and 0.11%. As a result, a mesh with $y^+ \leq 5$ was sufficient to give acceptable results for most simulations with different inlet velocities, as shown in figure 2a.

A validation of the above setups was verified with the data from the experiment by Burek and Habeb [15]. The flow rate at the outlet of the chimney was compared with the measured one in the case of the heat flux of $800 \text{ W/m}^2$. For the chimney gap in the range of 20 to 110 mm, the discrepancy between the predicted and measured results was less 5%, as shown in figure 2b. As a result, this numerical model can be applied for this problem.

3. Results and discussions

The aim of this study is to investigate factors that affect the performance of the system SC-EAHE in forced ventilation compared to the natural case [10]. In the computational model, airflow at 35°C entering the EAHE was examined in natural ventilation regime and three different forced ventilation regimes in which the velocity of the airflow at the inlet of the EAHE pipe were 0.2, 0.4 and 0.8 m/s. The temperature of the pipe walls was set at 25°C. Although the underground temperature was about 20°C [4,5], a higher temperature was fixed for EAHE pipe due to the thermal resistance of the pipe thickness.

Parameters consisting of the induced air flow rate, air temperature supplied to the room, and the averaged values of the air speed and temperature along the line at the height of 1.1 m [9] were assessed with regard to the variation of four factors: the heat flux, the gap of the solar chimney G, the length L and diameter of the EAHE pipe D, as denoted in figure 1b.

3.1. Effects of the applied heat flux on the system performance

For the effects of the heat flux, a range from 400 to 900 $\text{W/m}^2$ was inspected when the inlet velocity changed from 0.2, 0.4 to 0.8 m/s. The setup was similar to those of the natural configuration [10]. In particular, $G=0.3 \text{ m}$, $D=0.5 \text{ m}$, and $L=7.0 \text{ m}$. As the velocities were imposed at the EAHE inlet, the flow rates of the three flow regimes were proportional to their speeds in figure 3a. The flow rates in the three cases of forced ventilation were independent of the heat flux while there was an increase of 10% in the flow rate for the case of natural ventilation when the heat flux increased from 400 to 900 $\text{W/m}^2$[10]. An increase of about 30% was reported by Chen et al. [16], for a stand-alone chimney, when the heat flux varied from 400 to 600 $\text{W/m}^2$.

The number of times in one hour the air in the room, ACH, was calculated for both natural and forced ventilation cases. With the width of 4.0 m for the room and the width of 1.0 m for the chimney in figure...
1a, the ACH was 7.5, 15, and 30, respectively, for the inlet velocity of 0.2, 0.4, and 0.8 m/s. For the natural ventilation case, the ACH was in the range of 12.5-14 [10]. Compared to the ACH of 3.0 for residential buildings, these values were far above [9].

In figure 3b, similarly to the flow rate, the air speed along the line at 1.1 m from the floor changes with the heat flux. For both natural and forced ventilation cases, the speeds were in the range from 0.1 to 0.45 m/s. It is within the comfort range [9].

The air temperature at the SC outlet, $T_{\text{outlet}}$, increases with the heat flux, as shown in figure 3c. The highest temperature at the outlet was recorded as the inlet velocity was the lowest, which was the case of the velocity of 0.2 m/s. In contrast, the lowest $T_{\text{outlet}}$ corresponds to the case of the velocity of 0.8 m/s. It is due to a large amount of the heat from the absorbed surface transferred into the air when the flow circulates slowly along the chimney. A similarity in the $T_{\text{outlet}}$ results between the natural case and the case of 0.4 m/s velocity derives from the nearly 0.4 m/s air speed in the natural ventilation.

According to Li et al. [5], the air is cooled up to 10° K along a 57 m long EAHE pipe before supplying into the room. For such a 7 m long EAHE pipe, the reduction of the air temperature during its passage through EAHE pipes is expectedly lower in figure 5c. In contrast to a slight increase in $T_{\text{supply}}$ for the natural ventilation, $T_{\text{supply}}$ in forced ventilation cases is invariant within the range of the heat flux. Moreover, in figure 5d and 5e, the temperature along the line at 1.1 m from the floor is identical to the $T_{\text{supply}}$, which is due to no heat source existing inside the room, and the distribution of the temperature is uniform inside the room [10].

### 3.2. Effects of the chimney gap on the system performance

![Figure 4](image)

**Figure 4.** Performance of the system as the chimney gap changed.

The setup for the test on the chimney gap was as follows: the heat flux of 400 W/m$^2$, D= 0.5 m, and L= 0.7 m while the gap varied from 0.15 to 0.45 m. For a gap from 0.15 to 0.3 m, in figure 4a, the flow rate increases with the gap in the case of natural ventilation. For the gap above 0.3 m, the flow rate increases insignificantly, which is also reported by Khanal and Lei [17]. A slowdown in the increase in the flow rate is due to a reverse flow at the outlet of the chimney by examining the flow fields. In terms of the forced ventilation cases, the flow rate remains unchanged within the current range of the gap.

In figure 4b, the mean air speed at the height of 1.1 m increases with the gap from 0.15 to 0.3 m and slightly drops for the gap above 0.3 m in the case of natural ventilation. For the forced ventilation cases, the air speed is nearly unchanged although there is a small impact of the reverse flow. The air speeds satisfied comfort conditions [9]. The according ACH varies from 7.0 to 14.0 for natural setup while those for forced setup are invariant as 7.5, 15, and 30, respectively for velocity 0.2, 0.4, and 0.8 m/s.
For both natural and forced ventilation cases, $T_{\text{outlet}}$ decreases with the gap, as shown in figure 4c. For the inlet velocity of 0.8 m/s, although the temperature of the air supplied into the room is the highest, the temperature at the outlet is the lowest. It is because the time for the heat transfer into the air is reduced. Accordingly, a low velocity at the inlet results in a high temperature at the outlet.

The temperature along the line at the height of 1.1 m is similar to $T_{\text{supply}}$, as shown in figure 4d and 4e. In the forced ventilation cases, they are fixed when changing the gap. It is seen that their value depends on the air speed at the inlet. In the natural ventilation case, $T_{\text{supply}}$ and the temperature at the height of 1.1 m increases with the gap.

### 3.3. Effects of the EAHE pipe length on the system performance

![Figure 5. Performance of the system as the EAHE pipe length changed.](image)

To examine the effects of the EAHE length, the test was used in the range of the length from 0.6 m to 11.0 m. Other dimensions were set as follows: $G=0.3$ m, $D=0.5$ m, and the heat flux of 400 $W/m^2$. The flow resistance only influenced the flow rate in the natural ventilation case in which the flow rate was reduced when the length was extended (figure 5a). For the forced ventilation case, the flow rates are still invariant and proportional to the value of the inlet velocity. The distribution of the velocity fields at the height of 1.1 m tend to decrease in figure 5b. The temperatures at the outlet, the supply position, and line 1.1 decrease with the length, which is due to the heat exchanger within the EAHE pipes in a longer process when the pipe length increases, as shown in figure 5c, 5d, and 5e. The air speeds and the air temperature are suitable for comfort conditions.

### 3.4. Effects of the EAHE pipe diameter on the system performance

The test was set as follows: the heat flux of 400 $W/m^2$, $L=0.7$ m, $G=0.3$ m and the diameter $D$ varies from 0.25 to 0.6 m. An increase in the flow rate with the diameter is reported in the work of Serageldin et al. [8]. This is also illustrated in figure 6a. The flow rate increases with the diameter for both natural and forced ventilation cases. It can be explained by the fact that the air flow passes through the EAHE pipes with less flow resistance when the diameter increases in the natural case. The ACH was calculated.
and its range was from 4 to 14 and from 7.5 to 36, respectively, for the natural and forced ventilation cases.

Figure 6b shows the effects of the diameter on the air speeds. In figure 6c, 6d, and 6e, the temperature at the height of 1.1 m is similar to the $T_{\text{supply}}$. They increase with the pipe diameter and achieve a high value at high inlet speeds. However, lower inlet speeds result in higher temperatures at the outlet. The air speeds and the air temperatures satisfied the comfort conditions.

4. Conclusions
In this study, the configuration of the coupled solar chimney and Earth – to – Air Heat Exchanger system can satisfy the requirements for indoor thermal conditions by both natural and forced ventilation. The factors such as the heat flux, the gap of the solar chimney, the length and the diameter of the EAHE pipe were investigated. The results can be shown as follows:

For natural ventilation:
- The flow rate increases with the heat flux, the gap of the chimney, and the diameter of the EAHE pipe but decreases with the length of the EAHE pipe.
- The temperature supplied into the house slightly increases with heat flux, increases with the chimney gap, and the diameter of the EAHE pipe but decreases with the length of the EAHE pipe.
- The velocity at the height of 1.1 m increases with the heat flux and pipe diameter, decreases with the pipe length, increases with the chimney gap lower than 0.3 m but decreases with the chimney gap above 0.3 m.

For forced ventilation:
- The temperature supplied into the house is insensible to the heat flux, and the gap of the chimney increases with the diameter of the EAHE pipe but decreases with the length of the EAHE pipe.
- The velocity at the height of 1.1 m increases with the pipe diameter, decreases with the pipe length and remains unchanged compared with the heat flux and the chimney gap.

The air speeds and the temperature at the height of 1.1 m from the floor are within the comfort ranges. This work demonstrates an application of CFD in designing green buildings by considering both passive
and active solutions for ventilation and cooling. In future studies, numerical methods or artificial intelligence can be used to optimize the distribution of the temperature in buildings.

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