Design guideline for application of earth-to-air heat exchanger coupled with solar chimney as a natural heating system

A. P. Haghighi* and M. Maerefat
Department of Mechanical Engineering, University of Guilan, PO Box 3756, Rasht, Iran

Abstract
In the present paper, design of solar chimney (SC) and earth-to-air heat exchanger (EAHE) to meet the thermal need of flat buildings are studied regarding adaptive thermal comfort criteria. Investigation on the effects of geometric features shows that the design of SC with the air gap and outlet sizes of 0.2 m and also EAHE with the diameter and length of 0.5 and 25.0 m reveals better performance. Thermal comfort analysis shows that the SC is capable to power the underground heating system during few hours of the sunny days even at the ambient temperature as low as 0°C and the heating demand of 1000 W without needing the auxiliary devices. In addition, the required numbers of SCs and the underground air channels are strongly influenced by environmental outdoor conditions and heating demand of building and are approximately calculated by: room volume/50 and $2 \times (\text{room volume}/50) + 1$, respectively.

Keywords: Design; earth-to-air heat exchanger; natural heating; solar chimney

1 INTRODUCTION
Power plants, motor vehicles and industries burn fossil fuels and emit a large amount of pollutants, which imperil human health, impose heavy economic costs and degrade the natural environment. Although most of today’s energy comes from fossil fuels, new technologies offer a range of options for generating electricity, heating and cooling demands where they are needed. These new options include renewable energy technologies.

Energy consumption in the building for providing thermal comfort and ventilation continues to increase; however, new studies show that reduction or suppression of air conditioning may be achieved using passive or low-energy techniques. Two of such systems are the earth-to-air heat exchanger (EAHE) and the solar chimney (SC), which may be used for reducing energy consumption in the buildings. The EAHE ventilates air to the indoor spaces through one or several horizontally or vertically buried pipes. In this way, the ground large thermal capacity and relatively stable temperatures are used to preheat or pre-cool the supply fresh air, resulting in energy savings. The SC can be used to improve the natural ventilation and provides heating demand of buildings alone or together with an EAHE. It consists of a glass surface oriented to the south and an absorber wall that works as a solar radiation-capturing surface. The air in contact with this surface is heated up. Heating enhances the pressure difference between the inlet and outlet of the chimney; thus, the rate of natural ventilation increases significantly.

Many researchers have studied the EAHE for passive heating and cooling applications in the recent decades. Hollmuller [1] considered a periodic input for the air in the buried pipe, yielding a physical interpretation of the amplitude-dampening and the phase-shifting of the periodic input signal. Al-Ajmi et al. [2] developed a theoretical model of an EAHE for predicting the outlet air temperature and cooling potential of these devices. They showed that it has the potential for reducing cooling energy demand in a typical house by 30% over the peak summer season. Tittelein et al. [3] used response factors method for numerical modeling of earth-to-air heat exchanger. The results showed that the calculation time is reduced using response factors compared with 3D model based on the finite volume approach. Bansal et al. [4] investigated the use of earth–pipe–air heat exchanger to reduce the heating load of buildings in winter. A transient and implicit model based on computational fluid dynamics was developed to predict the thermal performance
and heating capacity of EAHE system. The results showed that the system performance is not significantly affected by the material of the buried pipe whereas the velocity of the air flow through the pipe affects the performance of the EAHE system significantly.

Solar chimneys have also attracted much attention of researchers. Bansal et al. [5] analytically studied an SC-assisted wind tower for natural ventilation of buildings. The estimated effect of the SC was shown to be substantial in inducing natural ventilation for low wind speeds. Gan and Riffat [6] investigated solar-assisted natural ventilation with heat-pipe heat recovery in naturally ventilated buildings, using a CFD technique. Mathur et al. [7] analytically studied the effect of absorber inclination on the air flow rate in a solar-induced ventilation system using roof SC. They showed that optimum absorber inclination depends on the latitude of the location. Maerefat and Haghighi [8] introduced and parametrically analyzed a new passive cooling system consisted of the EAHE together with the SC system. They showed that the SC can be perfectly used to power the underground cooling system during the daytime, without any need of auxiliary electrical fan. Haghighi et al. [9] studied the capability of one SC and EAHE to meet the required thermal need of one person in an insulated room. They showed that SC provides thermal comfort condition even at the ambient temperature as low as 5°C and the solar radiation of 185 (W m⁻²).

The previous available studies show that the detailed design of EAHE–SC system for passive heating of stand-alone-houses has not been fully investigated yet. The present study focuses on studying the effects of main geometric and environmental parameters on the system performance. In addition, the required numbers of SCs and underground air channels will be determined for different environmental operating conditions regarding the Adapted Comfort Standard (ACS). It should be noted that ACS does not recommend the ventilation rate [10]; therefore, the minimum ventilation rate is set as 3 air changes per hour [11]. According to this standard, when the indoor air temperature is in comfort zone, thermal comfort conditions will be realized. In addition, unlike the Fanger’s model used to evaluate thermal comfort conditions in room ventilated mechanically, the local undesirable cooling sense cannot be predicted when ACS (this standard is specially used for spaces ventilated passively) is used.

2 SYSTEM DESCRIPTION

Figure 1 shows schematic plan of the integrated EAHE and SC (EAHE–SC) system used for natural heating of stand-alone-buildings. This system realizes both heating and ventilation during daytime with the help of solar energy. It consists of two parts: the SC and the EAHE. The SC consists of a glass surface oriented to the south and an absorber wall that works as a capturing surface. The air is heated up in the SC by the solar energy and flows upward because of the stack effect. It causes driving force, which sucks the outside air through the heating pipes. The EAHE consists of horizontal long pipes that are buried under the bare surface at the specific depth. The pipes are spread under the ground in a parallel manner. The pipe spacing is considered more than the thickness of the heat penetrating depth to increase the heat exchange between the soil and the air.

3 MODELING THE SYSTEM

The modeling includes models of the EAHE (Figure 2) and the SC (Figure 3). The following assumptions are made in the analysis.

(1) Only buoyancy force is considered; wind-induced natural ventilation is not included.

(2) The flows in the channels are hydrodynamically and thermally fully developed.

(3) The glass cover is opaque for infrared radiation.

(4) Thermal capacities of glass and absorber wall are negligible.

(5) The air flow in the channels is radiative nonparticipating media.

(6) The soil is homogeneous, and the soil type does not change along the channel length.

(7) The system is at steady-state condition.

3.1 Mathematical modeling of EAHE

The cross section of the modeled EAHE surrounded by soil region is shown in Figure 2. Two vertical planes of symmetry bound the modeled soil region. Lower horizontal boundary is used to impose the ground thermal loads and is a plane with constant temperature of $T_{su}$. The lower-boundary (subsurface) temperature is determined by using the following equation [12]:

$$T_{su}(y, t) = T_m(\text{annual}) - A_s \left( \exp \left( -y \sqrt{\frac{\pi}{365 \times \lambda_s}} \right) \right) \times \cos \left( \frac{2 \pi}{365} \left( t - t_0 - \frac{y}{2} \sqrt{\frac{365}{\pi \times \lambda_s}} \right) \right)$$

(1)

where $T_m$ is the mean annual ground surface temperature and $A_s$ is amplitude of the temperature wave at the ground surface (K);
$\frac{dT}{dx} = 0.0$  

$\frac{dT}{dx} = 0.0$  

\[ \delta = \sqrt{\frac{2A_s}{\omega}} \]  

\[ R_{\text{total}} = \frac{1}{2\pi\Delta L} \times \left\{ \left( \frac{1}{h_\text{n}} \right) + \left( \frac{1}{k_\text{i}} \right) \ln \left( \frac{r_\text{i} + t_\text{i}}{r_\text{n}} \right) + \frac{1}{k_\text{s}} \ln \left( 1 + \frac{\delta_{\text{day}}}{r_\text{n} + t_\text{i}} \right) \right\} \]

Figure 2. Cross section of an EAHE with grid system of the soil region.

Figure 3. Schematic diagram of heat transfer in the SC.

$\text{sc}$, solar chimney; $su$, undisturbed soil; $s$, soil. $t$ and $t_0$ are the times of the year (in days) and the day of minimum surface temperature, respectively. The location of lower boundary depends on the soil diffusivity and the temperature cycle frequency and is obtained through the following equation [1]:

\[ \delta = \frac{2A_s}{\omega} \]  

where $\lambda_s = k_s/(\rho_s C_s)$, and $\omega$ is $2\pi$ day$^{-1}$ and $2\pi$ year$^{-1}$ for daily and annual variation, respectively, where $C$ represents specific heat of air (J kg$^{-1}$ K$^{-1}$).

The upper boundary temperature is considered to be equal to the ambient air temperature.

The general energy equation for solids used to determine soil temperature is as follows:

\[ \rho_s C_s \frac{\partial T_s}{\partial t} = \nabla \cdot k_s \nabla T_s \]

Because of the steady-state assumption, zero value is considered for the left-hand side of equation (3). Equation (3) is written for each node with the space derivatives approximated by finite difference. The soil region is divided into a grid system. The grid rows and columns are spaced $\delta_{\text{day}}$ (m) apart. The heat transfer from the soil to the air is modeled as a laminated cylinder with internal convection and external conduction. The following equation is used to calculate the rate of heat transfer:

\[ Q = \frac{2\pi(T_{\text{soil}} - T_1)}{R_{\text{total}}} \]

where $R_{\text{total}}$ represents the overall thermal resistance and is given by equation (5) as follows [8]:

\[ R_{\text{total}} = \frac{1}{2\pi\Delta L} \times \left\{ \left( \frac{1}{h_\text{n}} \right) + \left( \frac{1}{k_\text{i}} \right) \ln \left( \frac{r_\text{i} + t_\text{i}}{r_\text{n}} \right) + \frac{1}{k_\text{s}} \ln \left( 1 + \frac{\delta_{\text{day}}}{r_\text{n} + t_\text{i}} \right) \right\} \]

where $r$ represents radius (m); $t_i$, pipe; $i$, internal.

In the above equation, $\Delta L$ is the grid spacing along the EAHE and $T_{\text{soil}}$ represents the soil temperature, which is the distance-weighted average temperature of the three closest nodes to the tube node. A three-dimensional array is used to define the position of each node.

The convection heat transfer coefficient inside the pipe is defined by:

\[ h_\text{n} = \frac{Nu k_\text{n}}{2r_\text{n}} \]

Following Ref. [13], the Nusselt number for air flow in the pipe with smooth internal surface depends on Reynolds number and it is given by equation (7.a and b).

\[ Nu = 3.66 \quad \text{if} \quad Re < 2300 \]  

\[ Nu = \frac{(\xi/8)(Re - 1000)Pr}{1 + 12.7(\xi/8)(Pr^{2/3} - 1)} \quad \text{if} \quad 2300 \leq Re < 5 \times 10^6 \]

296 International Journal of Low-Carbon Technologies 2015, 10, 294–304
where

\[ \xi = (1.82 \log Re - 1.64)^{-2} \text{ if } Re \geq 2300 \]  

(8)

The system is discretized in 'n' sections that are perpendicular to the pipe cross section. The outlet air temperature along the EAHE from each grid is calculated by the following equation.

\[ T_{t_{\text{out}}}(z) = T_{t_{\text{in}}}(z) + \frac{Q}{mC_{\text{it}}} \]  

(9)

where \( f \) represents air flow; \( t \), pipe; \( i, \) in, inlet; \( o, \) outlet.

3.2 Mathematical modeling of SC

An element of the model for SC is shown in Figure 3. Based on the energy conservation law, a set of differential equations are obtained along the length of SC as follows.

The energy balance equation for the glass cover is as follows:

\[ \alpha_g A_g h_{\text{abs-g}} A_{\text{abs}}(T_{\text{abs}} - T_g) = h_g A_g (T_g - T_{\text{in}}) + U_{g-a} A_g (T_g - T) \]  

(10)

where \( A \) represents area (m\(^2\)); \( I \), total incident solar radiation (W\(^{-1}\) m\(^{-2}\)); \( g \), absorber wall; \( a \), glass.

The overall top heat loss coefficient from the glass cover to the ambient air \( U_{g-a} \) can be written as follows:

\[ U_{g-a} = h_{\text{wind}} + h_{g-sky} + h_{g-a} \]  

(11)

The convective heat transfer coefficient due to the wind is \( h_{\text{wind}} = 2.8 + 3.0u_{\text{wind}} \) as given in Ref. [14].

The radiative heat transfer coefficient from the outer glass surface to the sky and that between the absorber plate and the glass cover are adopted from Ref. [15]:

\[ h_{g-sky} = \frac{\sigma e_g (T_g + T_{\text{sky}}) (T_g^2 + 2T_{\text{sky}}^2) (T_g - T_{\text{sky}})}{T_g - T_a} \]  

(12)

\[ h_{\text{abs-g}} = \frac{\sigma (T_g^2 + T_{\text{sky}}^2) (T_g + T_{\text{sky}})}{(1/\varepsilon_g + 1/\varepsilon_{\text{abs}} - 1)} \]  

(13)

where the sky temperature is \( T_{\text{sky}} = 0.0552T_1^{1.5} \) [14].

The convective heat transfer coefficient is given by:

\[ h_{\text{forced}} = \frac{\nu u_c L_{\text{sc}}}{L_{\text{sc}}} \]  

(14)

All property values are evaluated at average surface air temperatures.

The following is the energy balance equation for air flow in the chimney:

\[ h_{\text{abs}} A_{\text{abs}} (T_{\text{abs}} - T_{\text{forced}}) + h_g A_g (T_g - T_{\text{forced}}) = \frac{-mC_{\text{forced}} (T_{\text{forced}} - T_{\text{in}})}{\gamma} \]  

(15)

Based on the experimental relation reported in Ref. [15], the mean air temperature is given by:

\[ T_{\text{forced}} = \gamma T_{\text{forced}} + (1 - \gamma) T_{\text{in}} \]  

(16)

Value of the constant \( \gamma \) is taken as 0.74 according to Ref. [15].

The energy balance equation for the absorber plate is written as follows:

\[ \alpha_{\text{abs}} A_{\text{abs}} (T_{\text{abs}} - T_g) = h_{\text{abs}} A_{\text{abs}} (T_{\text{abs}} - T_g) + U_{\text{abs-a}} A_{\text{abs}} (T_{\text{abs}} - T_a) \]

(17)

The overall heat transfer coefficient from the absorber wall to the room \( U_{\text{abs-a}} \) is given by:

\[ U_{\text{abs-a}} = \frac{1}{\nu u_{\text{forced}} / k_{\text{ins}}} \]  

(18)

In the above equation, \( \nu u_{\text{forced}} \) has been taken as 2.8 W m\(^{-2}\) K\(^{-1}\) according to Ref. [14].

3.3 Room ventilation and temperature

The buoyancy-induced pressure due to the increasing air temperature in SC sucks the air through the EAHE. The friction losses due to air flow through the channels and across the fittings resist the fluid flow. If the buoyancy pressure overcomes the sum of all flow pressure losses, the natural ventilation takes place. A mathematical model based on Bernoulli’s equation has been used to estimate the system flow rate. Thus, the chimney net draft can be calculated by the following equation:

\[ \text{Draft}_{\text{sc}} = (\rho_{\text{1}} - \rho_{\text{2}}) g L_{\text{sc}} \]

\[ - \left( \sum_{j=5}^{6} c_j + \xi_{\text{sc}} \left( \frac{L_{\text{sc}}}{d_{\text{hyd}}(L_{\text{sc}})} \right) \right) \left( \frac{\rho_{\text{1}} H_{\text{sc}}^2}{2} \right) \]  

(19)

where \( c_j \) is the discharge coefficients at the locations indicated in Figure 1, \( d \) represents diameter (m) and \( hyd \) hydraulic.

The values of discharge coefficients depend on the type of the opening and have been considered 0.8, 0.5, 0.5, 0.65, 0.7, 0.7 and 0.6 for \( c_1, c_2, c_3, c_4, c_5, c_6 \) and \( c_7 \), respectively [16].

The EAHE pressure loss \( \Delta P_{\text{EAHE}} \) is:

\[ \Delta P_{\text{EAHE}} = \sum_{j=1}^{4} c_j + \xi_{\text{EAHE}} \left( \frac{L_{\text{EAHE}}}{d_{\text{in}}(L_{\text{EAHE}})} \right) \left( \frac{\rho_{\text{1}} H_{\text{in}}^2}{2} \right) \]  

(20)

The chimney effects Draft\(_{\text{EAHE}}\) and Draft\(_{\text{Room}}\) can be expressed as:

\[ \text{Draft}_{\text{EAHE}} = (\rho_{\text{1}} - \rho_{\text{2}}) g (H_{\text{1}} - L_{\text{sc}}) \]  

(21)

\[ \text{Draft}_{\text{Room}} = (\rho_{\text{1}} - \rho_{\text{2}}) g H_{\text{sc}} - ro \]  

(22)

where \( H \) represents distance (m).

The required draft for heating system Draft\(_{\text{System}}\) is the sum of the pipe pressure loss \( \Delta P_{\text{EAHE}} \) and the positive pressure
Draft EAHE and Draft Room.

\[ \text{Draft System} = \Delta P_{\text{EAHE}} + \text{Draft EAHE} + \text{Draft Room} \]  

(23)

Under steady-state conditions, we can write:

\[ \text{Draft System} = \text{Draft sc} \]  

(24)

The air mass flow rate through the chimney and EAHE are the same if there is no air infiltration:

\[ m = \rho A u_{\text{Chimney outlet}} = \rho A u_{\text{Chimney inlet}} = \rho A u_{\text{EAHE}} \]  

(25)

By expanding equation (24), the air velocity in the SC can be obtained as:

\[ u_{\text{sc}} = \sqrt{\frac{2 \text{ Buoyancy terms}}{\text{Friction terms}}} \]  

(26)

Buoyancy terms = \( \left\{ \frac{(\rho_{\text{t0}} - \rho_{\text{tsc}})g(L_{\text{sc}} - (\rho_{\text{t0}} - \rho_{\text{t1}}) \times g(H_{\text{t1}} - L_{\text{sc}}) - (\rho_{\text{t0}} - \rho_{\text{tsc}})gH_{\text{sc}} - \rho_{\text{t0}})gH_{\text{sc}}}{d_{\text{hyd}}A_{\text{sc}}} \right\} \)

(27)

Friction terms = \( c_f \left( \frac{\rho_{\text{tsc}}A_{\text{sc}}}{\rho_{\text{t0}}A_{\text{t0}}} \right)^2 \rho_{\text{t1}} + \left\{ \sum_{j=1}^{4} c_j + c_6 + \xi \left( \frac{L_{\text{sc}}}{d_{\text{hyd}}A_{\text{sc}}} \right)^2 \right\} \rho_{\text{t1}} \)

(28)

The air change per hour (ACH) (h\(^{-1}\)) is calculated under steady-state conditions by the following equation [7]:

\[ \text{ACH} = \frac{3600 m}{\rho_{\text{tsc}}V} \]  

(29)

The room air temperature depends on room heat loss and is given by:

\[ T_r = T_{\text{fout}} - \frac{Q_r}{mC_{\text{ir}}} \]  

(30)

where \( Q_r \) is sum of the heats that the room misses through the walls and the heat generated by internal heat sources.

The coupled governing equations (9), (10), (15), (17) and (26) provide the full description of the system and have to be solved iteratively until the convergence of the results is achieved.

4 MODEL VALIDATION

To test and verify the adequacy of the suggested mathematical model, the calculation has been carried out for the SC and the EAHE separately and the results have been compared with the experimental studies of Ref. [17] and analytical and numerical of Refs. [1, 3] under same conditions of the references. The comparison of data obtained for the SC by the present model with experimental and theoretical data reported in Ref. [17] is presented in Table 1. It should be noted these data have been obtained for a room with volume of 27 m\(^3\). The comparison shows that the results of the present study are closer to the experimental results than the theoretical results of Ref. [17]. Therefore, the developed model has the satisfactory adequacy and can be successfully used in designing works of SC. A careful examination on grid independence of the numerical solutions was made here to ensure the accuracy and validity of the results of the model presented for EAHE. The accuracy of the numerical results was verified through numerous tests based on the grid size effect, and the computational grid that gives the grid independence results was found 45 x 45 (rectangular mesh was used here) for the soil region (X–Y plane) and 450 for the buried pipe. To evaluate the validity of the model presented for EAHE, the computed air temperature along EAHE was compared with two other models: the analytical results of [1] and numerical results of [3] for the conditions presented in Table 2. Figure 4 shows that the results of present study are very close to those of the analytical and numerical models of the literature. It indicates that the present model

Table 1. Comparison of experimental and theoretical results for SC-induced ACH number.

| Solar radiation (W m\(^{-2}\)) | Absorber length (m) | Inlet chimney dimension (m x m) | Ambient Temperature (K) | Experimental [17] | Theoretical [17] | Theoretical (present study) | Errors of [17] (%) | Present study (%) |
|-------------------------------|---------------------|--------------------------------|-------------------------|-------------------|-----------------|----------------------------|------------------|------------------|
| 300                           | 0.7                 | 1.0 x 0.3                      | 295–302                | 4.400             | 4.173           | 4.366                      | 5.16             | 0.77             |
|                               | 0.8                 | 1.0 x 0.2                      | 298–304                | 5.330             | 4.034           | 4.757                      | 23.94            | 10.75            |
|                               | 0.9                 | 1.0 x 0.1                      | 294–296                | 2.400             | 2.704           | 2.368                      | 12.66            | 1.33             |
| 500                           | 0.7                 | 1.0 x 0.3                      | 295–302                | 4.800             | 5.160           | 4.454                      | 7.50             | 7.21             |
|                               | 0.8                 | 1.0 x 0.2                      | 298–304                | 4.530             | 4.895           | 4.816                      | 8.06             | 6.31             |
|                               | 0.9                 | 1.0 x 0.1                      | 294–296                | 2.660             | 3.461           | 2.970                      | 30.11            | 11.65            |
| 700                           | 0.7                 | 1.0 x 0.3                      | 295–302                | 5.600             | 5.810           | 5.404                      | 3.75             | 3.5              |
|                               | 0.8                 | 1.0 x 0.2                      | 298–304                | 5.330             | 5.175           | 5.480                      | 2.91             | 2.81             |
|                               | 0.9                 | 1.0 x 0.1                      | 294–296                | 2.930             | 3.671           | 3.217                      | 25.29            | 9.79             |

298 International Journal of Low-Carbon Technologies 2015, 10, 294–304
and method can be used effectively to predict the air temperature quite accurately and the calculated results are reliable.

5 RESULTS AND DISCUSSION

The following dimensions and specifications are used in the modeling. The room has the size of $4.0 \times 4.0 \times 3.125$ m without air infiltration. The heating demand is varied within the range of $0.0–1000$ W in the calculations. An SC with the length of $3.125$ m, width of $4.0$ m and air gap depth of $0.2$ m is considered. The thickness and thermal conductivity of the insulation located in south wall of the room are $0.2$ m and $0.046 \text{ W m}^{-1} \text{ K}^{-1}$, respectively. The transmissivity of the glass wall is $0.84$, and the absorber wall has an emissivity and absorptivity equal to $0.95$. The outlets size of the SC and the room (Figure 1) are $0.05 \times 4.0$ m and $0.1 \times 4.0$ m, respectively. The heating pipe of EAHE is a PVC pipe with thermal conductivity of $0.23 \text{ W m}^{-1} \text{ K}^{-1}$, length of $25.0$ m, thickness of $0.01$ m and inside diameter of $0.5$ m and is buried $3.0$ m below the soil surface. At the beginning, the soil temperature at this depth is approximated to be $19^\circ\text{C}$ for a dry shaded soil surface condition, and it is also considered as the temperature of the lower boundary of the computational domain ($T_{su}$). It is assumed that this temperature does not change during the time in which system works. The system is set up in Tehran, having $35.44^\circ\text{N}$ latitude position and the homogeneous soil properties are as follows: conductivity, $0.52 \text{ W m}^{-1} \text{ K}^{-1}$; density, $2050 \text{ kg m}^{-3}$; specific heat, $1840 \text{ J kg}^{-1} \text{ K}^{-1}$.

5.1 Effective dimensions on the system performance

There are many geometrical dimensions that affect the system performance. To find the effect of each parameter, its value varied and the rest of parameters were kept constant.

The influence of the air gap depth on the ACH at various solar radiation values is shown in Figure 5a. It shows that the ACH increases as the air gap size rises, and gradually the influence becomes less significant and the ACH remains almost constant beyond $0.2$ m. Likewise, the effect of air gap depth on the variation of room air temperature has been presented in Figure 5b. It shows that as the air gap depth increases, the room air temperature decreases. The reason is that the time for heat transfer between absorber walls and air is shortened with the increase in ACH. A comparison between these figures shows that the system performance changes as the chimney air gap size increases up to almost $0.2$ m, and any further increase does not have a significant effect on the performance. Therefore, an air gap of $0.2$ m is considered as a maximum required value of the air gap.
the room air temperature. This means that around the noon, the system reaches to its highest effectiveness.

Other important dimensions that affect the system performance are the inlet and outlet size of room.

The ACH variation due to change of the inlet size of the room is shown in Figure 6a. This figure shows that there is an optimum inlet (z1) size beyond which the ACH would begin to decrease. By increasing z1 (Figure 1), the pressure loss decreases and it causes an increase in the ACH. However, increasing the room inlet size corresponds to the decrease in the absorber area, and consequently, the amount of heat transfer is reduced. Accordingly, the Draftsc (given by equation 19) and ACH tend to decrease. This optimum value is ≏0.2 m. The effect of room inlet size on the room air temperature is shown in Figure 6b. As shown in Figure 6b, increasing the z1 would finally lead to decrease in the room air temperature. It is due to the decrease in the energy gained by the absorber wall.

The outlet size of the room (z2) can also change the system performance. Figure 6c and d shows the effect of this parameter on the ACH and room air temperature, respectively. They indicate that the variation of outlet size of the room has less effect on the ACH and room air temperature. However, a design of room with variable inlet and outlet may assist the inhabitants to keep the room air temperature in the range of thermal comfort even at low solar intensity. The recommended size is 0.20 m for the SC outlet and 0.05 m for the room outlet.

The thermal performance of the EAHE–SC system is also affected by the pipe configuration. In this study, the effects of diameter and length of the EAHE have been investigated. The effect of the pipe diameter on the system performance is summarized in Table 3. The results indicate that smaller diameters are preferred from a thermal point of view, but they also correspond to higher friction loss and lead to lower ACH. A comparative survey shows that as the diameter of EAHE increases up to almost 0.5 m, any further increase does not have a significant effect on the ACH and the room air temperature. Therefore, this value is adopted as the default value of diameter in the present study. Table 4 shows the effect of length of EAHE on the system performance. When the pipe length increases, the lateral surface area of the buried pipe and consequently the amount of heat transfer will be increased. This leads to lower ACH, and the time for heat transfer along the SC and EAHE is increased. The findings show that under this condition, an increase in air temperatures through the SC compensates the reduction in mass flow rate; therefore, the room air temperature will increase. It is also found that the use of long EAHE for low insulated spaces may not be useful and the chimney effect can hardly compensate the total pressure losses and the system performance will be reduced significantly. Thus, for the pipe longer than 35 m, the comfort temperature may not be provided, and shorter EAHE should be employed.

5.2 Effects of environmental conditions on the system performance

Thermal behavior of the system is influenced by environmental conditions. The environmental conditions are comprised of
heating demand of inhabitant, outdoor ambient temperature, solar radiation and soil temperature. Table 4 shows the effects of heating demand on the system performance. It shows that when the heating demand increases, the ACH decreases. This is because of the reduction in room average air temperature that causes an increase in \( \text{Draft}_{\text{Room}} \) (last term of the equation 27) and finally leads to lower chimney effect. Although this effect increases the performance of EAHE, the indoor air temperature decreases due to the increase in the room heat loss. The findings also show that when the heating demand increases, the use of longer EAHE may not be efficient. Table 5 shows the summary of results of the calculations for different environmental conditions. According to the results, when the ambient air temperature increases, thermal comfort may be achieved at lower solar radiation. It should be noted that, when the solar intensity increases, the wall temperature of SC rises. This has two effects: higher ACH and air flow temperature, which enhance the heating gain. It is also found that when the heating demand is high, thermal comfort can be achieved only at higher solar radiation. However, with proper insulation and reduction of the

### Table 3. Effects of diameter of EAHE on the system performance.

| Heating demand (W) | Solar radiation (W m\(^{-2}\)) | Diameter of EAHE (m) | ACH | EAHE outlet air temperature (°C) | Room air temperature (°C) |
|--------------------|-------------------------------|----------------------|-----|---------------------------------|--------------------------|
| 0.0                | 300                           | 0.1                  |     | Thermal comfort cannot be provided |
|                    |                               | 0.3                  | 3.82| 15.10                           | 27.20                    |
|                    |                               | 0.5                  | 6.85| 13.70                           | 21.90                    |
|                    |                               | 0.7                  | 7.72| 13.20                           | 20.70                    |
|                    |                               | 0.9                  | 7.98| 12.90                           | 20.90                    |
| 0.0                | 500                           | 0.1                  |     | Thermal comfort cannot be provided |
|                    |                               | 0.3                  | 5.25| 14.60                           | 33.30                    |
|                    |                               | 0.5                  | 9.03| 13.40                           | 25.70                    |
|                    |                               | 0.7                  | 10.02| 13.00                           | 24.30                    |
|                    |                               | 0.9                  | 10.28| 12.70                           | 23.80                    |
| 500                | 300                           | 0.1                  |     | Thermal comfort cannot be provided |
|                    |                               | 0.3                  | 5.04| 14.00                           | 20.00                    |
|                    |                               | 0.5                  | 5.74| 13.50                           | 18.50                    |
|                    |                               | 0.7                  | 6.20| 13.10                           | 18.10                    |
| 500                | 500                           | 0.1                  |     | Thermal comfort cannot be provided |
|                    |                               | 0.3                  | 4.78| 14.80                           | 30.70                    |
|                    |                               | 0.5                  | 7.88| 13.60                           | 23.30                    |
|                    |                               | 0.7                  | 8.83| 13.10                           | 22.20                    |
|                    |                               | 0.9                  | 9.10| 12.80                           | 21.70                    |

Note: ambient air temperature = 10°C, required number of SC and EAHE = 1.

### Table 4. Effects of length of EAHE on the system performance.

| Heating demand (W) | Solar radiation (W m\(^{-2}\)) | Length of EAHE (m) | ACH | EAHE outlet air temperature (°C) | Room air temperature (°C) |
|--------------------|-------------------------------|-------------------|-----|---------------------------------|--------------------------|
| 0.0                | 300                           | 15.0              | 7.47| 12.40                           | 20.30                    |
|                    |                               | 25.0              | 6.85| 13.70                           | 21.90                    |
|                    |                               | 35.0              | 6.35| 14.90                           | 23.20                    |
|                    |                               | 45.0              | 5.89| 15.80                           | 24.40                    |
| 0.0                | 500                           | 15.0              | 9.56| 12.10                           | 24.10                    |
|                    |                               | 25.0              | 9.03| 13.40                           | 25.70                    |
|                    |                               | 35.0              | 8.59| 14.40                           | 27.10                    |
|                    |                               | 45.0              | 8.15| 15.30                           | 28.30                    |
| 500                | 300                           | 15.0              | 6.24| 12.60                           | 18.70                    |
|                    |                               | 25.0              | 5.04| 14.00                           | 20.00                    |
|                    |                               | 35.0              | 4.73| 15.20                           | 21.30                    |
|                    |                               | 45.0              |     | Thermal comfort cannot be provided |
| 500                | 500                           | 15.0              | 8.55| 12.30                           | 21.80                    |
|                    |                               | 25.0              | 7.88| 13.60                           | 23.30                    |
|                    |                               | 35.0              | 4.12| 16.00                           | 25.10                    |
|                    |                               | 45.0              |     | Thermal comfort cannot be provided |

Note: ambient air temperature = 10°C, required number of SC and EAHE = 1.
heating demand, SC can provide good indoor condition in the poor solar intensity of 250 W and low ambient air temperature of 0°C (see forth row of Table 5). The findings show that the system can provide the required indoor temperature and ACH number even at harsh environmental condition of low temperature of 0°C and high heating demand of 1000 W. As shown in Table 5, for poor insulated room with high heating demand, the use of EAHE with small length may be useful. Under this condition, when the buried pipe is longer than 15 m, the SC will not be able to provide the necessary stack effect and the use of a small fan can help the air to flow from EAHE into the room to realize thermal comfort condition.

Another parameter, which affects the system performance, is the soil temperature. Due to the fact that the ground exhibits high thermal inertia, the EAHE is usually placed below the ground surface at a certain depth where the soil temperature remains nearly constant throughout the year. This temperature is equal to the mean annual ground surface temperature and depends on climatic conditions of each region. Table 6 shows the system performance at different soil temperature. The findings show that when the soil temperature increases, thermal comfort may be achieved at lower solar radiation. This result is caused by the increase in the heat transfer from the earth, which leads to higher room air temperature. It is found that if the room is properly insulated, the EAHE–SC system will provide the thermal comfort condition even at the low soil temperature of 13°C. It is also concluded that this technique is suitable to supply the heating demand of building especially in the moderate climates where the mean annual air temperature is usually high.

Table 5. System performance at different outdoor conditions.

| Heating demand (W) | Length of EAHE (m) | Ambient Air temperature (°C) | Solar radiation (W m⁻²) | ACH | Room air temperature (°C) |
|--------------------|--------------------|-----------------------------|------------------------|-----|-------------------------|
|                    |                    |                             |                        |     |                         |
| 0.0                | 15                 | 0.0                         | 440                    | 8.59| 15.90                   |
|                    |                    | 5.0                         | 250                    | 6.28| 15.90                   |
|                    |                    | 10.0                        | 170                    | 5.21| 17.50                   |
| 0.0                | 25                 | 0.0                         | 250                    | 5.11| 15.90                   |
|                    |                    | 5.0                         | 185                    | 3.45| 15.90                   |
|                    |                    | 10.0                        | 120                    | 2.69| 17.50                   |
| 500                | 15                 | 0.0                         | 560                    | 8.73| 15.90                   |
|                    |                    | 5.0                         | 390                    | 6.79| 15.90                   |
|                    |                    | 10.0                        | 315                    | 5.65| 17.50                   |
| 500                | 25                 | 0.0                         | 550                    | 8.47| 15.90                   |
|                    |                    | 5.0                         | 320                    | 5.67| 15.90                   |
|                    |                    | 10.0                        | 280                    | 4.63| 17.50                   |
| 1000               | 15                 | 0.0                         | Thermal comfort cannot be provided |     |                         |
|                    |                    | 5.0                         | 500                    | 6.26| 15.90                   |
|                    |                    | 10.0                        | 380                    | 5.77| 17.50                   |

Note: outlet height of SC is 0.10 m, number of SC and EAHE = 1.0.

Table 6. System performance at different burial soil temperature.

| Heating demand (W) | Soil temperature (°C) | Ambient air temperature (°C) | Solar radiation (W m⁻²) | ACH | Room air temperature (°C) |
|--------------------|-----------------------|-----------------------------|------------------------|-----|-------------------------|
|                    |                       |                             |                        |     |                         |
| 0.0                | 16                    | 0.0                         | 340                    | 6.57| 15.90                   |
|                    |                       | 5.0                         | 200                    | 4.79| 15.90                   |
|                    |                       | 10.0                        | 165                    | 4.91| 17.50                   |
| 0.0                | 13                    | 0.0                         | 410                    | 7.82| 15.90                   |
|                    |                       | 5.0                         | 270                    | 6.56| 15.90                   |
|                    |                       | 10.0                        | 220                    | 6.40| 17.50                   |
| 500                | 16                    | 0.0                         | 470                    | 6.80| 15.90                   |
|                    |                       | 5.0                         | 350                    | 5.35| 15.90                   |
|                    |                       | 10.0                        | 310                    | 5.03| 17.50                   |
| 500                | 13                    | 0.0                         | 550                    | 7.88| 15.90                   |
|                    |                       | 5.0                         | 400                    | 6.76| 15.90                   |
|                    |                       | 10.0                        | 350                    | 6.44| 17.50                   |
| 1000               | 16                    | Thermal comfort cannot be provided |                        |     |                         |
| 1000               | 13                    | Thermal comfort cannot be provided |                        |     |                         |

Note: L_{EAHE} = 25 m, outlet height of SC is 0.10 m, number of SC and EAHE = 1.0.
show that the required number of EAHEs and SCs should be increased to retain the thermal comfort condition when the room size and heating demand are increased simultaneously. It is found that one 4.0/C2 3.125 m SC is required for each 50 m3. Accordingly, the required number of SC is calculated by (room volume/50. It is also found that the required number of EAHEs is \( \approx \frac{2}{C2} \) number of SCs + 1. The findings show that when the heating demand increases, thermal comfort is only realized at higher solar intensities. Moreover, with proper insulation, thermal comfort condition is provided during most times of a day, and the required number of EAHEs and SCs will be reduced.

### 6. CONCLUSIONS

Natural ventilation and heating a room using a passive system comprising of SCs and EAHEs was proposed and studied in this paper. This study shows that the system performance depends on solar radiation, outdoor air temperature, heating demand of room, the soil temperature, as well as the configuration of both the SC and the EAHE. It is found that there is an optimum size for air gap size of SC (0.2 m) and diameter of heating pipe (0.5 m). In addition, the indoor air temperature always decreases as the outlet sizes of SC increases. However, the effect of outlet sizes of

### Table 7. System performance at different indoor and outdoor conditions.

| Room volume (m³) | Ambient air temperature (°C) | Solar radiation (W m⁻²) | Heating demand (W) | ACH | Room air temperature (°C) | Number of SC | Number of EAHE |
|-----------------|-----------------------------|------------------------|-------------------|-----|--------------------------|-------------|---------------|
| 0.0             | 470                         | 1000                   | 8.29              | 15.90 | 2                        | 3           |               |
|                 | 560                         | 1500                   | 9.34              | 15.90 | 2                        | 3           |               |
|                 | 650                         | 2000                   | 10.43             | 15.90 | 2                        | 3           |               |
| 2 × 50          | 5.0                         | 350                    | 1000              | 6.46  | 15.90                    | 2            | 3             |
|                 | 425                         | 1500                   | 7.80              | 15.90 | 2                        | 3           |               |
|                 | 500                         | 2000                   | 8.93              | 15.90 | 2                        | 3           |               |
|                 | 10.0                        | 300                    | 1000              | 6.77  | 17.50                    | 2            | 3             |
|                 | 380                         | 1500                   | 8.21              | 17.50 | 2                        | 3           |               |
|                 | 460                         | 2000                   | 9.32              | 17.50 | 2                        | 3           |               |
| 0.0             | 480                         | 2000                   | 6.12              | 15.90 | 3                        | 6           |               |
|                 | 500                         | 2500                   | 8.86              | 15.90 | 3                        | 6           |               |
|                 | 570                         | 3000                   | 9.32              | 15.90 | 3                        | 6           |               |
| 3 × 50          | 5.0                         | 350                    | 2000              | 4.95  | 15.90                    | 3            | 6             |
|                 | 410                         | 2500                   | 7.80              | 15.90 | 3                        | 6           |               |
|                 | 470                         | 3000                   | 7.70              | 15.90 | 3                        | 6           |               |
|                 | 10.0                        | 340                    | 2000              | 7.15  | 17.50                    | 3            | 6             |
|                 | 400                         | 2500                   | 8.47              | 17.50 | 3                        | 6           |               |
|                 | 450                         | 3000                   | 9.24              | 17.50 | 3                        | 6           |               |
| 4 × 50          | 5.0                         | 380                    | 3000              | 5.12  | 15.90                    | 4            | 9             |
|                 | 420                         | 3500                   | 6.11              | 15.90 | 4                        | 9           |               |
|                 | 460                         | 4000                   | 7.05              | 15.90 | 4                        | 9           |               |
|                 | 10.0                        | 310                    | 3000              | 6.47  | 17.50                    | 4            | 8             |
|                 | 350                         | 3500                   | 7.51              | 17.50 | 4                        | 8           |               |
|                 | 380                         | 4000                   | 8.01              | 17.50 | 4                        | 8           |               |
| 0.0             | 470                         | 4000                   | 5.73              | 15.90 | 5                        | 11           |               |
|                 | 490                         | 3500                   | 6.04              | 15.90 | 4                        | 9           |               |
|                 | 540                         | 4000                   | 6.68              | 15.90 | 4                        | 9           |               |
| 5 × 50          | 5.0                         | 400                    | 4000              | 6.20  | 15.90                    | 5            | 11            |
|                 | 430                         | 4500                   | 6.93              | 15.90 | 5                        | 11           |               |
|                 | 460                         | 5000                   | 7.54              | 15.90 | 5                        | 11           |               |
|                 | 10.0                        | 380                    | 4000              | 8.18  | 17.50                    | 5            | 11            |
|                 | 410                         | 4500                   | 8.76              | 17.50 | 5                        | 11           |               |
|                 | 440                         | 5000                   | 9.28              | 17.50 | 5                        | 11           |               |
| 0.0             | 470                         | 5000                   | 5.33              | 15.90 | 6                        | 14           |               |
|                 | 490                         | 5000                   | 6.04              | 15.90 | 6                        | 14           |               |
| 6 × 50          | 5.0                         | 410                    | 5000              | 6.21  | 15.90                    | 6            | 14            |
|                 | 430                         | 5500                   | 6.64              | 15.90 | 6                        | 14           |               |
|                 | 460                         | 6000                   | 7.28              | 15.90 | 6                        | 14           |               |
| 10.0            | 390                         | 5000                   | 8.61              | 17.50 | 6                        | 13           |               |
|                 | 420                         | 5500                   | 9.15              | 17.50 | 6                        | 13           |               |

Note: \( L_{EAHE} = 25 \) m, outlet height of SC is 0.10 m, \( T_{soil} = 19^\circ \)C.
SC and room on indoor conditions is not significant when they are increased up to 0.2 m. The findings showed that the use of long EAHE for low insulated spaces may not be useful, and for the pipe longer than 35 m, the comfort temperature may not be provided. The results also showed that around the noon, the system reaches to its highest effectiveness, and when the ambient temperature is low and the heating demand is high, although providing thermal comfort is difficult, proper configuration of SC and EAHE could provide good indoor condition even in the poor solar intensity of 250 W m$^{-2}$ and low ambient air temperature of 0°C. The results showed that when the soil temperature increases, thermal comfort may be achieved at lower solar radiation, and the EAHE–SC system can provide thermal needs of inhabitants even at the low soil temperature of 13°C. Investigation on the use of proposed system for stand-alone building regarding thermal comfort criteria showed: the south wall of the building should be wholly considered as a SC; the required number of EAHEs should be increased by increasing the amount of heating demand and decreasing ambient air temperature; moreover, the required number of SCs and EAHEs are obtained approximately by: room volume/50 and $2 \times (\text{room volume}/50) + 1$, respectively.

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