Heat Transfer and Natural Ventilation Airflow Rates  
from Single-sided Heated Solar Chimney for Buildings  

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Abstract  
Heat transfer process and natural ventilation driven by a solar chimney attached to a sidewall of building are investigated with CFD technique (MITFLOW) in detail. In this paper, conditions and parameters studied in the modelling study are the cavity width of the solar chimney, the wall temperature, the height and breadth of the solar chimney, the ratio of outlet area to inlet area as well as the outlet location of the solar chimney. The ranges of calculation parameters focused on a solar chimney with single-sided solar collector (single-sided heated wall) cover following conditions: solar chimney length L = 0.5m~5.0m, breadth B=0.1m~0.5m, height H=2.0m~5.0m, and B/H=0.05~0.25. Heated wall surface temperature Tw is changed in the range of 30˚C~70˚C; the ratio of the outlet area to inlet area A2 is changed in the range of 0.6~1.0. It is found that for given building geometry and inlet areas, there is an optimum cavity width at which a maximum airflow rate can be achieved. Based on the prediction, the airflow rate reaches maximum when B/H is approximately 1/10. It is also found that for given chimney geometry, solar chimney ventilation flow rate can be increased with the enhancement of chimney height only the cross sectional area no more than the critical area, because cross section area has a strong effect on the transitional and/or turbulent convective heat transfer in an enclosure. From the view of economy technology, the optimized height of a solar chimney can be determined according to the optimized section ratio of breadth to height and available breadth in practice. On the analysis of CFD prediction, it is noted that optimized ventilation flow rate can be obtained when the outlet area takes the same area as the inlet area. Generally, there is good agreement among the numerical results, available experimental data from literature and theoretical analysis of natural ventilation from the solar chimney.  

Keywords: single-sided heated solar chimney; natural ventilation; airflow rate; numerical calculation; optimum design  

Introduction  
In the design of new buildings and retrofit of old buildings, the attention is turning towards a more integral energy design on optimal use of sustainable technologies such as natural ventilation (daytime comfort ventilation and night cooling)[1,3]. The current trend is to design buildings responsive to the climate with an acceptable indoor environment and high energy efficiency. For example, a recent survey in UK indicated that 90% of directors and senior managers preferred natural ventilated buildings without air-conditioning [4]. The limitations of conventional energy sources, in terms of cost and availability, and an increased awareness of environment issues, have led to renewed interest in passive building design. One important application of this technology is to intensify interior ventilation by using a solar chimney to induce buoyancy-driven flow.

Solar chimney natural ventilation has high ground in both developing and developed countries. For instance, innovative solar chimney natural ventilation design techniques have an historical basis and have been advanced in recent years [5, 6, and 7]. There are many examples using chimney effect to ventilation, cooling and smoke exhaust in China: courtyard, Xin Jiang arch building, and cave dwellings [5]. In UK, there has also been a development of solar chimney stack-induced cross ventilation design for non-domestic buildings, such as Auditoria and Offices, Inland Revenue Headquarters Buildings located in Nottingham. However, different heated sides and air outlet locations can result in different temperature fields and velocity fields. As a result, the airflow rate and exhaust temperature are also changed. Major uncertainty in the design of solar chimney is the effect of the geometrical structures, solar radiation and outdoor temperature. Unfortunately, we have little knowledge in determining those parameters for an efficient and effective design of the solar chimney natural ventilation systems [8,9]. This paper is focused on airflow and convective heat transfer inside the solar chimney. The emphasis is laid on the comparison
between different heated sides, outlet locations and the relationship between the outlet and inlet area, the temperature difference, and the optimum structural size.

**Turbulent mathematics mode and MITFLOW program**

This research is carried out through CFD calculation with theoretical analyses and MITFLOW program, which was developed by Chen, etc in MIT [10]. The temperature field and velocity field are showed by FORTRAN coded program and EXCEL2000. About 60 cases have been calculated to find out the optimum condition for solar chimney ventilation design. The rate of airflow can be calculated from these equations in various sizes of solar collector, seeing whether ventilation requirements can be satisfied.

Airflow inside solar chimney belongs to turbulent flow. In this research, MITFLOW equation model based on time average method is solved. Every grid is in conformity with the conservation of mass flow, i.e. the inlet mass flow is equal to the outlet flow. For one-sided heated solar chimney turbulent convective diffusion, its governing equations are concluded from the basic equations in fluid dynamics (continuity, momentum, energy) and time average method.

When zero governing equation is concluded, the primary assumptions are as the following

1. Airflow inside solar chimney is low speed, incompressible and conforms to ideal gas law.
2. Indoor air belongs to Newton fluids whose surface stress is conform to broadly Newton viscosity stress equation.
3. Boussingq assumption is applied.

Turbulence time average equations are obtained based on the assumptions above.

**Continuity**

\[
\frac{\partial \bar{V}_i}{\partial x_i} = 0 
\]  
(1)

\( \bar{V}_i \) average velocity in \( x_i \) direction

\( x_i \) coordinate

**Momentum**

\[
\frac{\partial \rho \bar{V}_i}{\partial t} + \frac{\partial \rho \bar{V}_i \bar{V}_j}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \mu_{eff} \left( \frac{\partial \bar{V}_i}{\partial x_j} + \frac{\partial \bar{V}_j}{\partial x_i} \right) - \rho \bar{g} \bar{g} \right] + \rho q_i - \rho \bar{g} \bar{g} T_i
\]  
(2)

\( \rho \) air density

\( \bar{V}_i \) average velocity in \( x_i \) direction

\( P_i \) pressure

\( \mu_{eff} \) effective viscosity coefficient

\( \beta \) coefficient of air thermal expansion

\( T_i \) temperature at the referent point

\( T' \) air temperature

\( \bar{g}_i \) acceleration of gravity in \( i \) direction

The last right item in equation is buoyancy.

**Energy**

In order to determine the temperature distribution and buoyancy item in (2), energy conservation equation should be solved.

\[
\frac{\partial \rho T}{\partial t} + \frac{\partial \rho V_i T}{\partial x_i} = \frac{\partial}{\partial x_i} \left[ \Gamma_{T, eff} \frac{\partial T}{\partial x_i} \right] + \frac{q_i}{c_p} 
\]  
(3)

\( \Gamma_{T, eff} \) temperature effective diffusivity

\( q_i \) heat source

\( C_p \) specific heat at constant pressure

In this research, the equation below is used to estimate the temperature effective diffusivity.

\[
\Gamma_{T, eff} = \frac{\mu_{eff}}{Pr_{eff}} 
\]  
(4)

\( Pr_{eff} \) general Prandtl number

Turbulent effects are united to turbulent effective diffusivity, which is the sum of turbulent diffusivity \( \mu \), and laminar viscosity coefficient.

\[
\mu_{eff} = \mu_t + \mu 
\]  
(5)

In the assumption of Prandtl-Kolmogorov, turbulent diffusivity \( \mu_t \) is the result of turbulent fluctuation momentum energy and turbulent fluctuation dimension.

\[
\mu_t = C_s \rho \bar{k}^{1/2} l 
\]  
(6)

\( C_s = 0.5478 \) is empirical constant [10]. According to the different methods to solve the unknown parameters \( K \) and \( L \), the turbulent viscosity models are divided into many forms. The simplest model is Prandtl mixing length model. In this research, turbulent viscosity is denoted with local average velocity and length scale by the simple algebraic equation [9,10].

\[
\mu_t = 0.03874 \rho \bar{V} l 
\]  
(7)

\( l \) length scale, the distance between envelope and nearest surface.

Those equations can be discretized into algebraic equations, and a series of algebraic equations can be solved by MITFLOW program[10]. Algebraic equations in up-wind difference form are used during modelling process [11].

**Numerical simulation results and analysis**

The theoretical model to describe single-sided solar chimney is idealized. Amongst other simplifications, it assumes that there is no external wind; that the density of the air outside the chimney is uniform; that the solar collector is derived from a plate of uniform temperature; and that the adjacent walls of the solar chimney are insulated. These studies are focused on 4 parameters, that is, \( H, B/H, A \) and \( L \). The case geometrical structures studied for single-sided heated solar chimney are presented in Fig.1. The calculations on airflow rate \( m \)
The ranges of calculation parameters are reported below:

- Solar chimney mode size: \( L \times B \times H \) (length) \( \times \) (breadth) \( \times \) (height), \( L=0.5 \sim 5.0 \text{m}, \ B=0.1 \sim 0.5 \text{m}, \ H=2.0 \sim 5.0 \text{m}, \ B/H=0.05 \sim 0.25 \)
- Heated wall surface temperature \( T_w = t_w + 273, t_w = 30^\circ\text{C} \sim 70^\circ\text{C}, t_m = 20^\circ\text{C} \)
- The ratio between outlet area and inlet area \( A_r \) \( =0.6 \sim 1.0 \)
- In considering practical architecture conditions, the distance between the upper edge of outlet and the top of solar chimney is 0.1H. The outlet is located at the heated wall.

In this paper, about 60 cases covering the influence of the solar collector wall temperature \( t_w \), inflow temperature \( t_m \), solar chimney breadth \( B \), length \( L \), height \( H \), as well as the ratio between outlet area and inlet area \( A_r \) on airflow and outlet (exhaust) temperature \( t_{\text{out}} \) are simulated in order to understand better the mechanism of solar chimney natural ventilation. The relationship between the airflow rates and solar chimney height parameter are demonstrated in Figure 2.

The airflow rate of solar chimney is notably affected by chimney height. When the solar collector (wall) temperature is in the range of 30°C ~ 50°C, airflow rates can reach the maximum at the height of \( H=4 \text{m} \). Meanwhile, from the Figure 2, when the height is increased to 4 m or more, the increase of airflow rate is gradually lower down. This phenomena can be partly explained by the natural convection in a channel formed by a single isothermal plate and an insulated plate. Only the solar collector surface, which is an isothermal surface, is involved in heat transfer, while the associated adjacent surfaces being adiabatic. The Nusselt number based on the temperature difference between the wall and the ambient air was once proposed by Bar-Cohen [13]

\[
Nu = \frac{1}{24} \left[ \frac{c_p \rho^2 g B B_s (t_w - t_m)}{\mu k H} \left( 1 - e^{-TH} \right) \left( 1 - e^{-TH} \right) \right] \quad (8)
\]
The highest convective heat transfer coefficients can be expected in vertical channel formed by an isothermal plate and an insulated plate at a certain height and width [13]. The airflow rate inside the solar chimney is exactly produced by the density difference or temperature difference caused by heat transfer. As a consequence, the optimum height and width could be anticipated (see Figure 6). It is thus possible to select the chimney height or breadth which will maximum the airflows or, alternatively, choose the height or breadth which will yields the maximum heat transfer from the entire solar collector.

On the other hand, in fact, the solar chimney to be investigated here is three-dimensional rather than two-dimensional as a channel mentioned above. The influence of three-dimensional flow, i.e., side inflow, or lateral edge effects, on the airflow should not be ignored. Clearly such effects can be anticipated to become progressively greater as the surface temperature is increased, seeing the curve at the wall temperature $t_w = 70^\circ C$ shown in Figure 2.

The exhaust temperature or outlet temperature is enhanced as the height or wall temperature is increased, as presented in Figure 3. From the view of energy conservative, the curve tendencies are easily to be understood. The exhaust temperature/outlet temperature will gradually increase as the height or solar collector temperature enhances.

The relationship among airflow rate $m$, the ratio of outlet area to inlet area $Ar$, is shown in Figure 4. In Figure 5, the exhaust temperature changes brought about by the ratio of outlet area to inlet area is presented. The exhaust temperature decreases with the increment of outlet areas or decrement of inlet areas.

When $B/H$ is varied but parameter conditions $L$, $H$, $T_{in}$, $V_{in}$ and $T_w$ remain constant, airflow rate $m$ and outlet temperature $T_{out}$ is predicted and shown in Figure 6 and Figure 7.

Moreover, airflow rate increases with the heated wall temperature increasing. The bigger the ratio of outlet area and inlet area, the more the increasing value.

In Figure 6, airflow rate varies with the variation of ratio of breadth to height. Airflow rate is up to the
maximum when the ratio of breadth to height is about 1/10. But when the ratio is increasing further, exceeding 1/10, and airflow rate will fall down a lot. This trend shown in the solar chimney could be explained by the buoyant plumes characteristics. This mean the reasonable breadth (space) could induce maximum air from the inlet at the bottom. In other words, too much breadth does not create the effective airflow rate enhancement. Figure 7 shows that temperature trends at the outlet while the ratios, breadth to height, as calculated from MITflow program.

When B, L, H, T_{in}, V_{in}, and T_{w} remain constant, however, the $A_r$ is varied, airflow rate $m$, outlet average temperature $t_{out}$ is investigated. The studied cases parameter conditions and outcome are reported in Figure 8.

In Figure 8, airflow rate varies with the variation of ratio of breadth to height. Airflow rate is up to the maximum when the ratio of breadth to height is about 0.1 (or 1/10). However, when the ratio is increasing further to the 0.15, airflow rate notably fall down a lot. These phenomena also totally coincide with the fact presented in Figure 6. Again there is evidence to show that the sizes of solar chimney are essential for the heat transfer and the airflow rates.

In Figure 9, exhaust temperature decreases with the increment of ratio of breadth to height. It might be the result of air mixing effect, as the ratio of breadth to height increases, there will be more space (cross sectional area) for airflow passage gradually.

It is also noted that effects on airflows from the breadth change outweighs the effects from height change. In the range of height 0.5 to 5m, the exhaust temperature does not vary much when the heights enhance but the breadth remains constant. So the suitable solar chimney height should be selected in designing the solar chimney, based on the view of ventilation enhancement and economics.

The effects of temperature difference between inlet and outlet on airflow rates are shown in Figure 10. The “bottle neck effect” caused by the cross section appears again. The airflow rate does not always increase with the enhancement of the temperature difference between inlet and outlet. The airflow rate will reach the maximum at a certain temperature difference between inlet and outlet for a given solar chimney sizes.

**Conclusion**

By the CFD prediction on the mechanism of natural ventilation, the relationship between the airflow rate and parameters for single-sided heated solar chimney is concluded. In the ranges of, solar chimney length $L = 0.5m$~$5.0m$, breadth $B = 0.1m$~$0.5m$, height $H = 2.0m$~$5.0m$, and $B/H = 0.05$~$0.25$, it is found that for a given building geometry and inlet area, there is an optimum cavity width at which a maximum airflow rate can be achieved. There is a “bottle neck effect” zone inside the chimney for the natural ventilation rates, and natural ventilation rates are restricted by this “bottle neck” phenomena.

Based on the present studied ranges, the airflow rate reaches maximum when $B/H$ is approximately 1/10. It is also found that ventilation mass rate may be increased with the enhancement of chimney height only the cross...
sectional area no more than the critical area. From the view of technology and economy, the optimized height of a solar chimney can be determined according to the optimized section ratio of breadth to height and available practical field conditions.

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Nomenclature

| Symbol | Description |
|--------|-------------|
| $A_o$  | the ratio of the outlet area to inlet area |
| $B$    | solar chimney breadth |
| $C_p$  | specific heat at constant pressure |
| $g_i$  | acceleration of gravity in $i$ direction |
| $H$    | solar chimney height |
| $L$    | solar chimney length |
| $P$    | pressure |
| $q$    | heat source |
| $T$    | air temperature |
| $T_w$  | wall surface temperature |
| $T_{ref}$ | temperature at the referent point |
| $V_i$  | average velocity in $x_i$ direction |
| $V_{ref}$ | average velocity in $x$ direction |
| $Pr_{eff}$ | general Prandtl number |
| $x_i$  | coordinate |
| $\rho$ | air density |
| $\mu_{eff}$ | effective viscosity coefficient |
| $\beta$ | coefficient of air thermal expansion |
| $\Gamma_{ref}$ | temperature effective diffusivity |

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