Model Experiment and CFD Analysis on a Solar Assisted Ventilation System

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Abstract
A prototype atrium building is suggested with a large solar chimney on top of the atrium, which is expected to promote natural smoke exhaust and accumulate smoke at the event of a fire and promote natural ventilation when outdoor climate is desirable. In this paper natural ventilation efficiency is evaluated. The solar chimney is similar to conventional chimneys except the south-facing wall is replaced by a glazing. Solar radiation transmits the glass and thermal energy is stored in the other three walls. Air in the chimney is heated and by stack effect natural ventilation is realized. Experiment is conducted on a 1/25 scale model to evaluate the efficiency of this solar assisted natural ventilation system. Several area conditions of inlet and outlet are chosen while other conditions keep the same. CFD simulation is simultaneously done. According to results of model experiment and simulation, natural ventilation promoted by the solar chimney is quite sufficient to meet the demands of atrium ventilation. As to the office rooms, if area is properly set, fresh air requirement can be satisfied only by natural ventilation. In the case of this study, when inlet area changes to 24m², necessary ventilation rate can be obtained.

Keywords: solar assisted natural ventilation system; solar chimney; atrium building; model experiment; simulation

1. Introduction
Atria have become popular in commercial, office and residential buildings because of their architectural appealing. However they present a challenge for fire-protection engineers because of their height and the lack of floor-to-floor fire separation that can limit the likelihood of fire and smoke spreading from the floor of fire origin to other areas of the building. At the same time large quantity of building energy consumption and bad indoor air quality become great concerns for building facility managers and occupants. Considering above problems, a prototype atrium building¹ is suggested with a large solar chimney on top of the atrium, which is expected to promote natural smoke exhaust and accumulate smoke when a fire happens and promote natural ventilation when outdoor climate is desirable. As the first part of this research, in this paper natural ventilation efficiency is evaluated. The purpose of natural ventilation is to take advantage of the optimum outdoor air quality and temperature and at the same time to reduce energy consumption. The solar chimney is similar to conventional chimneys except that the south-facing wall is replaced by a glazing, thus enable solar energy collection. Thermal storage will happen in the other three walls and by convection, air temperature in the chimney channel will goes up. The air temperature difference will cause pressure difference and this is usually called stack effect. Openings are set at the upper part of chimney and thus natural ventilation can be realized. Model experiment and computational simulation are simultaneously done to evaluate the efficiency of this solar assisted natural ventilation system.

2. Outline of the Prototype Building
Figure 1 illustrates the plan view and section of case building. It is supposed to be a south-facing 8-story office building with an atrium, on top of which a large solar chimney is set. The area of each floor is about 850m², atrium is about 280m² and corridor and utility are also about 280m².

3. Thermal Balance in the Solar Chimney
Each surface temperature within solar chimney increases because of solar radiation through the south-facing glass pane during the daytime. Heat conduction occurs through glass and walls, heat convection occurs between air and each surface, and heat radiation occurs between the high temperature surface and the low temperature surface within the solar chimney. Figure 2 illustrates thermal balance of glass surface and heat exchange between the air and the surfaces inside the solar chimney.
The temperature of each surface can be calculated through solving thermal balance equations. Thermal balance equation of each surface is presented by equation (1).

\[
\alpha_i A_i (T_i - T_e) + A_i \sum_{j=1,2,3,4} F_{ij} \varepsilon_j \varepsilon_j \sigma (T_{ij}^4 - T_e^4) + Q_i \\
\tau_i A_i (T_i - T_e) + A_i \sum_{j=1,2,3,4} F_{ij} \varepsilon_j \varepsilon_j \sigma (T_{ij}^4 - T_e^4) + Q_i \\
\tau_i A_i (T_i - T_e) + A_i \sum_{j=2,3,4} F_{ij} \varepsilon_j \varepsilon_j \sigma (T_{ij}^4 - T_e^4) + Q_i \\
\tau_i A_i (T_i - T_e) + A_i \sum_{j=2,3} F_{ij} \varepsilon_j \varepsilon_j \sigma (T_{ij}^4 - T_e^4) + Q_i
\]

Where:
- \( \alpha_i \): Absorptivity of glass, here assumed as 0.12;
- \( \tau_i \): Transmittance of glass, assumed as 0.85;
- \( I \): Solar radiation of each direction, W/m²;
- \( A_i \): Area of each surface, m²;
- \( T_i \): Interior temperature of each surface, i=1,2,3,4, K;
- \( h_i \): Inside film coefficient of each surface, i=1,2,3,4, here assumed as 9.3 W/m²K;
- \( F_{ij} \): View factor from i surface to j surface, i=1,2,3,4, j=1,2,3,4;
- \( \varepsilon_i \): Emissivity of each surface, here taken as 0.9;
- \( \sigma \): Stefan-Boltsman constant, 5.67 \times 10^{-8} W/m²K⁴;
- \( T_e \): Initial air temperature in solar chimney, K, here assumed as same as outside air temperature;
- \( Q_i \): Heat conducted from wall to outside, W, here we suppose the three thermal storage walls are perfectly insulated and thus \( Q_2, Q_3 \) and \( Q_4 \) can be neglected. \( Q_{G_i} \) is calculated by:

\[
Q_{G_i} = K_{G_i} A_i (T_i - T_{out})
\]

Where:
- \( K_{G_i} \): Overall heat transfer coefficient of glass, including conductivity of glass itself and outside film coefficient. Here assume conductivity of glass as 0.76 W/mK and outside film coefficient as 23 W/m²K.
- \( A_i \): Area of glass surface;
- \( T_{out} \): Temperature of outside air.

According to above equations, each surface temperature can be calculated by iteration method when climate data is available. In this paper expanded AMeDAS weather data of TOKYO is used. The data of a fine sunny day, May 17th in typical year is selected to calculate the temperature of each surface. Figure 3 shows...
To evaluate the efficiency of this solar assisted natural ventilation system, model experiment was conducted on a 1/25 scale model of only the atrium part. Walls are heated by attached panel heaters, on which surface temperature sensors are set and thus temperature can be controlled through temperature controller. Each surface temperature of the model chimney is given by the results of above calculation. Figure 4 shows the setting of model. 30mm thick polystyrene boards are attached to surface 2, surface 3 and surface 4 to reduce heat loss. Velocity and temperature are measured at inlet and outlet and the central temperature from bottom of atrium to top of solar chimney is simultaneously measured. Ambient temperature is also measured. Different area conditions of outlet and inlet are conducted as shown in Table 1. When inlet area is 4, 6 and 8m², only the first floor has openings. When inlet area is 12m², the first and the second floor have the same openings. When inlet area is 24m², same openings are made on the lower four floors.

5. Computational Simulation

To compare with the results of experiment, computational simulation is carried out. A zero-equation turbulence model⁵) is used for this simulation, in which Boussinesq approximation is used for thermal buoyancy. The approximation takes air density as constant in the momentum terms and considers the buoyancy influence on air movement by the difference between the local air weight and the pressure gradient. The indoor airflow is described by the following time-averaged Navier-Stoke equations for the conservation of mass, momentum and energy.

\[ \frac{\partial V_i}{\partial x_i} = 0 \quad (3) \]

Where
\[ V_i : \text{Mean velocity component in } x_i\text{-direction; } \]
\[ x_i : \text{Coordinate(for } i=1,2,3, \text{ } x_i \text{ corresponds to three perpendicular axes);} \]

\[ \frac{\partial}{\partial t} \left( \frac{\partial V_i}{\partial x_i} \right) + \frac{\partial}{\partial x_j} \left( \mu_{ij} \left( \frac{\partial V_i}{\partial x_j} + \frac{\partial V_j}{\partial x_i} \right) \right) + \rho g (T_0 - T) g_i = 0 \quad (4) \]

Where
\[ \rho : \text{Air density;} \]
\[ V_i : \text{Velocity component in } x_i\text{-direction;} \]
\[ P : \text{Pressure;} \]
\[ \mu_{ij} : \text{Effective viscosity;} \]
\[ \beta : \text{Thermal expansion coefficient of air, calculated as } 1/T; \]
\[ T_0 : \text{Temperature of a reference point;} \]
\[ T : \text{Temperature;} \]
\[ g_i : \text{gravity acceleration in } i\text{-direction.} \]

The last term on the right side of the equation is the buoyancy term.
The turbulent influences are lumped into the effective viscosity as the sum of the turbulent viscosity, \( \mu_t \), and laminar viscosity, \( \mu_l \):

\[
\mu_{eff} = \mu_t + \mu_l
\]  

(5)

In the zero-equation model, turbulent viscosity \( \mu_t \) is calculated by the following relationship:

\[
\mu_t = 0.03874 \rho V l
\]  

(6)

Where

- \( V \): Local mean velocity;
- \( l \): Distance from the nearest wall;

• Energy

To determine the temperature distribution and the buoyancy in equation (4), the equation for energy conservation must be solved, here gas phase radiation is not considered.

\[
\frac{\partial \rho \theta}{\partial t} + \frac{\partial \rho \theta V_j}{\partial x_j} = \frac{1}{\rho C_p} \frac{\partial}{\partial x_j} \left( \Gamma_{eff} \frac{\partial \theta}{\partial x_j} \right) + q \quad (7)
\]

Where

- \( \Gamma_{eff} \): Effective turbulent diffusion coefficient for \( T \);
- \( q \): Thermal source;
- \( C_p \): Specific heat, 1.01kJ/kg.K;

In this model the effective diffusive coefficient for temperature is estimated by:

\[
\Gamma_{eff} = \frac{\mu_{eff}}{Pr_{eff}}
\]  

(8)

Where

- \( Pr_{eff} \): Effective Prandtl number, here is taken as 0.9;

To solve above governing flow equations, in this study boundary conditions are set as listed in Table 2, which are the same as that of model experiment. Ambient temperature is set as 293K.

| Surface  | Temperature |
|----------|-------------|
| Surface 1| 295K        |
| Surface 2| 305K        |
| Surface 3| 307K        |
| Surface 4| 312K        |
| All other surfaces | Temperature 312K |
| Inlet    | Pressure    |
| Outlet   | Pressure    |

Table 2. Setting of Boundary Conditions

The convective heat transfer coefficient is determined from the following equation:

\[
h = \frac{\mu_{eff} C_p}{Pr_{eff} \Delta x_j}
\]  

(9)

Where

- \( \Delta x_j \): Distance between the surface and the first grid close to the surface.

There are total 96,028 grids mechanically generated for this model with the maximum size of 1 \( \times \) 1 \( \times \) 1m. Cells adjacent to walls and at the turn part from atrium to chimney are refined with the maximum size of 0.2 \( \times \) 0.2m. Because surface temperature is defined as fixed temperature, surface to surface radiation is not considered in simulation. Every case is calculated with 2000 iteration times under steady conditions.

6. Analysis of the Results of Experiment and Simulation

The practical similarity criteria, which are developed to simulate the air distribution of the space where the air motion is turbulent, is used to analyze the results of experiment. For the ventilated air motion, the similarity condition is the coincidence of the Archimedes number:

\[
\frac{\theta_M L_M}{U_M} = \frac{\theta_N L_N}{U_N}
\]  

(10)

Where,

- \( \theta \): reference temperature
- \( L \): reference length
- \( U \): reference air velocity

Subscripts M: model
N: prototype

In this experiment, model scale is 1/25, and the wall temperature is set as the same, therefore

\[
\frac{U_M}{U_N} = \left( \frac{\theta_M L_M}{\theta_N L_N} \right)^{1/5}
\]  

(11)

6.1 Temperature Distribution

Figure 5 shows the central temperature distribution of atrium according to the results of experiment and simulation.

![Fig.5(a). Temperature Distribution When Outlet is 12m² and Inlet is 4m²](image)

![Fig.5(b). Temperature Distribution When Outlet is 12m² and Inlet is 6m²](image)
simulation. From the results we can see that model experiment and simulation show relatively good coincidence. Keep outlet area unchanged and with the increasing of inlet area, temperature difference from bottom of atrium to top of solar chimney decreases. This is in accord with the increasing of mass flow rate. Although solar chimney is set on top of the atrium, air temperature below chimney is affected also. This is obvious especially in the results of experiment. When area of inlet is below 6 m², temperature distribution of model experiment and simulation agrees with each other well. When area of inlet changes to over 8m², air temperature below solar chimney hardly changes according to the results of simulation, while the results of experiment shows a curve. The reason can be considered as that all walls of atrium part is set as ambient temperature in simulation, while in experiment 3mm acrylic plastic panes are used, therefore it is inevitable that air temperature in the atrium will be affected by surrounding factors. In figure 5(d) and 5(e) we can find that air temperature near the turn point from atrium to chimney is very close.

6.2 Volumetric Airflow Rate

Variation of volumetric airflow rate with the change of area ratio of inlet and outlet is shown in figure 6. From the figure we can see, keep outlet area unchanged and with the increasing of inlet area, the volumetric airflow rate becomes greater and greater. The result of model experiment is quite lower than that of simulation because in fact there are many factors that will affect the results of model experiment. In simulation ideal boundary conditions can be set while in experiment, accuracy of instruments, measuring method and setting of measured points, the effect of surrounding air flow, infiltration and many other uncontrollable factors will affect the results of experiment. Suppose necessary fresh air volume for atrium is 3m³/m²•h', the total fresh air volume for studied atrium is about 1700m³/h, according to the results of experiment, when outlet area is 12m² and inlet area is 4m², volumetric airflow rate is about 16,000m³/h. It is quite enough to meet the demands of atrium ventilation. Consider the part of office rooms, suppose necessary fresh air volume as 5m³/m²•h', the total necessary fresh air volume should be about 33750m³/h. From the results of experiment we can see, when the area ratio of outlet and inlet is 0.5 (outlet 12m² and inlet 24m²), volumetric airflow rate is about 33,000m³/h, which can almost satisfy the requirement of fresh air for office rooms.
6.3 Pressure Distribution

As to natural ventilation of atrium buildings, control of the height of neutral plane is very important. Figure 7 shows pressure difference of bottom of atrium and top of solar chimney, and variation of the height of neutral plane with the change of inlet area. The data is got from CFD simulation and from the results we can see that pressure difference at the bottom decreases with the increasing of inlet area while at top of solar chimney pressure difference becomes greater and greater. This is in accord with the variation of velocity at inlet and outlet. The height of neutral plane falls down with the increasing of inlet area. It stays in solar chimney until the inlet area changes to 24m². This is undesirable for ventilation because polluted air from lower part of building may flows into upper part of building and causes second pollution. In this case, the eighth floor has the risk of being polluted when area ratio is 0.5 (outlet 12m² and inlet 24m²). Prediction of the height of neutral plane is necessary in designing phase.

7. Conclusions

In this paper model experiment and simulation are conducted to evaluate the solar assisted ventilation system in an atrium building. Following conclusions are derived:

1) Temperature distribution of experiment and simulation shows relatively good coincidence. Keep outlet area unchanged and with the increasing of inlet area, temperature difference from bottom of atrium to top of solar chimney decreases, which is accord with the increase of airflow rate.

2) According to the results of experiment, natural ventilation promoted by the solar chimney is quite sufficient to meet the demands of atrium ventilation. As to the office rooms, if proper area setting of outlet and inlet is available, fresh air requirement for office rooms may be satisfied only by natural ventilation. In the case of this study, when inlet area changes to 24m², the necessary volumetric flow rate can be obtained.

3) The height of neutral plane varies with the change of outlet and inlet. It is important to keep neutral plane stay above where ventilation is required.

In this paper we just study one kind of climate condition. With the increasing of solar radiation, better efficiency of this solar assisted ventilation system can be expected.

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