

Investigation on optimum design of natural ventilation system with solar chimney

Sung-Ki SONG

Department of Architecture and Civil Engineering, Toyohashi University of Technology, Toyohashi, Japan

ABSTRACT: In term of energy saving point of view as well as indoor air quality, research on natural ventilation system has become a growing interest for many researchers in recent days. Solar chimney is one kind of passive cooling and ventilating technology that utilizes solar irradiation to generate stack effect, thereby driving natural airflow through the chimney channel. The purpose of this paper is to show principle findings on suitable design of natural ventilation system with solar chimney. The investigation was carried out by CFD simulation validated by field measurement conducted in a four-storey school building located in Fukuoka city, Japan. Results of both CFD simulation and field measurement showed that ventilation rate was greatly influenced by not only the temperature difference of inside chimney and outdoor air, but also by the wind velocity where there was a significant increase of ventilation rate with the two parameters.

According to the CFD results, in case of the solar chimney outlet was attached with a hood, the ventilation rate was 12000 [CMH] when the wind direction was parallel to the chimney outlet and 13000 [CMH] when it was perpendicular to the chimney outlet. When the hood was not present, the ventilation rate of 14,000 [CMH] and 8,000 [CMH] were obtained when the wind direction were parallel and perpendicular to the chimney outlet, respectively. From these results, it can be concluded that the presence of hood was very effective and therefore favourable in enhancing natural ventilation of solar chimney regardless of wind direction.

Keywords: Natural Ventilation, Solar Chimney, Optimum Design

1. INTRODUCTION

Natural ventilation system has been continuing interest for many researchers due to its potential merits on energy saving and better indoor air quality (IAQ).

Solar chimney is a natural driving device which utilizes solar radiation energy to build up stack effect thereby inducing natural air flow through the chimney channel.

Numerous studies have been devoted to optimum design and better performance of solar chimney. Cho and Kimura [1,2]

reported investigations on a scale down model experiments and CFD simulation of solar chimney. It was shown that for a given section area, ventilation rate was highly dependent on the inside wall temperature and section ratio of solar chimney.

Awbi and Gen [3], Li [4], Chen *et al.* [5] investigated optimum chimney gap-to-height ratio by model experiments and numerical simulation. Using a CFD simulation and an analytical model, Miyazaki *et al.* [6] investigated the performance of a solar chimney, which was integrated into a south facade of a one-story

building on the heating and cooling loads of the building. All above studies indicated that the performance of solar chimney was mainly determined by the temperature difference between air inside the chimney and outdoor air.

However, Maesaka *et al.* [7] and Kimura *et al.* [8] reported that the ventilation performance of a solar chimney was influenced not only by the stack effect due to the temperature difference but also by the sucking effect of the outside wind. However, literatures lack investigations in which both effects are taken into considerations.

In order to evaluate the contributions of stack effect as well as outdoor wind on the natural ventilation of solar chimney, both field measurements and CFD simulation were carried out in this study for application in hot and humid region and performance and optimum design of solar chimney were discussed.

2. OUTLINE OF SOLAR CHIMNEY

The measured building was constructed in 2001 with the cool pit of more than 100 m long using the underground heat source and the solar chimney of 8 m high on the roof. Hoods covering were installed at the chimney outlet to prevent wind from entering into the solar chimney, as shown in Photo 1.



Photo 1: Solar chimney.

The north and east sides of the solar chimney are made of concrete and the south and west sides are made of glass window. In the natural ventilation mode, the outdoor air is sucked in through the outside air intake, then heat exchange is performed by underground cool pit, and it finally enters the corridor of each floor through the supply air shaft for natural ventilation. The indoor air is exhausted through the solar chimney, after flowing into the chimney shaft from the corridor of each floor. Positions of measuring facilities were displayed in Fig. 1.

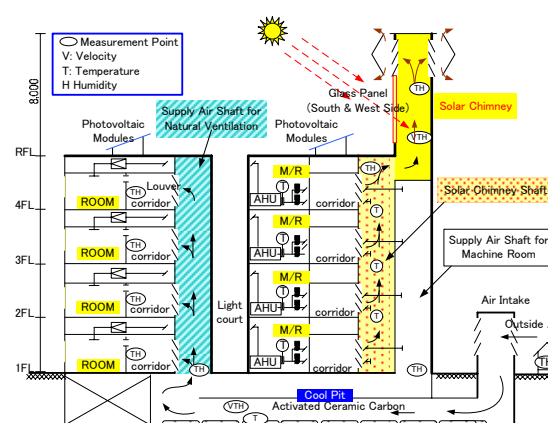


Fig. 1: Airflow in the natural ventilation

3. RESULTS OF MEASUREMENT

We analyzed moving average data of 10 minute-interval measured data of one month in March, 2001 when natural ventilation was performed. The ventilation rate and exhaust air volume from solar chimney were calculated from inside velocity. The temperature difference in this paper used air temperature difference between the inside and outside solar chimney.

3.1 Ventilation performance

Since the supply air volume from a cool pit was almost the same as the exhaust air volume (the so-called ventilation rate) from the solar chimney as shown in Fig. 2, as for the object building, it turned out that planned ventilation was performed.

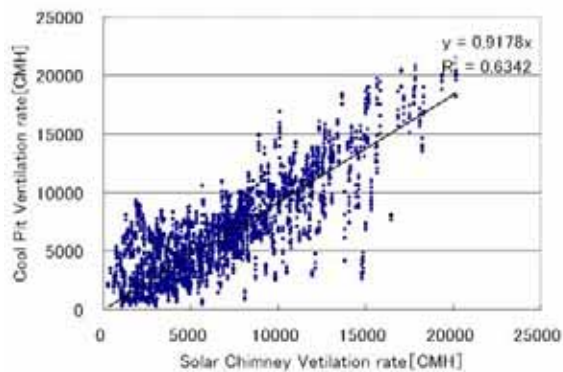


Fig. 2: Ventilation rate of cool pit and solar chimney.

Variation of ventilation rate estimated from the exhaust air volume exited from solar chimney is shown in Fig.3. The ventilation rate was measured continuously during the measurement period and the ventilation rate was ranging from 1000[CMH] to 20000[CMH] depending on outdoor wind velocity.

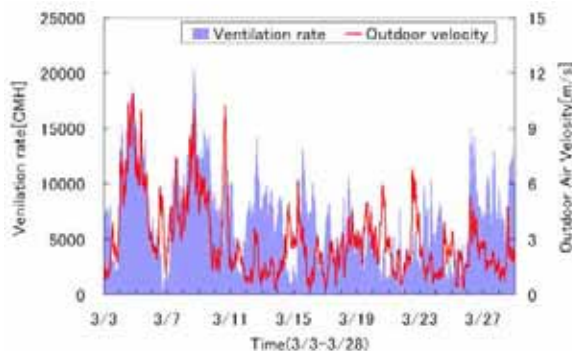


Fig. 3: Variation of solar chimney ventilation rate and outdoor wind velocity.

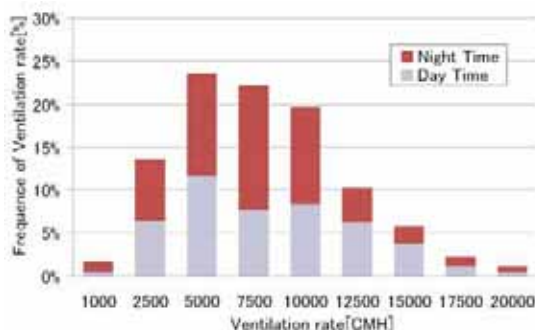


Fig. 4: Frequency of solar chimney ventilation rate.

Ventilation rate of the most appeared frequency during the measured period was

5000[CMH] for both day and night, as shown in Fig.4. The day and night times were classified as 8:00-18:00 and 18:01-7:59, respectively. It was also observed that the appeared frequency of the ventilation rate of more than 5000[CMH] (as about 0.5 times per hour) was about 85%.

3.2 Ventilation factors

Figure 5 shows that the ventilation rate increased as the chimney-outdoor temperature difference increased. Indeed, the increase of ventilation rate corresponded with the increase of wind velocity. This confirmed that the ventilation rate of solar chimney was influenced by both the temperature difference and outdoor wind velocity.

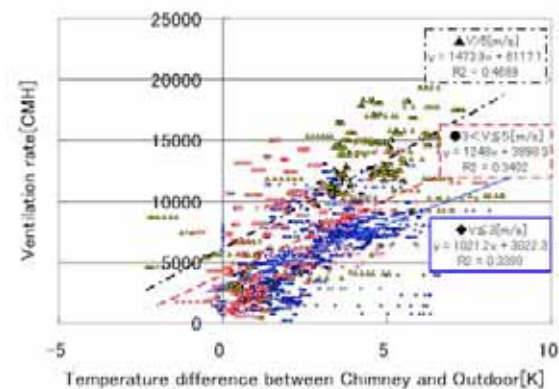


Fig. 5: Relation on solar chimney ventilation rate and temperature difference according to outdoor wind velocity.

As shown in Fig. 6, generally outdoor wind velocity and the ventilation rate were proportionally correlated. In addition, when temperature difference increased in the same wind velocity, the ventilation rate also tended to increase. This indicated that the ventilation rate increased by the synergy of temperature difference and wind velocity.

Moreover, when the temperature difference was 0 degree C or less, or in other words outdoor air temperature was higher than the indoor temperature of solar chimney, there was no adverse current into solar chimney and the increase of ventilation rate was solely influenced by the wind

velocity). This finding revealed natural ventilation of solar chimney by wind velocity could be performed even there was no temperature difference between the chimney and the outdoor air.

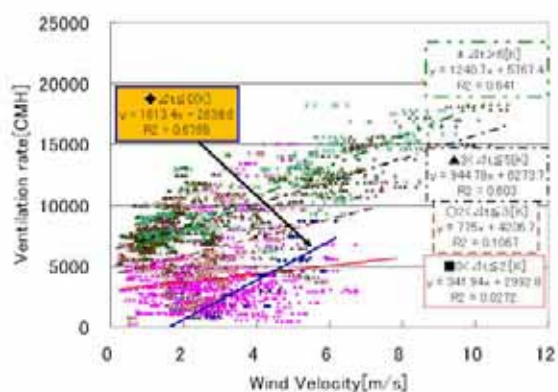


Fig. 6: Relation on solar chimney ventilation rate and outdoor wind velocity according to temperature difference.

The relation between outdoor wind velocity according to wind direction and ventilation rate is shown in Fig. 7. Since the correlation of wind velocity and the ventilation rate for south direction wind was not observed, the corresponding data was removed. In case of the same wind velocity, it was found that the ventilation rate of the northerly wind higher compared to those of the easterly and westerly winds. It was presumed that the increase of ventilation rate due the influence of wind direction was caused by position of the chimney outlet as well as by the presence of hood installed in the chimney outlet.

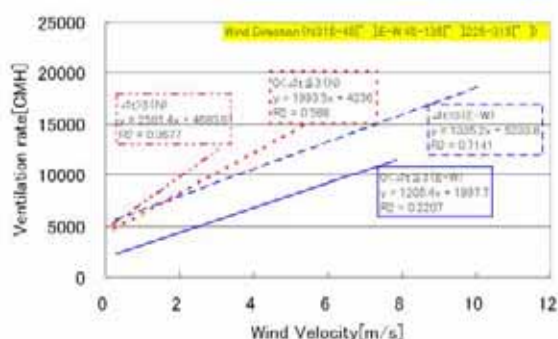


Fig. 7: Solar chimney ventilation rate and outdoor wind velocity according to wind direction.

4. CFD SIMULATION

4.1 Simulation Outline

CFD simulation of 8 cases, where the temperature difference between the solar chimney inlet and outdoor air was taken into consideration, were performed under the influence of outdoor wind direction and hoods.

During the survey period, temperatures of the chimney inlet were the same as air temperatures inside the chimney and its rises from outdoor air temperature were up to 10°C. In CFD simulation, it was assumed that the chimney inlet temperature was higher than outdoor air temperature by 5°C with in the same examined case. The simulation cases and its boundary conditions are shown in Table 1.

Table I: CFD simulation calculation case and boundary conditions.

CASE	HOOD	Chimney inlet/outdoor air temperature[°C]	Outdoor wind direction/ Velocity[m/s]	Chimney inside surface temperature[°C]
1	With	25.3/25.3	North/ 3	Top:32.5 North:30.2 South:30.9 East:29.9 West:31.5
2		($\Delta T=0$ [K])	East/ 3	
3		30.3/25.3	North/ 3	
4		($\Delta T=5$ [K])	East/ 3	
5	Without	25.3/25.3	North/ 3	
6		($\Delta T=0$ [K])	East/ 3	
7		30.3/25.3	North/ 3	
8		($\Delta T=5$ [K])	East/ 3	

4.2 Simulation results

As shown in Fig. 8, the chimney internal pressure near the outlet by the northerly wind (parallel to the chimney outlet) and the easterly wind (perpendicular to the chimney outlet) was -0.4 [Pa] and -1.7[Pa] for respectively. In this case, there was no hood attached to the chimney outlet. When the hood was present, the chimney internal pressure for above and below the chimney were -1[Pa] and -1[Pa], respectively. At the outlet chimney, the pressure is a value at the time of setting atmospheric pressure to 0 [Pa]. It was found that the chimney internal pressure near the outlet was easy to get high negative pressure when the chimney outlet and the wind direction were parallel. When the wind direction was perpendicular to the chimney outlet, the negative pressure inside the chimney was negligible. However the

presence of hood was very effective to create high negative pressure inside the chimney regardless of wind direction.

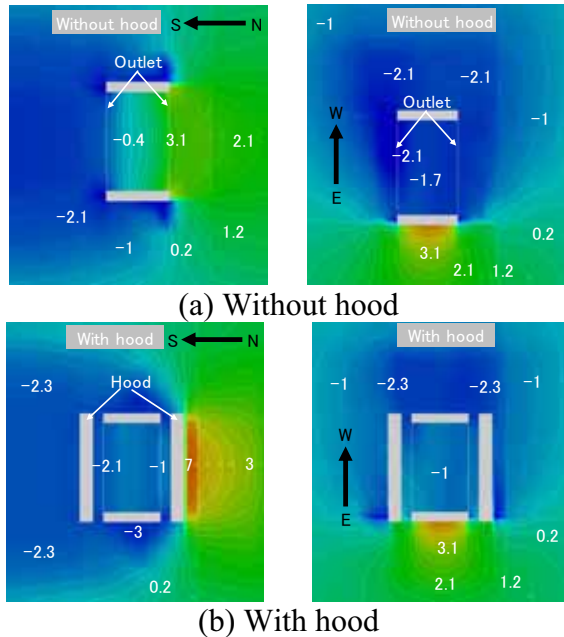


Fig. 8 Pressure distribution according to wind direction in the case $\Delta t=0^\circ\text{C}$. (Unit: [Pa])

Figure 9 reveals predicted ventilation rate calculated from the regression equation of Fig. 7 and the ventilation rate calculated from CFD simulation. Although the measured ventilation rate from the field survey and the predicted values from CFD were not the same, however, the ventilation rate according to wind direction showed similar trend hence it turned out that the CFD calculation was confident enough.

From the CFD calculation, it was confirmed that the ventilation rate increased regardless of outdoor wind direction and indeed the favourable existence of a hood when the temperature difference increased. In case of the temperature difference was 0°C , when the top part of solar chimney outlet was attached with a hood, the ventilation rate of the northerly wind and the southerly wind were 9,000 [CMH] and 10,000[CMH], respectively. But they were 6,000 [CMH] and 11,000 [CMH], respectively when the chimney outlet did

not have the hood. Since the influence of wind direction on the ventilation rate was small with the presence of hood, thus a hood was considered to be an item which could be effectively used to create sucking effect regardless of a wind direction.

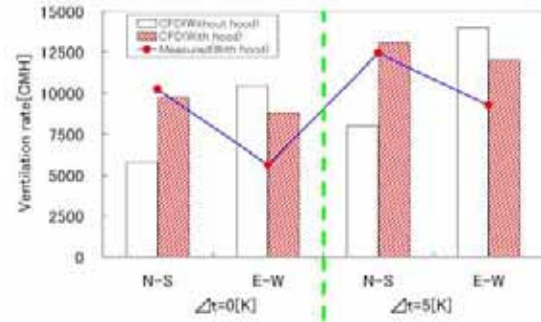


Fig. 9: Ventilation rate according to wind direction and with or without hood.

5. CONCLUSION

This study investigated the performance of solar chimney in hot and humid region, and examined the design of the chimney which can use effectively the both effect. The results of field measurement and CFD simulation are as follows. The main purpose of this study was to investigate the performance of solar chimney under the influence of inside-outside temperature difference as well as outdoor wind velocity. Field measurement and CFD simulation were performed and the main findings are as follows:

- 1) The ventilation was measured continuously during the measurement period and the observed ventilation rate was ranging from 1000[CMH] to 20000[CMH]. The appeared frequency of the ventilation rate more than 5000[CMH] (as about 0.5 times per hour) was about 85% of the measurement period. From these results, it turned out that the natural ventilation system with a solar chimney is very effective.
- 2) It was confirmed that the ventilation rate of solar chimney was influenced by the

temperature difference and outdoor wind velocity.

- 3) The results of the ventilation rate of the northerly wind were higher than those of easterly and westerly winds. This indicated that the solar chimney outlet which was parallel to the outdoor wind was very effective to induce natural flow.
- 4) When there is a hood, many a ventilation rate was obtained to all the wind directions. It shows that a hood is very effective in enhancing natural ventilation of solar chimney without considering the wind direction.
- 5) It is necessary to advance research on the optimal design of a chimney with the stack effect and the sucking effect from now on.

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