Fenestration Effects on Cross Ventilation for a Typical Taiwanese School Building When Applying Wind Profile

Wei-Hwa Chiang, Hao-Hsiang Hsu, Jian-Sheng Huang

***Abstract*—**Appropriate ventilation in a classroom is helpful for enhancing air exchange rate and student concentration. This study focuses on the effects of fenestration in a four-story school building by performing numerical simulation of a building when considering indoor and outdoor environments simultaneously. The wind profile function embedded in PHOENICS code was set as the inlet boundary condition in a suburban environment. Sixteen fenestration combinations were compared in a classroom containing thirty seats. This study evaluates mean age of air (AGE) and airflow pattern of a classroom on different floors. Considering both wind profile and fenestration effects, the airflow on higher floors is channeled toward the area near ceiling in a room and causes older mean age of air in the breathing zone. The results in this study serve as a useful guide for enhancing natural ventilation in a typical school building.

***Keywords*—**Cross ventilation, Fenestration effect, Wind profile, Mean age of air, CFD

I. Introduction

Elementary and high school buildings in Taiwan, unlike college or university buildings, do not rely heavily on mechanical ventilation or cooling but natural ventilation mechanism to remove heat and contaminants during summer time because the hottest period in July and August are summer vacations. In additions, the ample open space, greens, and large trees help to cool down the outdoor air temperature and increase wind velocity. Based on the mentioned above, passive cooling inducing natural wind becomes an attractive means in days with the ever-increasing consumption of energy.

Natural ventilation, especially cross ventilation, is also the most useful and energy-saving method of controlling indoor air quality under hot-humid climate in Taiwan. Cross ventilation requires the presence of two or more openings on opposite or nearly opposite sides of a building with airflow primarily induced by wind pressure.

Generally, the geometrical and physical parameters governing the accuracy of macroscopic airflow for predicting cross ventilation in buildings are related to wind field effect, and internal airflow structure. The wind field parameters includes the wind direction, wind velocity, and turbulence fluctuation. The influential factors of internal airflow structure include building façade configurations, such as structural attachments, window types, fenestration combinations, and interior divisions.

Outdoor wind field around the building is a complex problem involving severe pressure gradient, streamline curvature, swirl, separation and reattachment along with turbulence effect. Straaten's [1] experiment showed that the atmospheric boundary layer affects mean wind velocity increasing with height as a consequence of friction between the layer of moving air and ground. In addition, the magnitude and slope of the boundary layer depended on the roughness of the ground surface. Therefore, an assumption of the wind profile is necessary to be built in advance for the studied domain when modeling a building ventilation system.

The building façade configurations dominated wind airflow direction to enter a building from the site that has major effect on microclimate in a building. The study by Chiang et al. [2] and Prianto and Depecker [3] also verified the factors on opening size and positions, window types, and shading devices using numerical simulation. However, the sliding window type is usually used for elementary school classroom in Taiwan because hung, casement, and awning windows are less appropriate when confronting with severe typhoons. In addition, Ayad [4] used computational fluid dynamics (CFD) to study the ventilation properties for a room with different fenestrations. The results showed that the placement of openings in relation to one another may improve the indoor thermal environment but it does not always need a higher wind speed.

Therefore, this study focused on the airflow effect around the building windward side formed by wind profile and the fenestration effect with fixed opening size on sliding windows. Indoor and outdoor environments were considered simultaneously. Mean age of air and airflow pattern in the classrooms were calculated using CFD software.

II. Research Method

A. Building model

Based on the standard by the Architecture and Building Research Institute for elementary school classrooms [5], the size of a simulated classroom in this research was 9 m (L) × 7.8 m (W) × 3.6 m (H). Typically per window and door in a Taiwanese classroom were used that measure 1.2 m × 1.2 m and 0.9 m × 2.1 m, respectively [6]. The projected area of each

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table and chair in a classroom was 0.6 m × 0.4 m and 0.4 m × 0.4 m, respectively, as mentioned in Li's study [7]. To observe the wind profile effect, the prototype of this classroom was extended to a four-story building, as Fig. 1 illustrated.

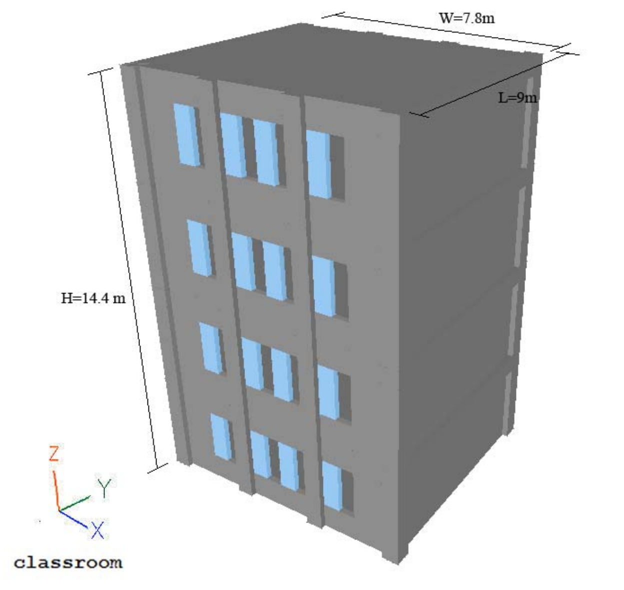


Fig. 1 The simulated building model

The inlet and outlet opening areas were set equal as one half of window areas according to the study by Santamouris and Asimakopoulos [8]. It proved that ventilation rate in a room was maximized when outlet area and inlet area were equal. Fig. 2 shows the four fenestration layouts used in this study. Sixteen fenestration combinations were produced by alternating with the four layouts on both the inlet and outlet sides. The opening area on either side is $4.32 m^2$ and 12.5% ratio of the façade area.

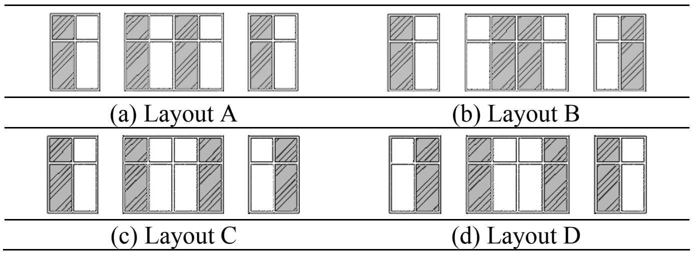


Fig. 2 The four fenestration layouts

B. Computational domain size

Previous studies generally considered indoor airflow conditions and outdoor wind field effect separately. However, external wind pressure is a primary force to determined internal airflow for a naturally-ventilated structure. Some experiments show that it is necessary to consider indoor and outdoor environments simultaneously. The compact integration method by Straaten [1], Kato et al. [9], Graça et al. [10], Zhai et al. [11] and Seifert et al. [12] revealed highly directional velocity vectors entering and exiting the windows to describe the real situation more accurately. Hence, the computational domain in this study considers outdoor and indoor environments at the same time.

The dimension of computational domain was set 111.44 m, 296 m, and 86.4 m in X, Y, and Z direction, respectively (Fig. 3). It was determined based on the guideline for CFD simulation setting of computational domain size suggested by Franke et al. [13] regarding COST Action 732 to ensure the validation of CFD simulation. For a single building model, followings are the guidelines:

a. The upper part of the computational domain should be at least 5H above the roof of the building, where H is the building height.
b. The requirement of lateral extension requires a distance of approximately 2.3H between the building's sidewalls and the lateral boundary.
c. At least 5H between the inflow boundary and the building façade is recommended if the wind profiles are well defined.
d. The extended region behind a single building should be positioned at least 15H to allow flow re-development to occur behind the wake region.

C. Numerical scheme

A commercial CFD code, PHOENICS, was used to simulate the airflow and mean age of air distribution. The standard k-ε turbulence model is widely used in many studies. However, a comparison of standard k-ε and RNG k-ε model by Karimipanah et al. [14] revealed that the standard k-ε model cannot predict velocity very well for indoor zones when the indoor and outdoor environments were considered simultaneously. On the other hand, the RNG k-ε model showed better feasibility to predict the indoor airflow velocity. For the RNG k-ε turbulence equation, the empirical turbulence coefficients in this study were set as: σ_k=0.72, σ_ε=0.72, $\sigma_{\varepsilon1}$= 1.42, $\sigma_{\varepsilon2}$= 1.68, and C_μ=0.08.

The numerical simulation accuracy depended on the resolution of the computational mesh. To obtain more detailed information around seats in the simulated room, the grid used in this study was not uniform, with greater density closer to the seats. The non-uniform grid consisted of 93 cells in the *x*-direction, 80 cells in the *y*-direction and 67 cells in the *z*-direction. The calculations proceeded through 25000 iterations to achieve the predetermined criteria of 10^{-5}.

D. Wind profile function

In previous papers that dealt with indoor conditions, inlet boundary conditions of wind field domain were generally set using a mean velocity, although the roughness of the terrain apparently influenced the gustiness of wind and the variability of its direction in practical situations. In this study, a suburban environment with the inlet boundary conditions associated with wind velocity profile is defined using wind profile function

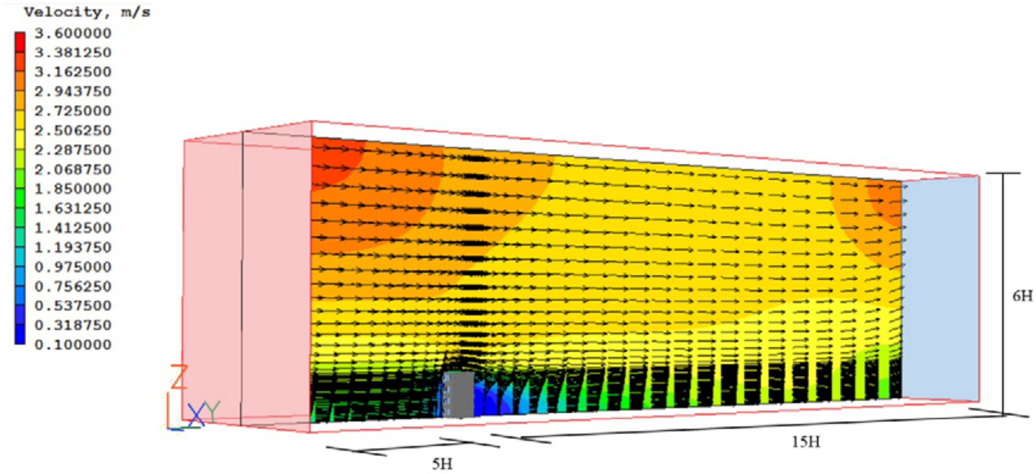


Fig. 3 Computational domain and wind profile effect

embedded in the PHOENICS code. The velocity profile can be specified, as Eq. (1) shown below [15]:

$$\upsilon/\upsilon_r = cH^a \tag{1}$$

υ (m/s): wind speed at datum level
υ_r (m/s): reference wind speed (obtained from meteorological data)
H (m): height of the building
c: parameter related to wind speed of terrain nature
a: an exponent related to wind speed versus the height above the ground

Based on the statistics of weather data from Central Weather Bureau in Taiwan, the velocity at 10 m height was set as 2 m/s as average value in Taipei.

E. Air exchange rate

Air exchange rate is a general index for evaluating building ventilation. It has units of 1/time. When the time unit is hours, the air exchange rate is also called air changes per hour (ACH). It can be obtained the air exchange rate from Eq. (2) as below [16]:

$$n = Q / V \tag{2}$$

n (1/hr): air changes per hour (ACH)
Q (m^3/s): volumetric flow rate of air into space
V (m^3): interior volume of space

Normally air exchange rates ranging from 4 to 12 ACH are considered sufficient to remove indoor containments for school buildings [17, 18]. Air exchange rates with much greater values can efficiently extract accumulated heat and improve thermal comfort.

F. Mean age of air

This study applied the concept of mean age of air to assess the "freshness" of air in a room. Many parameters are correlated to mean age of air, which is generally defined as the average time for air to travel from the opening to any location inside a ventilated room [19]. The concept of mean age of air is assumed to be zero at the inlet opening representing 100% fresh [20]. The "youngest" air appears at the point near the window where air enters the room by forced or natural ventilation. Conversely, the "oldest" air appears at certain locations inside the room or in the exhausted air. In "dead" zones, such as the recirculation areas, the time since entry reaches a large value because the air is trapped there [16]. The internal mean age of air ($\bar{\tau}$) has units of time in seconds, and can be obtained from the following transport equation:

$$U_i \frac{\partial \bar{\tau}}{\partial x} = \frac{\partial}{\partial x_i}\left[\left(\frac{\upsilon_t}{\sigma_\tau} + \frac{\upsilon}{\sigma}\right)\frac{\partial \tau}{\partial x_i}\right] + 1 \tag{3}$$

where υ and υ_t represent the laminar and turbulent kinematic viscosities, respectively. σ is the laminar Schmidt number of air and $\sigma_{\bar{\tau}}$ is the turbulent Schmidt number for the age of air.

Observing the air distribution for occupants, there were totally 30 measured points in the breathing zone at students' seats to calculate the mean age of air in the classroom.

III. Results and Discussions

A. Wind profile effect on mean age of air

The comprehensive results illustrated in Fig. 3 showed that the computational domain size should be ideally large enough for the building model to allow transition airflow to fully develop. Wind field greatly influenced the airflow on the building's windward side, forming upstream turbulence that had considerable effects on external flow reattachment and surface pressure coefficients. This in turn affected airflow through the building openings, and ultimately, the mean age of air distribution in a room. The simulations showed that the penetration flow entered the inlet opening with steep inclined angles due to the front eddy, and the flow exited from the outlet moving upward due to the outside re-circulating eddy. The higher inlet velocity occurred on higher floors with apparent airflow deflection (Fig. 4).

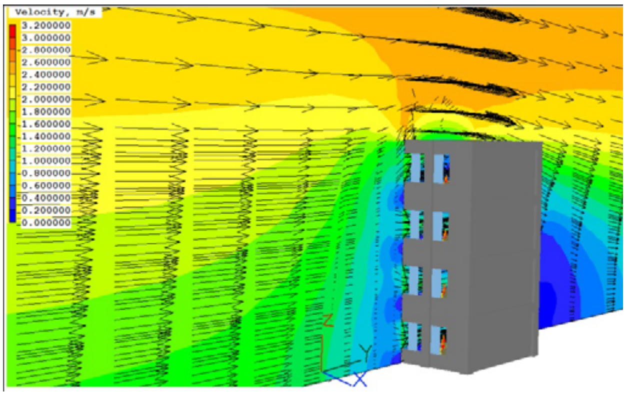


Fig. 4 Outdoor wind field with wind profile function

As listed in Table I, the air exchange rates in the room were, however, not significantly influenced by the airflow deflection. Air exchange rate was only slightly greater on higher floor. The average air exchange rates were roughly 22 ACH, much greater than the value suggested for removing indoor containments from school buildings. It is large enough for incoming wind flow to bring in sufficient cool air to remove heat inside the room. Therefore, the following discussions were focused on the distributions of mean age of air and airflow in the breathing zone rather than the entire classroom.

TABLE I
AVERAGE AIR EXCHANGE RATE ON EACH FLOOR

floor	1F	2F	3F	4F
ACH	21	21	22	24

Due to the wind profile effect, the deflective angles of the incoming wind performed differently on separate floors. Therefore, the results showed distinct mean age of air among floors even though the air exchange rate values were similar. Mean age of air value on the 4th floor was roughly 40 % more than the values on the other three floors. The difference among the 1st through the 3rd floor was rather small (Tables 2 though 5).

B. Fenestration effect on mean age of air

The results showed that the effects of the inlet layout on indoor mean age of air were more significantly than the effect of the outlet layout. Inlet layout A produced the smallest values among all four layouts on all floors. Nevertheless, the variation of mean age of air value due to change of inlet layout varied with varying floor. In other words, there are interactions among the effect of wind profile and the effect of fenestration.

Considering all floors, the maximum mean age of air value due to changes in fenestration combinations was roughly 33 % than the smallest one, indicating that significant variation in ventilation efficiency can be produced by the same sliding windows. The difference in mean age of air due to changes in both floor and fenestration combinations can be as large as 96 % (Fig. 5).

TABLE II
THE MEAN AGE OF AIR (S) ON THE 1ST FLOOR

outlet\inlet	A	B	C	D	Avg.
A	30.9	37.6	35.1	30.4	33.5
B	27.5	35.3	33.3	33.6	32.4
C	27.6	34.5	33.7	30.8	31.6
D	27.0	35.5	34.7	33.7	32.7
Avg.	28.3	35.7	34.2	32.1	32.6

TABLE III
THE MEAN AGE OF AIR (S) ON THE 2ND FLOOR

outlet\inlet	A	B	C	D	Avg.
A	26.5	33.1	32.7	29.9	30.5
B	26.8	33.4	32.4	33.6	31.5
C	28.1	32.6	34.4	29.9	31.3
D	28.7	32.4	33.2	32.2	31.6
Avg.	27.5	32.9	33.2	31.4	31.2

TABLE IV
THE MEAN AGE OF AIR (S) ON THE 3RD FLOOR

outlet\inlet	A	B	C	D	Avg.
A	29.1	33.5	33.0	36.0	32.9
B	29.1	34.5	33.8	35.3	33.2
C	28.4	35.1	34.0	31.0	32.1
D	29.4	37.1	35.2	33.0	33.7
Avg.	29.0	35.1	34.0	33.8	33.0

TABLE V
THE MEAN AGE OF AIR (S) ON THE 4TH FLOOR

outlet\inlet	A	B	C	D	Avg.
A	40.9	47.6	51.3	40.7	45.1
B	39.9	45.9	50.1	45.8	45.4
C	39.9	44.2	48.3	39.6	43.0
D	41.7	51.4	51.8	44.2	47.3
Avg.	40.6	47.3	50.4	42.6	45.2

The smallest values of mean age of air on individual floors were 27.0 s, 26.5 s, 28.4 s, and 39.6 s for the 1st through the 4th floor, respectively. Most of them were all resulted from inlet layout A except for the 4th floor. The largest values on the 1st through the 4th floor were derived from either inlet layout B or C. The C-D (inlet-outlet) fenestration combination obtained the highest mean age of air on the 4th floor. Even the best fenestration on this floor, the D-C combination, had a higher mean age of air value (39.6 s) than the worst one on the other floors.

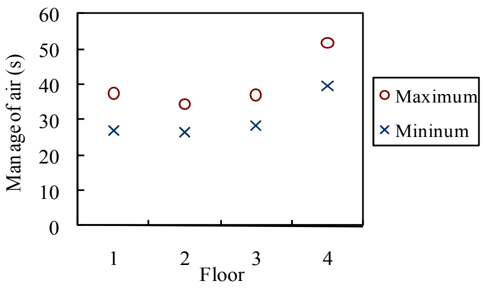


Fig. 5 Maximum and minimum mean age of air due to fenestration combination as a function of floor in the breathing zone

The average values of mean age of air for individual fenestration combination were shown in Table 6. Because of the interaction between wind profile and fenestration, the magnitude of variation due to change of fenestration combination was not as great as found for individual floors although the tendency was similar. The A-B combination produced the smallest value of mean age of air whereas the B-D one produced the greatest.

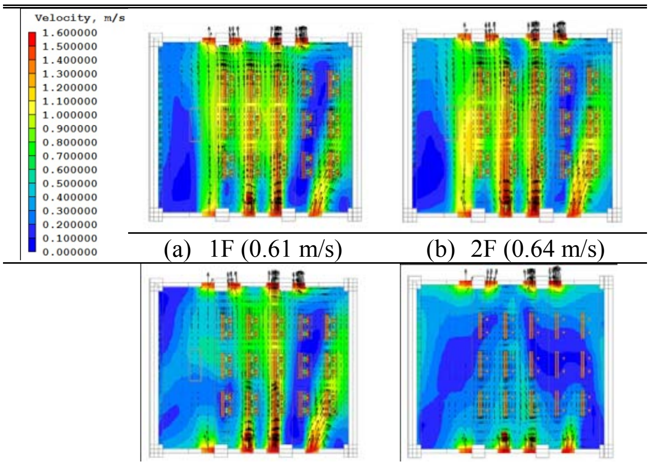
TABLE 6
AVERAGE VALUE OF MEAN AGE OF AIR (S) FOR THE 1ST TO THE 4TH FLOOR

outlet\inlet	A	B	C	D	Avg.
A	31.8	38.0	38.0	34.2	35.5
B	30.8	37.3	37.4	37.1	35.6
C	31.0	36.6	37.6	32.8	34.5
D	31.7	39.1	38.8	35.8	36.3
Avg.	31.3	37.7	37.9	35.0	35.5

C. Airflow pattern

The wind profile effect described the increasing deflection of airflow with height. Both wind profile and fenestration effects formed complicated and varying airflow patterns on each floor.

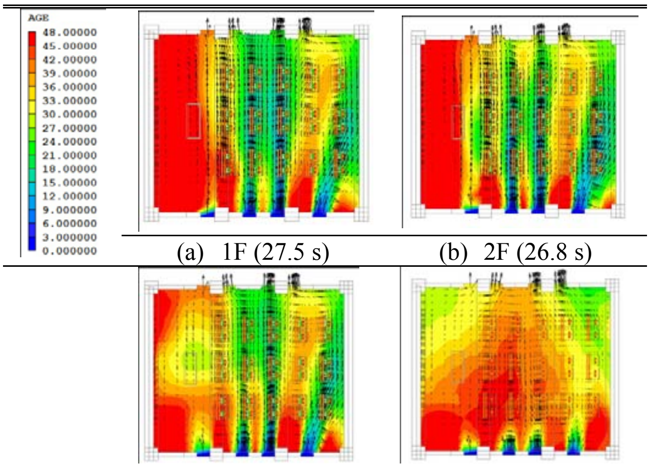
The simulated results on higher floors revealed much higher mean age of air and much lower air velocity in a classroom compared to lower floors (Figs. 6 and 7). Airflow with higher velocity on higher floors moved upward towards the ceiling obviously, making it difficult to exchange air in the breathing zone. On lower floors, the fenestration, especially inlet layout, played an important role on determining mean age of air distribution in a room.From simulated results, it can be known scattered inlet layout, especially leaning towards the back of the classroom, caused fewer stagnant areas in a classroom. The fenestration



(a) 1F (0.61 m/s) (b) 2F (0.64 m/s)

(c) 3F (0.52 m/s) (d) 4F (0.34 m/s)

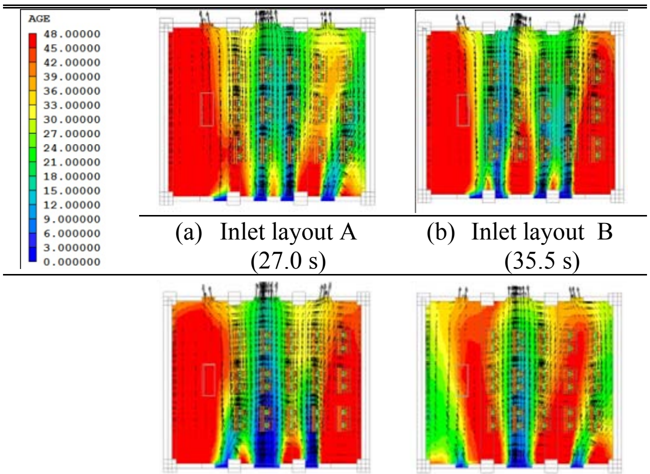
Fig. 6 Velocity contour for A-B fenestration combination on each floor



(a) 1F (27.5 s) (b) 2F (26.8 s)

(c) 3F (29.1 s) (d) 4F (39.9 s)

Fig. 7 AGE contour for A-B fenestration combination on each floor



(a) Inlet layout A (27.0 s) (b) Inlet layout B (35.5 s)

(c) Inlet layout C (34.7 s) (d) Inlet layout D (33.7 s)

Fig.8 AGE contour for outlet layout D on the 1st floor combinations with inlet layouts A and D obtained lower mean age of air and flew over most part of areas for occupants (Fig. 8). On the other hand, the simulations with inlet layouts B and C caused incoming wind to a straight-through airflow, causing stagnant areas at the back (right part of the graph) of the room. The airflow passed over the seat region rapidly and then flew out directly.

IV. Conclusion

Computational domain in this study combines outdoor with indoor environments to determine how fenestration affects the mean age of air and airflow patterns in the breathing zone of a typical classroom in Taiwan. This study presents the following conclusions:

a. Wind profile effect causes higher inlet air velocity on higher floor and causes inclined angle of wind that flows toward the ceiling. Deflective incoming wind with a larger velocity on higher floors does not help decrease the mean age of air in the breathing zone of a room.

b. The deflective airflow on higher floors causes higher mean age of air in the breathing zone. Therefore, building façade design or other devices that can channel incoming wind toward the breathing zone are more dominated than fenestration for higher floors to bring old air out.

c. Excluding the wind profile effect, the indoor airflow pattern is influenced much more by the inlet layout than by the outlet layout.

d. The best fenestration combination in this study decrease the mean age of air by 33% compared to the worst one on the same floor. The difference due to changes in floor and fenestration combinations can be as large as 96 %.

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