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Simulation of natural ventilation for semi-enclosed buildings

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Abstract. Energy-saving buildings have become a topical issue and widely used the energy-saving ventilation design, which aims to maximize the use of natural ventilation while reducing demand on mechanical ventilation. In this research, natural ventilation performance of two different semi-enclosed building layouts, "O" type and "L-L" type, are studied by numerical simulation. According to the simulation results, in the "O" type, the maximum indoor air velocity occurs in building A (orientation facing the inflow direction). The minimum indoor air velocity occurs in building C (orientation facing building A). In the "L-L" type, the maximum indoor air velocity occurs in building A (orientation facing the inflow direction). The minimum indoor air velocity occurs in buildings B and D (orientation parallel to the inflow direction). And air flow field simulation results show that, the "L-L" type exhibits better than the "O" type in natural ventilation. Furthermore, simulation results show that the natural ventilation performance in the room is influenced not only by the building orientation, but also by the window size.

1. Introduction

Energy-saving buildings has become a topical issue that highly valued by the government, and energy-saving ventilation design has been widely applied in that context. The energy-saving ventilation design aims to maximize the use of natural ventilation and, simultaneously, reduce reliance on mechanical ventilation through a well-designed building layout. This approach is intended to achieve energy savings[1].

In China, enclosed layout has been widely used in both residential and commercial buildings. The buildings along the street are often neatly arranged, creating a compact and unified building elevation. However, this layout can only ensure that some of the buildings have good orientation. Due to mutual occlusion, some buildings experience poor natural ventilation. The semi-enclosed buildings, which feature open areas in its layout, come in different types designed to enhance natural ventilation, including the "O" type, the "L-L" type, and others.

There are various factors that affect the natural ventilation of buildings. Chen Y et al.[2] focused on single bedrooms and how various factors, such as the window-wall ratio, influenced natural ventilation. Results revealed that under similar conditions, the volume of ventilation was positively associated with the window-wall ratio. Nomura M[3] selected 30 buildings and evaluated their air exchange rates, which ranged from 1 to 10 ac/h with no distinct peak. The results indicated that there was no clear association between air change rate and floor area, and natural ventilation primarily depended on the building design scheme. Zhang W et al.[4] used CFD to concentrate on hospital design and natural ventilation in buildings, aiming to enhance air quality. The results indicated that by setting reasonable types, locations, and heights of patios, the public space of a hospital could exhibit better natural ventilation, leading to improved comfort. Wu G. and Gan V.J[5,6] also used CFD to develop a model for enhancing the natural ventilation of high-rise buildings. Ma G et al.[7] used EnergyPlus to simulate natural ventilation of a railway station in Lianyungang City. Compared to mechanical refrigeration and air conditioner, using natural ventilation in conjunction with an air conditioner could reduce operation by 467h and save 13.1% of energy consumption. With the rise in air pollution, Ahmed T et al.[8] analyzed natural ventilation in warm climates. The results indicated that cross ventilation was effective in providing natural ventilation to lower indoor air temperatures. KazemiEsfeh M et al.[9] analyzed the natural ventilation of a curved roof at different wind angles and revealed that a semi-cylindrical curved roof could improve natural ventilation inside buildings. Bienvenido-Huertas D et al.[10] proposed the use of natural ventilation to de-crease cooling energy consumption during summer temperatures. Kyritsi E et al.[11] analyzed how window opening patterns impacted natural ventilation in office buildings. Gough H.L et al.[12] analyzed the impact of air flow direction on natural ventilation in an isolated building.

In this research, ANSYS is used to analyze the impact of window size and building orientation on natural ventilation for two different semi-enclosed building layouts, to provide suggestions for future building design.

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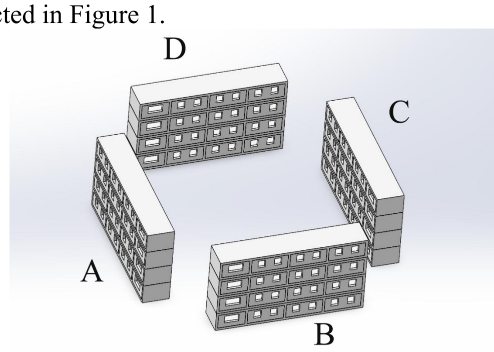
2. Simulation model and analysis methods

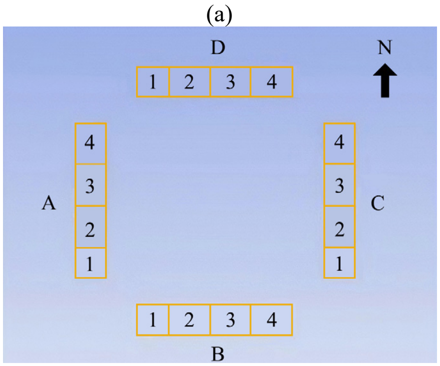
2.1. Building model

2.1.1. The "O" type

The four buildings are symmetrically arranged, looking like the letter "O". In this model, each building has four identical floors, and each floor contains four basic rooms. The doors of rooms are closed and the specific model is depicted in Figure 1.



(a)



(b)

Figure 1. Semi-enclosed buildings of the "O" type.

Each floor has four rooms with lengths of 6m, 8m, 8m, and 8m, as shown in Figure 3. The thickness of wall is 0.4m. The depth of each room is 6m, and the height is 3m. Assuming that the air flow direction is from left to right. As shown in Figure 1, the building that directly faces the direction of the air flow is designated as building A. Other buildings, in an anticlock-wise orientation, are labeled as buildings B, C, and D. The distance between building A and building C is 42m, and the distance between building B and building D is also 42m. The four rooms on the third floor of each building are designated as room 1, room 2, room 3, and room 4 respectively, as shown in Figure 2. There is only one window in room 1, sizing 3m×1.5m. While for room 2, 3 and 4, there are two windows in each room, with the same window size 1.5m×1.5m, as shown in Figure 3.

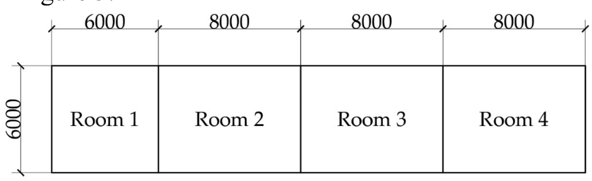


Figure 2. Floor plan.

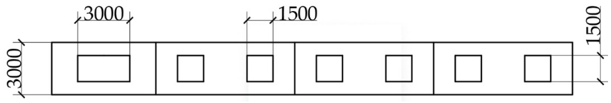
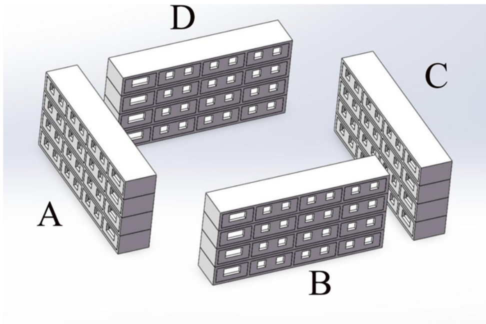


Figure 3. Floor elevation.

2.1.2. The "O" type

The two buildings are positioned in a way that looks like the letter "L". A pair of "L"s are placed symmetrically, forming an "L-L" shape. The doors of rooms are closed and the specific model is depicted in Figure 4. In this model, each building has four identical floors, and each floor contains four basic rooms, without considering the wall thickness. The room sizes are the same as the "O" type, as shown in Figure 3 and Figure 4. The distance between building A and building C is 42m, while the distance between building B and building D is 33m. Additionally, the distance between building A and building D, as well as building B and building C, is 6m.



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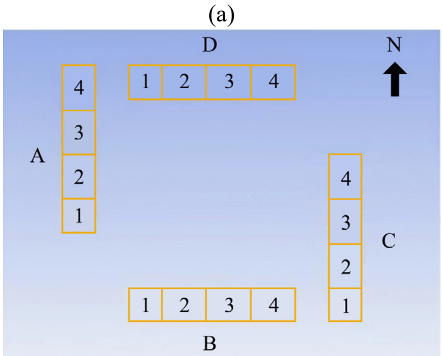

(b)

Figure 4. Semi-enclosed buildings of the "L-L" type.

2.2. Ventilation simulation and measurement method

2.2.1. Setting of air flow field

In this study, ANSYS Icepak is used to conduct numerical simulations of indoor natural ventilation. In the air flow field, the distance between the air intake boundary and building A is 82m. The distance between the air outlet boundary and building C is 164m. Additionally, the distance between the lateral air boundary and building B is 82m, as well as building D. The height of the air flow field is 97.2m, as shown in Figure 5 and Figure 6.

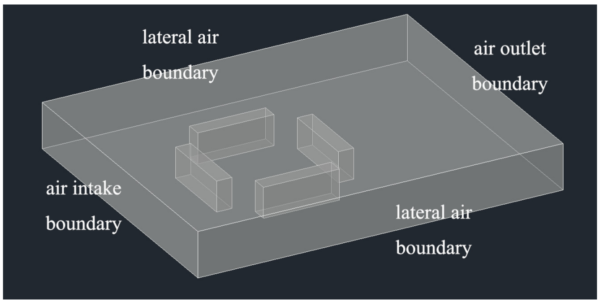

Figure 5. Air flow field of the "O" type.

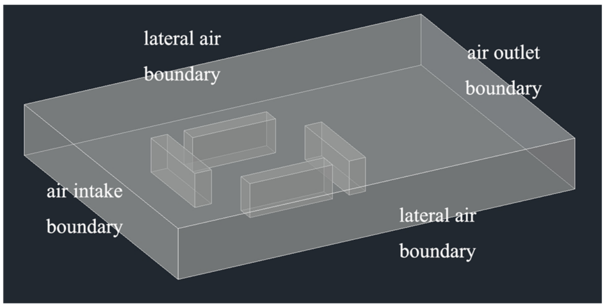

Figure 6. Air flow field of the "L-L" type.

2.2.2. Setting of air velocity and building design

According to the China Meteorological Data Set for Building Thermal Environment Analysis[13], the data for typical meteorological years in Shanghai is shown in Table 1. This research focuses on simple buildings in Shanghai, a representative area in the summer condition. The outdoor air velocity is set at 3.4m/s.

Table 1. Data of typical meteorological years in Shanghai.

Season	Dominant air flow direction	Frequency of air flow direction(%)	Average air flow velocity (m/s)
Spring	ESE(111.5°)	11.91	3.8
Summer	ESE(111.5°)	14.96	3.4
Autumn	NNE(22.5°)	14.41	3.8
Winter	NNE(22.5°)	14.24	3.5

Among basic structures, the school building is better suited to the requirements of semi-enclosed layout. Therefore, the building design is based on the school building in this research. According to GB 50099-2011: the Code for Design of School[14], the primary school main building should not exceed four floors, while the middle school main building should not exceed five floors. Consequently, in this research, a four floors building has been chosen as the standard research subject for modeling.

2.2.3. Assessing natural ventilation of the building

The natural ventilation performance of buildings can be evaluated on air velocity, ventilation volume, air change rate, air age and so on. And in this research, air velocity is adapted as the evaluation criterion.

2.3. Analysis method

According to the GB/T 50785-2012: Evaluation Standard for Indoor Thermal Environment in Civil Buildings[15], the sampling points should be arranged in places that are the most uncomfortable for people, including positions near windows and in-ner corners. The distance between the sampling points and adjacent walls should ex-ceed 0.5m. In this research, 5 sampling points are arranged in each room, and the av-erage air flow velocity of the 5 sampling points is taken as the mean air flow velocity of the room. Location of the sampling points are depicted in the Figure 7.

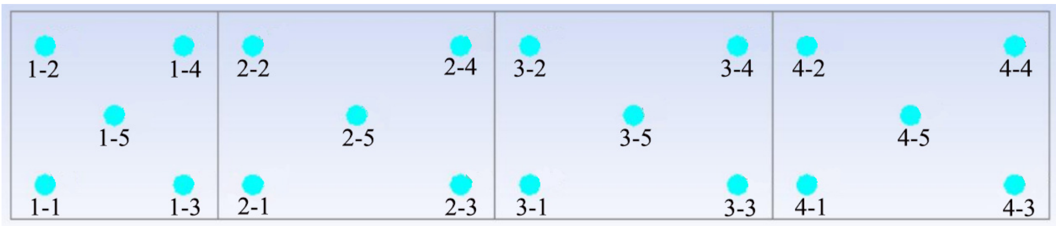

Figure 7. Location of the sampling points.

3. Simulation results

3.1. Ventilation simulation of the "O" type

The air flow is set from left to right with the velocity of 3.4m/s, and the calculation result of air flow field for the "O" type buildings is shown in Figure 8.

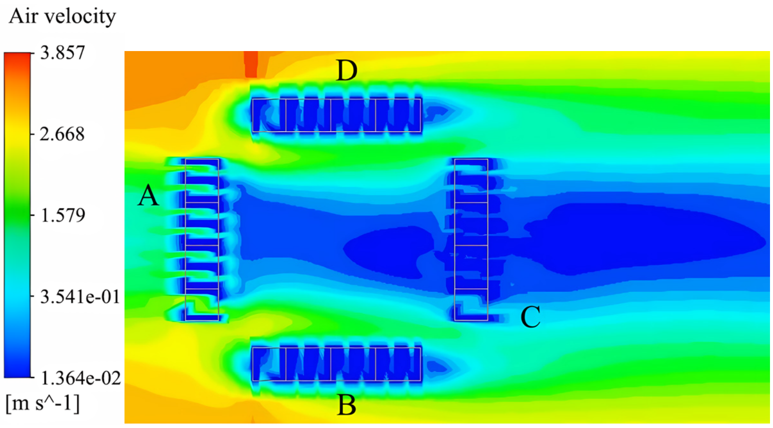

Figure 8. Air flow field of the "O" type

The color of air flow field in Figure 8 represents air flow velocity. In building A (orientation facing the inflow direction), the air flow velocity is highest. In building C (orientation facing building A), the air flow velocity in the other rooms is significantly lower. To assess the ventilation more accurately, this research quantitatively analyzes indoor air flow at sampling points located in the rooms on the 3rd floor.

In building A, according to Table 2, it could be observed that the maximum air flow velocity occurs in room 1, while the minimum air flow velocity occurs in the room 2. Room 1, with one large open window, performs significantly higher air flow velocity than the other 3 rooms that with two small open windows, indicating that the natural ventilation performance in the room will be reduced if one large window is divided into two small ones.

Table 2. Air flow velocity in building A of the "O" type.

Building A	Sampling point (m/s)					Average air flow velocity (m/s)
	1	2	3	4	5	
Room 1	0.33	0.21	0.21	0.38	1.20	0.446
Room 2	0.34	0.22	0.12	0.09	0.06	0.166
Room 3	0.36	0.21	0.19	0.18	0.10	0.208
Room 4	0.42	0.22	0.20	0.16	0.06	0.212

According to Table 3 and Figure 1, building B is parallel to the inflow direction, but the indoor air velocity of four rooms is still different. Room 1, with a large open window, exhibits higher air flow velocity than the other rooms. However, the average air flow velocity in building B is much lower than that in building A (orientation facing the inflow direction), indicating that the orientation of the building has significant influence on indoor natural ventilation in the "O" type.

Table 3. Air flow velocity in building B of the "O" type.

Building B	Sampling point (m/s)					Average air flow velocity (m/s)
	1	2	3	4	5	
Room 1	0.20	0.08	0.13	0.26	0.65	0.264
Room 2	0.12	0.08	0.10	0.17	0.06	0.106
Room 3	0.06	0.06	0.11	0.12	0.02	0.074
Room 4	0.07	0.07	0.10	0.14	0.06	0.088

According to Table 2 and Table 4 , the average air flow velocity in building C is significantly lower than that in building A. This indicates that building A (orientation facing the inflow direction) has significant influence on the indoor natural ventilation of building C (orientation facing building A) in the "O" type.

Table 4. Air flow velocity in building C of the "O" type.

Building C	Sampling point (m/s)					Average air flow velocity (m/s)
	1	2	3	4	5	
Room 1	0.12	0.10	0.08	0.04	0.32	0.132
Room 2	0.06	0.03	0.03	0.02	0.03	0.034
Room 3	0.12	0.03	0.08	0.04	0.06	0.066
Room 4	0.16	0.07	0.04	0.04	0.02	0.066

As shown in Figure 1, buildings B and D are symmetrically arranged. According to Table 3 and Table 5, the average air flow velocity in building D, is very close to that in building B that with the same orientations (orientation parallel to the inflow direction).

Table 5. Air flow velocity in building D of the "O" type.

Building D	Sampling point (m/s)					Average air flow velocity (m/s)
	1	2	3	4	5	
Room 1	0.19	0.09	0.14	0.28	0.72	0.284
Room 2	0.11	0.10	0.10	0.15	0.06	0.104
Room 3	0.10	0.07	0.11	0.16	0.06	0.100
Room 4	0.14	0.06	0.12	0.11	0.04	0.094

3.2. Ventilation simulation of the "O" type

The air flow is set from left to right with a velocity of 3.4m/s, and the calculation result of air flow field for the "L-L" type buildings is shown in Figure 9.

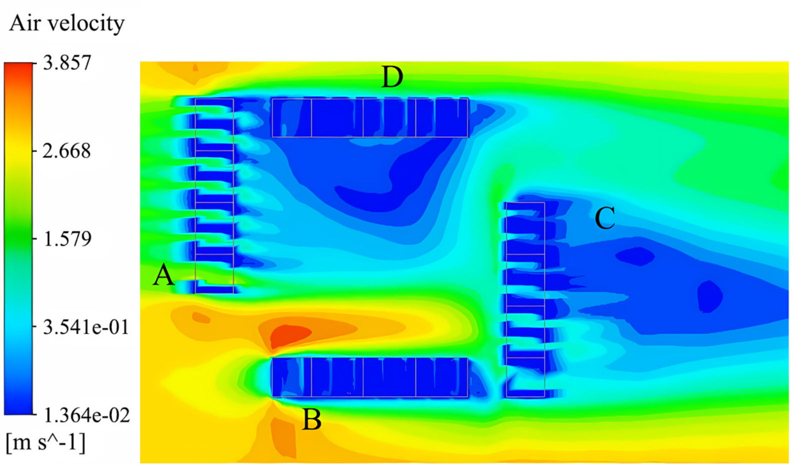

Figure 9. Air flow field of the "L-L" type.

The color of air flow field in Figure 9 represents air velocity. In building A (orientation facing the inflow direction), the air velocity is the highest. In buildings B and D (orientation parallel to the inflow direction), the air velocity of other rooms is significantly lower except for room 1 near building A. This research quantitatively analyzes indoor air flow velocity at sampling points located in four rooms on the 3rd floor.

In building A, according to Table 6, it could be observed that the maximum air flow velocity occurs in room 1, while the minimum air flow velocity occurs in room 2. Room 1, with one large open window, performs significantly higher air flow velocity than the other 3 rooms that with two small open windows, indicating that the natural ventilation performance in the room will be reduced if one large window is divided into two small ones.

Table 6. Air flow velocity in building A of the "L-L" type.

	Sampling point (m/s)					Average air flow velocity (m/s)
	1	2	3	4	5	
Room 1	0.36	0.08	0.19	0.42	1.40	0.490
Room 2	0.40	0.16	0.11	0.21	0.03	0.182
Room 3	0.42	0.18	0.10	0.20	0.02	0.184
Room 4	0.43	0.21	0.12	0.40	0.04	0.240

Building B is parallel to the inflow direction, as shown in Figure 4. According to Table 6 and Table 7, room 1, with a large open window, exhibits higher air velocity than the other rooms. However, the average air flow velocity in building B is much lower than that in building A (orientation facing the inflow direction), indicating that the orientation of the building also has significant influence on indoor natural ventilation in the "L-L" type.

Table 7. Air flow velocity in building B of the "L-L" type.

	Sampling point (m/s)					Average air flow velocity (m/s)
	1	2	3	4	5	
Room 1	0.12	0.02	0.12	0.21	0.36	0.166

Room 2	0.09	0.04	0.08	0.12	0.04	0.074
Room 3	0.04	0.03	0.06	0.11	0.02	0.052
Room 4	0.05	0.03	0.09	0.13	0.05	0.070

According to Table 8 and Table 9, the average air flow velocity in building C is close to that in building A. This indicates that building A (orientation facing the inflow direction) has little influence on the indoor natural ventilation of building C (orientation facing building A) in the "L-L" type.

Table 8. Air flow velocity in building C of the "L-L" type.

Building C	Sampling point (m/s)					Average air flow velocity (m/s)
	1	2	3	4	5	
Room 1	0.28	0.08	0.12	0.26	1.20	0.388
Room 2	0.31	0.12	0.08	0.18	0.04	0.146
Room 3	0.25	0.12	0.05	0.18	0.08	0.136
Room 4	0.22	0.10	0.06	0.08	0.02	0.096

Building D is parallel to inflow direction and is shielded by building A, as shown in Figure 4. According to Table 7 and Table 9, the average air flow velocity in building D is close to that in building B. This suggests that in the "L-L" type, building A (orientation facing the inflow direction) has little influence on the natural indoor ventilation of adjacent building D (orientation parallel to the inflow direction), and that the orientation of the building is the primary influencing factor.

Table 9. Air flow velocity in building D of the "L-L" type.

Building D	Sampling point (m/s)					Average air flow velocity (m/s)
	1	2	3	4	5	
Room 1	0.11	0.06	0.04	0.12	0.32	0.130
Room 2	0.05	0.04	0.11	0.02	0.10	0.064
Room 3	0.32	0.03	0.09	0.04	0.04	0.104
Room 4	0.06	0.05	0.09	0.11	0.02	0.066

4. Comparison Results

To analyze the natural ventilation of two types, the average air velocity in four rooms of the "O" and "L-L" types is compared, as shown in Table 10 and Table 11.

Table 10. Air flow velocity in rooms of the "O" type.

"O" type	Room (m/s)				Average air flow velocity (m/s)
	1	2	3	4	
Building A	0.466	0.166	0.208	0.212	0.263
Building B	0.264	0.106	0.074	0.088	0.133
Building C	0.132	0.034	0.066	0.066	0.075
Building D	0.284	0.104	0.100	0.094	0.146

Table 11. Air flow velocity in rooms of the "L-L" type.

"L-L" type	Room (m/s)				Average air flow velocity (m/s)
	1	2	3	4	
Building A	0.490	0.182	0.184	0.240	0.274
Building B	0.166	0.074	0.052	0.070	0.090
Building C	0.388	0.146	0.136	0.096	0.191
Building D	0.130	0.064	0.104	0.066	0.091

Table 10 shows that, for the "O" type, maximum average air flow velocity occurs in building A, while minimum average air flow velocity occurs in building C. The average air velocity in building C is 0.075m/s, which is significantly lower than that of 0.263m/s in building A. The results indicate that building A (orientation facing the in-flow direction) significantly reduces the natural ventilation of building C (orientation facing building A) in the "O" type. The average air flow velocity in building B and D is significantly lower than that in building A. The natural ventilation of building B and D (orientation parallel to the inflow direction) is worse than that of building A in the "O" type.

Table 11 shows that, for the "L-L" type, maximum average air flow velocity occurs in building A, while minimum average air flow velocity occurs in building B. The average air velocity in buildings B and D is approximately 0.09m/s, which is significantly lower than the 0.274m/s in building A. The results indicate that the natural ventilation of building B and D (orientation parallel to the inflow direction) is worse than that of building A (orientation facing the inflow direction) in the "L-L" type.

Comparing Table 10 with Table 11, in the "O" type, building A (orientation facing the inflow direction) significantly reduces the natural ventilation of building C (orientation facing building A). In the "L-L" type, the natural ventilation of building C (orientation facing building A) is slightly influenced by building A (orientation facing the inflow direction), and building C still exhibits good ventilation performance. Additionally, the average air velocity of four buildings in the "O" type is lower than that in the "L-L" type, indicating that the "L-L" type exhibits better natural ventilation.

5. Conclusions

Based on the results and analysis above, conclusions are obtained as below:

1. In the semi-enclosed buildings, the "L-L" type exhibits better natural ventilation than the "O" type.

2. In the semi-enclosed buildings, orientation facing the inflow direction exhibits better natural ventilation compared to orientation parallel to the inflow direction. This indicates that the orientation of a building significantly influences on natural ventilation.

3. In the semi-enclosed buildings, using one large open window instead of two small open windows can enhance natural indoor ventilation.

In the semi-enclosed buildings, reasonable building orientation, well-designed building layout and larger window size can enhance natural ventilation and reduce the demand on mechanical ventilation, which will lead to energy saving.

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