Design Parameters of Double-Skin Façade for Improving the Performance of Natural Ventilation in High-Rise Residential Buildings

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Abstract

In high-rise residential buildings, problems arise with the use of natural ventilation, as outdoor wind speed and pressure increase in accordance with the increase of building height. As an alternative for high-rise residential buildings, the double-skin façade offers a way to use natural ventilation. From a questionnaire conducted with residents of high-rise residential buildings and interviews with residential managers, problems relating to ventilation were identified and the improvement factors of natural ventilation were developed for the current plans of a double-skin façade. The evaluation parameters included the type of position for the inlet and outlet, the envelope module, external window, width of intermediate space, and internal windows. These parameters are derived from the method of architectural planning. The purpose of this study is to evaluate the natural ventilation performance in high-rise residential buildings, especially in terms of the decrement effect of wind speed and pressure and the adequacy of ventilation rate. Natural ventilation performance according to the parameters is evaluated by CFD simulation.

Keywords: double-skin façade; design parameters; natural ventilation; high-rise residential building

1. Introduction

During the past few decades, a large number of high-rise residential buildings have been constructed in Korea¹. As the number of high-rise residential building constructions increased, the air tightness performance of building envelope systems has strengthened. Safety concerns related to falling accidents have led to the installation of windows with limited-angle opening, and the consequent reduction in the window opening area is creating ventilation issues that have not been significantly considered in the past².

The forms of envelopes were changed due to the restriction of window openings in high-rise residential buildings. The value of residential buildings is increased by planning the envelope similar to that of office buildings. It is difficult to apply natural ventilation to high-rise residential buildings because of the strong wind pressure on their façades and their increased height. The existing balcony designs are extended to an interior space, which has the effect of destroying the buffer zone that connects the interior space to the outdoor environment³. As it became more difficult to naturally cool buildings using outdoor air, problems occurred such as the increase of energy cost. The double-skin façade is an architectural phenomenon driven by an aesthetic desire for an all-glass façade⁴,⁵. The advantages of a double-skin façade are reduction of the wind pressure and increase of the ventilation. The cavity between the two panes of glass in the double-skin façade can reduce the wind pressure, while a variety of openings can actively manage the ventilation according to the internal and climate conditions. Double-skin façades with cavities are viable design options for sustainable building strategies, since they effectively provide additional ventilation using natural ventilation and diminish the loads on mechanical ventilation systems⁶.

Residential buildings use natural ventilation as the main source of ventilation and the characteristics of residential buildings have not been considered in planning the window openings. Buildings require engineering during the early design stage. This is the origin of façade design and construction problems⁷. During the design stage, it is necessary to utilize a prediction model to analyze the air change rate of high-rise residential buildings⁸.

To solve the problems of wind pressure and safety in high-rise buildings, research on the double-skin façade has actively progressed. This study focused mainly on how a building envelope is designed, especially the naturally ventilated double-skin façade. In this study, the characteristics and problems of the envelope in high-rise residential buildings are identified. The parameters of the double-skin façade plan were

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observed and evaluated to improve the performance of natural ventilation. Evaluation will be continued in order to understand how to design the parameters of double-skin façades, such as inlets, outlets, intermediate space and external windows.

Ventilation can be categorized into buoyancy-driven ventilation and wind-driven ventilation. This study focuses on wind-driven ventilation because natural ventilation is mostly used in intermediate seasons at which time there is little temperature difference between indoors and outdoors and there is higher wind speed in high-rise buildings which makes wind-driven ventilation superior to buoyancy-driven ventilation.

2. Field Survey
2.1 Data analysis
The characteristics of high-rise residential buildings should be identified since the plan for the double-skin façade needs to be in accordance with the usage and characteristics of the building. For this purpose, the envelopes of high-rise residential buildings were investigated in this study and the problems related to natural ventilation were examined through a questionnaire and interviews with the occupants and managers of existing high-rise residential buildings. From an investigation of this material and of the standards and the building code related to natural ventilation, the required performance of natural ventilation in residential buildings was summarized to determine the criteria for evaluation concerning the performance of natural ventilation.

First, the investigation on ventilation is significant since the purpose of the research is to propose planning of the envelope considering the performance of natural ventilation. The opening form and area of ventilation are important factors to determine the ventilation rate, which then establishes the induction rate of external air. Accordingly, the current induction of outdoor air was understood through an examination of the form of opening for ventilation in high-rise residential buildings. The investigation was carried out on fifteen buildings in Seoul, where most of the high-rise residential buildings were constructed. In Fig.1, it can be seen that most of the high-rise buildings had top-hinged out swinging windows, except for the lower-level, in which top-hinged out swinging windows and side-hinged out swinging windows were used.

In order to determine the environmental performance of the envelope according to the occupants of high-rise residential buildings, a questionnaire and interviews with managers were conducted. The questionnaire was completed by participants who were residents of high-rise residential buildings in Seoul and structures with similar height and orientation were selected to improve the credibility of the questionnaire. Interviews with the managers were carried out to obtain information on the complaints made by occupants after the completion of construction. From the questionnaire results, the problems of the envelope that influences the performance of the indoor environment were indicated. The high wind pressure at the higher-level was also not considered and caused water leakages and infiltration through the envelope. The small opening area for ventilation resulted in a reduction of natural ventilation and the occupants' psychological satisfaction.

2.2 Problem analysis
The ventilation performance and improvements to meet the occupants' demands on the indoor environment are summarized. Based on an analysis of problems and causes in existing envelopes of high-rise residential buildings, the performance of natural ventilation was improved.

1) Security of natural ventilation performance through the inducement of external air
As high-rise residential buildings become taller the cooling load increases because the curtain wall system is applied in most of the buildings, which has a significant amount of glazed area. In contrast, the reduction of the opening area due to wind pressure and safety reduces ventilation. In this case, the building uses more energy because the free cooling effect cannot be applied, thus increasing the cooling period. Therefore, the proper opening area and angle should be achieved to increase the ventilation rate with the same opening method.

2) Security of the air flow speed
It appeared that the occupants of high-rise residential buildings want to feel the sensation of air flowing through the rooms by the introduction of external air. The occupants who had experienced cross ventilation in an existing plate type apartment before living in a high-rise residential building expressed a stronger

![Fig.1. Opening Windows of the Envelope of High-Rise Residential Buildings](image-url)
Table 1. Applying the Method of Double-Skin Façade Design Through an Analysis of the Problems of Existing Buildings

| Characteristic of residential buildings | Requirements | Application to DSF |
|----------------------------------------|--------------|-------------------|
| Floor height is lower than office buildings | To maximize buoyancy force | Inlets and outlets are located in front of the spandrel. |
| There is high demand for natural ventilation | To increase ventilation rate | External openable windows can be added. (Optional) |
| Children should be considered. | To allow occupants to feel air flow | The type of external openable windows cannot be sliding. |
| Reduction of the living area is a critical issue for occupants. | To make occupants safe | The depth of an external openable window is 15 cm. |
| Occupants maintain and clean DSF by themselves. | To maximize the living area | The depth of an Intermediate façade is 30 cm. |
| Most occupants use curtains for interior decoration. | To give occupants convenience for maintenance and operation of DSF | The type of internal window is sliding. |
| - | To provide a better view | The openable bays are placed at the edge of the façade. |

需求。因此，窗户的开启方式、开启面积和开启角度应考虑为保持足够新鲜空气的引入。

3) Psychological security concerning the feeling of openness

居民们对于开放感的追求不取决于实际的通风率。即使在相同的通风率下，高层建筑内部的通风情况与一般的住宅有所不同。通常，高层住宅的通风口比一般住宅的通风口大得多，避免了由单个通风口的开启导致的顶部开启的弊端。为了解决这些问题，需要进一步优化通风口的开启角度，使通风口的开启角度达到最大值，从而避免顶部开启的弊端。

2.3 Decision concerning the façade module

根据先前的研究，选择一个双层皮肤的外窗系统，使其在高层居住建筑中适用，可以降低建筑的重量和减少施工现场的材料用量。因此，双层皮肤的外窗系统被广泛应用于高层居住建筑。

3. The Procedure of a Double-Skin Façade Plan Considering Natural Ventilation Performance

3.1 The selection of a double-skin façade type suitable for high-rise residential buildings

根据先前的研究，在选择双层皮肤的外窗系统时，应考虑建筑的实际情况。对于高层居住建筑，应选择一个适合多层的双层皮肤的外窗系统。在单层的双层皮肤的外窗系统中，选择一个适合多层的双层皮肤的外窗系统，可以降低建筑的重量和减少施工现场的材料用量。因此，双层皮肤的外窗系统被广泛应用于高层居住建筑。

3.2 Choice of inlet and outlet arrangement type

选择通风口的排列方式可以决定建筑的规划。在多层的双层皮肤的外窗系统中，选择一个适合多层的双层皮肤的外窗系统，可以降低建筑的重量和减少施工现场的材料用量。因此，双层皮肤的外窗系统被广泛应用于高层居住建筑。
in some cases such as the Debit Tower, the external air was actively induced with only an opening in the external façade without an inlet and outlet. When the opening area of the external façade is increased, not only can more external air be induced, but the occupants can also have a greater feeling of openness, thus satisfying the required performance of natural ventilation. According to a previous study\(^9\), with the application of external windows, the ventilation rate was 1.4 to 3 times greater than the ventilation rate without the external window. Therefore, a Parallel Ausstell Fenster (PAF) type window was installed on the external side in this study to increase the ventilation rate.

### 3.5 Decision concerning the type of internal window

The occupants' convenience and desire for the feeling of openness should be considered in the decision of the type of internal window to be applied since the internal window is on the most internal side. Consequently, the sliding type is most suitable because it does not interrupt the living space and offers an easier approach to the intermediate façade from the side opening area. The WINDOW 5 program developed by the Lawrence Berkeley National Laboratory (LBNL) was used to analyze the U-value of general duplex glass and Low-e glass. They have a lower coefficient than 3.84 W/m\(^2\)K, which complies with the building code.

In the process of decision-making, the type of double-skin façade application for a high-rise residential building was considered. The procedure for the double-skin façade plan was also summarized to consider the performance of natural ventilation.

### 4. Modeling of Double-Skin Façade

#### 4.1 Evaluation model

This study was performed by conducting simulations to understand the effect of various envelopes. Computational fluid dynamic (CFD) models of double-skin façade were used. CFD methods were able to study the detailed airflow in DSF, compared with network models. Comprehensive double-skin façade models including turbulent flow are presented. In some studies\(^{10,11}\), CFD methods were adopted to analyze the airflow in ventilated double-skin façade, and proved to have good coincidence with the experimental results. The commercial CFD tool, STAR-CCM+ with the standard k-ε turbulent model was used. Table 2. shows a diagram of the double-skin façade which was planned by considering natural ventilation performance.

Primarily, evaluation on the different positions of inlet and outlet was conducted in the decision making process. Also, the performance according to the evaluation parameters was analyzed for each type of inlet and outlet of openings, intermediate space, and external window. The basic model of evaluation factors is shown in Table 3.

#### 4.2 Boundary condition

In order to analyze the performance of natural ventilation by the CFD analysis method, the boundary conditions of the outdoor wind velocity and direction needs to be considered. Wind induced pressures and thermal buoyancy are the main driving forces of natural ventilation. In this study, the intermediate season was selected because the majority of the ventilation occurs by wind pressure and the difference of indoor and outdoor temperature is small. In high-rise buildings, as wind speed is high, wind-driven ventilation is larger than buoyancy-driven ventilation. Thus, the analysis was conducted with an isothermal boundary condition and outdoor air velocity and direction were entered as a boundary condition. Outdoor air velocity accelerates the convective heat transfer from the envelope and is one of the most significant factors that affect the indoor air velocity.

After conducting a survey and interviewing the manager, natural ventilation was defined as the direct ventilation effect. Therefore, the discharge of heat in the intermediate space through airflow was excluded in this study. While planning high-rise buildings, the air velocity needs to be considered because it becomes

| Component | Explanation |
|-----------|-------------|
| Inlet and outlet | Height of inlet and outlet: 600 mm |
| Ratio of the breadth of inlet and outlet: | 1:1 |
| Width of cavity | 300 mm |
| External window | Opening method: PAF, Height: 1300 mm |

Table 3. Basic Model of Evaluation Factors

![Diagram of Double-Skin Façade](image-url)
greater as the height of the building increases.

To evaluate wind-driven ventilation, wind speed and direction were set as boundary conditions. The wind measuring heights from the National Weather Service are 10 m, 30 stories (97.5 m), and 50 stories (162.5 m) and these conditions were applied to evaluate the natural ventilation performance at a variety of heights. Typically, the façade is designed without consideration of orientation and height for the economical and aesthetic reasons. When façade design is applied according to the height of the high-rise buildings, the problems caused by the wind velocity and orientation needs to be considered in a façade design stage. The annual average wind velocity in the Seoul area was 2.3 m/s and maximum wind velocity was 10.2 m/s. For a conversion from the wind velocity in a current height to wind velocity in high-rise buildings, equation (1) was applied.

$$U_H = U_{met} \left( \frac{\delta_{met}}{H_{met}} \right)^{\alpha_{met}} \left( \frac{H}{\delta} \right)^{\alpha_{terrain}} \left( \frac{U_{H}}{U_{met}} \right)^{\alpha_{terrain}}$$ (1)

$U_H$: mean wind speed at height H
$\delta$: wind boundary layer thickness at local building terrain
$\alpha$: exponent for local building terrain
$H$: wall height above ground on upwind building face
$U_{met}$: meteorological station hourly wind speed measured at height $H_{met}$
$\delta_{met}$: wind boundary layer thickness at meteorological station
$\alpha_{met}$: exponent for the meteorological station
$H_{met}$: height of anemometer at meteorological station

Unlike typical residential buildings facing south, it is possible for high-rise residential units to face all directions and natural ventilation performance varies with wind direction. Accordingly, the incident angle of the wind, $\theta$, is in the range of 0–90° (absolute value) assuming application on a common square shaped building. Thus, an evaluation was performed concerning the wind speed and the incident angles of 0°, 30° and 90° according to the wind scale table by Beaufort. Also, the required wind speed for each incident angle was analyzed according to the natural ventilation performance.

5. Results and Discussions

5.1 Performance depending on the inlet and outlet evaluation parameter

The height of the inlet and outlet is an evaluation parameter of the diagonal and parallel types. However, the current basic model in the subject space is planned with the maximum value of 300 mm, which is the effective planning height. Thus, the height of the inlet and outlet is reduced to half and a performance variation was observed. The height of the diagonal type is reduced from 300 mm to 150 mm and 75 mm and that of the parallel type from 150 mm to 75 mm. 300 mm of the diagonal type opening area is equivalent to 150 mm of the parallel type opening area and 150 mm of the diagonal type opening area is equivalent to 75 mm of the parallel type opening area.

The reduction of ventilation rate varies depending on the wind direction. As shown in Fig.2., the fluctuation of the ventilation rate is diminutive at a 30° angle of incidence, while the 30° angle of incidence had the highest air exchange rate. Although the height of the inlet and outlet was reduced, the ventilation rate of the diagonal type increased at a 90° angle of incidence, because the distance to the internal window became closer as the height of the inlet and outlet was reduced.

The second evaluation parameter is the ratio of the inlet area and outlet area. When the ratio of the inlet area and the outlet area changes in the diagonal type, the inlet and outlet can be planned as a horizontal shape, which is similar to the parallel type. A horizontal shape may prevent the wind entering the building on a 90° angle of incidence for the diagonal type. For the case study, the ratio of inlet and outlet was set as 2:1 and 1:2. Also the inlet and outlet were arranged as in Fig.3. In (b) and (d), the inlet and outlet were horizontally connected with two 1,800 mm modules. In this case, 1,800 mm of the fixed window module and 900 mm of the opening window module were developed separately. The horizontal length of the inlet and outlet can be adjusted and added to in this case. Evaluation was performed with a wind direction of 90°, which has the most disadvantages. As shown in Fig.4., the ventilation rate has increased. With the connecting of the 1,800 mm module, the ventilation...
rate increased by more than two to three times.

For evaluation, the ratio of the inlet area and outlet area was configured as 2:1 and 1:2, respectively. As shown in Fig.5.(a) when the angle of incidence is 90° with a 2:1 ratio, the pattern of air flow in the outlet is similar to the pattern of air flow in the outlet with a 1:1 ratio. The portion of air from the outlet directly exhausts through the side and back wall of the outlet and the remaining air descends through the intermediate space.

A portion of the air from the inlet creates a turbulent flow in the intermediate space and the remaining air flows through the right side of the internal window. Thus, more air can flow into a room with a 2:1 ratio than with a 1:1 ratio, in which a lot of airflows through the side wall and exhausts through the outlet. Fig.5.(b) shows the air flow with a 1:2 ratio of the inlet area and outlet area which has a similar but reversed pattern from that of the 2:1 ratio.

### 5.2 Performance depending on the evaluation parameters of intermediate space

One of the evaluation parameters in the intermediate space is the depth. The depth of the intermediate space is 300 mm in the basic model, which is considered to be the maintenance depth with the opened internal window. The maximum depth of the intermediate space is 600 mm, which is considered the maintenance depth with a person inside. Fig.6. shows that the air exchange rate decreased for the diagonal type but significantly increased for the parallel type. To determine the reason for this, the air flow pattern of the inlet and outlet is observed.

As shown in Fig.7., the air through the inlet and outlet flows through the side wall and descends 300 mm into the intermediate space. However, the intake air from the inlet flows horizontally through and exhausts directly at 450 mm and 600 mm, the depths of intermediate space. In the horizontal section view of openings, changes of the ratio of the lateral to the longitudinal length cause different airflow. A greater ventilation rate appeared in the 2:1 ratio than in the 3:2 ratio for 600 mm of the intermediate space. For the 3:1 ratio with a 300 mm intermediate space, the ventilation rate was greater than for the 2:1 ratio with a 600 mm intermediate space. However, Fig.6. and
Fig. 7(b) demonstrate the increment of ventilation rates in multiples of 1.6 and 2.4 with different depths of intermediate space for the parallel type. Although the maximum inlet air velocity of the internal window is considerable, only the upper and lower parts of the inlet and outlet showed airflow in the basic model. As the depth of intermediate space increases, airflow developed throughout the intermediate space.

5.3 Performance depending on the evaluation parameters of an external window

Installing an external window critically affects the increment of ventilation rate. The evaluation parameters of the external window are the opening method and the height. Evaluation of the PAF type and top-hinged outward swinging type was performed.

The results of the evaluation are shown in Fig. 8. Compared with the basic model without external windows, in the case where the incident angle is 30°, the ventilation rate is increased by more than 1.5 times and the incident angle is increased by more than 8 times. In Fig. 9, even though both the superiority and inferiority of the ventilation ratio of the window types differ according to the direction of the wind, considering the fact that a 90° wind direction is the most frequent, it seems that a PAF with a higher ventilation ratio at the incident angle of 90° would be advantageous. In addition, in the case where an incident angle of 90° was decreased to less than 1/7 of that without an external window, the efficiency of ventilation was improved and it was confirmed that the air circulated throughout the entire room.

Sandberg’s proposed ventilation efficiency expressed with mean age, which is the period of time that fresh air is supplied. As the mean age of air in the indoor breathing space is smaller, ventilation efficiency becomes greater. Ventilation rate does not have absolute standards but it can be utilized for relative comparison. In the case where the external window was the PAF type, it was possible to ventilate more efficiently due to the fact that the maximal value of the age of the air was small.

As the ventilation rate increased, large quantities of external air were induced; thus, the speed of air flow was also increased. However, ventilation rates lower than 1.5 m/s created an unpleasant atmosphere for the occupants. In contrast, when the general air speed flowed between 0.25-1.50 m/s in the room, a pleasant feeling was created for the occupants because they could feel the flow of the air.
The performance of natural ventilation was evaluated with the height changes of the external window in the PAF type, which is a more effective opening method. In the basic model, the maximum height of the external window is 1,300 mm. Since the long width of the window is inefficient for ventilation, the minimum height of the exterior window is evaluated as 900 mm. 1,100 mm of the external window height was also evaluated. From the results, when the height of the external window was decreased from 1,300 mm to 1,100 mm, the amount of ventilation was decreased by 14% while when decreased to 900 mm, 8% of that of 1,100 mm appeared to further decrease. However, even in the case of the 900 mm height, a ventilation rate of more than 70 times per hour was possible; moreover, if an external window was installed the ventilation rate was sufficient even though the window was small.

Depending on the external window, planning of the inlet, outlet, and intermediate space differs. Without an external window, the buoyancy force needs to ventilate the indoor space, and the inlet, outlet and intermediate space should be considered during the planning stage. When an external window is applied, the inlet, outlet, and intermediate space are designed with consideration given to the cooling and heating load.

6. Conclusions

The parameters of the double-skin façade plan were selected while considering the natural ventilation performance of high-rise residential buildings. The ventilation rate and air flow distribution was then evaluated based on the parameters of the double-skin façade plan.

The results of the investigation show that the occupants of high-rise residential buildings demand the security of natural ventilation performance, the speed of air flow and the feeling of openness through the inducement of external air.

The areas in which priority of decision-making was necessary in terms of the architectural plan were the type of arrangement for the inlet and outlet, the module of the façade, the presence of the external window, the internal window and the opening ratio of the cavity floor. The evaluation parameters are derived according to decisions concerning the components.

Among the different domestic types of arrangement of the inlet and outlet in high-rise buildings, the diagonal type and parallel type are selected and evaluated. The opening area of the diagonal type significantly affected natural ventilation. The depth of the intermediate space in the diagonal type should be smaller than 2/3 that of the inlet and outlet area. In the parallel type, the intermediate space depth considerably affected the performance of natural ventilation. In the range of 300 mm to 600 mm, the increment of depth increased the circulation throughout the room as well as the ventilation rate.

When an external window is not applied in the double-skin façade, the single window needs to be constantly opened for natural ventilation, because the air velocity of the room is not fast enough. However, depending on the arrangement of the inlet and outlet, the ventilation rate is too low at 0° and 90°. The application of the external window increases the natural ventilation by at least 1.5 times and significantly affects the performance of natural ventilation.

This paper proposes a method for planning an envelope with improved ventilation in a simulation based on the wind direction and speed condition in high-rise residential buildings. In the future, additional research needs to be performed that considers the temperature, solar, wind speed, and wind direction which affect the ventilation by buoyancy and wind pressure. Data comparison through experiment and applicability in the field need to be conducted through further research.

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