The climatic potential for a double skin facade integrated with cross ventilation

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Abstract

When it comes to natural ventilation performance for large space cooling during summer time or intermediate seasons, double skin facade(DSF) integrated with cross ventilation(CV) exhibits more energy efficiency than single-side ventilated DSF. In this case, ventilation performance is remarkably affected by climatic conditions. Therefore, it is important to analyze micro climatic conditions before applying this passive technique.

To date, many studies have been done regarding DSF, however, there are very few studies pertaining to feasibility have existed in Korea. In this paper, a case study of four models with weather data of Seoul was conducted based on the following criteria: existence of DSF, opening/closing modes of the DSF openings, and ventilation types. The results showed that the annual cooling load of the cross-ventilated DSF was less than that of the single-side ventilated DSF by 7.9%, and the ACH of the cross-ventilated DSF was 1.2~6.2 times more than that of the single-side ventilated DSF.

Keywords: Cross-ventilation, Double skin facade, Stack effect, Natural ventilation, Airflow network

1. Introduction

1.1. Background and Purpose

Many architects and clients prefer to implement highly glazed facades for aesthetic reasons or to showcase the transparent image of enterprises(Oesterle et al., 2001). Buildings designed with glass facades exhibit less thermal resistance performance than those with insulated walls and introduce more solar radiation. Considering that office buildings have more occupants and equipments than other buildings, such design characteristics cause higher energy consumption for maintaining an indoor thermal comfort. The double skin facade (DSF) system, which was introduced as an alternative solution to these issues, has become rapidly popular in Europe because not only does it uphold the green image of buildings, it also allows natural ventilation in buildings and performs the role of a thermal buffer space in winter.

Compared to mechanical ventilation, natural ventilation is much harder to control. Therefore, an integrated analysis of the building plan and climatic condition is essential not only to increase energy efficiency but also to create a comfortable indoor environment. The most frequently implemented natural ventilation method used in the DSF system is single-sided ventilation, in which ventilation occurs between the cavity of the DSF and the adjacent indoor space. Single-side ventilated DSF affects only part of the rooms adjacent to the cavity, and yields minimal effect on buildings with deep plan buildings (Straube and Straaten, 2001). Also, the effective depth of external air in single-sided ventilation is limited to 8 m from the opening, at an air velocity of 1 m/s (Gan, 2000). As a result, the effect of natural ventilation in DSF implemented large buildings can be maximized by combining cross-ventilation(CV).

The airflow behavior of single side ventilated DSF is governed mainly by the stack effect caused by the temperature difference. However, the airflow behavior of cross ventilated DSF coupledly depends on stack effect due to solar radiation, wind direction and speed, and operational mode of the upper and lower openings. It has been generally accepted that the ventilation performance is affected largely by the climatic characteristics. Therefore, good DSF design and its performance can be expected only after a thorough analysis of the climatic characteristics of the surroundings.

There have been many DSF studies mainly focusing on the thermal and airflow behavior based on the opening and shading operation modes and the possibility of a load reduction. Most of the studies are on single-sided ventilation and associated with European weather conditions ignoring the humidity effect. However, the humidity must be considered particularly in hot and humid climates such as the summer time in Korea, ventilation performance completely changes from what was considered in previous studies. There have been few studies on the possibility of DSF integrated with CV.

Therefore, this study aims to examine the ventilation performance of DSF combined with CV and its applicability by conducting ventilation performance and building load analysis using a dynamic building energy simulation tool.

1.2. Methodology and procedure

This research was conducted using the following procedure:

(1) Analysis of the factors in the performance of natural ventilation using hourly weather data of Seoul;

(2) Establishment of four models based on the existence of DSF, the opening operational modes in DSF, and the ventilation types;

(3) Simulation of each model based on the weather data analyzed in (1); and

(4) Comparative analysis of the cooling load, ventilation performance, and direction of the airflow for each model.

2. Simulation Tool and Calculation Method

2.1. Airflow network method

Airflow network method evaluates the airflow in a building by assuming airflow as a network of nodes and simplifying the linkage to which airflow passes from one to another node. In the calculation process, the law of conservation of mass is applied to the airflow caused by the pressure difference. While this method can only give quantitative information of airflow and can not offer detailed information of internal air circulation or temperature distribution like CFD, it offers fast evaluation speed.

This study used Airflow Network of EnergyPlus 4.0 for evaluating ventilation performance and applicability of a target model.

2.2. Calculation method

In the airflow network model, each path consists of two nodes, each of which has an inlet and an outlet. Each path is linked by components (i.e., the opening and HVAC system, etc.) that correspond to the airflow and the pressure. If n and m are two continuous nodes, and assuming that the pressure difference between components is governed by Bernoulli's equation, pressure difference can be expressed as below:

$$\Delta P = \left(P_n + \frac{\rho v_n^2}{2}\right) - \left(P_m + \frac{\rho v_m^2}{2}\right) + \rho g(z_n - z_m) \quad \text{(Eq.1)}$$

where,

ΔP: The pressure difference between nodes n and m [Pa]

$P_{n,\ m}$: The pressure at nodes n and m [Pa]

ρ: The air density [kg/m^3]

$v_{n,\ m}$: The air velocity at nodes n and m [m/s]

g: The gravity acceleration [Pa]

$z_{n,\ m}$: The height at nodes n and m [m]

If each term is rearranged and the effect of the wind pressure is added, Eq. 1 can be expressed as in the following airflow network model:

$$\Delta P = P_n - P_m + P_s + P_w \quad \text{(Eq.2)}$$

where,

P_s: The pressure difference due to the difference of density and height [Pa]

P_w: The pressure difference due to the wind [Pa]

Fig. 1 shows the flowchart of factors that influence airflow distribution in buildings. More detailed calculation algorithm of many components can be found in the COMIS Fundamental Manual (1990) which was the basis of the airflow network implemented in EnergyPlus.

3. Weather Data Analysis

Wind speed and wind direction are important environmental factors in implementing DSF combined with CV. These variables directly affect the wind pressure coefficient of the external surface of a building and must be analyzed before implementing this type of natural ventilation.

The hourly weather data of Seoul used in this study is generated by using the ISO Test Reference Year (TRY) method. This data is based on 20 years data (1985-2005) from the Korea Meteorological Administration (KMA).

Figs. 2 shows the relative frequency of the wind speed and Fig. 3 shows the monthly average wind speed from April to October, when natural ventilation is used. The wind speed of 1-3 m/s occurs most frequently, and the total average wind speed in this period is 2.18 m/s. It is generally believed that wind direction in Korea is northwester in winter due to the Siberian air mass, and the oceanic southeaster in summer. Analysis of the climatic data used in this study, however, and Yoon's study (2003) on the climatic data collected by the KMA for the 30 years, showed a different result. Fig. 4 shows the relative frequency of each wind direction. The figure shows that the northward wind distribution is relatively more frequent than southward. In natural ventilation that combines DSF and cross-ventilation, most of the DSF is fixed southward to address the stack effect. Therefore, cross-ventilation that introduces outdoor air from the north and exhausts indoor heat to the southward DSF is an effective energy conservation strategy.

4. Simulation

4.1. Simulation model

As shown in Fig. 5, two simulation models were made depending on the existence of DSF. The DSF model in Fig. 5 (a) is again divided into three cases based on the operation mode of the DSF's lower openings and the types of ventilation, as shown in Fig. 6. Table 1 shows the summary of the four cases. Case 1~3 correspond to the model in Fig. 5 (a), and Case 4, to the

model in Fig. 5 (b).

The basic information on the target models is in Table 2. Except for the existence of the DSF space, all the models have identical conditions. All the detailed size and structure of model (a) is in Fig. 7. Case 4, in which no DSF was implemented, used ventilation through all the windows, except for the southward curtain-wall facade. The blinds were installed 0.5 m apart from the outer layer of the DSF in Case 1~3, and inside the southward façade in Case 4. The blinds were set to operate under the intensity of solar-radiation over 200 W/m2. It is assumed that the existence of the blinds did not affect airflow in the building.

The thermal characteristics of building envelope, internal heat gain, and HVAC operational conditions are shown in Tables 3, 4, and 5, respectively.

4.2. Control scheme of the opening

Humidity is relatively low in spring and fall in Korea, and does not significantly affect the indoor thermal comfort. However, this can be an important factor in summer. Thus, it is appropriate to apply the enthalpy control scheme, rather than temperature control, to the opening and closing of windows for natural ventilation.

In this study, windows were set to be open, as shown in Fig. 8, when the indoor enthalpy (H_{in}) is higher than the outdoor enthalpy (H_{out}). The windows are fully open at the point of the enthalpy difference between outdoor and indoor (ΔH) is the smallest, and the opening rate decreases proportionally until the ΔH reaches the maximum of 42,000 J/Kg. Regardless of this control scheme, however, the openings of the upper and lower DSF were set to be always open at its maximum from April to October. All the openings are closed during the rest of time period.

5. Results

5.1. Load analysis

Fig. 9 shows the annual cooling loads of the four cases by floor. In all the cases, the profile of the cooling load tends to increase as the floor gets higher. The annual cooling load increased from Case 1 through Case 4 in order.

While the annual total cooling load in Case 1 showed a better result than Case 2, such result is not always the case, as shown in the monthly cooling load in Fig. 10. The cooling load of Case 1 in April and May is less than Case 2, but from June to October, Case 2 exhibits less than Case 1. Case 2, with both the upper and lower openings open, has more airflow rate of cavity zone, and the resulting decrease in the surface temperature in the inner layer of the DSF is believed to have led to the decrease in the cooling load.

The annual cooling loads in Case 1 and 2, in which cross-ventilation was implemented, were less by 7.9% and 5.5%, respectively, than that in Case 3, in which single-sided ventilation was implemented. Cases 1 to 3, in which DSF was applied, showed a decrease in their annual cooling load of as little as 29.4% (Case 3) and as much as 34.9% (Case 1) compared to Case 4, in which the facade was a curtain-wall.

5.2. Analysis of the air change rate (ACH)

Figs. 11 and 12 show the monthly average ACH of the conditioned zone of Cases 1 to 4 between April and October, and the monthly average ACH in the DSF zone in Cases 1 to 3, respectively.

Cases 1, 2, and 4, in which cross-ventilation was implemented, showed a ACH in the conditioned zone that was 1.2 (Case 2 in April) to 6.2 (Case 1 in June) times higher than that in Case 3, in which single-sided ventilation was used. The total average ACH from April to October, when natural ventilation can be used, was highest in

Case 1, followed by Cases 2 and 4, each of which showed an average ACH 4.7, 4.2, and 3.7 times higher than that in Case 3, respectively. The ventilation performance was highest in June, and relatively smaller in April and October than in the other months due to the huge difference between the indoor and outdoor enthalpies. The outcome will differ if the ventilation is made without implementing the opening control strategy.

The ACH of the DSF zone was reversed to the amount of ventilation in the conditioned zone. Case 1, with the lower opening closed, showed a lower result than Cases 2 and 3, with both the upper and lower openings open. Such result was also shown in the profile. While the ACH in Case 1 was identical to the profile in Fig. 11, which is the monthly ACH of the conditioned zone. However, the ACH in Cases 2 and 3 were affected by the external wind speed and direction, as analyzed in Figs. 3 and 4, regardless of the ACH profile of the conditioned zone. In other words, the ACH in Case 1 was affected by the opening control strategy based on the temperature and humidity, whereas that in Cases 2 and 3 was affected by the wind speed and direction.

Fig. 13 shows the average ACH in June by floor. The ACH in Cases 1, 2, and 4, with cross-ventilation, exhibited superior ventilation performance compared to that in Case 3, with single-sided ventilation.

The comparison of Cases 1 and 2 showed that the amount of ventilation in Case 1, with the lower DSF opening closed, was larger than that in Case 2. This was due to the air inside the DSF staying longer in Case 1 than in Case 2, thus causing more stack effect. In Cases 1, 2, and 4 with DSF, the stack effect decreased as with the higher stories, and therefore, the amount of ventilation also decreased. In Case 4 without DSF, however, the amount of ventilation increased as with the higher stories, and this is congruent with the wind speed profile of external boundary.

5.3. Airflow analysis

Fig. 14 shows the airflow between the DSF cavity and the indoor (airflow across the openings of inner layer of DSF), and between the indoor and the outdoor (summation of airflow across the openings of the eastward, westward and northward directions.) A sunny day of June 2nd was selected for this graph.

In the lower floors, the airflow from outdoor to indoor to the cavity is predominant. This is the positive airflow, taking indoor heat into the cavity zone and discharge into the upper opening of DSF. Through this process, the building's cooling load can be reduced. However, as the floor gets higher, the air of DSF cavity flows back to the indoor space (Cavity->Indoor->Outdoor) because of the weakened stack effect. Especially on the fifth and sixth floors, the flow from the cavity to the indoor overwhelms the flow from indoor to cavity. This means the high-temperature air in the DSF cavity reflux to the conditioned zone. This phenomenon is affected not only by height but also by the difference between indoor and outdoor temperature. The air that flows back not only raises the indoor cooling load but also degrades the indoor thermal comfort.

Fig. 15 shows the relative cooling load increase rate of each floor compare to second floor from April to October. In Case 4 without DSF, the cooling load increase rate profile is not as steep as the other cases, whereas the cooling load increase rate in Cases 1 to 3 with DSF increased by a large margin especially fifth and sixth floors. The airflow in the cavity which flows back to indoor is the main reason for the increase of cooling load and this can be a critical factor in the thermal comfort and indoor load. Therefore, it is necessary to conduct research on an appropriate opening control strategy or DSF cavity zoning.

6. Conclusion

This case study of four models with weather data of Seoul was performed based on DSF existence, operational mode of DSF's upper and lower openings, and ventilation types. The conclusions were made as the following.

(1) In large office buildings with DSF, it is more beneficial to implement cross-ventilation than single-sided ventilation for reducing the cooling load.

(2) In natural ventilation combining DSF and cross-ventilation, only the DSF's upper opening exhibited better results than both the DSF's upper and lower openings in terms of the annual cooling load and ACH of the conditioned zone. It is more beneficial, however, to open both the upper and lower openings for the cooling load during summer when there is strong solar radiation.

(3) In multi-story DSFs, the decrease in stack effect on a higher floor not only reduces the amount of ventilation but also increases the cooling load. To prevent this phenomenon, appropriate cavity zoning or a control strategy that reflects the changing environment condition is needed.

Acknowledgments

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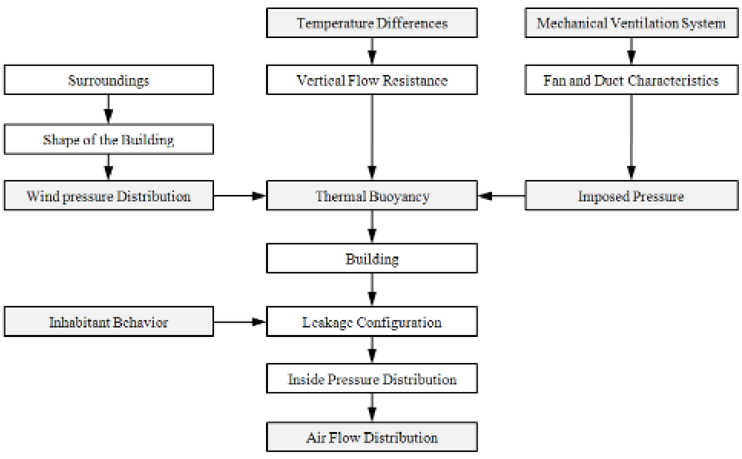


Fig. 1 Influences on the Air-Flow Distribution in Buildings (Feustel 1990)

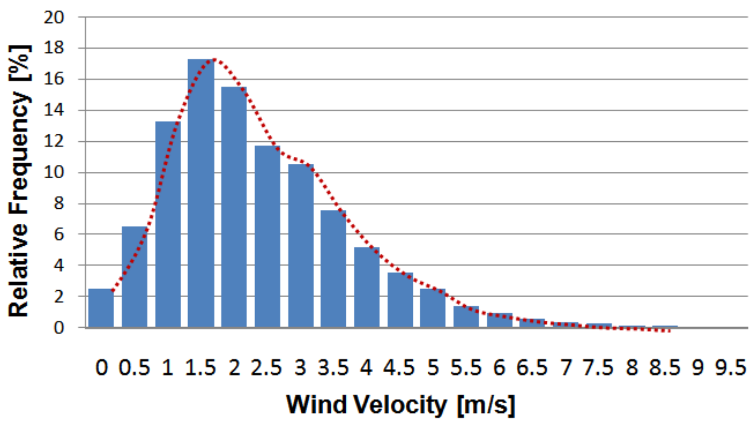


Fig. 2 Relative frequency of wind speed

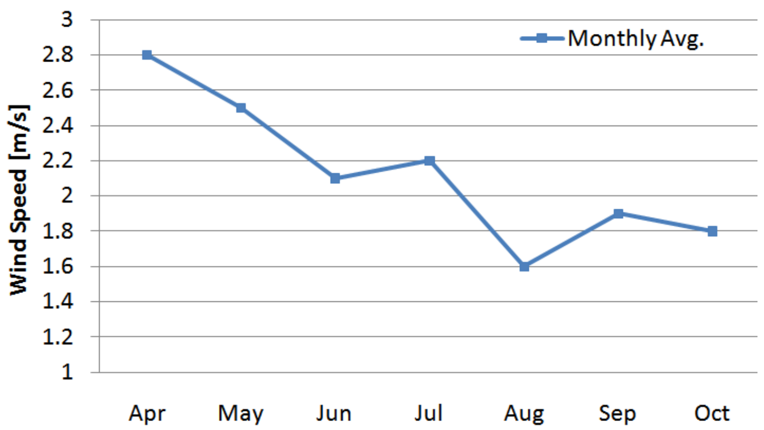


Fig. 3 Monthly average wind speed

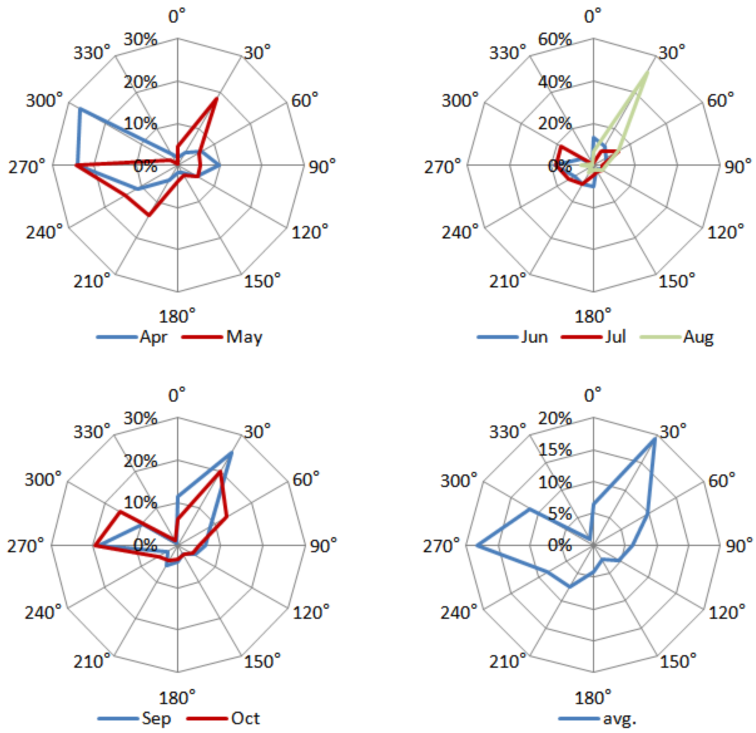
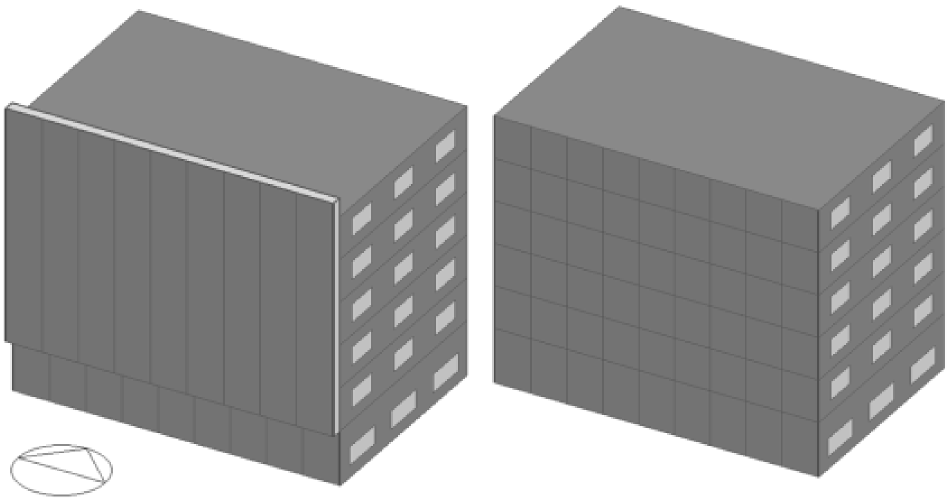


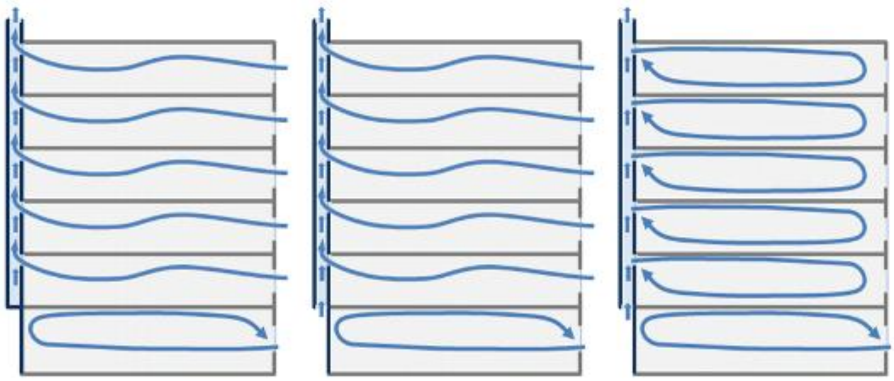
Fig. 4 Relative frequency of wind direction



(a) DSF model

(b) Curtain-wall model

Fig. 5 Simulation model



(a) Case 1 (b) Case 2 (c) Case 3

Fig. 6 Conceptual charts of the ventilation types by case

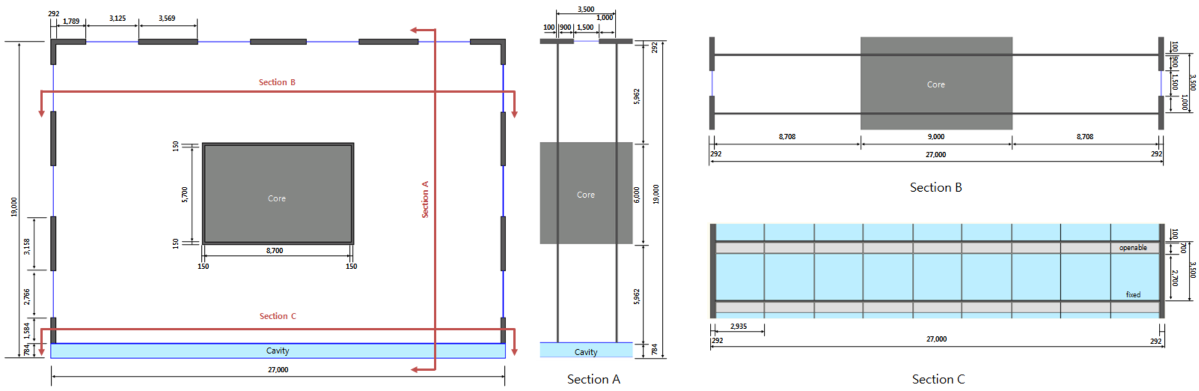


Fig. 7 Floor plan and cross sections

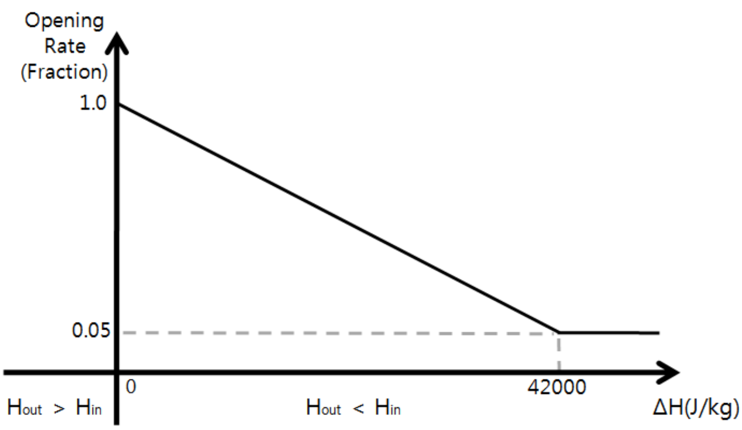


Fig. 8 Opening control strategy

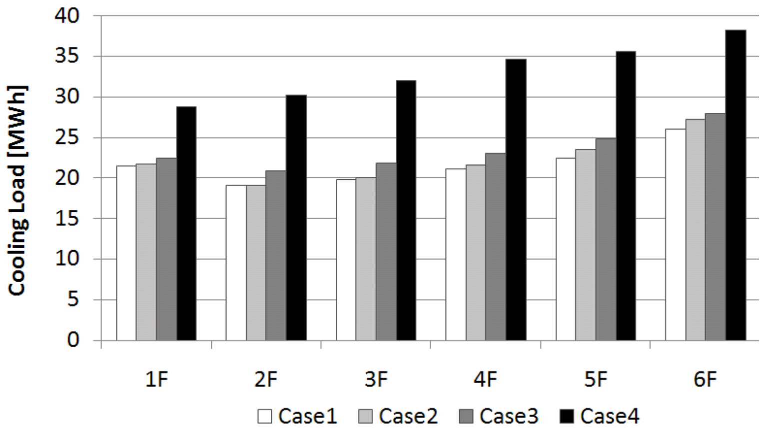


Fig. 9 Annual cooling load by floor

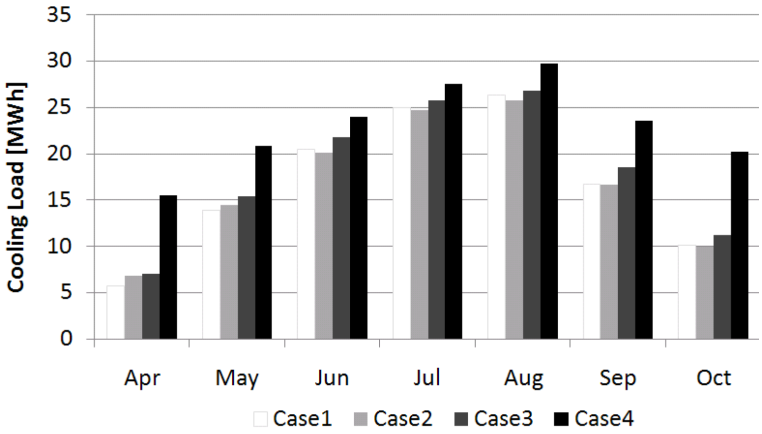


Fig. 10 Monthly cooling load

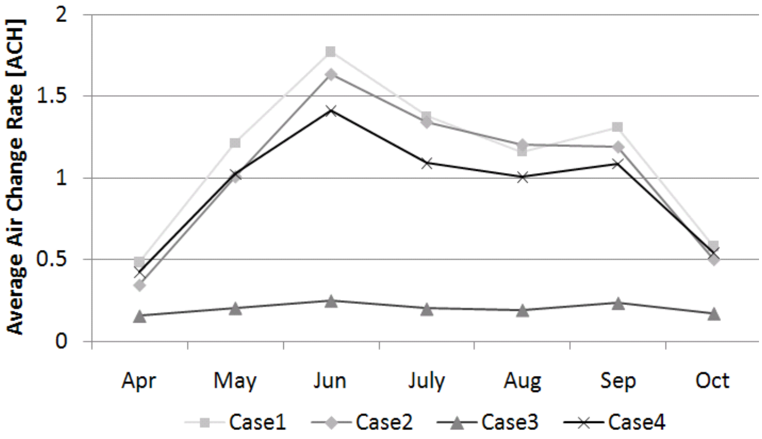


Fig. 11 Monthly average ACH in the conditioned zone

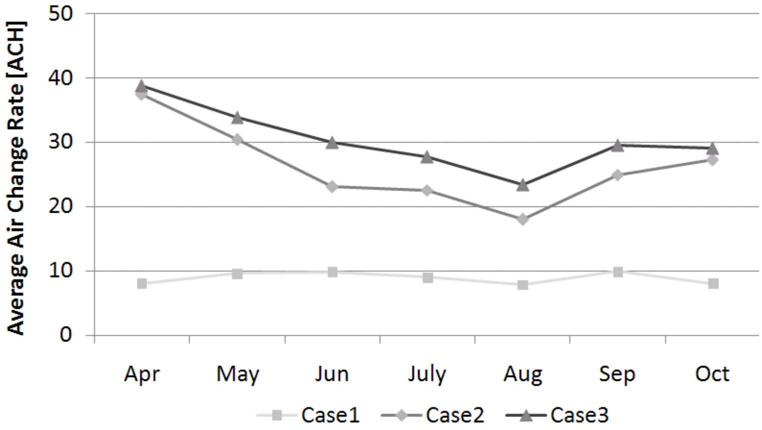


Fig. 12 Monthly average ACH in the DSF zone

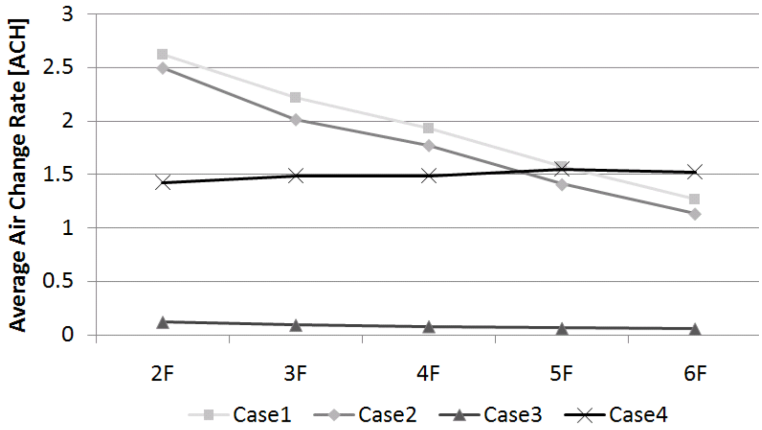


Fig. 13 Average ACH in June by floor

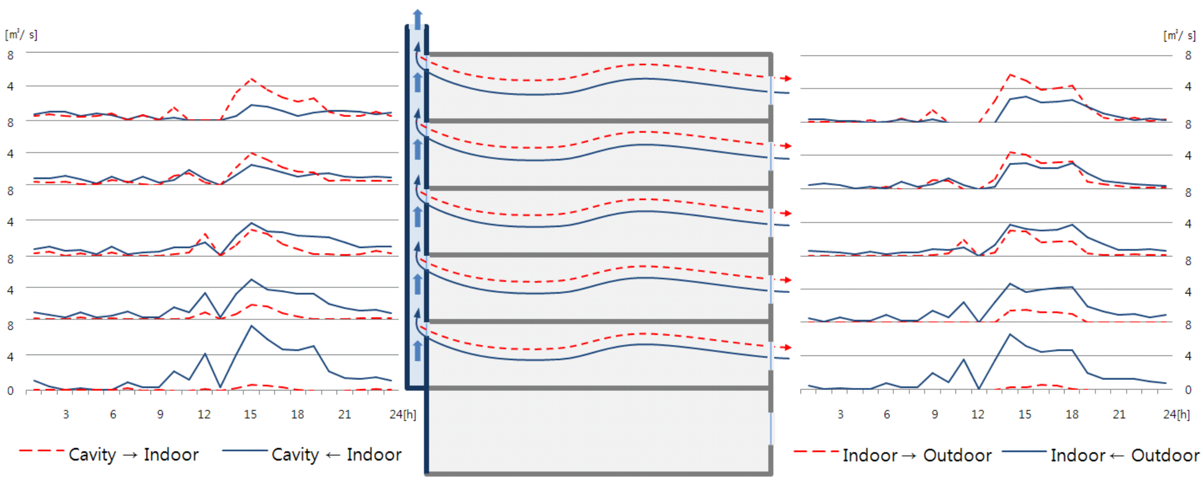


Fig. 14 Airflow between the cavity and the indoor(Left), the indoor and the outdoor(Right)

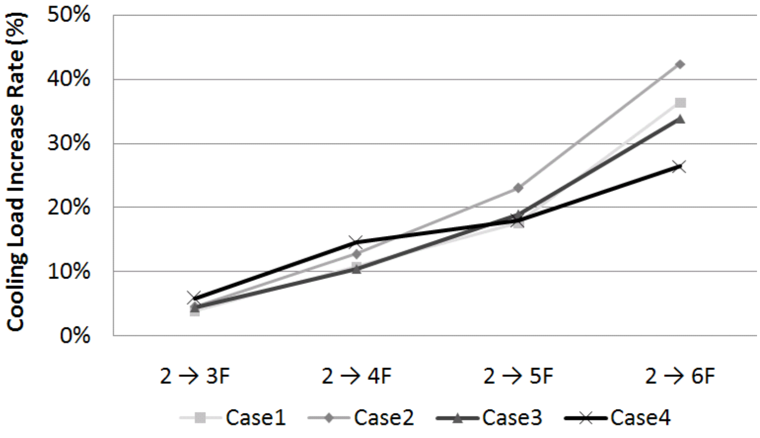


Fig. 15 Cooling load increase rate compare to second floor

Table 1 Simulation cases

Case	DSF	DSF Opening Status	Venting Type
Case1	○	Upper Only	Cross
Case2	○	Upper and Lower Opened	Cross
Case3	○	Upper and Lower Opened	Single
Case4	×	-	Cross

Table 2 Basic information on the model

Stories	6F
Height	22 m+1.5 m(DSF)
Total Building Area	2898.93 ㎡
Net Conditioned Area	2548.78 ㎡
Width of the Air Cavity	784 mm

Table 3 Thermal properties of the simulation model

Component		Thickness (mm)	SHGC	U-Value (W/㎡·k)	Solar Transmittance	Solar Reflectance
Roof Ground Floor		350	-	0.25	-	-
Exterior Wall		292	-	0.35	-	-
DSF	Outer	6-(Clear)	0.810	6.121	0.775	0.071
DSF	Inner	6-(Low-e) 13-(Air) 6-(Clear)	0.563	1.772	0.474	0.17 - 0.071
Outer window		6-(Low-e) 13-(Argon) 6-(Clear)	0.564	1.499	0.474	0.17 - 0.071
Blind		1	0.9*		0.3	0.3

*Thermal Conductivity (W/m·k)

Table 4 Indoor heat gain

People	10W/㎡	Based on ASHRAE Fundamentals (2009)
Equipment	10.76W/㎡	
Lighting	11W/㎡	

Table 5 HVAC operation

	Summer	Winter
Set Point Temperature	26℃	21℃
Period	Apr～Oct	Nov～Mar
Operation Time	08:00～18:00	