Ventilation Rate and Thermal Environment Properties of Double Skin Façade Considering Wind Profile and Direction

Geum-Hee Kim¹, Hyuk-Min Kwon² and Jeong-Hoon Yang*³

¹ Master’s Student, Graduate School, Yeungnam University, Korea
² Doctor’s Student, Graduate School, Yeungnam University, Korea
³ Professor, School of Architecture, Yeungnam University, Korea

Abstract

This study analyzes the impact of a windy environment on the ventilation rate and the thermal environment of a double skin façade (DSF). The wind profile was used to change the direction of the wind to the front, back, and side directions. Three cases were examined using computational fluid dynamics (CFD) analysis. There were two openings on the front of the DSF in Case 1, openings on the lower and front parts of the DSF in Case 2, and two openings on the front of the DSF for each story in Case 3. The results are as follows. 1) The front wind direction interrupted the release of the cavity’s interior air, and the ventilation rate decreased by an average of 47.6% in comparison to the results with wind from the side and back directions. 2) The ventilation rate was highest for the back direction in Cases 1 and 3 and for the side direction in Case 2. The ventilation rate of Case 3 was the lowest. 3) The total heat transfer rate of the highest story of the DSF was inversely proportional to the ventilation rate.

Keywords: double skin façade; cavity; ventilation rate; wind profile; CFD

1. Introduction

International regulations are being tightened to prevent environmental pollution and save energy, and double skin façades (DSFs) are gaining attention as an environmentally friendly passive technology. A DSF consists of a transparent skin and a thick cavity. The skin of the DSF can reduce energy loss and regulate the impact of solar radiation through blinds. It also allows natural ventilation in high wind pressures at high stories and is also advantageous for soundproofing.¹² However, a greenhouse effect may occur in a DSF during summer or in dry and hot climates. Thus, the thermal environment may eventually deteriorate from solar radiation into the cavity.³⁴ Nevertheless, appropriate openings and awning plans with optimized design of the cavity can help to address this issue.³⁵ The ventilation of the cavity and the cooling functions are critical for the DSF. Many studies have examined this issue. Sung et al.⁵ proposed a solar chimney channel (SCC) to activate airflow in the cavity of a DSF and provided data to reduce the cooling load in the summertime. Barbosa et al.⁶ proposed a DSF design option to maximize the comfort of a residential area by evaluating the key design parameters of a DSF. Zhen et al.⁸ simulated the natural ventilation of a DSF interior with venetian blinds installed through a computational fluid dynamics (CFD) analysis method using a porous media model.

The majority of previous studies did not take into account the direction of the wind when simulating the wind environment of a building’s surroundings and instead applied a uniform wind speed.⁶⁻⁸ However, some studies did consider the impact of solar radiation or the radiation heat transfer of the cavity or interior.⁸⁻⁹ The wind direction, wind speed, and solar radiation have significant effects on the ventilation rate and the thermal environment of the cavity. Therefore, this study comprehensively applied the wind direction, wind profile, solar radiation, and radiation heat transfer in order to conduct a more detailed analysis of the ventilation and cooling function of a DSF during the summertime. The results could be used as basic data when designing a DSF.

A virtual commercial building was designed according to the "Energy Conservation Design Conditions for Buildings" proposed by Korea’s Ministry of Land, Infrastructure, and Transport. The design conditions for target buildings are shown in Table 1. The study results from Lopez et al.¹² and ASHRAE¹¹ were used as references for the properties of the component materials. Three cases were used to identify the functional changes according to the placement of the openings of the double skin.¹³⁻¹⁶ A case without DSF was also analyzed for comparison. CFD was used to compare the temperature conditions.
2. Concept and Function of the DFS

A general DSF comprises inner and outer skins of glass with low thermal resistance. The DSF was designed to have strong insulation properties based on the air space, which has significant heat transfer resistance and reduces the heat transmission coefficient (U-value) of the whole skin. Openings were created in the inner and outer skins to allow natural ventilation. \(^1\)

The heat transfer and airflow of the DSF are shown in Fig. 1. \(^6\) The solar radiation that penetrates the skin is a significant heat source for the DSF. The inner airflow of the DSF is affected by the stack effect, which is mainly caused by solar radiation and the wind environment around the building. The external air that flows in through the building’s openings penetrates the residential area and is heated by solar radiation and heat transfer. In addition, the inner and outer skins of the DSF are heated by solar radiation and increase the air temperature within the cavity. As a result, pressure is generated within the cavity due to buoyancy, as shown in equation (1). The heated air moves to the upper region of the cavity and is released externally as thermal energy according to equation (2). The release of air decreases the pressure within the cavity, and airflow is generated into adjacent spaces. \(^3\)

\[
\Delta P_{th} = \Delta \rho \times g \times \Delta h \times \Delta t_m \quad (1)
\]

\[
Q_{conv} = \rho \times C \times v \times \Delta t \quad (2)
\]

\[
Q_v = C_D A \sqrt{\frac{2g \Delta h \Delta t}{t_i}} \quad (3)
\]

\[
Q_v = C_D A \sqrt{\frac{\Delta C_p \times v^2}{2}} \quad (4)
\]

Equation (3) demonstrates that the airflow circulation due to the stack effect is affected by key variables such as the height of the building, the area and location of the openings, and the temperature difference within and outside of the cavity. Equation (4) indicates that the direction of the wind has an impact on the rate of ventilation through the openings.

CFD was used to analyze the airflow circulation and thermal environment of the DSF. It assumed that the spaces adjacent to the DSF were completely airtight and that there was no air circulation between the DSF and adjacent spaces.

3. CFD Benchmark Test

A verification was carried out based on guidelines from the Architectural Institute of Japan (AIJ). \(^{14-15}\) The guidelines are based on the results of a wind tunnel test (WTT). The size of the computational domain for CFD is 20.5b \((x) \times 13.75b \((z) \times 11.25b \((y)\), where b is 0.08 m. The building dimensions are 2b (height) \times 1b (width) \times 1b (depth). For the CFD benchmark test, three turbulence models were used for the analysis: Realizable k-ε, RNG k-ε, and SST k-ω. WTT data were used for the airflow conditions of the velocity inlet. Other details are available from the AIJ guidebook. \(^{14-15}\)

The wind speed measurement points are shown in Fig. 2. Based on the building, five lines were established.

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Table 1. Target Buildings and Design Conditions According to Energy Conservation Design Conditions

| Target building | Components | Material | \(\delta_{\text{thermal}}\) | \(\rho\) | \(C_p\) | \(\lambda\) | \(R\) | \(U_{\text{eq}}\) |
|-----------------|------------|----------|----------------|------|------|-----|-----|-------|
| Exterior wall   | Insulation | 130      | 43             | 1210 | 0.03 |     |     | 4.55  |
|                 | Concrete   | 180      | 2240           | 900  | 1.95 |     |     | 4.61  |
|                 | Gypsum board | 20      | 800            | 1090 | 0.16 |     |     | 0.26  |
|                 |            | 330      |                 |     |     |     |     |       |
| Roof            | Insulation | 220      | 43             | 1210 | 0.03 |     |     | 7.55  |
|                 | Concrete   | 180      | 2240           | 900  | 1.95 |     |     | 7.55  |
|                 | Gypsum board | 20      | 800            | 1090 | 0.16 |     |     | 0.15  |
|                 |            | 420      |                 |     |     |     |     |       |
| Bottom floor    | Insulation | 130      | 43             | 1210 | 0.03 |     |     | 4.55  |
|                 | Concrete   | 180      | 2240           | 900  | 1.95 |     |     | 4.55  |
|                 | Gypsum board | 20      | 800            | 1090 | 0.16 |     |     | 0.26  |
|                 |            | 330      |                 |     |     |     |     |       |
| Floor           | Concrete   | 180      | 2240           | 900  | 1.95 |     |     | 0.217 |
|                 | Gypsum board | 20      | 800            | 1090 | 0.16 |     |     | 4.61  |
|                 |            | 200      |                 |     |     |     |     |       |
| Interior & Exterior Facade | Single glass | 15 | 2220 | 830 | 1.03 |     |     | -     |
and 10 measurement points were designated along the height of the building. The difference between the X-directional WTT result was greatest among the X-, Y-, and Z-directional wind speeds in all the turbulence models. Thus, the X-directional wind speeds (U) of the WTT and CFD results with respect to lines 1 to 3 are given in Fig.3(a). For line 1 at the front of the building, all three turbulent flow models appeared to be similar to the WTT data, while for lines 2 and 3, turbulence was generated at the back of the building. The difference in wind speed increased with the horizontal distance from the building. In contrast, the difference decreased as the vertical distance from the building increased, and the influence of the turbulence was reduced.

Fig.3(b) shows the wind speed ratios of the WTT and CFD results with respect to each wind speed measurement point. The maximum inflow wind speed in the WTT was 6.75 m/s. The diagonal dotted line in the graph represents 30% deviation of the wind speed ratio. Stathopoulos et al. reported there was generally a 30% deviation in the CFD analysis regarding the wind environment of a building. This occurs because of the significant number of uncertain variables involved in the mathematical modeling of turbulent winds. In the present study, 30% deviation was included in the measured values when using the Realizable k-ε turbulence model. The Realizable k-ε turbulence model was thus the most accurate and used to investigate the impact of the wind environment of the DSF.

4. Outline of CFD Analysis of the DSF System

4.1 Target Cases for Analysis

The performance of the DSF is affected by the various design parameters. The most typical DSF analysis case was therefore selected after investigating previous studies and applications. Fig.4. is a schematization of the target case. Cases 1 and 2 are multistory DSFs with the same height and volume of the cavity. The DSF of Case 1 has two openings at the front, but that of Case 2 has openings at the bottom and the front.

The DSF of Case 3 has the form of a corridor, in which the DSF space is separated for each individual story. There are two openings on each floor of the DSF. The openings provide inflow or outflow according to the wind environment. The area of the openings of Cases 1 and 2 is 2 m × 0.3 m (width × length). The area of the openings in Case 3 is 2 m × 0.1 m, and the total area of all openings is the same as those of Cases 1 and 2.

Studies by Joe et al. and Torres et al. were used as references for the cavity depth. Both studies reported that the annual cooling load and total energy consumption were lower for a narrow cavity.
A cavity depth of 0.4 m generates the lowest cooling load in the summertime and was therefore selected for this study.

### 4.2 Computational Domain

Actual buildings are half-closed spaces with infiltration ventilation. However, this study analyzed the impact of adjacent spaces according to the type of DSF. Therefore, the computational domain aside from the DSF was designed as a completely closed space without any infiltration ventilation. The size of the computational domain was that proposed by the AIJ guidebook.\(^{14-15}\) The CFD analysis space is shown in Fig.5. The outer surface of the domain was symmetrical except for the velocity inlet and outflow region.

The analysis grids of the analysis space were created by combining hexahedral and cut-cell meshes.\(^{20-21}\) The components of the building and the DSF were created as meshed walls using cut-cell meshes (see Fig.6.). The surroundings of the building and the DSF were also created with cut-cell meshes, whereas the other spaces were created using hexahedral meshes. The meshes have a minimum size of 4.5e\(^{-2}\) m and a maximum size of 1.44 m, and their growth rate is 1.2. The number of analysis grids is about 1.4 million.

### 4.3 CFD Boundary Conditions

The commercial code ANSYS FLUENT 17.1 was used for the CFD analysis. The Realizable k-ε model was chosen as the turbulence model, which demonstrated the highest accuracy in the benchmark test. Wind from the front, back, and side directions of the DSF was investigated. The wind speed was set as 2.5 m/s at 10 m based on 10 years of weather data from 2001 to 2010, which were aggregated by the Korea Meteorological Administration.\(^{22}\) The wind profile was obtained by the exponential law stated in the Korea Building Code 2014. An \(\alpha\) value of 0.33 was applied for the ground surface roughness. A second-order upwind scheme was used with the Coupled algorithm. This pressure-based coupled algorithm enables full pressure-velocity coupling in ANSYS Fluent.\(^{23}\) It is advantageous to use coupled algorithms when analyzing heat transfer, heat radiation, and solar radiation at the same time. The standard wall function was used in the near-wall treatment of all the walls.

Convection and radiation due to solar radiation and the external temperature were included in the analysis. The discrete ordinates (DO) model was used for the radiation analysis, and solar ray tracing was used for solar radiation. The target region was Seoul, and the solar radiation of summertime at noon (12 pm, August 14\(^{th}\)) was applied. This time is when the greenhouse effect of the DSF is most intense. The external temperature was set at 303.1K, which is the average temperature on August 14\(^{th}\) according to the Korea Meteorological Administration.\(^{22}\)

The components of the building and the DSF were created as meshed walls and consist of solid materials and walls. The boundary conditions for each solid material were set to be "interior." The properties of the solid materials are shown in Table 1., and the boundary conditions for the walls are given in Table 2.
Table 2. Boundary Conditions

| Object          | Condition                                                                 |
|-----------------|---------------------------------------------------------------------------|
| Solar load      | • Sun direction vector : X 0.386, Y 0.909, Z -0.155                       |
|                 | • Direct normal solar irradiation (W/m²) : 882.183                       |
|                 | • Ground reflected solar irradiation (W/m²) : 91.268<sup>(a)</sup>        |
|                 | • Diffuse solar irradiation (W/m²) : 86.774<sup>(a)</sup>, 110.415<sup>(b)</sup> |
| Velocity inlet  | • Wind profile (m/s) : \( v = v_0 \left( \frac{Z}{Z_0} \right)^{0.23} \)   |
|                 | • Temperature (K) : 303.1                                                |
| Concrete wall   | • Thermal conditions : Mixed                                             |
|                 | • Temperature (K) : 303.1                                                |
|                 | • Radiation emissivity : 0.91                                            |
|                 | • Diffuse fraction : 1                                                   |
|                 | • BC type : Opaque                                                      |
|                 | • Heat transfer coefficient (W/mK) : 0.22                               |
|                 | • Solar absorptivity : 0.6                                               |
| Gypsum wall     | • Thermal conditions : Coupled                                           |
|                 | • Radiation emissivity : 0.91                                            |
|                 | • Diffuse fraction : 1                                                   |
|                 | • BC type : Opaque                                                      |
|                 | • Solar absorptivity : 0.6                                               |
| Glass wall      | • Thermal conditions : Coupled                                           |
|                 | • Radiation emissivity : 0.88                                            |
|                 | • Diffuse fraction : 0.5                                                 |
|                 | • BC type : semi-transparent                                            |
|                 | • Absorption coefficient (m<sup>-1</sup>) : 300<sup>(c)</sup>, 450<sup>(d)</sup> |
|                 | • Solar absorptivity : 0.15                                              |
|                 | • Solar transmissivity : 0.75                                            |

<sup>(a)</sup>vertical surface, <sup>(b)</sup>horizontal surface, <sup>(c)</sup>visible band, <sup>(d)</sup>infrared band

ASHRAE handbook<sup>(1)</sup> was used as a reference for the physical properties. Building insulation was created with only solid materials because the concrete and the gypsum boards share the wall boundary conditions.

The ground was set as concrete. For the wind profile, the wind speed at the horizontal ground surface was 0 m/s. An arbitrary value was also used for the heat transfer coefficient of the ground.

5. CFD Analysis Results

5.1 Airflow and Wind Pressure Distribution

The airflow and wind pressure distribution of each case with different wind directions are as shown in Table 3. The airflow circulation from within the cavity was expected to be most active with the front wind direction. However, due to the wind profile, the applied wind speed increased along the building's height, and high wind pressure was generated at the openings of the upper part of the building. As a result, the release and circulation of the air within the cavity was noticeably reduced. With the front wind direction in Case 1, the average wind speeds at the upper and lower parts of the opening were 2.71 m/s and 1.83 m/s, respectively (a difference of approximately 0.88 m/s).

With the side wind direction, the direction of the cavity's released airflow and the airflow around the building were identical, and the airflow circulation was therefore active. In the case of the back direction, the inflow of air at the lower part of the opening was active due to the turbulence generated at the outer skin of the DSF. However, external air partially flowed into the cavity through the upper opening for all cases with the back wind direction, which caused air circulation within the cavity.

The wind pressure distribution of the building's outer skin was analyzed for each case. In Case 2, where the opening was located in the lower part, there was lower wind pressure for all wind directions in comparison to Case 1. With the front direction, the wind pressure of the lower opening was an average of 35.4% lower than that of Case 1. This was due to the building's protruding DSF, which caused the wind speed to be low around the lower opening in Case 2.

In comparison to Cases 1 and 2, Case 3 revealed a lower difference in the wind pressure since the openings of each story did not differ much in height. Although the total area of the openings in Case 3 was the same as in other cases, the area of the individual openings at each story was 1/3 smaller than that of the other cases. Therefore, Case 3 did not show much air circulation compared to the other cases.

5.2 DSF Ventilation Rate and Interior Temperature of the Cavity

Fig. 7 shows the DSF's ventilation rate and the cavity's internal temperature for the different directions. The bars in the graph indicate the internal temperature of the cavity, and the lines indicate its ventilation rate. C3-2, C3-3, and C3-4 of the graph's horizontal axis indicate the 2<sup>nd</sup> story to the 4<sup>th</sup> story in Case 3.

In Case 3, the ventilation rate of the cavity increased along the height of the building. The ventilation rate for the front wind direction was lower by an average of 47.6% compared to that of the side and back directions. The decrease of the ventilation rate was the greatest in Case 1 at approximately 74.0%. The ventilation rates for the back wind direction were 1.52 and 0.2 kg/s for Case 1 and Case 3, respectively, which was the highest compared to the other wind directions. In Case 2, the ventilation rate was 1.3 kg/s for the side wind direction, which was highest compared to the other wind directions.

The DSF of Case 3 was in the form of a corridor, which caused the height of the cavity to be low, and the temperature difference between the upper and lower regions of the cavity was also low. In addition, the ventilation rate was lowest in Case 3 compared to the other cases due to the small area of the opening.

The ventilation rate and the internal temperature of the cavity were inversely proportional. When the front wind direction was applied and the ventilation rate was at its lowest, the internal temperature of the cavity was an average of 15.6% higher than that of the other wind directions. The cavity temperature of Case 3 was an average of 23.2% higher than that of the other cases. In Case 1, the cavity temperature was approximately
0.1K higher for the back wind direction than for the side direction, despite the higher ventilation rate for the back wind direction. This resulted from the significant heat transfer with adjacent spaces generated by the air circulation within the cavity for the back wind direction. However, the impact of the air circulation within the cavity was not great since the height of the cavity was low in Case 3.

5.3 Interior Temperature of the Highest Story and Total Heat Transfer Rate

The indoor temperature difference and the rate of total heat transfer (THTR) through the highest story's walls, ceiling, and glass are as shown in Fig.8. The indoor temperature difference in the graph indicates the difference in indoor temperature for each case compared to the temperature of the 4th story (409.6K) for the front wind direction in the case without the DSF. CFD calculation of the static state was conducted, and the spaces adjacent to the DSF were presumed to be completely airtight. However, the resulting temperatures of the adjacent spaces were unrealistic. Nevertheless, the relative variation compared to the reference case could be examined since a temperature change usually takes place because of the impact of the surrounding environment.
The THTR was inversely proportional to the ventilation rate of the DSF. This occurred because of the decrease in the THTR after the high ventilation rate caused a loss of heat in the glass. In the no-DSF case, a low THTR of 780.9 W was generated for the front wind direction because of the direct impact of the wind on the inner glass. Moreover, the lowest indoor temperature was 409.7K. Aside from the no-DSF case, the indoor temperature of the highest story and the THTR was highest for the front wind direction in all cases. The values were lowest for the side wind direction.

6. Conclusion

In this study, the wind directions, wind profile, solar radiation, and radiation models were applied to analyze their effects on the ventilation rate and thermal environment of a DSF. The results are as follows.

1) In the results of the CFD Benchmark test, the CFD using the Realizable k-ε turbulence model revealed a deviation of less than 30% with the test values. The physical reproducibility of the CFD analysis was verified through this process.

2) Due to the wind profile, the applied wind speed and wind pressure were increased along the height of the building.

3) The front wind direction interfered with the release of air within the cavity, and the ventilation rate decreased by an average of 47.6% compared to when the side and back directions were applied.

4) The ventilation rate of the DSF was highest for the back wind direction in Cases 1 and 3 and for the side wind direction in Case 2. The ventilation was lowest in Case 3 since the area of each story's openings was smaller compared to the other cases.

5) The THTR of the DSF in the highest story was inversely proportional to the ventilation rate. In all cases, the indoor temperature and THTR of the highest story was highest for the front wind direction, which had the lowest DSF ventilation rate. The values were lowest for the side direction.

6) CFD analysis was applied to the static state, and the building's computational domain without the DSF was modeled to be completely airtight. Thus, no infiltration ventilation was generated between the DSF and adjacent spaces. Accordingly, the temperature of the adjacent spaces was quite unrealistic. A more accurate analysis will be necessary to overcome the limitations of this study.

For the wind profile, the wind speed of the horizontal ground surface was 0 m/s. Thus, an arbitrary value was used for the heat transfer coefficient of the ground. The effects on the analysis results and the validity of this method will also require further review in the future.

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Symbols

1) y.δ : material thickness (mm)
2) δ : material total thickness (mm)
3) ρ : density (kg/m³)
4) λ : thermal conductivity (W/mK)
5) Cp : specific heat (J/kgK)
6) Ustn : standard thermal transmittance (W/m²K)
7) U : overall thermal resistance (m²K/W)
8) ∆t : temperature difference between supplied air and released air (K)
9) Qv : air flow rate (m³/s)
10) C : discharge coefficient of the opening
11) ΔH : vertical distance from the neutral pressure line (NPL) to the aperture (m)
12) C : cosm : amount of energy released by cavity ventilation (kW)
13) Δ : mean excess temperature (K)
14) C : mean air volume released through the opening (m³/s)
15) C : thermal capacity of air (kJ/kgK)
16) v : air volume released through the opening (m³/s)
17) Δt : air temperature in cavity (K)
18) Q : air flow rate (m³/s)
19) C : discharge coefficient of the opening
20) A : area of opening (m²)
21) ΔH : vertical distance from the neutral pressure line (NPL) to the aperture (m)
22) t : air temperature in cavity (K)
23) t : outdoor temperature (K)
24) ΔC : local wind coefficient according to wind direction (by ASHRAE)
25) \( \nu \): average wind speed at the height in question (m/s)
26) \( V \): wind speed of air supplied through a CFD inlet (m/s)
27) \( V_{r} \): wind speed measured by the Korea Meteorological Administration (m/s)
28) \( Z \): height of the inlet (m)
29) \( Z_{r} \): height of the wind speed measured by the Korea Meteorological Administration (m)
30) \( \alpha \): surface roughness

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