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The Impact of Double-Skin Façades on Indoor Airflow in Naturally Ventilated Tall Office Buildings

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Abstract Natural ventilation has proven to be an effective passive strategy in improving energy efficiency and providing healthy environments. However, such a strategy has not been commonly adopted to tall office buildings that traditionally rely on single-skin façades (SSFs), due to the high wind pressure that creates excessive air velocities and occupant discomfort at upper floors. Double-skin façades (DSFs) can provide an opportunity to facilitate natural ventilation in tall office buildings, as the fundamental components such as the additional skin and openings create a buffer to regulate the direct impact of wind pressure and the airflow around the buildings. This study investigates the impact of modified multi-story type DSFs on indoor airflow in a 60-story, 780-foot (238 m) naturally ventilated tall office building under isothermal conditions. Thus, the performance of wind effect related components was assessed based on the criteria (e.g., air velocity and airflow distribution), particularly with respect to opening size. Computational fluid dynamics (CFD) was utilized to simulate outdoor airflow around the tall office building, and indoor airflow at multiple heights in case of various DSF opening configurations. The simulation results indicate that the outer skin opening is the more influential parameter than the inner skin opening on the indoor airflow behavior. On the other hand, the variations of inner skin opening size help improve the indoor airflow with respect to the desired air velocity and airflow distribution. Despite some vortexes observed in the indoor spaces, cross ventilation can occur as positive pressure on the windward side and negative pressure on the other sides generate productive pressure differential. The results also demonstrate that DSFs with smaller openings suitably reduce not only the impact of wind pressure, but also the concentration of high air velocity near the windows on the windward side, compared to SSFs. Further insight on indoor airflow behaviors depending on DSF opening configurations leads to a better understanding of the DSF design strategies for effective natural ventilation in tall office buildings.

Keywords Double-skin façade, Natural ventilation, CFD simulation, Tall office building, Parametric study

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1. Introduction

Many tall office buildings (i.e., buildings of or taller than 200 m (656 ft)) are on rise around the world. As well known, the building sector is responsible for a large amount of energy consumption and CO_2 emissions. As interpreted from the database of U.S. Department of Energy in Wood & Salib (2013), the Heating, Ventilation, and Air Conditioning (HVAC) systems in typical tall office buildings built after 1980 in 16 U.S. cities are responsible for 33% or more of overall building energy consumption. Due to the use of new types of electronic equipment and existing technologies such as computers, office equipment, etc., the total amount of electricity consumed in commercial buildings has been consistently increased over the years (EIA 2012). In addition to energy consumption in tall office buildings, occupant health has drawn more attention since the emergence of "green buildings". Most tall office buildings currently highly rely on mechanical ventilation as they are sealed to reduce the impact of outdoor conditions and easily maintain indoor thermal comfort. Only a few tall office buildings are naturally ventilated but partially under limited conditions by some means such as perforated panels with hinged windows. Those sealed tall office buildings can cause Sick Building Syndrome (SBS) that consists of various nonspecific symptoms, due to malfunctioning HVAC systems and less outdoor air ventilation. According to some studies, there is a relationship between SBS symptoms occupants experience and insufficient ventilation in buildings. Moreover, insufficient ventilation can cause occupant health problems and a decrease in occupant productivity (Sundell et al.; 2011, Fisk et al., 2012). Therefore, the energy-efficiency and healthy environment of tall office buildings has become an important concern, given the current environmental challenges and health considerations.

Natural ventilation has proven to be one of the effective strategies to reduce the operating time of the HVAC systems and enhance the work environment in buildings. However, natural ventilation strategies have not been commonly adopted to tall office buildings due to the high wind pressure that are particularly experienced at the upper floors. The additional skin and the cavity of DSFs can attenuate the high wind pressure to allow the windows on the inner skin to open and bring fresh air into the indoor spaces. However, minimizing the impact is not the only concern as the wind pressure is still required as an important driving force of natural ventilation. Thus, more importantly, the wind pressure should not be minimized but regulated by the variations of DSF components such as openings and cavities. The properly configured DSFs would provide refined airflow through semi-outdoor conditions in the cavity in case the occupants control the windows. Another crucial factor for effective natural ventilation is airflow distribution in the indoor spaces. In many cases of tall office buildings with open office layouts, single-skin façades (SSFs) can cause the concentration of high air velocity near the windows. DSF components would help move the air to the deep spaces through pressure differential and simultaneously reduce excessive wind pressure.

There are numerous studies (e.g., Radhi et. al 2013; Sanchez et. al 2016; Larsen et. al 2015) that investigated stack effect caused by temperature differences between outdoors and the cavities of DSFs. On the other hand, only a few studies (e.g., Nasrollahi & Salehi 2015) focused on wind-driven ventilation and the impact of design components, such as openings, cavities, and chimneys, on the indoor airflow behavior in the buildings with DSFs. The wind speed affects the mass flow inside the cavity of DSFs as much as the temperature difference based on the long-term measurement in low and mid-rise office buildings with DSFs (Pasquay 2004). Since tall buildings dynamically respond to winds with respect to high wind pressure and turbulent characteristics around the buildings, wind effect can be more dominant than stack effect within the DSFs designed for tall buildings. Therefore, the way of responding to wind effect is one of the significant determinants of effective natural ventilation in tall office buildings with DSFs. According to a review paper, the study on naturally ventilated buildings with DSFs is still in the early stage as most studies on DSFs assumed that the indoor spaces are mechanically ventilated or air conditioned (Barbosa & Ip 2014). The design aspects of DSFs in naturally ventilated tall office buildings to account for wind-driven ventilation have not been extensively studied despite the importance of wind effect. Furthermore, it is still a challenge to predict the performance of DSFs and the impact on airflow behavior in tall office buildings in the early design stage.

Table 1. Average subjective reations to various velocities (Auliciems & Szokolay 1997)

Air velocity	Average reactions
<0.25 m/s	Unnoticed
0.25-0.5 m/s	Pleasant
0.5-1.0 m/s	Awareness of air movement
1.0-1.5 m/s	Drafty
>1.5 m/s	Annoyingly drafty

This parametric study investigates the impact of DSF configurations, specifically focusing on opening size, on indoor airflow at various heights of tall office buildings with DSFs under isothermal conditions. Further insight on indoor airflow behaviors depending on DSF configurations leads to a better understanding of the DSF design strategies for effective natural ventilation in tall office buildings.

2. CFD Simulation

ANSYS Fluent (CFD simulation software) was used to analyze airflow behavior in a hypothetical tall office building with DSFs as CFD can make comprehensive predictions and provide detailed information on airflow distributions such as air velocity and airflow pattern. As shown in the workflow (Figure 1), there are two tasks of the CFD simulation, such as ‘external environment simulation’ and ‘cavity and indoor space simulation’. The two tasks interact with each other as the results obtained from the first task are used as boundary conditions for the second task. The performance of DSF configurations is assessed based on the air velocity criteria suggested by Auliciems & Szokolay (1997). The study provides average subjective reactions to various velocities based on common experience in case natural winds and fan-generated airflow have a cooling effect (Table 1). In this study, only airflow was simulated without internal loads, solar load, nor mechanical exhaust.

In the ‘external environment’ simulation, only the airflow was simulated around a hypothetical 60-story and 780-foot (238 m) tall office building to examine the impact of wind profile on the building (Figure 1). It was assumed that a large computational domain is the external environment in which the logarithmic wind profile is used to specify the boundary conditions. The domain size was determined based on the suggestions by Franke et al. (2004) to avoid misleading results affected by the walls.

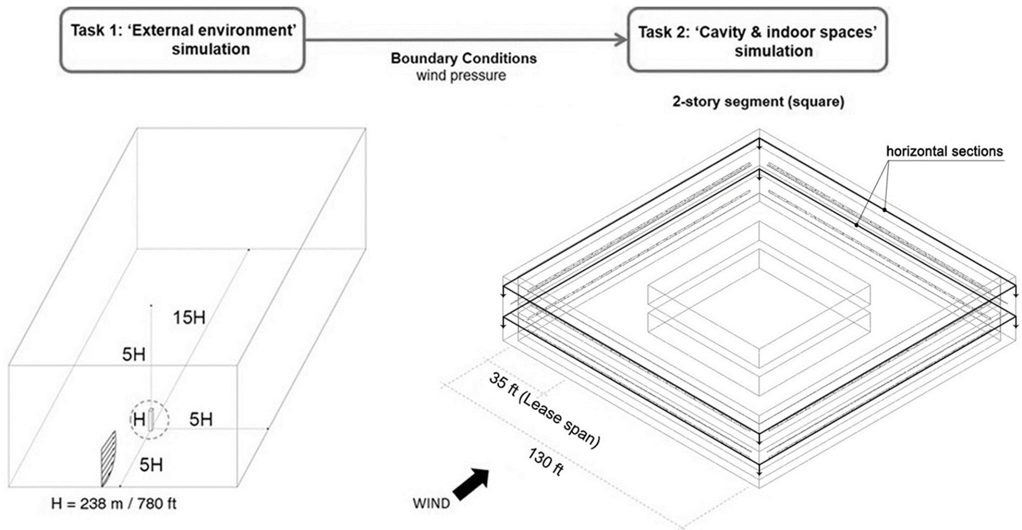

Figure 1. Two tasks of CFD simulation.

The wind pressures, calculated from the first task of CFD simulation, on the four façades of the tall office building were used as boundary conditions for the 'cavity & indoor space' simulation. For the assessment of air velocity and airflow pattern, the velocity contour was visualized on two horizontal sections of a 2-story office block, representing the occupied zone (i.e., 1.8 m above the floor) of each floor. The selection of 2-story office block was determined to minimize the complexity of CFD model and computational model. Thus, the 2-story office block represented higher floors (i.e., 55-56F), middle floors (i.e., 30-31F), and lower floors (i.e., 5-6F) of the 60-story office building depending on three different air velocities in CFD simulation. In addition to the number of stories per office block, the CFD model consisted of a cavity depth of 4 ft (1.2 m), a staggered opening configuration and one outer skin opening per every two floors.

The open office layout was chosen for the indoor spaces with the wall-to-wall distance of 130 ft (39.6 m), lease span of 35 ft (10.7 m), floor-to-floor height of 13 ft (4 m), and ceiling height of 9 ft (2.7 m). The multi-story façade was selected for this study, among four types of DSFs, that Oesterle et al. (2001) classified, including box window façade, shaft-box façade, and corridor façade. Moreover, a modified multi-story DSF with multiple openings (e.g., one outer skin opening per every two floors) was created to analyze only wind effect as the typical multi-story DSF is the most appropriate type for stack effect due to the vertically continuous cavity with only two openings at the top and the bottom.

Table 2 shows the design parameters and variables defined for the second task of CFD simulation to concentrate on the outer and inner skin opening size as an important determinant of effective wind-driven natural ventilation and the comparison between SSFs and DSFs. 'Opening size' configurations consist of nine variations of outer and inner skin opening size such as 2-10% and 10-30%, respectively with fixed cavity depth and segmentation, and the same number of outer skin openings per floor. The opening size gradually increases in the configurations, assuming that high wind pressure can be experienced at upper floors of tall office buildings when the occupants open windows. SSFs were also taken into account in the CFD simulations not only to identify the impact of high wind pressure on indoor airflow in case of traditional tall office buildings, but also to explore the feasibility of DSFs to regulate the high wind pressure. For 'Façade system' configurations, the smallest openings were selected. SSFs comprised only one skin which was identical to the inner skin of DSFs. Outer skin openings were applied to every floor of the DSF configuration for proper comparison with SSFs that consisted of operable windows on every floor. Therefore, the outer and inner skins of DSF configuration are identical to the skin of SSF configuration to investigate the direct impact of the additional skin on indoor airflow in tall office buildings.

In the table, the wind speed represents the values calculated from the logarithmic wind profile equation for each location of the 2-story office block when the wind speed is 4 m/s at a reference height of 33 ft (10 m). The roughness length in the equation was set to 3 meters to assume that the tall office building is located in a large city and surrounded by tall buildings based on the roughness length categorized in Aynsley et al. (1977). As shown in Figure 2, the wind speeds at the three heights of the interest in this study are 11.7 m/s, 10.1 m/s, and 5.5 m/s, respectively. Although the wind pressures determined from the 'external environment' simulation were the boundary conditions fed into the second task, the calculated wind speeds are still indicators of the variations of wind speed throughout the tall office building.

Table 2. Design parameters and variables – 'façade system' and 'opening size' configurations

		Outer Skin Height - % of Floor-Floor Ht	Inner Skin Height - % of Floor-Ceiling Ht	Number of outer skin openings per floor	Cavity depth ft	Cavity segmentation	Location of the segment in a tall office building	Wind Speed m/s
'Façade system' configurations	H0	N/A	10 % (10.8 in)	1 *inner skin opening	N/A	2-story	higher floors	11.7
	H1	2 % (3.12 in)	10 % (10.8 in)	1	4.0	2-story	higher floors	11.7
'Opening size' configurations	H1		10 % (10.8 in)	0.5	4.0	2-story	higher floors	11.7
	H2	2 % (3.12 in)	20 % (21.6 in)	0.5	4.0	2-story	higher floors	11.7
	H3		30 % (32.4 in)	0.5	4.0	2-story	higher floors	11.7
	H4		10 % (10.8 in)	0.5	4.0	2-story	higher floors	11.7
	H5	5 % (7.8 in)	20 % (21.6 in)	0.5	4.0	2-story	higher floors	11.7
	H6		30 % (32.4 in)	0.5	4.0	2-story	higher floors	11.7
	H7		10 % (10.8 in)	0.5	4.0	2-story	higher floors	11.7
	H8	10 % (15.6 in)	20 % (21.6 in)	0.5	4.0	2-story	higher floors	11.7
	H9		30 % (32.4 in)	0.5	4.0	2-story	higher floors	11.7
'Façade system' configurations	M0	N/A	10 % (10.8 in)	1 *inner skin opening	N/A	2-story	mid floors	10.1
	M1	2 % (3.12 in)	10 % (10.8 in)	1	4.0	2-story	mid floors	10.1
'Opening size' configurations	M1		10 % (10.8 in)	0.5	4.0	2-story	mid floors	10.1
	M2	2 % (3.12 in)	20 % (21.6 in)	0.5	4.0	2-story	mid floors	10.1
	M3		30 % (32.4 in)	0.5	4.0	2-story	mid floors	10.1
	M4		10 % (10.8 in)	0.5	4.0	2-story	mid floors	10.1
	M5	5 % (7.8 in)	20 % (21.6 in)	0.5	4.0	2-story	mid floors	10.1
	M6		30 % (32.4 in)	0.5	4.0	2-story	mid floors	10.1
	M7		10 % (10.8 in)	0.5	4.0	2-story	mid floors	10.1
	M8	10 % (15.6 in)	20 % (21.6 in)	0.5	4.0	2-story	mid floors	10.1
	M9		30 % (32.4 in)	0.5	4.0	2-story	mid floors	10.1
'Façade system' configurations	L0	N/A	10 % (10.8 in)	1 *inner skin opening	N/A	2-story	lower floors	5.5
	L1	2 % (3.12 in)	10 % (10.8 in)	1	4.0	2-story	lower floors	5.5
'Opening size' configurations	L1		10 % (10.8 in)	0.5	4.0	2-story	lower floors	5.5
	L2	2 % (3.12 in)	20 % (21.6 in)	0.5	4.0	2-story	lower floors	5.5
	L3		30 % (32.4 in)	0.5	4.0	2-story	lower floors	5.5
	L4		10 % (10.8 in)	0.5	4.0	2-story	lower floors	5.5
	L5	5 % (7.8 in)	20 % (21.6 in)	0.5	4.0	2-story	lower floors	5.5
	L6		30 % (32.4 in)	0.5	4.0	2-story	lower floors	5.5
	L7		10 % (10.8 in)	0.5	4.0	2-story	lower floors	5.5
	L8	10 % (15.6 in)	20 % (21.6 in)	0.5	4.0	2-story	lower floors	5.5
	L9		30 % (32.4 in)	0.5	4.0	2-story	lower floors	5.5

Notes:
1. For the numbering in the list, 'H', 'M', and 'L' represent the location of the segment (e.g., H - higher floors 55-56F, M - mid floors 30-31F, and L - lower floors 5-6F)
2. 'H0', 'M0', and 'L0' represent single skin façade configurations

3. Results

The following figures contain contours of the air velocity magnitude in the indoor spaces based on two horizontal sections of the 2-story office block at each height (i.e., higher, middle, and lower floors), and radar type charts adjacent to the contours. Each one presents the air velocity and the distribution on the lowest floor of

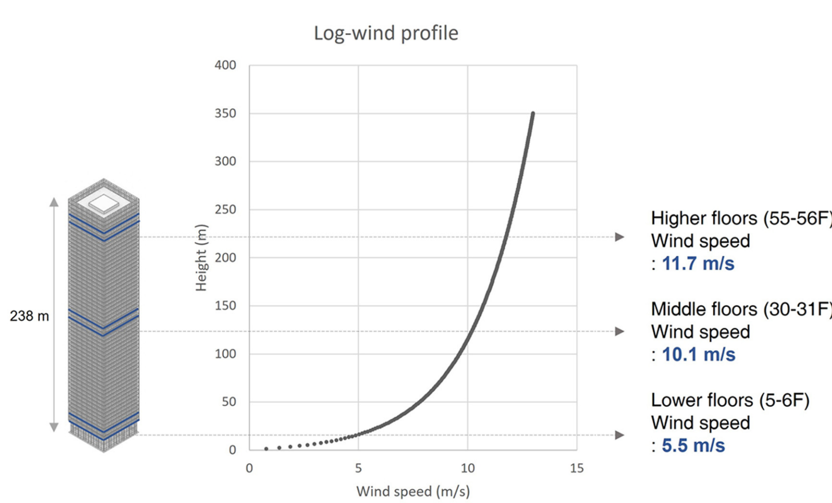

Figure 2. The logarithmic wind profile with a reference wind speed of 4 m/s at 10 meters for the 'large city center' condition

the 2-story office block, at the respective height of the zone in the model.

As shown in Figure 3, DSFs generally reduce the air velocities across the entire floor plan and significantly decrease them through the variations of opening size and location. The air velocities on the suction sides cannot be considerably reduced in the DSF configuration where the same opening size and location are applied as those of the SSF configuration. However, the DSF configuration can eliminate the concentration of high air velocities on the windward side. This implies that the 4 ft (1.2 m)-cavity on the windward side can effectively mitigate the high wind pressure without the impact of opening size and location. Also, the difference in velocity contours is larger between the lower and middle floors than the middle and higher floors as expected based on the difference in the calculated wind speeds at the three different heights (Figure 2). These results indicate that DSFs are likely to improve the airflow distribution as well as the air velocity due to the impact of air cavity, without adjusting the opening size and location.

The analysis of CFD simulation results for 'opening size' configurations involves three parts such as 'outer skin opening size', 'inner skin opening size', and '(both) opening size' configurations. First, as seen in Figure 4, the air velocities increase obviously with the outer opening size particularly on the windward and both sides due to the increase in pressure difference between them. There is no meaningful difference in indoor airflow between the three locations even though a slight difference in air velocity is observed near the windows on the windward side between the lower and middle floors. In the cases of 5% and 10% outer skin opening size, the direction of airflow is more noticeable at the corners of the building core on the windward side than the 2% case, due to the higher air velocity. Specifically, the directed airflow causes some vortexes on the leeward side once it hits the inner skin and thus, prevents well-distributions of airflow.

The radar charts suggest that '10%' outer skin opening size configurations can achieve more desired air velocities on the four sides than the others as the average air

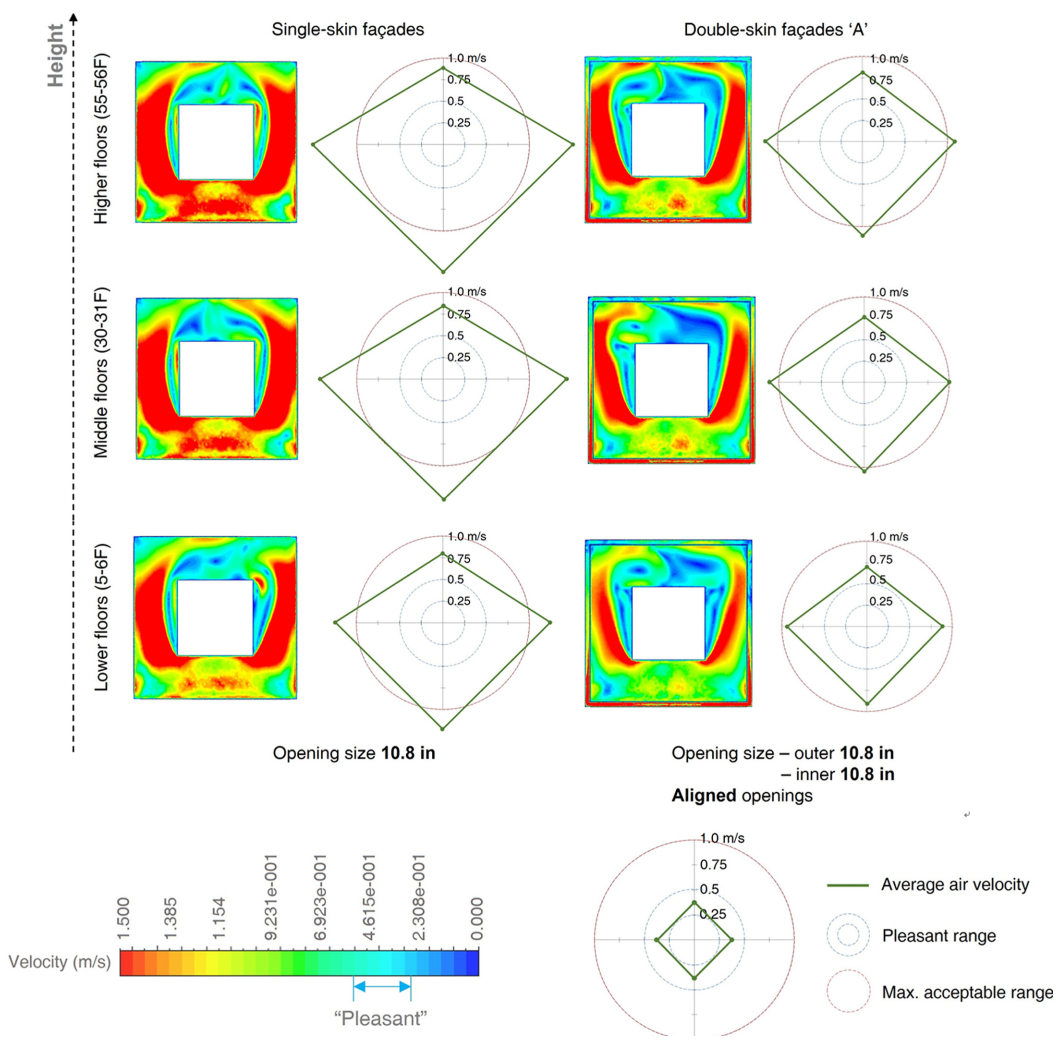

Figure 3. CFD simulation results – single-skin façades vs double-skin façades. (i.e., H0, H1, M0, M1, L0, and L1 from Table 2)

velocity on the charts is within the “pleasant” range. However, ‘5%’ configurations can provide a better airflow distribution with acceptable air velocities based on the velocity contours that is another indicator of the quality of airflow.

As shown in Figure 5, the variations of indoor airflow are relatively neglectable in ‘inner skin opening size’ configurations compared to the case of outer skin opening size. However, the air velocities on the windward side still slightly increase with the height and the inner skin opening size. Although similar phenomena are observed with respect to the direction of airflow at the corners of building core on the windward side, all the configurations are likely to be acceptable as the air velocities are within the “pleasant” range.

There are still some zones in which the air velocity is zero as the average air velocity on radar charts is less than 0.25 m/s in most cases. The results indicate that the influence of outer skin opening size on air velocities is much more dominant than the inner skin opening size while the similar airflow pattern is observed in both cases.

Figure 6 demonstrates the relationship between the size of outer skin openings and inner skin openings at the higher floors. As expected, the outer skin opening size is more influential on indoor airflow than the inner skin opening size on all the four sides of the tall office building. The results also show that the larger the outer skin openings are, the more the indoor airflow varies between the three inner skin opening configurations on the windward and both sides. In the case of 10% outer skin opening size, the larger inner skin openings deliver better airflow distributions on the leeward side despite the higher air velocities on the windward side. All the 2% outer skin opening size configurations and a 5% outer/10% inner skin opening size configuration are acceptable based on the visualized airflow distribution on velocity contours. According to radar charts, 5% outer/20% and 30% and 10% outer/10% inner skin opening size configurations can be acceptable, but the airflow distribution and the concentration of high air velocities should be considered for those cases.

4. Conclusion and Discussion

The conclusion addresses several important issues in wind-driven natural ventilation in tall office buildings by means of DSFs. In order to facilitate natural ventilation, DSFs can not only reduce the direct impact of wind pressure on indoor airflow, but also help regulate the pressure through the variations of openings. Moreover, the results indicate that DSFs can mitigate the fluctuation of indoor airflow governed by the wind pressure at various heights particularly in the case of smaller openings.

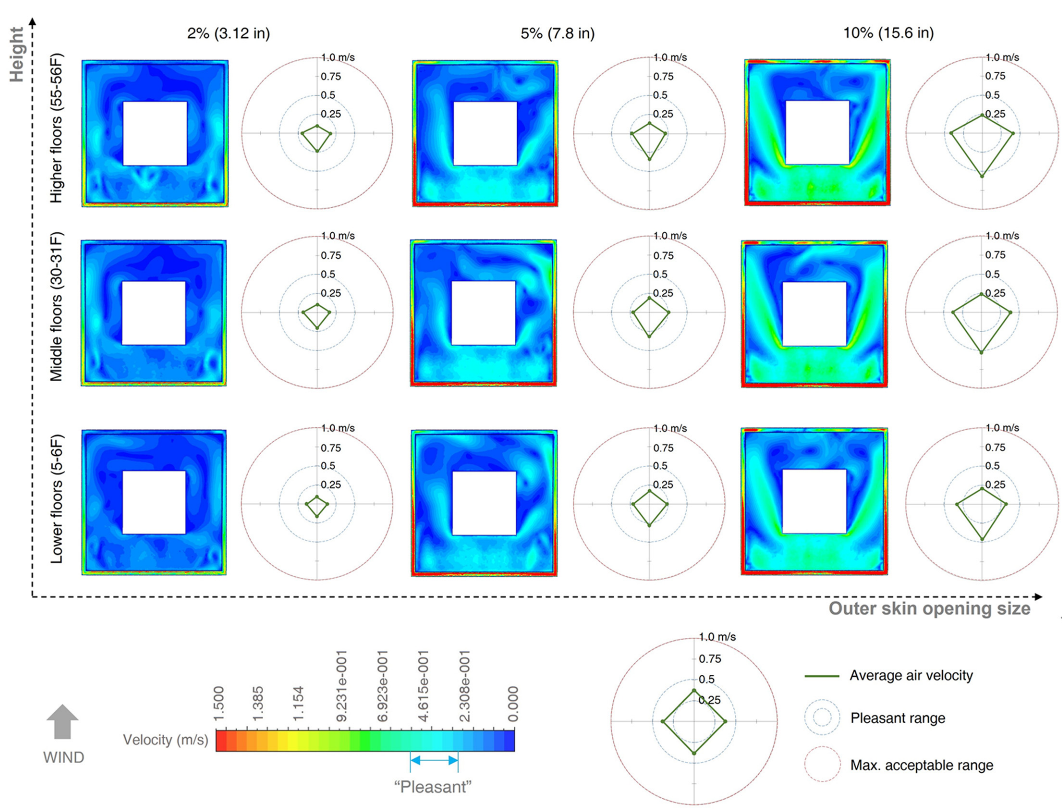

Figure 4. CFD simulation results – ‘outer skin opening size’ configurations (i.e., H1, H4, H7, M1, M4, M7, L1, L4, and L7 from Table 2)

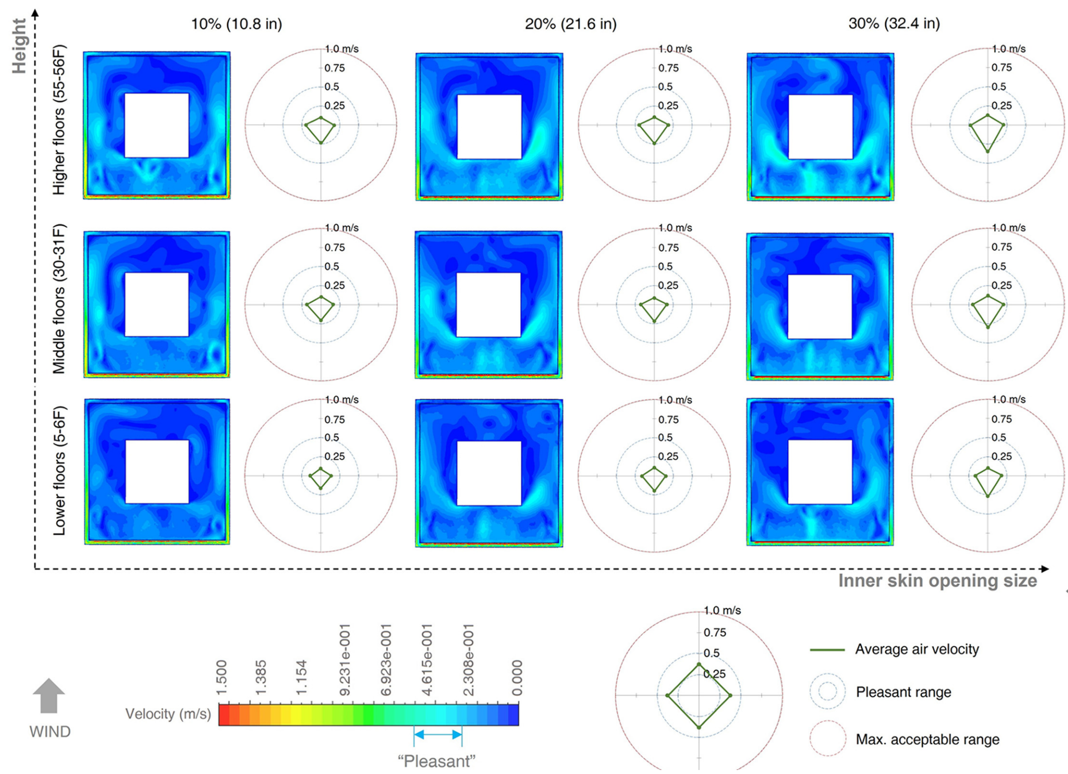

Figure 5. CFD simulation results – 'inner skin opening (operable windows) size' configurations (i.e., H1, H2, H3, M1, M2, M3, L1, L2, and L3 from Table 2)

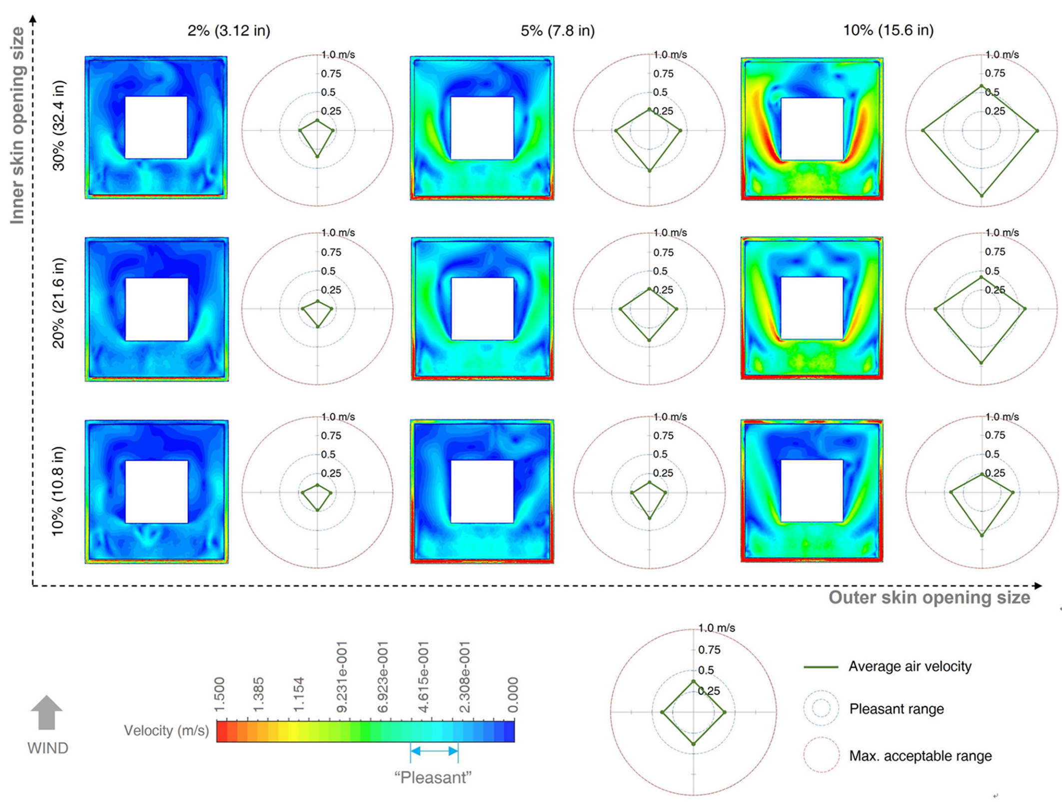

Figure 6. CFD simulation results – 'opening (outer and inner) size' configurations (i.e., H1, H2, H3, H4, H5, H6, H7, H8, and H9 from Table 2)

Although DSFs can significantly mitigate the extreme air velocities in indoor spaces compared to SSFs, properly designed openings and cavities are necessary to generate acceptable airflow. The smaller outer and inner skin openings enable to provide better indoor airflow at all the three locations with respect to air velocity and airflow distribution that are main criteria for the assessment. DSFs with larger outer and inner skin openings would generate the similar airflow patterns to SSFs even though DSFs can reduce the high air velocities on the windward side.

The simulation results show that the impact of outer skin opening is more dominant than the inner skin opening. However, adjusting the inner skin opening size would be an appropriate way to improve the indoor airflow and draw more fresh air into the indoor spaces, within the desired velocity range, due to the moderate interaction with indoor airflow.

Indoor airflow behavior does not considerably vary depending on the location of floors (i.e., higher, middle, and lower floors) in the opening size configurations. Specifically, the airflow behavior at higher floors and middle floors is very similar to each other, but the airflow behavior at lower floors is slightly different due to the lower wind pressure.

The key findings in this study enable architects to come up with ideas to design DSFs for naturally ventilated tall office buildings in the early design stage where rapid and iterative decisions are made. Architects and designers can take advantage of the velocity contours and radar charts, for the initial design ideas, which provide specific information on indoor airflow behaviors on each side based on various wind velocities, such as the visualized airflow distribution and the magnitude of average air velocity.

Future studies can be conducted to focus on other factors of effective natural ventilation in tall office buildings, such as aerodynamic modifications of building shapes, additional DSF configurations, various building locations under thermal conditions (e.g., big cities around the world), façade retrofits, and multiple scenarios of active DSF systems responding to specific climatic conditions.

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