Climate Responsive Automatic Operation Strategies for Double Skin Façade (DSF) System of High-Rise Buildings

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ABSTRACT

Double skin façade (DSF) systems are increasingly used in high-rise buildings in hot summer and cold winter climate cities for the enhancement of acoustic insulation, aesthetic appearance, thermal insulation, natural ventilation, and energy efficiency. However, inappropriate DSF configuration can cause an increase in the risk of overheating in the cavity space during summer, which is one of the main disadvantages of DSF systems. In order to improve DSF configuration, as a means of increasing energy efficiency, an effective analysis method for thermal performance evaluation that considers all possible thermal parameters should be used. However, widely used current analysis methods are mostly focused on the evaluation of thermal performance by changing the façade optical properties in the DSF cavity space. In addition, the opening system in DSF is mostly operated as one unit. Taking into consideration these limits, this study focuses on the fact that wind speed and ambient temperature can change the airflow movement in the cavity with opening operation. In addition, the temperature and heat flow in the cavity can differently affect inside thermal performance depending on the height of the room. It is important to consider all possible parameters that can affect thermal performance including wind speed and building height for effective thermal analysis in a DSF configuration. This study explored the applicability of a climate-responsive automatic opening system for high-rise DSF buildings. Detailed Computational Fluid Dynamics (CFD) simulation was used to develop an automatic opening pattern which was individually operated to optimize thermal character of the cavity.

INTRODUCTION

A double skin façade (DSF) of a building can be defined as a façade system that consists of two parallel glass skins with cavity space between them. A DSF can provide acoustic insulation, aesthetic enhancement, natural ventilation, solar heat gain reduction, and thermal insulation (Choi et al. 2012, Chan and Chow 2014). These characteristics of the DSF directly affect the building energy performance. More specifically, the cavity space in DSF building plays a significant role as the thermal buffer zone between the external and internal building environment, and these DSF performances offer building energy saving opportunities. With these advantages, DSF systems have gained increased interests and, recently various types of DSF systems have been increasingly used in high-rise buildings in cities (Gratia and De Herde 2007, Moon 2009, de Gracia et al. 2013).

However, the DSF system has a risk of overheating of the cavity space on hot summer days leading to higher cooling energy demands (Høseggen et al. 2008). Consequently, it is important to design an appropriate configuration and to develop operation strategies for the DSF system to achieve optimized DSF performance. In order to develop the best performing DSF system, as a means of increasing energy efficiency, all possible thermal parameters have to be considered using effective analysis methods. However, in real practice, predicting the DSF performance with consideration of all possible design parameters is not a trivial task (Hensen et al. 2002, Doebber and McClintock 2006). Numerous studies about DSF performance revealed that developed analysis methods such as airflow network and Computational Fluid Dynamics (CFD) simulation can overcome the difficulties of DSF performance analysis (Pappas and Zhai 2008, Guardo et al. 2011)

In addition to the DSF configuration analysis, the development of operation strategies is essential to avoid the cavity overheating phenomenon. Choi et al. (2012) simulated three DSF opening activation strategies and validated their results with data collected from an actual DSF building. They found that a 41% reduction of heating energy consumption was achieved in the case of a hybrid ventilated DSF building during the heating season. The main purpose of a DSF operation is to support buoyancy-driven airflow inside the cavity for accelerating ventilation performance.

In connection with these DSF system performance for building energy efficiency, intensive studies have been conducted to verify the energy savings of DSF systems (Gratia and De Herde 2007, Kim and Park 2011). However, due to the relative short history and the lack of experimental and monitoring data from DSF systems, these DSF studies were not comprehensive (da Silva and Glória Gomes 2008, Choi et al. 2012). For instance, the majority of the previous studies about DSF cavity configuration were mainly focused on the analysis of thermal and optical aspects based on transmittance and solar heat gain. In the area of DSF operation development, very few studies have been conducted, and there have been very limited numbers of previous studies focused on DSF systems in high-rise buildings.

This study approaches the DSF operation strategies integrating Building Energy Management System (BEMS) for high-rise DSF buildings. More specifically, the airflow movement in the DSF cavity at different heights is analyzed using CFD simulation, and in order to accelerate the airflow, separately operated DSF opening strategies are demonstrated. The results will be useful in developing a climate responsive automatic operation system for BEMS in high-rise buildings.

STUDY PROCESS AND METHODOLOGY

As an initial step, a conceptual high-rise DSF building (with a height of 230 ft.) model is created. The ventilated cavity integrating with the opening system on each floor can either be a sealed or a ventilated cavity (Hollingsbee et al. 2009). In general, a sealed cavity is ideal for cold climate region to provide the DSF cavity's thermal insulation function during the heating season. On the other hand, the ventilated cavity is beneficial for hot climate areas to increase internal ventilation. The conceptual model created has a ventilated cavity with opening system, and it also functions as sealed cavity when the opening system is closed. The main reason for choosing this hybrid type of DSF cavity is to evaluate the feasibility of DSF buildings in various climate areas. A depth of cavity of 5 ft. (1.5 m) is selected for the simulation based on previous studies. Even though most studies have found that the DSF cavity depth does not have a large effect, the range of most cavity depth is from few inches to 5 ft. (Pappas and Zhai 2008).

Depending on the ventilation mode in the cavity, DSF systems can be categorized as either mechanically ventilated or naturally ventilated DSF. The air movement in a mechanically ventilated DSF building is controlled by mechanical components. In contrast to the mechanical ventilation DSF, natural ventilation in the cavity is controlled by meteorological conditions such as differences in temperature and wind pressure (El-Sadi et al. 2010). Since the primary purpose of this study is to identify the airflow movement at different floor levels in a high-rise building and to develop opening operation strategies, a natural ventilated cavity mode is used in this study.

In a naturally ventilated DSF cavity, theoretically, the air flow rate can be increased due to the stack effect. The major driving forces of the stack effect are buoyancy and wind pressure, and the airflow movement varies depending on meteorological conditions (Wong et al. 2008, Hashemi et al. 2010). Additionally, Doebber and McClintock (2006) pointed out that airflow in a cavity can be highly erratic and airflow fluctuation with reversed airflow direction can take place. Based on these uncertainties of airflow movement in the DSF cavity, this study considers the fact that there can be a high possibility of airflow fluctuation in a high-rise DSF cavity. In order to overcome these limitations, the feasibility of a new control system which is a separately operable opening control system based on different level of height will be evaluated using CFD simulation.

The primary mechanism of control system in DSF is to shift air flow from a certain position to other position in the cavity. Generally, controlled airflow movement in the DSF cavity is implemented by an appropriate outer-wall opening strategy. If the wall opening is not properly operated, the air flow in the cavity can cause negative effects on the indoor environment such as increase in temperature and a different level of pressure in the cavity. Most current DSF opening strategies assign outer wall opening time based on the predefined temperature predictions (Jiru et al. 2011, Choi et al. 2012). This means that the current strategy may not properly respond to meteorological conditions including wind speed, pressure, and direction. A new control system integrated with automatic climate responsive opening and closing system will be analyzed for this study.

SIMULATION MODEL

A 20 story conceptual high-rise DSF building was created as shown in Figure 1. It has a 230 ft. height, 120 ft. width, and 60 ft. depth with integration of a 200 ft. height DSF cavity with 5 ft depth. The height of the opening system on each floor is set at 2 ft. above the finished floor level. The U-value and transmittance of external glazing in this DSF model are set to 5 W/m^2K and 0.5 g-value, respectively.

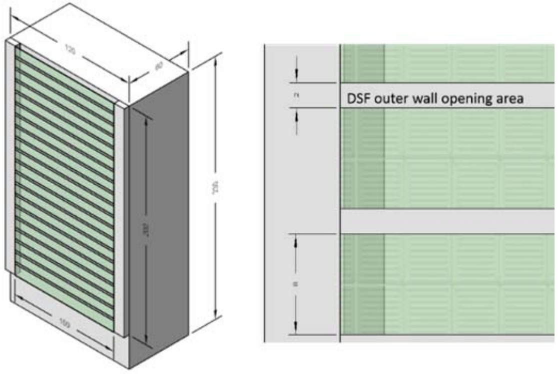


Figure 1. Dimension of conceptual DSF building

Prior to running the CFD simulation, wind speed and outdoor temperature input data have been grouped within the certain ranges in order to reduce simulation time. The ranges of input data are shown in Table 1. Another reason for grouping input data is to facilitate opening operation. In real practice, frequent opening operation due to small change of environmental conditions may not be effective. In addition, operation strategies were developed based on the combination of each input data.

Table 1. Representative input value of wind speed and temperature for CFD simulation

Wind Speed [km/h]		Outdoor Temperature [°C]	
Range	Input value	Range	Input value
5 - 10	10	16 – 20	20
11 - 15	15	21 - 25	25
16 - 20	20	26 - 30	30
21 - 25	25	31 - 35	35
26 - 30	30	36 - 40	40

Basically, wind speeds below 5 km/h were not considered in this study since low wind speeds did not affect wind flow movement in the cavity space (Hashemi et al. 2010, Jiru et al. 2011). Similarly, outdoor temperatures less than 15° C are not evaluated in this study because the opening operation is not required for this range of temperatures. Instead, the function of sealed cavity is needed at low temperatures for improved thermal insulation (Joe et al. 2013). Therefore, a wind speed of 10 km/h and a temperature of 20 °C were determined as the minimum values of input data in this study.

The CFD simulation in this study is performed using Autodesk CFD simulation 2014. For the setup process in the CFD simulation, this study assumes that the wind direction is perpendicular to the external DSF to facilitate the identification of the effect of wind speed (velocity) magnitude and movement inside the cavity. In addition, for the configuration of the boundary conditions of DSF cavity, each combination of wind speed and temperature is applied to the created DSF building geometry, and a k-epsilon turbulence model is added to wind flow simulation model. The iteration is set to 300 times.

2D airflow movement stratification images are created through CFD simulation depending on the combination of each designated wind speed and temperature input. Also, the lowest wind speed values at specific locations in the cavity are detected with frequency of turbulence inside the cavity. Based on the results from generated images and numerical data, various opening strategies for each case are developed for the DSF and airflow movement simulation is conducted.

RESULTS

The airflow movement pattern at 20 km/h with changing of temperature inside the cavity is stratified with 2D images as shown in Table 2. Based on the results shown in Table 2, airflow movement in the DSF cavity increases with the increase of the outside temperature. The results verify the findings of many previous studies that stack effect in the cavity increases if the outdoor temperature increases (Jiru et al. 2011, Ghadimi et al. 2013, Chan and Chow 2014).

Table 2. Wind flow movement in cavity by change of outdoor temperature at 20 km/h of wind speed

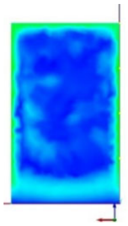
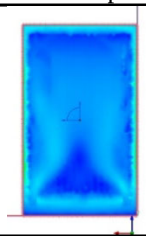
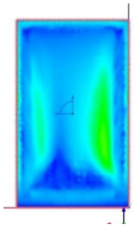
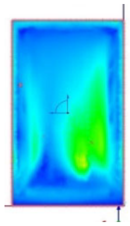
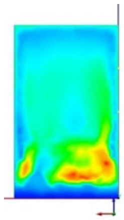
	At wind speed of 20 km/h				
2D image					
Outdoor temperature [°C]	20	25	30	35	40
Wind speed inside cavity [km/h]	0.05	0.08	0.12	0.17	0.24
Wind speed at upper level outlet [km/h]	0.05	0.06	0.09	0.09	0.12
Detected level of lower wind speed [floor]	4 to 6 16 to 18	2 to 5 19 to 20	2 to 5 19 to 20	2 to 4 19 to 20	1 to 2 15 to 17

Table 3 shows the different airflow movements at a fixed 30 °C temperature with changing wind speed. As shown in Table 3, change of wind speed also has an effect on the movement of airflow in the DSF cavity. Airflow movement in the DSF cavity increases with the increase of the wind speed. The simulations of other combinations are conducted in the same fashion and produce similar results. From these results, it can be inferred that wind speed and outdoor temperature control the airflow movement in the DSF cavity. The simulation determined the height from ground level elevation where the airflow rate is insufficient for the stack effect to occur (see Tables 3 and 4). In order to accelerate low wind speeds at a certain floor level, the opening system at the level needs to be opened. For facilitation of the opening operation, the opening systems are grouped for every five floors as shown in Table 4.

Table 3. Wind flow movement in cavity by change of wind speed at 30 °C of outdoor temperature

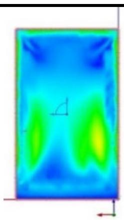
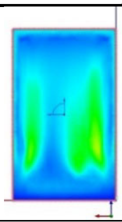
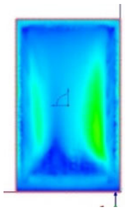
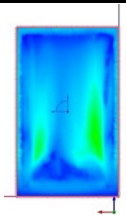
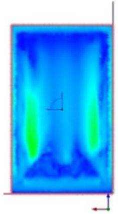
	At outdoor temperature of 30 °C				
2D image					
Wind speed [km/h]	10	15	20	25	30
Wind speed inside cavity [km/h]	0.05	0.07	0.12	0.37	0.49
Wind speed at upper level outlet [km/h]	0.04	0.07	0.09	0.29	0.43
Detected level of lower wind speed [floor]	3 to 7 16 to 20	6 to 8 18 to 19	2 to 5 19 to 20	18 to 20	18 to 20

Table 4. Opening System Units

Floor levels	Unit name
1 through 5	A
6 through 10	B
11 through 15	C
16 through 20	D

For example, if a low airflow rate is detected at Floor level 8 in Group B, then the Group B opening system will be activated and an airflow rate will be increased. The change of airflow movement for each case implemented with an opening operation pattern is summarized in Table 5. The change of airflow rate inside the cavity and at upper level outlet is calculated as a percentage of differences between the closed DSF and the strategically opened DSF. For example, at the condition of wind speed of 25 km/h with outdoor temperature of 30 °C, the opening system at 16 to 20 floor level will be opened, resulting in increase of 3.11 % and 4.52% of wind speed inside cavity and wind speed at outlet, respectively.

DISCUSSION

The main objective of this study was to develop climate-responsive automatic opening strategies in high-rise DSF building to stimulate airflow movement in cavity. In this study, it was determined that wind speed and outdoor temperature affect the airflow movement in a high-rise DSF cavity. More specifically, increasing outdoor temperature indirectly accelerates the stack effect in a DSF cavity. On the other hand, high wind speed increases the airflow movement in the cavity. In addition, limited vertical movement of airflow was detected at certain floor levels. Taking into consideration these findings, the developed climate-responsive opening strategies, which are operated differently depending on weather change, can accelerate airflow movement in the cavity, and it has potential for BEMS application in high-rise DSF building with the integration of a web-based or a locally based real time weather data collection system.

Table 5. Change of wind velocity magnitude in cavity with implementation of developed open operation strategies

Wind speed [km/h]	Outdoor temperature [°C]	Applied opening system floor	Change of wind speed inside cavity [%]	Change of wind speed at upper level outlet [%]
10	20	A,B,C, and D	7.54	5.18
	25	A,B,C and D	7.10	5.82
	30	A,B,C and D	8.92	6.11
	35	A,B,C and D	8.81	6.54
	40	B, C, and D	9.29	6.12
15	20	A, B, C, and D	5.17	6.16
	25	A, B, and D	5.85	6.00
	30	A, B, and D	7.62	7.18
	35	B,C, and D	7.85	7.10
	40	B, and C	8.08	5.14
20	20	A, B, and D	12.21	8.15
	25	A, B, and D	11.01	7.17
	30	A, B, and D	12.09	8.81
	35	A, B, and D	13.20	8.14
	40	A, and D	13.18	6.61
25	20	B, and D	4.02	4.14
	25	B, C	2.84	3.22
	30	D	3.11	4.52
	35	D	1.58	2.62
	40	C	2.08	0.84
30	20	C, and D	3.52	7.11
	25	B, C, and D	4.62	8.04
	30	D	2.89	6.98
	35	D	2.31	6.84
	40	None	0	0

In this study, CFD simulation is conducted based on consideration of one way wind with change of temperature and wind speed. For more reliable and accurate DSF opening strategies, other factors, such as wind direction and solar radiation should be considered in future studies. In addition, comparisons with other CFD simulation results is needed to validate the result of this study.

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