Analysis of Heat Transfer in a Slim Double Skin Façade using CFD Simulation

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Abstract

In this study, we analyzed the heat transfer mechanism in a slim double skin facade (SDSF). Computational fluid dynamics (CFD) simulations were exploited and the model was validated with measured data from full-scale experiments. Based on the simulations, we analyzed both the type and amount of heat that entered a room, in addition to the amount of heat released through the cavity. We also performed a parametric study on the effect of the type of outer glass on heat transfer. The results indicate that it is advantageous to use colored or low-emissivity glass as the outer glass to improve cooling performance using SDSF.

Introduction

Many buildings built with curtain walls experience the problem that excessive solar radiation enters through the glass of curtain walls thereby resulting in large cooling loads during summertime (Yoon et al., 2011). To address this problem, the double skin façade (DSF) has been actively used for many years. The DSF has a cavity between two façade layers to prevent overheating of the cavity using ventilation. Nevertheless, this is a complicated system and it is difficult to apply this solution to small or existing buildings (Hendriksen et al., 2000, Cho and Cho, 2018).

A slim double skin façade (SDSF) is an alternative method that is used to solve the overheating problem (Young-sub et al., 2017). The SDSF is a 50 mm slim window system that consists of an outer single glass, an inner double glass, and a cavity between them (Figure 1). It has two openings at the top and the bottom of the façade, with a height of 0.02 m. This structure can prevent overheating of the cavity via natural ventilation, as in the case of DSF, and thus reduces indoor cooling loads. Young-sub et al. (2017) experimentally demonstrated that SDSF reduces the cooling loads during summertime compared to triple glass. Moreover, SDSF is smaller and simpler than DSF, so it can be installed in small offices and can reduce cooling loads caused by windows.

To optimize the performance and utilize the SDSF properly, it is important to understand the heat transfer mechanism of this approach. The heat transfer mechanism of the DSF has been previously investigated; however, there are no published reports on the analysis of heat transfer of SDSFs.

Generally, computational fluid dynamics (CFD) simulation is frequently used in the analysis of heat transfer using a complicated window system. Pappas and Zhai (2008) analyzed the thermal performance of DSF cavities with a buoyancy-driven airflow using a building energy simulation program and CFD. Jiru et al. (2011) conducted airflow and heat transfer simulations for a DSF with a Venetian blind, also using CFD. Iyi et al. (2014) conducted CFD investigations on modeling strategy, blind proximity, and inclination of a DSF with a Venetian blind.

The aim of this study is to perform a detailed analysis of heat transfer in SDSF using CFD simulation. In addition, this study explores the influence of the outer glass on the heat transferred to the indoor space.

For this purpose, both experiments and CFD simulations were performed. A full-scale experiment was performed to measure the temperature of the cavity and the outer glass, indoor and outdoor temperature, and solar radiation. The results were used for validation of the CFD model. The heat transfer of the SDSF was then analyzed using the validated CFD model. Finally, the heat transfer of the three types of outer glass was analyzed and the solar heat gain was compared for three cases.

Figure 1: A conceptual diagram of a SDSF

Figure 2: The facility for full-scale experiment

Figure 3: Temperature measurement positions in SDSF vertical section

Full-scale measurements

Experimental set-up

A full-scale experiment was conducted in August 2016 at a facility in Yongin, Gyeonggi – do (Figure 2). The investigated façade is in the southwest and the SDSF used was 1.7 m high and 1.67 m wide. One side of the SDSF was exposed to environmental weather conditions, while the other side faced a thermally conditioned room that was maintained at approximately 24 °C using conditioned air. The outdoor air temperature, indoor air temperature, outer glass surface temperatures, air in cavity temperatures and global solar radiation were all measured. The vertical positions of the sensors are shown in Figure 3. The horizontal position of the sensor is represented by the central line of the window. The temperatures were measured using thermocouples (T-type) and all the data were recorded at intervals of 5 mins.

Temperature distribution and solar radiation throughout measurements

Figures 4 and 5 show the temperature and solar radiation, respectively, on August 26th. On this day, the solar radiation was high and the outdoor air temperature was also high. It can thus be regarded as a typical summer day in Yongin. As shown in Figure 4, the outdoor air temperature reached 38 °C. As the outside temperature increased, the upper and lower temperatures of the outer glass surface are clearly stratified, and the temperature difference increased to approximately 6 °C. The air temperature in the cavity was very similar to the outer glass temperature. Such a stratification in the cavity induces buoyancy flow. Figure 5 shows the measured time-averaged global solar radiation. In addition, the direct and diffuse radiation are separated from each other using a decomposition model (Ineichen et al., 1992). The global solar radiation had a maximum of 740 W/m² on the façade, with direct solar radiation accounting for 69% and diffused solar radiation accounts for 31%.

Figure 4: The measured outer glass, air in cavity, outdoor, indoor temperature on August 26, 2016

Figure 5: The time-averaged solar irradiation measured on August 26, 2016

Figure 6: Geometrical model for CFD simulation

CFD simulation

Computational model

To analyze the heat transfer of the SDSF in detail, a steady-state CFD simulation was employed. This study modeled the three-dimensional SDSF as well as the adjacent room and external environment as shown in Figure 6. In the CFD modeling of the DSF, the external environment is known to be an important factor that affects the quality of the simulation (Pasut and De Carli, 2012). An external domain of (8.5 m high (z) × 10.0 m wide(y) × 2.0 m deep (x)) is large enough relative to the SDSF (1.7 m high × 1.67 m wide × 0.05 m deep) so that the domain boundaries do not affect airflow at the cavity openings. The adjacent room is 2.3 m high, 3.24 m wide and 4.68 m deep. Trimmer cells were employed, and 489,882 cells were created for the entire computational domain.

Table 1: Layer properties of the facade

Layer Number	Name	Thickness (mm)	Solar transmittance (dimensionless)	Reflectance outside (dimensionless)	Reflectance inside (dimensionless)	Emissivity inside (dimensionless)	Emissivity outside (dimensionless)
1	Clear glass	6	0.765	0.073	0.073	0.837	0.837
2	Cavity	20	-	-	-	-	-
3	Low-emissivity glass	6	0.390	0.231	0.309	0.837	0.057
4	Argon	12	-	-	-	-	-
5	Low-emissivity glass	6	0.390	0.309	0.231	0.057	0.837

Turbulence & Radiation model

In this study, the conduction and convection in the glass in addition to the radiation on the surface of the glass were simultaneously considered. The conductivity of the glass was set at 1.4 W/m·K. A commercial CFD program, STAR-CCM+, was employed to solve the Reynolds–Average Navier–Stokes Equations (RANS). The $k-\varepsilon$ RNG turbulence model was used to simulate the overall turbulence effect on the mean airflow. A surface-to-surface (S2S) radiation model was used to calculate the thermal radiation heat transfer based on the assumption that the surfaces were diffused. In addition, we chose a multiband thermal radiation model consisting of a long-wave band (3–100 μm) and a short-wave band (0.1–3 μm) (Xue and Li, 2015). A solar load model was used to account for solar incidence angles. For the convenience of interpretation, only direct solar radiation was considered in the CFD model because the diffuse effects are expected to be negligible (Iyi et al., 2014).

Boundary conditions

At the time of analysis, we chose 2 pm on August 26 as the time point for which the effect of buoyancy ventilation in the SDSF could be clearly observed owing to the maximum solar radiation and lack of wind. The steady-state simulation conducted in this study was based on global solar radiation of 740 W/m² on the test façade as the boundary condition. The corresponding outdoor air temperature and indoor air temperature were 34 °C and 24 °C respectively. In addition, a windless situation was assumed for the simulation. The horizontal boundaries at the frame were assumed to be adiabatic and the glass properties were calculated using the LBNL WINDOW program (LBNL, 2013) based on the properties of the actual glasses that were used in the experiment. Table 1 shows the solar and infrared properties of all the layers.

A comparison of the CFD model with measurements

Figure 7 presents the results of the CFD predictions for the temperature distribution and air velocity. The top, middle, and bottom vertical sections (central line of width) of the SDSF are represented in the figure. Figure 7-(a) shows that there is a distinct temperature stratification along the top and bottom of both the glass and cavity. Consequently, the buoyancy effect can be seen (Figure 7-(b)). Low-temperature air is introduced into the lower opening, and heated air is exhausted from the upper opening.

The maximum temperature of the air in the cavity occurred near the top. This result is the same as that reported based on Manz (2004)’s study of DSF, which is similar to the SDSF but with a wider cavity width. On average, the airflow at the openings was approximately 0.3 m/s. In addition, the air velocity at the inlet and outlet was high. However, the analysis demonstrates that the air flow stagnates at the center of the cavity.

CFD predictions for the outer glass surface temperatures (P1, P2) and the air temperatures in the cavities (P3, P4) were compared with measured values. Table 2 shows the temperature values and the corresponding errors. The measurements revealed a rise in the outer glass surface temperature from 47.7 °C (P2) to 48.6 °C (P1), in addition to an increase in the air temperature in the cavity from 46.3 °C (P4) to 48.2 °C (P3). The CFD analysis also recorded such a temperature rise and confirmed the observed stratification phenomena in the outer glass and air in the cavity. Overall, the CFD prediction was generally in agreement with the measurements.

Figure 7: CFD results of temperature distribution and air velocity in a section of the SDSF

Table 2: Comparison of measurement and simulation

	P1	P2	P3	P4
Measurement (°C)	48.6	47.7	48.2	46.3
Simulation (°C)	48.0	46.0	47.4	42.5
Absolute error (°C)	0.6	1.7	0.8	3.8

CFD results for heat transfer

The heat transfer of an SDSF is complicated because it involves incident solar radiation, solar reflection, solar transmission, solar absorption, convection heat transfer, long-wave radiation, and other aspects. The two most important factors that determine the cooling load are:

- Transmitted solar radiation
- The secondary internal heat flow

The secondary internal heat flow refers to the absorbed solar radiation that enters the room in the form of thermal radiation and convection (Manz, 2004). The transmitted solar radiation plus the secondary internal heat flow is the total solar heat gain, which is the indoor cooling load due to incident solar radiation. Furthermore, another important value is the heat released by free convection in the cavity. This represents the effectiveness of the SDSF's thin cavity. The analysis of the heat transfer of SDSF was focused on these three values as shown in Figure 8. The figure shows the distribution of relative heat flow when the incident solar radiation is set to 1. The actual value of the incident solar radiation is 2020 W.

Using short-wave radiation, 13% of the incident solar radiation is instantaneously transmitted into the room. The reflected solar radiation is very small and 80% of the solar radiation is absorbed throughout the SDSF. After absorption in the façade, 16% of the incident solar radiation flows into the room by convection and long-wave infrared radiation. The total solar heat gain is therefore approximately 29% of the incident solar radiation. In addition, 16% of the incident solar radiation is discharged by convective heat transfer in the cavity.

The total solar heat gain can be divided into radiation and convection depending on the heat transfer mechanism (Table 3). Radiation can be divided into short-wave radiation and long-wave radiation. Short-wave radiation is transmitted radiation and has a value of 263 W. Long-wave radiation is found inside the room as secondary heat flow and the associated value is 290 W. Convection is also included in the secondary heat flow into the room, with a value of 43 W. The ratio of the radiation to the total solar heat gain is 93%, which is much larger than in the case of convection.

Figure 8: Heat transfer in SDSF in steady-state

Table 3: Total solar heat gain divided by radiation and convection heat transfer

Total solar heat gain		596 W	100%
Radiation	short-wave radiation	263 W	93%
	long-wave radiation	290 W	
Convection	convection	43 W	7%

Parametric study

Case description for simple parametric study

Parametric studies are often used to optimize the performance of complex window systems (Jiru et al., 2011, Iyi et al., 2014). The parameters that can be considered in the SDSF are the outer glass type, the vent size, and the cavity size, etc. Among these, the outer glass type is the key parameter because it is easy to change according to the user's demand, determines the appearance of the building, and greatly affects the thermal performance in the cavity. In this study, we focused on the outer glass type and analyzed the heat transfer by three types of outer glass: clear glass (Case 1), colored glass (Case 2), and low-emissivity glass (Case 3). Clear glass is the base model that was analyzed earlier, whereas colored glass and low-emissivity glass were selected as glasses that are commonly used in Korean offices. A CFD simulation was used for the analysis, and all boundary conditions except the optical properties of the glass were the same as the conditions previously described. The optical properties of the glass were calculated using the LBNL WINDOW software and the values are shown in Table 4.

Analysis and comparison of heat transfer in the three cases

Figure 9 shows the temperature distributions for Case 2 and Case 3 as determined using CFD simulation. The temperature distribution for Case 1 is presented in Figure 7-(a). When compared to Case 1, Cases 2 and 3 have a relatively high outer glass temperature and a low secondary glass (layer 3) temperature. In addition, Case 3 has a lower overall glass temperature and air temperature in the cavity compared to Case 2.

An overall analysis of the heat transfer for the three cases is presented in Figure 10. This figure represents the incident solar radiation as 1 and the other values as relative values similar to Figure 8.

In Case 2, 8% of the incident solar radiation is transmitted to the room, which is lower than in Case 1. The absorbed radiation increased to 86% but the secondary heat that entered the room decreased to 13%. The total solar heat gain is consequently 21% of the incident solar radiation. The convection heat transfer from the cavity also decreased from 16% to 11%. In Case 3, the transmitted amount is reduced to 7% of the solar radiation and the secondary heat that enters the room is also 12%. Therefore, the total solar heat gain is 19% of the incident solar radiation, the smallest of the three cases. Convection heat transfer in the cavity is also the smallest at 10% of the incident solar radiation.

Table 4: Outer glass properties in three cases

	Name	Thick ness (mm)	Solar transmittance (dimensionless)	Reflectance outside (dimensionless)	Reflectance inside (dimensionless)	Emissivity inside (dimensionless)	Emissivity outside (dimensionless)
Case 1	Clear glass	6	0.765	0.073	0.073	0.837	0.837
Case 2	Color (green) glass	6	0.485	0.057	0.057	0.837	0.837
Case 3	Low-emissivity glass	6	0.390	0.231	0.309	0.837	0.057

In general, Case 2 and Case 3 have lower total solar heat gain than Case 1. In Case 2, the total solar heat gain is reduced by 27%, whereas the reduction is 35% for Case 3 compared to Case 1. However, it was observed that not only the total solar heat gain, but also the heat released as convective heat transfer in the cavity was reduced. This means that when the outer glass type is changed, the overall thermal performance of the SDSF can be improved, even though the buoyancy ventilation in the cavity is less active.

Figure 9: CFD results of temperature distribution in Case 2 and Case 3

Conclusion

In this study, we analyzed the heat transfer of the SDSF in detail using CFD simulations to provide building designers with both an in-depth understanding and basic data for optimization of the performance of the SDSF. Numerous previous studies have analyzed the heat transfer mechanism of the DSF, but this study is different in that it analyzes a window with a very slim cavity, as is the case of an SDSF.

Based on the results of the full-scale experiment, it was determined that the temperature difference between the lower and upper part of the cavity was approximately 6 °C. It was also observed that this temperature stratification caused buoyancy ventilation of the SDSF.

Analysis of the heat transfer mechanism of the SDSF using CFD simulations revealed that 13% of incident solar radiation entered the room in the form of short-wave radiation. In addition, solar radiation absorbed into the glass enters the room in the form of long-wave radiation and convection. This represents 14% and 2% of the incident solar radiation, respectively. However, free convection in the cavity released 16% of the solar irradiation received by the façade. This is a significant amount and demonstrates the effectiveness of the cavity of an SDSF in reducing the secondary heat flow into a room. It is necessary to investigate ways of improving the efficiency of the cavity ventilation in the future.

As a result of the parameter study according to the type of outer glass, it was determined that the total solar heat gain was reduced by 27% colored glass is used compared to clear glass. When low-emissivity outer glass was used, the total solar heat gain was reduced by 35% compared to clear glass. The decrease in the total solar heat gain implies that the indoor cooling load is reduced. Therefore, it is advantageous to use colored or low-emissivity outer glass to improve cooling performance with SDSF.

One of the limitations of this study is that only the type of outer glass was investigated among the possible parameters. In the future, it is necessary to optimize the performance of SDSF by studying other parameters including the vent size, cavity width, and cost.

Finally, this study included an analysis of the steady-state condition by choosing a summertime point such that the performance of the SDSF could be maximized to prevent an increase of the cooling load through the transparent envelope. However, the cavity of the SDSF may pass through the cold outside air during winter, which may increase the indoor heating load.

Therefore, further study is required to analyze the heat transfer of SDSF in the winter. Ultimately, the annual energy evaluation of SDSF will be performed.

Figure 10: Calculated heat flow for three cases

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