Optimal Control of Circuit type Double Skin Façade using Air Conditioning Exhaust in a Cascade Manner

Yuko Morishige[1], Yasuyuki Shiraishi[1]

1 The University of Kitakyusyu
1-1 Hibikino, Wakamatsu, Kitakyusyu, Fukuoka
Japan 808-0135

ABSTRACT

In recent years, there has been increasing number of cases using the double skin façade to satisfy both the indoor views and energy saving. In summer, the double skin façade has a heat shielding effect by exhausting solar heat through natural ventilation and in winter, in addition to the thermal insulation effect by the air layer, a heat collecting effect of solar heat can also be expected. On the other hand, the natural ventilation performance of the double skin façade in summer strongly depends on the outdoor conditions, making it difficult to achieve a stable heat shielding effect. Additionally, high thermal insulation effectiveness is difficult to determine since the air layer is directly influenced by outdoor air temperatures. For this reason, the school facility that is the subject of this study is improving its envelope performance by introducing air conditioning exhaust from classrooms into the circuit-type double skins and using it as a cascade manner. The objective of this paper is to verify the basic performance of this circuit-type double skin façade by unsteady computational fluid dynamics (CFD) analysis, then to propose an optimal control method to improve the effect of reducing the skin load and to clarify its effectiveness by the analysis. In this control, exhaust of air conditioning system cascading into the double skin façade and the direction of airflow (clockwise or counterclockwise) are switched to reduce the skin load by predicting the skin load.

The following results were obtained,

1) It was confirmed that air temperature in double skin façade was stabilized and heat-load from the surface of buildings was reduced by cascade use compared to a typical double skin façade.
2) Since introduction of the proposed optimal control method makes it possible to select the optimum operation mode, thermal transmission load reduction effect was further improved.

KEYWORDS

School Building Cascade Manner Double Skin Facade Unsteady CFD analysis

1 INTRODUCTION

In recent years, there have been an increase in the number of cases that use a double-skin façade to satisfy both indoor views and energy savings. In the summer, a double-skin façade has a heat shielding effect by exhausting solar heat through natural ventilation. In addition to the thermal insulation effects by the air layer in the winter, heat collecting effects from solar heat can also be expected. Various field surveys and simulations have been conducted to understand this thermal performance. However, the natural ventilation performance of a double-skin façade in the summer strongly depends on the outdoor conditions, making it difficult to achieve a stable heat shielding effect. Additionally, high thermal insulation effectiveness is difficult to determine since the air layer is directly influenced by outdoor air temperatures.

Hence, this study aimed to examine and improve the envelope performance of a double-skin façade installed on the extension building by introducing air conditioning exhaust into the circuit-type double skin and using it in a cascade manner. The double-skin façade used in this study is not a typical double-skin façade; it is instead a circuit-type double skin façade that utilises the air conditioning exhaust for the double-skin that encloses the building. Since there are no similar design cases or previous studies, it is unclear whether the assumed performance can be achieved. Therefore, we performed computational fluid dynamics (CFD) analysis on the circuit-type double skin façade using a cascade method to understand its basic performance. To improve the unsteady, real operational performance of the circuit-type double skin façade, we propose an optimal control method that minimises or maximises the effects of solar radiation in each direction, which varies from time to time, that will clarify the effectiveness through unsteady CFD analysis.

2 VERIFICATION OF BASIC PERFORMANCE

2.1 Overview of the subject building and system

An overview of the subject building is shown in Table 1, and a plan of the second floor of the building and an overview of the system are shown in Figure 1. The subject of this study is a circuit-type double skin façade that is installed on the second-floor perimeter.

Table 1: Overview of the subject building

Site	Tokyo, Japan
Construction	Steel Frame, Steel-framed Reinforced Concrete, Reinforced Concrete
Purpose	School
Floor number	1F-3F
Total floor space	Existing building : 11,138 m^2, Extension building : 2,700 m^2
Completion year	September, 2022

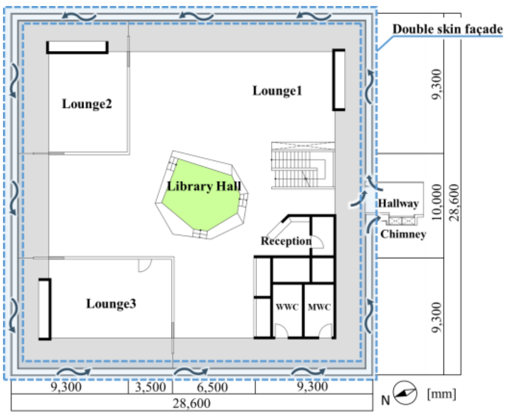

Figure 1: Plan of the second floor and overview of the system

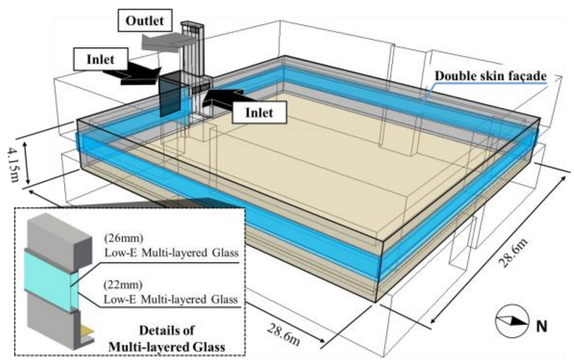

Figure 2: Analysis model of the system

2.2 CFD analysis model

The CFD analysis model is shown in Figure 2. The space to be analysed is the double skin façade on the second floor of the extension building and the corridor, which includes the chimney. The unsteady basic performance of the circuit-type double skin façade was clarified by CFD analysis.

2.3 Analysis conditions and cases

The analysis conditions are shown in Table 2. The analysis period was 3 days, including pre-analysis (2 days), and the analysis time interval was 5 s. The indoor boundary conditions for the inner glazing were 28 °C in the summer and 22 °C in the winter. The outer glass boundary condition was given Sol Air Temperature (SAT) that accounts for solar radiation, and the inner glass was given the heat absorption of solar radiation as volumetric heat value. This reproduced the effect of solar radiation on the double-skin façade.

The analysis cases are shown in Table 3. CASE 1 series were for the summer and CASE 2 series were for the winter; CASE 1-1 was the natural ventilation mode with top and bottom openings, CASE 2-1 was the adiabatic mode, and CASE 1-2 and CASE 2-2 were the modes with cascade use. By comparing these modes, we verified the effect of cascade use on the reduction of the thermal transmission load from surfaces of the building. The representative days are selected from expanded Automated Meteorological Data Acquisition System (AMeDAS) weather data for the standard year: sunny days with high solar radiation load in the summer, and cloudy days with low solar radiation heat in the winter.

Table 2: Conditions for CFD analysis

Domain	32.6m(x)×28.6m(y)×9.35m(z)	
Mesh	128(x)×121(y)×65(z)=1,006,720	
Turbulence Model	Standard k-ε model	
Inlet boundary conditions	Extension building	Flow rate:1,505×2 ㎥/h Temperature:28℃(summer),22℃(winter)
	Existing building	Flow rate:890 ㎥/h Temperature:28℃(summer),22℃(winter)
	$k_{in} = (U_{in}/10)^2$, $\varepsilon_{in} = C_a^{3/4} \cdot k_{in}^{3/2}/l_{in}$	
Outlet boundary conditions	Fixed velocity, zero-gradient condition	
Boundary conditions	Velocity	Logarithmic law
	Temperature	Indoor：Summer 28℃, Winter 22℃ (Convective heat transfer coefficient:9W/㎡ K)
		Outdoor：Standard year weather data for Tokyo (Overall heat transfer coefficient:23W/㎡ K)

U_{in} ：Outlet air wind speed[m/s], k_{in} ：Outlet air turbulence energy[㎡/s²]
ε_{in} ：Dissipation rate of k_{in}[㎡/s³], C_μ ：Model constant(=0.09)[-], l_{in} ：Length scale[m]

Table 3: Analysis cases

	Operation mode	Inlet temperature	Day
CASE1-1	Natural ventilation mode	Outdoor air temperature	Aug. 29 （Sunny day）
CASE1-2	Cascade mode	28℃	
CASE2-1	Airtight(Adiabatic mode)	-	Jan. 16 （Cloudy day）
CASE2-2	Cascade mode	22℃	

2.4 Analysis results

A time series of the thermal transmission load for the air conditioning operating hours for each case are shown in Figure 3.

Compared to CASE 1-1 with natural ventilation, CASE 1-2 with cascade use increased the thermal transmission load in the mornings when outdoor temperatures were low but reduced thermal transmission load by an average of 66% and a maximum of 79% during the hours of high outdoor temperature and high solar radiation load. This confirms the effects of cascade use in the summer, which reduced the thermal transmission load from the building surfaces. A comparison of CASE 2-1 with airtight and CASE 2-2 with cascade use revealed that the thermal transmission load loss in the morning, when the outdoor temperature was low, was significantly reduced by using the cascade, with an average reduction of 42% and a maximum reduction of

49%. This also confirms that cascade use in the winter season can reduce the thermal transmission load from the building surface.

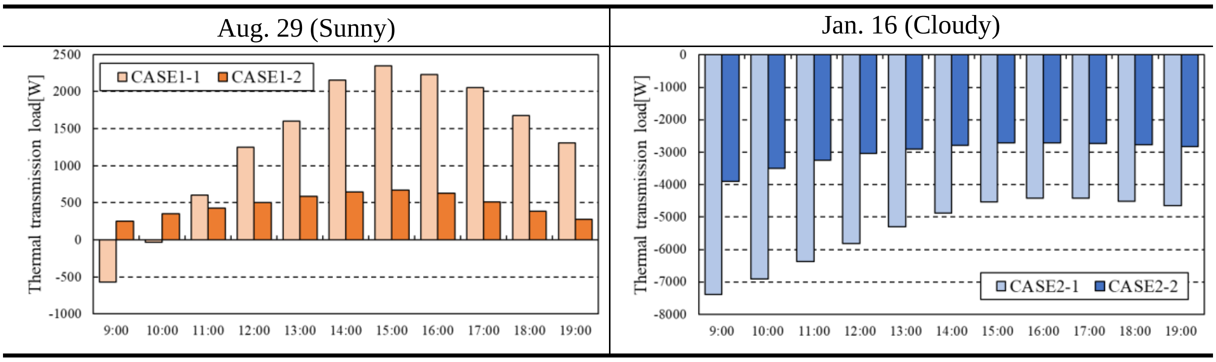

Figure 3: Thermal transmission load by time for each case

3 OPTIMAL CONTROL OF CIRCUIT-TYPE DOUBLE SKIN

Here, we proposed and verified an optimal control method to further improve the envelope performance of the double skin façade. The solar radiation load on the double skin façade in each direction changed from moment to moment. Therefore, by changing the flow direction in the double skin façade at different times of the day, it was possible to suppress the rapid temperature rise or drop near the air inlet in the around the corridor.

3.1 Overview of optimal control methods

In this analysis, the following four modes of operation were proposed. ① Basic mode with cascade use as designed, ② reverse mode with clockwise double-skin flow, ③ outside air introduction mode (outside air is introduced directly into the double-skin façade), and ④ a mode to stop the introduction of air conditioning exhaust and to collect solar radiation heat instead. An optimization flow diagram is shown in Figure 4. For optimal control, each mode was selected according to the situation to determine the daily operation schedule: In STEP 1, the disturbance of the next day was estimated (utilising weather forecasts); in STEP 2, the objective function (thermal transmission load) based on a one-dimensional heat transfer model was minimised to determine the optimal hourly operation mode. The next day, when the air-conditioning system in the extension building was put into operation, the double skin façade was utilised according to the operational schedule determined in STEP 2 (STEP 3). After STEPS 1–3 were completed, the process returns to STEP 1 again, and the optimal control repeats this process.

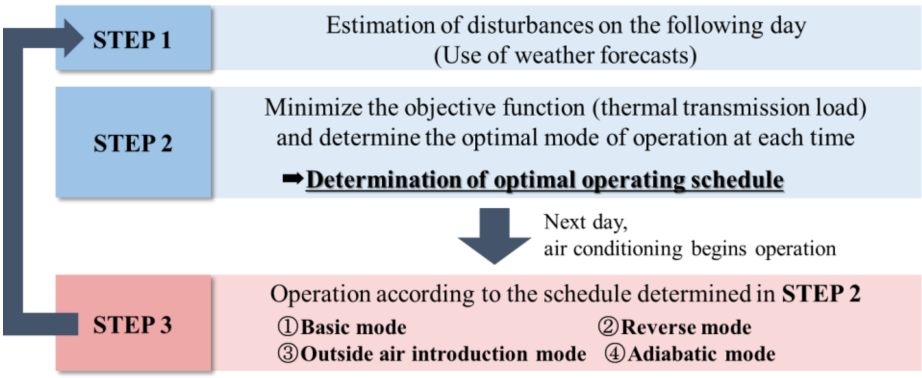

Figure4: Optimization flow

3.2 Overview of analysis

The CFD analysis model is the same as in Figure 2. The analysis cases were CASE 3-1, in which the system operated with optimal controls (Fig. 4); CASE 3-2, in which the system operated in basic mode (①) all day; and CASE 3-3, in which the system operated in reverse mode (②) all day. The analysis period was four days, with the first two days of operation in the basic mode as a run-in period, and the latter two days were cloudy and sunny days in each case.

3.3 Analysis results

Figure 5 shows the thermal transmission load by time of day for each representative day and Figure 6 also shows the cumulative value of the thermal transmission load for the day when the air conditioning was in operation. The results of CASE 3-1 are shown as plots, and the results of CASE 3-2 and 3-3 are shown as bar graphs. By introducing outside air and suppressing the temperature rise in the double skin façade on cloudy days, the thermal transmission load at 1:00 p.m. after changing the operation mode was reduced. The cumulative value of thermal transmission load per day was reduced by 6 MJ when compared to that in CASE 3-2. This

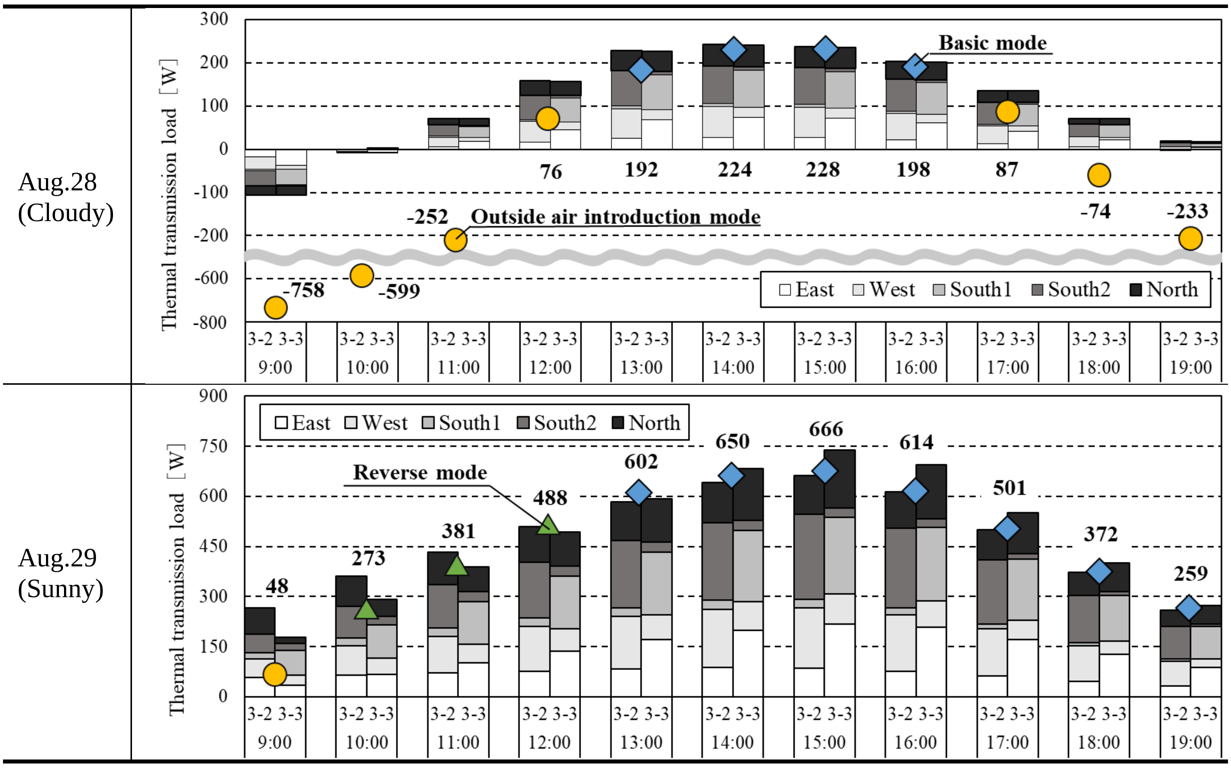

Figure 5: Thermal transmission load by time

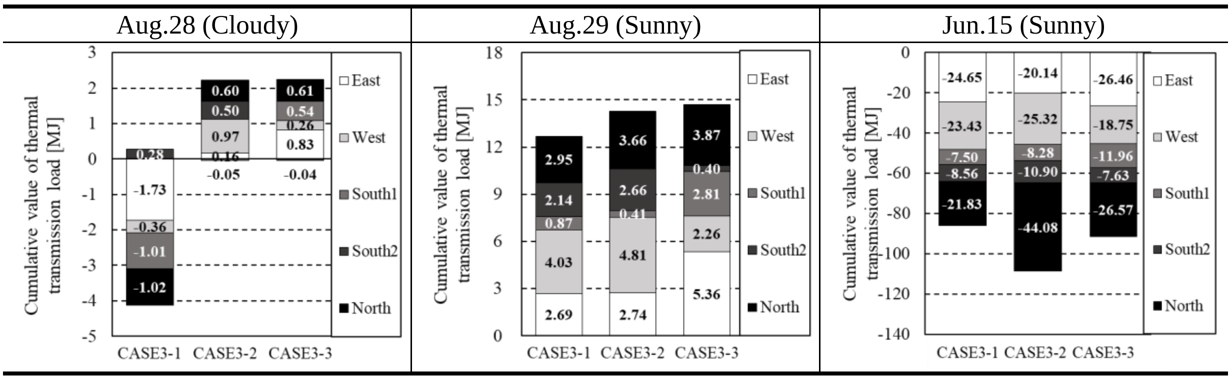

Figure 6: cumulative value of thermal transmission load

suggests that the introduction of outside air may significantly reduce the air conditioning load on cloudy days. On a sunny day, the thermal transmission load decreased after changing the operation mode at 10:00 a.m., as on a cloudy day, but increased after changing the operation mode at 1:00 p.m. This is presumably due to the time required to process the hot air near the outlet just before the switch. The cumulative value of the thermal transmission load per day in CASE 3-1 was reduced by 1.6 MJ compared to that in CASE 3-2, suggesting the possibility of reducing the envelope load by changing the flow direction of the double skin as appropriate.

Similarly, in the winter season, the cumulative value of the thermal transmission load per day was reduced by 22.7 MJ compared to that in CASE 3-2, suggesting the possibility of reducing the envelope load by collecting solar heat during the daytime when the peak of solar radiation gain, while changing the flow direction in the double skin as appropriate. These results confirm the effectiveness of the optimal control method using the four operational modes proposed in this study.

4 CONCLUSIONS

We clarified the basic performance of the circuit-type double skin with the cascade manner and verified the effectiveness of the proposed optimal control method to reduce the envelope skin load.

1) It was confirmed that the air temperature in the double skin was stabilised, and the thermal transmission load from the building surfaces was reduced by cascade use compared to a typical double skin.
2) Introduction of the proposed optimal control method makes it possible to select the optimal operation mode, thus improving the reduction effects of thermal transmission.

5 ACKNOWLEDGMENT

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