

Effectiveness of Reducing Heating and Cooling Load by Using Double-skin Facade Coupling the Earth-to-air Heat Exchanger

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ABSTRACT: A double-skin facade was adopted in the Izumi Media Building of Meiji University located in Tokyo in order to reduce the noise and dust emanating from an expressway which runs by the south side of the building, as well as for energy conservation purposes. For similar reasons, the bottom of the double-skin facade of the south side was connected to a subterranean pit for seismic isolation, which allowed for the introduction of outside air from the north side. In this paper, field measurements were performed in order to study the effectiveness of reducing the thermal load on the double-skin. Furthermore, the improvement of the performance of the thermal load reduction by combining the use of the double-skin with an earth-to-air heat exchanger was studied by numerical simulation. Compared to other window systems (single skin), the double-skin was confirmed to be highly effective with respect to reducing the thermal load due to its superior ability to shade solar radiation in summer and to reduce heat loss caused by thermal transmission in winter. Compared to the case where only a double-skin was used, the combined use of the double-skin and the earth-to-air heat exchanger improved the effectiveness of reducing thermal load by about 33%, owing to the fact that air which is cooler than outside air in summer or warmer than outside air in winter can be introduced into the double-skin. In summary, it was demonstrated that the combined use of a double-skin facade and an earth-to-air heat exchanger utilized the subterranean pit efficiently and improved the effectiveness of reducing thermal load on the double-skin.

Keywords: Double-skin facade, Earth-to-air heat exchanger, Numerical simulation, Field measurement, Conservation of heating and cooling load

1. Introduction

The energy consumption of commercial and residential buildings accounts for 25% of the total energy consumption in Japan. In commercial buildings, 40% to 50% of the energy in the entire building is consumed by air conditioning systems. Recently, there have been concerns that the popularization of glass architecture is likely to increase the thermal load from outer surfaces of the skin. In this regard, the double-skin design is considered as a countermeasure to this problem.

Double-skin facades feature an external double-glass cover. In summer, solar radiation is

blocked by shading devices, such as venetian blinds located between double glass walls, and excess heat can be exhausted by natural ventilation, thus reducing the solar heat gain in rooms. In winter, the air between the double walls is not exhausted, creating an effect similar to the greenhouse effect, which can reduce heat loss caused by thermal transmittance. On the other hand, the double-skin has its disadvantages. It is considered that the heat gain by thermal transmission increases, especially at higher floors, since the temperature in the double-skin increases in summer. In regions with a warm climate and an excess of solar radiation, the

temperature in the double-skin increases, and heat needs to be exhausted by ventilation even in winter.

On the other hand, heat loss caused by thermal transmission is considerable, especially at lower floors, since cool outside air inflows from the lower apertures into the double-skin. Consequently, by connecting an earth-to-air heat exchanger, which introduces cool or warm air from outside into the double-skin, the increase in air temperature in summer in the upper parts and the drop in air temperature by influent outside air in winter in the lower parts of the double-skin can be reduced, thus increasing the performance of the double-skin.

This paper describes the results of field measurements performed in summer and winter on the abovementioned university building, which features a combination of a double-skin and an earth-to-air heat exchanger. In addition, the effects of reducing the thermal load on the double-skin were studied. Furthermore, the increase in performance caused by the combined use of the double-skin and the earth-to-air heat exchanger was studied by numerical simulations.

2. Overview of the double-skin and the earth-to-air heat exchanger

The building subjected to the field measurements was Izumi Media Building of Meiji University located in Tokyo, which is a 7-story building. A double-skin facade was adopted for the building in order to reduce the noise and dust emanating from an expressway which runs on the south side of the building, as

well as for energy conservation purposes. For similar reasons, it was decided that the place of intake of outside air for introduction to the south double-skin must not be on the south side. Therefore, the bottom of the south double-skin was connected to a subterranean pit for seismic isolation, as shown in the A-A' section in Figure 1, which allowed the introduction of outside air from the north side. The air which passes through the pit is introduced to the south double-skin. Figure 2 shows the plan of a typical floor (4F). The south and north facades utilize the double-skin.

Figure 3 shows the south and north elevations. The south double-skin is of the multistory type (1-7F). It is 80.0m in width from east to west, and 36.5m in height. The upper aperture of the south double-skin has pivot windows, and its opening area aggregate is 55m². The north

double-skin is also of the multistory type (3-7F). It is 80.0m in width from east to west, and 26.7m in height. Finally, the opening area aggregate of the upper aperture of the north skin. Figure 2 shows the plan of a typical floor (4F). The south and north facades utilize the double-skin. Figure 3 shows the south and north elevations. The south double-skin is of the multistory type (1-7F). It is 80.0m in width from east to west, double-skin is 55m², which is the same as the south double-skin. The double-skin consists of clear float glass. The thickness of the outer glass is 10mm, and that of the inner glass is 6mm. The distance between the outer and the inner glass is 1075mm. There are light-colored venetian

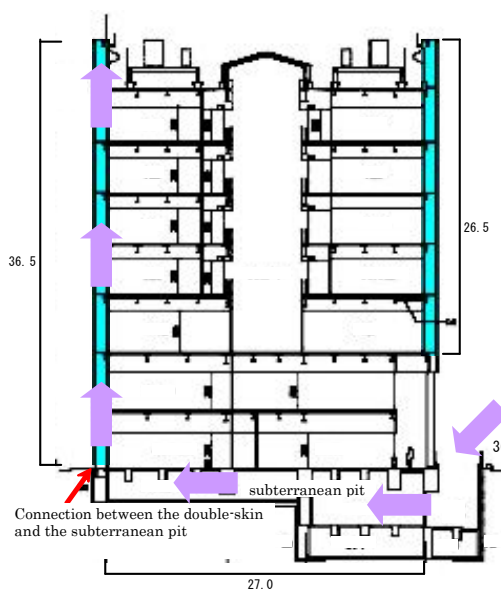


Figure 1: A-A' section of the building

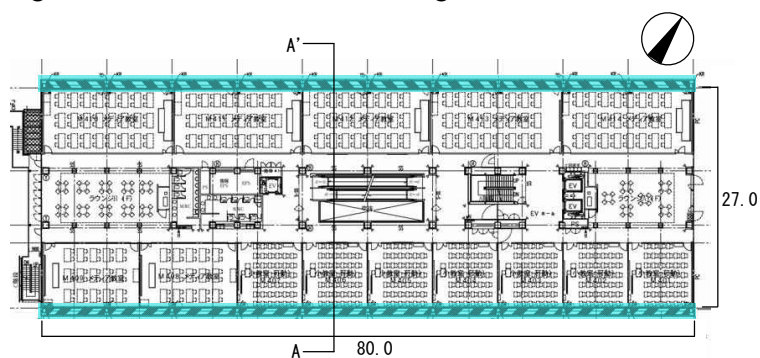


Figure 2: Plan of a typical floor (4F)

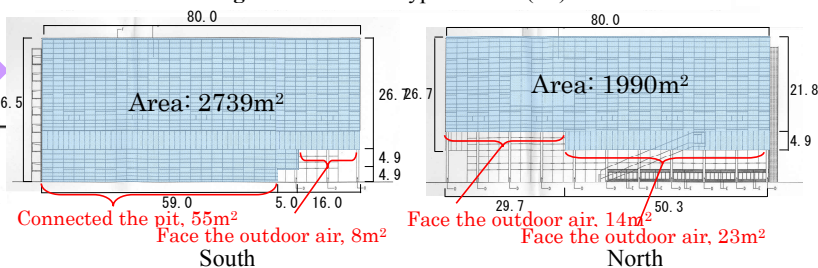


Figure 3: Elevations

Table 1: Points of measurement in summer

Point	Instrument	Measuring object	Number	Point	Instrument	Measuring object	Number
Pit	Thermo couple	Air temperature in pit	11	4F	Data logger	Room air temp. and humidity	1
	Thermo couple	Surface temperature in pit	5		Globe thermometer	Globe temperature in room	1
1F	Data logger	Air temperature in DS	5		PMV meter	PMV in room	1
	Data logger	Room air temperature	1		Pyrheliometer	Amount of solar radiation in DS	3
2F	Thermo couple	Air temperature in DS	16	5F	Data logger	Air temperature in DS	5
	Thermo couple	Glass surface temperature	3		Data logger	Room air temperature	1
	Data logger	Air temperature in DS	4	6F	Thermo couple	Air temperature in DS	16
	Data logger	Room air temperature	1		Thermo couple	Glass surface temperature	3
3F	Data logger	Air temperature in DS	5		Data logger	Air temperature in DS	4
	Data logger	Air temperature in DS	4		Data logger	Room air temperature	4
	Data logger	Room air temp. and humidity	1		Data logger	Room air temp. and humidity	1
	Globe thermometer	Globe temperature in room	1		Anemometer	Wind speed in DS	4
	PMV meter	PMV in room	1	7F	Data logger	Air temperature in DS	5
4F	Thermo couple	Air temperature in DS	52		Data logger	Room air temperature	1
	Thermo couple	Glass surface temperature	3		Data logger	Air temperature in DS	1
	Data logger	Air temperature in DS	4	Penthouse	Pyrheliometer	Amount of solar radiation	1
	Data logger	Room air temperature	12		Data logger	Ambient temp. and humidity	1

blinds on the side of the inner glass of the double-skin, where the position and the angle of their slats are coordinated with electric operation. When the air temperature at the top of the double-skin exceeds a preset temperature (26°C in summer, 22°C in winter), the upper and the lower apertures are opened, and the excess heat is released from the double-skin.

The earth-to-air heat exchanger (the subterranean pit for seismic isolation), combined with the south double-skin, is 27m in length (north-south direction), about 80m in width (east-west direction), and 2.6m in height, and thus occupies a relatively large space. In this way, the subterranean pit can be used efficiently, and it can be said that the effectiveness of the reduction of the thermal load on the double-skin is improved since the heat exchanged in the earth-to-air heat exchanger can be introduced into the double-skin.

3. Outline of the field measurements

The measurement periods were set between August 23 and August 30, 2005 in summer and between February 28 and March 8, 2007 in winter. The measurements focused on the double-skin, and the time interval between each measurement was 5 minutes. Tables 1 and 2 show the points of each measurement in summer and winter.

During the summer measurement period, the air temperature in the rooms on each floor and the surface temperature of the window glass on 2F, 4F and 6F in the center of the south side of the building were measured. In the rooms on 4F, the amount of solar radiation at two points in the double-skin and one point in the room in the window portion were measured. Furthermore, during the winter measurement period, the items which were measured were similar, although the number of measurement points was reduced.

Table 2: Points of measurement in winter

Point	Instrument	Measuring object	Number
Pit	Data logger	Air temp. and humidity in pit	6
4F	Data logger	Room air temp. and humidity	2
	Data logger	Air temperature at air outlet	2
	Data logger	Air temperature at air inlet	2
	Globe thermometer	Globe temperature in room	2
	PMV meter	PMV in room	2
7F	Thermo couple	Air temperature in DS	12
	Thermo couple	Glass surface temperature	6
	Data logger	Room air temp. and humidity	5
	Data logger	Air temperature at air outlet	5
	Data logger	Air temperature at air inlet	5
	Globe thermometer	Globe temperature in room	4
	PMV meter	PMV in room	4
	Pyrheliometer	Amount of solar radiation in DS	6
Penthouse	Data logger	Ambient temp. and humidity	1
	Pyrheliometer	Amount of solar radiation	3

The central monitoring system kept a log of the weather condition, the air temperature and the wind speed in the double-skin, the condition of the apertures of the double-skin, and so on. These data were also used in the analysis below.

4. Thermal characteristics of the double-skin and the earth-to-air heat exchanger

4.1 Thermal Performance of double-skin

Figure 4 shows the outdoor temperature and the amount of solar radiation during the summer measurement period. The outdoor temperature, which was measured on the roof of the building, was 36.8°C at maximum, 21.6°C at minimum, and 27.2°C on average. The amount of south vertical solar radiation 920W/m² at maximum, and the integrated amount of solar radiation per day in vertical direction on the south side was 3.4kWh/(m²·day) on average. Figure 5 shows the outdoor temperature, the air temperature in the south double-skin and the air exchange rate of the south double-skin. The air exchange rate was calculated by dividing the amount of air exchange obtained from the wind speed at the 7F level, by the airspace of the double-skin. At the level of 7F (32.3m in height), the temperature rose to 46.2°C at maximum, in

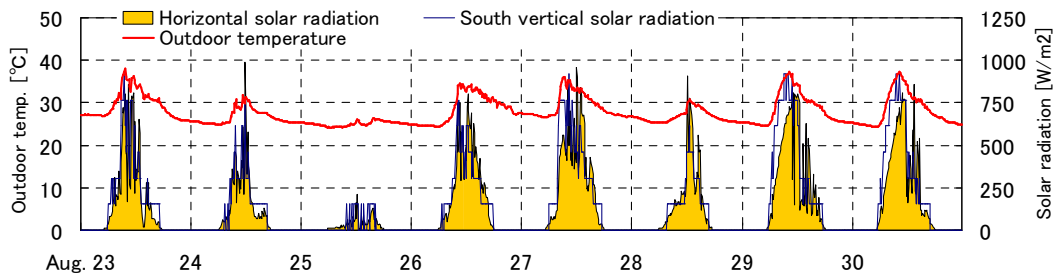


Figure 4: Outdoor conditions during summer measurement

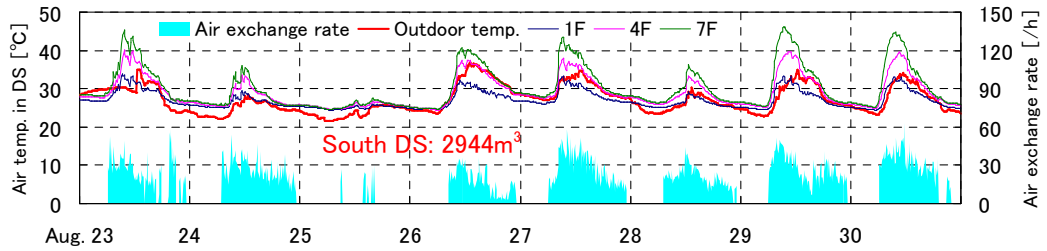


Figure 5: Aspect of south DS in summer

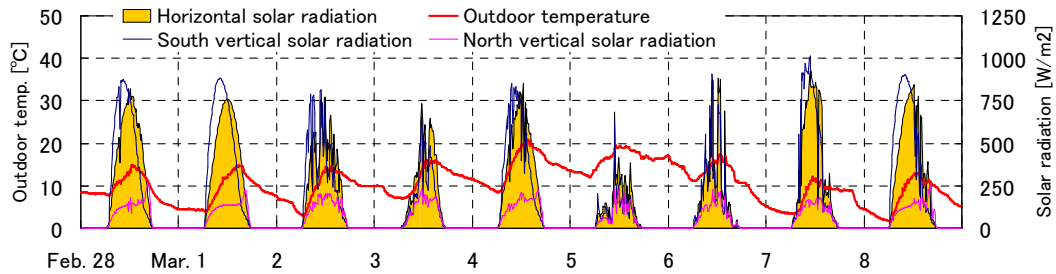


Figure 6: Outdoor conditions during winter measurement

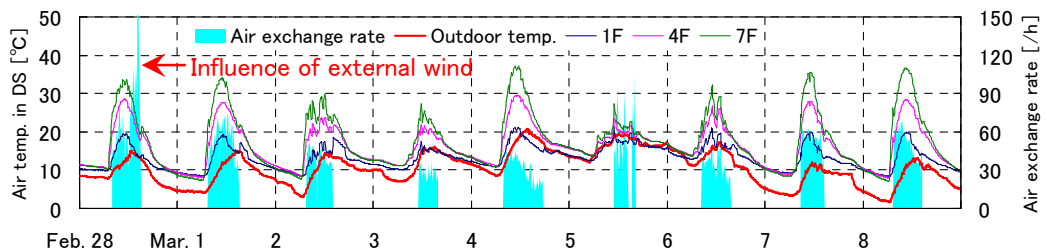


Figure 7: Aspect of south DS in winter

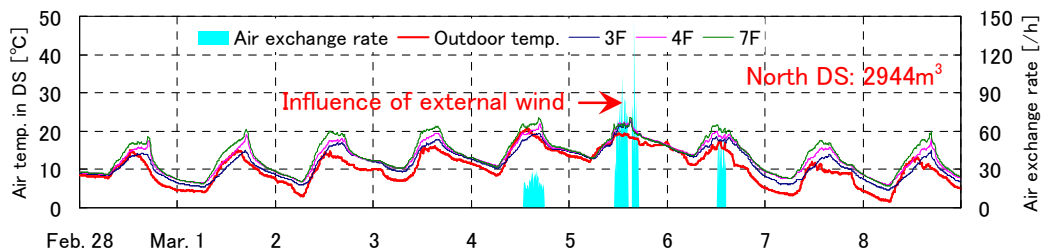


Figure 8: Aspect of north DS in winter

which the difference in temperature in comparison with the 1F level (4.6m in height) was about 14°C at maximum. The air exchange rate was 25.5/h on average. The air temperature in the north double-skin was 38.7°C at maximum, and the air exchange rate was 31.6/h on average.

Figure 6 shows the outdoor temperature and the amount of solar radiation during the winter measurement period. The outdoor temperature was 20.8°C at maximum, 1.3°C at minimum, and 10.6°C on average. The amount of south vertical solar radiation was 1017W/m² at the maximum, and the integrated amount of south

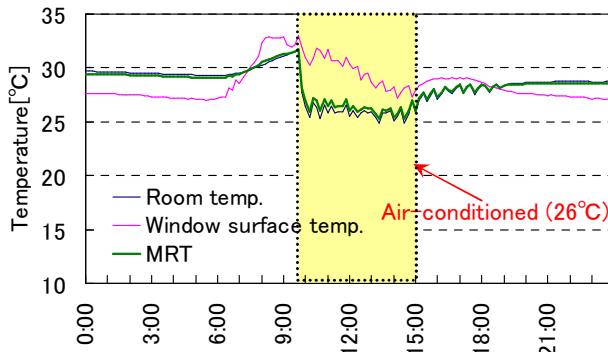


Figure 9: Thermal environment of south room (6F) on Aug. 29

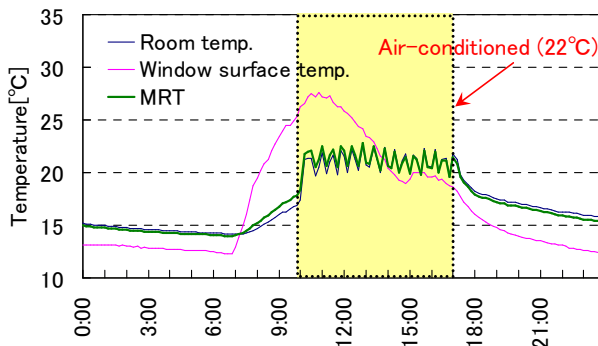


Figure 10: Thermal environment of south room (7F) on Feb. 28

vertical solar radiation per day was $4.0\text{kWh}/(\text{m}^2 \cdot \text{day})$ on average. Furthermore, the north vertical solar radiation was $273\text{W}/\text{m}^2$ at maximum, and the integrated amount of north vertical solar radiation per day was $1.3\text{kWh}/(\text{m}^2 \cdot \text{day})$ on average. Figures 7 and 8 show the outdoor temperature, as well as the air temperature and the air exchange rate in the south and north double-skins. At the 7F level, the temperature in the south double-skin rose to 37.1°C at maximum, and the difference with the temperature at the 1F level was about 17°C at maximum. On the other hand, the temperature at the 7F level in the north double-skin rose to 23.5°C at maximum, and the difference with the temperature at the 3F level (14.4m in height) was about 6°C at maximum. Usually, double-skins are operated with their apertures closed in winter. However, when the air temperature in the double-skin becomes too high, the apertures sometimes need to be opened in order to exhaust the excess heat in the double-skin. During the measuring period, the apertures of the south double-skin were open for a total of 60 hours, and the air exchange rate was $45.4/\text{h}$ on average. On the other hand, the apertures of the north double-skin were open for a total of 12 hours in daytime within the two-day period from March 5 to March 7, and the air exchange rate was $42.5/\text{h}$ on average.

Figures 9 and 10 show the measured values of the air temperature in the rooms, the temperature

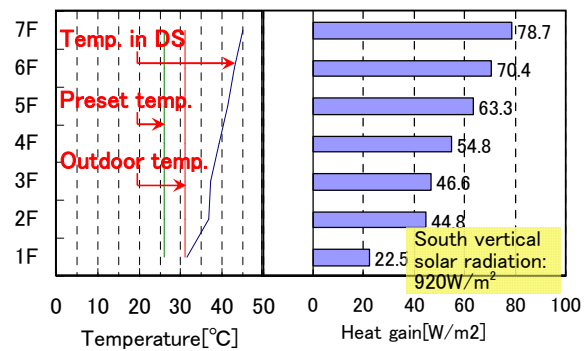


Figure 11: Heat gains of south rooms on Aug. 29 10:00

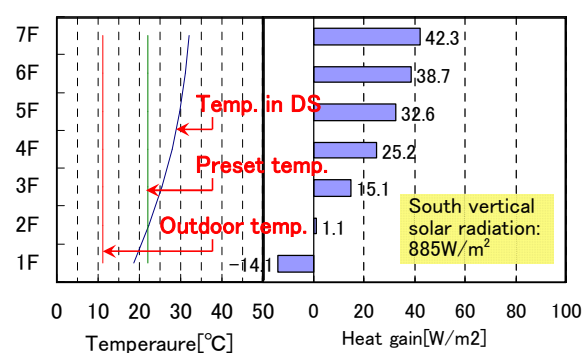


Figure 12: Heat gains of south room on Feb. 28 10:00

of the window glass surfaces, and the mean radiant temperature MRT^{*1} in the rooms located on the south side (6F in summer, 7F in winter) on August 29 and February 28, respectively. On these days, the rooms were air-conditioned, and since the amount of solar radiation was relatively high throughout the day, the venetian blinds in the double-skin were closed in both occasions. Although deterioration of the thermal environment on the upper floors in buildings with multistory-type double-skins does occur, it was not considered in this investigation.

Figures 11 and 12 show the heat gain from window surfaces in the rooms on each floor in summer (August 29 10:00) and in winter (February 28 10:00), respectively. In the case of August 29, the 7F rooms received nearly 3 times more heat transferred via vertical temperature distribution than the 1F rooms. On February 28, the air temperatures in the double-skin on the 2F level and above were higher than 22°C , which is the preset temperature of the rooms, and the heat transferred from window surfaces was considered as thermal gain.

4.2 Effects of reducing the thermal load on double-skin

The effects of reducing the thermal load on the double-skin was studied by comparing the heat gain or loss^{*2} from window surfaces of the double-skin with that of other window systems (single skin). Table 3 shows specifications^[1] of

the compared window systems, and Table 4 shows heat gains into the room from thermal transmission and solar light in the south double-skin at 10:00 and 16:00 on August 29 in comparison to the single-skin systems.

On August 29, due to the rise in air temperature in the double-skin, the heat gain into the room due to thermal transmission increased. However, the double-skin effectively blocked the solar radiation. In particular, at 10:00, when there was a large amount of solar radiation, the effectiveness of the double-skin with respect to blocking the solar radiation was prominent.

Table 5 shows the heat loss from the room caused by thermal transmission in the south double-skin at 10:00 and 16:00 on February 28 in comparison to single-skin systems. At 10:00, when the amount of solar radiation was large, the room gained heat. However, at 16:00, when the amount of solar radiation was small, the effectiveness of the double-skin was superior to other systems with respect to heat insulation. Taking the air-conditioning period as the interval from 8:00 to 18:00, Figures 13 and 14 show the integrated amount of heat gain on August 29 and the integrated amount of heat loss on February 28, respectively. Compared to the HF+BD system, which has the most effective thermal performance, the double-skin exhibited a 37% reduction of heat gain on August 29 and 86% reduction of heat loss on February 28.

4.3 Cooling and heating effects of the earth-to-air heat exchanger

The cooling and heating effects of the outdoor air based on the earth-to-air heat exchanger effect were studied by using data collected by the central monitoring system. The studied periods were from June 10 to September 20,

2005 (summer) and from November 20, 2006 to March 8, 2007 (winter).

For this study, we used the data for the air temperature at the outdoor air inlet on the north side of the building (earth-to-air heat exchanger inlet), the air temperature at the south double-skin inlet (earth-to-air heat exchanger outlet), and the volume of air which passed through the earth-to-air heat exchanger was calculated from the wind speed in the south double-skin at the 7F level and the condition of the apertures.

Figure 15 shows the fluctuations in the inlet and the outlet of the earth-to-air heat exchanger and in the amount of exchanged heat. During the summer measurements (Fig. 15, upper part), the apertures of the south double-skin were open for 1666 hours, and the volume of air which passed through the earth-to-air heat exchanger was 56,845 m³/h on average. The average air temperature of the earth-to-air heat exchanger was 26.3°C at the inlet and 24.9°C at the outlet. Furthermore, the average temperature drop was about 1.4°C (8.9°C at maximum) in summer. On the other hand, during the winter measurements (Fig. 15, lower part), the apertures of the south double-skin were open for a total of 443 hours,

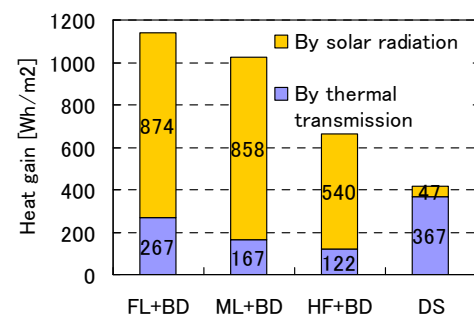


Figure 13: Integrated amount of heat gain on Aug. 29

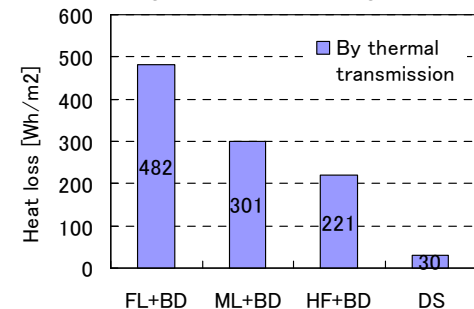


Figure 14: Integrated amount of heat loss on Feb. 28

Table 3: Specifications of the compared window systems

Window systems		Overall heat transfer coefficient	Shading Coefficient
FL+BD	Float glass + light-colored inner blinds	4.8 [W/m ² ·K]	0.55
ML+BD	Double-glazed glass (layer of air: 6mm) + light-colored inner blinds	3.0 [W/m ² ·K]	0.54
HF+BD	Highly-insulated double-glazed glass (layer of air: 6mm) + light-colored inner blinds	2.2 [W/m ² ·K]	0.34
DS	Double-skin	Undefined	Undefined

Table 4: Comparison of heat gains into the room on Aug. 29

Window systems	10:00 on August 29				16:00 on August 29			
	FL+BD	ML+BD	HF+BD	DS	FL+BD	ML+BD	HF+BD	DS
Heat gain by thermal transmission [W/m ²]	24.0	15.0	11.0	54.4	28.8	18.0	13.2	22.6
Solar heat gain [W/m ²]								
Radiation + convection	197.3	193.7	122.0	9.1	26.2	25.7	16.2	0.0
Transmission of solar radiation								
Heat gain [W/m ²]	221.3	208.7	133.0	63.6	55.0	43.7	29.4	22.6

Table 5: Comparison of heat losses from the room on Feb. 28

Window systems	10:00 on February 28				16:00 on February 28			
	FL+BD	ML+BD	HF+BD	DS	FL+BD	ML+BD	HF+BD	DS
Heat loss by thermal transmission [W/m ²]	52.3	32.7	24.0	-20.1	49.9	31.2	22.9	19.2

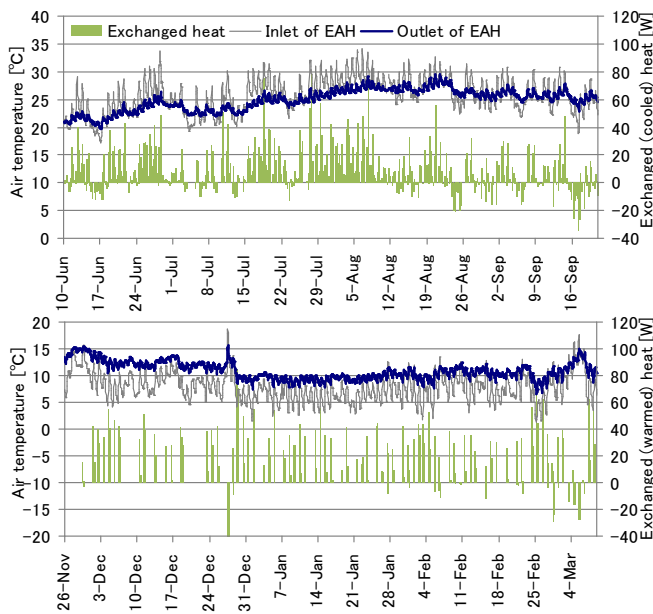


Figure 15: Cooling and heating effects of EAH

which was considerably shorter than during the summer measurements, and the volume of air which passed through the earth-to-air heat exchanger was 116,938 m³/h on average.

The average air temperature of the earth-to-air heat exchanger at the inlet and the outlet were 9.0°C and 10.5°C, respectively, and the average temperature rise was about 1.5°C (5.1°C at maximum) in winter. The air introduced into the earth-to-air heat exchanger was heated when the air temperature at the inlet was lower than about 20°C in summer, and was cooled when the air temperature at the inlet was higher than about 14°C in winter. However, it was confirmed that outdoor air introduced in the double-skin was cooled in summer and heated in winter by the earth-to-air heat exchanger most of the time during each period. The amount of heat received through the operation of the earth-to-air heat exchanger was 7.0 kW on average (78.4 kW at maximum) in summer and 15.8 kW on average (85.2 kW at maximum) in winter.

5. Effects of the combined use of a double-skin and an earth-to-air heat exchanger

As shown in Section 4.3, air which is cooler than the outside air in summer and warmer than the outside air in winter can be introduced into the double-skin through the connection between the lower aperture on the south double-skin and the subterranean pit. Consequently, it is considered that the efficiency of reducing the thermal load on the double-skin can be improved in both summer and winter if the double-skin is used together with the earth-to-air heat exchanger.

On the other hand, when the earth-to-air heat exchanger is combined with the double-skin, the air resistance of the subterranean pit can restrict the ascension of air current into the double-skin. There is a possibility that the effectiveness of the double-skin is reduced since not enough natural ventilation occurs, which results in a higher air temperature in the double-skin. Therefore, the effectiveness of the combined use of the double-skin and the earth-to-air heat exchanger was evaluated and verified quantitatively with the following numerical analysis model.

5.1 Outline of the numerical analysis model of the double-skin

Figure 16 shows the outline of the numerical analysis model^{*3[2]} which was used in this study. The outer glass, the inner glass, the blinds and the layer of air which comprise the double-skin were divided into a finite number of segments heightwise. In addition, the convective heat transfer, the radiation, the advective flow, the presence of multiple reflections of solar radiation and the mutual radiation were taken into account for the heat balance of each member.

For the glass and the blinds, the variation in the transmittance according to the incidence angle of direct solar radiation was taken into account for the transmittance, reflectance, and absorption of light. Furthermore, the wall and the grating in the double-skin, which absorb solar radiation and re-radiate it as heat, were ignored.

Figure 17 shows the flow of the numerical calculation. The input and output conditions are shown in the left part of Fig. 17. The temperatures of the members and the air in each segment were calculated, and the amount of ventilation was obtained from the temperature distribution of the air in the double-skin. This process was repeated, and steady convergent solutions were obtained at each iteration.

5.2 Validity assessment of the numerical model

For the summer and winter measurement periods shown in Section 4.3, the measured values of the outside air temperature, the flux of global solar radiation, and the air temperature of the lower aperture of the double-skin (outlet of the earth-to-air heat exchanger) were assigned, and the thermal behavior of the double-skin was simulated.

The air temperatures in the rooms were set to 26°C in summer and 22°C in winter, and the

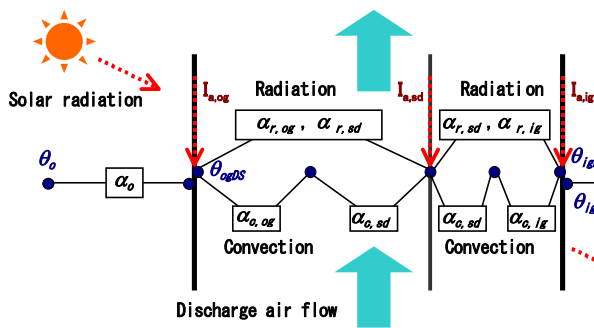


Figure 16: Outline of the numerical analysis model

Table 6: Calculation conditions

Physical value		Value
Azimuth angle of double-skin	[°]	-33.0
Inclined angle of double-skin	[°]	90.0
Height of double-skin	[m]	36.5
Thickness of outer glass	[mm]	10.0
Thickness of inner glass	[mm]	6.0
Thickness of outer air layer divided by blinds	[m]	0.9
Thickness of inner air layer divided by blinds	[m]	0.1
Slat angle of blinds	[°]	45
Solar transmittance of blinds	[-]	0.1
Solar absorptance of blinds	[-]	0.6
Emissivity of blinds	[-]	0.95
Emissivity of glass	[-]	0.837
Flow coefficient of lower aperture	[-]	0.23
Area of lower aperture	[m ² /m]	0.34
Flow coefficient of upper aperture	[-]	0.30
Area of upper aperture	[m ² /m]	0.69
Ground reflectance	[-]	0.14

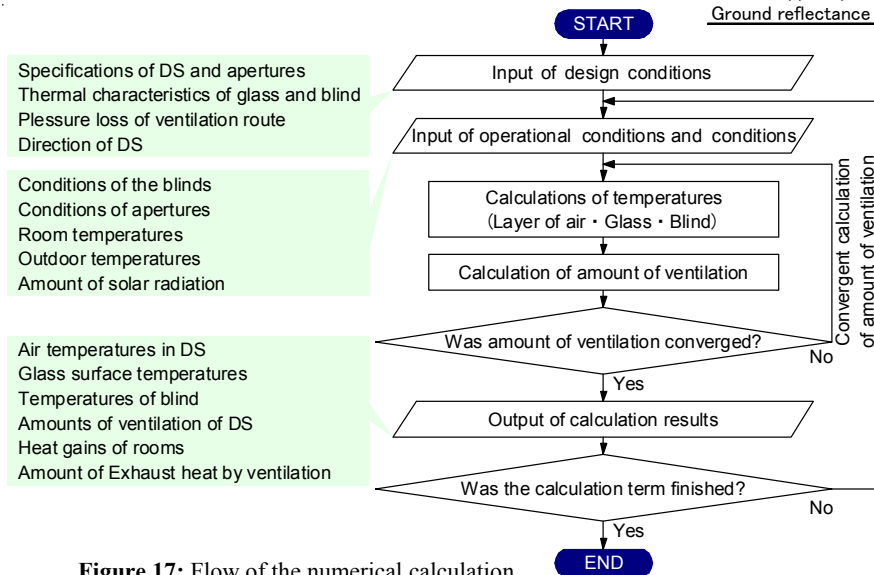


Figure 17: Flow of the numerical calculation

declination of the slats of the venetian blinds was set to 45 deg. In addition, the calculation conditions used in the analysis are shown in Table 6. The flow coefficients of the upper and the lower apertures of the double-skin were given the values in Table 6, and the friction and form resistance of the earth-to-air heat exchanger ($\zeta=18.6$) was taken into account for the lower aperture.

Figures 18 and 19 show the results of the simulation. For the summer and winter calculation periods, the calculated mean temperature in the double-skin (Fig. 18) was slightly lower than the measured value. The differences in temperature were 3.0°C on average in summer and 4.4°C on average in winter. It is considered that although the room air temperatures used in the simulation were 26°C in summer and 22°C in winter, not all rooms were air-conditioned, which indicates that the temperatures used in the simulation differed from the temperature in the rooms which were in direct contact with the double-skin of the building.^{*4}

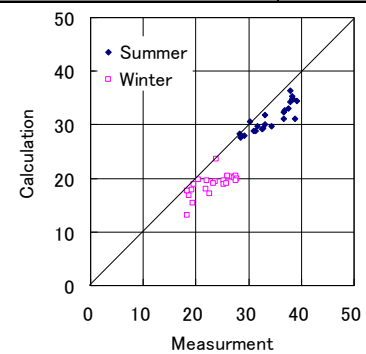


Figure 18: Mean temp. in DS

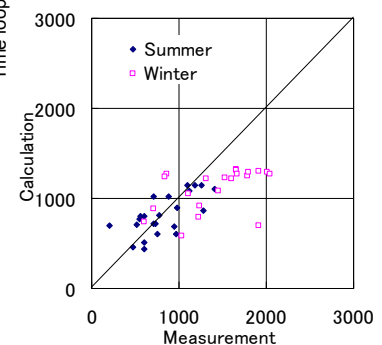


Figure 19: Amount of ventilation in DS

The calculated amount of ventilation in the double-skin (Fig. 19) was smaller than the measured value by about 1% in summer and by about 32% in winter. Although the differences were large for the winter measurements, the reason for this was considered to be due to the differences between the room temperatures used in the simulation and the actual room temperatures as described above. In addition, it can be said that this numerical model can reproduce the thermal behavior of the double-skin.

5.3 Effectiveness of the combined use of an earth-to-air heat exchanger and a double-skin

The effectiveness of the combined use of the earth-to-air heat exchanger and the double-skin was examined through a numerical simulation.

Table 7: Simulation cases

	With EAH	Without EAH
Air temperature of DS inlet	Input temp. of EAH outlet	Input outdoor temp.
Flow coefficient of DS inlet	0.23	0.57

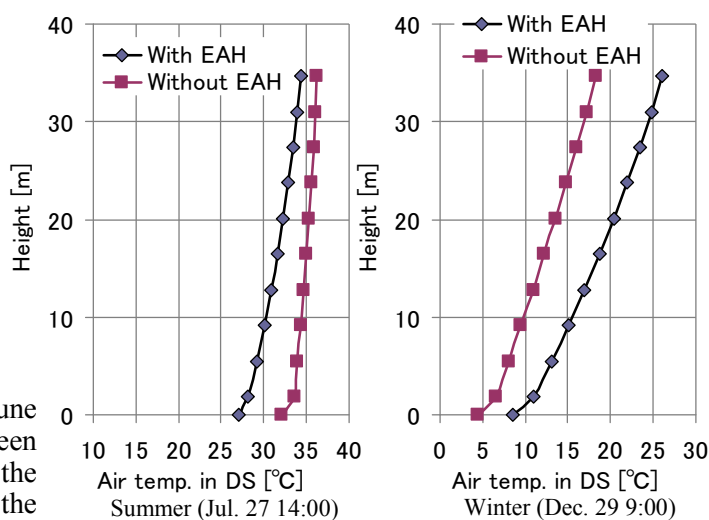
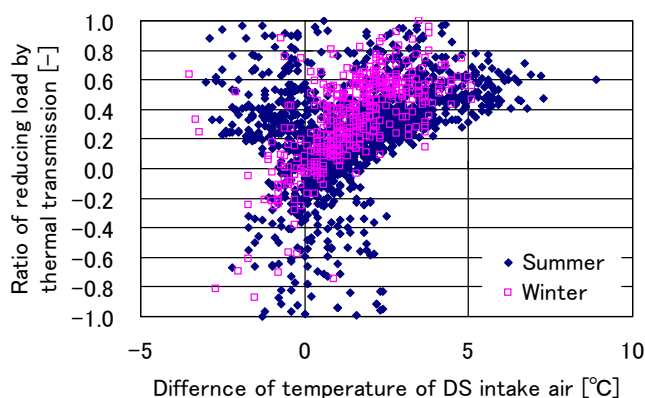
Table 8: Effects of combination use with EAH

Heat gain by transmission [W/m ²]	14:00 on July 27	9:00 on December 29
With EAH	23.2	-11.9
Without EAH	37.2	-39.3
Ratio of reduction	37.6%	69.7%

The calculation periods were set between June 10 and September 20, 2005 and between November 20, 2006 and March 8, 2007, and the outside air temperature, the temperature at the outlet of the earth-to-air heat exchanger, the amount of solar radiation and the conditions of the apertures of the double-skin as recorded by the central monitoring system of the building were used in the simulation.

Table 7 shows the simulation cases. In this examination, the cases with and without the earth-to-air heat exchanger were simulated and compared. In the case where the earth-to-air heat exchanger was not used, the temperature at the inlet of the earth-to-air heat exchanger was taken as the temperature of the lower aperture of the double-skin. Then, the flow coefficient of the lower aperture was given a value which did not include the resistance of the earth-to-air heat exchanger.

Figure 20 shows the vertical temperature distribution in the double-skin for a typical day in summer and winter. The typical times were set to 14:00 on July 27 in summer and in 9:00 on December 29 in winter, when the cooling or heating effects of the outside air brought by the earth-to-air heat exchanger were the largest. In summer (Fig. 20, left), the air temperature introduced into the double-skin dropped by 5.1°C, and therefore the average temperature in the double-skin dropped by 3.4°C and the temperature at the top floor level dropped by 1.9°C. On the other hand, in winter (Fig. 20, right), the temperature of the air introduced into the double-skin increased by 4.2°C, and therefore the average temperature in the double-skin increased by 6.4°C. From the comparison of the two cases, the respective amounts of ventilation at the typical time in summer and winter when the earth-to-air heat exchanger was used was smaller by about 16.4% and 39.1% than in the case without the earth-to-air heat exchanger. It was shown that the impact of the resistance of the earth-to-air heat exchanger is

**Figure 20:** vertical temp. distribution in DS for a typical day**Figure 21:** Relation between the effects of AEH and reducing thermal transmittance load

large in winter, when the amount of natural ventilation is comparatively large. Subsequently, the heat gain and loss of the rooms associated with thermal transmittance were calculated from the results in Figure 20. The thermal conductions were calculated with the differences in temperature in the double-skin and the rooms, and the overall heat transfer coefficient*⁵ of the inner glass and blinds.

The results are shown in Table 8. The combined use of the earth-to-air heat exchanger reduced the thermal transmittance gain and loss at the typical time in summer and winter by 37.6% and 69.7%, respectively. Figure 21 shows the relation between the temperature decrease or increase of the intake air caused by the earth-to-air heat exchanger, as well as the effect of reducing the thermal transmittance gain or loss from the windows for the entire period of the summer and winter measurements. The effectiveness of reducing the thermal transmittance load from the windows is proportional to the extent of decrease or increase

of air intake by the double-skin caused by the combined use of the earth-to-air heat exchanger and the double-skin. Consequently, it was ascertained that the combined use of the earth-to-air heat exchanger had the additional effect of reducing the thermal transmittance load from the windows by 32.7% for the entire period of summer and winter, as compared with the case without the earth-to-air heat exchanger.

6. CONCLUSION

The field measurements and the numerical analysis performed in this study confirmed the effectiveness of the combined use of the earth-to-air heat exchanger and the double-skin. It was also confirmed that the double-skin is more effective at reducing the thermal load as compared to the case of single skin due to its superior effectiveness in blocking solar radiation in summer and reducing heat loss by thermal transmission in winter.

According to the results of the numerical analysis, the effect of adopting a double-skin design can be improved further by combining it with an earth-to-air heat exchanger. Future studies will examine the effectiveness of the double-skin design under different weather conditions.

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APPENDIX

*1 The mean radiant temperature (MRT) was calculated by using the emissivity of the window surface, the inner wall surface, taken as 1.0, and the surface temperature of the inner wall, excluding the windows, which is assumed to be equal to the air temperature in the room.

*2 Calculation of the heat gain of the room

-For single skin

Heat gain by thermal transmittance = $U_{ss} * (\theta_o - \theta_i)$

Heat gain by solar radiation = $SC * I_G$

-For double-skin

Heat gain by thermal transmittance = $U_{ig} * (\theta_{air} - \theta_i)$

Heat gain by solar radiation = I_T

θ_i : 26°C in summer, 22°C in winter

U_{ig} : Reffer to *5

*3 The heat balance equations for the double-skin

Heat balance equation for layer of air in DS

$$\rho c V \frac{\partial \theta_{air}}{\partial z} = \alpha_c (\theta_{ogDS} - \theta_{air}) + \alpha_c (\theta_{igDS} - \theta_{air}) + 2\alpha_c (\theta_{sd} - \theta_{air})$$

Heat balance equation for the outer glass

$$\alpha_o (\theta_{og} - \theta_o) + \int_{S_{ogds}} \alpha_r G_{ss'} (\theta_{ogDS} - \theta_{ss'}) ds' + \alpha_c (\theta_{ogDS} - \theta_{igDS}) = I_{aog}$$

Heat balance equation for the blind

$$\int_{S_{ogds}} \alpha_r G_{ss'} (\theta_{sds} - \theta_{ss'}) ds' + \int_{S_{sdi}} \alpha_r G_{ss'} (\theta_{sds} - \theta_{ss'}) ds' + 2\alpha_c (\theta_{sd} - \theta_{air}) = I_{asd}$$

Heat balance equation for the inner glass

$$\int_{S_{sdi}} \alpha_r G_{ss'} (\theta_{igDS} - \theta_{ss'}) ds' + \alpha_c (\theta_{igDS} - \theta_{air}) + \alpha_i (\theta_{ig} - \theta_i) = I_{aig}$$

*4 Only some rooms were air-conditioned since both measurement periods in summer and winter coincided with the respective vacations. The preset temperatures of the air conditioners were 26°C in summer and 22°C in winter. In summer, the temperature in the non-air-conditioned rooms appeared to be higher than 26°C. However, it is conceivable that the temperature in non-air-conditioned rooms in winter was higher than 22°C, which was the preset temperature, since the heat loss via thermal transmission was reduced and solar radiation penetrated into the rooms.

*5 The overall heat transfer coefficient of the 6mm thick inner clear float glass and the blinds of double-skin (U_{ig}) was calculated using thermal resistances^[1] of blinds (aluminum), layer of air and inner glass, and heat transfer coefficients of blinds surface and indoor surface of inner glass. Heat transfer coefficient of blinds surface was calculated using Jürges equation for rough surface, and fluctuation of air velocity in the double-skin was took into account.

NOMENCLATURE

θ : Temperature [°C], α : Heat transfer coefficient [W/(m²·K)], V : Amount of ventilation [m³/(s·m)], c : Specific heat of air [kJ/(kg·K)], ρ : Density of air [kg/m³], G : Coefficient of emission for absorption [-], SC : Shading coefficient [-], I_G : Standard solar gain [W/m²], I_a : Amount of absorbed solar radiation [W/m²], U_{ss} : Overall heat transfer coefficient of single skin system [W/(m²·K)], U_{ig} : Overall heat transfer coefficient of inner glass and the blind of DS [W/(m²·K)]

-subscript

o : Ambient, i : Room, og : Outer glass, ig : Inner glass, sd : Blind, air : Air, $igDS$: DS side surface of inner glass, $ogDS$: DS side surface of outer glass, c : Convection, r : Radiation, DS : Double-skin, SS : Single-skin