

INDOOR AIR AND THERMAL ENVIRONMENT OF ENVIRONMENT-FRIENDLY HOUSE BY PASSIVE DESIGN IN JAPAN

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ABSTRACT

In recent years, with actualization of a global warming issue, the need for simultaneous pursuit of progress of comfort in living space at residential house and energy saving is now becoming greater and greater. In this study, we investigated the indoor thermal environment and air distribution by natural ventilation at earth sweet home in summer, middle and winter seasons in Japan. This house is designed so that the effect of natural ventilation may become high. We report the results with focus on the effects of indoor thermal and air environment by opening window in middle season. By using a skylight, it is showed that the cross-ventilated air volume is increased and the effect of SET* fall is high at the second floor room in this house. Also, this house is planed that the bathroom and the changing room protrude on the north side. Since this bulge has achieved the window catcher's effect, it has succeeded in passing indoor the wind is blown from the east side which is a predominant wind direction in this region. As a result, in indoor habitation space, it turned out that the air distribution environment of suitable wind velocity is formed in the wide range. Moreover, it is shown by here that the effect of the SET* fall by a cross-ventilated air is high similarly. In addition, we report that effects of heating insulation of whole in house, double sliding screen and thermal storage floor in summer and winter season too. As a result, through every year, to outside-air-temperature change, change of room temperature is small and has proved insulative effect, and also indoor thermal environment is improved by using double sliding screen in both seasons. And, the improvement effect of the thermal environment is acquired by gaining solar radiation heat from thermal storage floor in this measured house. From here onwards, it is thought that the energy saving effect of winter is fully expectable by gaining solar radiation heat from thermal storage floor.

KEYWORDS

Passive design, Natural ventilation, Cross-ventilation, Taiko-shoji, Thermal storage floor

1 INTRODUCTION

In recent years, Japan has an increasing demand for the compatibility between residential comfort and energy saving. That leads an increase of the number of the study cases about environment-friendly house, and double skins and solar chimneys recently receive much attention. In addition, the technological innovation in building equipments such as solar power generation and fuel cells is outstanding, and an idea of the energy storage with electric vehicles has appeared. However, the primary mind of architectural environmental engineering is that architectural planning methods (passive methods) predominantly make indoors comfortable and architectural equipments works complementally. So, it can be said that the effect of passive methods greatly influence on the effects of architectural equipments and the amount of consumption energy. This study therefore conducted a survey of an environment-friendly house which has some devices on the floor planning and kinds of passive technologies are installed on the house itself.

2 THE OUTLINE OF THE HOUSE

Fig.1 shows the floor plan and Table 1 shows the outline of the house. This house has no wall dividing rooms. A garage and SOHO are placed in the eastside of the house, but this study sets only the area west to the stairs for the target in this survey. In Japan, the solar elevation in summer is high and it is low in winter, so the balcony on the first floor functions as the eave for the living room on the ground floor. The eave enables to block sun rays in summer and to take sunlight inside of the room in winter. The floor of Room 1 adjacent to the veranda-like porch is a concrete thermal storage floor. Woods in the southern garden and the wall greening block the sun rays in summer. Twofold shoji screens (Taiko-shoji) which involve airspace between them are installed inside of each window. The floor plan of the house also considers the gain of the cross-ventilation airflow. The wall surface of the washroom in the north functions as a wind catcher to send airflow effectively into the living room.

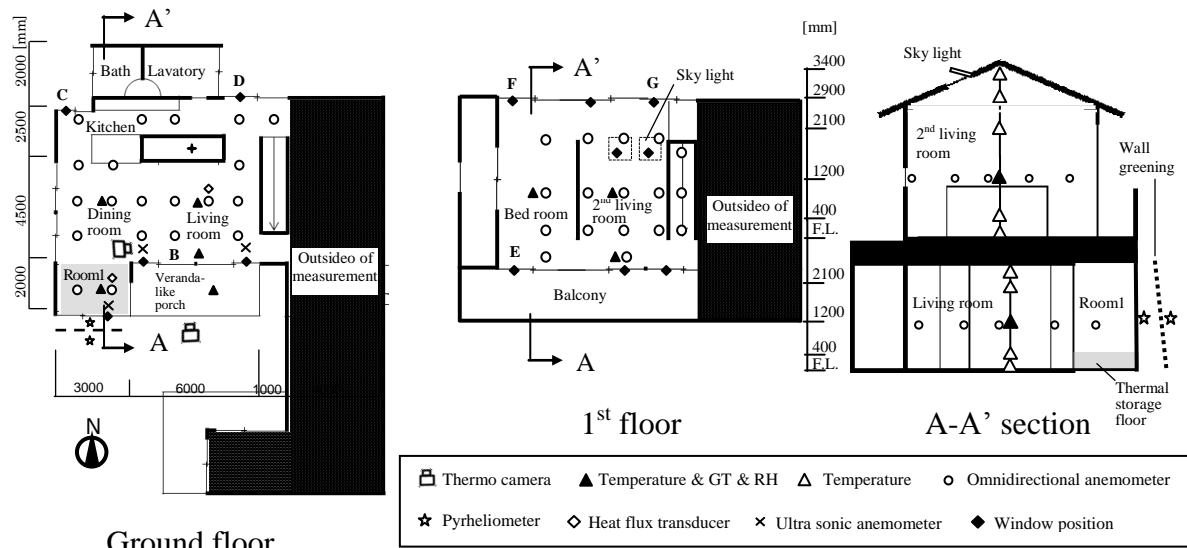


Figure 1. Plan, section and measurement point

Table 1. Outline of objective house

Location	Architecture	Measurement area
Kanagawa pref. JP	Two-story wooden house	Ground floor: 80.25 [m ²], 1 st floor: 45.50 [m ²]
Thermal storage floor spec		
Contexture: Tile (15mm) + Mortar (30mm) + Concrete (450mm)		
Taiko-shoji spec		
Contexture: Shoji paper (3mm) + Airspace (30mm) + Shoji paper (3mm), Shoji material: Wahron paper		
Sky light spec		
Low-e pair glass + inner window shade, Size: 970 [mm] * 970 [mm]		

3 OUTLINE AND RESULTS OF THE SURVEY

The survey was conducted in the 3 periods: summer (Aug.), mid-time (Sep. – Oct.), and winter (Dec. – Feb.). The main measurement items are shown in Table 2. Indoor temperature was measured with thermocouples and thermo recorders. Air velocity was measured with 3D ultrasonic anemometer and thermal omnidirectional anemometer. pyrheliometer were set in the front and back of the wall greening. A heat flux transducer was placed on the surface of the floor of Room 1 to measure heat flows. The followings are the detail conditions in each measurement periods.

Table 2. Measurement item and points

Item	Instrument	Measurement points	Interval
Indoor temp.	Thermocouple	GF: Ceiling, FL+0, 400, 1200, 2100 [mm]	1 [min]
		1F: Ceiling, FL+0, 400, 1200, 2100, 2900, 3400 [mm]	
Globe temp.	Globe thermometer	All rooms: FL+1200 [mm]	1 [min]
Heat flux	Heat flux transducer	Living room floor, Room1 floor	1 [min]
Solar radiation	Pyrheliometer	FL+1200 [mm]	1 [min]
Indoor RH	Thermo recorder	All rooms	30 [min]
Indoor air velocity	Omnidirectional anemometer	FL+1200 [mm]	1 [min]
Air velocity through window	Ultrasonic anemometer	Center of each window	1 [sec]
Outdoor climate		Wather observation station (Yokohama)	10 [min]

3.1 Outline of summertime measurement

The measurement in summer was conducted from August 8th till 22nd in 2011. From Aug. 8th till 17th was the period for the fundamental performance measurement of the house, and the distribution of indoor temperatures were examined without opening windows and Taiko-shoji. From Aug. 18th till 22nd, the measurement was conducted under the condition which assumes real-life situations, and indoor environment was controlled by using of windows, Taiko-shoji, and air conditioning. In this summertime measurement, adiabatic effectiveness of the building and Taiko-shoji, and insolation shielding effectiveness of the wall greening were considered.

3.2 Results and discussion of the summertime measurement

(1) The building's adiabatic effectiveness

Fig. 2 shows the temperature changes in vertical direction in the center of the living room on ground floor. The maximum difference in vertical direction was about 2 degrees C, and it can be judged as small. The change of indoor temperature in whole day was about 3 degree C on the ground floor, and it can be said as small. The first floor showed similar findings to the ground floor. From the results of temperature measurements in several measurement points, generally uniform thermal environment was formed, and this building's adiabatic effectiveness is considered to be high.

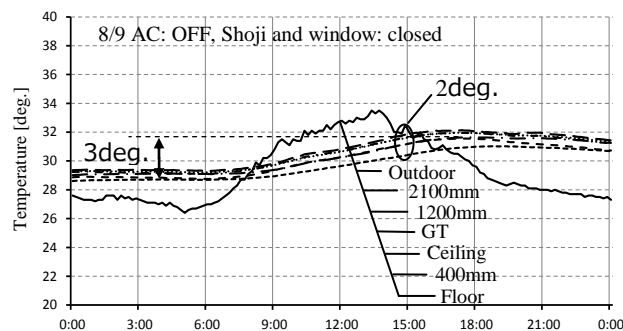


Figure 2. Temperature change at living room

(2) Adiabatic effectiveness of Taiko-shoji

Fig. 3 shows the deference ($= \Delta t$) between the external temperature and the indoor temperature in the center of the living room on the ground floor (1200 mm height). The data

of Aug. 11th when Taiko-shoji were open from 9 a.m. to 6 p.m. was compared with that of Aug. 9th when Taiko-shoji were closed all day. The difference between the external and indoor temperature ($=\Delta t$) on Aug. 11th rose and close to 0 line because of opening Taiko-shoji. Closing Taiko-shoji enables inside of room insusceptible to external temperature, so it is a good way to enhance adiabatic effectiveness.

(3) Insolation shielding effectiveness of the wall greening

Room 1 has no eaves to take a lot of sunlight into inside of it, and insolation in summer seems to influence on its indoor condition. Therefore, wall greening were installed in front of the window to consider their insolation shielding effectiveness. Fig. 4 shows the results of the amount of isolation in front and back of the green. Inside of the wall greening, the amount of isolation decreased more than 300W/m² (about 50% shielding effectiveness) in daytime. From this result, thermal load shielding effectiveness of the wall greening is big and have potential for energy saving effect.

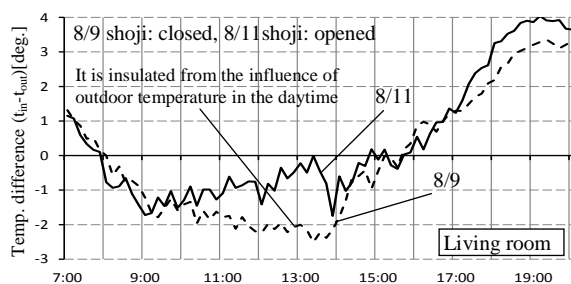


Figure 3. Heat insulating effect of Taiko-shoji

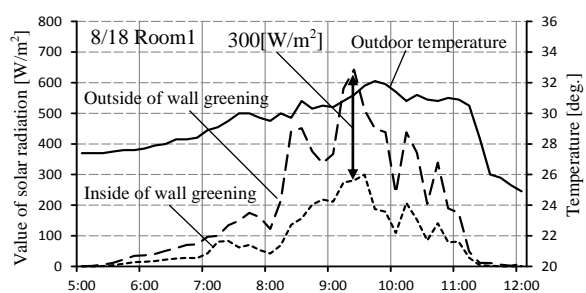


Figure 4. Insolation shielding effectiveness of the wall greening

(4) Consideration with integrated values of temperature differences

Table 3 shows the integrated values (degree C · hour) of the differences between indoor temperature with or without Taiko-shoji from 9 a.m. to 6 p.m. (in the center of each room , 1200mm height) and preset temperature of air conditioning (28 degree C). However, the data in the condition that the indoor temperature falls below the preset temperature were cut off. It is found from the table that about 17 (degree C · hour) decreased on the ground and first floor by closing Taiko-shoji. From this result, it can be said that Taiko-shoji has inhibiting effect of indoor temperature increase.

Table 3. Integrated values of temperature differences (Indoor temp. – 28 deg.) [degree * hour]

Condition		Ground floor		1 st floor	
AC	Shoji	Dining room	Living room	Bed room	Living room
OFF	Opened	44	45	69	66
	Closed	28	27	52	49
ON	Opened	0.3	0.4	-	-
	Closed	0.2	0.2	-	-

3.3 Outline of mid-term measurement

Mid-term measurement was conducted from Sep. 27th till Oct. 5th. In this season, external temperature decreases, and indoor environment can be improved with cross-ventilation. Windows were opened from 9:30 a.m. to 6:00 p.m. in this measurement. The windows which were chosen for opening are presented as A through G in Fig 1. Opening space of each

window were shown in Table 4. Temperature, globe temperature (GT), and relative humidity were measured in the center of each room. To examine the indoor air velocity distribution, thermal omnidirectional anemometer were placed at almost regular intervals as in Fig. 1 (25 points on ground floor, 18 points on 1st floor, 1200mm height). In addition, amount of passing air at the windows were measured by setting 3D ultrasonic anemometer at the center and in front of the window. SET was calculated with the values of temperature, GT, and relative humidity which were measured in the middle (1200mm) height in the room, and the average value of air velocity at 1200 mm height. The amount of clothing was set at 0.6 clo, and the amount of metabolism was set at 1 met. With combination use of the skylight which is characteristics of this house, the 8 patterns of window openings as in Table 5 were compared one another.

Table 4. Window opening area

	Window position						
	A	B	C	D	E	F	G
Area [m ²]	2.46	1.48	0.97	1.96	0.58	0.33	0.96

Table 5. Window opening pattern

Window	mode0	mode1	mode2	mode3	mode4	mode5	mode6	mode7
GF all	Closed	Opened	Opened	Opened	Opened	Closed	Closed	Opened
1F all	Closed	Opened	Opened	Closed	Closed	Opened	Opened	Opened(south side only)
Skylight	Closed	Closed	Opened	Closed	Opened	Closed	Opened	Closed

3.4 Results and discussion of mid-term measurement

(1) Comparison of amount of passing airflow at window

Table 6 shows the comparison of the air velocity in each opening pattern, and Table 7 shows the amount of airflow with and without the skylight. The data only in the case that the external wind direction and air velocity were almost equal were extracted for this comparison. The amount of passing air was at maximum in mode 2, and it was at minimum in mode 5. The windows of the wall surfaces on 1F are small, so it is found that opening these windows does not bring a big cross-ventilation effect. The amount of passing air increased by 35% in mode 2 in which the skylight is opened with all other windows compared with mode 1 with all the windows except of the skylight opened.

Table 6. Air volume through windows [unit: m³/h]

Window Position	mode1	mode2	mode3	mode4	mode5	mode6	mode7
South side	4793	6243	6580	5531	1968	2013	3905
North side	7399	10146	9039	7979	2355	4127	4282

Table 7. Air volume ratio depend on the presence or absence of skylight

Window Position	Mode2 / mode1	Mode4 / mode3	mode6 / mode5
South side	1.30	0.84	1.02
North side	1.37	0.88	1.75

Besides, the results of measurements with tracer-gas shows that air change rate increased by 1.5 times in the living room on the first floor by opening the skylight (Table 8). The results of this measurement show that opening both the skylight and windows on surface wall are expected to have a decreasing effect of indoor temperature and energy saving effects with air conditioning, in the case that external temperature is lower than indoor temperature.

Table 8. Air change rate of 1st floor living room

Ventilation Number [-/h]	mode1	Mode2
Living room (1 st Floor)	25.31	38.58

(2) Distribution of indoor air velocity

The distribution of indoor airflow velocity of each floor in mode 1 and 2 were shown in Fig. 5 and 6 respectively. In mode2, the air velocity at the northern window and the southern window is 1.5 and 1.8 times respectively as faster as that in mode 1 because of the influence of opening the skylight. In addition, the main wind direction during the measurements was north to east, and the eastern surface wall of the washing room works as a wind catcher in the northern part of the ground floor. So, the air velocity become very fast at the opening D on the ground floor. The average air velocity of each room is in Table 9. The result was different from that of passing air amount that the average air velocity was relatively big in mode 3 for the ground floor and in mode 5 for the 1st floor. In the residential area on the 1st floor, the average air velocity didn't change in mode 5 and 6 regardless of the additional opening of the skylight in mode 6. The factor of this result can be that airflow passed along with the surface walls and didn't pass through the residential area.

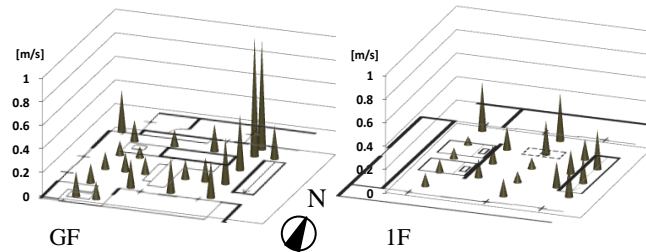


Figure 5. Indoor air velocity distribution (mode1)

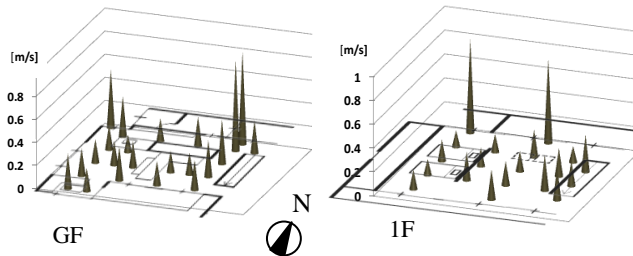


Figure 6. Indoor air velocity distribution (mode2)

Table 9. Averaged air velocity in each room [unit: m/s]

Room		mode1	mode2	mode3	mode4	mode5	mode6	mode7
GF	Dining room	0.15	0.21	0.26	0.18	-	-	0.15
	Living room	0.21	0.21	0.26	0.39	-	-	0.21
	Room1	0.17	0.23	0.51	0.31	-	-	0.19
1F	Living room	0.19	0.22	0.05	0.11	0.30	0.16	0.06
	Bed room	0.12	0.15	0.04	0.06	0.21	0.14	0.05

(3) Consideration with integrated values of temperature differences

Table 10 shows the integrated values (degree C · hour) of the differences between indoor temperature in each mode (in the center of each room , 1200mm height) and the external temperature from 9 a.m. to 6 p.m. Mode 0 with no window opened resulted in 27 degree C in average on the ground floor and 36 degree C in average on the 1st floor. By opening windows,

the temperature decreased both in the ground and 1st floor. In addition, the results of mode 5 and 6 show that opening skylight with the other windows decrease the temperature on the 1st floor more greatly than only the windows on surface walls. As mentioned above, energy saving effect is expected by opening both the skylights and windows on surface walls in the condition that external temperature is lower than indoor temperature.

Table 10. Integrated values of temperature differences (Indoor temp. – Outdoor temp.) [degree * hour]

Room		Mode0	Mode1	Mode2	Mode3	Mode4	Mode5	Mode6	Mode7
GF	Dining room	24	5	10	8	10	-	-	7
	Living room	28	7	11	9	10	-	-	8
	Room1	28	11	14	8	10	-	-	45
1F	Living room	34	13	14	-	-	20	15	24
	Bed room	38	17	17	-	-	23	18	21

(4) Comparison of SET* decreasing effect

In this part, SET* decreasing effect was considered with the formula in Fig. 7. Table 11 is the results of SET* decreasing effect in each mode. In the living room on the ground floor, with and without opening the skylight didn't show any apparent difference. In living room on the 1st floor, opening the skylight led indoor air velocity and produced bigger SET* decreasing effect than temperature difference decreasing effect mentioned before. Especially, SET* decreasing effect enhanced immediately after opening windows, so the thermal comfort enhancing effect of opening windows is considered to be great.

$$\text{Decrease ratio of the SET*} = \frac{\text{SET* in situation window closed} - \text{SET* in situation window opened}}{\text{Time taken to SET* decrease}}$$

Figure 7. Equation of decrease ratio of SET* [unit: degree / min]

Table 11. Decrease ratio of SET* results [degree / min]

	Mode0	Mode1	Mode2	Mode3	Mode4	Mode7
Living room (GF)	-0.01	-0.13	-0.13	-0.19	-0.17	-0.08
Living room (1F)	-0.01	-0.07	-0.20	-0.01	-0.10	-0.08

3.5 Outline of wintertime measurement

The wintertime measurement was conducted in the two times: from Dec. 26th, 2011 to Jan. 5th, 2012, and from Feb. 14th to 21st in 2012. Throughout the measurement period, the windows were not opened, and indoor environment was controlled by Taiko-shoji, floor heating, and air conditioning. This measurement reports the adiabatic effectiveness of the building and Taiko-shoji, and the effect of thermal storage floor.

3.6 Results and discussion of wintertime measurement

(1) The building's adiabatic effectiveness

Fig. 8 is the temperature distribution in vertical direction in the center of living room on the 1st floor. This is on the day with windows closed and without heaters, but Taiko-shoji in the living room on the ground floor was opened from 9 a.m. to 6 p.m. The temperature difference in vertical direction was about 2 or 3 degree C, that of whole day was about 6 degree C at maximum, and that at the same measurement point was about 4 degree C at maximum. These

changes are smaller than the external temperature changes, so the indoor temperature is not relatively influenced by the external temperature.

(2) Adiabatic effectiveness of Taiko-shoji

Fig. 9 is the temperature changes in the center of the living room on the ground floor on Dec. 31st, when Taiko-shoji was closed whole day. By closing Taiko-shoji, the difference of indoor temperature distribution became smaller. The differences in one day and at the same measurement point also became smaller as about 4 and 2 degree C at maximum respectively. Fig. 10 shows the difference between the indoor and external temperature in the living room (1200mm height) on the 1st floor in 2 cases: Case 1 in which Taiko-shoji was closed from 6 p.m. to 9 a.m. in the next morning, and Case 2 in which Taiko-shoji was opened in the same period of time. In Case 2, the indoor temperature drastically fell in about 4 degree C from midnight, and dropped in about 8 degree C at maximum after that. In Case 1, however, a rapid decrease of indoor temperature was not found, and the temperature showed gradual decline for 9 a.m. in the next morning.

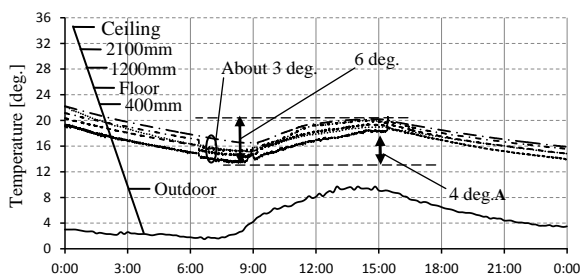


Figure 8. Temperature change at living room (12/27)

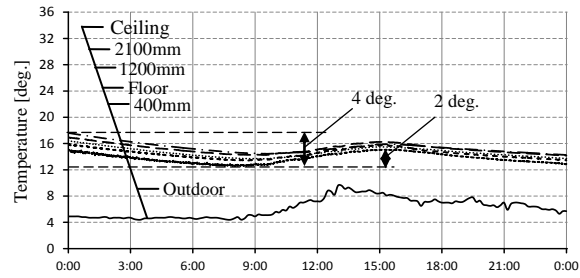


Figure 9. Temperature change at living room (12/31)

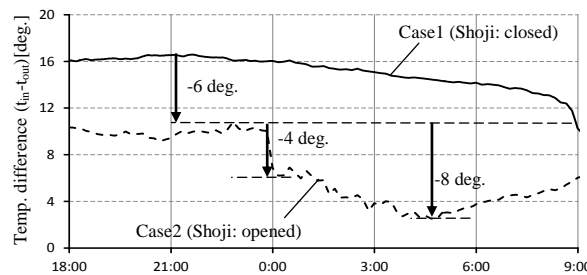


Figure 10. Heat insulating effect of Taiko-shoji

(3) Indoor environmental enhancing effect of insolation intake

The picture and thermal image of the southern window in the living room on the ground floor, which were taken in out of doors, were shown in Fig. 11. In wintertime, sunlight penetrates into the surface of the window, and the temperature of surface window near the floor was about 25 degree C higher than that of the center of the window. Fig. 12 shows the picture and thermal image of the same area, which were taken from the inside of the room. The floor was heated by sunlight and the temperature increased about 12 degree C. These results show the thermal environmental enhancing effect with insolation around the windows in wintertime.

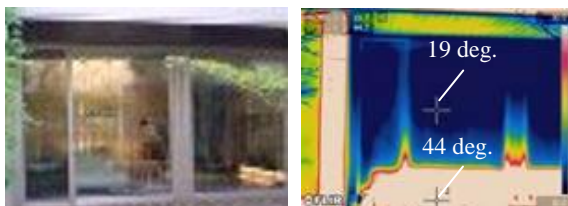


Figure 11. Picture and thermal image at veranda-like porch

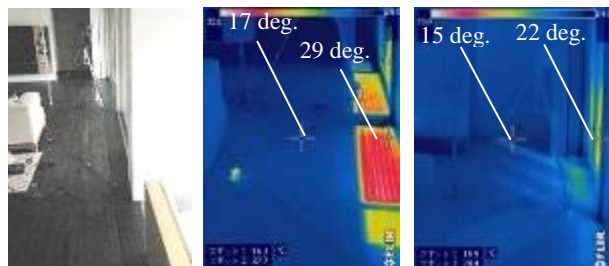


Figure 12. Picture and thermal image at south side perimeter in living room

(4) The effect of thermal storage floor

1) Consideration on surface floor temperature

Fig. 13 shows the surface temperature of the thermal storage floor of Room 1 and wooded floor of the living room on the ground floor. At 4 p.m. on 16th, the surface temperatures were 13 degree C in the living room and 15 degree C in Room 1. After floor heating worked, the temperature of the living room floor rapidly increased, but the thermal storage floor gradually increased. In night after floor heating stopped, the way of surface floor temperature decreasing differed because of the thermal storage effect. Besides, the surface floor temperature at noon on 19th were 15 degree C in the living room, but it increased to 30 degree C in thermal storage floor even when floor heating didn't work then. These results show that thermal storage floor can intake sunlight and function like floor heating.

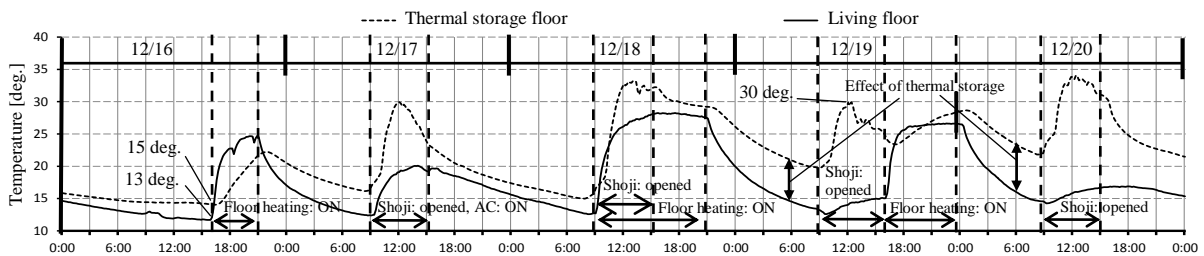


Figure 13. Floor temperature change

2) Consideration on the difference between surface floor and indoor temperature

Fig. 14 shows the difference between the surface floor and indoor temperature in Room 1 and the living room on the ground floor. The temperature of the thermal storage floor was always higher than that of indoor. In converse, it has already found that the temperature of thermal storage floor was always lower than that of indoor in summertime.

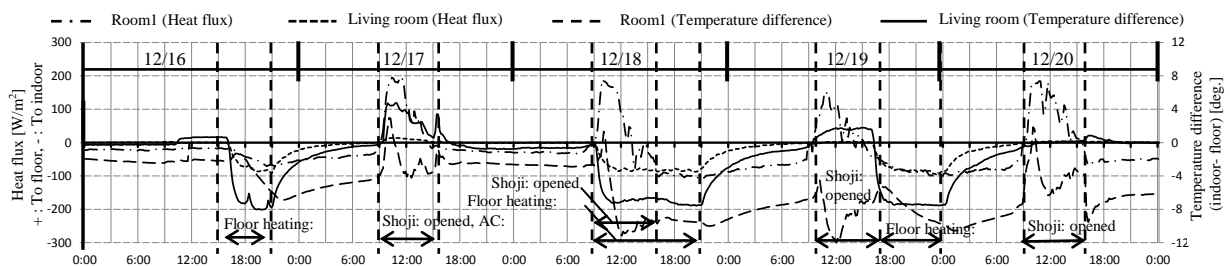


Figure 14. Heat flux and Temperature difference (indoor - floor surface) change

3) Consideration on heat flux

Fig. 14 shows the results of heat flux transducers set on the surface floor of the thermal storage floor and floor of living room floor. From this figure, heat flew in the surface of thermal storage floor and was stored in daytime, and the floor emitted heat into the room in night.

(5) Consideration with integrated values of temperature differences

Table 12 and 13 show the integrated values of the differences between indoor temperature of each room on the ground floor (in the center of each room, 1200mm height) and the preset temperature of heaters (22 degree C). Table 12 shows the comparison of opening and closing

Taiko-shoji from 9 a.m. to 4 p.m. With closing Taiko-shoji and without heaters, the values was 67 (degree C *hour) in each room. With opening Taiko-shoji, the values decreased to 45 (degree C *hour) in the living and dining room, and to 32 (degree C *hour), less than half of closing case, in Room 1. Table 13 compares the results of during 4 p.m. to 9 p.m. based on the 2 condition in earlier time than 4 p.m. (Taiko-shoji was closed after 4 p.m. in both cases.). When Taiko-shoji was opened by 4 p.m., heat stored in daytime was maintained. The integrated value of this case was about 50 % of that of the case without opening Taiko-shoji in daytime. From these results, appropriate opening and closing Taiko-shoji was found to increase the enhancing effectiveness of indoor thermal environment, so heating load can be reduced and energy saving effect can be expected.

Table 12. Integrated values of temperature differences between 9 a.m.-4 p.m. [degree * hour]

Situation between 9 a.m. – 4 p.m.	Dining room	Living room	Room1
Shoji : closed, AC : OFF	66	66	69
Shoji : opened, AC : OFF	45	46	32

Table 13. Integrated values of temperature differences between 4 p.m.-9 p.m. [degree * hour]

Situation before 4 p.m.	Dining room	Living room	Room1
Shoji : closed, AC : OFF	33	33	39
Shoji : opened, AC : OFF	18	19	19

4 CONCLUSION

The results of measurements in whole year revealed that the building's adiabatic performance is high. Taiko-shoji is an effective way to enhance adiabatic effect, and appropriate use of it leads a big energy saving effect in wintertime. In mid-term, the combined use of the skylight increased amount of airflow and significantly boost the effectiveness for comfort. The east surface wall of the northern washing room in the house played a big role of wind catcher, and induced great amount of airflow into the rooms. With the devises in floor plan like this house, increase of amount of passing air become possible, and cooling load can be reduced by emitting excess heat inside of the rooms with cross-ventilation when the external temperature is lower than that of indoor. In addition, the sense of airflow is expected to improve comfort. Comfort enhancement brings raise of the residents' awareness in window opening. Therefore, daily opening windows from the mid-term of April and May can delay the beginning period of cooling use in summertime.

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