Thermal Effect of ‘Changing Clothes Building’ with Changeable Thermal Property of Wall Surfaces

Yukio Ishikawa[1*], Hiroaki Kitano[1] and Takeshi Iwata[1]

[1] Division of Architecture, Graduate School of Engineering, MIE University,
1577, Kurimamachiya-cho, Tsu-city, Mie Prefecture, Japan
[*] Yukio Ishikawa, ishikawa@arch.mie-u.ac.jp

Abstract

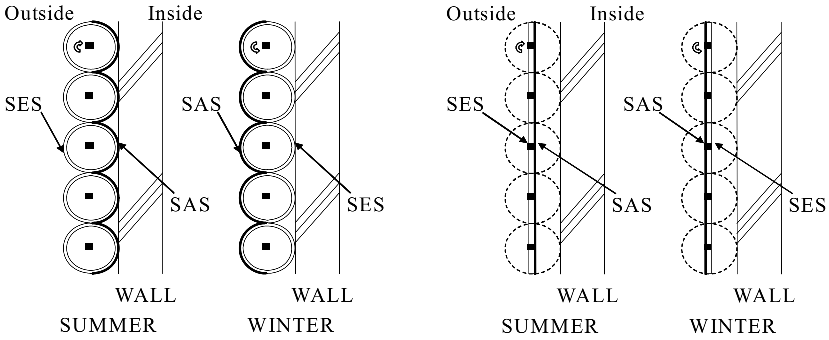
To realize a desirable building environment by saving energy and low global emission, the authors have developed an environmentally harmonized “Biomimetic Building”, which has the environment physiological functions of human and other organisms as well as human wisdom for environment symbiosis and control. This paper takes up the “Changing Clothes Function” as human wisdom, describing firstly its application to buildings and experimental results of the thermal effect by using experiment wall models whose surface thermal properties, such as absorptivity and emissivity, can change, depending on their temperatures. The experimental results showed that the temperature decrease of the ‘changing clothes wall models’ with selective emission surface was 32-37 ºC in summer compared to ‘non changing clothes wall model’, while the temperature increase with selective absorption surface was 3-29 ºC in winter. Further described is the thermal effect estimated theoretically of the “Changing Clothes Building (CCB)”. According to the simulation results of annual heat load, the saving energy effect due to the “Changing Clothes Function” of the typical detached house in Japan was 7 to 32% in sensible heat load compared to the “Non Changing Clothes Building (NCCB)”. The “CCB” enabled us to confirm the remarkable thermal effectiveness.

1. Introduction

To realize a desirable building environment by saving energy and low global emission, it is important to learn more about physiological function of organisms and human wisdom for environmental symbiosis and control. Our idea of “Biomimetic (Creature-imitative) Building”, where the environment physiology mechanism of the human body and other creatures are applied to the environment symbiosis and control, has been developed. This paper takes up the “Changing Clothes Function” as the human wisdom of environment symbiosis and control. The purpose of the study is to experimentally and theoretically verify the thermal effectiveness of the “Changing Clothes Function” of the building whose roof and wall surfaces can, depending on their temperatures, autonomously change their thermal properties, such as absorptivity and emissivity.

2. Changing Clothes Building

The “Changing Clothes Building (CCB)” has a “function” which can change the thermal properties of the building surface autonomously; they become low solar absorptivity with high emissivity (selective emission surface) in summer and become opposite (selective absorption surface) in winter. According to the building surface temperature, this “function” is fulfilled by the following ways shown in Fig.1. One is to transform the “thermo sense transformation material” or “bimetal” with different thermal properties on both sides of the fin plates, one side of which is a selective emission surface and the other selective absorption, set to the building. The other is to use the torque of the shape-memory alloy (SMA) to rotate the fin plates with different thermal properties on both sides or the cylinder with different thermal properties on each half of the circumference, set to building.



(a) Cylinder type (b) Flat plate fin type

[SAS:Selective Absorption Surface SES:Selective Emission Surface]
Fig.1 System examples to fulfill "Changing Clothes Function" of walls

3. Experiment on Thermal Effect

3.1 Outline of experiment

For the building concrete wall, 5 kinds of south-facing experiment wall models were made. The experiment wall models were 'normal wall model' with fixed surface thermal properties throughout the year, and 4 'changing clothes wall models' the changing clothes unit installed onto. The size of each wall model was 0.6 m in height, 1.5 m in width and 0.03 m in thickness, which was assumed to almost 1/5 scale of the exterior wall. A concrete wall model in thickness 0.03m was substituted with the plywood in thickness 3 mm which makes almost the heat conductance equivalent to the concrete wall. To remove the thermal influences from the edges and the backside of the wall models, thermal insulation of 0.1 m thickness was installed at the edges and in the backside of the models. The surfaces of those insulators were covered with aluminium foil to prevent them from absorbing solar radiation. The experiment was carried out in Tsu city, Mie Prefecture, Japan, (34°44′N, 136°31′E) in summers and winters from July 2007 to February 2009.

3.2 Experiment wall models

Fig.2 shows the experiment wall models and Table 1 shows the measurement results of surface thermal properties of the models.

(1) Normal wall model (Fig.2 (a))

A 'normal wall model' designed for a normal existing concrete wall was painted gray twice by zinc spray on the surface of the plywood.

(2) Changing clothes wall model

1) 'Horizontal rotation pipe' (Fig.2 (b))

The changing clothes unit consisted of the pipes of 20 mm diameter arranged horizontally, set onto the 'normal wall model'. Each pipe was painted with selective emission on a half of circumference and with selective absorption on the other half.

2) 'Vertical rotation pipe' (Fig.2 (c))

It was similar to the ‘horizontal rotation pipe’ except the pipes were arranged vertically. Surface thermal properties changed the same way as the ‘horizontal rotation pipe’.

3) ‘Flat rotation plate type 1’ (Fig.2 (d))

A unit consisted of long strips of aluminum fin plate arranged horizontally, 1.2m in length × 0.02m in width × 2mm in thickness, painted with selective emission on the front surface and selective absorption on the back. The selective emission surface faced outside in summer, while the selective absorption surface in winter. In the experiment practice, one aluminum plate, 1.2m in length × 0.6m in width, painted with selective emission and selective absorption on each surface, was used, because the tightly arranged horizontal long strips of aluminum fin plate were equal in form to a piece of plate when seen vertically.

4) ‘Flat rotation plate type 2’ (Fig.2 (e),(f))

It was similar to the ‘flat rotation plate type 1’, but the selective emission was painted on one surface of the long aluminum plate, and the other side was without painting. The selective emission surface of the plate faced outside in summer, while aluminum flat fin plates with selective emission surface on the upper side were arranged horizontally in winter. The selective absorption material for this type was so spread on the plywood surface that it could easily absorb the reflected solar radiation from the aluminum flat fin plates in the daytime in winter.

3.3 Measurement item and measurement point

Table 2 shows the measurement items and points. Fig.2 shows the temperature measurement points of the wall models. The temperature at the plywood backside is a temperature at the boundary between the plywood and heat insulator, which is supposed to be the inner surface temperature of the exterior wall. The measurement time interval was set to be 300 sec.

Table 1 Measurement results of surface properties

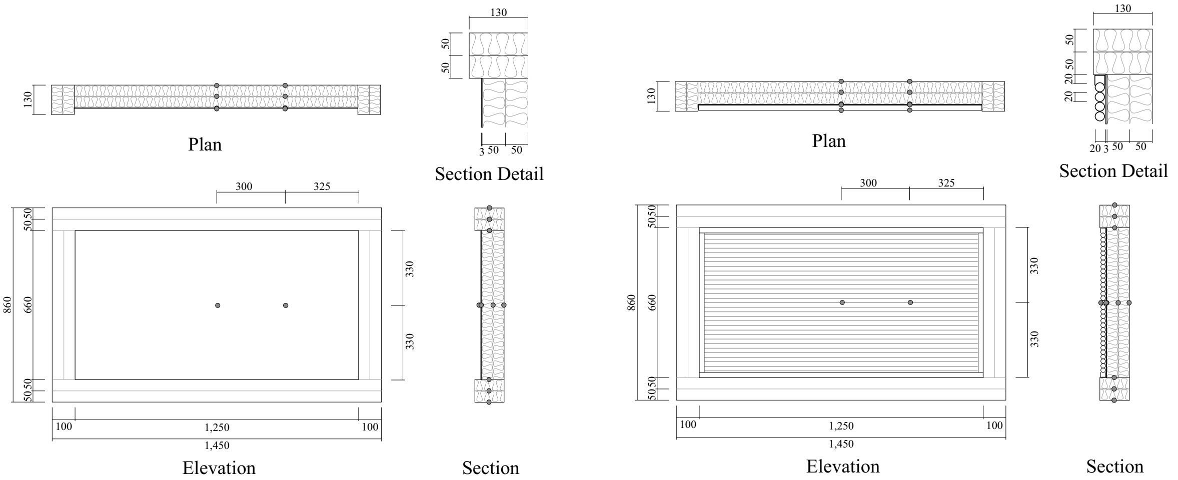
Experiment Wall Model (Material)	**Absorptivity (Short wave-length)**	**Emissivity (Long wave-length)**
Normal wall (plywood)	0.82	0.69
Selective absorption surface (plywood)	0.95	0.91
Aluminum plate	0.84	0.72
Selective emission surface (aluminum plate)	0.15	0.89
Selective absorption surface (aluminum plate)	0.94	0.53

Table 2 Measurement items and points

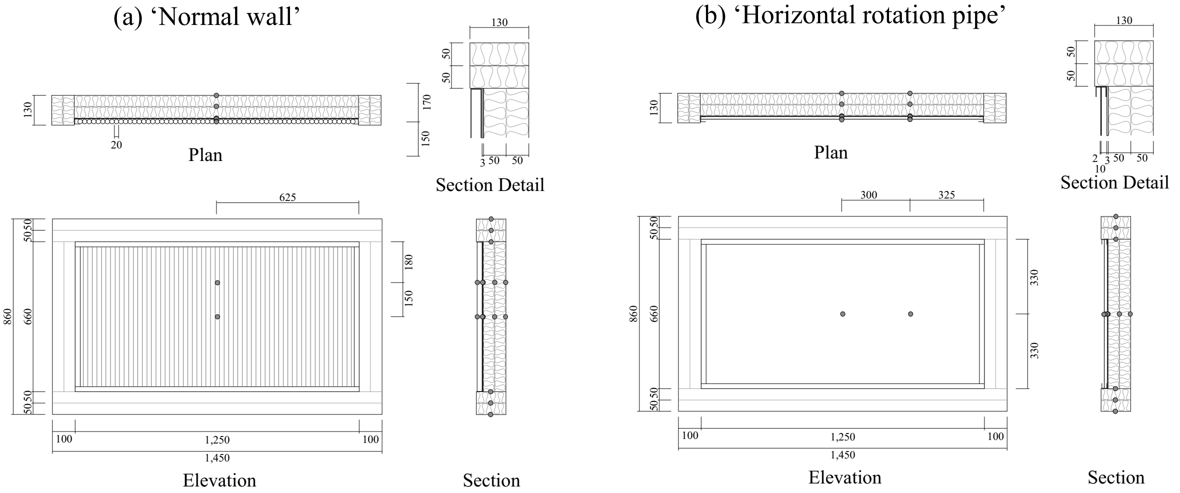
Measurement items	**Measurement points**
Outside condition	Temperature, Humidity, Atmospheric radiation , Solar radiation (horizontal-, south and north vertical-plane)
	Wind velocity, Precipitation
Experiment wall model	Surface temperatures of wall
	Inner temperatures of wall
	Thermography of wall surface

3.4 Results of experiment

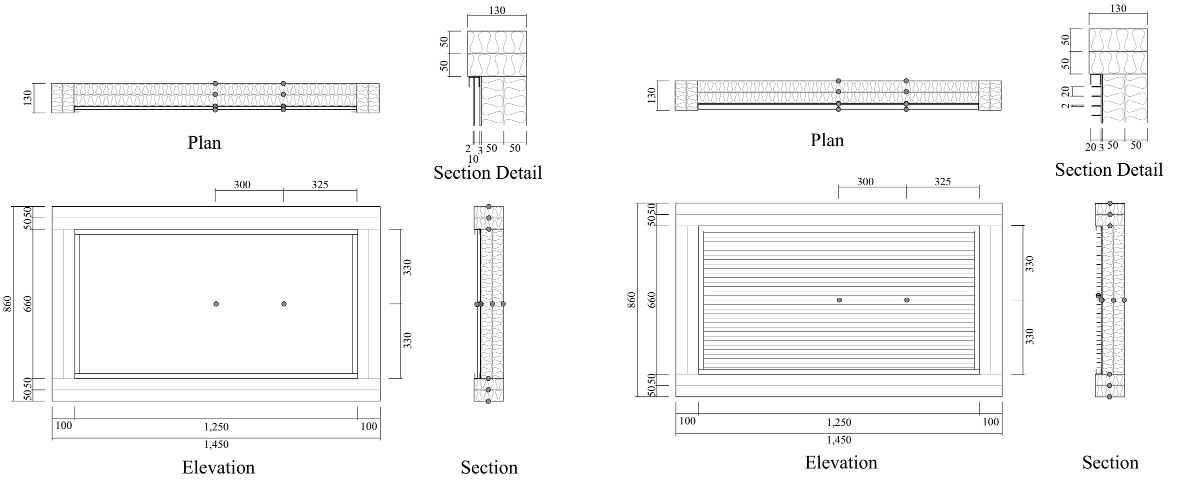
As the example results of the experiments, Fig.3-4 show the temperature variance at the plywood backside of each wall model on the representative days in summer and winter when the solar radiation rate was relatively steady; Summer: Sept.9, 2008 and Winter: Dec.27, 2007.



(a) ‘Normal wall’ (b) ‘Horizontal rotation pipe’



(c) ‘Vertical rotation pipe’ (d) ‘Flat rotation plate type 1’

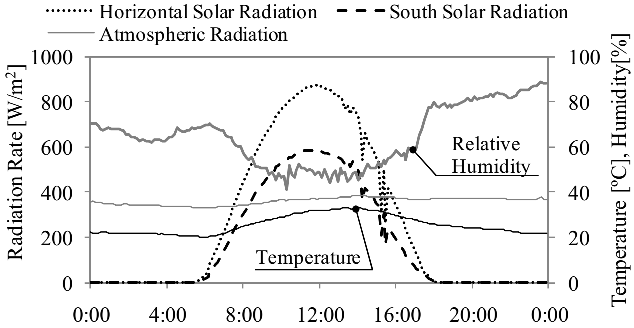


(e) ‘Flat rotation plate type 2’: in summer (f) ‘Flat rotation plate type 2’: in winter

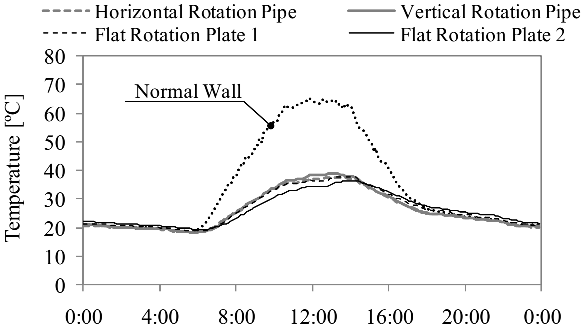
Fig.2 Experiment wall models (•:Temperature measurement point)

3.5 Consideration of experiment

Table 3 shows the maximum temperature difference at the plywood backside of each wall model between the ‘changing clothes wall model’ and the ‘normal wall model’ in summer and in winter. The maximum temperature decrease at the plywood backside was about 32-37 ºC in summer compared to the ‘normal wall model’ by making the surface selective emission. By making them selective absorption in winter, the maximum temperature increase at the plywood backside was about 3-29 ºC. The thermal effect of the ‘flat rotation plate type 1’ was the highest of all throughout summer and winter. In winter the temperature at the plywood backside of the ‘flat rotation plate type 2’ was mostly lower than that of the ‘normal wall model’, because the outside surface of the plywood faced directly to the outside air, unlike the other ‘changing clothes wall models’, and the selective absorption performance of the plywood surface was not demonstrated from the measurement result of the surface thermal properties shown in Table 1. The long wave-length emissivity of the plywood surface was large, namely 0.91 while the short wave-length absorptivity was 0.95.

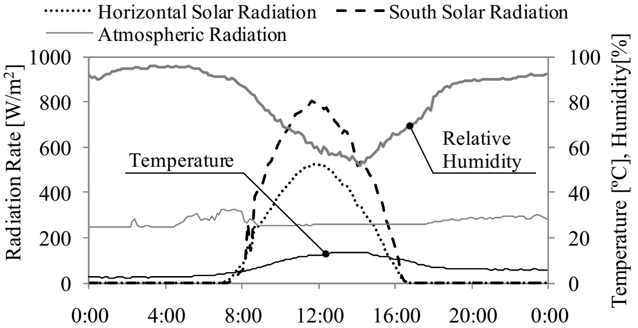


(a) Outdoor conditions

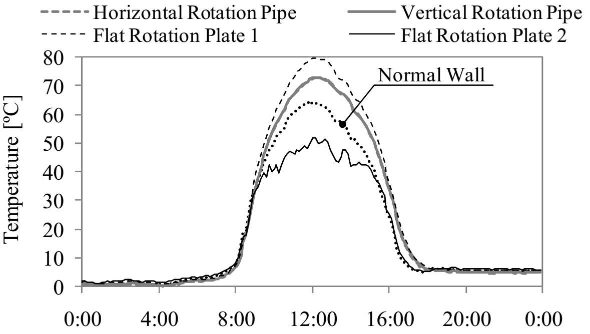


(b) Temperatures of each model at the plywood backside

Fig.3 Results of the experiment (Summer: Sept.9, 2008)



(a) Outdoor conditions



(b) Temperatures of each model at the plywood backside

Fig.4 Results of the experiment (Winter: Dec.27, 2007)

Table 3 Maximum Temperature difference at the plywood backside (ºC) (Each ‘Changing clothes model’ – ‘Normal wall model’)

Experiment Wall Model	Summer	Winter
Horizontal pipe rotation	-32.6	20.2
Vertical pipe rotation	-32.8	18.3
Flat rotation plate 1	-34.4	28.4
Flat rotation plate 2	-36.4	3.3

4. Simulation on Thermal Effect

The thermal effect of the “CCB” was theoretically estimated. The room temperature and heat loads of the “CCB” were examined by comparing the results between the various “Changing Clothes Mode (CCM)” of the “CCB” and “Non Changing Clothes (usual) Building (NCCB)”.

4.1 Analysis method and algorithm

The method adopted was of calculating multi room temperature, heat load and ventilation rate with the use of simultaneous non linear equations of room heat balance, room air rate balance, wall outer and inner surface heat balance, with room temperature, room pressure, wall outer and inner surface temperatures for each room set as unknown quantities, which was shown in literature [1]. As for the heat conduction calculation of the wall, the finite difference method (implicit scheme) was used.

4.2 Simulation model

A detached house was taken up as a simulation model. The plan and elevation views are shown in Fig.5, the building material specifications in Fig.6, and the schedules of various items in Fig.7. The areas taken up were Sapporo(43°4´N, 141°21´E) as a cold weather region, Tokyo(35°39´N, 139°41´E) and Osaka(34°41´N, 135°30´E) as mild weather regions, and Naha(26°12´N, 127°41´E) as a hot weather region, and the Standard year of expanded AMeDAS weather data 1981-2000 for each area were used. The "flat plate thermo sense transformation material" or some others set to the wall surface will express the change of surface thermal properties. In the simulation, 8 ideally changing modes were set as shown in Fig.8. Mode A is "Non Changing Clothes", which means the thermal properties do not change through the year; solar absorptivity(a) is set at 0.9, emissivity(ε) at 0.9. The modes from B to H are "Changing Clothes", where the thermal characteristics are assumed to vary linearly between two set temperatures high and low. The properties of materials considered, solar absorptivity(a) is set at 0.2-0.9, emissivity(ε) at 0.2-0.9. From mode B to D, the set high and low temperatures become higher gradually. Mode E has a wider range of set temperatures. The variation of the surface thermal properties can be fulfilled by rotating the cylinder and by changing a sunward surface ratio of selective emission to selective absorption (Fig.1 (a)). The modes from F to H are also "CCM", where the thermal properties are assumed to change at a certain temperature, which can be fulfilled by rotating and turning over the flat plates with different properties between front and back surfaces (Fig.1 (b)). From mode F to H, the set temperature becomes gradually higher. The room set temperature and humidity were 27 ºC, 60 % in the cooling period, and 20 ºC, 40 % in the heating period.

4.3 Simulation results

As the example results of the simulation, Fig.9 shows the house total monthly and annual heat load in mode A, "Non Changing Clothes" and in mode G, the minimum mode of total heat load of the "CCB" in Tokyo. Table 4 shows the saving energy effect of the house total annual heat load (cooling load +|heating load|) in each "CCM", where the saving energy effect is expressed; (heat load$_{NCCM}$ − heat load$_{CCM}$)/ heat load$_{NCCM}$. The saving energy effect in the cooling period became the most evident in mode B (84.4% in sensible heat load (SH)) in Sapporo, mode B (36.4% in SH) in Tokyo, mode B (35.8% in SH) in Osaka, and mode B (31.2% in SH) in Naha. Further the effect in the heating period became the most evident in mode D (5.7% in SH) in Sapporo, mode D (14.7% in SH) in Tokyo, mode D (10.3% in SH) in Osaka, and mode D (37.7% in SH) in Naha. As the result, the most effective mode all through the year was mode D (7.2% in SH) in Sapporo, mode G (15.8% in SH) in Tokyo, mode G (16.2% in SH) in Osaka, and mode F (31.9% in SH) in Naha.

4.4 Consideration of simulation

As for the "Changing Clothes Mode", mode B and F had a great effect in the cooling period; solar absorptivity was small while emissivity was big even from low surface temperature. Mode D was effective in the heating period; solar absorptivity was big while emissivity was small from high surface temperature. The annually effective modes were, on the whole, mode D in the cold weather, mode G in the mild weather and mode F in the hot weather, which means, in cold weather regions in Japan, the most effective mode in the heating period was considered as annually effective, while in hot weather regions, the effective one in the cooling period was.

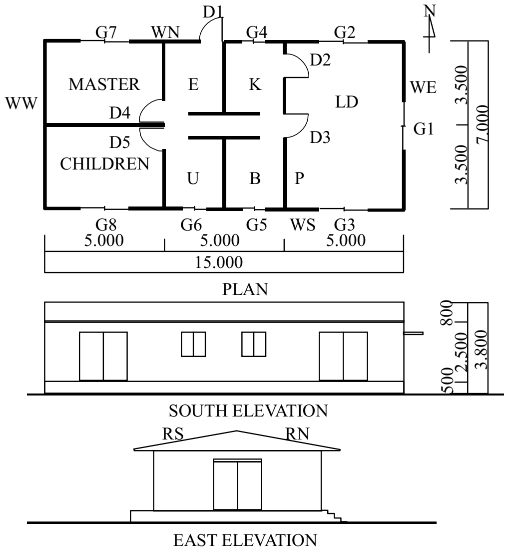


Fig.5 Plan and elevation views of detached house

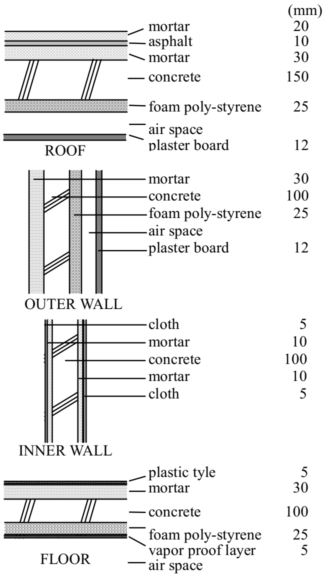


Fig.6 Building material specifications

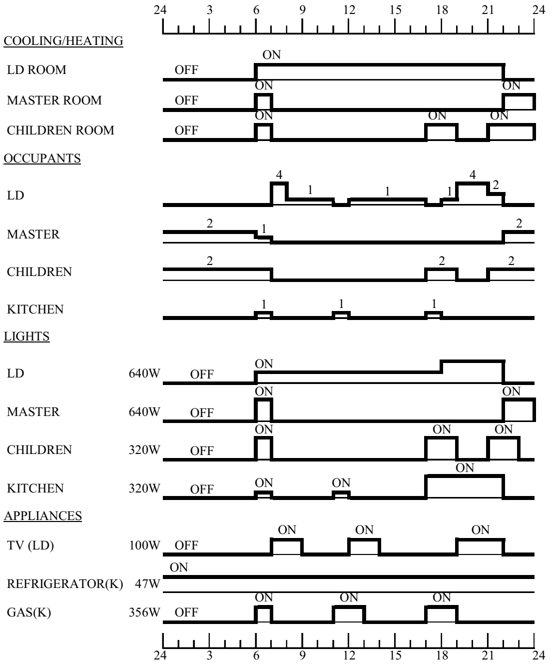


Fig.7 Schedule of various items

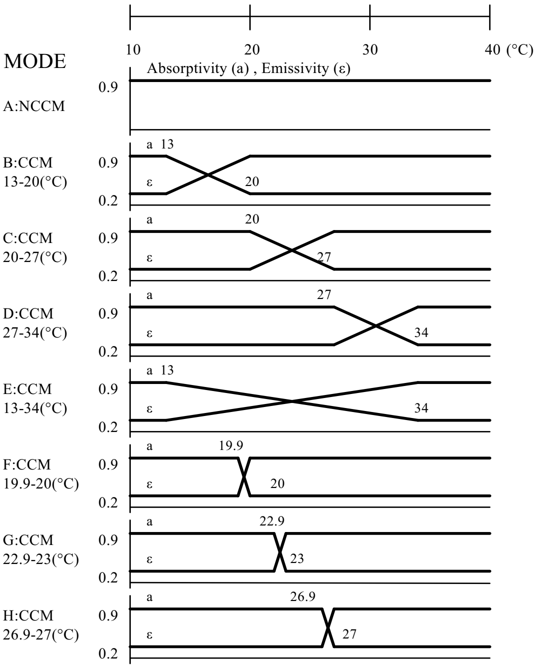
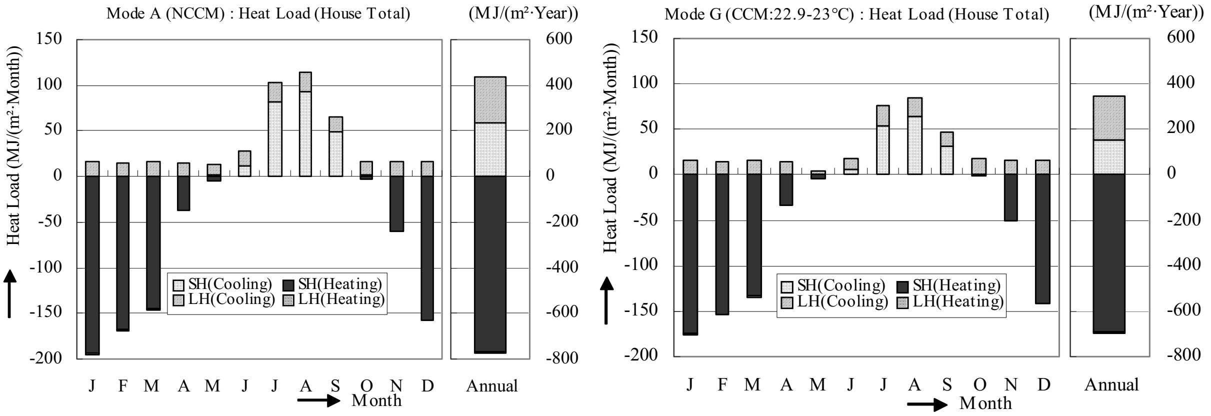


Fig.8 Variation of surface thermal properties

5. Discussion

This paper describes the experimental and analytical verification of the thermal effect of the “Changing Clothes Building (CCB)” whose roof and wall surfaces can autonomously change their thermal properties, such as solar absorptivity and emissivity. The experimental results showed that the maximum temperature decrease of the ‘changing clothes wall models’ with selective emission



(a) Tokyo (mode A)

(b) Tokyo (mode G)

Fig.9 Monthly and annual heat load (SH:Sensible heat load, LH:Latent heat load)

Table 4 Energy saving effect (TH:Total heat load= SH+LH)

(a) Sapporo

(%)

Effect	Cooling Period				Heating Period				Annual			
	SH		TH		SH		TH		SH		TH	
big	B	84.4	F	62.3	D	5.7	D	5.7	D	7.2	G	6.3
↕	F	78.0	B	54.8	H	5.6	H	5.6	H	6.6	H	6.3
	C	62.6	E	43.1	C	5.3	C	5.3	G	6.0	C	6.2
	E	60.6	G	42.7	G	5.3	G	5.3	C	6.0	D	6.2
	G	60.3	C	41.5	E	4.9	E	4.9	E	5.3	F	5.9
	D	37.0	H	16.2	F	4.9	F	4.9	F	5.2	E	5.6
small	H	34.0	D	-6.0	B	4.2	B	4.2	B	3.6	B	4.1

(b)Tokyo

(%)

Effect	Cooling Period				Heating Period				Annual			
	SH		TH		SH		TH		SH		TH	
big	B	36.4	B	27.7	D	14.7	D	11.6	G	15.8	G	13.9
↕	F	36.1	F	27.2	H	10.5	H	10.5	C	15.3	C	13.5
	G	34.3	G	26.8	C	9.5	C	9.4	F	14.9	H	12.6
	C	32.0	C	25.0	G	9.3	G	9.2	H	14.3	F	12.3
	E	27.6	E	21.6	E	8.3	E	8.3	D	13.4	D	11.8
	H	22.7	H	17.2	F	8.1	F	8.0	E	13.0	E	11.6
small	D	14.7	D	11.1	B	5.4	B	5.3	B	11.7	B	9.5

(c)Osaka

(%)

Effect	Cooling Period				Heating Period				Annual			
	SH		TH		SH		TH		SH		TH	
big	B	35.8	F	30.9	D	10.3	D	10.3	G	16.2	F	14.0
↕	F	35.7	B	29.6	H	9.7	H	9.6	C	15.9	G	13.6
	G	33.1	G	26.5	C	8.6	C	8.6	F	15.8	C	13.5
	C	32.2	C	25.9	G	8.6	G	8.5	H	14.8	H	12.5
	E	28.2	E	22.7	E	7.3	E	7.3	E	13.5	E	11.4
	H	24.7	H	19.6	F	7.3	F	7.3	D	13.0	D	11.0
small	D	16.4	D	12.0	B	4.7	B	4.7	B	12.9	B	10.9

(d)Naha

(%)

Effect	Cooling Period				Heating Period				Annual			
	SH		TH		SH		TH		SH		TH	
big	B	31.2	B	25.6	D	37.7	D	37.6	F	31.9	F	23.5
↕	F	31.2	F	25.6	H	33.8	H	33.2	G	30.6	G	22.9
	G	30.1	G	24.6	G	27.0	G	27.0	B	30.4	B	22.9
	C	28.9	C	23.6	C	25.3	C	25.3	C	29.5	C	22.1
	E	24.9	E	20.3	F	18.1	F	18.1	E	25.1	E	18.8
	H	23.6	H	19.2	E	12.7	E	12.7	H	23.2	H	17.2
small	D	14.8	D	11.9	B	-21.0	B	-20.9	D	15.3	D	11.2

surface was 32-37 ºC in summer compared to ‘non changing clothes model’, while the temperature increase with selective absorption surface was 3-29 ºC in winter. The regional variation of thermal effect and the desirable “Changing Clothes Mode” of the thermal properties of wall surface have been demonstrated theoretically. The saving energy effect due to the “Changing Clothes Function” of the typical detached house in Japan was 7 to 32% in house total sensible heat load compared to the “Non Changing Clothes Building (NCCB)”. The “CCB” enabled us to confirm the remarkable thermal effectiveness.

Acknowledgement

The authors would like to express their sincere thanks to Dr.Masato Tazawa, Dr.Hiroshi Kakiuchida, National Institute of Advanced Industrial Science and Technology, and Mr.Makoto Mihata, Takenaka Corporation, for their cooperation in the execution of the experiment.

References

[1] Ishikawa Y., A study on simplified room temperature calculation of multi-room building roof sprayed and thermal effect of roof spraying Part 1.Outline of calculation method, Transactions of SHASEJ (The Society of Heating, Air-conditioning and Sanitary Engineers of Japan), No.30 (1985), pp21-30

[2] Ishikawa Y. and Kitano H., Regional thermal effect of building whose wall surfaces have changeable thermal characteristics, Transactions of SHASEJ, Special issue (2006), pp1213-1216