THE ANALYSIS OF A THERMAL STORAGE SYSTEM UTILIZING BUILDING MASS IN A COLD REGION

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ABSTRACT

The principle of the thermal storage in building mass (TSBM) is storing thermal energy in building thermal mass, such as concrete slab, at night and discharging thermal energy naturally in daytime. It is expected that the thermal storage will be effective for reducing the heating load at the beginning of the operation in a cold region. Adding to that, the indoor thermal environment will improve because it heats up the cold floor slab directly. The simulation model was constituted to recreate features of TSBM, which were observed in a field survey in an office building. It was estimated by simulation that the maximum heating load at the beginning of the operation would be reduced in spite of the several-percent increase of the total heating load and that the temperature around the foot would rise. The balance of thermal environment and thermal load was considered from the simulation result and appropriate TSBM operation was proposed.

KEYWORDS

Thermal Storage, Building Mass, Periodical Equilibrium

INTRODUCTION

The principle of the thermal storage in building mass (TSBM) is storing thermal energy in building thermal mass, such as concrete slab, at night and discharging thermal energy naturally in daytime. The application of TSBM has been increasing in warm regions of Japan to flatten cooling load. Many TSBM systems adopt blowing supply air directly to the slab surface above ceiling for thermal storage and to lead return air through ceiling slits to the ceiling plenum for discharge.

Several papers have reported simulation of TSBM for cooling. Ishino (2003) analyzed the characteristics of building component by simulation. Roh and Udagawa (2001) studied the effect of parameters such as storage hours, specification of building components like windows and internal heat production. They compared the effectiveness of thermal storage, reduction ratio of maximum thermal load and the increment of total thermal load.

It is difficult for TSBM to control the amount of thermal energy discharged from building mass, which means that the amount of discharged thermal energy is greater in the morning than in the afternoon when TSBM is used at night. It will be useful for TSBM to reduce maximum hourly heating load in a cold region, which is observed at the beginning of air-conditioning with intermittent operation. The indoor climate is expected to improve because TSBM, like floor heating system, directly heats up the floor slab that is cooled down at night. The indoor climate and energy consumption has been studied for TSBM of heating purpose (Miura 2002), but the relationship of the environment and the energy consumption has not studied enough yet.

A field survey in an office building in Sapporo, which is in a cold region of Japan, was conducted and temperature distribution was observed when TSBM was used for heating. A simulation model with appropriate conduction paths of thermal energy was constituted from the result of the survey. The simulation was compared with the measurement and qualitative similarity was confirmed. The characteristics of TSBM was studied on storage hours and building insulation. The reduction ratio of maximum thermal load and the increase of total thermal load were revealed. Improvement of thermal environment and increase of thermal load were studied and the appropriate TSBM operation was proposed.

TEMPERATURE CHANGES WITH TSBM

A field survey was conducted in an office building located in Sapporo, Hokkaido. The building had ten stories above the ground and one basement under the ground. The measurement area for slab temperature and the location of AHUs above ceiling space are shown in Figure 1. Structure of the building was steel reinforced concrete, and the envelope was RC 160mm with the insulation of 30-mm urethane on the inner surface. The window glass was double pane with low emission coating. TSBM was operated from 5 a.m. to 7 a.m. with the AHU in Area B in Figure 1. Outlet air about 40 °C blew up directly to the slab for TSBM. The AHUs air-conditioned room and return air went through ceiling slits to the ceiling plenum for normal operation. Figure 2 shows the weekly change of slab temperature measured in January 2004. Slab temperature lowered in the weekend and rose up gradually from Monday to Friday. Intermittent air-conditioning is common in Japan and the figure shows that slab temperature changes according to outdoor temperature when the AHU was not in operation. The figure also shows that the daily temperature change in the slab area with outlet for TSBM (Area A) was greater than that with inlet of AHU (Area B).

Figure 3 shows the daily temperature changes measured in the room and above ceiling on January 27, which was included in the period of Figure 2. The air temperature close to slab in Area A rose up to 35 °C when TSBM was operated but that of Area B rose up to only 32 °C. A structural beam that separated the space above ceiling brought the temperature difference. The temperature in Area B was higher than in Area A when the AHU was in normal operation. The reason was that Area A was in contact to the envelope. The vertical temperature difference in Slab B was greater when AHU was in normal operation than it was when the AHU stopped.

CONSTITUTION OF SIMULATION MODEL

The following features are necessary for TSBM simulation model according to the measurement result above.

(1) Recreation of horizontal temperature difference in slab area

(2) Recreation of temperature difference between separated spaces by beam

(3) Recreation of vertical temperature difference above ceiling

The vertical temperature difference by TSBM for cooling was confirmed (Ohwada 2003), which should be considered one of typical characteristics by direct blowing-up to the slab by TSBM. The room has to be included in the model for the consideration of thermal comfort. The measurement also revealed that the cooling effect by the outdoor in the weekend should be considered, which leads to the consideration on simulation period. The period should be one week at least and the result should be in periodical equilibrium.

Consideration on prediction method for temperature difference

A prediction method for temperature difference was proposed (Togari et al. 1993, Arai et al. 1994). The method divides the inner space into several zones and considers three major paths for heat transfer; (1) heat transfer between a zone and wall surface, (2) heat transfer and air movement between zones, (3) heat transfer for wall. The heat balance and the air balance are considered to calculate the temperature distribution. The outline of calculation methods for heat transfer is shown in the following paragraphs.

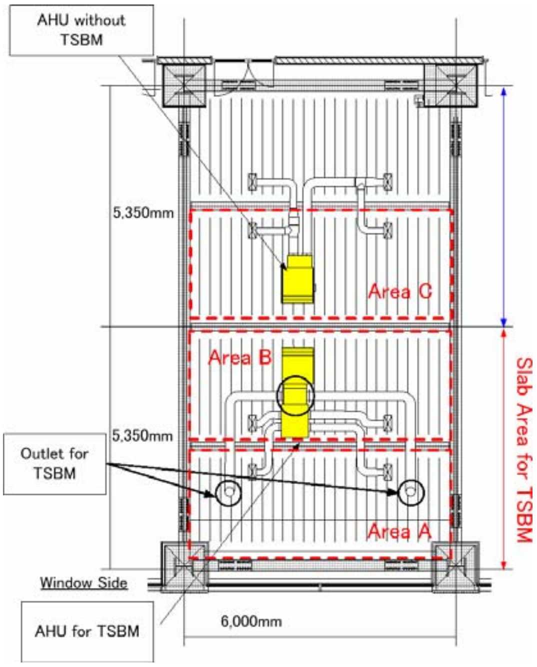


Figure 1 Placement of the AHU above Ceiling

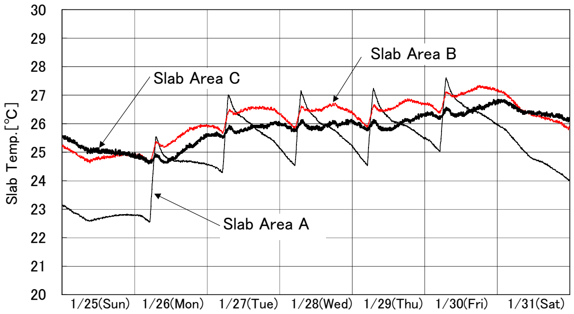


Figure 2 Weekly Change of Slab Temperature

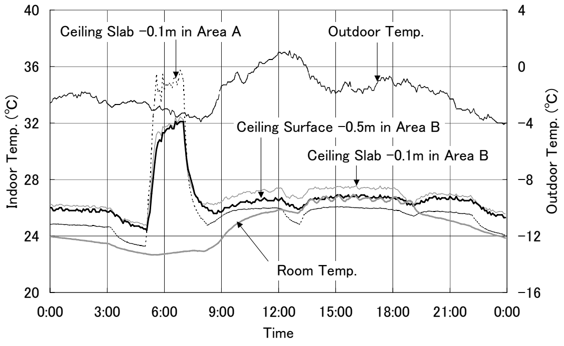


Figure 3 Daily Change of Air Temperature above Ceiling (January 27, 2004)

(1) Heat transfer between a zone and wall surface

Heat transfer between a zone and wall surface occurs as convective heat transfer. One wall surface is in contact only to one zone. Currents of cold air on the inner surface of envelopes and windows are modeled to cool down lower zones (Togari et al. 1993). The convective heat transfer is considered for structural beams, envelopes and slab, which brings the effect of building thermal mass. The convective heat transfer coefficient on the slab surface in the area with outlet increases when TSBM system is in operation

(2) Heat transfer and air movement between zones

Heat transfer between zones occurs with two paths. Air infiltration through ceiling is supposed not to occur during storage hours because air temperature above ceiling is higher than in the room.

1) Heat transfer though boundary of zones

The amount of heat transferred though horizontal boundary is calculated by the temperature difference between two zones. The heat transfer coefficient is 2.3 W/m^2°C for downward heat flow and 116 W/m^2°C for upward heat flow (Togari et al. 1993). The heat transfers though vertical boundary is similar to ventilation by temperature difference through simple opening between two zones.

2) Air movement between zones

The volume of supply air is given to the zone of outlet, which is in contact to slab, and returns to the inlet of AHU during storage hours. The supply air is given through the outlets located on the ceiling and returns though ceiling to the AHU inlets during normal operation. The supply air from outlets are modeled as non-isothermal free jets, which induce air from the passing zones and give total air volume to the terminate zone.

(3) Heat transfer for wall

Radiative and convective heat transfer occurs on the surface of the wall. Shape factor is not considered for radiative transfer. Instead, the weighted average surface temperature of closed space is used as mean radiant temperature. One dimensional heat conduction is supposed to occur in the wall. The forward difference method is used for heat conduction.

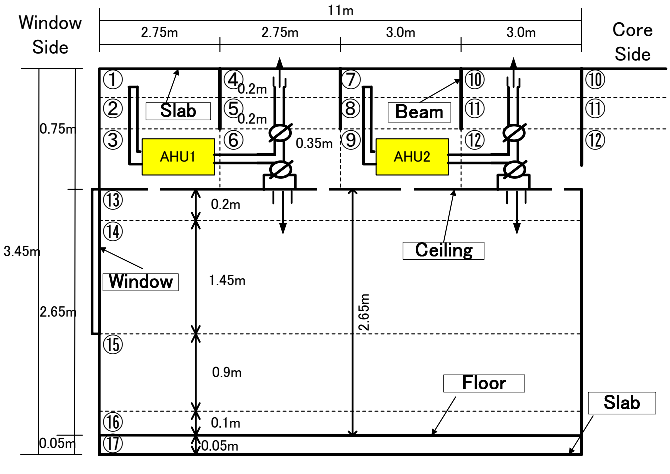


Figure 4 Constitution of Simulation Model

The air volume balance in zone I is expressed by Equation 1. The energy balances in zone I without ceiling nor floor is expressed by Equation 2 (Arai et al. 1994). For zones with ceiling or floor, the term of the convective heat transfer is added respectively to Equation 2. In Equation 2, the first term expresses the heat transfer by the current on the wall and the last two terms are used selectively according to $V_c(I) > 0$ or $V_c(I+1) > 0$.

$$
\begin{aligned}
0 &= \gamma \cdot V_{si}(I) - \gamma \cdot V_{so}(I) \\
&+ \sum_{L=1}^{n} \gamma \cdot V_E(L,I) - \sum_{L=1}^{n} \gamma \cdot V_E(I,L) \\
&+ \sum_{K=1}^{m} \{\gamma \cdot V_{in}(I,K) - \gamma \cdot V_{out}(I,K)\} \\
&+ \gamma \cdot V_C(I+1) - \gamma \cdot V_C(I)
\end{aligned}
$$

... Equation 1

$$
\begin{aligned}
0 &= \sum_{K=1}^{m} \sum_{L=1}^{n} r(I,L,K) \cdot \alpha_c(I,K) \cdot A_W(I,K) \\
&\cdot \{3T(I) + T_W(I,K) - 4T(I)\} \\
&+ C_B(I) \cdot A_B(I) \cdot \{T(I-1) - T(I)\} \\
&+ C_B(I+1) \cdot A_B(I) \cdot \{T(I+1) - T(I)\} \\
&+ \sum_{L=1} C \cdot \gamma \cdot V_E(L,I) \cdot \{T(L) - T(I)\} \\
&+ C \cdot \gamma \cdot V_C(I+1) \cdot \{T(I+1) - T(I)\} \\
&- C \cdot \gamma \cdot V_C(I) \cdot \{T(I-1) - T(I)\}
\end{aligned}
$$

...Equation 2

Modeling of Building for Simulation

Simulation model was constituted according to the same building of Figure 1. The model included one span (floor area: 57.75m^2, 5.25m x 11m) of the standardized plan, but the ratio of window area to floor area was corrected to that of the standardized plan. Direction of the window was to the south. The space above ceiling was divided into 12 zones of 3 layers and the room was into 4 zones. The room had underfloor space (Figure 4). The number in circle means zone number. There were supposed to be the same room as the model on the upper and the lower floor. There was thermal capacity in the room as furniture and paper materials. The amount of thermal capacity was decided according to Ishino et al. (1987). The heat transfer coefficients are in Table 1 and the building element specification is in Table 2.

Modeling of AHU

There were two AHUs in the model, which had the same capacity, and both were used for TSBM. The outlets for TSBM were in Zone 4 and Zone 10 and AHU inlet were in Zone 1 and Zone 7. The location of outlet and inlet to the envelope were changed from Figure 1. The volume of supply air was 900CMH for one AHU and the same volume was blown for TSBM and normal operation. The volume of outdoor air was zero during storage hours and pre-heating period, and was 150CMH for one AHU in normal operation. There was no heat recovery system. The exhausted air was taken from the zone of inlet. The control of AHU was done by supply air temperature (set point 40ºC) during storage, and by air temperature of Zone 14 (set point 22 ºC) in normal operation.

Table 1 Heat Transfer coefficients for Simulation

1. Convective heat transfer coefficient
   4.7 W/m^2^{o}C (on vertical surface)
   4.7 W/m^2^{o}C
   (upward heat flow on horizontal surface)
   2.3 W/m^2^{o}C
   (downward heat flow on horizontal surface)
   9.3 W/m^2^{o}C
   (for the slab when blown up by supply air during storage)
2. Radiative heat transfer coefficient
   4.7 W/m^2^{o}C

Table 2 Specification of Building Element

Envelope: ceramic tile 30mm
concrete 160mm
urethane 30mm
plaster board 13mm
floor slab: concrete 120mm
ceiling: rock wool board 12mm
structural beam: steel 10mm-15mm
(rock wool 25mm on surface)
window: double pane glass 12mm

The AHU capacity has to be considered for simulation. It is possible for TSBM to reduce it but the capacity depends on storage hours. The capacity was decided by preliminary calculation to equate the maximum thermal load during storage hours and during normal operation in CASE1, which operated thermal storage only from 10 p.m. on Sunday to 8 a.m. on Monday. The capacity for TSBM was decided 76 W/m^2. The capacity for conventional system was decided 166 W/m^2, which was large enough to cope with the thermal load.

Climatic Condition and Occupied Condition

The simulation conducted to achieve periodical equilibrium for one week. The climatic condition was for heating system design in Sapporo (JABMEE 1987) with excess probability 20%. The same condition was supposed to continue for one week. It is rare for the severe climatic condition to continue for one week and careful consideration may be required on suitable climatic condition for weekly periodical equilibrium. Occupied condition was shown in Table 3.

Table 3 Inner Heat Productions and Schedule

Occupied hour: 9 a.m. to 20 p.m. on weekday
Density of Occupants: 5 m^2/person
(10m^2/person for 12 p.m. to 1 p.m. and after 6p.m.)
Lighting: 20 W/m^2
Machinery: 20 W/m^2
(10 W/m^2 for 12p.m. to 1 p.m. and after 6p.m.)
Air exchange rate for out door air infiltration :
0.1 times/h

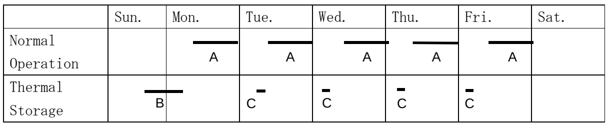
Time step and the calculation period of simulation

Time step for calculation was two minutes and the total calculation was done for 60 days. The periodical equilibrium was confirmed by comparing the temperature changes.

SIMULATION RESULT

Calculation Cases

Table 4 shows the time schedule of calculation case. Total of 4 cases were prepared for calculation; one was for conventional system (CASE 0) and three were for TSBM. Preparatory heating was done for one hour, from 8 a.m. to 9 a.m. For all TSBM cases, the storage hour from 10 p.m. on Sunday to 8 a.m. on Monday was common, and in the morning on weekday, CASE 1 had no storage hour, CASE 2 had 2 hours from 6 a.m. to 8 a.m., and CASE 3 had 5 hours from 3 a.m. to 8 a.m. In this paper, ‘thermal load’ means the amount of heating load by the heating coil of AHU. All kinds of thermal load are expressed by the value for unit floor area.



	A: Normal Operation	B:TSBM (Sun. to Mon.)	C: TSBM (Others)
CASE 0	8a.m. ～ 8p.m.	−	−
CASE 1	8a.m. ～ 8p.m.	10p.m. ～ 8a.m.	−
CASE 2	8a.m. ～ 8p.m.	10p.m. ～ 8a.m.	6a.m. ～ 8a.m.
CASE 3	8a.m. ～ 8p.m.	10p.m. ～ 8a.m.	3a.m. ～ 8a.m.

Table 4 Time Schedules of Simulation Cases

Calculation Result

Figure 5 shows the temperature changes of simulation result of CASE 2. It should be considered that the inlet was close to the envelope contrary to Figure 1, where the outlet was close to the envelope. The temperature above ceiling rose up when storage hours started and temperature in Zone 4, which was close to outlet, rose up close to 30 ºC at 7 a.m. The temperature in Zone 1 and Zone 3, which were located beyond structural beam from Zone 4, rose up only to about 26 ºC at the same time. During normal operation, the temperature in Zone 1 and Zone 3 was lower than that of Zone 4. These temperature changes above ceiling were similar to the field survey explained earlier. The vertical temperature difference between Zone 1 and Zone 3 only showed up during AHUs stopped. The vertical temperature difference might change according to the relative location to the envelope.

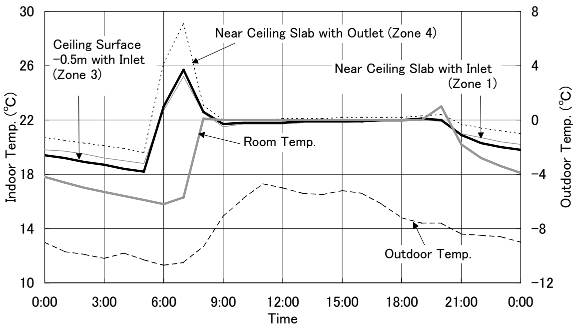


Figure 5 Simulation Result of Air Temperature above Ceiling (Tuesday)

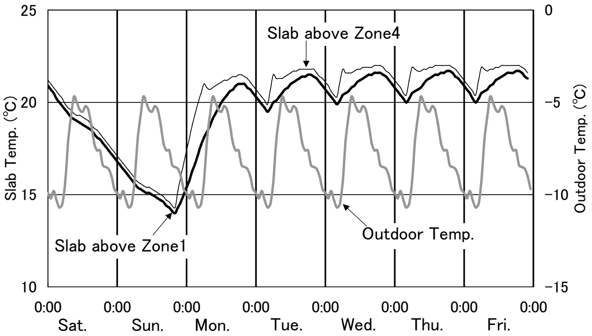
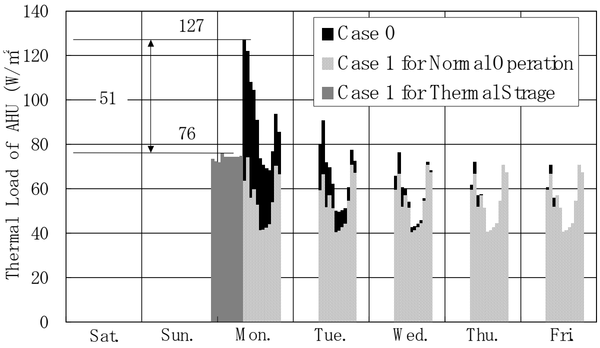


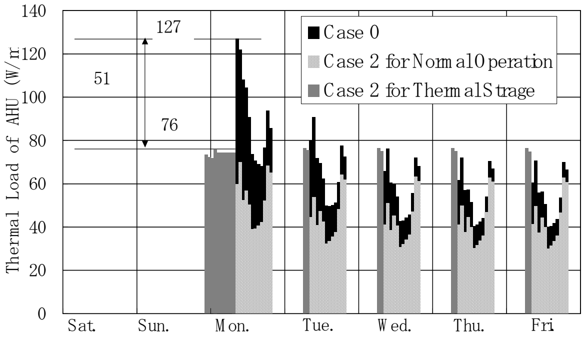
Figure6 Comparison of Slab Temperature

Figure 6 shows the comparison of slab temperature between slab above Zone1 (with inlet) and slab above Zone 4 (with outlet). The inlet slab was slightly lower than the outlet slab because the former slab was in contact to the envelope. The outlet slab showed the quick rise in temperature change in storage hours, but the temperature of inlet slab gradually rose up. These features were similar to the field survey. But the daily change was different from the survey. In the survey the temperature of the outlet slab, which was in contact to the envelope, fell down while the room was occupied. But the temperature of the slab in contact to outer surface, which was the inlet slab, did not fell down but rose up during occupied hours in the simulation. The reason seems to be the difference of heat conduction from the envelope to the slab. The building in the survey was constructed with steel reinforced concrete and had the insulation on the inner surface. It means that the heat conduction was three-dimensional and the envelope cooled the slab directly. But the heat conduction in the model was supposed to be one-dimensional and the wall did not cool down the slab. The heat conduction of simulation model was similar to the building with insulation on the outer surface, whose heat conduction would be closer to one-dimensional.

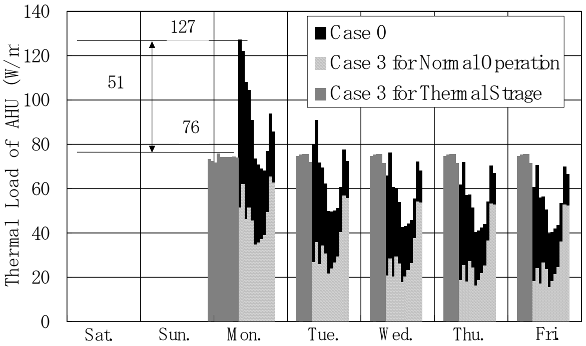
Figure 7 shows the comparison of the hourly thermal load for one week between CASE 0 and one TSBM case. The thermal load changed by climatic condition and internal heat production. In conventional system with one hour preparatory heating, the maximum hourly thermal load (127 W/m^2) showed up 8 a.m. on Monday. The daily thermal load decreased gradually from Monday to Friday. Contrary to that, the maximum hourly load showed up during storage hours in all TSBM cases and the values was almost the same as the capacity of AHU. The reduction percentage of maximum hourly thermal load was about 40% when TSBM was adopted. The effect to reduce hourly thermal load by TSBM was seen during normal operation hours on Monday. It means that TSBM has large effect in the morning but has some effect in the afternoon.



(a) Case1



(b) Case2



(c) Case3

Figure 7 Thermal Load of AHU

Figure 8 shows the weekly thermal load and the ratio among simulation cases. The thermal load of CASE 0 (3.87 kWh) is set as standard (100%). The latent load of AHU was 0.86 kWh, which was the same for all cases. The weekly load for CASE 1, which operated thermal storage only from 10 p.m. on Sunday to 8 a.m. on Monday, was 3.90 kWh, the increment was 3% and the ratio of storage was 20%. The weekly load increased according to the increase of weekday storage hours; it was 4.07 kWh for case 2 and 4.24 kWh for CASE 3. The increment of CASE 2 was 5% and that of CASE 3 was 10%. The ratio of storage also increased; it was 35% for CASE 2 and 57% for CASE 3.

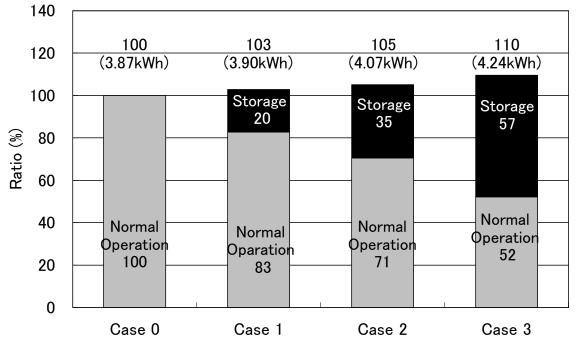


Figure 8 Weekly Summation of AHU Thermal Load

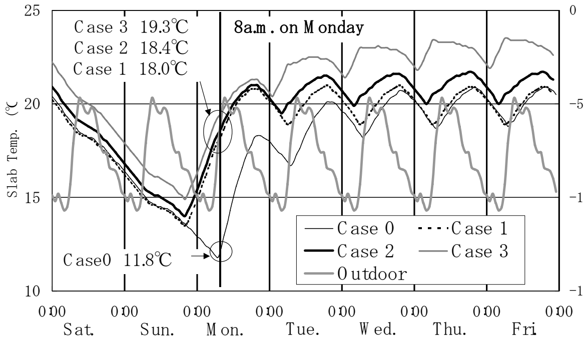


Figure 9 Weekly Changes of Slab Temperature

Figure 9 shows the weekly average temperature changes of the slab close to the envelope (slab above Zone 1). In all cases, the temperature fell down to the lowest after weekend and just before the AHU operation started. The time of the week for the lowest slab temperature was 8 a.m. on Monday for CASE 1 and the value was 11.8 °C. The temperature rose up gradually from Monday to Friday. It means the slab was cooled down in the weekend and heated up on weekdays. In TSBM cases, the lowest temperature showed up at 10 p.m. on Sunday and the temperature rose up to around 18°C or 19 °C at 8 a.m. on Monday. The lowest temperature of weekdays did not change much from Monday to Friday for CASE 1. It means that the thermal storage from Sunday night to Monday morning canceled the cooling effect on slab during weekend by climate. The lowest temperature of the day rose up again from Monday to Tuesday in CASE 2 and became stable. For Case 3, the lowest temperature of the day rose up from Monday to Friday gradually.

Figure 10 shows the temperature changes of Zone 14 (center of the room) and Zone 16 (close to the room floor) for CASE 0 and CASE 1. The temperature of Zone 14 was close to the set point 22 °C during normal operation. The vertical temperature difference between Zone 14 and Zone 16 was about 1 °C in CASE 1 and there would be no problem on indoor thermal comfort. But the temperature of Zone 16 in CASE 0 was 16.4 °C at 9 p.m. on Monday. It may cause the thermal comfort problem by coolness around foot.

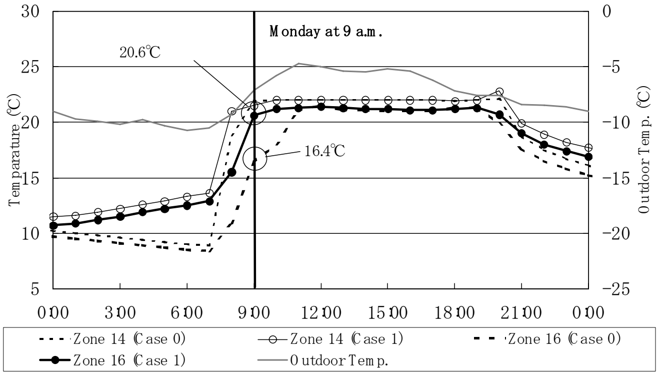
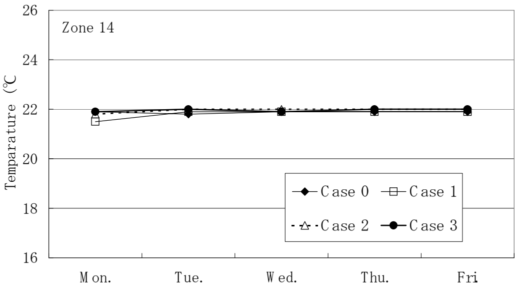
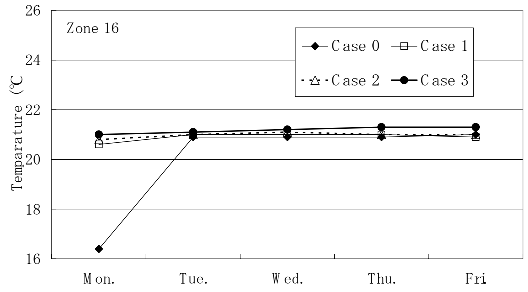


Figure 10 Daily Change of Room Temperature in Simulation



(a) Zone 14



(b) Zone 16

Figure 11 Temperatures at 9 a.m. for Weekdays

Figure 11 shows the temperature of Zone 14 and Zone 16 at 9 a.m. on weekdays. The temperature of Zone 14 was almost 22 °C. Only that of CASE 1 on Monday was 21.5 °C, which was slightly lower than other cases. It means that temperature in the room did not rise up to the unnecessary level by TSBM. The temperature of Zone 16, which was close to the floor, was about 21 °C for most of the cases. But it was 16.4 °C for CASE 0 on Monday. It means that the temperature at 9 a.m. did not change much once thermal storage was done from Sunday to Monday.

DISCUSSION

The Effect of Thermal Insulation

The simulation model above has good thermal insulation of 30-mm urethane on the inner surface of the envelope and double pane window. Additional simulation was conducted to survey the effect of insulation on the reduction ratio of maximum thermal load and the increase ratio of weekly thermal load. The model for the additional simulation did not have the insulation on the envelope. Two schedules were selected from Table 3, CASE 0 and CASE 2. In additional simulation, they were renamed CASE N0 and CASE N2. The capacity of AHU was decided 90 W/m^2 for CASE N2 from preliminary calculation. Figure 12 shows the hourly thermal load of the two cases for one week. The maximum hourly thermal load was shown up at 8 a.m. on Monday in CASE N0. The hour of the week did not change by the insulation but the value rose up to 150.9 W/m^2, which increased 19 % from CASE 0. The maximum load showed up during storage hours in CASE N2 and the value rose up to 75.9 W/m^2, which also increased 19 % from CASE 2. The comparison leads to the same reduction ratio of the maximum hourly thermal load by 40%.

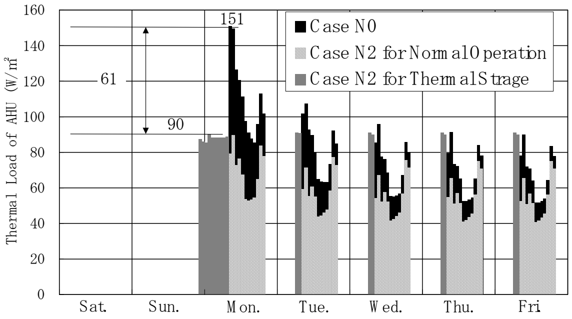


Figure 12 Thermal Load of AHU (Without Insulation)

Figure 13 shows the comparison of the weekly thermal load. The weekly load without TSBM (CASE N0) was 4.80 kWh, which increased 0.93kWh (24%) from CASE 0. The weekly load with TSBM (CASE N2) was 5.08 kWh, which increased 1.01 kWh (25%). The increase of thermal load from CASE N0 to CASE N2 was 6%. The storage ratio was 35% for CASE 2 and 33% for CASE N2. There seemed little difference in the weekly load by the insulation. In the additional simulation, the value of thermal load changed much by the insulation but the characteristics of TSBM showed little difference. The reason is that the capacity of AHU had modified by preliminary calculation.

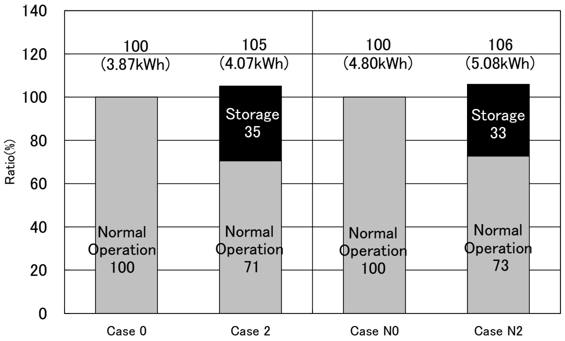


Figure 13 Comparison of Weekly Summation of AHU Thermal Load

Consideration on Indoor Thermal Environment and Thermal Load

Figure 11 shows that the problem on thermal comfort may occur at 9 a.m. on Monday without TSBM and that the temperature around foot does not differ much by TSBM after Tuesday. It may conclude that the thermal storage from Sunday to Monday enables to prevent the problems on indoor thermal environment. On the other hand, Figure 8 shows that TSBM increases the weekly thermal load according to the total hours of storage hours. CASE 1 seems appropriate, judging from thermal environment and thermal load.

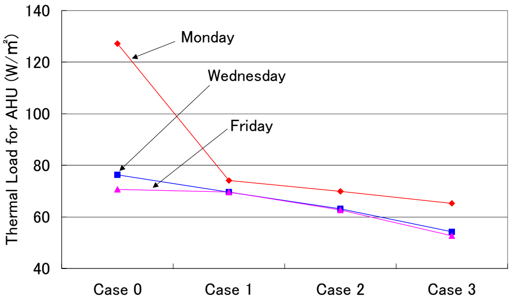


Figure 14 Maximum hourly Thermal Loads for Weekdays

There is another purpose to adopt TSBM. The reduction of AHU capacity by TSBM is important for designers. Figure 14 shows the comparison of the maximum hourly thermal load during occupied hours on Monday, Wednesday and Friday. The value on Monday without TSBM is much higher than others and the value decreases from Monday to Friday. It means that the efficient treatment of thermal load caused by thermal capacity is important to reduce the capacity of AHU for intermittent air-conditioning system. The same AHU was used for all TSBM cases in the original simulation. The maximum value shows up at 9 a.m. on Monday and Wednesday and at 7 p.m. on Friday for CASE 1 and CASE 2. For CASE 3, the maximum value shows up at 7 p.m. on every weekday. The required AHU capacity depends on the storage hours. It is necessary to adjust the

AHU capacity in designing to realize the balance of thermal environment and thermal load. Once the system is in operation, it is necessary to adjust the storage hours to minimize the weekly thermal load. The comparison of energy was done in respect to thermal load in this paper. There is no limitation on heat source for TSBM. Utilization of heat source with high efficiency will realize appropriate HVAC system with comfortable thermal environment and conservative energy consumption.

CONCLUSION

The simulation of thermal storage in building mass (TSBM) for heating in a cold region of Japan was conducted.

(1) The features of TSBM were analyzed from a survey in an office building. The simulation model to recreate the temperature distribution was constituted and the calculated temperature changes were similar to the survey.

(2) The simulation enabled the quantitative evaluation of the characteristics of TSBM, such as the reduction ratio of the maximum hourly thermal load and the increase ratio of the weekly thermal load.

(3) The simulation calculated the vertical temperature difference in the room, which led to the evaluation of indoor thermal environment.

(4) The effect of insulation was studied. There was little effect on the characteristics of TSBM.

(5) The design method was proposed to consider both of thermal environment and thermal load.

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NOMENCLATURE

I, L	zone number in a large space
K	vertical wall number
$T(I)$	air temperature in zone I
$T_w(I,K)$	interior surface temperature of vertical wall K
C	specific heat of air
γ	specific gravity of air
$A_w(I,K)$	area of vertical wall K to zone I
$\alpha_c(I,K)$	coefficient of convective heat transfer
$V_{out}(I,K)$	volume of air flowing out of zone I along wall K
$V_{in}(I,K)$	volume of air flowing into zone I from the surface current along wall K
$r(I,L,K)$	ratio of volume of air flowing into zone L to volume of air in descending current generated in zone I on wall K
$V_{si}(L)$	volume of supply air
T_{si}	temperature of supply air
$V_{so}(L)$	volume of return air
$A_B(I)$	area of boundary between zone $I-1$ and zone I
$V_E(I,L)$	volume of air entrained from zone I to primary air, and flowing into zone L
$V_c(L)$	volume of air transferred from zone L to zone $L-1$ through zone boundary
$C_B(I)$	heat transfer factor according to difference in temperatures between adjacent zones

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