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A SIMULATION STUDY ON THE RESPONSE OF CHARGED AND DISCHARGED THERMAL ENERGY IN BUILDING THERMAL MASS STORAGE SYSTEMS

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ABSTRACT

This study discusses charging and discharging performance in building thermal mass storage systems. Building thermal mass storage systems utilize the thermal masses of the beams and the concrete floor slab to absorb cool energy that is produced using less expensive night electric power. The ratios of charged energy, discharged energy, and retrieved energy to the injected energy were obtained through numerical simulations. These ratios were used to evaluate the effects of various system and building design factors on the cooling system. A simplified charged energy and retrieved energy estimation method was proposed for the design of thermal mass storage systems.

INTRODUCTION

Intermittent air-conditioning is common in Japan. Water thermal storage systems that take advantage of nighttime power discount rates have been installed in many buildings. In these systems, chilled water or ice is produced at night using the less expensive electric power, and then the chilled water or ice is used during the day to provide air-conditioning. Recently, the storage of building thermal mass has been proposed, and several such systems have been investigated. This paper discusses the performance of a building thermal mass storage system that uses air insufflation. In this system, an air-handling unit (AHU) cools the air in the ceiling plenum during the night and charges the concrete floor slab and the beams with cold energy. The cold air is directed onto the floor slab in order to increase the amount of charged energy. During the day, the majority of the energy is discharged by the return airflow through the ceiling plenum and by conduction from the ceiling boards and the floor slab, thereby cooling the room. The remainder of the energy is lost through the outside walls of the ceiling plenum.

The effects of various factors such as charging time, thermal capacity of the floor slab, beams and furniture, wall insulation and air leakage of the ceiling boards on the charging and discharging performance have not yet been clearly quantified. Also, there isn't any calculation method for designing the air-conditioning load for rooms with a building thermal mass storage system. Therefore, it is desirable to establish a simple estimation method for determining the quantity of charged and retrieved energy that the system provides in order to reduce the designed load for the air-conditioning system.

There have been several studies on building thermal mass storage systems. In these studies, the temperature distribution on the surface and the interior of the floor, the energy balance in the room, and the relationship between the nighttime energy consumption and the daytime air-conditioning energy were investigated using measurements and numerical simulations. The results were found to be dependent upon the weather, the internal heat generation, and quantity of daytime air-conditioning.

It is impossible to determine an accurate charging rate, discharging rate and retrieval rate when the conditions are also affected by the weather, internal heat generation and daytime air-conditioning. Heat flux at the surface of the floor slab, beams and furniture is caused by weather, internal heat generation and air-conditioning other than by energy injection at night and the portion caused by energy injection can not be separated. The current study acknowledges this point. Instead, simulations were performed to obtain accurate responses of charging, discharging and retrieving energy for a periodic excitation without thermal disturbances such as weather, internal heat generation and daytime air-con-

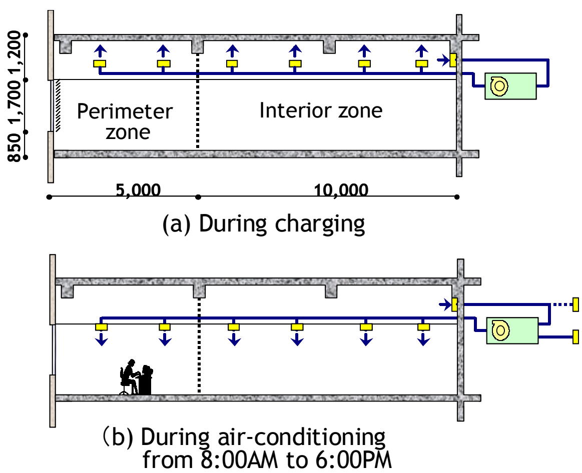


Figure 1 Office space and air-conditioning system

ditioning.

METHODOLOGY

Figure 1 depicts the section of a typical office section that was used in the simulation analysis. The room has perimeter zone and interior zone. Cold energy is injected in the ceiling plenums of both two zones. Heat balance equations cosisting of 4 unknown air temperatures and 21 unknown surface temperatures were solved for this section. The 25 unknown temperatures are represented as points in **Figure 2**. Transient heat transfer through walls and furniture was simulated using the response factor method. The response factors for the office furniture were determined from the results of a previous experimental study (Ishino et al. 1987). Simulation program is ENV that was developed by Ishino and Kohri (1986). The conditions for the standard case are given in **Table 1**. In the standard case, the charging time is 5 hours, from 3:00 AM to 8:00 AM. The cool energy introduced to the system was maintained at a constant 100 W/m2 during the charging period. The air-conditioner was in use from 8:00 AM to 6:00 PM. It was assumed that the AHU does not cool the air or supply fresh air for ventilation during this period; it only circulates the air between the room and the ceiling plenum. Unsteady state simulations were performed on this system when energy was periodically injected during the daily charging period.

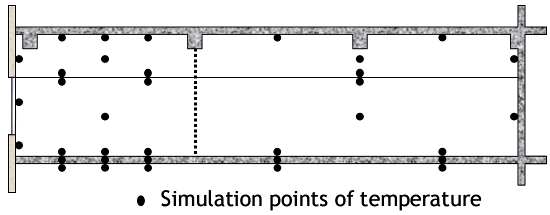


Figure 2 Simulation points of temperature in the office space

Table 1 The conditions for the standard case

(Room description)
Floor: 6mm carpet+22mm GRC+air space +140mm concrete
Ceiling board: 9mm plaster board
Window: single glazing
Wall insulation: styrenefoam 13mm for the exterior walls of the room, 50mm for the exterior and interior walls of the ceiling plenum
Surface area of the beams; 0.3m2 per unit floor area
Thermal capacity of furniture in the room; 15kJ/m3K
Infiltration rate: 0.2 ACH comparing to the room volume
Air exchange rate between the perimeter and interior zone; 20 ACH comparing to the perimeter zone volume
Air leakage rate through the ceiling boards; 0.3 ACH comparing to the room volume
Convective heat transfer coefficients in the ceiling plenum [W/m2K]: 4.5 during air-conditioning, 2.5 during the inoperative period, and 5.5 for the floor surface and 4.5 for the other surfaces during charging
(Air-conditioning system)
Charging time: 3:00AM - 5:00AM (for 5 hours)
Air-conditioning time (only air circulation); 8:00AM - 6:00PM (for 10 hours)
Supply airflow rate: 7 ACH comparing to the room volume

The following indices were used to evaluate the charging and discharging performance.

1) Indices of charging performance

Charging ratio and its details (charging ratio in the floor slab, the beams, and the furniture)

The charging ratio is the daily ratio of the total charged energy to the total injected energy.

2) Indices of discharging performance during air-conditioning

Daily retrieval ratio and its details (daily retrieval ratio due to the returned air, the lower surface of the ceiling boards, and the upper surface of the floor and the furniture)

Hourly retrieval ratio

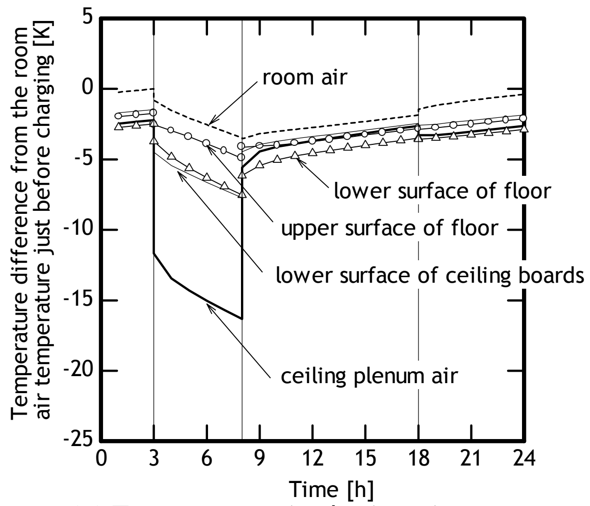
The retrieved energy is the portion of the discharged energy that cools the room during air-conditioning. The daily retrieval ratio is the ratio of the total retrieved energy to the total injected energy over a one-day period. The hourly retrieval ratio is the ratio of the hourly retrieved energy to the energy injected per hour.

RESULTS

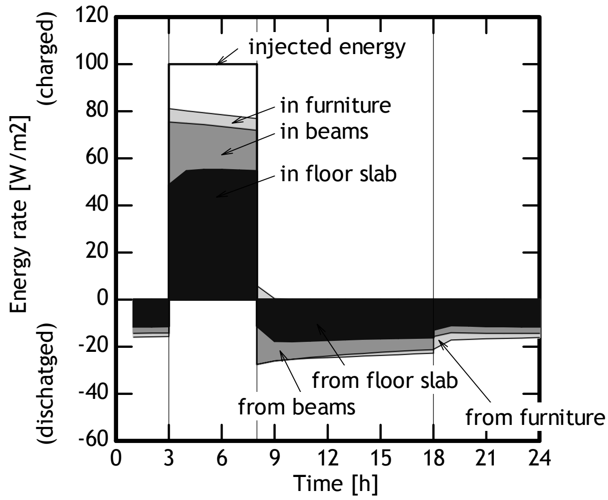
Analysis of the Standard Case

Figure 3 shows the hourly change in the temperature and the energy rate on the final stable state day for the standard case. The 5-hour charging period was found to decrease the ceiling plenum temperature by approximately 15 degrees K and the room air temperature by approximately 3 degrees K. During the air-conditioning time, the discharging energy rate from the floor slab, the beams and the furniture was found to be around 24 W/m2. The amount of energy transferred to the room from the ceiling plenum during air-conditioning suggests that the amount of retrieved energy is approximately equal to the rate of discharged energy.

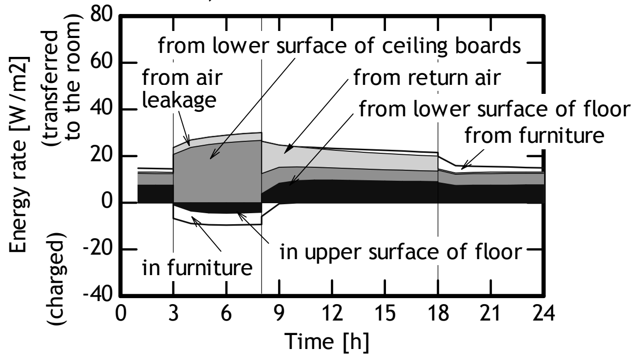
Energy balances were conducted for the three periods: charging time, air-conditioning time, and the inoperative time. **Figure 4** presents the results for these three periods using the standard case. As shown in **Figure 4(a)**, the charging ratios in the floor slab, beams, and furniture are 54%, 20% and 5%, respectively, resulting in a total value of 79%. Therefore, the energy loss during charging is 21% of the injected energy. **Figure 4(b)** shows that the total daily retrieval ratio is 46%, with 18% coming from the upper surface of the floor, 16% from the returned air, 11% from the lower surface of the ceiling boards, and 1% from the furniture. The energy loss during the air-conditioning period is 2% of the daily injected energy. The energy discharged during the inoperative period is considered an energy loss, and was found to be 30% of the injected energy.



(a) Temperature in the interior zone

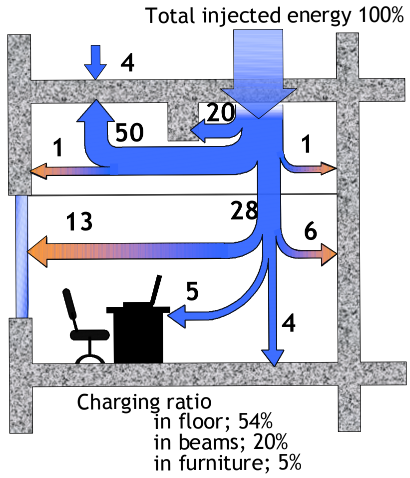


(b) Energy rate charged in and discharged from the floor slab, beams and furniture

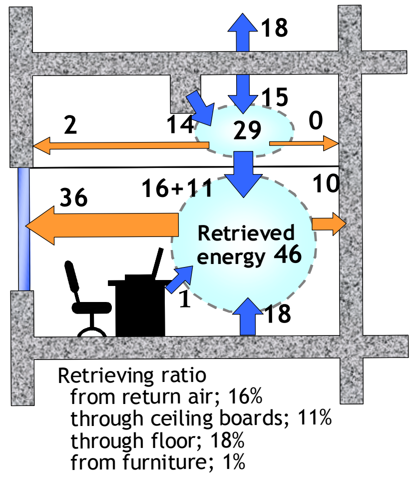


(c) Energy rate transferred to the room from the ceiling plenum and charged in the floor and furniture by the cooled room air

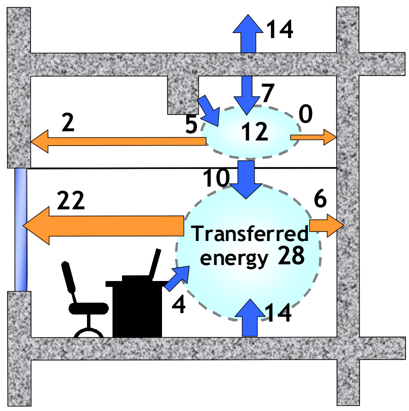
Figure 3 Hourly change in the temperature and the energy rate for the standard case



(a) Energy balance during 5-hour charging



(b) Energy balance during air-conditioning

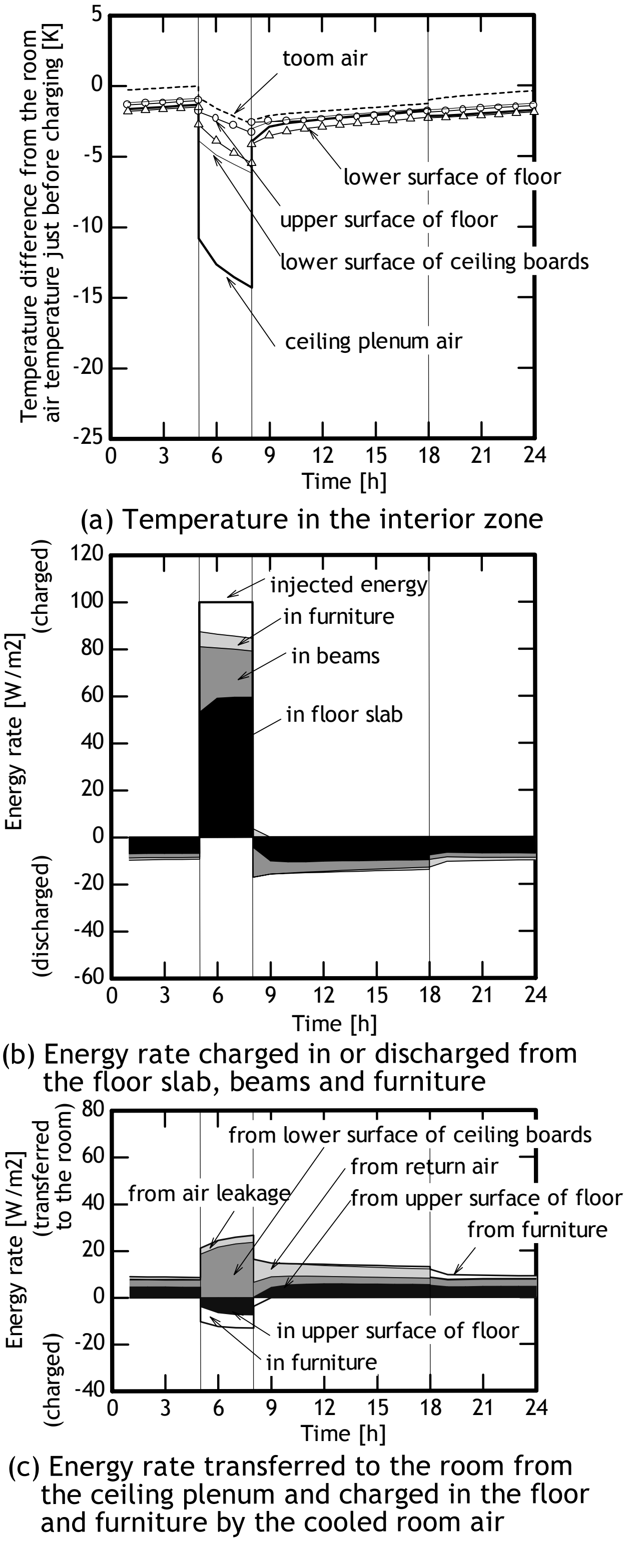


(c) Energy balance during the inoperative period

Figure 4 Energy balances for the standard case

Effect Analysis of Various Factors

Charging and discharging performance depend upon a variety of factors, such as charging time, thickness of the floor slab, number of beams, quantity of furniture, air leakage through ceiling boards, insulation of walls, and the convective heat transfer coefficient at the lower surface of the floor slab. The effects of these factors were determined through simulations. In the following cases, the unspecified conditions are the same as those in the standard case.

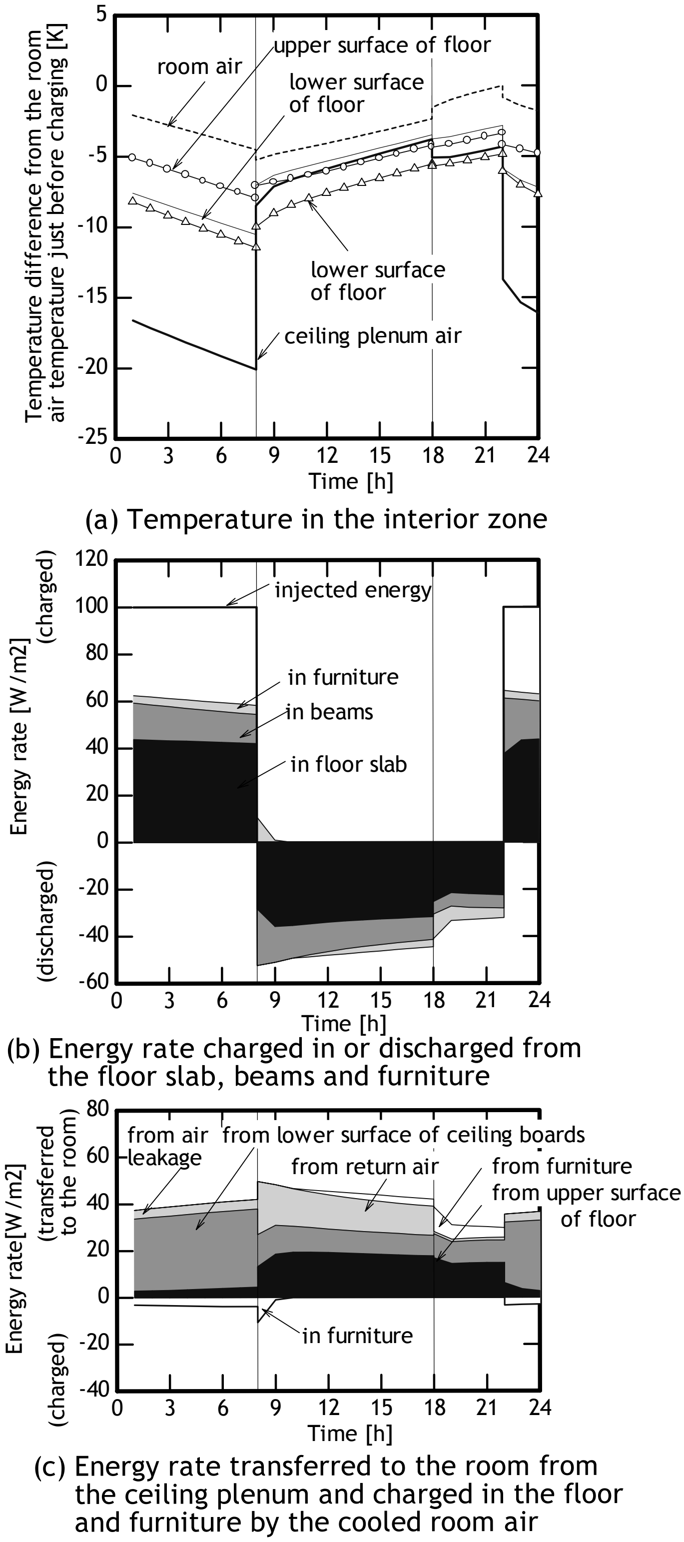


(a) Temperature in the interior zone

(b) Energy rate charged in or discharged from the floor slab, beams and furniture

(c) Energy rate transferred to the room from the ceiling plenum and charged in the floor and furniture by the cooled room air

Figure 5 Hourly change in the temperature and the energy rate for the case with 3-hour charging

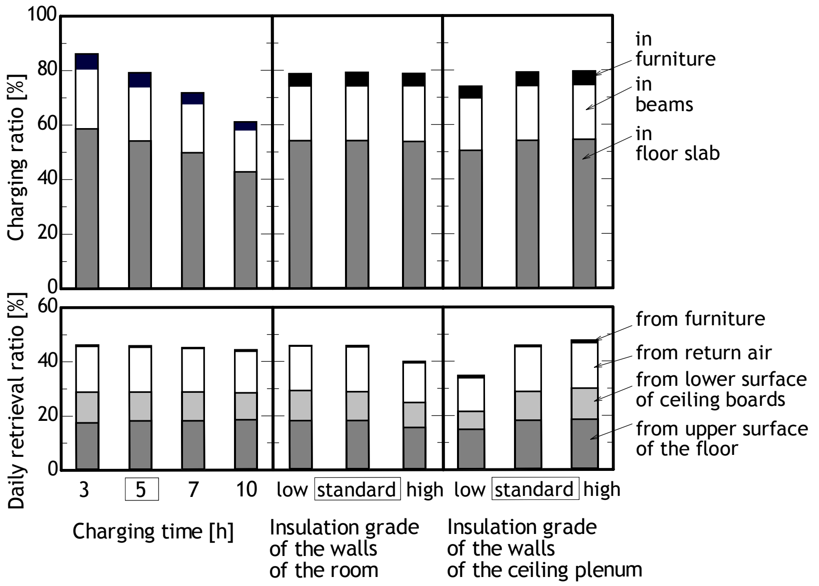


(a) Temperature in the interior zone

(b) Energy rate charged in or discharged from the floor slab, beams and furniture

(c) Energy rate transferred to the room from the ceiling plenum and charged in the floor and furniture by the cooled room air

Figure 6 Hourly change in the temperature and the energy rate for the case with 10-hour charging



Notes
1) Insulation grade of the walls of the room
low: uninsulated exterior walls, standard: standard condiions (Table1), high: 100mm insulation for the exterior walls and double glazing
2) Insulation grade of the walls of the ceiling plenum
low: uninsulated exterior and interior walls, standard: standard conditions (Table1), high: 100mm insulation for the exterior and interior walls

Figure 7 Charging and retrieval ratios for the cases with different charging times and insulation grades

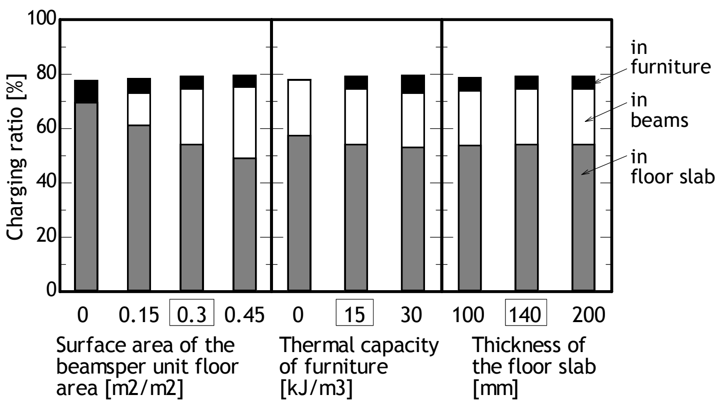


Figure 8 Charging ratios for the cases with different thermal capacity

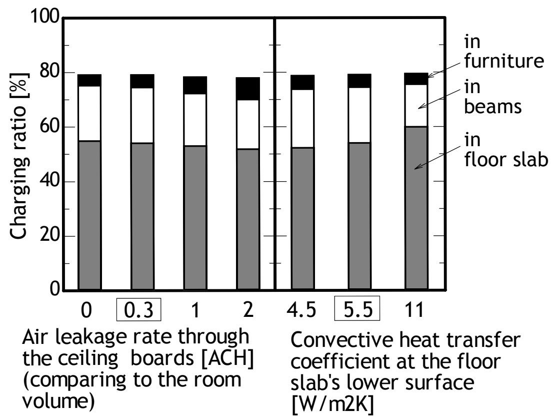
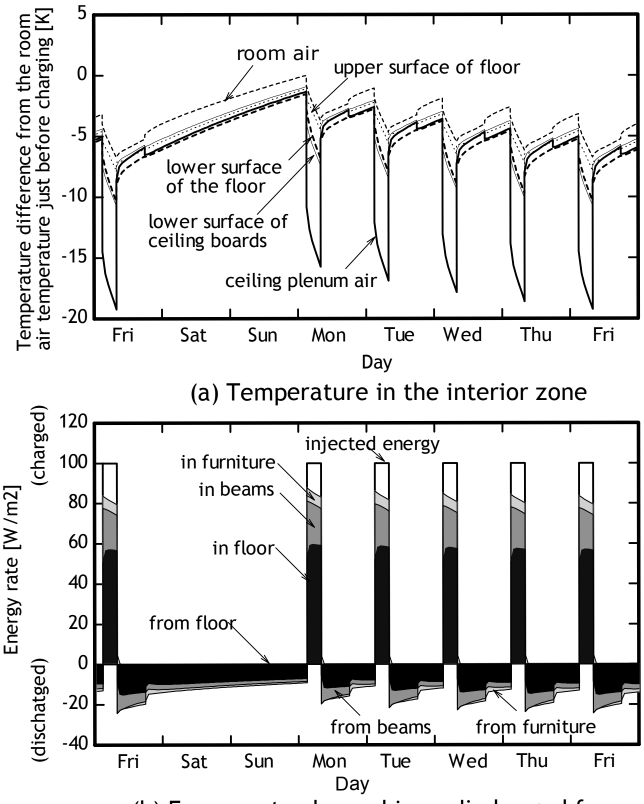


Figure 9 Charging ratios for the cases with different air leakage grades of ceiling boards and different convective heat transfer coefficients at the floor slab's lower surface

Figures 5 and **6** show the simulation results for the cases with charging times of 3 and 10 hours, respectively. As the charging time increases, the charged energy per unit time decreases. **Figures 7**, **8** and **9** show the effects of various factors on the charging and retrieval ratios. It was found that the charging time has the greatest effect on the charging ratio. As can be seen in **Figure 7**, the charging ratio is 86% for 3 charging hours and 61% for 10 charging hours. The retrieval ratio, however, is not affected by charging time. The large amount of insulation on the room walls reduces the retrieval ratio and the limited insulation on the walls of the ceiling plenum reduces both the retrieval ratio and the charging ratio. The effects of the thermal capacity factors on the charging ratio are presented in **Figure 8**. Although the size of the beams and the quantity of furniture affect certain aspects of the charging ratio, the overall charging ratio is not affected by these factors. This characteristic also holds for the effect of the air leakage rate through the ceiling boards and the convective heat transfer coefficient at the floor slab's lower surface on the charging ratio, as can be seen in **Figure 9**. Although the retrieval ratio coefficients are not shown in F**igures 8** and **9**, they were found to not be affected by these factors, as well. The purpose of the effect analysis is to study the characteristics of daily periodic excitation of injected energy. The charging and air-conditioning cycle is typically run for 5 days a week. **Figure 10** shows the change in the temperature and the energy rate for a standard 5 day-a-week operation. The charged energy rate is higher and the retrieved energy rate is lower on Mondays than on the other weekdays.

PROPOSAL OF DESIGN ESTIMATION METHOD



(a) Temperature in the interior zone

(b) Energy rate charged in or discharged from the floor slab, beams and furniture

(c) Energy rate transferred to the room from the ceiling plenum and charged in the floor and furniture by the cooled room air

Figure 10 Hourly changes in the temperature and the energy rate for the standard case with operation for 5 day-a-week

The following results were obtained from the effect analysis:

1) Charging time has a substantial impact on the charging ratio.

2) The insulation grade of the walls affects both the charged energy and retrieved energy.

3) The number of operating days in a week affects both the charged energy and retrieved energy.

A new charged energy and retrieved energy estimation method has been proposed. This method can be used for a building with an adequate level of plenum wall insulation and a typical amount of wall insulation in the room. For this method, the air-conditioning time is assumed to be 10 hours. The daily charged energy rate and the hourly retrieved energy rate can be estimated for two different cases: 5 day-a-week operation and 7 day-a-week operation.

Table 2 Equations for estimation of charged energy and retrieved energy

Daily total of charged energy rate Q_{ST} [kJ]

$$Q_{ST} = k_{OP,ST} \cdot k_{ST} \cdot Q_{IN} \quad \text{...(1)}$$

Retrieved energy rate at time j $q_{R,j}$ [W]

$$q_{R,j} = k_{OP,R} \cdot k_{R,j} \cdot q_{IN,AVE} \quad \text{...(2)}$$

$k_{OP,ST}$: operation factor for charging energy [-]
k_{ST} : charging ratio [-]
Q_{IN} : daily total of injected energy rate [kJ]
$k_{OP,R}$: operation factor for retrieved energy [-]
$k_{R,j}$: retrieving ratio [-]
$q_{IN,AVE}$: average injected energy rate for charging time [W]

Table 3 Charging ratio k_{ST}

Charging time [h]	3	5	7	10
Charging ratio *kst* [-]	0.82	0.77	0.72	0.65

Table 4 Operation factor $k_{OP,ST}$ and $k_{OP,R}$

$k_{OP,ST}$: operation factor for charged energy [-]
$k_{OP,R}$: operation factor for retrieved energy [-]

Operation	Conditions	$k_{OP,ST}$	$k_{OP,R}$
5 day-a-week	Monday	1.04	0.86
	Tuesday	1.02	0.95
	Wednesday	1.00	1.00
	Thursday	0.99	1.04
	Friday	0.98	1.07
7 day-a-week	3h-charging	0.97	1.24
	5h-charging	0.96	
	7h-charging	0.93	
	10h-charging	0.89	

Table 2 presents the equations for the charged energy and the retrieved energy estimation. The daily charged energy rate can be obtained by multiplying the daily injected energy rate by the operation factor $k_{OP,ST}$ and the charging ratio k_{ST}. The retrieved energy at time j can be obtained by multiplying the average injected energy rate by the operation factor $k_{OP,R}$ and the retrieving ratio $k_{R,j}$. The charging ratios and the operation factors are provided in **Tables 3** and **4**. The hourly retrieval ratio values are provided in **Table 5**. This table also includes the room air temperature values for the standard case with a 5 day-a-week operation.

(Estimation Example)

Table 10 Retrieving ratio $k_{R,j}$ for different charging time

KR,j: (during air-conditioning) retrieval ratio at time j [-]
(during charging and during the inoperative period) the ratio of cool energy transferred to the room from the ceiling plenum at time j to the injected energy [-]
tR: temperature decrease of room air on Wednesday due to charging for the standard case with operation for 5 day-a-week [K]

3-hour charging			5-hour charging			7-hour charging			10-hour charging		
Time	KR,j	tR	Time	KR,j	tR	Time	KR,j	tR	Time	KR,j	tR
5	0.06	0.0	3	0.10	0.0	1	0.14	0.0	22	0.20	0.0
5	0.15	-0.8	3	0.19	-0.8	1	0.23	-0.8	22	0.29	-0.8
6	0.16	-1.6	4	0.20	-1.6	2	0.24	-1.5	23	0.30	-1.5
7	0.17	-2.2	5	0.21	-2.1	3	0.25	-2.1	24	0.30	-1.9
8	0.17	-2.7	6	0.21	-2.6	4	0.25	-2.5	1	0.31	-2.3
8	0.14	-2.4	7	0.22	-3.1	5	0.26	-3.0	2	0.32	-2.7
9	0.12	-2.1	8	0.23	-3.6	6	0.27	-3.4	3	0.33	-3.1
10	0.12	-2.0	8	0.22	-3.6	7	0.27	-3.9	4	0.33	-3.5
11	0.11	-1.9	9	0.20	-3.2	8	0.28	-4.4	5	0.34	-3.9
12	0.11	-1.8	10	0.19	-3.1	8	0.30	-4.5	6	0.35	-4.3
13	0.11	-1.8	11	0.19	-2.9	9	0.28	-4.2	7	0.35	-4.8
14	0.11	-1.7	12	0.18	-2.8	10	0.27	-4.0	8	0.36	-5.2
15	0.10	-1.6	13	0.18	-2.7	11	0.26	-3.8	8	0.41	-5.6
16	0.10	-1.5	14	0.17	-2.6	12	0.25	-3.7	9	0.39	-5.3
17	0.10	-1.5	15	0.17	-2.5	13	0.25	-3.6	10	0.38	-5.1
18	0.10	-1.4	16	0.17	-2.4	14	0.24	-3.4	11	0.37	-4.9
18	0.07	-1.2	17	0.16	-2.3	15	0.24	-3.2	12	0.36	-4.7
19	0.06	-1.1	18	0.16	-2.2	16	0.23	-3.1	13	0.35	-4.4
20	0.06	-1.0	18	0.12	-1.8	17	0.23	-2.9	14	0.34	-4.2
21	0.06	-0.9	19	0.10	-1.6	18	0.22	-2.7	15	0.33	-4.0
22	0.06	-0.8	20	0.10	-1.5	18	0.16	-2.3	16	0.32	-3.8
23	0.06	-0.8	21	0.11	-1.3	19	0.14	-2.0	17	0.32	-3.5
24	0.06	-0.7	22	0.11	-1.2	20	0.15	-1.8	18	0.31	-3.3
1	0.06	-0.6	23	0.11	-1.1	21	0.15	-1.6	18	0.23	-2.7
2	0.06	-0.6	24	0.11	-1.0	22	0.15	-1.4	19	0.20	-2.2
3	0.06	-0.5	1	0.11	-0.9	23	0.15	-1.3	20	0.20	-1.9
4	0.06	-0.5	2	0.11	-0.8	24	0.15	-1.1	21	0.21	-1.7

Notes) End of charging is at 8:00AM. Air-conditioning time is from 8:00AM to 6:00PM.

Find the total charged energy and retrieved energy at 2:00 PM on Monday. The injected energy is 80 W/m2 for 7 hours. The charging and air-conditioning cycle is operated 5 days a week.

From **Table 3**, the charging ratio k_{ST} is found to be 0.72. The operation factors $k_{OP,ST}$ and $k_{OP,R}$, found from **Table 4**, are 1.04 and 0.86, respectively. The retrieval ratio at 2:00 AM $k_{R,14}$ is 0.24, which was found from **Table 5**. Substituting these values into Equations (1) and (2) in **Table 2**, the total charged energy Q_{ST} and retrieved energy $q_{R,14}$ are obtained. The results are displayed below.

$$Q_{ST}=(1.04)(0.72)((3.6)(7)(80))=1510 \text{ kJ}$$

$$q_{R,14}=(0.86)(0.24)(80)=17 \text{ W}$$

CONCLUSIONS

The results from the study are summarized below.

1) For the standard 5-hour charging case, the charging ratio is 79%, with 54% of the energy absorbed by the floor slab, 20% by the beams, and 5% by the furniture. The retrieval ratio is 46%.

2) The effect analysis determined that the charging time was found to have the greatest impact on the charging ratio. The charging ratio is 86% for 3 hours of charging and 61% for 10 hours of charging. On the other hand, the thermal capacity of the floor slab, the beams, and the furniture does not affect the overall charging ratio, although it affects certain aspects of the ratio's details. The charging ratio and retrieval ratio are independent of all of the factors except charging time, wall insulation, and the number of operating days in a week.

3) A mean to improve retrieval ratio is improved thermal insulation of walls in the ceiling plenum. Improved thermal insulation of walls in the ceiling plenum and short charging time improve the charging ratio.

4) A simplified charged energy and retrieved energy estimation method, which can be used in the design of air-conditioning equipment, was proposed.

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