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# Computational Study on Thermal Properties of HVAC System with Building Structure Thermal Storage


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**Abstract:** Building structure thermal storage (BSTS) HVAC systems can store heat during nighttime thermal storage operation (nighttime operation hours) by using off-peak electricity and release it in the daytime air-conditioning operation (daytime operation hours) by utilizing a large amount of the thermal capacity of building structures such as beams, columns and floors composed of concrete. These BSTS systems have recently been considered as one method for leveling hourly electricity demands for HVAC on a day-to-day basis. Through a simulation using a model developed with experimental data, this paper describes how various factors for the design and operation of a BSTS quantitatively affect the charge/discharge performances of a HVAC system. As a result, the following was revealed: the thermal performance of the system is strongly influenced by the daily heat storage operation hours, supply air volume and supply air temperature during the nighttime operation hours, stored heat caused the total daytime cooling extraction to decrease by 11% to 58% and the daily total cooling extraction through nighttime to daytime to increase by 4% to 17% compared with the values of non- thermal storage HVAC system.



**Key words:** HVAC system, Building Structure Thermal Storage, Thermal Performance, Simulation


## 1. INTRODUCTION

The growth in the commercial building sector has caused power demands, especially the daytime demands, to increase more and more rapidly. To reduce these sharply pointed power demands, building architects and engineers have actively been researching methods that level the demands. Therefore, they are investigating the widely developed and popular thermal storage systems to shift peak electricity demand from the daytime to the nighttime to level off the hourly consumption. Building structure thermal storage (BSTS) HVAC systems have the potential to be effective for this purpose. These systems can charge heat to building structures such as beams, columns and floors composed of concrete by using cheap nighttime electricity and discharge the stored heat in the daytime. Compared with non-thermal storage HVAC systems, the thermal load and electric consumption for heating and cooling in the daytime can be decreased. Also, because few additional devices are needed for thermal storage compared with those needed for ice storage or hot/chilled water storage systems, the equipment installation costs can be reduced. However, the usage of the thermal capacity of the building structure causes difficulties in controlling the charge/discharge heat freely and instantaneously. It is very important to choose the optimal design or operation parameters by taking into account the system's characteristics. Adjusting the daily heat storage operation hours, supply air volume and supply air temperature are the proposed approaches for optimization.

In this paper, the thermal performance of BSTS with a ceiling plenum chamber (Figs. 1 and 2) is analyzed and evaluated at a high cooling load condition using experimental apparatus of the actual size used in a building. A computational model using the experimental data is then developed and its validity is also verified. In addition, the influence of each design/operation parameter on the system performance is analyzed by performing a simulation using the model.

## 2. EXPERIMENT OUTLINE

Table 1 shows the experimental testing room (TR) specifications. The floor is composed of flat deck concrete 141 mm thick and the south façade is mostly glass. Figs. 1 and 2 show the testing room HVAC operation. During the nighttime operation hours, cold air is supplied to the ceiling plenum through the header type openings to keep the ceiling slab surface cool, as shown in Photo 1 and Fig. 3. The air that cools the slab flows into the return openings in the ceiling plenum and returns to the air-handling unit. During the daytime operation hours, the cold air, which is supplied through the diffusers to the room, flows through the openings in the ceiling board to the ceiling plenum and returns to the air handling unit (AHU) along the same route as in the nighttime. The TR is surrounded with six buffer spaces, which are called guard rooms (GR*). GR1 is connected to the south side of the TR (Fig. 1, on the left side), and its temperature is controlled to be the same as that of the outdoor air for the maximum cooling load calculation, which fluctuates daily. The GRs connected with the east, north and west sides can each be controlled to be the same room air temperature as that of the TR. Additionally, the upper surface temperature of the ceiling concrete slab, which is connected to the upper floor room (GR5) is controlled so that it is the same as that of the floor concrete slab by varying the room temperature of GR5. The lower surface temperature of the floor concrete slab connected to the lower floor room (GR6) is also controlled to be the same as that of the ceiling slab by varying the room temperature of GR6 (Appendix, Fig. 13). That is, the TR can behave as the middle floor in a multi-story office building, and so on. Table 2 shows the experimental conditions: the nighttime operation hours are 2.5 h and the daytime operation hours are 10 h. The heat from lights and office machines is

**Photo 1 Header type openings installed in the ceiling space**

**Table 2 Experiment conditions**

| | | |
|---|---|---|
| Nighttime thermal storage operation | Operation hours | 2.5 h (5:30～8:00) |
| | Supply cold air volume | 1500 [m3/h] |
| | Supply cold air temperature | 10 [℃] |
| Daytime air-conditioning operation | Operation hours | 10 h (8:00～18:00) |
| | Supply cold air volume | VAV system |
| | Supply cold air temperature | 13 [℃] |
| | Set temperature of TR | 26 [℃] |
| | Lighting heat gain | fluorescence lamp : 32 [W]x60=1920 [W] |
| | Electrical devices heat gain | 100 [W]x20=2000 [W] |

**Table 1 Building specifications**

| Items | Specifications |
|---|---|
| Floor area of TR | 60 m2 |
| Upper or lower slab of TR | Flat deck concrete 141 mm thick |
| South wall of TR | Full double sliding windows, clear glass 5 mm thick |
| Other walls of TR | Double plasterboard 12 mm thick |
| Ceiling board of TR | 640*640 mm rock wool sound board 15 mm thick |
| Free access floor board of TR (OA-floor board) | Floor board 30 mm thick, 600*600 mm silica calcium board with carpet |
| Ice thermal storage tank | Open type, 3 m3, Direct expansion system |
| AHU -Cooling coil | Plate fin coil, Fin intervals, 3.2 mm, 6 rows, 14 tubes, Single flow type<br>Cooling capacity, 28 kW (24,100 kcal/h), inlet air temperature 27.9 ℃, outlet air temperature 13.2 ℃, inlet water temperature 5 ℃, outlet water temperature 10 ℃, 81 L/min |
| AHU -Fan | Maximum flow rate, 3,240 or 2,000 m2/h |
| VAV damper | 250 mmφ, opposed blade type |
| Two-way valve (chilled water) | Motorized two-way valve |

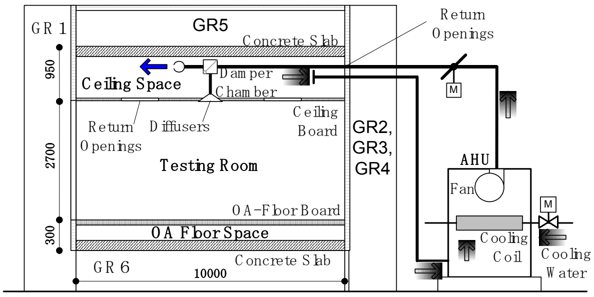



**Fig. 1 HVAC system of experimental testing room, allows indicate nighttime (thermal storage) operation**

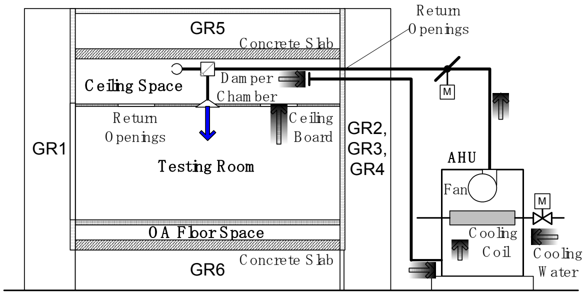



**Fig. 2 Daytime (air-conditioning) operation**

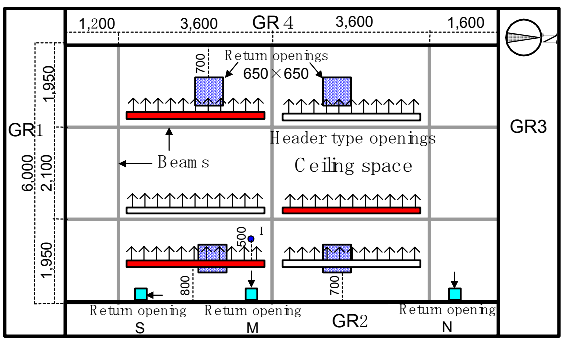



**Fig. 3 Plan of ceiling space**

only generated during daytime operation hours. During this time, the curtain in GR1 closed to keep out sunlight.

## 3. SIMULATION OUTLINE AND BSTS MODELING

The TR, ceiling plenum and free access floor (OA-floor) are selected as the elements of the mathematical modeling. TRNSYS-16 software is used to estimate the temperature and heat of each space. The air temperature measurements of the six sides of the GRs are used for the boundary condition. The supply air volume and temperature to the ceiling plenum or the TR are input conditions. Other parameters for the calculation are shown in Table 3. The values of the convective heat transfer coefficient (CHTC) are separately used in the case of upward thermal flow and downward thermal flow on the concrete slab surface. The following four parameters are unknown: CHTC on the lower surface of the ceiling concrete slab during the nighttime operation hours, the outdoor air change rate through the exterior walls of the TR and the ceiling plenum, the air change rate between the two spaces and the heat gain rate from the lamps to the ceiling plenum.
These values are chosen by trial-and-error, so the optimal values can be found where the calculated values are in accordance with the measured values.

## 4. MODEL VERIFICATION

Figs. 4 and 5 show both the calculated and measured values of the TR temperature, ceiling plenum temperature and average ceiling concrete slab temperature. During the nighttime, the cold air supply to the ceiling plenum brought the TR temperature down to about 3 K, and the average slab temperature was 1 K in both the experiment and simulation, and the ceiling plenum temperature was 7 K in the experiment and 8 K in the simulation. During the daytime operation, the measured TR temperature was controlled to be the set-point (26°C) and the measured average ceiling slab temperature slowly rose because it discharged the cold heat charged at night. The calculated values generally followed the measured values. Fig. 6 shows the average measured heat flux at 12 spots of the ceiling concrete slab and the calculated value, which is about 40 W/m$^2$ maximum in the heat storage mode. During the nighttime operation hours, the calculated values are smaller than the measured values and mostly the same as those during the daytime and non-operation hours. Fig. 7 shows both the calculated and measured cooling loads during the nighttime and daytime operations hours. The calculated cooling load at night is almost the same as the measured data. Fig. 8 shows both the calculated and measured values of the charge and discharge heat of the concrete slab. The slab charged the cold heat at 304 [kJ/m$^2$] (based on the floor area)

**Table 3 Simulation conditions**

| | | |
|---|---|---|
| Convective heat transfer coefficient | Upward heat flux | 4.7 [W/m2K] |
| | Downward heat flux | 2.3 [W/m2K] |
| | Lower surface of the ceiling slab in nighttime operation hours | 6.0 [W/m2K] |
| Air change of infiltration | TR 0.4/h (based on the TR volume) | |
| | Ceiling space 0.4/h (based on the ceiling space volume) | |
| Air change between TR and ceiling space in nighttime operation hours | 3/h (based on the TR volume) | |
| Lighting gain ratio between TR and ceiling space | TR 0.9 [-], Ceiling space 0.1 [-] | |

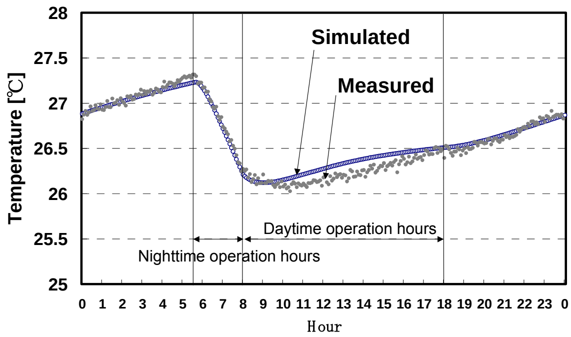



**Fig. 4 Average ceiling concrete slab temperature**

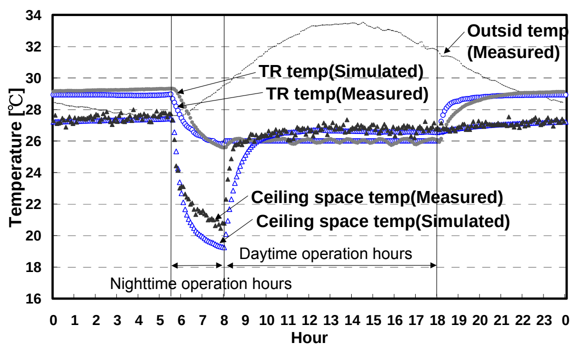



**Fig. 5 TR and Ceiling space temperature**

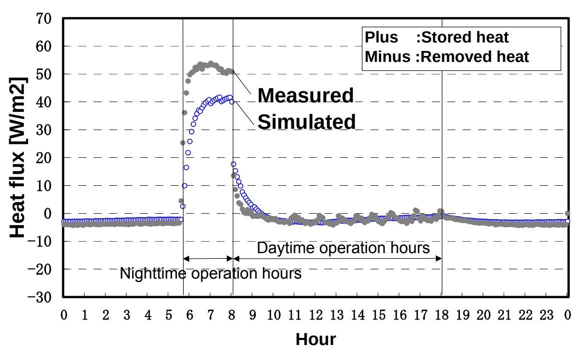



**Fig. 6 Heat flux on the lower surface of the ceiling concrete slab**

in the experiment and 286 [kJ/m$^2$] in the simulation during the nighttime operation, and discharged at 33 [kJ/m$^2$] and 87 [kJ/m$^2$] during the daytime operation and 272 [kJ/m$^2$] and 195 [kJ/m$^2$] during the non-operation hours in the experiment and simulation, respectively. The small amount of discharged heat during the daytime operation is mainly caused by insufficient amount of charged heat (due to the short charging operation hours. The developed model simulates well the experimental performances from the above-mentioned procedure and enables us to analyze how the BSTS should be optimally designed and operated through the following simulation.

## 5. SIMULATION OUTLINE

Table 4 shows the design and operation factors and conditions of the simulation. Table 5 shows eight factors, such as nighttime operation hours (NO H), supply air temperature during the nighttime operation hours (NST), supply air volume during the nighttime operation hours (NSV), internal heat gains, air change rate between the TR and ceiling plenum during the nighttime operation hours (CTC), CHTC on the lower surface of the ceiling slab during the nighttime operation hours, infiltration through the outer walls and windows and window area ratio (WAR). Two levels of each factor are analyzed for their effect on the storage performance using the method of the experiment. To clarify the performance of BSTS, non-thermal storage HVAC system is also considered.

## 6. ANALYSIS OF CHARGE/DISCHARGE RESPONSE

The simulations are conducted under a day cycle steady state. Fig. 9 shows the mean values of the charge/discharge performances of all cases. Approximately 86% of the cooling heat supplied to the ceiling plenum in the nighttime was charged to

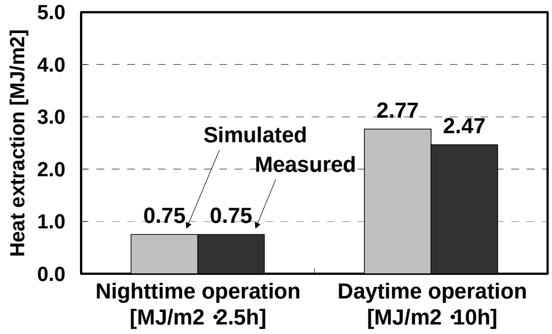



**Fig. 7 Comparison between measured and calculated heat extractions**

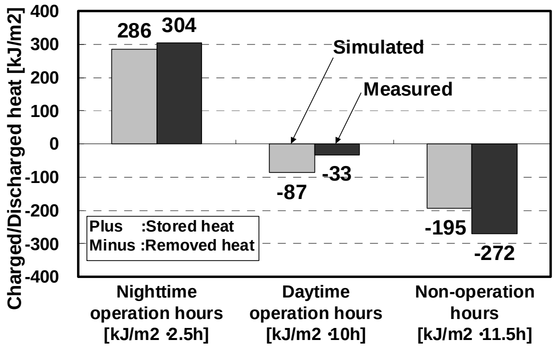



**Fig. 8 Comparison between measured and calculated Charge/discharge heat of the ceiling slab in three operation modes**

**Table 4 Design/operation factors and conditions of calculation**

| | | | |
|---|---|---|---|
| Nighttime operation hours | 5 h (3:00～8 :00) or 2.5 h (5:30～8 :00 ) | | |
| Daytime operation hours | 10 h (8:00～18:00) | | |
| | Nighttime operation hours | Daytime operation hours | Non-operation hours |
| Lighting gains | 0% | 100% | 0% |
| Devices gains | 0% | 100% | 0% |
| Infiltration | 100% | | |
| CTC | 100% | 0% | |

**Table 5 Factors and levels for simulation**

| | Nighttime operation hours [h] | Nighttime supply air volume [m3/h] | Nighttime suuply air temperature [℃] | Internal gain [W] | Air change between TR and CS [1/h] | CHTC [W/m2K] | Infiltration between indoor and outdoor [1/h] | Area ratio of walls and windows* [-] |
|---|---|---|---|---|---|---|---|---|
| CASE1 | 5 | 1500 | 10 | 4000 | 4 | 10 | 0.6 | 0.75 |
| CASE2 | 5 | 1500 | 10 | 2300 | 2 | 6 | 0.2 | 0.3 |
| CASE3 | 5 | 1500 | 15 | 4000 | 4 | 6 | 0.2 | 0.3 |
| CASE4 | 5 | 1500 | 15 | 2300 | 2 | 10 | 0.6 | 0.75 |
| CASE5 | 5 | 750 | 10 | 4000 | 2 | 10 | 0.2 | 0.3 |
| CASE6 | 5 | 750 | 10 | 2300 | 4 | 6 | 0.6 | 0.75 |
| CASE7 | 5 | 750 | 15 | 4000 | 2 | 6 | 0.6 | 0.75 |
| CASE8 | 5 | 750 | 15 | 2300 | 4 | 10 | 0.2 | 0.3 |
| CASE9 | 2.5 | 1500 | 10 | 4000 | 2 | 6 | 0.6 | 0.3 |
| CASE10 | 2.5 | 1500 | 10 | 2300 | 4 | 10 | 0.2 | 0.75 |
| CASE11 | 2.5 | 1500 | 15 | 4000 | 2 | 10 | 0.2 | 0.75 |
| CASE12 | 2.5 | 1500 | 15 | 2300 | 4 | 6 | 0.6 | 0.3 |
| CASE13 | 2.5 | 750 | 10 | 4000 | 4 | 6 | 0.2 | 0.75 |
| CASE14 | 2.5 | 750 | 10 | 2300 | 2 | 10 | 0.6 | 0.3 |
| CASE15 | 2.5 | 750 | 15 | 4000 | 4 | 10 | 0.6 | 0.3 |
| CASE16 | 2.5 | 750 | 15 | 2300 | 2 | 6 | 0.2 | 0.75 |

* Area ratio of walls and windows [-] = windows area [m2] / (windows area [m2] + area of external walls [m2])

the storage devices and 14% was lost because of the overall heat transfer. The heat charged to the concrete slab, beams, fixtures of the TR and free access floor board accounts for 47%, 18%, 13%, 6% of the total heat charged to all the storage devices in the nighttime, respectively. Figs. 10 and 11 show the estimation of the effects of the eight design parameters. The average charged heat in the nighttime is 626 [kJ/m$^2$], and the average discharged heat in the daytime is 491 [kJ/m$^2$]. The three factors for nighttime operation hours, nighttime supply air volume and nighttime supply air temperature have significant effects on both the charged and discharged heat, whereas CHTC, by contrast, causes few changes.

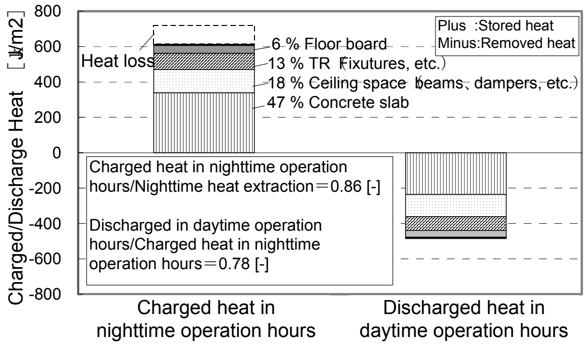



**Fig. 9 Average charge/discharge heat of the storage devices of all cases**

## 7. EVALUATION INDEXES

The various evaluation indexes of the BSTS HVAC system are shown in Table 6. Fig. 12 shows heat extractions in case No. 2, No. 3 and No. 15 and those with non-thermal storage HVAC systems. Heat extraction in the nighttime can reduce that during the daytime. The nighttime heat extraction ratio (NER), defined as the heat extraction in the nighttime operation hours to the total day heat extraction, ranges from 11% to 58% and increases with the increment of the operation hours. The heat extraction increasing ratio (HIR), defined as the total day heat extraction to the total daily heat extraction with a non-thermal storage HVAC system, ranges from 1.04 to 1.17 and indicates the same tendency as NER, which shows that the nighttime operation hours should be selected as needed. The efficiency of reducing the heat extraction in the nighttime operation hours (ERE), defined as (heat extraction with non-thermal storage HVAC system - heat extraction in the nighttime operation hours) to the heat extraction in the nighttime operation hours, indicates how effectively the heat extraction in the nighttime operation hours can contribute to the reduction of the heat extraction in the nighttime operation hours. This index, which has an average value of 0.664, increases with the increment of the storage operation hours. However, it decreases as the window area and infiltration volumes increase.

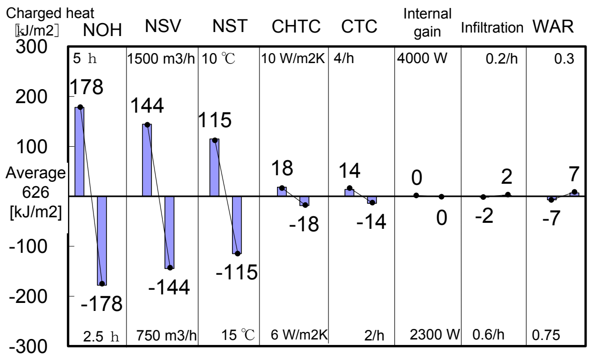



**Fig. 10 Nighttime heat charge performances due to difference of each factor and level**

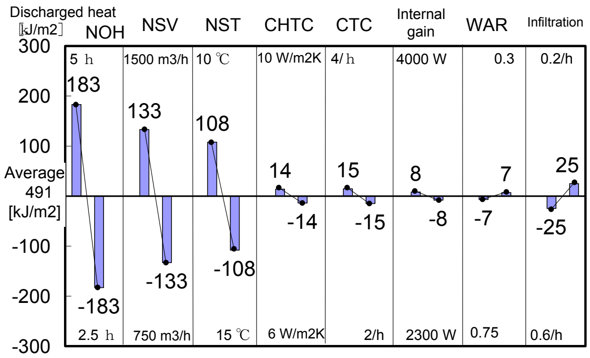
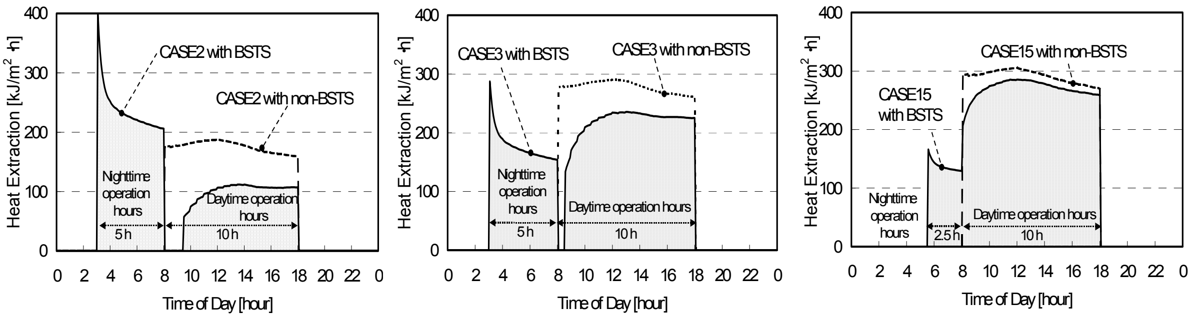



**Fig. 11 Daytime heat discharge performances due to difference of each factor and level**




CASE2 CASE15

**Fig. 12 Comparison of cooling load between BSTS and non-BSTS systems**

**Table 6 Evaluation indexes**

| CASE | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Nighttime heat extraction [MJ/day] | 85 | 71 | 53 | 58 | 51 | 54 | 37 | 37 | 43 | 48 | 33 | 32 | 29 | 29 | 21 | 20 | 44 |
| Daytime heat extraction [MJ/day] | 154 | 52 | 126 | 115 | 128 | 118 | 189 | 79 | 146 | 111 | 183 | 93 | 186 | 96 | 162 | 131 | 129 |
| Total heat extraction (THE) [MJ/day]*1 | 239 | 124 | 179 | 173 | 179 | 171 | 226 | 116 | 189 | 159 | 216 | 125 | 215 | 125 | 183 | 151 | 173 |
| Total heat extraction of non-thermal strage HVAC system cases [MJ/day] | 212 | 105 | 167 | 150 | 167 | 150 | 212 | 105 | 175 | 143 | 204 | 114 | 204 | 114 | 175 | 143 | 159 |
| Nighttime extraction ratio (NER) [−]*2 | 0.35 | 0.58 | 0.30 | 0.34 | 0.29 | 0.31 | 0.16 | 0.32 | 0.23 | 0.30 | 0.15 | 0.25 | 0.13 | 0.23 | 0.11 | 0.13 | 0.26 |
| Heat discharge ratio (HDR) [−]*3 | 0.87 | 0.89 | 0.88 | 0.78 | 0.87 | 0.78 | 0.74 | 0.79 | 0.71 | 0.79 | 0.72 | 0.65 | 0.74 | 0.60 | 0.53 | 0.61 | 0.75 |
| Effective discharge ratio (EDR) [−]*4 | 0.74 | 0.83 | 0.82 | 0.63 | 0.79 | 0.63 | 0.56 | 0.72 | 0.63 | 0.69 | 0.59 | 0.58 | 0.57 | 0.52 | 0.44 | 0.48 | 0.64 |
| Extraction sharing ratio (ESR) [−]*5 | 0.40 | 1.13 | 0.35 | 0.32 | 0.32 | 0.29 | 0.11 | 0.33 | 0.19 | 0.29 | 0.11 | 0.20 | 0.09 | 0.16 | 0.06 | 0.07 | 0.28 |
| Heat extraction increasing ratio (EIR) [−]*6 | 1.13 | 1.17 | 1.07 | 1.15 | 1.07 | 1.14 | 1.07 | 1.10 | 1.08 | 1.11 | 1.06 | 1.10 | 1.05 | 1.10 | 1.04 | 1.06 | 1.09 |
| Efficiency of reducing heat extraction in daytime operation (ERE) [−]*7 | 0.68 | 0.74 | 0.78 | 0.61 | 0.76 | 0.61 | 0.61 | 0.72 | 0.68 | 0.67 | 0.64 | 0.65 | 0.64 | 0.62 | 0.62 | 0.60 | 0.66 |

Definition of evaluation indexes

*1 :THE = nighttime heat extraction + daytime heat extraction
*2 :NER = nighttime heat extraction / total heat extraction
*3 :HDE = discharged heat from building structure in daytime operation hours / nighttime extraction ratio
*4 :EDR = discharged heat from building structure in daytime operation hours / charged heat to building structure in nighttime operation hours
*5 :ESR = discharged heat from building structure in daytime operation hours / heat extraction in nighttime operation hours
*6 :EIR = total heat extraction / total heat extraction with non-thermal storage HVAC system
*7 :ERE = (heat extraction with non-theramal storage HVAC system - heat extraction for daytime operation) / heat extraction for nighttime operation

## 8. CONCLUSIONS

A thermal model of building structure thermal storage is proposed. The model is based on measured experimental data. From these profiles, the following results are derived:

1. **A**bout the average 86% of the heat extracted by the supply cold air in the ceiling space during the nighttime operation hours is stored in concrete slab, beams, fixtures of the TR and free access floor. The other 14% is lost as the heat transmission of the exterior wall etc.
2. Of the many factors that influence the amount of thermal storage, the thermal storage time is the most significant factor, followed by the quantity of the supply cold air and temperature of the supply cold air.
3. The convection heat transfer coefficient is not as effective as the cold air volume and cold air temperature for increasing the amount of thermal storage.
4. A building with a wider window space, weaker thermal insulation for the envelope and larger infiltrations is not suitable for implementation of a BSTS system.
5. In calculations, BSTS system decrease the total daytime cooling heat extraction by 11% to 58% and increase the daily total cooling extraction through nighttime to daytime by 4% to 17% compared with values of non-thermal storage HVAC system.

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## APPENDIX

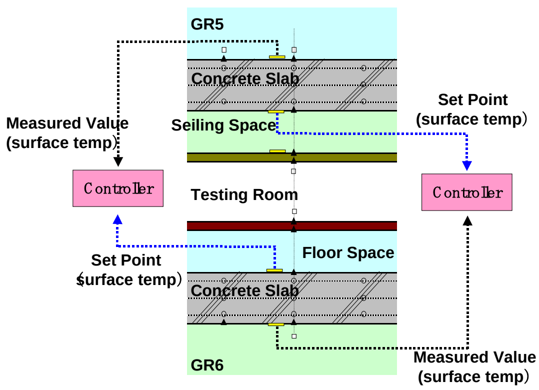


**Fig. 13 Heat flow control on the surface concrete slab**