# NUMERICAL ANALYSIS ON THE PRODUCTION OF COOL EXERGY BY MAKING USE OF HEAT CAPACITY OF BUILDING ENVELOPES

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## ABSTRACT

This paper describes a method to calculate cool and warm exergies stored by building envelopes and the result of a case study in terms of passive cooling strategy using the building envelope heat capacity. The concept of exergy enables us to show explicitly the cooling potential of a substance that is colder than its ambient. We call the cooling potential "cool exergy" and the heating potential "warm exergy". The value of either cool or warm exergy is positive without exception. We made a case study to examine the combined effects of shading and natural ventilation on making a better use of heat capacity of concrete walls for passive cooling during the nighttime in summer in Tokyo. The amount of cool and warm exergies stored by the building envelopes and the variation of their rate of storage were calculated. It was confirmed that the cool exergy could be obtained from the concrete walls even during the daytime of a hot day in summer, provided that an appropriate combination of shading, natural ventilation, and the heat capacity is designed.

## INTRODUCTION

The theory of heating/cooling load and room temperature calculations is based on the law of energy conservation, the first law of thermodynamics. But, there is the other law, the law of entropy generation, the second law of thermodynamics. The theorem of the exergy consumption is derived from both the first and second laws. We have been studying extensively on the use of the concept of entropy and exergy for the evaluation of the building environmental control systems (Shukuya and Komuro,1996; Nishikawa and Shukuya,1998). The extent to which these concepts can be applied has become gradually clear by these studies.

Here in this paper, we describe the use of the concept of exergy to evaluate passive cooling strategy using the heat capacity of building envelopes. The reason that we try to use the concept of exergy to tackle with this problem is as follows:

1) When we suppose a case that we are going to cool a certain substance, we often say that we supply a certain amount of "cooling ability"contained by substance, which is colder than the substance to be cooled. "Cooling ability" cannot be directly indicated by an amount of energy contained by a substance, because we need to remove some amount of energy from this substance to let it have a certain amount of "cooling ability". The concept of exergy can show explicitly such cooling capability; it can show both "warming ability" and "cooling ability" as positive value. The former is called "warm exergy" and the latter "cool exergy".
2) According to our everyday experience, coolness obtained during nighttime due to outdoor-temperature fluctuation energies as a certain amount of cooling ability during the following daytime. This is again directly shown by the concept of exergy. The calculation of exergy inflow and outflow through building envelopes and exergy storage within the building envelopes would clearly shows how cool exergy can be obtained and how we can utilize it.

This paper first describes the theoretical basis of warm and cool exergies and then presents some results of exergy calculation on a detached house in terms of with or without shading with trees and with or without natural ventilation.

## METHOD OF EXERGY EVALUATION

### ROOM MODEL

We assume a room shown in Figure 1. The floor of the room is made of concrete with external insulation. One of the six exterior envelopes is glass window. For simplicity, we assume the following:

1) No heat conduction is assumed through four building envelopes except the glass window and the concrete floor. Exergy transfer by infiltration and natural ventilation is included in the calculation.
2) We assume four nodes: single-paned glass window, the surface of the concrete floor, the center of the concrete floor, and room air. The heat capacity of the insulation was ignored, because it is very small than concrete.
3) Solar radiation which transmits the glass window is absorbed by the whole surface of the floor.
4) We assume that the environment, which is necessary for exergy calculation, is ambient air, $T_o$ [K].

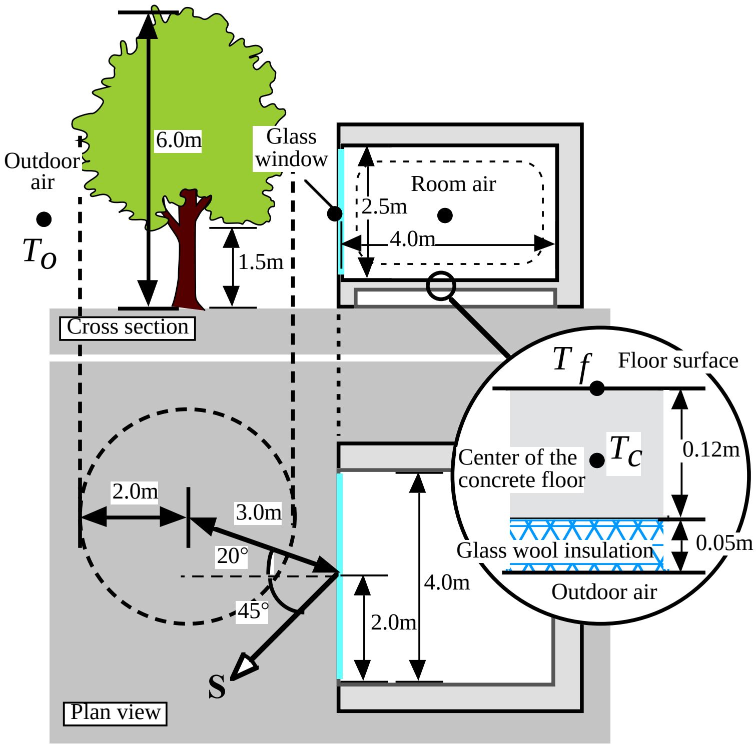


**Fig. 1**. A room model. A single glazed window covers all of the southwest facing. No heat conduction is assumed through walls except the concrete floor, namely adiabatic wall. A deciduous tree in front of the window shades solar radiation coming from the west.

EXERGY BALANCE EQUATION

Exergy as a quantity of state contained by the concrete floor, $E_o$ [J], which is a function of concrete temperature, $T_c$ [K], and the environmental temperature, can be shown as follows.

$$E_c = E_c\left(T_c, T_o\right) = \left(H_c - H_o\right) - T_o\left(S_c - S_o\right)$$
$$= Q_c\left(T_c - T_o\right) - Q_c \cdot T_o \cdot \ln\frac{T_c}{T_o} \qquad (1)$$

where $H_c$ is enthalpy as a quantity of state contained by the concrete floor [J]; $H_o$ is enthalpy as a quantity of state contained by the concrete floor on the condition of $T_c = T_o$ [J]; $S_c$ is entropy as a quantity of state contained by the concrete floor [J/K]; $S_o$ is entropy as a quantity of state contained by the concrete floor on the condition of $T_c = T_o$ [J/K]; $Q_c$ is heat capacity of the concrete floor [J/K].

The characteristics of eq. (1) is that exergy as a quantity of state is 0 in the case of $T_c = T_o$ , and in the cases of both $T_c > T_o$ and $T_c < T_o$ exergy is positive. The case that $T_c$ is higher than $T_o$ is that the concrete floor contains a certain amount of warming ability, namely "warm exergy". The case that $T_c$ is lower than $T_o$ is that the concrete floor contains a certain amount of ccoling ability, namely "cool exergy".

The exergy balance equation can be derived in the following manner. Entropy balance equation is first set up along with exergy balance equation. Then, each term of the entropy balance equation is multiplied by the environmental temperature and the resultant terms are extracted from the corresponding terms of the energy balance equation. For example in the case of the concrete floor, the following exergy balance equation is obtained.

$$A_f \cdot C_{fc}\left(T_f - T_c\right)\left(1 - \frac{T_o}{T_f}\right) - A_f \cdot s_{gc} \cdot T_o$$
$$= Q_c \frac{dT_c}{dt}\left(1 - \frac{T_o}{T_c}\right) + \frac{A_f \cdot C_{co}\left(T_c - T_o\right)^2}{T_c} \qquad (2)$$

where $T_f$ is surface temperature of the floor [K]; $T_c$ is temperature of the node in the center of the concrete floor [K]; $T_o$ is temperature of the crawl space under the floor which is assumed to be equal to outdoor air temperature [K]; $A_f$ is the surface area of the floor [m$^2$]; $C_{fo}$ is heat transfer coefficient between the floor surface and the node in the center of the concrete floor [W/(m$^2$•K)]; $C_{co}$ is heat transfer coefficient between the center of the concrete floor and the crawl space [W/(m$^2$•K)]; $s_{gc}$ is entropy generation rate caused by the heat conduction inside the floor [W/(m$^2$•K)].

**Table 1** Storage and release of exergy at the center of the concrete floor as a thermal exergy storage sysytem.

| | | Exergy as a quantity of state (eq. (1) ) | |
|---|---|---|---|
| | | $T_c < T_o$ | $T_c > T_o$ |
| The rate of the exergy storage (the 1st term of the right-hand side of eq. (2) ) | increase + | Cool exergy stored | Warm exergy stored |
| | decrease - | Cool exergy release | Warm exergy release |

The first term of the left-hand side of eq. (2) is the exergy flow from the floor surface to the inside of the floor. The second term is exergy consumption rate (The product of entropy generation rate and $T_o$ ) caused by the heat conduction from the surface of the floor to the inside of the floor. The first term of the right-hand side is the rate at which exergy is stored inside the concrete floor, and the second is the exergy flow from the inside of the floor toward the crawl space under the floor.

The first term of the right-hand side of eq. (2) can become positive or negative. When positive, it means that exergy is stored; when negative, it means that exergy is released.

The energy, entropy and exergy balance equations for the three nodes other than the concrete floor are also set up in the manner described above.

Table 1 shows how the center of the concrete floor as a thermal storage system works in relation to exergy as a quantity of state, eq. (1), and exergy storage rate, the first term of the right-hand side of eq. (2). For example, the concrete floor contains the “warm” exergy if $T_c > T_o$ , and if the rate of exergy storage is positive, it means that “warm” exergy is being stored. The concrete floor contains the “cool“ exergy if $T_c < T_o$ , and if the rate of exergy storage is negative, it means that “cool” exergy is being released.

## NUMERICAL EXAMPLES

### OUTLINE OF NUMERICAL EXAMPLES

The four energy balance equations were reduced to finite-differential equations and solved in terms of temperature. The values of exergy are obtained substituting four calculated temperatures into eq. (1) and exergy balance equations. The solar exergy is calculated by a formula described by Asada and Shukuya (1994). The exergy accompanied with effective sky radiation is calculated by a formula given by Shukuya (1994).

**Table 2** Assumptions for example calculation.

| Room | Passive cooling strategy: Shading | Natural ventilation |
|---|---|---|
| 1 | Nothing | Nothing |
| 2 | Nothing | All day through |
| 3 | By tree | Nighttime |

The amount of solar radiation transmitting through the tree is calculated by a method proposed by Tateno, Nishikawa and Shukuya (1997). Nighttime is from 19:00 to 6:00. The number of air change in the room during the ventilation was estimated from an empirical relationship between wind direction and wind speed obtained by Kataoka et al. (1992). We assumed that the number of air change in the room for infiltration is assumed to be 0.5 times per 1 hour.

Example calculation was made for three identical rooms shown in Table 2. Room 1 is assumed that the glass window has no shading device, and the glass window and the door are always closed, namely no natural ventilation. Room 2 is assumed that the glass window has no shading device, and the glass window and the opposite door are always opened for natural ventilation. Room 3 is assumed that a deciduous tree in front of the window shades the solar radiation, otherwise incident on the glass window. The glass window and door are opened during the nighttime ventilation from 19:00 to 6:00.

The calculation was made on hourly basis for two months, July and August, using Tokyo weather data. July was regarded as the preparatory period for the unsteady calculation. The assumptions for the calculation were summarized in the footnote of Table 2.

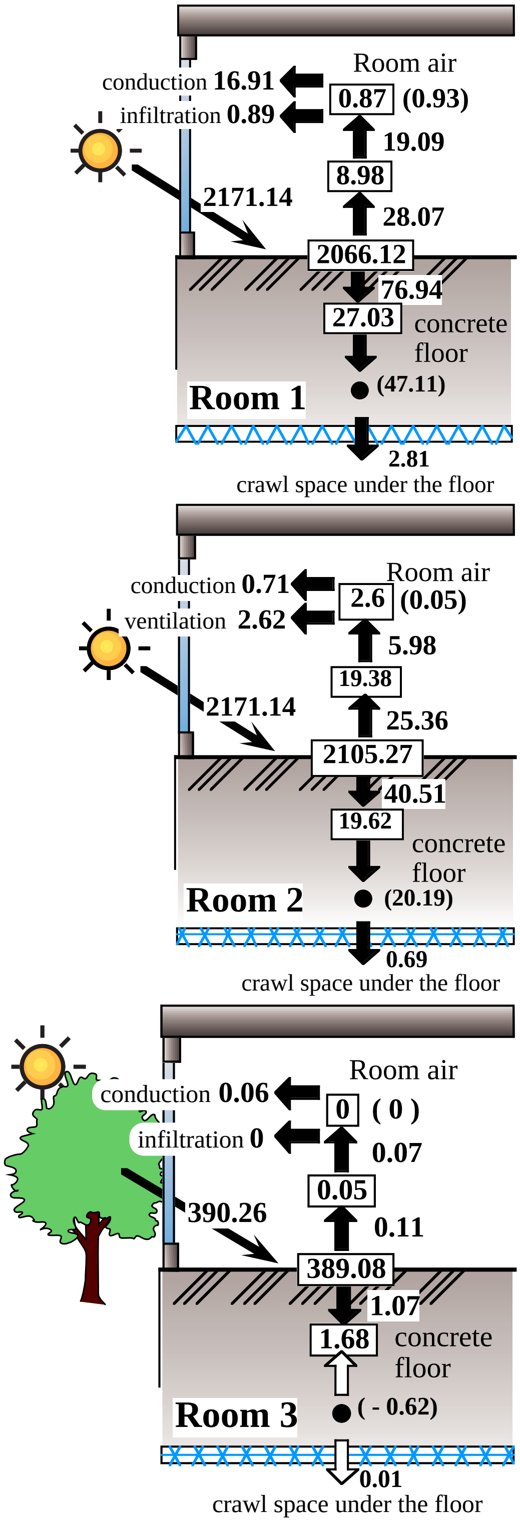


**Fig. 2** A comparison of exergy balance for three rooms at 16 o'clock, August 4th in Tokyo, at which direct solar radiation is incident on the window. The unit is W.

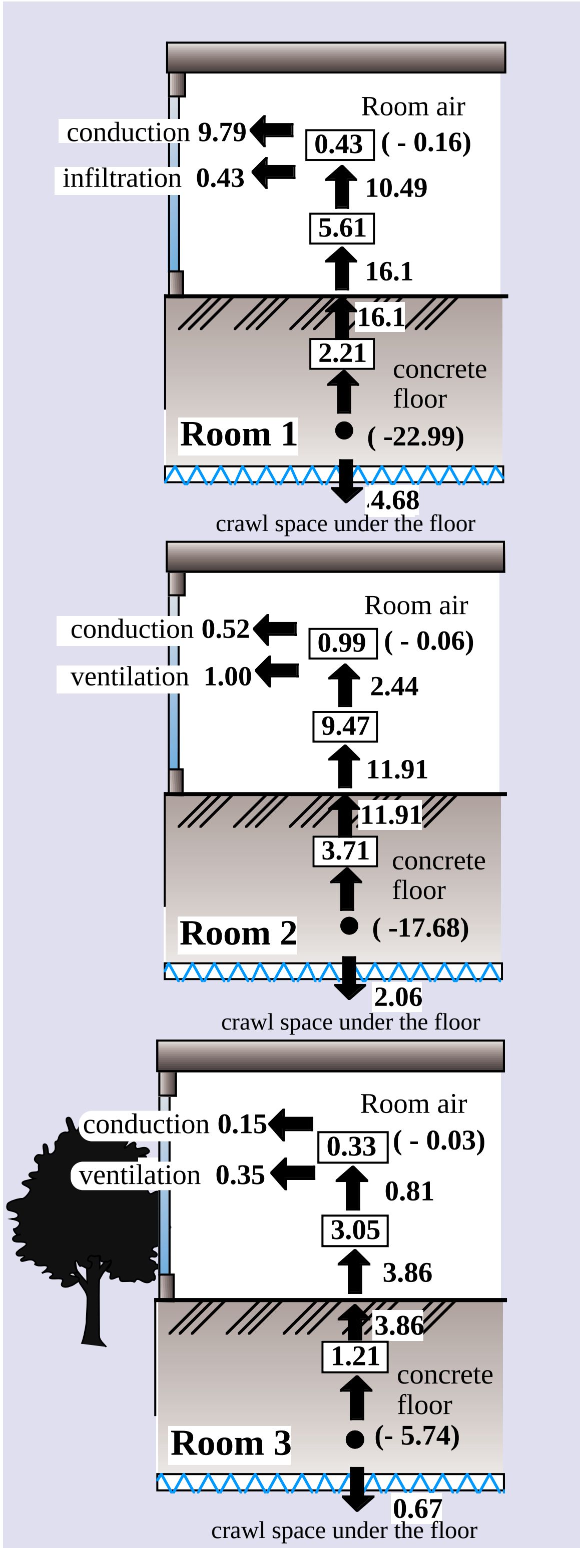


**Fig. 3** Exergy balance for three rooms at 23 o'clock on August 4th in Tokyo. The unit is W.

## EXERGY BLANCE WITHIN THE ROOM SPACE

Figure 2 shows the exergy flows, exergy consumption and exergy stored within the room air and the concrete floor for three rooms at 16 o'clock, August 4th, when direct solar radiation is incident on the glass window. This is a typical hot day in summer in Tokyo. The numbers in the open squares are exergy consumed, and those in the parentheses are exergy stored. The open arrows show the cool exergy flow, and the closed arrows show the warm exergy flow and the solar exergy.

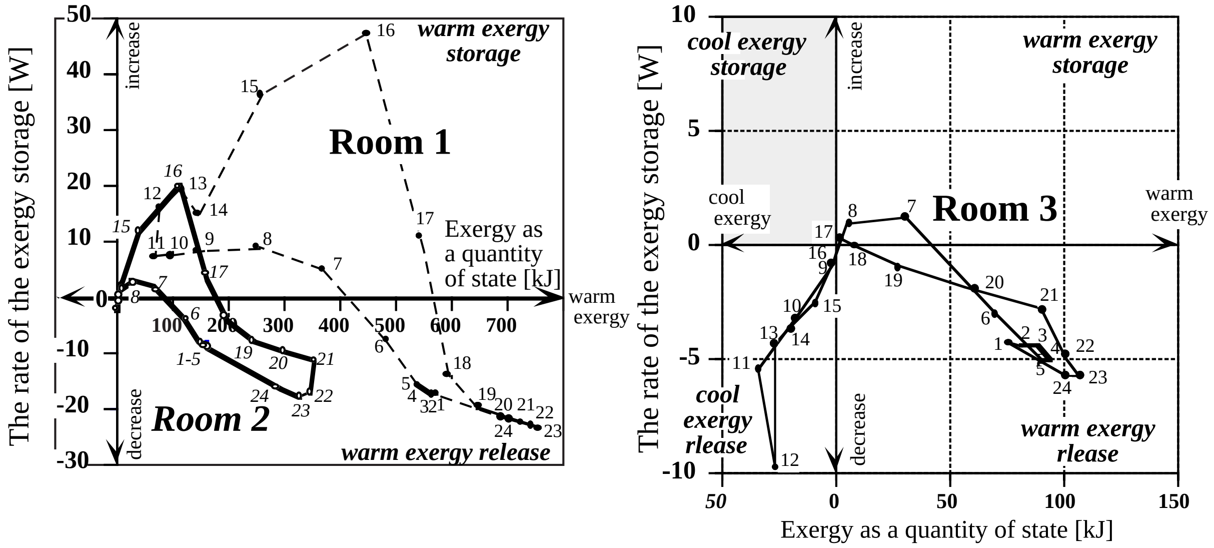


**Fig. 4** Relationship between "the exergy as a quantity of state" and "the rate of exergy stored" within the concrete floor. The left-hand side graph is for Room 1 and Room 2 and the right-hand side for Room 3. The numbers near the plots denote the time of the day. The polygons show one-day cycle of the storage and release of cool exergy or warm exergy. The first quadrant is for warm exergy storage, the second for cool exergy storage, the third for cool exergy release, and the fourth for warm exergy release.

In the case of Room 1, the exergy of 2066.12 W is consumed as the transmited solar exergy of 2171.14 W is absorbed by the concrete floor surface and thereby the warm exergies of 76.94 W and 28.07 W flow into the concrete floor and into the room air, respectively. The warm exergies of 47.11 W and 0.93 W are stored by the concrete floor and by the room air, respectively. The warm exergy flow of 16.91 W is delivered from the room air toward the glass window by over-all heat transfer and is consumed totally until it reaches the outdoor. In the case of Room 2, the amount of exergy thrown away from the room air with ventilation is large compared to that with infiltration in the case of Room 1. The same is true in terms of the exergy consumption within the room air. Warm exergy thrown away from the room air toward the glass window by over-all heat transfer is also small compared to Room 1. Due to these facts, warm exergy storage by the room air in the case of Room 2 becomes small: this in turn means that the room air temperature in the case of Room 2 is not so higher than outdoor air temperature. In other words, the room air temperature in the case of Room 1 is much higher than outdoor air temperature.

In the case of Room 3, the cool exergy of 0.62 W is produced within the concrete floor and the cool exergy of 0.61 W is supplied toward the floor surface. The reduction in solar exergy transmission in the case of Room 3 is large due to the shading by tree compared to the case of Room 2. This causes the amount of warm exergies flowing into the concrete floor and into the room air very small. These mean that neither the room air nor the floor surface is hot during the daytime.

Figure 3 showed the results at 23 o'clock on the same day. In all cases, the warm exergy is released from the center of the concrete floor toward the surface of the floor, and this warm exergy is gradually and finally consumed totally until it reaches the outdoor air. In the room air, the warm exergy is released in all three cases. This is because the warm exergy flowing from the room air by over-all heat transfer and infiltration or ventilation is larger than warm exergy flowing from the concrete floor into the room air.

## ONE-DAY CYCLE OF EXERGY STORAGE AND RELEASE AT THE CONCRETE FLOOR

Figure 4 shows the relationship between the exergy as a quantity of state of concrete floor and the exergy storage rate of the concrete floor. The left-hand side graph in Fig. 4 is for Room 1 and Room 2 and right-hand for Room 3. The numbers near the plots denote the hour of the day. The first quadrant is for warm exergy storage, the second for cool exergy storage, the third for cool exergy release, and the fourth for warm exergy release.

During the daytime, both the concrete floor of Room 1 and the concrete floor of Room 2 store the warm exergy from 7:00 to 17:00. During the nighttime the warm exergy is released from the concrete floor from 1:00 to 6:00 and 18:00 to 24:00. In these two cases, Room 1 and Room 2, only warm-exergy storage and release occur; cool-exergy storage and release never occur. The heat capacity of the concrete floor plays a role of controlling warm exergy flow and consumption within the room space for a period of one day. But, there is no production of the cool exergy in the concrete floor throughout the day.

The area within the lines connecting the plots in the

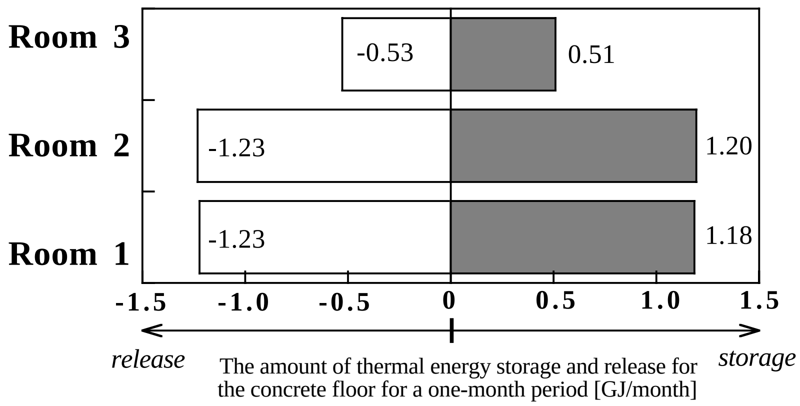


**Fig. 5** The amount of thermal energy storage and release for the concrete floor for a one-month period of August. The storage are indicated in the right of the center, and the release in the left.

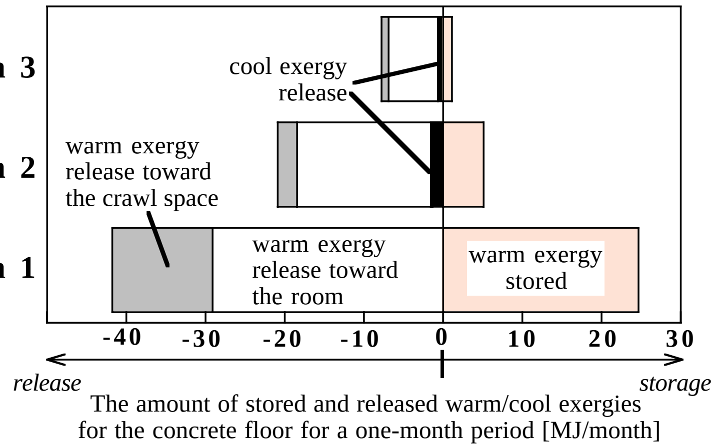


**Fig. 6** The amounts of stored and released warm/cool exergies for the concrete floor for a one-month period of August. The storage are indicated in the right of the center, and the release in the left.

case of Room 2 is smaller than that in the case of Room 1; this means that the temperature within Room 2 is always lower than Room 1.

In the case of Room 3, the warm exergy is stored by the concrete floor from 7:00 to 8:00 and released by the concrete floor during the nighttime. The cool exergy is released (supplied) by the concrete floor from 9:00 to 17:00, and the warm exergy. The reason that cool exergy storage does not happen is that we assume no cooling source in the room space. The area within the lines connecting the plots for Room 3 is smaller than that for Room 2; this means that the temperature within Room 3 is always lower than Room 2. This is because transmitted solar exergy through the glass window is reduced by the tree as a shade and the room air is well-ventilated so that the room temperature in Room 3 is almost the same as outdoor air temperature throughout the day. The reason that the cool exergy is produced is that the heat capacity of building envelopes makes it possible the temperature of the concrete floor slightly lower than the outdoor air temperature during the daytime.

TOTAL EXERGY STORAGE FOR ONE-MONTH

Here we discuss a comparison of the result of energy calculation to evaluate the concrete floor as a thermal storage system and the corresponding result of exergy calculation. This is because the comparison will show explicitly an asset to use the concept not only of energy but also of exergy. Figure 5 show the amount of thermal energy that the concrete floor stored and released for a one-month period of August. Figure 6 show the corresponding amounts of stored and released warm/cool exergies. Both in Figures 5 and 6, the storage are indicated in the right of the center, and the release in the left.

In all three cases, the amount of thermal energy storage and the amount of thermal energy release are almost equal. The reduction in the amounts of both thermal energy storage and release in the case of Room 3 compared to Room 2 is about 60%. But, there is no difference in the amounts of both the thermal storage and release between Room 1 and Room 2.

On the other hand, as can be seen in Fig.6, the amounts of exergy storage and exergy release are not equal. In the case of Room 1, while the warm exergy of 24.6 MJ is stored, the warm exergy of 29.0 MJ is released toward the room space and the warm exergy of 12.8 MJ is released toward the crawl space under the floor. In the case of Room 2, while the warm exergy of 5.2 MJ is stored, the warm exergy of 16.9 MJ is released toward the room space and the warm exergy of 2.5 MJ is released toward the crawl space under the floor. Note that the cool exergy of 1.5 MJ is released toward the room space. In the case of Room 3, while the warm exergy of 1.2 MJ is stored, the warm exergy of 6.1 MJ is released toward the room space and the warm exergy of 0.9 MJ is released toward the crawl space. The cool exergy of 0.7 MJ is also released toward the room space. The cool exergy production is brought about by the reduction of the warm exergy storage.

## CONCLUSION

We first described the exergy storage and release at the concrete floor along with showing how to set up exergy balance equations. Then we showed the results of the calculation of the warm and cool exergies within three rooms during one-month period, August in Tokyo. The following results are obtained;

1) It was confirmed that the cool exergy could be obtained from the concrete walls even during the daytime of a hot day in summer, provided that an appropriate combination of shading, natural ventilation, and the heat capacity is designed.
2) The reason that the cool exergy is produced is that the heat capacity of building envelopes makes it possible the temperature of the concrete floor slightly lower than the outdoor air temperature during the daytime of a hot summer day.

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## NOMENCLATURE

$A_f$ the surface area of the floor [m$^2$].

$C_{co}$ heat transfer coefficient between the center of the concrete floor and the crawl space [W/(m$^2$•K)].

$C_{fo}$ heat transfer coefficient between the floor surface and the node in the center of the concrete floor [W/(m$^2$•K)].

$E_o$ Exergy as a quantity of state contained by the concrete floor [J].

$H_c$ enthalpy as a quantity of state contained by the concrete floor [J].

$H_o$ enthalpy as a quantity of state contained by the concrete floor on the condition of $T_c = T_o$ [J].

$Q_c$ heat capacity of the concrete floor [J/K].

$s_{gc}$ entropy generation rate caused by the heat conduction inside the floor [W/(m$^2$•K)].

$S_c$ entropy as a quantity of state contained by the concrete floor [J/K].

$S_o$ entropy as a quantity of state contained by the concrete floor on the condition of $T_c = T_o$ [J/K].

$T_c$ temperature of the center of the concrete floor [K].

$T_f$ temperature of the floor surface [K].

$T_o$ outdoor air temperature and temperature of the crawl space under the floor [K].