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A STUDY ON THERMAL PERFORMANCE OF HEAT STORAGE SYSTEM CONNECTED WITH HEAT PUMP FOR RESIDENTIAL HOUSES

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ABSTRACT

In this paper, we present a heating system with thermal storage using a heat pump which supplies heat to the thermal storage equipment installed in the crawl space of residential house insulated at the foundation walls. This system can charge heat by using cheap nighttime electricity and discharge the stored heat at daytime. The thermal performance of the heating system and the effects of various factors on it are analyzed through simulation on the premise that a heat pump which has generally spread is used. The main results are as follows: (1) It is possible to control the system efficiently adjusting the lifestyle by change the start time of the operation of the ventilator connected to the thermal storage equipment to discharge the stored heat. (2) Using the latent thermal storage materials, the change of the room temperature can be made moderate.

KEYWORDS

Heating system, Thermal storage, Heat pump, Off-peak electricity, Crawl space

INTRODUCTION

Electrical energy consumption varies significantly during the day and night in Japan. If some of the peak load could be shifted to the off-peak load period, better power generation management and significant economic benefit can be achieved. In order to shift some of the peak load to the off-peak load period, the electrical price at night, 23:00 to 7:00, is about 1/3-1/4 of that at daytime.

Recently, a heating system with thermal storage using the cheap off-peak electricity has attracted much attention. A heating system with thermal storage using an electric heater as a heat source has been used in some buildings (Lin et al. 2004). By utilizing a heat pump as a heat source, we can expect more efficient heating, because it can output several times the energy spent.

A foundation-insulation method of residential houses have been attracting attention in Japan because of its effectiveness in preventing condensation in the crawl space (Iwamae et al. 2000, Honma et al. 2000). In a house with foundation insulation, generally, the thickness of the foundation insulation is about 0.05-0.1 m and the thermal conductivity is about 0.03-0.04 W/(mK), and the air change rate of the crawl space is about 0.1-0.2 times per hour. The thermal environment of the crawl space is near to that of indoors. We can expect the crawl space to be used as a space for installing the thermal storage equipment and as a duct for heat transport as in a traditional 'Ondol' in Korea.

In this paper, we present a heating system with thermal storage using a heat pump which supplies heat to the thermal storage equipment installed in the crawl space insulated at the foundation walls. The thermal storage equipment is charged by the heat pump by using cheap off-peak electricity and it is discharged into the crawl space by a ventilator at daytime. Thus, the crawl space and the floor are heated and it can make the room environment same as radiant heating. Although the general floor heating system warms only the installed area, this heating system warms the whole of the first floor.

The objective of this work is: (1) to develop a model of analyzing the thermal performance of this heating system; (2) to study the influences of various factors, the property of the thermal storage materials, the quantity of them, and the operation methods of the ventilator connected to the thermal storage equipment, on the thermal performance of this system.

MATHEMATICAL MODEL

Figure 1 shows a schematic diagram of the thermal exchanges considered with this model. The house has one room and one crawl space. A heat pump, a ventilator and a thermal storage equipment are installed in the crawl space. The thermal storage equipment consists of thermal storage materials and spaces that air flows through. It is connected to the heat pump and the ventilator. Air from the heat pump or air from the ventilator flows through the thermal storage equipment exchanging the heat with the thermal storage materials. The thermal exchange between the room and the outdoor is by heat transmission and ventilation. The foundation wall is supposed to be insulated, the thermal exchange between the crawl space and the outdoor is not considered. For the floor and the ground, a onedimensional conductive heat transfer model is considered and the temperature is calculated by

$$\rho C \frac{\partial T}{\partial t} = \lambda \frac{\partial^2 T}{\partial x^2}, \tag{1}$$

and the boundary condition is expressed as

$$-\lambda \left.\frac{\partial T}{\partial x}\right|_{x=0} = h(T_{air} - T_s). \tag{2}$$

The temperature under the surface of the ground to 10 m is constant at the annual average temperature of the outdoor.

Temperature of spaces between thermal storage materials

The spaces between the thermal storage materials are divided into some control volumes as shown in Fig.1. The rate of airflow from the control volume n to the next control volume n+1 is calculated as follows from the energy conservation equation:

$$v_{n\to n+1}^{TS,af} = \frac{\sum h^{TS,s} S_j^{TS,s}\left(T_j^{TS,s} - T_n^{TS,air}\right) + \rho_{n-1}^{TS,air} C_P T_{n-1}^{TS,air} v_{n-1\to n}^{TS,af}}{\rho_n^{TS,air} C_P T_n^{TS,air}}. \tag{3}$$

The mass conservation equation of the control volume n is written as

$$V_n^{TS,air} \frac{d\rho_n^{TS,air}}{dt} = v_{n-1\to n}^{TS,af} \rho_{n-1}^{TS,air} - v_{n\to n+1}^{TS,af} \rho_n^{TS,air}. \tag{4}$$

Using the following equation

$$\rho^{air} T^{air} = 353.25(const.), \tag{5}$$

the temperature of the control volume n at the next time step is calculated as

$$T_{n,new}^{TS,air} = \frac{1}{\left(\dfrac{d\rho_n^{TS,air}}{353.25} + \dfrac{1}{T_n^{TS,air}}\right)}. \tag{6}$$

Temperature of thermal storage materials

In the thermal storage materials, a two-dimensional conductive heat transfer model is considered as shown in Fig.1. The net conductive heat transfer to the control volume i,j is calculated as

$$\begin{aligned} q_{i,j}^{TS} = {} & \frac{\lambda_{i-1,j\to i,j}^{TS}}{dy}\left(T_{i-1,j}^{TS} - T_{i,j}^{TS}\right)dxdz - \frac{\lambda_{i,j\to i+1,j}^{TS}}{dy}\left(T_{i,j}^{TS} - T_{i+1,j}^{TS}\right)dxdz \\ & + \frac{\lambda_{i,j-1\to i,j}^{TS}}{dx}\left(T_{i,j-1}^{TS} - T_{i,j}^{TS}\right)dydz - \frac{\lambda_{i,j\to i,j+1}^{TS}}{dx}\left(T_{i,j}^{TS} - T_{i,j+1}^{TS}\right)dydz \end{aligned}, \tag{7}$$

where the thermal conductivity of latent thermal storage materials is calculated as

$$\lambda_{i-1,j\to i,j}^{TS} = \frac{\lambda_{i-1,j}^{TS} + \lambda_{i,j}^{TS}}{2}, \tag{8}$$

$$\lambda_{i,j}^{TS} = \frac{\lambda_{liq}^{TS} \sum Q_{l\,i,j}^{TS} + \lambda_{sol}^{TS}\left(Q_m^{TS} - \sum Q_{l\,i,j}^{TS}\right)}{Q_m^{TS} M_{i,j}^{TS}}. \tag{9}$$

The boundary condition at the surface of the thermal storage material is expressed as

$$-\lambda \left.\frac{\partial T}{\partial y}\right|_{y=0} = h^{TS,s}\left(T^{TS,air} - T_j^{TS,s}\right). \tag{10}$$

The quantity of heat stored into the latent thermal storage materials as a function of the temperature is considered as shown in Fig.2.

At solid phase

The energy conservation equation of the control volume i,j at the solid phase is written as

$$C_{sol}^{TS} \rho_{sol}^{TS} dxdydz \frac{dT_{i,j}^{TS}}{dt} = q_{i,j}^{TS}. \tag{11}$$

From the equation (11), the temperature of the control volume i,j at the next time step is calculated as

$$T_{i,j,new}^{TS} = \frac{q_{i,j}^{TS} dt}{C_{sol}^{TS} \rho_{sol}^{TS} dxdydz} + T_{i,j}^{TS}. \tag{12}$$

When using latent thermal storage (hereafter called LTS) materials, because it has the liquid phase and the solid-liquid coexistence phase other than the solid phase, the following treatment is needed.

If $T_{i,j,new}^{TS} > T_m^{TS}$, the quantity of latent heat stored into the control volume i,j is calculated as

$$Q_{l\,i.j}^{TS} = q_{i,j}^{TS} dt - C_{sol}^{TS} \rho_{sol}^{TS} dxdydz\left(T_m^{TS} - T_{i,j}^{TS}\right). \tag{13}$$

If $Q_{l\,i,j}^{TS} \le Q_m^{TS}$, the phase of the control volume i,j is solid-liquid coexistence, the temperature at the next time step is written as

$$T_{i.j,new}^{TS} = T_m^{TS}. \tag{14}$$

If $Q_{l\,i,j}^{TS} > Q_m^{TS}$, the phase of the control volume i,j is liquid, the temperature at the next time step is calculated as

$$T_{i,j,new}^{TS} = \frac{Q_{l\,i,j}^{TS} - Q_m^{TS}}{C_{liq}^{TS} \rho_{liq}^{TS} dxdydz} + T_m^{TS}. \tag{15}$$

At solid-liquid coexistence phase

The total quantity of heat stored into the control volume i,j at the next time step is calculated as

$$\sum Q_{l\,i,j,new}^{TS} = \sum Q_{l\,i,j}^{TS} + q_{i,j}^{TS} dt. \tag{16}$$

If $0 \le \sum Q_{l\,i,j,new}^{TS} \le Q_m^{TS}$, the phase of the control volume i,j is solid-liquid coexistence, the temperature at the next time step is written as

$$T_{i.j,new}^{TS} = T_m^{TS}. \tag{17}$$

If $\sum Q_{l\,i,j,new}^{TS} > Q_m^{TS}$, the phase of the control volume i,j is liquid, the temperature at the next time step is written as

$$T_{i,j,new}^{TS} = \frac{\sum Q_{l\,i,j,new}^{TS} - Q_m^{TS}}{C_{liq}^{TS}\rho_{liq}^{TS}dxdydz} + T_m^{TS}. \tag{18}$$

If $\sum Q_{l\,i,j,new}^{TS} < 0$, the phase of the control volume i,j is solid, the temperature at the next time step is written as

$$T_{i,j,new}^{TS} = \frac{\sum Q_{l\,i,j,new}^{TS}}{C_{sol}^{TS}\rho_{sol}^{TS}dxdydz} + T_m^{TS}. \tag{19}$$

At liquid phase

The energy conservation equation of the control volume i,j at the liquid phase is written as

$$C_{liq}^{TS}\rho_{liq}^{TS}dxdydz\frac{dT_{i,j}^{TS}}{dt} = q_{i,j}^{TS}. \tag{20}$$

From equation (20), the temperature of the control volume i,j at the next time step is calculated as

$$T_{i,j,new}^{TS} = \frac{q_{i,j}^{TS}dt}{C_{liq}^{TS}\rho_{liq}^{TS}dxdydz} + T_{i,j}^{TS}. \tag{21}$$

If $T_{i,j,new}^{TS} < T_m^{TS}$, the quantity of latent heat stored into the control volume i,j is calculated as

$$Q_{l\,i.j}^{TS} = Q_m^{TS} + q_{i,j}^{TS}dt + C_{liq}^{TS}\rho_{liq}^{TS}dxdydz\left(T_{i,j}^{TS} - T_m^{TS}\right). \tag{22}$$

If $Q_{l\,i,j}^{TS} \le Q_m^{TS}$, the phase of the control volume i,j is solid-liquid coexistence, the temperature at the next time step is written as

$$T_{i.j,new}^{TS} = T_m^{TS}. \tag{23}$$

If $Q_{l\,i,j}^{TS} < 0$, the phase of the control volume i,j is solid, the temperature at the next time step is calculated as

$$T_{i,j,new}^{TS} = \frac{Q_{l\,i,j}^{TS}}{C_{sol}^{TS}\rho_{sol}^{TS}dxdydz} + T_m^{TS}. \tag{24}$$

Temperature of crawl space

The rate of airflow from the crawl space to the room through the floor is calculated as follows from the energy conservation equation of the crawl space:

$$v_{CS\to R} = \frac{\left\{\begin{array}{l} h^{FUS}S^{FUS}\left(T^{FUS} - T^C\right) + h^{G,s}S^{G,s}\left(T^{G,s} - T^C\right) \\ + \sum h^{TS,s}S_j^{TS,s}\left(T_j^{TS,s} - T^C\right) \\ + \rho_{out}C_PT_{out}V_{out} - \rho^CC_PT^CV_{in} \end{array}\right\}}{\rho^CC_PT^C}, \tag{25}$$

where, V_{in} is the rate of airflow inhaled to the heat pump from the crawl space, and it is calculated using the mass conservation equation in the heat pump

$$v_{in} = \frac{v_{out}\rho_{out}}{\rho^C}. \tag{26}$$

The mass conservation equation of the crawl space is written as follows:

if $v_{C\to R} \ge 0$,

$$V^C\frac{d\rho^C}{dt} = v_{out}\rho_{out} - v_{in}\rho^C - v_{C\to R}\rho^C, \tag{27}$$

if $v_{C\to R} < 0$,

$$V^C\frac{d\rho^C}{dt} = v_{out}\rho_{out} - v_{in}\rho^C - v_{C\to R}\rho^R. \tag{28}$$

The temperature of the crawl space at the next time step is calculated as

$$T_{new}^C = \frac{1}{\left(\dfrac{d\rho^C}{353.25} + \dfrac{1}{T^C}\right)}. \tag{29}$$

Temperature of room

The rate of airflow from the outdoor to the room through the wall is calculated as follows from the energy conservation equation of the room:

if $v_{C\to R} \ge 0$,

$$v_{O\to R} = \frac{\left\{\begin{array}{l} -K^WS^W\left(T^O - T^R\right) - h^{F,s}S^{F,s}\left(T^{F,s} - T^R\right) \\ -\rho^CC_PT^Cv_{C\to R} + \rho^RC_PT^Rv^{VEN} \end{array}\right\}}{\rho^OC_PT^O}, \tag{30}$$

if $v_{C\to R} < 0$,

$$v_{O\to R} = \frac{\left\{\begin{array}{l} -K^WS^W\left(T^O - T^R\right) - h^{F,s}S^{F,s}\left(T^{F,s} - T^R\right) \\ -\rho^RC_PT^Rv_{C\to R} + \rho^RC_PT^Rv^{VEN} \end{array}\right\}}{\rho^OC_PT^O}. \tag{31}$$

The mass conservation equation of the room is written as follows:

if $v_{C\to R} \ge 0$ and $v_{O\to R} \ge 0$,

$$V^R\frac{d\rho^R}{dt} = v_{O\to R}\rho^O + v_{C\to R}\rho^C - v^{VEN}\rho^R, \tag{32}$$

if $v_{C\to R} \ge 0$ and $v_{O\to R} < 0$,

$$V^R\frac{d\rho^R}{dt} = v_{O\to R}\rho^R + v_{C\to R}\rho^C - v^{VEN}\rho^R, \tag{33}$$

if $v_{C\to R} < 0$ and $v_{O\to R} \ge 0$,

$$V^R\frac{d\rho^R}{dt} = v_{O\to R}\rho^O + v_{C\to R}\rho^R - v^{VEN}\rho^R, \tag{34}$$

if $v_{C\to R} < 0$ and $v_{O\to R} < 0$,

$$V^R\frac{d\rho^R}{dt} = v_{O\to R}\rho^R + v_{C\to R}\rho^R - v^{VEN}\rho^R. \tag{35}$$

The temperature of the room at the next time step is calculated as

$$T^R_{new} = \frac{1}{\left(\dfrac{d\rho^R}{353.25} + \dfrac{1}{T^R}\right)} \cdot \tag{36}$$

VALIDATION OF THE MODEL

Assuming that it is a steady stage including the ground, the energy conservation equation of the room and that of the crawl space for one day are written as

$$\left(K^W S^W + \rho C_P N V^R\right)\left(T^R - T^O\right) = K^F S^F \left(T^C - T^R\right), \tag{37}$$

$$8/24 Q_g = K^F S^F \left(T^C - T^R\right) + K'^G S^G \left(T^C - T^{G10}\right), \tag{38}$$

where

$$K'^G = 1/\left(1/h^{G,s} + 10/\lambda^G\right) \tag{39}$$

Under the conditions that the outdoor temperature is maintained at 10 °C and there is 5 kW heat generation from 23:00 to 7:00 in the crawl space of the house the properties of which are shown in Table 1, the temperatures of the room and the crawl space are calculated with the equations (37)-(39) as they are about 21.1 °C and 30.4 °C respectively.

Under the same conditions, the daily average temperature of the room and that of the crawl space calculated with the above model after they become diurnally a periodic steady state are 21.2 °C and 30.2 °C respectively. The validity of this model is confirmed by these calculations.

SIMULATION PROCEDURE

The physical properties of the house used for simulations are shown in Table 1. Heat transmission coefficient of the wall is considered as an area average of that of the windows, the roof, etc., and the house's thermal insulation level complies with the strictest standard now in force in Japan.

The physical properties of the sensible thermal storage (hereafter called STS) material used for simulations are shown in Table 2. The thickness of one piece of STS material is set 0.05 m. The number of the layers of the STS material is set 6, taking that the height of the crawl space is 0.5 m and the space for the air to flow between the STS materials is needed into consideration. The division width dX of airflow space in the STS equipment is 1/10 of the length X. The grid size of STS materials dx is 1/100 of the length X, and dy is 0.01 m (Fig.1).

The physical properties of the LTS material used for simulations are shown in Table 3. Though the thermal properties of the LTS are not the same with the solid phase and the liquid phase generally, we treated them as the same in this calculation. If the properties of the two phases are clear, we can also use them of course. The thickness of one piece of LTS material is set 0.02 m. The number of the layers of the LTS material is set 9. The division width dX of airflow space in the LTS equipment is 1/10 of the length X. The grid size of LTS materials dx is 1/100 of the length X, and dy is 0.002 m (Fig.1).

Instead of covering upper surface of the thermal storage equipment with insulation, the convective-heat-transfer coefficient on the surface is set 0.5 W/(m^{2}K).

Although the height of the space for the air to flow between the thermal storage materials is about 0.01-0.02 m in practice, it is set 0.1 m in calculation in order to lengthen the simulation time step to 1 s. The influence of this modification appears in the temperature of the spaces between the thermal storage materials calculated by equation (4) and (6), but it is very small and it is checked separately that the whole thermal performances are hardly affected.

The width Z and the length X of the thermal storage equipment are examined in the chapter 'RESULTS AND DISCUSSION'.

The volume of the air which the heat pump supplies to the thermal storage equipment is set to 600 m^3/h and the temperature is set to 50 °C. These values are determined from the capability of the heat pump which is generally used.

The outdoor temperature is represented as

$$T^O = 15.29 - 10.867\cos\left(2\pi f_{year} t - \frac{2\pi}{3}\right), \quad - 2.9626\cos\left(2\pi f_{day} t - \frac{\pi}{6}\right) \tag{40}$$

where $f_{year} = 1/3600/24/365$, $f_{day} = 1/3600/24$.

It is expressed an annual cycle and a daily cycle of the temperature based on the outdoor temperature measured in Osaka, Japan. The influence of solar radiation is not taking into consideration.

The simulation starts on October 1. The influence of initial conditions is got rid of in two months and the operation of heat pump begins on December 1. The heating period is set as three months from December to February. In the heating period, the heat pump is operated from 23:00 to 7:00.

RESULTS AND DISCUSSION

Using STS materials

We describe about the case STS materials are used. The quantities of heat generated by the heat pump and those stored into the thermal storage equipment in the period from 23:00 on January 31 to 7:00 on February 1 in the case the ventilator is operated from

7:00 with the 'width Z' × 'length X' of the STS equipment are shown in Fig.3. The quantities of generated heat are almost the same and they are about 140 MJ. The quantities of stored heat are not proportional to the volumes. As the 'width Z' × 'length X' become larger than 2 m × 4 m, the quantities of stored heat do not enlarge very much. This is because the temperatures of the thermal storage materials about 4 m ahead from the windward of the thermal storage equipment do not rise very much as shown in Fig.4. For the following analysis, we use the 2 m × 4 m thermal storage equipment.

Figure 5 shows the room temperatures for the different operation methods of the ventilator on February 1. In the case the ventilator is not operated, the room temperature continues falling from 7:00 to 23:00. This is because the stored heat is hardly discharged into the crawl space. In the case the ventilator is operated from 7:00, the room temperature continues rising and becomes the maximum temperature at 15:00. In the cases the ventilator is operated from 12:00, 15:00, or 18:00, the room temperatures begin to rise with the operation start of the ventilator and become maximum temperature 3-4 hours after the start. In the case the direction of the airflow in the thermal storage equipment from the ventilator is reversed to that from the heat pump, the room temperatures from the operation start of the ventilator to 0:00 are higher than the case the direction of the airflow from the ventilator is the same as that from the heat pump. This is because, in the case the direction of the airflow is reversed, the temperature of the leeward materials in the thermal storage equipment at the time starting ventilation is higher than that of the windward ones. Figure 6 shows the average temperatures of the room in the period from 18:00 to 23:00 on February 1 with the quantities of heat generated by the heat pump. In the case the ventilator is operated from 15:00, the average room temperature from 18:00 to 23:00 can be most efficiently kept high.

Using LTS materials

We describe about the case LTS materials are used. The quantities of heat generated by the heat pump and those stored into the LTS equipment in the period from 23:00 on January 31 to 7:00 on February 1 in the case the ventilator is operated from 7:00 with the phase transition temperature of the thermal storage materials and the 'width Z' × 'length X' of the thermal storage equipment are shown in Fig.7. The quantities of generated heat are almost the same and they are bout 140 MJ. In the case the phase transition temperatures are 36 °C and 41 °C, the quantities of stored heat are increasing with the increase of the volume, whereas in the case the phase transition temperature is 32 °C, those of stored heat do not increase very much as the volumes become large. As shown in Fig.8, in the case the phase transition temperature is 32 °C, the temperatures of the thermal storage materials about 2 m ahead from the windward of the thermal storage equipment are phase transition temperature 32 °C and constant, and the differences of the temperatures between the air layers and the materials are very small. So the heat convection to the materials at the surfaces are very small. This is the reason the quantities of stored heat do not increase very much as the volumes become large in the case the phase transition temperature is 32 °C.

Figure 9 shows the surface temperatures of the thermal storage materials at the leeward of the 'width 2 m' × 'length 4 m' equipment on February 1 in the case the ventilator is operated from 7:00 for different phase transition temperatures of the materials. In the case the phase transition temperature is 32 °C, it is stable at 32 °C, whereas in the cases the phase transition temperatures are 36 °C and 41 °C, they are not stable. The difference of this thermal performance also affects the room temperatures. As shown in Fig.10, the width of amplitude of the room temperature in the case the phase transition temperature is 32 °C is the most narrow.

As shown in Fig.11, in the case there is no heat generation in the room and the ventilator is operated from 7:00, the daily average temperature of the room is 15-17 °C during the heating period. It is rather low when compared with general heating temperature 20-22 °C. In the case there is 1000 W heat generation in the room, the daily average temperature of the room is 20-21 °C. As shown in Fig.12, the width of amplitude of the room temperature in the case there is 1000 W heat generation in the room is about 0.6 °C wider than that in the case there is no heat generation in the room. This is because the temperature of the thermal storage materials at the leeward of the equipment in the case there is 1000 W heat generation in the room is not stable unlike that in the case there is no heat generation as shown in Fig.13.

CONCLUSIONS

The paper developed a model to study the thermal performance of the heating system with thermal storage using a heat pump which supplies heat to the thermal storage equipment installed in the crawl space of residential house insulated at the foundation walls.

We simulated on the premise that a heat pump which has generally spread is used.

Even if the volume of the thermal storage materials becomes larger than a certain size, the quantities of stored heat do not increase very much. About the relation between the heating area or the outdoor temperature and the suitable volume, more detailed work is needed.

It is possible to control the system efficiently adjusting the lifestyle by change the start time of the operation of the ventilator connected to the thermal storage equipment.

Using the LTS materials, the change of the room temperature can be made moderate. About the suitable phase transition temperature, more detailed work is needed.

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Nomenclature

C	specific heat (J/(kgK))
C_P	specific heat at constant pressure (J/(kgK))
h	convection coefficient (W/(m^{2}K))
K	heat-transmission coefficient (W/(m^{2}K))
M	mass (kg)
N	air change rate (times/s)
Q_g	quantity of generated heat in crawl space (J)
Q_l	quantity of latent heat storage (J)
Q_m	heat of fusion (J/kg)
q	convective heat transfer (W)
S	area (m^2)
T	temperature (°C)
T^{G10}	temperature under surface of ground to 10 m (°C)
T_m	phase transition temperature (°C)
v	rate of airflow (m^3/s)
v_{out}	rate of airflow from thermal storage equipment to crawl space (m^3/s)
v_{in}	rate of airflow into heat pump from crawl space (m^3/s)
$v_{A \to B}$	rate of airflow from A to B (m^3/s)
V	volume (m^3)
λ	thermal conductivity (W/(mK))
ρ	density (kg/m^3)

Subscripts

air	air
C	crawl space
F	floor
FUS	floor under surface
G	ground
in	air which goes into heat pump from crawl space
liq	liquid phase
new	next time step
O	outdoor
out	air which comes from thermal storage equipment to crawl space
R	room
s	surface
sol	solid phase
TS	thermal storage material
TS,af	airflow in thermal storage equipment
TS,air	air in thermal storage equipment
VEN	ventilation from room to outdoor
W	wall

Table 1 Physical properties of house

Area of floor	74.75 m^2
Height of room	2.5 m
Height of crawl space	0.5 m
Area of wall (include roof)	164.75 m^2
Coefficient of wall heat-transmission	0.68W/(m^{2}K)
Thickness of floor	0.03 m
Thermal capacity of floor	1128 kJ/(m^{3}K)
Thermal conductivity of floor	0.18 W/(mK)
Air change number of room	0.5 times/h
Convection coefficient of floor surface	6 W/(m^{2}K)
Convection coefficient of floor under surface	10 W/(m^{2}K)
Convection coefficient of ground surface in crawl space	3 W/(m^{2}K)

Table 2 Physical properties of STS material

Specific heat	954 J/(kgK)
Density	3750 kg/m^3
Thermal conductivity	2.7 W/(mK)
Rate of surface area	1.5

Table 3 Physical properties of LTS material

Specific heat (solid and liquid)	2500 J/(kgK)
Density (solid and liquid)	900 kg/m^3
Thermal conductivity (solid and liquid)	0.219 W/(mK)
Heat of fusion	175 (kJ/kg)

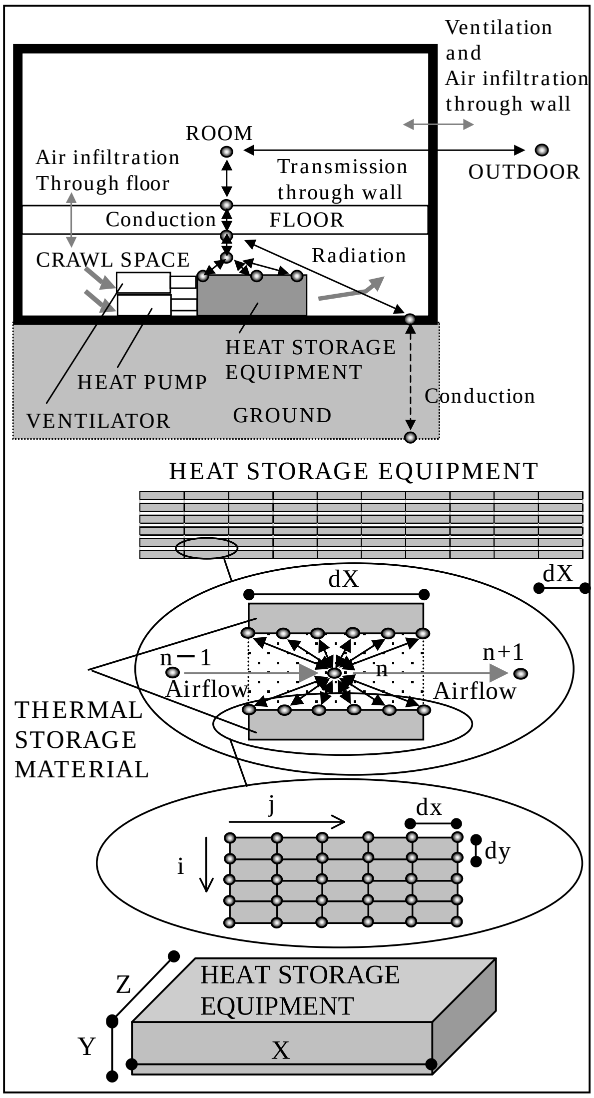

Figure 1 Schematic diagram of thermal exchanges and rough sketch of heat storage equipment

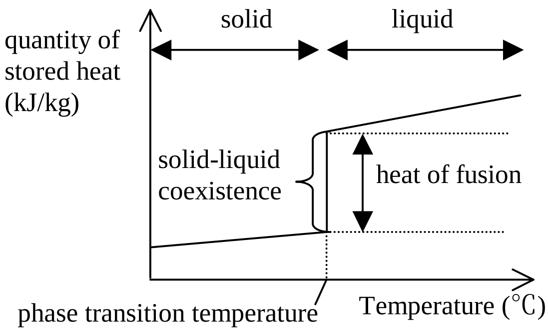

Figure 2 Quantity of heat stored into LTS materials as a function of temperature

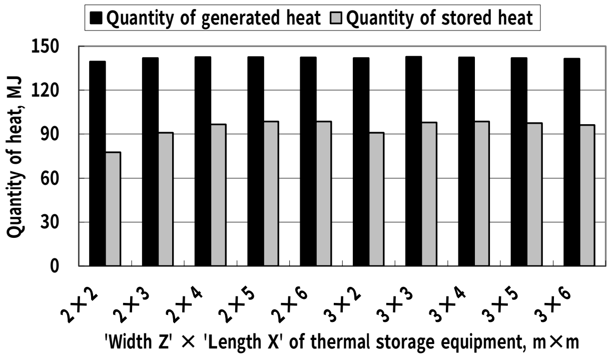

Figure 3 Quantities of heat generated by heat pump and those stored into STS equipment from 1/31 23:00 to 2/1 7:00 (ventilator is operated from 7:00)

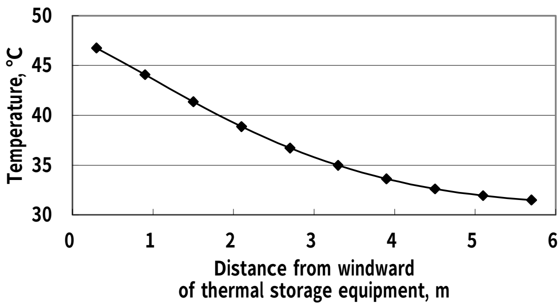

Figure 4 Temperatures of STS materials in thermal storage equipment of '2 m × 6 m' at 2/1 7:00 (ventilator is operated from 7:00)

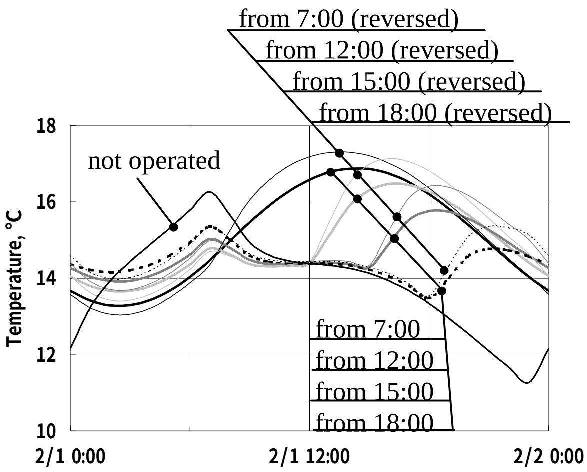

Figure 5 Room temperature for different start time of ventilator operation on 2/1 ('2 m ×4 m', STS)

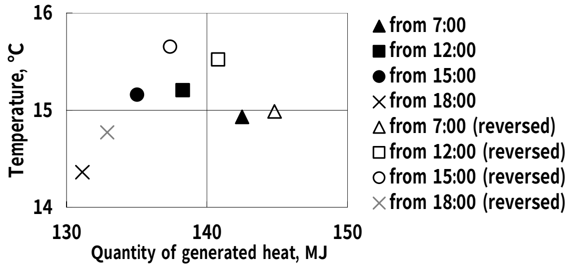

Figure 6 Average temperatures of room from 2/1 18:00 to 23:00 with quantities of heat generated by heat pump ('2 m ×4 m', STS)

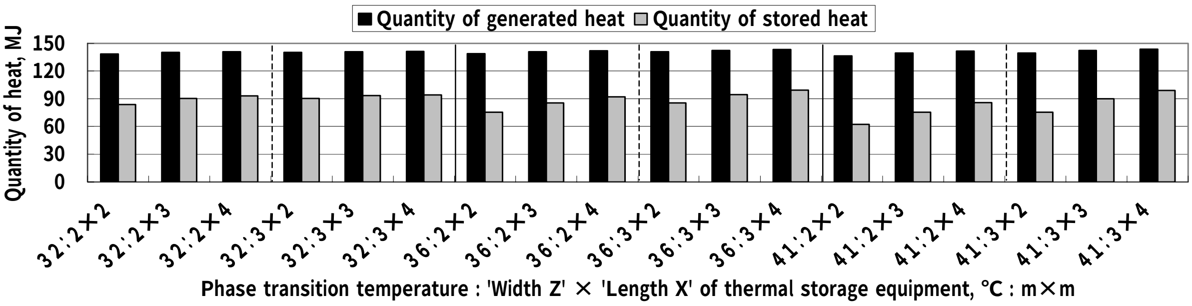

Figure 7 Quantities of heat generated by heat pump and those stored into LTS 1/31 23:00 to 2/1 7:00 (ventilator is operated from 7:00)

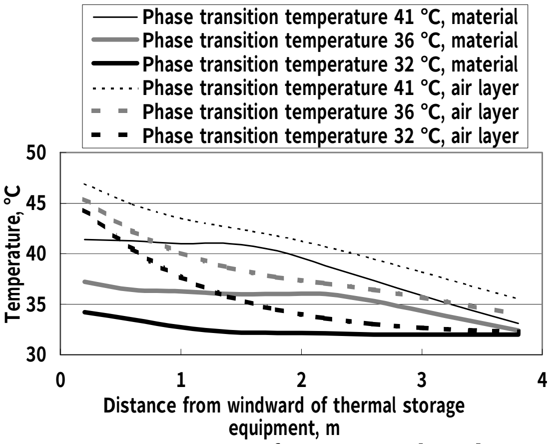

Figure 8 Temperatures of LTS materials and air layers in thermal storage equipment of '2 m × 4 m' at 2/1 3:00 (ventilator is operated from 7:00)

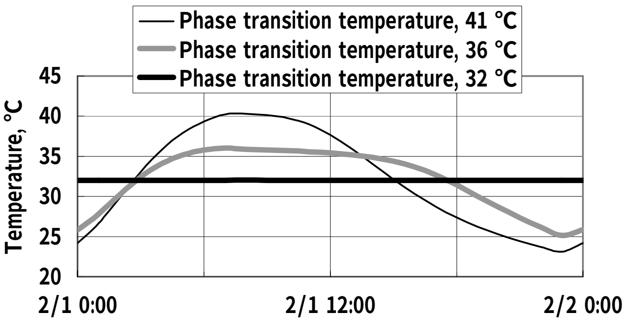

Figure 9 Surface temperatures of LTS materials at leeward of '2 m × 4 m' on 2/1 (ventilator is operated from 7:00)

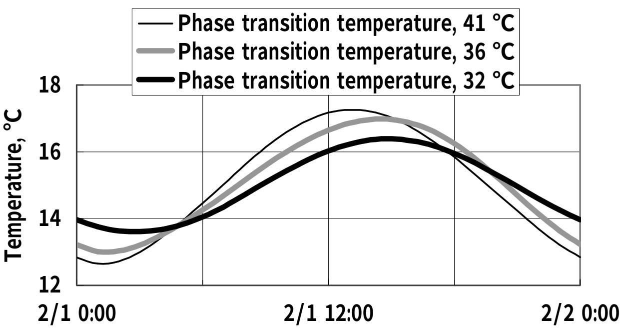

Figure 10 Room temperatures on 2/1 ('2 m × 4 m' LTS equipment, ventilator is operated from 7:00)

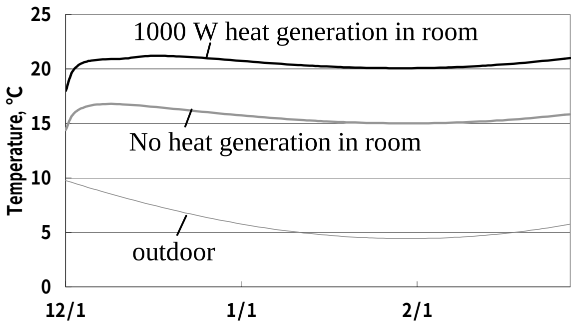

Figure 11 Daily average temperature of room ('2 m × 4 m' LTS equipment, ventilator is operated from 7:00)

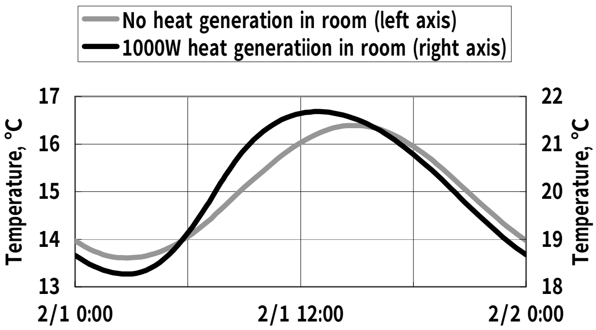

Figure 12 Room temperatures on 2/1 ('2 m × 4 m' LTS equipment, ventilator is operated from 7:00)

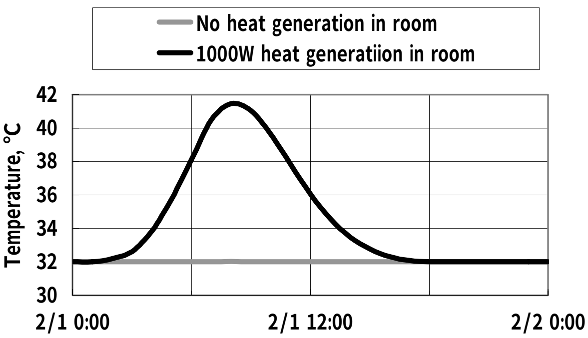

Figure 13 Surface temperatures of LTS materials at leeward of equipment on 2/1 ('2 m × 4 m' LTS equipment, ventilator is operated from 7:00)