Heat Recovery Hybrid Ventilation System With a Thermal Storage

Akira Fukushima[1], Sayaka Murata[*2], Masahiro Uozumi[3]

1 Hokkaido University of Science
Maeda 7-15-4-1 Teine-ku
Sapporo006-8585, JAPAN
fukushima-a@hus.ac.jp

**2 Hokkaido Research Organization*
Kita 19 Nishi 11, Kita-ku
Sapporo 060-0814, JAPAN
s.murata@hro.or.jp

3 Hokkaido University of Science
Maeda 7-15-4-1 Teine-ku
Sapporo006-8585, JAPAN

ABSTRACT

A “heat recovery hybrid ventilation system” is the combination of passive stack ventilation and mechanical push-pull ventilation. Two heat storage boxes are connected to the natural EA stack and the underfloor natural OA duct. The alternation is done periodically in a way of that the outdoor air is drawn through one of 2 boxes contains earth tiles and the indoor air is exhausted through the other box. After the heat in the exhaust air is stored in the box connected to the stack in time of the natural ventilation, the stored heat is recovered by the supply air in time of the mechanical backward ventilation. The system functions reversed in the box connected to the natural OA duct. Fan operation is controlled by the air temperature in in-outside chambers of the box.

The purpose of this study is the development of the heat storage box and the appropriate control system. First of all, the prototype box was made considering space to install and the sizes of parts as follows.

- Box: Readymade Expanded Polystyrene box size of 600mm long, 350mm wide, and 200mm deep inside.
- Earth tile: Interior finishing tile made from diatomaceous earth size of 6.5mm thick, 300x150mm.
- Backward fan: 12V DC propeller fan with 120mm in diameter

In this paper, we proposed the numerical simulation model to simulate heat transfer in the heat storage box and evaluated the adequacy of the model by comparing the measurement and the numerical simulation results on the prototype box. The measurement has been done in 2 constant temperature rooms, and the exhaust fan was installed to simulate natural stack ventilation.

As a result, assuming that the amount of heat storage material is about three times as high as that of the prototype box and the EA / OA is switched when the outside and inside temperature of the box becomes the intermediate temperature between the room and the outdoor, it is estimated that the heat recovery efficiency is about 70% and switching time is 16 - 17 minutes.

KEYWORDS

Hybrid Ventilation, Heat Recovery, Thermal Storage, Numerical Simulation Model, Control System

1 INTRODUCTION

Due to the high thermal insulation of houses, the ratio of ventilation load to the space heating energy consumption is increasing, and the reduction of ventilation load is required to achieve further energy saving. However, the adoption of a mechanical push-pull ventilation system with heat exchanger, which is a typical ventilation load reduction method, has a problem of increasing energy consumption for fan power. On the other hand, the passive ventilation system can reduce the energy consumption for fan power (Akira Fukushima, 1997) and the maintenance load, but cannot reduce the heating load. Although there is a heat recovery type passive ventilation system using water circulation for buildings (C.A. Hviid, S. Svendsen, 2015), there is no simple system for detached houses yet.

In this study, we proposed a hybrid heat recovery ventilation system that combines passive ventilation with respiratory heat recovery technology. The system collects heat of the EA by alternately passing the supply and the exhaust air to the heat storage material. The purpose of this study is the development of the heat storage box and the appropriate control system.

2 THE CONCEPT OF THE SYSTEM

Fig. 1 shows the concept of the system. Two heat storage boxes are connected to the natural EA stack and the underfloor natural OA duct. The alternation is done periodically that the outdoor air is drawn through one of 2 boxes contains heat storage material and the indoor air is exhausted through the other box. After the heat in the exhaust air is stored in the box connected to the stack in time of the natural ventilation, the stored heat is recovered by the supply air in time of the mechanical backward ventilation. The system functions reversed in the box connected to the natural OA duct. Fan operation is controlled by the air temperature in in-outside chambers of the box.

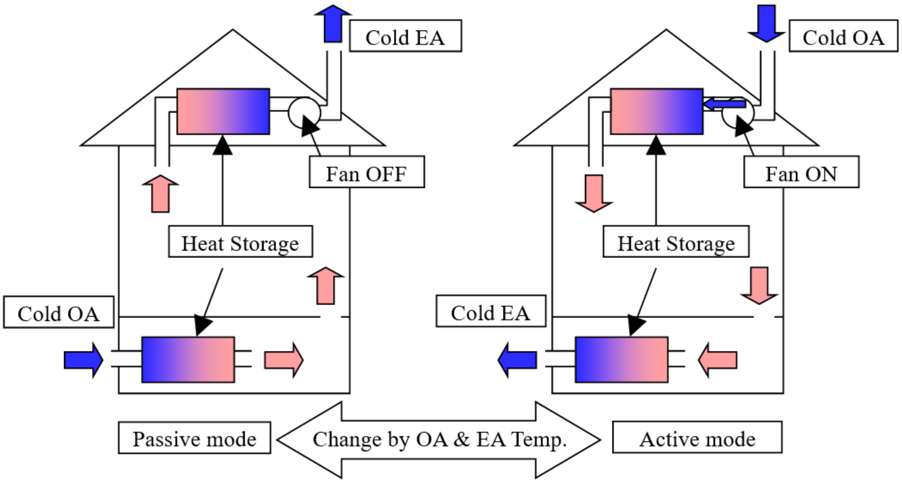

Figure 1: The concept of the system

3 TEMPERATURE SIMULATION OF THE HEAT STORAGE BOX

The simulation of the temperature of the heat storage box is carried out to examine the amount of heat storage material and control method, to keep the supply air temperature above a certain level and the heat recovery rate at 70%. This is a basic performance for a conventional push-pull mechanical ventilation system for general cold regions in Japan. The control method is investigated by the setting of the temperature at which switching between supply and exhaust is performed.

3.1 Simulation Method

First, the temperature simulation method of the heat storage box is developed, and the temperature of actual measurement is compared with simulated one. Next, several simulations are carried out by changing the amount of heat storage material and control method. Then, the proper control method for achieving the target of heat recovery rate is obtained.

Fig. 2 shows the simulation model.

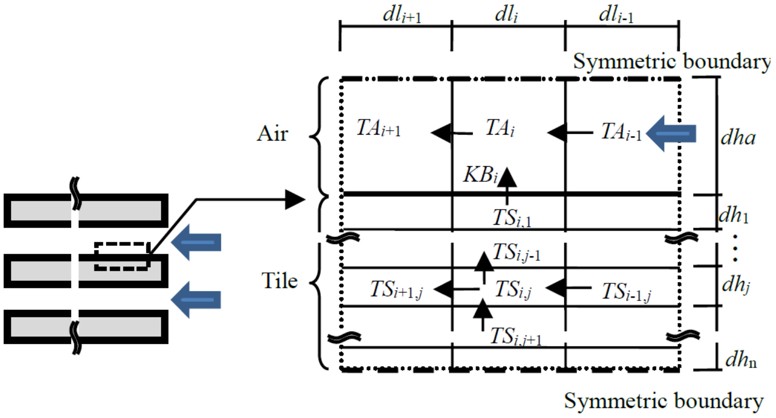

Figure 2: Thermal simulation model in the heat storage

The heat balance per unit width of one cell of air between the heat storage materials, is as follows

$$c\cdot\rho\cdot VA_i\frac{dTA_i}{dt}=c\cdot\rho\cdot Q\cdot\left(TA_{i-1}-TA_i\right)+KB_i\cdot\left(TS_{i,1}-TA_i\right)\cdot dl_i \qquad (1)$$

Where:

$$VA_i=dl_i\cdot dha \qquad (2)$$

$$KB_i=\frac{1}{1/\alpha+{dh_1/2}/KS} \qquad (3)$$

c: specific heat of air [W/kg·K]
ρ: density of air [kg/m^3]
α: surface heat transfer coefficient [W/m^2·K]
KS: thermal conductivity of heat storage material [W/m·K]
TA_i: temperature of air cell i [℃]
$TS_{i,j}$: temperature of heat storage material, cell (i, j) [°C]
dl_i: length of cell i [m]
dl_i: air cell thickness [m]
dh_j: heat storage material (i, j) thickness [m]
dh_j: calculation time interval [h]

Heat conduction between the air is ignored since it is considered to be extremely small as compared with advection (the amount of heat transferred by the air flow). The surface heat transfer varies with wind speed and temperature, but the radiation heat transfer coefficient is constant. So, the convective heat transfer coefficient is proportional to the wind speed. The numerical value is adjusted to match the actual measurement results.

The heat balance per unit width of one cell of the heat storage material is as follows

$$CS\cdot VS_{i,j}\frac{dTS_{i,j}}{dt}=HTL_{i,j}\cdot dl_i+KS\cdot\left[\frac{TS_{i-1,j}-TS_{i,j}}{\left(dl_{i-1}+dl_i\right)/2}-\frac{TS_{i,j}-TS_{i+1,j}}{\left(dl_i+dl_{i+1}\right)/2}\right]\cdot dh_j \qquad (4)$$

Where:

$$\begin{cases} \text{When } j = 1 & HTL_i = KS \cdot \dfrac{TS_{i,j+1} - TS_{i,j}}{(dh_{j+1} + dh_j)/2} - KB_i \cdot (TS_{i,1} - TA_i) \\ \text{When } j = n & HTL_i = KS \cdot \dfrac{TS_{i,j} - TS_{i,j-1}}{(dh_j + dh_{j-1})/2} \\ \text{Other} & HTL_i = KS \cdot \left[\dfrac{TS_{i,j+1} - TS_{i,j}}{(dh_{j+1} + dh_j)/2} - \dfrac{TS_{i,j} - TS_{i,j-1}}{(dh_j + dh_{j-1})/2} \right] \end{cases} \tag{5}$$

$$VA_i = dl_i \cdot dh_j \tag{6}$$

CS: heat capacity of heat storage material [W/m^3]
n: number of divisions in the thickness direction of the heat storage material
The time interval of calculation was set to 0.0001s.

3.2 Analysis of the results

From the results of the temperature simulation, the heat storage rate (*S*) and the heat recovery rate (*E*) are obtained as follows.

Heat storage rate (*S*)
$$S = \frac{T_R - \overline{T_{EA}}}{T_R - T_O} \tag{7}$$

Heat recovery rate (*E*)
$$E = \frac{Q_S \cdot (\overline{T_{SA}} - T_O)}{Q_E \cdot (T_R - T_O)} \tag{8}$$

Where:

T_o: outdoor temperature [℃]
$\overline{T_{SA}}$: average OA temperature inside the box at the time of supply [℃]
T_R: room temperature [℃]
$\overline{T_{EA}}$: average EA temperature outside the box at the time of exhaust [℃]
Q_S: supply air volume [℃]

4 COMPARISON BETWEEN SIMULATION AND MEASUREMENT

4.1 Heat storage box

Fig. 3 shows the prototype heat storage box and the measuring device.

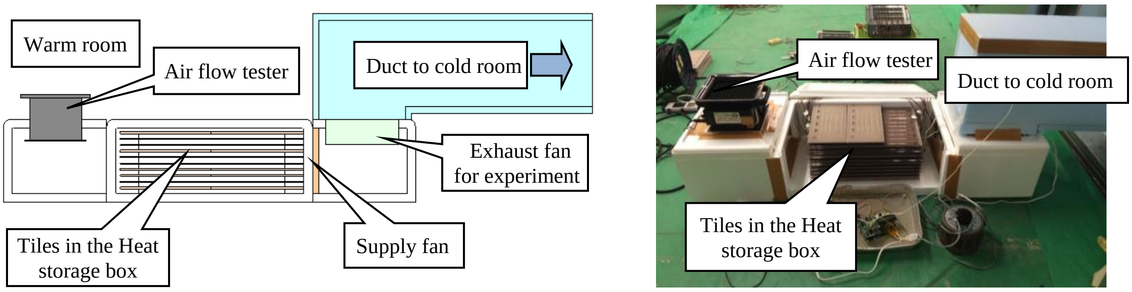

Figure 3: The prototype heat storage box and the measuring device.

Three ceramic tiles having a length of 303 mm, a width of 151 mm, and an average thickness of 6.75 mm were stacked in ten layers of a corrugated plate made of plastic having a height of 15 mm interposed therebetween.

The box was installed in the normal temperature room of two thermostatic chambers. It was connected to low-temperature room by the duct made of XPS. An exhaust fan was installed in the outside chamber to simulate natural ventilation. The air flow rate was measured by a hot wire type air flow meter at the indoor side of the heat storage box.

Thermocouples were used to measure the surface temperature of each layer of the ceramic tile, air temperature between layers and air temperature in the chambers both side of the heat storage box. The air temperatures in the in-outside chambers of the heat storage box were compared with the simulation results.

4.2 The conditions of measurement and simulation

We compare the simulation with the actual measurement results under the following two different control conditions.

- Switching on a steady state: Switch the supply and the exhaust every 5 hours.
- Temperature control: Switch to the supply at outside exhaust air temperature of 17°C, and switch to the exhaust at inside supply air temperature of 5°C.

Table 1 shows the conditions of measurement and simulation.

Table 1: The conditions of measurement and simulation

			Steady state	Temperature control
Tile for Heat Storage	Thermal conductivity	W/mK	0.3	
	Heat capacity	kJ/m^3K	1620	
	Thickness	mm	6.75	
	width	mm	303	
	length	mm	453	
	Stacked Number		10	
	Stage spacing	mm	15	
Air flow rate	exhaust	m^3/h	80	80
	air supply	m^3/h	50	100
Temperature	Warm Room	℃	20	20
	Cold room	℃	−3	0

4.3 Actual measurement

Fig. 4 shows the actual measurement results when it is steady state switching, and Figure 5 shows the simulation result under the same condition.

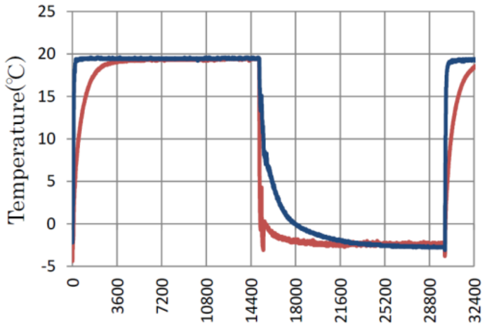

Figure 4: The test result (steady switching)

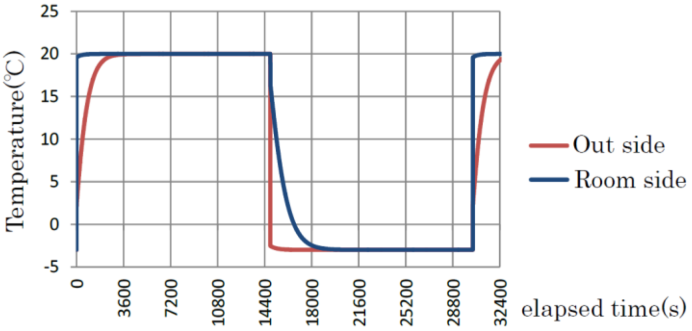

Figure 5: The simulation result (steady switching)

The figures show the temperature variation of one cycle of supply and exhaust. As you can see from the figures, both temperature of the actual measurement and the simulation reach a steady state in about 1 hour after switching to the exhaust, and the temperature change is similar. After switching to the supply, the temperature reaches a steady state for about 2 hours in the actual measurement and about 1.5 hours in the simulation. The reason why the simulation resulted in a shorter time may be the characteristics of the measuring device.
Fig. 6 and Fig. 7 show the actual measured and simulated temperature variation respectively when switching was done with temperature control.
As you can see from the figures, the time for the exhaust is almost the same between the actual measurement and the simulation, but the time for supply seems to be somewhat shorter time in case of simulation. This is probably because the actual air supply volume may be less than 100 m^3/h set as before. In spite of this results mentioned above, it is possible to grasp the temperature fluctuation generally, and also to predict the efficiency and switching temperature by the simulation for designing the performance.

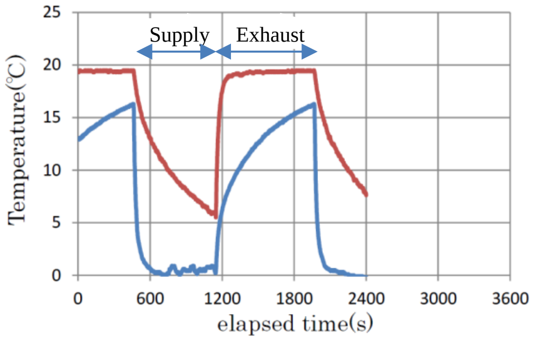

Figure 6: The test result (temp. control)

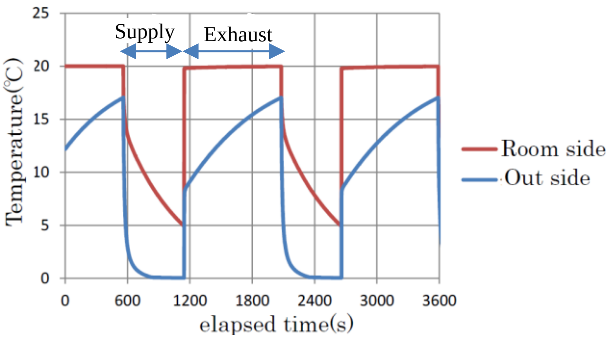

Figure 7: The simulation result (temp. control)

5 PERFORMANCE DESIGN BY SIMULATION

5.1 Thermal storage material

The heat recovery rate in Fig. 7 calculated by the equation (8) is about 44%. If the switching temperature is lowered, the efficiency increases, but if the blowing temperature to the room is low, it becomes uncomfortable. Therefore, it is necessary to increase the amount of heat storage material in order to obtain higher recovery rate and to avoid frequent switching. The simulation was conducted under the condition shown in Table 2 (prototype, 2 to 4 times). The air flow rate was 80 m^3/h for both supply and exhaust, and the outdoor temperature was 0°C, and the room temperature was 20°C.

Table 2: Conditions for Heat Capacity Simulation

Tiles		Prototype	2 times	3 times	4 times
length	mm	453	453	453	**604**
Stacking Number		10	**20**	**30**	30
Stacking Space	mm	15	7.5	5	5

Fig. 8 shows the heat storage rate, the heat recovery rate, the time of exhaust and supply at 10°C both at the switching temperature between supply and exhaust. Increasing the heat storage amount increases the heat storage rate and the heat recovery rate, and the switching time also becomes longer. Generally speaking, if the heat storage amount is tripled, the heat recovery rate exceeds 60% and the switching time also exceeds 10 minutes, so it is estimated that the amount of heat storage material is necessary about 3 times of prototype.

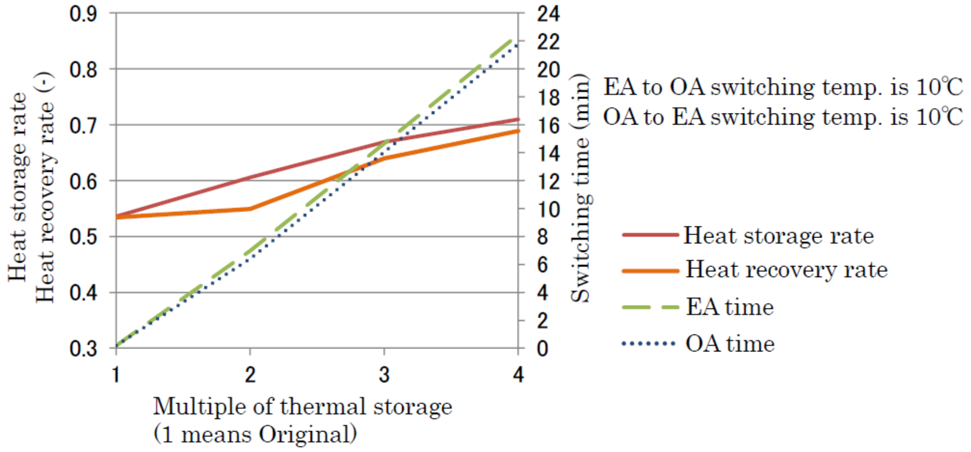

Figure 8: Simulated thermal performance of the box with the amount of heat storage material

5.2 Control method

Up to 24 ceramic tiles (the thermal storage material) can be stacked to be accommodated in the box, 604 mm for the length of 4 sheets of tiles, and the size of air space was set to 5 mm, which was tripled of the prototype heat storage material amount. Table 3 shows the conditions of air flow rate and switching temperature.

Table 3: Conditions for Control Method simulation

	OA	EA
Air flow rate[m^3/h]	80（partry100）	
Switching temperature [°C]	5, 7.5, 10	5, 10, 15
Outdoor temperature [°C]	0, −10	
Room temperature [°C]	20	

Fig. 9 shows the heat storage rate, the heat recovery rate, and the switching time when the outdoor temperatures are 0 and -10°C.
When the outside air temperature is 0°C and the switching temperature is 10°C, the heat recovery rate is around 70%. The lower the switching temperature from the exhaust to the supply, the shorter the switching time interval. When the switching temperature is 10°C, the times of supply and exhaust are equal.

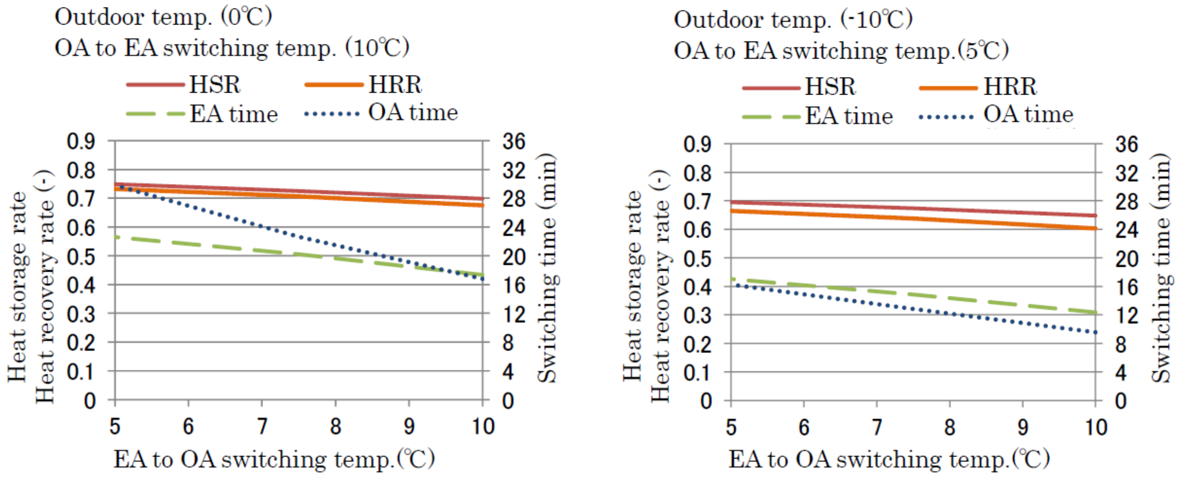

Figure 9: Simulated performance of the box with the switching time

When the outdoor temperature is -10°C and the switching temperature is 5°C, the heat recovery rate is about 68%. In addition, the switching time between supply and exhaust becomes almost equal when the switching temperatures are 5°C both of supply and exhaust. From the above, when the switching temperature is set to an intermediate temperature between the rooms (20°C) and the outdoor, the heat recovery efficiency is about 70% and the switching time is 16 to 17 minutes.

6 CONCLUSION

The target of this study is the breathable hybrid heat recovery ventilation system using the heat storage material. We investigated the amount of heat storage material of the heat storage box and the proper switching temperature by the numerical simulation of the temperature in the heat storage box. As a result, assuming that the amount of heat storage material is about three times as high as that of the prototype model and the switching temperature is the intermediate temperature between the room and the outdoor, the heat recovery efficiency of 70% can be expected. The switching time can be 16 - 17 minutes.

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