Performance Evaluation of the Natural Ventilation System with Phase Change Material

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Abstract
Performance of natural ventilation using stack effect of staircase of building in which phase change material (PCM) is installed was investigated. Study was conducted by field measurement and simulation. The results showed that the inclusion of PCM to a staircase would reduce the ventilation airflow during charging but increase it during discharging, in comparison with the staircase without PCM. To evaluate the effect of PCM on performance of natural ventilation, three different operation modes were developed. 1) Natural ventilation is carried out from 9:00 to 22:00. In this mode, two patterns of the day time natural ventilation were conducted. First is the case that heat is charged to and discharged from PCM during day time natural ventilation and second is the case that only charging heat to PCM is performed. In the second pattern, there are two passages of ventilated air flow at the top of staircase. PCM is installed in one passage. From 9:00 to 18:00, the ventilated air flows through the passage without PCM. From 18:00 to 22:00 the ventilated air flows through the passage with PCM. 2) During the day time (from 9:00 to 18:00), the rooms are ventilated forcibly by adopting a constant quantity of fresh air, and during the night time (from 18:00 to 22:00) natural ventilation is performed. 3) The rooms are air conditioned from 9:00 to 18:00. Natural ventilation is carried out from 18:00 to 22:00. In all modes, the openings of staircase are open only during natural ventilation time.

Keywords - passive method, natural ventilation, phase change material, ventilation network calculation

1. Introduction

In Japan, energy consumptions increase year by year, and the growth rate of the energy consumption of the commercial section is the biggest. In the commercial section, small-scale office building occupy a considerable
ratio, however energy-saving measures are insufficient. Natural ventilation is one of the effective energy-saving measures.

Moreover, placing PCM in a staircase as the stack can enhance the effect of natural ventilation system. When PCM is added, it absorbed solar radiation during the day time and release heat during the night time. Therefore, in comparison with the staircase where PCM is not installed, temperature of the staircase with PCM installed is lower in the day time but higher in the night time (Fig.1), which means natural ventilation effect of the case with PCM is lower in the day time but higher in the night time. As a result, effect of natural ventilation can be improved since it is bigger in night time than day time.

![Fig.1 Image of temperature of the staircase with PCM and without PCM](image)

In this study, the performance evaluation of natural ventilation system in a small office building using stack effect of staircase where PCM is installed was conducted by field measurement and simulation.

In the following sections, simulation method, field measurement result, calculation result will be explained.

2. Simulation method

2.1 Ventilation network calculation

Fig.2 shows the image of target building and it is modeled as shown in Fig.3. Heat generating elements a room are shown in Fig.4.
For ventilation network calculation, the building is divided into 8 rooms including staircase. PCM is put at the top of the staircase (R8). Heat transfer through walls and ventilation is calculated in steady state. Temperature of each room is calculated by (1) with thermal capacity of walls is examined. When 15% of thermal capacity was considered, calculation results became closest to the measurements.

\[ T_{i,t+\Delta t} = T_{i,t} + \frac{(Q_{\text{FIN}} - Q_{\text{FOUT}} + Q_{\text{W}} + Q_{\text{IN}})\Delta t}{c_{\rho}V_i + n_c\rho_cV_c} \]  

(1)

- \( Q_{\text{FIN}} \): heat capacity of inflow air [W]
- \( Q_{\text{FOUT}} \): heat capacity of outflow air [W]
- \( Q_{\text{W}} \): heat transmission [W]
- \( Q_{\text{IN}} \): internal heat [W]
- \( c \): specific heat of air [J/kgK] 
- \( \rho \): density of air [kg/m³] 
- \( V_i \): room capacity [m³] 
- \( n \): considered percentage of thermal capacity of walls [%]

### 2.2 Modeling of PCM
#### 2.2.1 Modeling of specific heat of PCM
Specific heat of PCM largely varies by temperature change. In this study, measurement result of Differential Scanning Calorimeter (DSC) is simplified to be used in calculation. Result is shown in Fig.5.

#### 2.2.2 Modeling of heat transfer in PCM
PCM installed in the staircase has 84 sheets with the same dimensions of 800mm length, 250mm height and 21mm thickness. These 84 sheets are considered as an unified mass and it is divided as shown in Fig.6.

Surface temperature and internal temperature of PCM is calculated by (2) and (3).
\[ T_{F,t+\Delta t} = T_{F,t} + \frac{2\lambda \Delta t}{c_p(T_{F,t})(\Delta x)^2} (T_{1,t} - T_{F,t}) + \frac{2\Delta t}{c_p(T_{F,t})A_{PCM} \Delta x} I_{PCM} + \frac{2\Delta t}{c_p(T_{F,t})A_{PCM} \Delta x} Q_F \] (2)

\[ T_{1,t+\Delta t} = T_{1,t} + \frac{\lambda \Delta t}{c_p(T_{1,t})(\Delta x)^2} (T_{F,t} + T_{2,t} - 2T_{1,t}) \] (3)

\( I_{PCM} \): solar radiation absorbed in PCM [W/m²], \( A_{PCM} \): surface area of PCM [m²], \( Q_F \): heat transfer between R8 and PCM [W], \( \dot{\lambda} \): thermal conductivity of PCM (-), \( C_p \): heat capacity of PCM [J/kgK]

3. Validity of ventilation network calculation

3.1 Climatic condition

To evaluate the validity of ventilation network calculation, calculation result is compared with measurement on May 27th, 2013. Periodic steady state calculation was performed. For outside air temperature condition, measurement on May 27th, 2013 is used from 10:00 to 19:00. In the remaining time, since measurement was not performed, AMEDAS data of Meteorological Agency is used. For solar radiation and outside wind velocity, AMEDAS data is used.

3.2 Comparison of calculation result and measurement

As shown in Fig.7 (a), there is 1-2 degree C of temperature difference between calculation result and measurement of temperature of R2, but they show good agreement in 16:00 when the temperature is maximum. Calculation result of air flow rate of this room is close to measurement as shown in Fig.7 (b). R3 has the same result. Therefore, it can be said that the analysis model could almost reproduce the measurement.

Fig.7 Calculation and measurement value of R2
4. Sensitivity analysis of performance of natural ventilation

4.1 Calculation condition

Outdoor condition as shown in Fig. 8 is average year data of April 7th which was picked up from NEDO insolation Database. The maximum temperature is about 20 degree C and solar radiation is large, thereby natural ventilation effect seems to be promising.

![Fig. 8 Outdoor condition (April 7th)](image)

4.2 Effect of PCM on performance of natural ventilation

When PCM is put in the top of the staircase (R8), it absorbs solar radiation in the day time and temperature of R8 is lower than that of the case without PCM. While PCM releases heat in the night time and temperature of R8 is higher than that of the case without PCM. As shown in Fig. 9, the air temperature difference between R8 and outside becomes smaller in the day time and higher in the night time with PCM. As a result, it enhances the effect of natural ventilation in the night time and improves the total effect of natural ventilation system.

![Fig. 9 Temperature difference between R8 and outside](image)

4.3 Sensitivity analysis

Sensitivity analysis was conducted with parameters as follows;
1) solar radiation absorption factor of PCM
2) number of PCM sheets
3) outside wind velocity

Calculation cases are shown in Table 1. Solar radiation absorption factor of PCM installed in real building is 0.4. "None" means the case of PCM is not installed.

<table>
<thead>
<tr>
<th>Case name</th>
<th>PCM solar radiation absorption factor</th>
<th>Number of PCM sheets</th>
<th>Outside wind velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>0.4 , 1.0</td>
<td>84 , none</td>
<td>2m/s</td>
</tr>
<tr>
<td>Case 2</td>
<td>0.4 , 1.0</td>
<td>252 , none</td>
<td>2m/s</td>
</tr>
<tr>
<td>Case 3</td>
<td>0.4 , 1.0</td>
<td>84 , none</td>
<td>0m/s</td>
</tr>
<tr>
<td>Case 4</td>
<td>0.4 , 1.0</td>
<td>252 , none</td>
<td>0m/s</td>
</tr>
</tbody>
</table>

In each case, heat capacity which is removed by natural ventilation of R2 in day time (from 9:00 to 16:00) and night time (from 16:00 to 22:00) are compared between the case with PCM and the case without PCM. Removal heat capacity is calculated by (4) and results is shown in Fig.10

\[
Q = Q_{\text{FOUT}} - Q_{\text{FIN}}.
\]

\(Q_{\text{FIN}}\): heat capacity of inflow air [W], \(Q_{\text{FOUT}}\): heat capacity of outflow air [W]

![Fig.10 Removal heat capacity of R2](image)

4.3.1 Effect of solar radiation absorption factor

Calculation results of Case 1 is shown in Fig.10 (a). Removal heat capacity of the case with PCM is smaller in the day time and bigger in the night time, in comparison with that of the case without PCM. Total removal heat capacity in a whole day increases, which means the efficiency of natural ventilation is improved with PCM. When solar radiation absorption factor of PCM increases from 0.4 to 1.0, the daytime removal heat capacity decreases and the night time removal heat capacity increases.
4.3.2 Effect of number of PCM sheets

In Case 2, when changing number of PCM sheets increases from 84 to 252, calculation result has similar variation trend with that of the case when solar radiation absorption factor of PCM increases. As shown in Fig.10 (b), removal heat capacity of R2 decreases in the day time and increases in the night time.

4.3.3 Effect of outside wind velocity

Calculation result of Case 3 is shown in Fig.10 (c). Influence of outside wind velocity to removal heat capacity is around 10-15%. The effect of PCM to natural ventilation in the night time is larger when it is windless.

5. Position of PCM

When PCM is put in lower staircase room, the warmed air goes up and exchanges heat with upper space. On the other hand, when PCM is put in the top of the staircase, warmed air is exhausted and heat exchange with lower space does not happen. Thereby, when PCM is put in lower space, average temperature of staircase is higher than that when PCM is put in the top of the staircase, which means buoyancy effect is enhanced.

To prevent the reversal of temperature distribution when PCM is put in lower staircase room, the space was integrated with upper staircase room. Periodic steady state calculation when PCM is put in R7' (integrated space of R7 and R8) was performed.

Results are shown in Fig.11 and Fig.12. Temperature of R7' increases by approximately 0.5-1.5 degree C in comparison with average temperature of R7 and R8 of the case when PCM is put in R8. Total air flow rate of the whole building shows an increment of about 14% comparing with the case when PCM is put in R8. Maximum temperature decrement of R2 is around 0.4 degree C.

![Fig.11 Temperature of R8](image)

![Fig.12 Temperature of R2](image)
6. Operation patterns

To evaluate the effect of PCM on performance of natural ventilation, three different operation modes as follows were developed. In all modes, the openings of staircase are open only during natural ventilation time.

1) Natural ventilation is carried out from 9:00 to 22:00. In this mode, two patterns of the day time natural ventilation were conducted. Standard case (Case 0) is when heat is charged to and discharged from PCM during the day time. This natural ventilation pattern is used in calculations in above sections. Case 1 is when only charging heat to PCM is performed.

In Case 1, there are two passages of ventilated air flow at the top of staircase. PCM is installed in one passage (R9). From 9:00 to 18:00, openings of R9 are closed and ventilated air flows through R8. From 18:00 to 22:00 openings of R8 are closed and air flows through R9. The capacity of R8, R9 in this case are 21.68m³ and 6.4m³, respectively. Inner walls of R9 are well insulated to prevent heat loss between PCM and staircase.
2) The rooms are ventilated forcibly from 9:00 to 18:00 by adopting a constant quantity of fresh air. The inflow quantity of fresh air in R1 and R2 is 360m$^3$/h and 540m$^3$/h, respectively. Natural ventilation is carried out from 18:00 to 22:00 (Case 2).

![Fig.15 Case 2](image)

3) Mode 3: The rooms are air conditioned from 9:00 to 18:00. Natural ventilation is carried out from 18:00 to 22:00 (Case 3).

![Fig.16 Case 3](image)

Calculation results of average air flow rate during the night time of R1 and R2 are shown in Fig.17. In comparison with Case 0, air flow rate of R1 of Case 1, Case 2 and Case 3 increased by 6.25%, 6.27% and 11.17%, respectively. Air flow rate of R2 increased by 9.18%, 11.56% and 15.44%, respectively. In Case 1, natural ventilation time is as same as Case 0, but heat charged to PCM isn't discharged in the day time, therefore discharging heat from PCM in the night time is larger than Case 0. In Case 2 and Case 3,
because openings are closed during the day time, the air temperature inside staircase (R9) increases and buoyancy effect in the night time is enhanced.

![Fig.17 Total air flow rate of R1, R2 during the night time (18:00 - 22:00)](image)

### 7. Conclusion

In this study, performance of natural ventilation using stack effect of staircase of building in which phase change material (PCM) is installed was investigated. The results showed that the inclusion of PCM in staircase would reduce airflow during the day time but increase it in the night time.

Increasing of solar radiation absorption factor of PCM or number of PCM sheets would enhance the effect of natural ventilation system. When it is windless outside, the effect of PCM to natural ventilation in the night time is more promising, as only temperature difference ventilation occurs. Regarding to position of PCM, calculation results showed that effect of natural ventilation is bigger when PCM is put in the lower staircase room.

Total air flow rate in the night time is higher when openings are closed during the day time. Operation pattern which combine air conditioning and natural ventilation would postpone the time when natural ventilation is possible in a year.

Since a detailed calculation of heat transfer inside walls was not incorporated, it needs to be considered in further investigation. Furthermore, the variation of specific heat of PCM needs to be investigated, since it is different between the melting process and the solidification process.

### Reference