Estimating the Adaptability of Phase Change Material Board on Building Envelope of Telecommunications Base Stations

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Abstract

A mathematical model about the energy storage/release of phase change material (PCM) board on building envelope was developed. Energy and mass efficiency (EME) was proposed to evaluate the performance of PCM board in telecommunication base stations (TBSs) located in various climatic regions in China. The influence on EME of parameters, including phase transition temperature of PCM, indoor and outdoor air temperatures and temperature differences between daytime and nighttime, was analysed. The optimal thickness of PCM board with optimal melting temperature increased with the increase of the heat transfer coefficient of building wall.

1. Introduction

Telecommunications base stations (TBS) are the transmission and reception stations of communication signals. The number of these stations increases as the information technology develops. As a result of the higher power and thermal density of TBSs, air conditioners work 24 hours per day all year round, which cost 30-50% electricity of the total energy consumption in TBSs [1].

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To reduce the energy consumption of TBSs, Rong et al. [2] studied the cooling load in TBSs located in severe cold and cold climatic regions. Based on this research, the optimal heat transfer coefficient of the envelope was put forward. Tu et al. [3] proposed that the TBS envelope should be designed according to its location and heat dissipation. It was reported that phase change material (PCM) could reduce the heat flux of building envelope by 41% [4]. Bontemp et al. [5] pointed out that PCM could reduce the indoor air temperature by 3 °C during spring and summer. Pasupathy and Velraj [6] concluded that a two-PCM panel system, one panel with a melting temperature of 32 °C and a thickness of 4 cm and the other with a melting temperature of 27 °C and a thickness of 2.5 cm could maintain a ceiling temperature of 27 °C.

PCM could reduce the heat gain through building envelope, resulting in a reduction of energy consumption of air conditioning system. To figure out the adaptability of PCM board on TBS envelope in different climatic regions, a heat transfer model of building envelope with PCM board was established. The concept of energy and mass efficiency (EME) was introduced to assess the performance of building envelope with PCM board. In addition, the factors that influenced EME were analyzed, including phase transition temperature, outdoor and indoor air temperatures and the air temperature difference between daytime and nighttime.

2. Method

The application of PCM on building envelope includes mixing PCM with building material or installing PCM board on building envelope. The thermophysical parameters of PCM may change with the former method. In addition, it is hard to mix the PCM and building material uniformly, which will induce the temperature non-uniformity of indoor air. Therefore, the later method was adopted in this paper. PCM board was installed on the inside face of TBS building envelope, as shown in Figure 1.

PCM was solidified by the outdoor air when outdoor air was cold during nighttime. The heat flux during solidification was:

\[ q_{in} = \frac{T_{out} - T_{w2}}{R_h + R_w} = \frac{T_{w2} - T_{m,s}}{R_{PCM,s}} \]  

(1)
where $T_{\text{out}}$, $T_{\text{in}}$, $T_{m,s}$ were the outdoor air temperature, the inner surface temperature of TBS building envelope and the solidification temperature of the PCM, respectively, °C; and $R_{h1}$, $R_w$, $R_{PCM,i}$ were the outdoor air heat convective resistance, the wall conduction resistance and the solid PCM conduction resistance, respectively, (m²·°C)/W.

PCM was melted by indoor air when indoor air was hot during daytime. The heat flux during melting was:

$$ q_{\text{out}} = \frac{T_{\text{in}} - T_{w3}}{R_{h2}} = \frac{T_{w3} - T_{m,l}}{R_{PCM,l}} $$

where $T_{\text{in}}$, $T_{w3}$, $T_{m,l}$ were the indoor air temperature, the inner surface temperature of PCM board and the melting temperature of the PCM, respectively, °C; and $R_{h2}$ and $R_{PCM,l}$ were the indoor air heat convective resistance and the liquid PCM conduction resistance, respectively, (m²·°C)/W.

The heat transfer of PCM was simplified into one dimension along with the thickness of PCM board, as shown in Figure 2. The governing equation for the heat transfer was shown in Eq. (5). The phase transition of PCM was assumed into a heat transfer with a moving heat source or sink.

$$ k \frac{\partial^2 T(x,t)}{\partial x^2} + (-1)^n \rho \Delta h \frac{dx(t)}{dt} \delta[x - x(t)] = \rho c \frac{\partial T(x,t)}{\partial t} \quad 0 < x < L, t > 0 $$

where $\delta[x - x(t)]$ was Dirac equation, as follows:

$$ \delta[x - x(t)] = \begin{cases} 0 & x \neq x(t) \\ 1 & x = x(t) \end{cases} $$

$$ n = \begin{cases} 0 & T_b < T_m \\ 1 & T_b > T_m \end{cases} $$

The boundary and initial conditions were:

$$ T(x,t) = T_m \quad 0 < x < L, t = 0 $$

Fig. 2. Heat transfer process of PCM board. (a) Heat release (cold storage) process; (b) Heat storage (cold release) process
\[ x(t) = 0 \quad x = 0, t = 0 \]  
\[ T(x, t) = T_b \quad x = 0, t > 0 \]  
\[ T(x, t) = T_m \quad x = x(t), t > 0 \]

where \( k \) was the heat conduction coefficient of PCM, \( W/(m^2\cdot{\degree}C) \); \( \rho \) was the density, \( kg/m^3 \); \( \Delta h \) was the latent heat of fusion, \( kJ/kg \); \( c \) was the thermal capacity, \( kJ/(kg\cdot{\degree}C) \); \( T_b \) was the boundary temperature, \( ^{\circ}C \); \( T_m \) was the phase transition temperature of PCM, \( ^{\circ}C \); \( x(t) \) was the position of solid-liquid interface, \( m \); and \( L \) was the thickness of PCM board, \( m \). All the variables were expressed as dimensionless numbers as follows:

\[ F_0 = \frac{at}{L^2} \]  
\[ S_{te} = \frac{c(T_b - T_m)}{\Delta h} \]  
\[ X = \frac{x}{L} \]

where \( \alpha \) was the thermal diffusivity of PCM, \( m^2/s \); \( F_0 \) was the dimensionless time, \( S_{te} \) was the dimensionless boundary temperature, and \( X \) was the dimensionless position of the solid-liquid interface. The thermophysical parameters of PCM were in Table 1.

| \( T_m \)  
(\(^{\circ}C\)) | \( \Delta h \)  
(kJ/kg) | \( k_s \)  
\([W/(m^2\cdot{\degree}C)]\) | \( \rho \)  
\([kg/m^3]\) | \( c \)  
\([kJ/(kg\cdot{\degree}C)]\) |
<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>27.4</td>
<td>243.5</td>
<td>0.358</td>
<td>778</td>
<td>775</td>
</tr>
</tbody>
</table>

Fig. 3. Position of phase change interface of PCM during melting
Figure 3 shows the position of solid-liquid interface during heat storage. The solid-liquid interface moved away from its initial location in an exponential manner as a function of time. There was excellent agreement between computational solutions and data from Hasan [7].

3. Results

The application of PCM board in TBS was simulated in five cities located in different climatic regions. The meteorological parameters in these cities were from Meteorological Information Center of the China [8], as shown in Table 2. The solar irradiance was neglected for the reason that the cold energy was stored during night and released into indoor during day. The parameters of TBS building envelope were from Practical HV&AC design handbook [9], as shown in Table 3.

<table>
<thead>
<tr>
<th>City</th>
<th>Climatic Region</th>
<th>Mean Annual Temperature (°C)</th>
<th>Temperature RMSE</th>
<th>$T_{d} - T_{m}$ (°C)</th>
<th>Temperature Difference RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shenyang</td>
<td>Severe Cold</td>
<td>8.6</td>
<td>13.4</td>
<td>11.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Zhengzhou</td>
<td>Cold</td>
<td>14.7</td>
<td>10.4</td>
<td>10.0</td>
<td>4.2</td>
</tr>
<tr>
<td>Kunming</td>
<td>Mild</td>
<td>15.5</td>
<td>5.6</td>
<td>8.6</td>
<td>3.6</td>
</tr>
<tr>
<td>Changsha</td>
<td>Hot summer &amp; Cold winter</td>
<td>17.4</td>
<td>9.0</td>
<td>7.1</td>
<td>3.7</td>
</tr>
<tr>
<td>Guangzhou</td>
<td>Hot summer &amp; warm winter</td>
<td>22.2</td>
<td>6.5</td>
<td>7.6</td>
<td>2.8</td>
</tr>
</tbody>
</table>

To promise the energy savings, the PCM used should store the maximum cold energy in one day. Under this condition, the thickness of PCM board was:

$$L_{\text{max}} = \frac{\max \left( \sum_{j=20}^{24} q_{in}^{j} \times \tau_{j} + \sum_{j=4}^{7} q_{in}^{j+1} \times \tau_{j} \right)}{\rho \Delta h}$$  \hspace{1cm} (11)

where $L_{\text{max}}$ was the maximum thickness of PCM board, $m$; $q_{in}^{j}$ and $q_{in}^{j+1}$ were the heat flux during cold energy storage at time $j$ in day $i$ and time $j$ in day $i+1$, respectively, W; $\tau_{j}$ and $\tau_{j+1}$ were time $j$ in day $i$ and time $j$ in day $i+1$, respectively, 3600s.
Figure 4 shows the maximum thicknesses of the PCM board in different cities. It increased with the increase of phase transition temperature. For example, the thickness of PCM board increased by 0.5 mm when the phase transition temperature changed from 24°C to 26°C. The maximum thickness of PCM board decreased with the increasing outdoor air temperature and the decreasing temperature difference between indoor and out air. Under these conditions, the natural cold energy was less. As a result, the need of PCM was reduced.

To assess the utilizing efficiency of natural cold energy, the utilization of natural cold energy was proposed, which was the ratio of the released cold energy to the stored cold energy in one energy storage/release cycle, as shown in Eq. (12). According to this definition, the utilization of natural cold energy increased with the increase of energy release and the decrease of energy storage. The utilization of natural cold energy for PCM board with maximum thickness was shown in Figure 5. The utilization decreased with the increasing phase transition temperature. The thickness of PCM board increased to store more cold energy when the phase transition temperature increased, as shown in Figure 4. However, the energy release did not change because of the stable indoor air temperature. In addition, the utilization decreased with the decreasing outdoor air temperature and the increasing temperature difference between indoor and out air, which resulted in an increase of the cold energy storage.

\[
\eta_E^{i+1} = \frac{\sum_{j=8}^{19} q_{in}^{i+1,j} \times \tau_{i+1,j}}{\sum_{j=20}^{24} q_{out}^{i,j} \times \tau_{i,j} + \sum_{j=1}^{7} q_{out}^{i+1,j} \times \tau_{i+1,j}} \times 100\% \tag{12}
\]

where \(\eta_E^{i+1}\) was the utilization of natural cold energy in day \(i+1\), %.

Based on the definition of the maximum thickness of PCM board, PCM board with maximum thickness can store the maximum cold energy in one day. However, this maximum cold energy only appeared in one or several days. The PCM board was not fully charged by cold energy at most time. To assess the utilizing efficiency of PCM board, the utilization of PCM board was proposed, as the ratio of stored cold energy to the maximum cold energy that PCM board can store. The mathematical definition of the utilization of PCM board was shown in Eq. (13). Figure 6 shows the utilization of PCM board with maximum thickness. The utilization decreased with decreasing outdoor air temperature (except the city of Kunming). The thickness of PCM board increased when outdoor air temperature decreased. However, the temperature distribution was non-uniform. Compared with the meteorological parameter in Table 2, the mean air temperature in Kunming was lower than it in Changsha; and the temperature root-mean-square-
error (RMSE) in Kunming was also lower than it in Changsha. That was, the temperature distribution in Kunming was more uniform than it in Changsha. Therefore, the utilization of PCM board was higher in Kunming. The lowest utilization appeared in Shenyang, which has the lowest outdoor air temperature and the highest temperature RMSE.

\[
\eta^i_M = \frac{\sum_{j=20}^{24} q_{in}^{i,j} \times \tau_j + \sum_{j=1}^{19} q_{in}^{i+1,j} \times \tau_j}{\rho \Delta h L_{\text{max}}} \times 100\%
\]

(13)

where \( \eta^i_M \) was the utilization of PCM board, %.

Fig. 6. Utilization of PCMB board

4. Discussion

From above analysis, the selection of PCM board thickness was vital. The appropriate thickness can make good use of natural cold energy as well as PCM board. To design the thickness of PCM board, an energy and mass efficiency (EME) of building envelope with PCM board was proposed to estimate the application of PCM board in TBS. The definition of EME for the PCM board with different thickness was the product of utilization of natural cold energy and the utilization of PCM board, as shown in Eq. (14).

\[
\text{EME}^i = \eta^i_e \cdot \frac{L}{L_{\text{max}}} \cdot \eta^i_M \times 100\%
\]

(14)

where \( \text{EME}^i \) was the energy and mass efficiency in day \( i \), %; \( L_{\text{max}} \) was the maximum thickness of PCM board in day \( i \), m.
Figure 7 shows the variation of annual mean EME of TBS building envelope with PCM board in five cities. With the increasing thickness of PCM board, the EME increased and then decreased. When the thickness of PCM board increased, the utilization of natural cold energy increased, resulting in an increase of EME. However, the utilization of PCM board decreased. When the thickness came to a certain point, the utilization of PCM board reduced significantly, which overwhelmed the increase of utilization of natural cold energy. As a result, the EME decreased. The optimal thickness was the one when EME achieved to its peak, as shown in Table 4.

Table 4. The optimal PCMB thickness in five representative cities (T_m=25°C)

<table>
<thead>
<tr>
<th>City</th>
<th>Thickness (mm)</th>
<th>EME(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shenyang</td>
<td>6.2</td>
<td>98.2</td>
</tr>
<tr>
<td>Zhengzhou</td>
<td>4.4</td>
<td>96.4</td>
</tr>
<tr>
<td>Kunming</td>
<td>4.2</td>
<td>98.1</td>
</tr>
<tr>
<td>Changsha</td>
<td>3.6</td>
<td>97.1</td>
</tr>
<tr>
<td>Guangzhou</td>
<td>2.3</td>
<td>89.0</td>
</tr>
</tbody>
</table>

5. Conclusions

To estimate the adaptability of PCM board in TBS, an energy and mass efficiency (EME) was proposed. The EME was simulated in TBSs located in five climatic regions in China in one whole year. The following conclusions were made: 1) The utilization of natural cold energy and utilization of PCM board decreased with the increasing phase transition temperature and temperature difference between daytime and nighttime and the decreasing of outdoor air temperature. 2) The optimal thicknesses, which results in the peak EME, for PCM board with phase transition temperature of 25 °C in TBS were: 6.2 mm in Shenyang, 4.4 mm in Zhengzhou, 4.2 mm in Kunming, 3.6 mm in Changsha and 2.3 mm in Guangzhou.

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References