Development of Solar Chimney with Built-In Latent Heat Storage Material for Natural Ventilation

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Abstract A prototype solar chimney with built-in latent heat storage system for prolongation of the ventilation system operation until evening / night or even 24 hours was designed and developed. Sodium Sulfate Decahydrate “Na₂SO₄·10H₂O” (melting point 32 °C, latent heat of fusion 126 kJ/kg) was used as a Phase Change Material (PCM) for latent heat storage. Experiments to evaluate the thermal performance of solar chimney with the effect of parameters such as gap spacing (100 mm - 300 mm) between the absorber plate and glass cover, air mass flow rate, inclination angle (45°, 60° and 75°) under different atmospheric conditions like ambient air temperature, solar radiation etc are in progress. This paper shows the example of experimental results and the thermal analysis to predict the airflow rate and temperatures of the component of the system with experimental results.

Keywords: Solar Chimney, Latent Heat Storage, Phase Change Material, 24-hours Ventilation

1. INTRODUCTION
Solar-induced ventilation could be provided by incorporation solar chimney with building. This technique is being popularized in new constructions that exploit renewable resources to save conventional energy and extend indoor thermal or air quality comfort. There are many numerical and experimental studies, especially for calculation of airflow rate of such chimneys. Bansal et al. [1] developed a simple equation based on the stack pressure concept that can be used to estimate the induced ventilation rate. Moshfegh et al. [2] discussed heat transfer characteristics of buoyancy-driven air convection in vertical panels. Recently, Bansal et al. [3] developed a simple mathematical model for window-sized solar chimney for ventilation. It was found that the highest air velocity in the chimney was 0.24 m/s, which shows the potential to apply the concept of solar chimney in the existing window design followed by minor modifications. In particular, different trombe wall systems [4], solar chimney [5] and also double glass façades have been studied for designing natural ventilated building façades [6].

Authors [7][8] has been conducted an experimental and mathematical study of such a chimney using a full-scaled model heated by electrical heater. The experimental parameters are heat generation rate, size of chimney gaps and inclination of chimney. The new calculation model for predicting the airflow rate was proposed and the calculated results are in good agreement with the experimental ones. Halldorsson et al. [9] conducted a similar study and it was found that the flow rate inside the chimney shows the maximum at a chimney inclination angle of around 45°. This is perfectly the same result as authors’ result.

Above-mentioned studies aims the solar chimney ventilation during the daytime, but the ventilation also during the nighttime is desired if it is possible. Authors’ idea is very simple. The latent heat storage to storage the heat of daytime is possibly used for the nighttime ventilation by solar chimney. No work has been studied for designing natural ventilated building façades.

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2. DESCRIPTION OF THE PROTOTYPE SOLAR CHIMNEY
The prototype of the solar chimney with built-in latent heat storage was fabricated and installed on the roof of a Department of Architectural Engineering, Osaka University for testing thermal performance. A sectional view and photograph of the prototype solar chimney using PCM are shown in Fig. 1 and Fig. 2. The dimensional size for tested solar chimney was 1.3 m length x 0.85 m wide x 0.01 m channel gap. The chimney could be tilted with different angles from the horizontal. The air gap could be set at pre-adjusted values of 0.1 m, 0.2 m and 0.3 m for air flow over the absorbing plate and inside the chimney. The chimney was covered with 6 mm thick transparent glass glazing for trapping the heat.

An innovative idea has been applied to design an absorber of the present prototype solar chimney. This absorber consist an aluminum (Al) plate with built-in PCMs for latent heat storage. Sodium Sulfate Decahydrate “Na₂SO₄·10H₂O” (melting point 32 °C, latent heat of fusion 126 kJ/kg) was used as PCM for latent heat storage and encapsulated in rectangular slab with the dimensions of 0.6 m length x 0.25 m width x 0.025 m.

Encapsulated PCM modules were packed behind the black coated absorbing aluminum (Al) plate. Six PCM modules were utilized in the experiments and these are originally used for the floor heating. The total mass of the PCM is about 23.16 kg. A gasket was used around the glass edges to prevent any heat leakage. The specifications of the prototype set-up and thermo-physical properties of the PCM are given in Table 1. The transmitted solar radiation from the glass cover is partly absorbed by rectangular encapsulated PCM modules and stored in the PCM, as latent heat thermal energy, and partly transferred to the air flowing over the absorber surface. As collected solar energy transferred to the PCM raises its temperature from the initial temperature to the higher temperature over the melting point. Hence, the air temperature also increases and reaches its maximum at the collector outlet. The increase in the air temperature difference, a density gradient between the inside and outside the chimney is obtained that in turn induces a natural upward moment of air. Ventilation and storage in PCM occur...
during daytime simultaneously, while evening / night ventilation is induced mainly by the latent heat storage of PCM. PCM transferred stored heat to air, which flows over the aluminum (Al) plate. This stored heat is used for generating the temperature difference in evening or when sun irradiation is weak. The thermally induced flow depends on the level of solar radiation, weather conditions, geometry and orientation of the system, and the PCM’s storage properties.

![Fig. 1: Sectional view of chimney with built-in PCM storage](image)

Seventy-seven ‘T’ type calibrated thermocouples, accuracy ± 0.2°C, were used to measure the temperatures of the various elements of the chimney. These points were located on/in the absorbing (Al) plate, inside the PCM, surface of the PCM modules, air temperature inside the chimney, outer surface of the glazing, top and bottom of the of the polystyrene, inside the glass wool insulation, ambient air temperature and so on. The positions of thermocouple are shown in Fig.3. A pyranometer was used to measure solar irradiance at inclined surface with the accuracy of 1.5%. Another pyranometer was used to measure the solar irradiance on a horizontal surface with the accuracy of 2.5%. All data were recorded at intervals of 6 s.

![Fig.3: Thermocouples position inside the solar chimney](image)

### 3. THERMAL ANALYSIS

The transmitted solar radiation from the glass cover is absorbed by the PCM via absorbing (Al) plate. The air flows above the Al-plate where it is heated along its path. The energy balance equations of the solar chimney with built-in PCM storage components (see Fig. 4) are as follows:

\[
\begin{align*}
\frac{d\theta_{\text{air}}}{dt} = q_{\text{in}} - q_{\text{out}} - q_{\text{w}} + q_{\text{PCM}} - q_{\text{Al}} + q_{\text{Al}}^\text{b} - q_{\text{w}}^\text{b} - q_{\text{in}}^\text{b} - q_{\text{out}}^\text{b} + q_{\text{pass}}
\end{align*}
\]

where

\[
\begin{align*}
q_{\text{in}} &= \rho_{\text{am}} C_{\text{p,air}} V_{\text{air}} \Delta \theta_{\text{am}} \\
q_{\text{out}} &= \rho_{\text{am}} C_{\text{p,air}} V_{\text{air}} \Delta \theta_{\text{am}} \\
q_{\text{w}} &= U_{\text{g}} (\theta_{\text{in}} - \theta_{\text{air}}) \\
q_{\text{PCM}} &= C_{\text{PCM}} V_{\text{PCM}} \Delta \theta_{\text{PCM}} \\
q_{\text{Al}} &= \alpha_{\text{Al}} A_{\text{Al}} \left( \frac{2}{\rho_{\text{am}}} \right) (-P_{\text{in}}) \\
q_{\text{w}}^\text{b} &= U_{\text{g}} (\theta_{\text{Al}} - \theta_{\text{in}}^\text{b}) \\
q_{\text{in}}^\text{b} &= \alpha_{\text{in}} A_{\text{in}} \left( \frac{2}{\rho_{\text{in}}} \right) (-P_{\text{in}}) + \Delta \theta_{\text{in}}^\text{b} \\
q_{\text{out}}^\text{b} &= \alpha_{\text{out}} A_{\text{out}} \left( \frac{2}{\rho_{\text{out}}} \right) (-P_{\text{in}}) + \Delta \theta_{\text{in}}^\text{b}
\end{align*}
\]

with

\[
\begin{align*}
\alpha_i &= \frac{1}{\sqrt{\xi_i + 1}} \\
\alpha_o &= \frac{1}{\sqrt{1 + \xi_o + \frac{L}{D}}} \\
D &= \frac{2ab}{a+b} \\
\rho &= \frac{353.25}{\theta} \\
m &= \rho_{\text{am}} Q_{\text{in}} = \rho_{\text{air}} Q_{\text{out}}
\end{align*}
\]

This chimney is oriented to face south and tilted 45°, 60° and 75° with respect to the horizontal. The solar chimney is tested outdoors under the natural convection mode of operation.
Re-arranged the heat balance equation for aluminum (Al) plate, air and PCM and $\theta_{Al}$, $\theta_{air}$, $\theta_{PCM}$ and $\theta_{amb}$ are obtained by Finite Difference Method. These temperatures along with the equations (10), (11) and (13) can be used to obtain the mass flow rate of air. In the above set of equations, the intensity of incident solar radiation and ambient air temperature are the external inputs. The other factors and constants are described in the Table 2.

![Diagram for the heat balance inside the solar chimney](image_url)

**Fig. 4: Diagram for the heat balance inside the solar chimney**

**Table 2: Numerical values of the constants and various factors used in the thermal analysis of the solar chimney**

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L$ [m]</td>
<td>1.3</td>
</tr>
<tr>
<td>$W$ [m]</td>
<td>0.85</td>
</tr>
<tr>
<td>$\theta_{Al}$ [-]</td>
<td>45</td>
</tr>
<tr>
<td>$A_{Al}$ [m$^2$]</td>
<td>0.15</td>
</tr>
<tr>
<td>$A_{air}$ [m$^2$]</td>
<td>0.15</td>
</tr>
<tr>
<td>$a_{Al}$ [-]</td>
<td>0.78</td>
</tr>
<tr>
<td>$a_{air}$ [-]</td>
<td>3.83</td>
</tr>
</tbody>
</table>
| $C_{PCM}$ [kJ/kgK] | 3.6 (at $\theta_{PCM} < 20$ °C)  
11 (at 20°C < $\theta_{PCM} < 36$ °C)  
3.5 (at 36°C ≤ $\theta_{PCM}$) |

### 4. RESULTS AND DISCUSSIONS

Experiments have been conducted to predict the air flow rate and prolong the ventilation operation using PCM through the solar chimney. In this paper, two conditions have been discussed: (i) PCM completely melted. (ii) PCM did not melt. Variation of aluminum (Al) plate, PCM and ambient air temperatures are shown in Figure 6 and 7. These Figures show the variation of temperatures on the top and bottom of the solar chimney. As shown in Figure 6 and 7 the collected solar energy transferred to the PCM via aluminum (Al) plate raises its temperature from the initial temperature to the higher temperature around the melting point. Initial change in temperature is a faster process because of the high heat transfer rate to the PCM. After this rapid increase, the temperature becomes somewhat constant during the melting period. PCM was almost melt on 14 -15 Feb. 2005 (Fig. 6) and it was maximum (41.8 °C) around the 13:30 P.M. at maximum solar radiation (906 W/m$^2$) which was received on the collector. Maximum temperature difference between PCM and the ambient was 20 – 25 °C, and that of Al-plate and ambient was 40 – 46°C respectively. Fig. 7 shows results when PCM was not melt on 23 -24 Jan., 2005 with maximum temperature and solar radiation of 12.4 °C and 325 W/m$^2$ respectively.

PCM, Al-plate and air temperatures and airflow rate were calculated using above-mentioned equations. Results are shown in Figure 8 and 9. Simulated results for the temperatures shows the good agreement with the experimental results for $h_t = 15$. Fig. 8 (a) shows the simulated results of volume airflow rate and it increases from initial to maximum as solar radiation increased with the time of the day. Simulated maximum airflow rate (224 m$^3$/h) was noticeable around 13:30 P.M. at maximum solar radiation (906 W/m$^2$). At 17:00 P.M., solar radiation reached to the minimum value (~0 W/m$^2$). After sunset (17:00 P.M.), latent heat stored in the PCM facilitates supplied airflow rate and prolong the ventilation operation in evening and during the night. PCM storage managed the night ventilation and supplied maximum and average air flow rate of 224 m$^3$/h and 155 m$^3$/h respectively from 17 P.M. to 05:30 A.M for the air gap of 0.20 m between absorbing (Al) plate and glazing with 45 degree inclination angle from the horizontal due to south.

![Variation of the aluminum (Al) plate, PCM and ambient air temperature on 14 – 15 Feb. 2005](image_url)

**Fig. 5: Variation of the aluminum (Al) plate, PCM and ambient air temperature on 14 – 15 Feb. 2005**

![Variation of the aluminum (Al) plate, PCM and ambient air temperature on 23 – 24 Jan. 2005](image_url)

**Fig. 6: Variation of the aluminum (Al) plate, PCM and ambient air temperature on 23 – 24 Jan. 2005**
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NOMENCLATURE

\( A_{\text{i}}, A_{\text{o}} \) : Inlet and outlet opening area of the solar chimney (m²)
\( C_{\text{sv}} \) : Specific heat of the air (J/kgK)
\( C_{\text{Al}} \) : Specific heat of absorbing aluminum (Al) plate (J/kgK)
\( C_{\text{PCM}} \) : Specific heat of PCM (J/kgK)
\( h_{\text{t}} \) : Convective heat transfer coefficient (W/m²K)
\( L \) : Length of the solar chimney (m)
\( m \) : Mass flow rate of air (kg/s)
\( q_{\text{i}} \) : Total incident solar radiation on the collector (W/m²)
\( q_{\text{conv}} \) : Amount of heat from the environment to the chimney (W/m²)
\( q_{\text{con}} \) : Amount of heat from the chimney to the environment (W/m²)
\( q_{\text{t}} \) : Transmission of heat from glazing to the environment (W/m²)
\( q_{\text{c}} \) : Convective heat flow from the wall to the flowing fluid (W/m²)
\( q_{\text{h}} \) : Heat flow from the aluminum (Al) plate to PCM (W/m²)
\( q_{\text{h}} \) : Convective heat loss from wall (W/m²)
\( Q_{\text{in}} \) : Volume flow rate of air at inlet of the chimney (m³/s)
\( Q_{\text{out}} \) : Volume flow rate of air at outlet of the chimney (m³/s)
\( U_{\text{g}} \) : Overall heat transfer coefficient of the glazed (W/m²K)
\( U_{\text{w}} \) : Thermal conductivity of the wall of the solar collector (W/mK)
\( U_{\text{p}} \) : Overall heat transfer coefficient from the back side (W/m²K)
\( V_{\text{cf}} \) : Volume of the flowing fluid (air) (m³)
\( V_{\text{PCM}} \) : Volume of the PCM (m³)
\( W \) : Width of the solar chimney (m²)
\( \theta_{\text{ci}} \) : Air temperature inside the chimney (°C)
\( \theta_{\text{c0}} \) : PCM temperature (°C)
\( \theta_{\text{Al}} \) : Aluminum (Al) plate temperature (°C)
\( \theta_{\text{air}} \) : Ambient air temperature (°C)
\( \theta_{\text{ini}} \) : Inlet angle of solar chimney from the horizontal (degree)
\( \rho_{\text{air}} \) : Air density (kg/m³)
\( \rho_{\text{Al}} \) : Density of the absorbing aluminum (Al) plate (kg/m³)
\( \rho_{\text{PCM}} \) : Density of the PCM (kg/m³)
\( \alpha \) : Overall absorptivity of the absorber (-)
\( \alpha_{\text{i}} \) : Inlet discharge coefficient (-)
\( \alpha_{\text{o}} \) : Outlet discharge coefficient (-)
\( \tau \) : Transmittivity of the collector (-)

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