Analyzing heat transfer through brick with air enclosure including phase change material

ADEL E. ALSHAYJI

Kuwait University
E-mail: a.alshayji@ku.edu.kw

Abstract - In this study, heat transfer through brick with air enclosure including phase change material (PCM) was simulated; this study focuses on reducing the heat transfer through the enclosure by considering the effect of several filling levels of PCM inside the air enclosure. The brick in this study is subject to transient ambient condition for the outer side, while the temperature kept constant in the inner side, to represent the actual daily change of temperature this brick may face. Five different levels of PCM (0%, 25%, 50%, 75%, and 100%) were considered in this study. The PCM help in reducing the total heat transfer into the inner part of the brick by up to 40% compare to pure concrete brick and up to 23% compare to brick with only air gap.

Index Terms - Heat Transfer, Brick, Air Enclosure, Phase Change Material.

I. INTRODUCTION

Heat can be transferred into and out of a subject in three forms conduction, convection, and radiation. In some cases, when it comes to air, convection is considered the highest denominator in the heat transfer equation when compared with conduction, which is very insignificant. All over the world insulations are used to control the heat transfer rate through various systems and the effectiveness of these insulations vary with the significance of the media it is preserving, for example bricks, which are common building materials that widely used in building structures. Having bricks with special insulating features, in addition to strength propriety needed for construction, can help in reducing heat transfer into building and thus reduces energy consumption to cool building especially in hot climate area. In such placed, the outer ambient temperature may reach up 50°C during the summer season. Having bricks with air enclosure can help in reducing the heat transfer, since the air can act as insulator due to its low conductivity behavior. Adding phase change materials (PCM) to the brick can enhance its ability to reduce heat transfer since some of the energy will be use to melt the solid state of the PCM when temperature rises.

Esam M. Alawadhi[1] studied the thermal analysis of a building brick containing PCM to be used in hot climates. The objective of his study is to utilize its high latent heat of fusion to reduce the heat gain by absorbing the heat in the bricks through the melting process before it reaches the indoor space. The considered model consists of bricks with cylindrical holes filled with PCM. The thermal effectiveness of the proposed brick-PCM system is evaluated by comparing the heat flux at the indoor surface to a wall without the PCM during typical working hours. A paramedic study is conducted to assess the effect of different design parameters, such as the PCM’s quantity, type, and location in the brick. The results indicate that the heat gain is significantly reduced when the PCM is incorporated into the brick, and increasing the quantity of the PCM has a positive effect.

Raghavendra Rohith Kasibhatla[2] considered PCM capsule to understand of the phase change process under the influence of air in a capsule. In his work, two immiscible fluids PCM and air have been modeled using a continuum surface force (CSF) model. The wetting of the melted PCM on the capsule wall is taken into account by implementing a contact angle boundary condition. The surface tension of the PCM with air is just contributed to the liquid phase of the PCM. The results obtained from the complete numerical model have shown a great acceptance when compared with experiments. Despite several small deviations in the results, the numerical modelling is a potential tool to optimize the efficiency of thermal storage units.

Karunesh Kan[3] considered in his study building bricks containing PCM when subjected to ambient weather conditions such as solar radiation and ambient temperature. In his thermal model presented in his work, the PCM filled cylindrical cavity of the bricks. The effectiveness of PCM in the building bricks was evaluated by comparing the three different cases - the normal bricks, bricks with air filled in the cylindrical cavity and bricks with PCM filled in the cylindrical cavity. Additionally, the study has also considered different PCMs, with a varying quantity. The obtained results indicate that the Capric acid is more effective PCM in comparison to the Paraffin and RT-25. The maximum heat flux reduction is found to be 8.31% with Capric acid filled in three cylindrical cavities. He concluded that the application of PCM in building brick could be an effective technique for passive thermal control of buildings.

II. PROBLEM DEFINITION

This research focus on the design of brick wall with an air enclosure filled with phase change material. This
brick operates between an inside surface temperature of 20°C and variable outside surface temperature between 31°C to 46°C as shown in Figure (1). This temperature variation represents ambient temperature change in hot climate area during the summer season. The brick model used in this study consist of three different materials, concrete brick, air gap, and PCM, as shown in Figure (2). The level of PCM in this study were changes gradually from 0%-fill, means no PCM, to 100%-fill, means totally filled with PCM. The total heat transfer magnitude was measured at the inner side of this brick to examine the effect of PCM level inside the air enclosure. More details will be shown in the result analysis and discussion section below.

Table 1: Concrete brick properties.

<table>
<thead>
<tr>
<th>Property</th>
<th>Concrete Brick</th>
</tr>
</thead>
<tbody>
<tr>
<td>ρ (kg/m³)</td>
<td>2000</td>
</tr>
<tr>
<td>C_p (J/kg.K)</td>
<td>900</td>
</tr>
<tr>
<td>k (W/m.K)</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Table 2: Phase change material properties.

<table>
<thead>
<tr>
<th>Property</th>
<th>Solid Phase</th>
<th>Liquid Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>ρ (kg/m³)</td>
<td>830.9</td>
<td>778.2</td>
</tr>
<tr>
<td>C_p (J/kg.K)</td>
<td>5000</td>
<td>2100</td>
</tr>
<tr>
<td>k (W/m.K)</td>
<td>0.65</td>
<td>0.166</td>
</tr>
<tr>
<td>μ (Pa.s)</td>
<td>1e5</td>
<td>0.0044</td>
</tr>
</tbody>
</table>

IV. MATHEMATICAL FORMULATION

The analysis of the multi-material brick with the air gap, and phase change material was done by using equations that combined the heat transfer in solid and fluid layer. The equations were used to solve for the energy balance through the brick and for the gravitational force applied on the air due to the shift in the density inside the air enclosure. In the momentum equation, it was assumed that the laminar flow is incompressible and that the air inside the enclosure is an ideal gas and the gravity effect is only applied in the vertical directions.

Continuity equation:

\[
\frac{\partial u_x}{\partial x} + \frac{\partial u_y}{\partial y} = 0
\]

Momentum equation:

\[
\begin{align*}
\rho \frac{\partial u_x}{\partial t} + \rho u_x \frac{\partial u_x}{\partial x} + \rho u_y \frac{\partial u_x}{\partial y} &= -\frac{\partial p}{\partial x} + \nu \left( \frac{\partial^2 u_x}{\partial x^2} + \frac{\partial^2 u_x}{\partial y^2} \right) \\
\rho \frac{\partial u_y}{\partial t} + \rho u_x \frac{\partial u_y}{\partial x} + \rho u_y \frac{\partial u_y}{\partial y} &= -\frac{\partial p}{\partial y} + \nu \left( \frac{\partial^2 u_y}{\partial x^2} + \frac{\partial^2 u_y}{\partial y^2} \right) + \rho g_z
\end{align*}
\]

Energy equation:

\[
\begin{align*}
\frac{\partial T}{\partial t} + u_x \frac{\partial T}{\partial x} + u_y \frac{\partial T}{\partial y} &= \alpha \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right)
\end{align*}
\]
V. BOUNDARY AND INITIAL CONDITIONS

The model was set at a certain boundary and initial conditions. The model was initially set at temperature 20°C for all the layers and at zero atmospheric pressure for the air enclosure. On the other hand, the model was set at the following boundary conditions:

1. $T_{out} = 31$-46°C (300 K) for the outer surface of the brick as shown in Figure (1).
2. $T_{in} = 20°C$ for the inner surface of the brick.
3. No-slip condition for the walls inside the air enclosure.
4. Adiabatic boundary condition at the upper and lower horizontal surfaces.

VI. RESULTS ANALYSIS AND DISCUSSION

After solving this numerical problem starting from mid-night time (0 hr.) by using COMSOL Multiphysics software, the effects PCM level on heat transfer rate through the brick is examined. Figure (3), (4), and (5) show the numerical results for the temperature and phase transformation in the computational domain for three different levels of PCM at 2 pm, where the ambient temperature reach maximum of 46°C.

In Figure (6) the melting process of the PCM inside the air enclosure is examine. The melting become maximum when the outside temperature reaches the maximum value of 46°C at 2 pm for all filling percentage of PCM. Also, we notice that the melting start at 8 am when outside temperature start to rice and then end around 10 pm when the temperature starts to cool down.

The average heat transfer rate at each hour is computed as shown in Figure (7). This figure shows that the maximum heat transfer rate happens at hour 14 (2 pm) for all filling percentage of PCM inside the air enclosure. It is also noticeable that when PCM fill 25% of the air enclosure the heat transfer rate become the minimum at all time. While when the filling precent become 50%, the results become similar to the one without filling. It is also noticeable that when the filling percentage exceed 50%, (75%, and 100%), the PCM will act negatively in reducing the heat transfer through the modeled brick.

At 2 pm, when the outer temperature and heat transfer become maximum, the variation of heat transfer rate with brick highs are plotted in Figure (8) for different filling of PCM. It is noticeable from this figure that the PCM enhance the heat transfer especially when the filling percentage exceed 50%; however, at 25% filling of PCM the brick block good amount of the heat through this brick especially in the middle area.

Figure (9) to (13) show the variation of heat transfer rate with brick height at 0%, 25%, 50%, 75%, and 100% PCM filling percentage respectively.
Figure 6: Change of melting percentage of PCM in the air enclosure with time at different PCM filling percentage.

Figure 7: Variation of average heat transfer rate with time at different PCM filling percentage.

Figure 8: Variation of heat transfer rate with brick height at different PCM filling percentage (at time = 2 pm).

Figure 9: Variation of heat transfer rate with brick height at 0% PCM filling percentage and selected times.

Figure 10: Variation of heat transfer rate with brick height at 25% PCM filling percentage and selected times.

Figure 11: Variation of heat transfer rate with brick height at 50% PCM filling percentage and selected times.

Figure 12: Variation of heat transfer rate with brick height at 75% PCM filling percentage and selected times.

Figure 13: Variation of heat transfer rate with brick height at 100% PCM filling percentage and selected times.
CONCLUSION

In this study focused on the effect of using phase change material (PCM) inside brick with air enclosure to reduce the heat transfer through this brick. From the results and analysis, we noticed that the PCM can help in reducing the heat transfer especially when they partially fill the air enclosure and fill less than 50% of the air enclosure. When PCM fill more than 50% of the air enclosure, the PCM act in negative way and enhance the heat transfer. While the results suggest the when the PCM fill exactly 50% of the air enclosure, it act exactly as when not PCM used at all. In conclusion having brick with air enclosure filled with less that 50% PCM, or have no PCM at all will act better that having solid concrete brick when reduction of heat transfer is sought.

REFERENCES