

Numerical simulation analysis on the thermal performance of a building walls incorporating Phase Change Material (PCM) for thermal management

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Abstract. Phase Change Material (PCM) plays an essential role in a thermal energy storage device, mainly, by utilizing its relatively high storage density, and latent heat property. PCM is potentially applicable as buildings material as it is possible to incorporate in the building envelope for energy conservation. Energy Plus is the chosen software to simulate phase change material in the building envelope. This paper will discuss in detail the numerical analysis of building thermal characteristics using PCM materials on the walls for climatic conditions of Banda Aceh City. The PCM used is beeswax. The weather data used in the simulation was customized for the year 2015 from the National Renewable Energy Laboratory (NREL) website. Some separate parametric studies, i.e., a variation of PCM thermal conductivity, and temperature range, and results are presented. It was discovered that a PCM with a melting point from 21 to 23 °C led to maximum energy savings and greater peak load time shift, and is more suitable than other PCM temperature ranges for lightweight building construction.

1. Introduction

Indonesia's energy consumption pattern for housing sector for heating or cooling reached 43%, water heater 27%, lighting 3.4%, appliances 26.6%. As for the use of electrical energy to reach 50% of the total electricity demand absorbed in the building sector, the residential sector plays a significant role in consuming electricity for lighting purposes, household appliances as well as for space conditioning. Indonesia as a developing country will undoubtedly move to improve the living standard of its population. Hence the pattern of energy use for residence will mostly be used for achieving spatial comfort through air system, lighting system, and water heater. The energy consumption pattern for the commercial building sector reaches 50-60% for the air conditioning system, 30% for lighting and the rest for other machine tools [1].

Lightweight concrete buildings are currently used as a relatively cheaper home-building solution, although it has not yet provided indoor thermal comfort due to the use of this building material. Lightweight concrete building materials can store some amount of heat so that at night the heat is released back to the room. Research on energy-efficient building sector in Indonesia has been aimed only at energy consumption, but never questioned energy efficiency through the selection and use of building materials.



Among these techniques, latent heat storage utilizing PCM has attracted researchers due to its superiority in storing high energy and small temperature changes. Latent heat storage can be delivered through solid-solid, solid-liquid, solid-gas-gas-liquid-gas phase [2]. However, an energy-intensive, economically superior system is attractive for use in thermal energy storage systems.

Most of the studies conducted by many researchers used inorganic PCM as a heat sinking material, due to its high latent heat enthalpy, excellent thermal conductivity, non-flammable and inexpensive [3]–[5]. However, most of the inorganic PCM is corrosive, mostly metal, and has a decomposition phase [6],[7]. There are some inherent predicaments in inorganic-PCM, which can be addressed by considering the use of organic PCM as a heat storage medium [8]–[10]. Organic PCM have stable, non-corrosive, non-toxic chemical properties and possess high latent heat enthalpy. However, for the utilization of organic PCM in the building, it is necessary to select the temperature change phase in the comfort zone of human that is in the range 18-26°C [11]–[13].

Which have other stable forms of composition, The use of eutectic-PCM for composite development has not yielded good results and limited information on the thermo physical properties of PCM [14],[15].

Therefore, to overcome this problem, in this study will be proposed the use of beeswax and paraffin as PCM for the development of stable-form PCM composite. The beeswax has a melting temperature in the indoor thermal comfort range, having a high latent heat capacity, economical and easy to obtain. While, paraffin other than having a melting temperature in the thermal comfort range, the latent heat capacity, economical, inert, non-corrosive, chemical properties have a low vapour pressure in the form of molten, exhibiting small volume changes during the transition phase, harmless and inexpensive. During the research, bentonite bolt used as the binding agent.

Therefore, to address this problem, the focus of this research is to develop a macro-encapsulation PCM preparation method using epoxy as a coating material to avoid leakage and graphite powder used for enhanced macro-encapsulation thermal conductivity. This paper will discuss in detail the numerical analysis of building thermal characteristics using PCM materials on the walls for climatic conditions of Banda Aceh City.

2. Building energy analysis method

Energy analysis was conducted on buildings with total area of 418.22 m². The building has three zones with area of each zone are: zone 1 = 202,53 m², zone 2 = 110,70 m² and zone 3 = 86,99 m². Each wall in each zone is installed 40% of the glass window as shown in Figure 1.

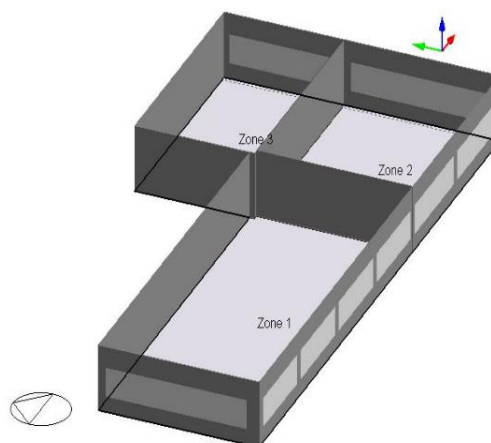


Figure 1. The building sketch for energy analysis.

Material for construction of building walls, consisting of plaster of cement, bricks, PCM composite, and plaster of cement. Figure 2 shows the composition of the material and its thickness for the walls and roof of the building.



Figure 2. The composition of material for wall and roof.

PCM modelling is very complicated because of the complexity of the transition phase. Storage and release of latent heat and changes in the thermo physical properties of materials during phase change and the constant temperature at the time of phase change contribute to this complexity. There are various thermal simulation programs can model PCM. Some of them have unique modules designed for PCM modelling purposes.

Energy Plus energy analysis software and thermal simulation on buildings, which calculate the energy requirements on heating and cooling processes of buildings required to maintain certain thermal conditions. A graphical representation of the heat balance for the building wall portion as illustrated in Fig 3.

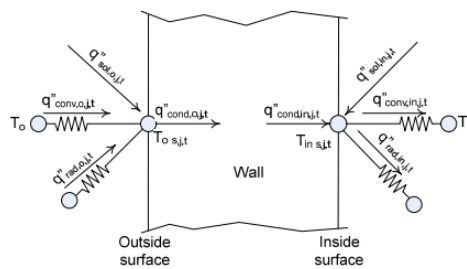


Figure 3. The scheme of heat balance circuit on the wall of the composite building.

The heat balance on the wall can be expressed in the form of:

$$q_{cond,o,j,t} = q_{sol,o,j,t} + q_{conv,o,j,t} + q_{rad,o,j,t} \quad (1)$$

where,

- $q''_{cond,o,j,t}$ = heat conduction flux to wall (W/m²)
- $q''_{sol,o,j,t}$ = heat flux of absorbed energy (W/m²)
- $q''_{conv,o,j,t}$ = heat flux of convection (W/m²)
- $q''_{rad,o,j,t}$ = heat flux of incoming thermal radiation (W/m²).

The combination of building materials and PCM is an efficient way to increase the thermal energy storage capacity of building components. The technique of combining with encapsulation-PCM composite form is the most straightforward method, practical and economical method, and has attracted many researchers in the last decade[16]. However, some issues still need to be resolved in the development of composite PCM.

$$q''_{cond,o,j,t} = q''_{sol,o,j,t} + q''_{conv,o,j,t} + q''_{rad,o,j,t} \quad (2)$$

$$\sum_{j=1}^N A_j q_{\text{conv},j,t}'' + q_{\text{infiltration},t}' + q_{\text{sys},t}' + q_{\text{internalconv},t}' = 0 \quad (3)$$

The solution of the phase change problem has a high degree of difficulty due to simultaneous changes of solid and liquid phases, the solid-liquid phase change is continuously moving, and its position is unknown. The energy equations needed to be written separately for both phases and their temperature must couple in the interface phase. Therefore, an equation is needed to determine the location of the interface phase. The enthalpy method is the approach that overcomes these difficulties. The enthalpy method in the energy equation shows as follows:

$$\nabla \cdot (k \nabla T) = \rho \frac{\partial H(T)}{\partial t} \quad (4)$$

alternatively, in another form:

$$k \cdot \left(\vec{i} \frac{\partial^2 T}{\partial x^2} + \vec{j} \frac{\partial^2 T}{\partial y^2} + \vec{k} \frac{\partial^2 T}{\partial z^2} \right) = \rho \frac{\partial H(T)}{\partial t} \quad (5)$$

Where: Δ = Del operator k , k = material thermal conductivity, T = Temperature, ρ = material density, $\partial H(T) / \partial t$ = enthalpy change with time.

The boundary conditions for PCM materials in melt conditions can be described as shown in Fig. 4. At $t = 0$, the melting begins to occur to an ambient temperature higher than T_m , with time T_m remaining constant, and the heat absorption process begins.

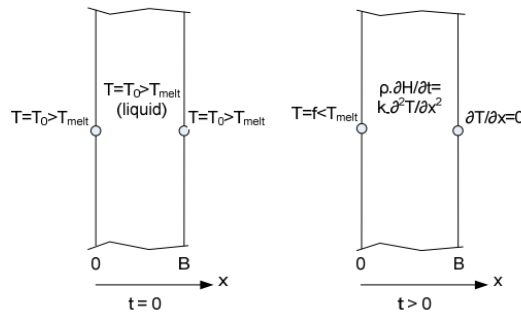


Figure 4. Schematic of boundary conditions of the enthalpy equation on energy equilibrium.

The boundary condition equation can be written

$$\rho \frac{\partial H}{\partial t} = k \left(\frac{\partial^2 T}{\partial x^2} \right), \quad \text{for } 0 < x < B, t > 0 \quad (6)$$

$$T = f, \quad \text{at } x = 0, t > 0 \quad (7)$$

$$\rho \frac{\partial T}{\partial t} = 0, \quad \text{at } x = B, t > 0 \quad (8)$$

$$T = T_0 \text{ (or } H = H_0), \quad \text{for } t = 0, 0 \leq x \leq B \quad (9)$$

Differential equations for boundary conditions $0 \leq x \leq B$ can be written:

$$\rho \frac{H_i^{n+1} - H_i^n}{\Delta t} = k \frac{T_{i-1}^{n+1} - 2T_i^{n+1} + T_{i+1}^{n+1}}{(\Delta x)^2} \quad (10)$$

Where H = enthalpy, T = Temperature Δt = time difference, $\Delta x = B / M$ where M the number of sections in the region $0 \leq x \leq B$, i = nodal i, n = number of nodes. The boundary conditions for pure PCM material for equation 10 can be written:

$$T = T_m, \quad C_p T_m \leq H \leq (C_p T_m + L) \quad (11)$$

$$T = \frac{H - L}{C_p}, \quad H > (C_p T_m + L) \quad (12)$$

The enthalpy change for PCM material can be drawn as shown in Fig. 5. The PCM material in the form of pure melting material occurs at constant temperature (T_m), whereas in the material a mixture of melting occurs in the range of temperature T_s to T_l . The amount of the enthalpy of fusion is obtained from the measurement of $C_p T$.

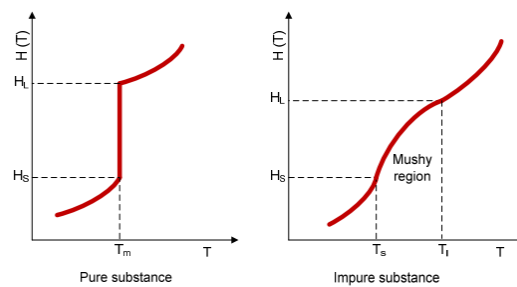


Figure 5. Graph of change of enthalpy of pure PCM material and mixed PCM.

The final form of equation five can be written as:

$$\frac{\rho C_p \Delta x (T_i^{n+1} - T_i^n)}{\Delta t} = \frac{k (T_{i-1}^{n+1} - T_i^{n+1})}{\Delta t} + \frac{k (T_{i+1}^{n+1} - T_i^{n+1})}{\Delta t} \quad (13)$$

$$C_p = \frac{H_i^{n+1} - H_i^n}{T_i^{n+1} - T_i^n} \quad (14)$$

Energy analyzes were performed on buildings without PCM and buildings equipped with PCM. The PCM properties used in this analysis are given in Table 1, whereas the enthalpy change to the temperature of PCM is given in the graph as shown in Figure 6.

Table 1. Phase change material properties.

Thermal conductivity (W/m K)	Specific heat (J/kg K)	Density (kg/m ³)	Melting Temperature (°C)
0.11	1620	998	22-23

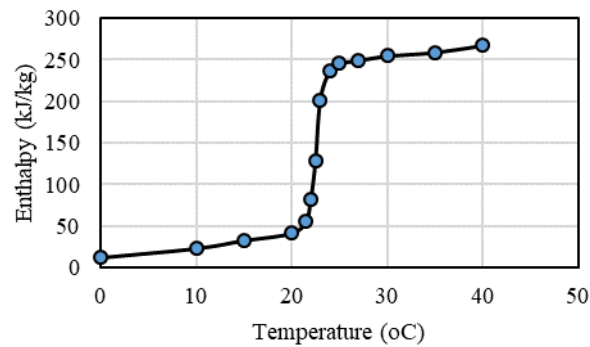


Figure 6. Variation of PCM enthalpy to temperature.

To know the effect of PCM on energy consumption, the variation is done:

- Thermal conductivity (k) PCM, with variations $k = 0.2, 0.3, 0.4$ and $0.5 \text{ kW/m}^2 \text{ } ^\circ\text{C}$.
- Thickness (x) PCM composite, with variations $x = 10 \text{ mm}, 20 \text{ mm}, 30 \text{ mm}$ and 40 mm .
- Room temperature settings, with variations of $20 - 24 \text{ } ^\circ\text{C}$, $24 - 28 \text{ } ^\circ\text{C}$, and $28 - 32 \text{ } ^\circ\text{C}$.

3. Result and discussion

Analysis of energy use in buildings is done with the software Energy Plus. The analysis was performed for buildings located in the city of Banda Aceh, with the coordinates of latitude 5.573 and longitude 95.369, and the intensity of solar radiation and ambient temperature each month are given in Figure 7 and Figure 8

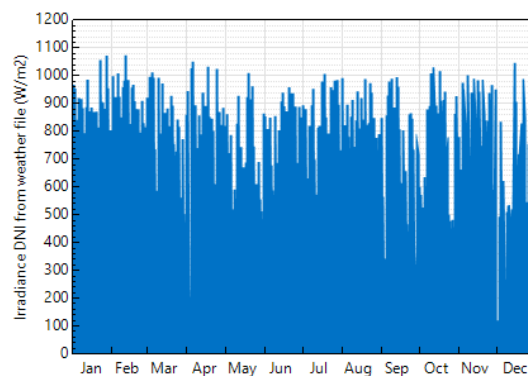


Figure 7. Solar radiation of Banda Aceh City.

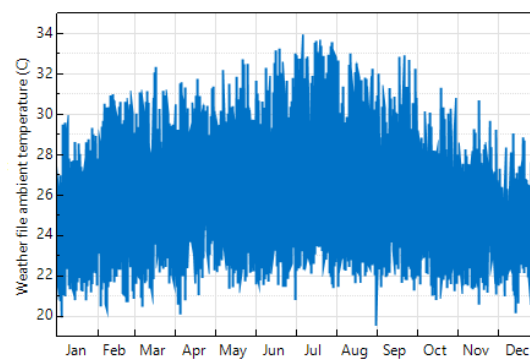


Figure 8. Ambient temperature of Banda Aceh City.

From the solar radiation data obtained the largest solar radiation occurred in January, February, July, and October. While the highest ambient temperature occurred on July, and the lowest occurred in December. Simulation results obtained energy needed to maintain room temperature in the range of 24-28 °C, shown in Figure 9. The largest energy consumption occurs in July, both for buildings without PCM and buildings with PCM. From the figure also shows that the use of PCM will be able to reduce energy demand due to energy storage in PCM composite. This can be seen from the temperature difference in the building wall as shown in Figure 10. The results obtained show the same trend as those given Lie,et. al [17] for analysis of climatic conditions of Singapore cities.

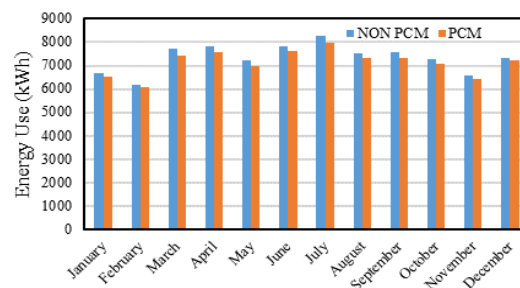


Figure 9. The calculation results for energy usage.

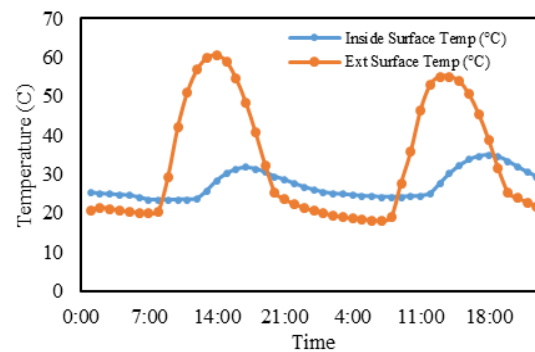


Figure 10. Wall temperature.

The result of the simulation of the effect of PCM thermal conductivity is given in Figure 10. Energy consumption increases with increasing thermal conductivity of PCM, this is due to the increase of the overall heat transfer coefficient of the wall, thereby increasing the rate of heat transfer from outside the wall into the room resulting in the increasing need of cooling energy to maintain room temperature at the desired condition.

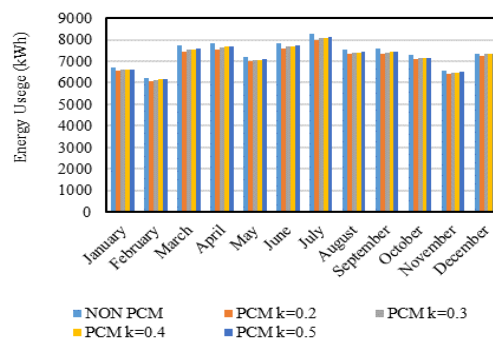


Figure 11. Result of simulation of PCM thermal conductivity effect.

The simulation results of the effect of room temperature on energy consumption are given in Figure 11. In this simulation, The PCM temperature range in walls, ceilings, and floors varies the keeping of all other parameters constant. The temperature ranges chosen for the simulation are 20-24 °C, 24-28 °C, and 28- 32 °C.

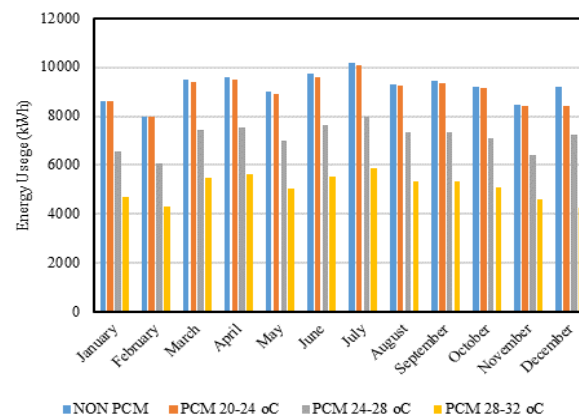


Figure 12. Simulation results of energy consumption on indoor temperature variations.

From the graph can be seen, with increasing temperature in the room, the energy consume to cool the room will decrease, this is because ambient temperature of Banda Aceh city averages around 26 °C, if indoor temperature is in the range of 28-32 °C, small energy requirements for cooling are required to maintain indoor conditions, and this only occurs in hours with maximum solar radiation on the building wall, this is also due to energy storage by PCM building walls.

4. Conclusion

From the results of numerical analysis of the use of PCM on the walls of the building can be concluded that PCM is able to store heat energy from solar radiation, thus reducing energy consumption for cooling the room. Increasing the thermal conductivity of PCM will increase the value of the overall heat transfer coefficient of the wall resulting in increased energy consumption for room cooling. From the simulation results can be concluded the use of PCM on the walls of buildings can reduce energy consumption for cooling the room.

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