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Article

Preliminary Study of Passive Cooling Strategy Using a Combination of PCM and Copper Foam to Increase Thermal Heat Storage in Building Facade

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Abstract: The innovation of phase change material (PCM) for thermal heat storage is one sustainable passive strategy that can be integrated into building designs. This research was conducted to study and evaluate the performance of the existing materials integrated with PCM and to propose a design strategy that would improve the system. This research suggested copper foam as a medium to be integrated with microencapsulated PCM. Applications of these combined materials will benefit the industry by improving indoor environments and by delivering sufficient thermal comfort for residents as in the case study of the existing 1.6 million terrace houses in Malaysia.

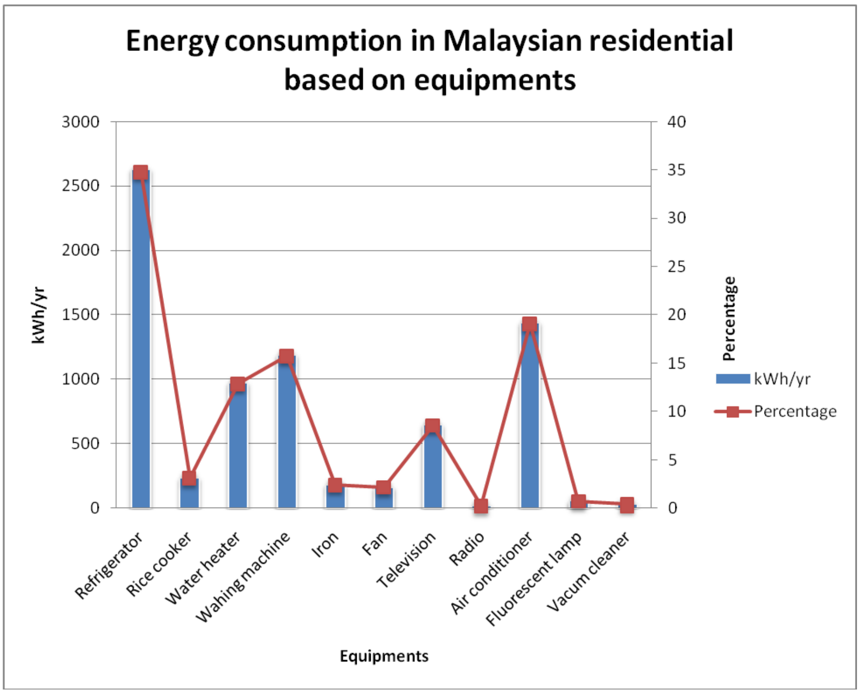
Keywords: phase change material; latent heat storage; thermal comfort; sustainable design technology

1. Introduction

Malaysia experiences a hot, humid climate with temperatures ranging from 22 °C to 33 °C throughout the year. Since it is like summer all year around, cooling is the main issue regarding Malaysian homes. In terms of housing types, most Malaysians who settled in urban areas choose to live in terrace houses. Terrace houses accounted for 44% of the existing housing in urban areas as of 2000 [1]. Today, the total number of terrace houses is over 1.6 million. These are inhabited by more than seven million people. Most of these houses were built using cement or clay bricks with cement render and were shaded by cement or clay roof tiles. Moreover, most of these houses have no insulation material installed, except for a thin layer of reflective film under the roof tiles. As a result, these houses act like a sauna, where most of the building façades are exposed to excessive solar radiations that absorb heat throughout the day. The heat is then conducted to the inner spaces, thereby creating thermal discomfort for the building occupants. To make the situation worse, most of these houses have poor ventilation and air circulation, since openings are only located in the front and rear façades. As a result, the heat inside the house is normally trapped by room partitions and doors that increase the internal temperature.

Research shows that most Malaysian residents open windows during the day and close windows at night. This indicates that most Malaysian terrace house dwellers do not apply night ventilation, and this contributes to the increase in energy consumption for cooling especially at night [1]. When considering thermal discomfort, some may not be concerned, since they have the luxury of an air conditioning unit. In Malaysia, energy use for residences accounted for 19% of the total energy supplies. In fact, a recent study shows that 21% of the total residential energy consumption was used to power air-conditioning units and another 2% was used to power mechanical fans for cooling purposes (Figure 1).

Figure 1. Malaysian average residential energy consumption according to electrical source. Adapted from [2].

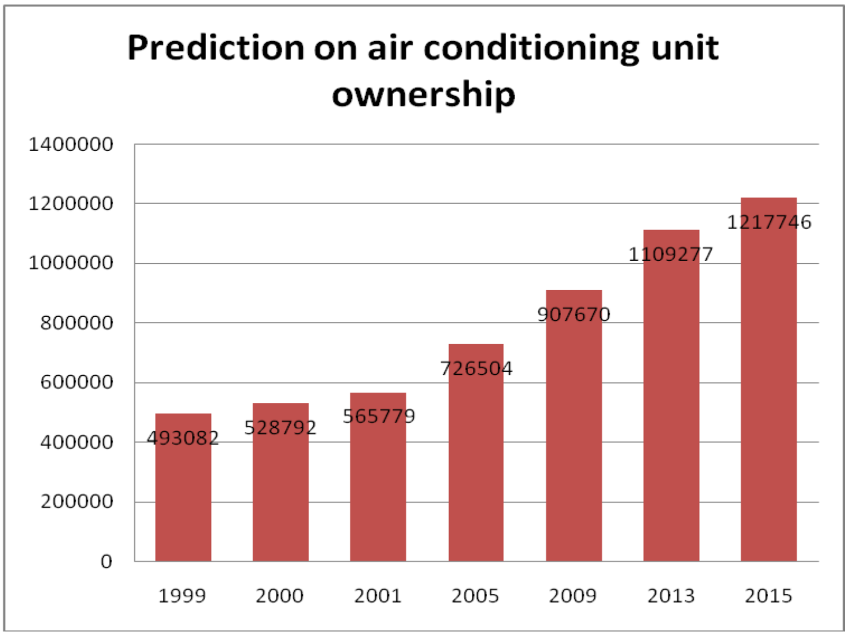


It can be clearly seen that space cooling consumed more than a fifth of the total energy consumption in the residential sector especially for terrace houses. However, this number only estimated that residences were installed with only one air conditioning unit. With an improve of living standard and

GDP, it is common to see some houses installed with more than one air conditioning unit, such as in every bedroom or even in the common spaces such as the living room or television room.

Regarding the residential sector, Malaysians owned 493,082 air conditioning units in 1999 (Figure 2). The number increased by 6.7% in 2000 with a total of 528,792 air conditioning units. In fact, it was predicted to increase dramatically to 907,670 units by 2009, an increase of 42% [3]. It is important to stop this tendency in order to reduce energy consumption in residential building especially in terrace houses.

Figure 2. A prediction of air conditioning unit ownership in Malaysian residences based on collected data from 1999 to 2000. Adapted from [3].



On average, a Malaysian pays at least Ringgit Malaysia 100 per month (that is equal to USD 28) to operate an air-conditioning unit in a typical home. This cost varies depending on the energy consumption by different types of air conditioning units. With the high price of electricity for cooling, many people try to find solutions by applying cheap passive strategies like thermal energy storage (TES). TES technology has been successfully applied throughout the world, with a lot of advantages such as reduced energy consumption and hence costs, improved indoor air quality, reduced pollutant emissions, and increased efficiency and effectiveness of equipment utilization [4].

In Europe, the applications of phase change material (PCM) as latent heat storage in building façades show good potential to be used in passive cooling and heating strategies. Some manufacturers have produced PCM integrated wallboard to be installed in building façades to store ambient outdoor heat during the day, and release it at night to warm the internal spaces when the ambient temperature drops. The end result is a thermal balance created for indoor environments. In a climate like Malaysia's that experience high ambient temperatures during the day and night, the strategy mentioned above cannot work. Instead, the stored heat needs to be released back to the environment when the ambient temperature is cooler. PCM has never been tested in a hot humid climate like Malaysia, and thus the potential benefits remain uncertain, especially for the residential sector.

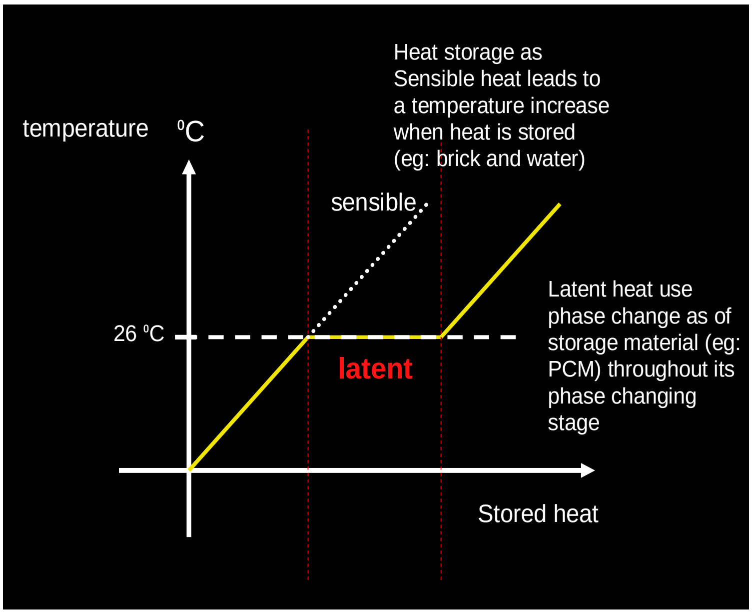
This study investigates the potential of using PCM for thermal heat storage in building façades in hot humid climates, and considers other materials such as copper foam that could be integrated with PCM. This integration will likely cause an increase in heat transfer that will increase heat storage capacity and reduce internal temperature fluctuations compared with other materials that have been used until today.

2. Latent Heat Storage

2.1. Phase Change Material (PCM)

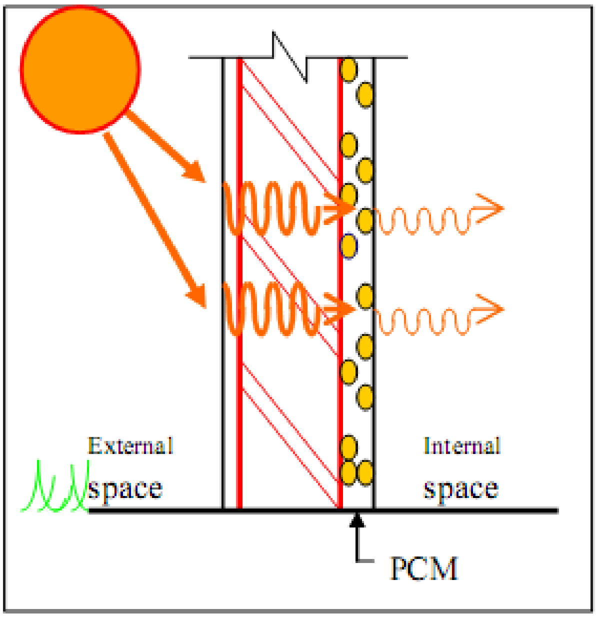
The application of PCM, such as ice, has been used since the late 1800s as a thermal storage mechanism. There are two ways of storing heat: either via sensible heat or latent heat (Figure 3). Heat storage via sensible heat leads to an immediate temperature increase. On the other hand, heat storage as latent heat uses phase change of a storage material to delay the heat transfer.

Figure 3. Heat storage as sensible heat leads to a temperature increase (brick and water). Heat storage as latent heat prevents temperature increase throughout the phase changing state of the storage material (PCM).



Over the years, PCM has been integrated into building façade design since it was discovered as a potential technology to reduce the energy consumption of a building. The main purpose of using PCM is that it can store a large amount of energy within its phase transition. The temperature of PCM is nearly constant during the melting and solidification process. Figure 4 further explains how this process takes place when excessive heat from solar radiation heats up a building façade and transfers the heat through conduction to the building internal space. Typical façades without the installation of PCM will conduct solar radiation and dramatically heat up the internal space. In contrast, building façades installed with PCM will gradually change its phase and store heat throughout the day instead of conducting all heat into the internal space. As a result, PCM can guarantee more stable internal temperatures, with no dramatic fluctuations, thus providing thermal comfort to the dwellers. By installing PCM in the building façade, heat will be stored and only a small amount of heat will be conducted to the internal space if the transition process is complete; when PCM cannot store heat anymore.

Figure 4. Heat transfer in a building façade where solar radiation heats up the building façade and heat is conducted to the building internal space.



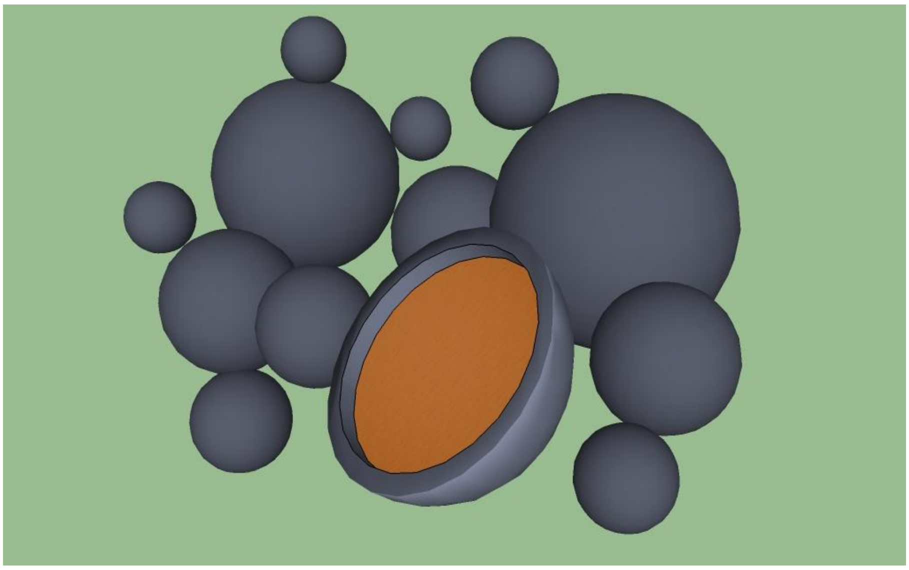
There are four types of PCM available on the market: organic PCM, inorganic PCM, eutectic PCM, and composite PCM. Each type of PCM has different characteristics that cover different melting temperatures. Organic PCM, such as paraffin wax, is the most common PCM used in the construction industry, since paraffin wax is thermally stable and compatible with most building materials. As a result, it tends to be the more popular PCM. Moreover, it has proven to provide better performance and is generally cheaper. For this study, paraffin wax with a melting and solidification temperature of 26 ℃ is used. This was best suited for the temperature tolerance of Malaysian building occupants (between 23.1 ℃ and 28.1 ℃). It is important to choose the right type of PCM because, for a given climate condition and building type, if the melting and solidification temperature of the PCM is too high, the quantity of solar radiation heat that can be stored is reduced. On the other hand, if the temperature is too low, it is difficult to maintain the indoor temperature within the temperature tolerance range if the building façade receives high solar radiation and isolations [6]. An analysis of PCM walls indicated that the optimal diurnal heat storage occurs with a melting temperature of 1 ℃ to 3 ℃ above the average room temperature [6,7].

2.2. Microencapsulated PCM

In the early years of PCM applications, PCM was integrated directly into the building materials, such as mixing granulated paraffin wax with concrete or cement. However, direct integration of PCM without encapsulation can interfere with building structures and change the properties of the medium materials. In fact, leakage could be a major problem over many years [8]. For instance, salt hydrate

PCM could affect steel bars in a building structure, thereby leading to corrosion. A new way to integrate PCM is to keep it in hard shells called microcapsules. An example of microencapsulated PCM is illustrated in Figure 5. This capsule form can be integrated into building materials and structures so that adverse reactions do not occur. It is claimed that the encapsulation process protects the wax in its pure form, meaning the heat storage capacity is permanently guaranteed [9].

Figure 5. A sphere shaped microencapsulated PCM with polymer coating, a size of 2–20 µm, and melting and solidification temperature of 26 ℃.



The conventional method of PCM application involved integrating large PCM granulates into building construction. As a result, the performance of the heat storage capacity of the PCM fell below expectations. This is because PCM has a low thermal conductivity and the large size of the PCM granules slows the heat from reaching the centre core. Moreover, it is difficult for the PCM to complete the phase transition from solid to liquid or *vice versa*. These factors all cause the system to be inefficient.

For this study, it is suggested that microencapsulated PCM with sizes ranging from 2 µm to 20 µm be used. The distribution of the small PCM microcapsules in a wall offers a larger heat exchange surface where the heat transfer rate to charge and discharge the stored heat is raised significantly [8]. Basically, PCM is encapsulated in copper or a hard plastic shell, such as acrylic resin. The resultant materials are well suited for further treatment as they are impervious to the grinding and cutting throughout the construction and renovation processes. Moreover, since the size is very small, it is visibly indestructible [9]. As for its performance, most of microencapsulated PCMs can undergo more than 10,000 phase transition cycles that make the product life span last for more than 30 years. For this study, microencapsulated PCM with copper coating is recommended. In fact, based on a comparative study on the performance of various materials to encapsulate PCM, the results show that PCM with copper coating melts faster than with coatings such as acrylic and aluminium.

2.3. Medium Integrated with PCM

The medium for this system could be defined as materials that could be used to channel or conduct heat to the microencapsulated PCM. There are many materials that have the potential to be integrated with microencapsulated PCM. The most commonly used materials are gypsum and concrete. The relevant differences between these materials are the specific heat capacity of each material as well as the thermal conductivity that will affect the performance of the system. For this study, copper foam is the proposed medium to be integrated with copper microencapsulated PCM. It is known that copper has good conduction for electricity as well as for heat. The copper foam will be produced using Lost Carbonate Sintering (LCS) with controlled porosity. The high porosity of copper foam allows air to pass through it. So it acts as a metal sponge that absorbs heat and stores it. Moreover, for a given size, copper foam relatively has a five to 10 times larger surface area compared to a similar size flat metal plate. As a result, more heat can be conducted and stored in it. Previous study shows the performance of three different metal foams integrated with microencapsulated composite PCM such as copper foam, aluminium foam, and carbon steel foam. For a given specific porosity of different metal foams, it is show that the influence of the effective thermal conductivity on the melting time is higher for the PCM of low thermal conductivity than for PCM of high thermal conductivity [11].

It can be seen that copper foam has the lowest effective melting time compared with the other two metal foams. Also, the copper microencapsulated PCM has the lowest effective melting time compared to the acrylic resin microencapsulated PCM. The ideal conditions for a latent heat storage system are high heat storage capacity and high phase change rate. In order to keep high heat storage capacity, porosity should be near unity, whereas high phase change rate can be obtained by a lower porosity with a decreased amount of PCM [11]. This is why porous metal such as copper foam is better than other mediums, such as gypsum and concrete, to be integrated with microencapsulated PCM in building façades.

The comparison of the physical and thermal performance of different materials that could be integrated with PCM is shown in Table 1. It is clear that copper foam has a better physical and thermal performance than gypsum and concrete. Since the thermal conductivity of copper foam is higher than two other materials, heat could be transferred faster to be stored in the PCM. Moreover, since the specific heat capacity is the lowest, it guarantees that the PCM will complete its phase transition. As a result, the system using a combination of copper foam integrated PCM will be more efficient.

Table 1. Materials integrated with PCM: physical and thermal performances.

Specification	**Copper foam**	**Gypsum**	**Concrete**
Specific heat capacity *Cp*, J/kg K	383	1,090	880
Thermal conductivity, W/m K	350	0.19	3.46
Thermal conductance, m^2/h	0.261	0.17	0.003
Flow resistance, m^2 K/W	0	0.85	0.09

3. Suggested Design Proposal

PCM integrated building façades can store heat during the day and discharge it back to the environment at night, thus decreasing the cooling load of a building. This system provides a significant economic benefit by reducing the use of energy for cooling during expensive peak time. For this study, the system will use a hybrid of passive and active strategies to optimize performance. The system consists of copper foam integrated microencapsulated PCM panels, ventilation holes, and a low energy ventilator to increase ventilation rates. If the house is equipped with renewable power generation systems such as photovoltaic panels or wind turbines, the low energy ventilator is easily powered by these sustainable technologies to make this system green and carbon free.

This experiment proposes to study the heat transfer in the building façades of terrace houses. A comparative study will be made of the façade without copper foam integrated microencapsulated PCM and one with it installed. This experiment also tries to find the time delay or time lag of heat transfer from the external wall to the internal space. Moreover, this experiment will determine whether copper foam and copper coating of the microencapsulated PCM could increase the conduction rate of heat to the PCM and transfer more heat to the PCM itself. However, this experiment will also involve design strategies to manipulate night cooling in order to obtain a lower indoor temperature at night as well as to improve the panel's efficiency. The results from this experiment will be compared with the results obtained based on simulation with TRNSYS. This comparison will help with understanding the performance of the system in both actual and simulated tests.

Finally, the experimental results for the copper foam integrated microencapsulated PCM panel could be used to compare the thermal performance and efficiency of the studied system with other systems available in the market today.

3.1. Case Study

The building model proposed for this research is to represent terrace houses, since this type of house is the most common in Malaysia. Another reason why terrace houses have been chosen is because this architectural style does not complement architecture details of traditional Malaysian residential architectures in terms of planning, design strategies, materials, and the layout that existed for hundreds of years. The traditional Malay house is a timber structure that has tall windows and doors, large roof overhangs, is built on stilts, equipped with permanent ventilation holes on top of the windows, and gaps between the layers of the walls and floors to allow maximum ventilation. The modern terrace house, on the other hand, has a high thermal mass with 150 mm thick walls made of bricks, standard size windows either louvered or glass panel, without permanent ventilation holes on top of the windows and doors, and is built on the ground. Moreover, a terrace house has many internal wall partitions that block air circulation and that increase the internal temperature and humidity. Even though the building wall is thick, it is still not thick enough to block the solar radiation heat from penetrating to the building internal space. Moreover, it is hard to evacuate heat that is stored in the terrace house's façades in the day time compared with the traditional Malay house.

Adapting copper foam integrated PCM panel to the building wall provides the chance to increase thermal capacity of thin building envelope without having thicker building walls like the average 250 mm wall thickness in a typical British Colonial house in Malaysia. Research was performed which measured the thermal properties of two units of identical double storey terrace houses in the state of Johor, Malaysia. It was found that, for the housing area, the maximum outdoor temperature was between 34 °C and 36 °C while the minimum outdoor temperature was between 24 °C and 25 °C. With a daytime ventilation strategy where the windows were open only during the day, the internal temperature dropped to 33 °C (only 1 °C lower than the maximum outdoor temperature). On the other hand, if night ventilation was applied (where the windows were open only at night), the indoor temperature dropped further to 28 °C [1]. This study showed that a terrace house was hot and uncomfortable to live in. If people were given a choice, most will choose to live in a Malay traditional house, which is more comfortable. Unfortunately, to build Malay traditional house in urban areas will not get approval by the Malaysia Uniform Building By Law (UBBL), under the rule of District City Councils, since it was clearly stated that housing made of timber is not allowed to be built in urban areas unless it is highly treated to be safe against fire, which is expensive and not affordable for most people. However, a more comfortable terrace house may be possible by applying copper foam integrated PCM panels in building façades. It is hoped that the internal temperature will be dropped to, and maintained at, 26 °C in order to provide better thermal comfort to the building occupants.

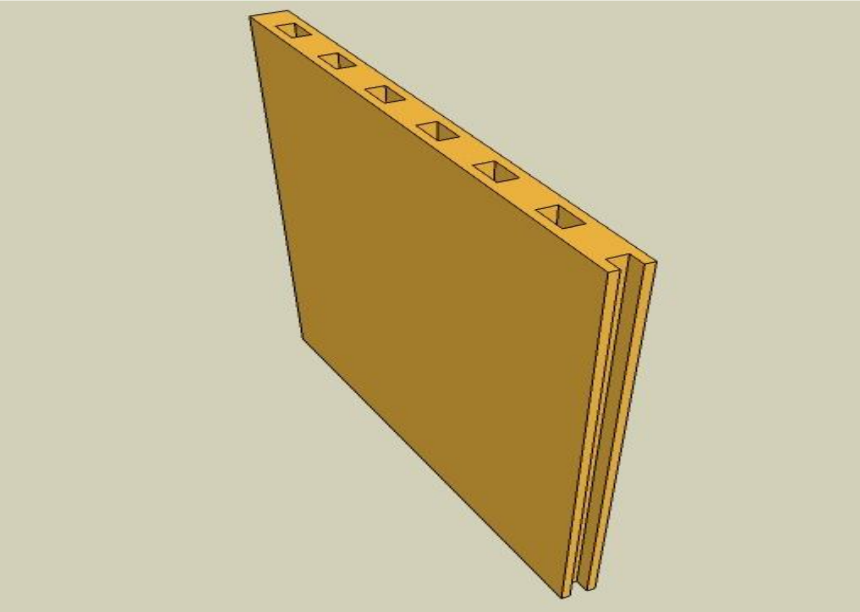
Figure 6. The front façade of a typical terrace house: Two identical typical double storey terrace houses in Kedah, Malaysia.

3.2. Copper Foam Integrated PCM Panel

The most common PCM integrated wallboard panel on the market is gypsum. In four seasons climate, PCM integrated wallboard is installed widely as one passive technology for space heating and cooling strategies. However, for this application, the PCM integrated wallboards are installed on the outer layer of the internal walls. The system works by storing heat during the day and discharging it back to the internal space and the building façade when there is no solar radiation available. This continuous process can provide sufficient cooling and heating. In contrast, this system is not suitable for buildings in Malaysia since the temperature is high during the day and night. For this study, copper foam integrated PCM panel will be developed with a new and improved design to suit climate conditions in Malaysia. Figure 7 shows the sectional perspective of the copper foam integrated coated PCM panel.

What makes this system different from the existing systems? Based on the design proposal, the copper foam will be produced using the *lost carbonate sintering* process also known as LCS. This new technology is different from conventional methods of making metal foams such as melt-gas injection, melt infiltration, powder foaming, and melt foaming. The panel will be produced by mixing metal particles with non-metal particles such as salt crystals and potassium carbonate. This mixture will be packed and sintered by heating it so that the metal particles in the mix are soft enough to adhere. The casted metal foam is then dissolved in water to remove all the non-metal particles and leaving a metal foam panel with a controlled porosity [9]. For this experiment, the size of each panel is 0.25 m × 0.25 m with controlled porosity of 80%. This metal foam is then heated enough for the copper microencapsulated PCM to stick in the pores of the metal foam. For each panel, approximately 0.75 kg of copper coated paraffin wax microencapsulated PCM with a melting and solidification temperature of 26 °C will be integrated.

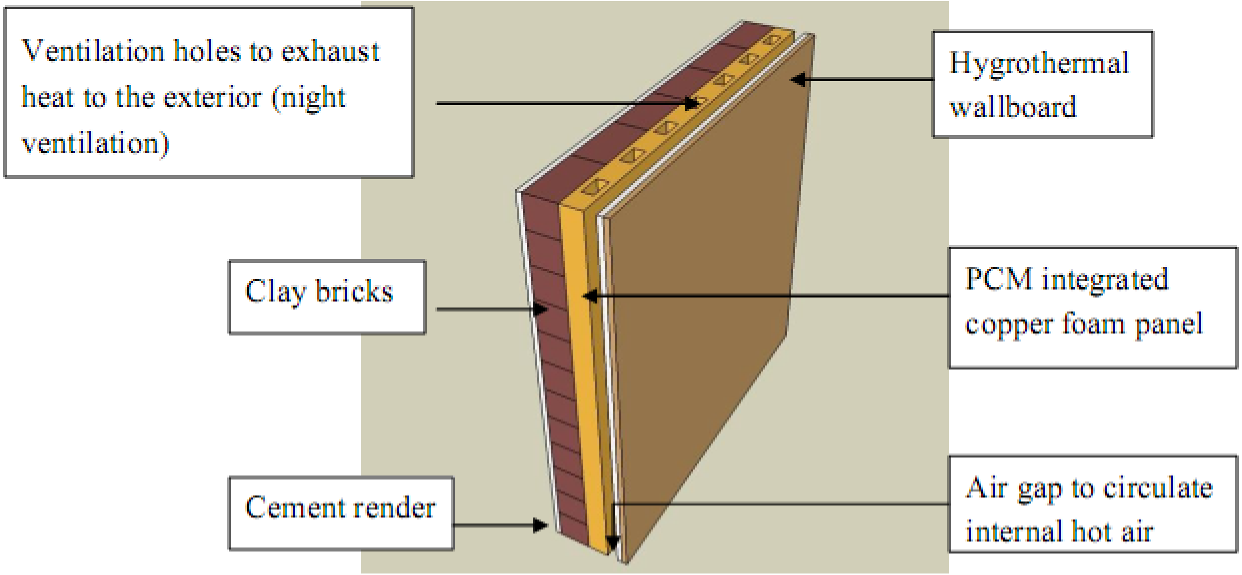
Figure 7. Illustration of a copper foam integrated PCM paneling with ventilation holes.



Unlike the conventional installation of gypsum PCM wallboard in buildings in European countries, this panel will be installed in the internal part of building walls and will be protected by wallboards as the interior finishes. However, since a terrace house only has two façades, at the front and rear, the panels will be fixed only on these two façades. This system will also integrate low energy ventilation fans to circulate internal air for cooling so that a comfortable internal temperature ranging between 23 °C and 28 °C will be achieved throughout the day and night. In every kilogram of microencapsulated PCM, the specific heat capacity is 110 kJ. This shows that for every 1 m^2 of the panels, the specific heat capacity is 330 kJ and its equivalent of 330 W/m·K of energy will be stored.

The integration of the copper foam integrated PCM panel into the building wall is shown in Figure 8. The panel is installed directly onto the surface of the brick wall. This will help to increase the heat transfer via conduction from the heat source to the panel itself. In order to increase its performance, ventilation hole and air gap have been introduced in the design so that the performance of the system could be maximized. These systems are explained further in Subtopic 3.4.

Figure 8. Wall materials of the new system that is installed with copper foam integrated PCM panels.



3.3. Building Model

For this study, a building model measuring 3.0 m in depth, width, and height will be built. This building model that represents the terrace house will be built in a climate chamber with a controlled temperature and humidity to match the climate conditions of Malaysia. Moreover all the materials used are the exact same materials of a typical terrace house. However, for this building model, only one side of the wall will be installed with copper foam integrated panels whereas the other three walls will be installed with insulation material. This will be done since terrace houses are connected and the façades installed with insulation materials will be considered as internal partitions of the house. It is because these areas do not receive any solar radiation. Figure 9 illustrates how the copper foam integrated PCM panels will be installed into the internal wall. Then, these panels will be covered with wallboards as wall finishes. The green colored material inside the other side of the wall is the insulation material to act as a partition wall. These insulation materials will be installed into the other three walls. In the actual situation, these walls are connected to the other house units to separate the terrace houses. Figure 10, on the other hand, shows how the internal walls look after the wallboards cover the copper foam integrated PCM panels as well as the insulation materials.

3.4. Ventilation

This system will use two ventilation strategies that will run separately from one another. Figure 9 in Subtopic 3.2 shows ventilation holes in the copper foam integrated PCM panel as well as an air gap between the copper foam integrated PCM panels and the outer layer of the internal wallboard.

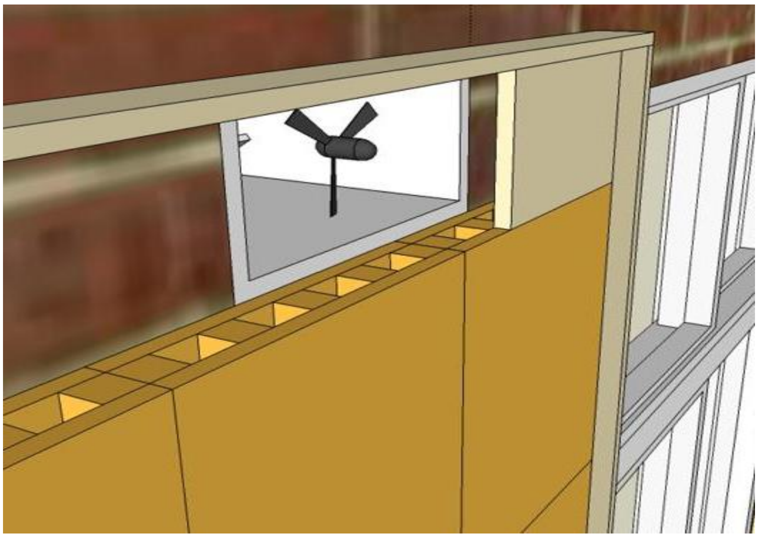
Figure 9. The application of copper foam integrated PCM panels onto a building façade. The green colored wall shows the insulation material to imitate wall partitions that do not receive any solar radiation.

Figure 10. Building model to be built and tested in the climate chamber. Wallboards cover the copper foam integrated PCM panels as well as the insulation materials.

The first ventilation strategy is to circulate hot air trapped in the top part of the internal space into the air gap between the copper foam integrated PCM panels and the wallboard. There will be a low energy ventilation fan to suck the hot air into the top ventilation openings of the internal wallboard. By doing this, heat from the air will be transferred to the copper foam integrated PCM panels that will reduce the air temperature. Then, this cooler air will be exhausted back to the internal space through ventilation openings located at the bottom part of the internal wallboard to provide a more comfortable air temperature for the building occupants.

The second ventilation strategy is to manipulate night cooling from low ambient temperature. Some studies show that in order to utilize night cooling naturally, the outdoor temperature must be 18 °C or lower. Since the usual outdoor temperature at night in Malaysia, especially in urban areas, is between 24 °C and 25 °C, force ventilation is necessary to maximize cooling with air circulation. Moreover, based on recent study, the mean outdoor air velocity in terrace house residential areas is around 0.4 m/s [1]. Since the outdoor air velocity is low, forced ventilation is needed in order to increase the system performance. Air will be circulated into the ventilation openings located on the bottom part of the external wall into the ventilation holes of the copper foam integrated PCM panel and out through the ventilation holes and openings located in the top part of the external wall. It is known that at night, when the ambient temperature is low, the PCM inside the panels will start discharging heat. The expectation is that heat stored during the day will be discharged back into the environment that will reduce the temperature of the copper foam integrated PCM panels rapidly, and the PCM will reverse the phase transition from liquid back to a solid ready to store heat in the next day. The installation of a low energy ventilation fan onto the system is shown in Figure 11. This fan can be operated passively by using energy generated by solar panels or a small-scale wind turbine.

Figure 11. Low energy fan on the top part of the internal wall to exhaust heat that has been trapped in the copper foam integrated PCM panels.



4. Findings

Based on this study, the first enhancement for a PCM system in a warm climate is to use small size encapsulated PCM. Microencapsulated PCM performs better than that of bigger sizes. With larger surface area, heat is easily transferred to the centre core of the microencapsulated PCM that makes the PCM fully transformed.

The second step in enhancing the performance of the system is force ventilation. Unlike in European countries where the daily temperature difference is greater during the day and night, in Malaysia it is found that force ventilation is needed for night cooling. This is because, in European countries, the heat stored during the day helps to heat up the building structures at night, when the ambient temperature drops, and provides comfort to the building occupants. In contrast, ambient temperature at night in Malaysia is high and cooling is needed to provide comfort to occupants.

Therefore, force ventilation is added to the system to discharge heat that has been stored in the PCM out to the environment.

Thirdly, to enhance the ventilated release of heat, a panel-type installation is better than direct integration of PCM into the building structure. Moreover, in terms of house renovation, this type of panel is easily dismantled and reinstalled onto a new wall. Concerning sustainability of materials, this panel is predicted to perform at its best for more than 30 years. The panels can also be recycled to serve other purposes.

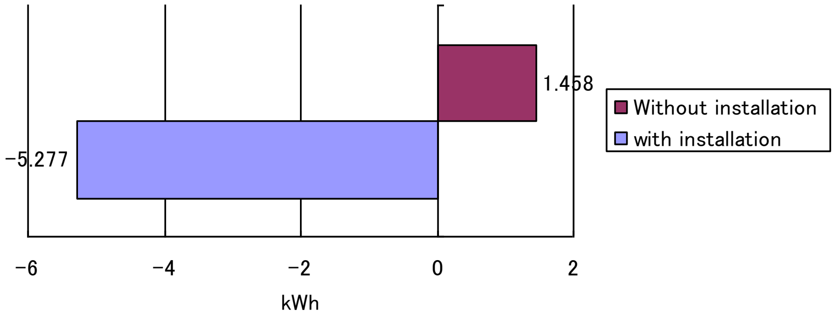
Finally, for a mathematical explanation of the performance of the proposed system, the cooling load of the building model has been calculated as follows:

$$\text{Cooling load, } Qc = [Qs - (Qf + Qv)] \text{ kWh} \qquad (1)$$

Data for heat gain on the building façade has been generated from Malaysian climate data using a simulation tool called Ecotact. Without the installation of the copper foam integrated microencapsulated PCM panels, heat gain of the building model was 1.638 kWh and heat loss was 0.180 kWh. For this calculation, heat losses from roof and wall surfaces are omitted since these two façades receive direct solar radiation during the day and the heat stored and conducted from the external to the internal spaces was more than the possible heat losses. Also, heat gains from electrical equipment and building occupants were not calculated since the study focuses on heat transfer throughout the building façades. As a result, the cooling load for this building model was 1.458 kWh. It means that 1.458 kWh of heat energy need to be removed from this building model. If one of the wall façades is installed with the proposed PCM panels with a total area of 8.56 m², the cooling load will drop significantly to –5.277 kWh. These findings are better explained in Figure 12.

Even though the cooling load is −5.277 kWh, this does not means that the house is cool enough to provide thermal comfort to the building occupants. This is because this amount does not include heat gain from electrical equipments and building occupants. By adding heat gain by various sources, this amount (−5.277 kWh) is predicted to be near 0 kWh, which is good enough to provide thermal comfort to the building occupants. In this case, no mechanical means such as air conditioning unit, portable chiller or fan are needed in order to provide thermal comfort to the building occupants. This calculation has proven to this study that the installation of copper foam integrated PCM panels could provide more comfortable indoor environment to the building occupants thus saving energy for cooling purposes that will reduce the CO_2 emissions to the environment.

Figure 12. Cooling load for walls with or without the installation of copper foam integrated PCM panels.



5. Conclusions

Thermal energy storage is known as one of the best solutions for tackling cooling and heating issues as well as one of the most environmentally friendly technologies. This study shows the potential of applying a TES system in terrace houses in a hot humid climate like Malaysia to suit the temperature tolerance of residents. The preliminary results show that the system dramatically reduces the cooling load. For future research, the panel system will be tested on a building model in a climate chamber and on a simulation using TRNSYS in order to compare the performances of example and theoretical models. Other materials such as hygrothermal wallboards will be integrated and tested for thermal comfort provided to the building occupants. It is hopped that hygrothermal wallboards may further enhance the system by reducing the high relative humidity levels as well as the temperature for the indoor environment in Malaysian terrace houses.

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References

1. Kubota, T.; Ahmad, S. The effects of night ventilation technique on indoor thermal environment for residential buildings in hot-humid climate of Malaysia. *Energ. Bldg.* **2009**, *41*, 1-11.
2. Ar Chan, S.A. Energy Efficiency: Designing Low Energy Buildings Using Energy 10, Pertubuhan Arkitek Malaysia. In *Proceedings of the 7th CPD Seminar*, Kuala Lumpur, Malaysia, 7 August 2004; pp. 1-18.
3. Saidur, R.; Masjuki, H.H.; Jamaluddin, M.Y.; Ahmed, A. Energy and associate greenhouse gas emissions from household appliances in Malaysia. *Energ. Policy* **2007**, *35*, 1648-1657.
4. Dincer, I.; Rosen, M.A. *Thermal Energy Storage Systems and Applications*; John Wiley & Sons: Hoboken, NJ, USA, 2002; p. 580.
5. Zhang, Y.; Zhou, G.; Lin, K.; Zhang, Q.; Di, H. Application of latent heat thermal energy storage in buildings: State-of-the-art and outlook. *Build. Environ.* **2007**, *42*, 2197-2209.
6. Peippo, K.; Kauranen, P.; Lund, P.D. Multi component PCM wall optimized for passive solar heating. *Energ. Bldg.* **1991**, *17*, 257-270.
7. Schossig, P.; Henning, H.M.; Gschwander, S.; Haussmann, T. Micro-encapsulated phase change materials integrated onto building materials. *Sol. Energy Mater. Sol. Cells* **2005**, *89*, 297-306.
8. Schmidt, M. *Phase Change Materials-Latent Heat Storage for Indoor Climate Control: Innovative Raw Materials for the Construction Chemical Industry*; BASF (Badische Anilin und Soda-Fabrik): Ludwigshafen, Germany, 2008; pp. 1-32.
9. Hrvey, K. *How to Get More from Less*; Research Intelligence, University of Liverpool: Liverpool, UK, May 2006; Available online: http://www.liv.ac.uk/researchintelligence/issue28/pdf/ri28.pdf (accessed on 23 July 2010).
10. Shiina, Y.; Inagaki, T. Study on efficiency of effective thermal conductivities on melting characteristic of latent heat storage capsules. *Int. J. Heat Mass Transfer* **2005**, *48*, 373-383.

11. Abhat, A. Low temperature latent heat thermal storage: Heat storage materials. *Sol. Energy* **1983**, *30*, 313-332.
12. Feldman, D.; Shapiro, M.M.; Banu, D. Organic phase-change materials for thermal energy storage. *Sol. Energy Mater.* **1986**, *13*, 1-10.
13. Ahmad, M.; Bontemps, A.; Sallee, H.; Quenard, D. Experimental investigation and computer simulation of thermal wallboards containing a phase change material. *Energ. Bldg.* **2006**, *38*, 357-366.
14. Voss, K.; Herkel, S.; Pafferott, J.; LÖhrnet, G.; Wagner, A. Energy efficient office buildings with passive cooling results and experiences from a research and demonstration program. *Sol. Energy* **2007**, *81*, 424-434.
15. Voelker, C.; Kornadt, O.; Ostry, M. Temperature reduction due to the application of phase change materials. *Energ. Bldg.* **2008**, *40*, 937-944.
16. Castellon, C.; Medrano, M.; Roca, J.; Nogués, M.; Castell, A.; Cabeza, L.F. Microencapsulated phase change material (PCM) for building applications. *Energ. Bldg.* **2007**, *39*, 113-119.
17. Dyball, D.; Ip, K.; Miller, A. Development of Phase Change Wall-lining to Enhance Thermal Storage of Buildings. In *Proceeding of The 2005 World Sustainable Building Conference,* Tokyo, Japan, 27–28 September 2005; pp. 27-29.
18. Weinlader, H.; Beck, A.; Fricke, J. PCM-façade-panel for day lighting and room heating. *Sol. Energy* **2005**, *78*, 177-186.
19. Salyer, I.O.; Sircar, A.K.; Chartoff, R.P.; Miller, D.E. Advanced Phase-Change Materials for Passive Solar Storage Applications. In *Proceedings of the 20th Intersociety Energy Conversion Engineering Conference*, Warrendale, PA, USA, 18–23 August 1985; pp. 699-709.
20. Tyagi, V.V.; Buddhi, D. PCM thermal storage in buildings: A state of art. *Renew. Sustain. Energy Rev.* **2007**, *11*, 1146-1166.
21. Zhao, X.; Liu, S.; Riffat, S.B. Comparative study of heat and mass exchanging materials for indirect evaporative cooling systems. *Bldg. Environ.* **2008**, *43*, 1902-1911.
22. Khudhair, A.; Farid, M. A review on energy conservation in building applications with thermal storage by latent heat using phase change materials. *Energ. Conv. Manage.* **2004**, *45*, 263-275.
23. El-Hadek, M.A.; Kaytbay, S. Mechanical and physical characterization of copper foam. *Int. J. Mech. Mater. Des*. **2008**, *4*, 63-69.
24. Zalba, B.; Marin, J.M.; Cabeza, L.F.; Mehling H. Free-cooling of buildings with phase change materials. *Int. J. Refrig*. **2004**, *27*, 839-849.
25. Lin, K.P.; Zhang, Y.P.; Jiang, Y. Simulation and Designing of PCM Wallboard Rooms Combined with Night Ventilation. In *Proceedings of the International Conference on Energy and Environment*, Shanghai, China, 22–24 May 2003; pp. 1103-1108.
26. Ip, K.; Miller, A.; Corner, T.; Dyball, D.L. *Smart & Sustainable Built Environment: Development of Phase Change Thermal Storage Wall Coverings in Buildings*; Blackwell Publishing: Oxford, UK, 2005; pp. 95-102.
27. Neeper, D.A. Thermal dynamics of wallboard with latent heat storage. *Sol. Energy* **2000**, *68*, 393-403.

28. Silva, N.; Aguiar, J.B.; Braganca, L.M.; Freire, T.; Cardoso, I. Properties of Gypsum-pcm Based Mortars for Interior Plastering of Construction Systems. In *Proceedings of Materials 2007-13 Conference of Sociedade Portuguesa de Materials/IV International Material Symposium*, *Part II*, Porto, Portugal, 1–4 April 2007; p. 702.
29. Hawlader, M.N.A.; Uddin, M.S.; Khin, M.M. Microencapsulated PCM thermal-energy storage system. *Appl. Energ.* **2003**, *74*, 195-202.
30. Mesalhy, O.; Lafdi, K.; Elgafy, A.; Bowman, K. Numerical study for enhancing the thermal conductivity of phase change material (PCM) storage using high thermal conductivity porous matrix. *Energ. Conv. Manage.* **2005**, *46*, 847-867.
31. Beckerman, C.; Viskanta, R. Natural convection solid/liquid phase change in porous medium. *Int. J. Heat Mass Transfer* **1988**, *31*, 35-46.
32. Akgün, M.; Aydin, O.; Kaygusuz, K. Experimental study on melting/solidification characteristics of a paraffin as PCM. *Energ. Conv. Manage.* **2007**, *48*, 669-678.
33. Bhattacharya, V.; Calmidi, V.; Mahajan, R. Thermophysical properties of high porosity metal foam. *Int. J. Heat Mass Transfer* **2002**, *45*, 1017-1031.
34. Zain, Z.M; Taib, M.N.; Mohd, S.B.S. Hot and humid climate: Prospect for thermal comfort in residential building. *Desalination* **2007**, *209*, 261-268.
35. Franger, P.O. Calculation of thermal comfort: introduction of basic comfort equation. *ASHRAE Trans.* **1967**, *73*, 4.
36. Ulgen, K. Experimental and theoretical investigation of effects of wall’s thermophysical properties on time lag and decrement factor. *Energ. Bldg.* **2002**, *34*, 273-278.