PHASE CHANGE MATERIALS FOR AUTONOMOUS ENERGY STORAGE IN BUILDINGS

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ABSTRACT

This research summarizes the findings from a simulation study that explores the potential of using phase change materials (PCMs) when integrated into envelope system of residential buildings. A typical residential building with PCM-embedded layer is analyzed using a whole-building simulation tool "TRNSYS" under two climates of Oman. Although not significant, the simulation study shows that PCM can reduce energy consumption of buildings. The PCM is found to autonomously store and release thermal energy under desirable environmental conditions. The set of simulation runs are found helpful to explore the potential of PCM and the results can be used by architects and engineers to carefully propose PCM in their energy-efficient building designs. It was concluded that the optimal melting temperature of PCM is 1°C above the cooling setpoint in hot-humid climate but found 2-3°C above or below the setpoint in the warm tropical climate. A tight melting temperature range for PCM was favored. Overall, the PCM poorly performed (i.e., being less than 2% savings in annual cooling load) in a continuously operated dwelling due to the lack of passive means to discharge the absorbed heat. Future research is found crucial to better understand the dynamic thermal behavior of PCM under hot climates. In particular, it will be useful to explore its performance when coupled with natural ventilation.

INTRODUCTION

Worldwide, buildings are the major consumer of energy. In developing countries, the high energy consumption in buildings is mainly attributed to the lack of local energy standards and energy-efficiency programs. In the latest report released by the Authority for electricity regulation (AER) of Oman, residential and commercial buildings consumed between 60 to 70% in 2012 (Authority for Electricity Regulation-Oman, 2013). The bulk of this energy is primarily used by air conditioning systems. This statement has recently been supported by a short term monitoring of energy use in residential buildings, which indicated that air conditioning alone is responsible for 70% of energy consumption in Oman (Japan International Cooperation Agency and Tokyo Electric Power Generation, 2013). The AER annual report has also indicated an increase of 31% and 63% in energy intensity for residential and commercial sector between year 2005 and 2012 (Authority for Electricity Regulation-Oman, 2013). The increase in energy intensity is substantial and is considered unsustainable on the long run. In order to alleviate this major dilemma, the AER has suggested implementing series measures such as introducing Cost-Reflective Tariffs and promoting energy efficiency measures.

In addition to the energy consumption, peak electrical load is another important factor. Due to the seasonal nature of electrical load, the peak electrical demand in summer is few times higher than that in other seasons. This has signified in the last few years due to the construction boom in Oman. Between 2005 and 2010, the residential buildings alone have doubled which necessitates extra electrical capacity (Authority for Electricity Regulation-Oman, 2012). In order to meet the increased electrical demand, continuous efforts are made to secure additional electrical capacity either by building new power stations or renting extra power capacity. Although this expensive strategy has shown to temporarily solve the problem, it is not sufficient to meet the 10% yearly increase of electrical demand as has been continuously reported by AER. Since energy is generated, transmitted and finally distributed to the end users, it is perhaps prudent to solve the energy crises at the demand side by promoting energy efficiency measures. Implementing proper energy efficiency measures could potentially improve the energy and thermal performance of buildings at marginal capital cost, yet operated at optimal running cost. Many design strategies are, however, available to improve the energy efficiency of buildings. Examples include incorporating new and advanced envelope designs, improving the efficiency of mechanical and electrical systems, and adopting appropriate control strategies. Despite the general awareness about the importance and relevance of reducing energy consumption in buildings, studies on energy-efficient buildings in developing countries such as Oman are still rare. Al-Hinai, for example, has investigated various passive design concepts to reduce the heat gain through the roof of a single zone room (Al-Hinai, 1992). The passive design strategies include the addition of insulation, shading, air-cooling of the roof, and roof pond. His analysis revealed that the combination of a water diode roof pond and insulated brick wall construction could potentially reduce the heat gain by more than 90%, when compared to a room with un-insulated roof and single-leaf concrete block walls. A scoping study for residential energy use in Oman has recently been completed (Sweetnam, 2014). The study showed that energy can be reduced by 4-7.5% if a current poor envelope system is upgraded to a slightly better energy-efficient envelope system. A recent move in promoting eco-friendly houses was initiated by the research council (TRC) of Oman in 2011. TRC has organized a national competition involving several higher institutions in Oman (Oman Ecohouse design competition, 2014). The project has significantly contributed to raise awareness about energy efficiency and renewable energy systems in buildings. In all eco-friendly houses, energy efficiency measures are proven to be viable design strategies for paving the way for future self-sustained buildings.

For skin-load dominant buildings such as residential buildings, envelope systems become an attractive candidate to reduce the energy consumption and consequently improve the building performance. For this particular building typology, energy use is characterized by heat loss or gain through exterior envelope. Since the system is exposed to outside environment, it is imperative to consider the thermal characteristics of building envelope. Thermal characteristics include the heat transmission, thermal energy storage, solar heat gain and air infiltration (Fazio, Athienitis, Marsh, & Rao, 1997). An important and exciting element that influences the dynamic behavior of buildings is the thermal energy storage. Thermal energy storage (TES) or thermal mass is a property of materials that describes its ability to absorb, store and release heat depending on the surrounding environmental conditions. A dynamic thermal mass such as phase change materials (PCMs) has been considered as a promising technology to alleviate the inherited climatic deficiency of modern buildings. The apparent advantage of using PCMs lies on the amount of latent heat stored within a small volume of PCM layer compared to a sensible heat storage material such as concrete. As a result, the use of PCMs has recently attracted great attentions for improving thermal and energy performance of buildings (Arkar, Vidrih, & Medved, 2007; Cabeza et al., 2007; Castell, Martorell, Medrano, Pérez, & Cabeza, 2010; Koschenz & Lehmann, 2004; Zalba, Marín, Cabeza, & Mehling, 2004; Zhang, Lin, Yang, Di, & Jiang, 2006).

SIMULATION OF PCM-ENHANCED ENVELOPE SYSTEMS

Unlike experimental field studies, computational modeling is inexpensive yet an effective tool for analyzing, optimizing and fine tuning designs of PCMs in buildings. The literature shows that simulation tools have been widely used to evaluate the thermal performance of PCMs. The US National Renewable Energy Laboratory (NREL) research team has used EnergyPlus to simulate the PCM integrations into different envelope systems using a typical house under Phoenix, AZ weather file (Tabares-Velasco, Christensen, & Bianchi, 2012). For the best PCM application in the wall, a maximum reduction of around 8% in peak cooling was achieved in the month of May with only 4% peak cooling reduction in July. A simulation study using EnergyPlus has been conducted for office space under the climate of Seoul, Korea (Seong & Lim, 2013). Four PCM layers with different melting temperatures integrated into insulated lightweight wall has been studied. With all PCM types, annual heating loads have marginally increased but peak loads has decreased by 3.2% for PCM with 21°C melting temperature. The maximum reduction of 1.2% in annual cooling load and a maximum reduction of 1.3% in peak cooling load were achieved. The PCMs with melting temperature close to the heating and cooling setpoints (T_{clg}=26°C, T_{htg}=22°C) are showing the highest potential. The study further uses the natural ventilation to discharge the absorbed heat. On average for all PCM layers, a reduction of 9% and 10.5% are achieved for annual cooling and peak cooling load, respectively. However, a 7.5% reduction in annual cooling load and a reduction of 10.2% in peak cooling load are solely due to natural ventilation. Another simulation study using EnergyPlus was performed for a residential flat under a tropical climate of Hong Kong (Chan, 2011). The simulation study has indicated a reduction of only 2.9% in annual cooling energy. The study concluded that the PCM installation in this climate is not feasible due to the long payback period.

Other proprietary simulation packages have also been used to evaluate energy savings potential of PCM in buildings. At the University of Dayton, Kissock et. al. (Kelly Kissock, Michael Hannig, Whitney, & Drake, 1998) built a testing facility solely to validate a PCM numerical model. Kissock used this validated model to study the impact of PCM integration into concrete sandwiched walls (Kissock, 2000). The peak and annual cooling loads were reduced by 19% and 13%, respectively. When PCM is discharged using cold air via natural ventilation, the annual cooling load could be reduced by as much as 17%; a 4% enhancement. A simulation study using RADCOOL found that a PCM integrated into wallboard can reduce the peak cooling load by 28% in California climate for a typical office building(Stetiu & Feustel, 1998). The claimed savings can be facilitated when PCM is coupled with mechanical night ventilation. In another simulation study for a coastal climate of California, Lee has used a validated computer model to evaluate the potential of PCM (Lee, 2013). The study concluded that the average reduction in peak-heat transfer rate of all four walls could reach 12%. A simulation study using HEATING 8 has been conducted to evaluate the PCM performance for two US climates: Phoenix, AZ and Baltimore, MD (Childs & Stovall, 2012). The study has investigated many PCM design configurations in a base residential wall case and various thermal properties for four wall orientations individually. The focus of the study was to evaluate the potential in reducing the cooling energy. The study found that when PCM placed to the interior side achieves slightly better performance but is sensitive to the zonal thermostat set-point. When PCM is blended with full insulation thickness, the performance is less sensitive. For PCM full thickness, the reduction in wall-related cooling electricity ranges from 6-10% and 35-62% for Phoenix and Baltimore respectively. For both climates, west and south orientations are the best for PCM integration. For Phoenix, the optimal melting temperature range is about 2°C and 1°C above cooling set-point (i.e., 25°C) for North and East walls and about 1°C above cooling set-point for South and West. For Baltimore climate, the optimal midpoint temperature is always the cooling set-point temperature.

Athienitis (Athienitis, Liu, Hawes, Banu, & Feldman, 1997) has validated a numerical model for evaluating gypsum board soaked in PCM using a testing facility built in Montreal, Canada. The savings in total heating load was predicted to be 15% under the cold climatic condition of Montreal. Utilizing a self-developed computer model, a small room was modeled using Algeria weather file (Diaconu & Cruceru, 2010). The study found that a maximum reduction in annual cooling energy and peak cooling load are 1% achieved with 24.5°C melting temperature and 24% achieved with 33.2°C melting temperature, respectively. In addition, a maximum reduction of 12.8% in annual heating energy and a 35.4% reduction in peak heating load are achieved using PCM with 19.8°C and 19°C melting temperature, respectively.

The overall goal of this paper is to explore the potential of embedding phase change materials as a passive energy storage technology into building envelope under hot climate environment. In order to accomplish this task, a computational approach using TRNSYS, a whole-building simulation program, has been utilized (Bradley & Kummert, 2005).

METHODOLOGY

Simulation Environment

This study utilizes TRNSYS for modeling PCM embedded in wall systems. TRNSYS is a modular program where components "TYPES" are linked together in which output of one type can be an input to another in the model. TRNSYS uses a multi-zone Type-56 to simulate several zones in a building. This type uses transfer function method (TFM) to approximate the heat transfer mechanism across building envelope. However, TFM can't handle the latent heat evolution observed in PCM walls but TRNSYS provides flexibility to integrate external types using the concept of boundary temperature in Type-56. Using this capability, a PCM-enhanced wall can externally be modeled and consequently provide the surface temperature as a boundary condition to Type 56. Utilizing this coupling approach, both types exchange intermediate values in iterative process until convergence is achieved during a time step.

Development of Latent Heat Storage Wall Type "Type-285" in TRNSYS

Type-285 is developed using FORTRAN programming language and compiled for use in TRNSYS. This module uses the boundary temperature concept via a massless dummy layer with a very small resistance in Type-56. **Figure 1** illustrates the concept of interaction between the developed type and other components in simulation studio of TRNSYS. The wall's thermo-physical properties are provided through an external text file.

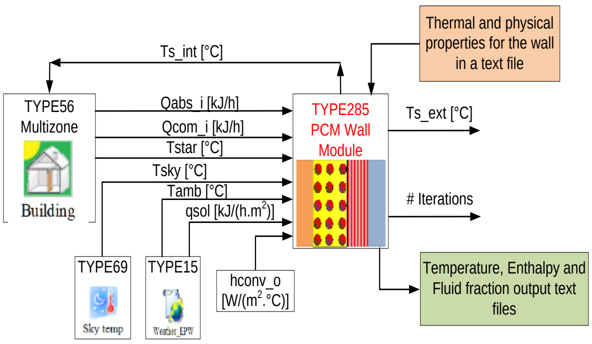

Figure 1 Configuration of Type-285 within TRNSYS simulation studio

A linearized enthalpy method proposed by Swaminathan and Voller (Swaminathan & Voller, 1993) is adopted for modeling PCM. The developed numerical model is based on a one-dimensional heat transfer equation. A fully implicit time stepping scheme is utilized and the spatial discretization is based on the finite volume method. The hysteresis and sub-cooling of PCMs are disregarded in this model (Ramprasad, Edwin S., & Daniel E., 2013; Shukla, Fallahi, & Kosny, 2012). The mathematical model, numerical discretization, and the calculation procedure and validation have been described and analyzed (Al-Saadi & Zhai, 2015). The developed type shows a root mean squared error (RMSE) of less than 0.1°C when temperature prediction across the PCM layer is compared to the experimental data which is within the uncertainty range of the experimental data acquisition equipment. Hence, the type can be reliably used for modeling PCM-enhanced walls.

Housing model in TRNSYS

The house is modeled assuming a single storey, detached house. As a simplification, the house is modeled with only one thermal zone with its envelope systems defined as shown in **Figure 2**. The physical and thermal characteristics as well as the architectural design of a typical residential building are defined as shown in **Table 1**. Other data are assumed to be typical based on simulation practice in other regional countries that are similar in cultural context to Oman (Al-Saadi S. & Budaiwi, 2007).

TRNSYS can be used to model HVAC systems in a building at two modeling levels: energy rate control and temperature level control (TRANSSOLAR Energietechnik GmbH, 2007). In this work, the energy rate control modeling approach is adopted to evaluate the impact of PCM on the annual cooling loads at zone level. This approach assumes simple HVAC system with an ideal control of thermal zones (TRANSSOLAR Energietechnik GmbH, 2007). The method is quick, simple and more appropriate for studies that are aimed at zone level evaluation and therefore deemed to be satisfactory for this work. For this analysis, two major cities are selected; Muscat (the capital), and Salalah in south of Oman as shown in **Figure 3**.

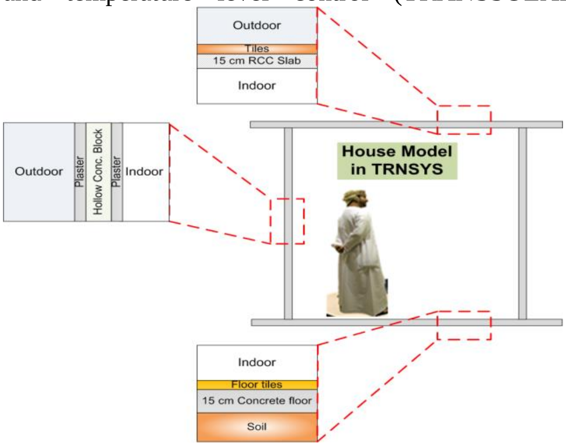

Figure 2 Housing Model in TRNSYS simulation

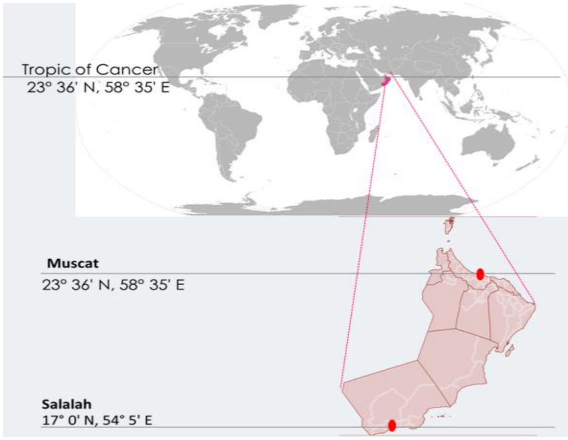

Figure 3 Geographic location of the simulated cities

Table 1 Characteristics of Architectural System for a Typical Single-Family Residential Building in Oman

Characteristics	Description of the Base Case
Location	Muscat: warm in winter, hot-humid climate in summer Salalah: warm in winter, tropical climate in summer
Orientation	Front Elevation facing North
Plan Shape	Rectangular
Number of floor	One floor
Floor to Floor Height	3.5 m
Floor Area	300 m^2
Floor Dimension	15 x 20 m
Window Area	15% of the gross wall area, Uniformly Distributed
Type of Glass	4 mm Single Green Tinted Glazing
Solar Absorbance	0.70 for external walls (medium color), 0.70 for the roof (medium color)
Exterior Walls	15mm cement plaster + 200 mm CMU Hollow Block + 15 mm cement plaster, (U-Value= 2.6 $W/m^2.k$)
Roof	Tiles + 150 mm Reinforced Concrete Slab + 15 mm Cement Plaster, (U-Value= 1.62 $W/m^2.k$)
Floor	Tiles+ 150 mm slab on grade
Occupancy Density	6 People
Lighting Power Density	10 W/m^2
Equipment Power Density	12 W/m^2
Infiltration	0.75 ACH
Cooling Setpoint	25 °C

PCM design parameters

The thermal behavior of PCMs is highly dynamic. Outside the phase change regime, PCMs behave in a similar fashion to other sensible materials. The design determinants are based on many factors such as PCMs location in the wall, wall orientation, solar radiation, internal gains, color of the surface, ventilation rate, latent heat, melting temperature, melting range (Soares, Costa, Gaspar, & Santos, 2013). For this study, all external walls in the base case house are placed with PCM to the interior side as shown in **Figure 4**. Many researches revealed that the best PCM location is when it is placed into direct contact with indoor environment (Neeper, 2000; Peippo, Kauranen, & Lund, 1991; Soares, Gaspar, Santos, & Costa, 2014; Stovall & Tomlinson, 1995; Wang, Long, Qin, & Xu, 2013). Under the two climatic conditions, several simulation cases were tried as shown in **Table-2**.

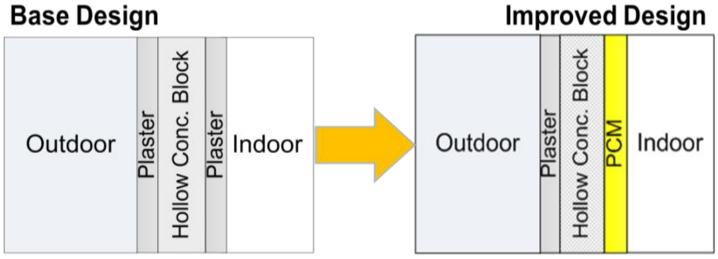

Figure 4 Base wall design versus improved wall design

Table 2 Simulation trials for the base case housing model under the two cities climatic conditions

City / Simulation	Muscat	Salalah
Case-1	Latent heat=50 kJ/kg Melting Temperature (Tm) varies between 22-28°C on 1°C increment Melting Range (ΔTm) varies between 0.1-8°C	Latent heat=50 kJ/kg Melting Temperature (Tm) varies between 23-30°C on 1°C increment Melting Range (ΔTm)=0.1°C
Case-2	Latent heat=100 kJ/kg Melting Temperature (Tm) varies between 22-28°C on 1°C increment Melting Range (ΔTm) varies between 0.1-8°C	Latent heat=300 kJ/kg Melting Temperature (Tm) varies between 23-30°C on 1°C increment Melting Range (ΔTm)=0.1°C
Case-3	Latent heat varies from 50-250 kJ/kg on 50 increment Melting Temperature (Tm)= 26°C Melting Range (ΔTm)=0.1°C	
Case-4	Change the $T_{cooling\_setpoint}$ from 25°C to 24°C Latent heat varies from 50-250 kJ/kg on 50 increment Melting Temperature (Tm)= 25°C Melting Range (ΔTm)=0.1°C	

DISCUSSION AND RESULT ANALYSIS

The external wall in the base case is modified by placing a 12.5 mm thickness PCM layer. The percentage savings in annual cooling load is chosen to be a performance indicator and is determined using the following relationship:

$$\% \text{ Savings} = \frac{\text{Load}_{\text{base case}} - \text{Load}_{\text{PCM case}}}{\text{Load}_{\text{base case}}} * 100 \qquad (1)$$

Muscat City

For the first simulation trial, the latent heat of PCM layer is kept constant at 50 kJ/kg while the melting temperature and melting range are varied as indicated in **Table-2**. **Figure 5** shows the percentage savings in annual cooling load. Although the savings is insignificant (being less than 2%), the optimal melting temperature for this latent heat case is 26°C (i.e., a degree above the cooling setpoint) with narrow melting range.

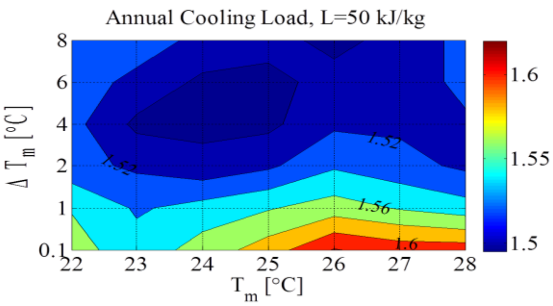

Figure 5 Simulation trial-1 (latent heat=50 kJ/kg) for Muscat

Then in the second simulation trial, the latent heat was increased to 100 kJ/kg and similar parametric study is performed. As shown in **Figure 6**, similar trend is observed where the optimal melting temperature is found to be 26°C and melting range is 0.1°C. The results are less significant than the 50 kJ/kg case.

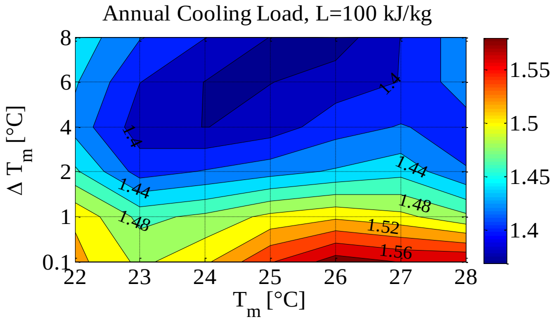

Figure 6 Simulation trial-2 (latent heat=100 kJ/kg) for Muscat

From the previous two cases, it was clear that the optimal melting temperature is 26°C and melting range is 0.1°C. These optimal values are then fixed in the third simulation trial and the latent heat of PCM was varied between 50-250 kJ/kg as shown in **Figure 7**. The results show that as the latent heat increases, the savings becomes less significant. Since there is no passive mechanism to discharge the absorbed heat, the energy savings are becoming insignificant. Instead of depending on air-conditioning system to remove the absorbed heat, proper passive discharging mechanism such as using natural ventilation can be utilized to flush this heat and prepare the PCM layer for the next charging cycle.

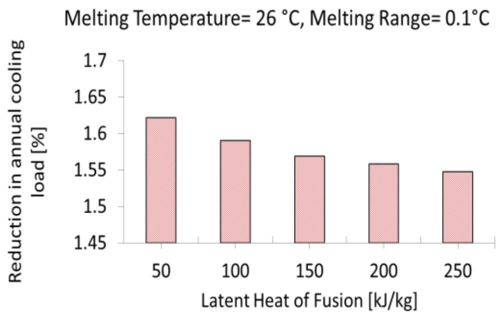

Figure 7 Simulation trial-3 (latent heat varies) for Muscat

A fourth simulation experiment was conducted. For this case, the cooling setpoint was changed from base case assumption of 25°C to 24°C. The melting temperature was set to 25°C (a 1°C above the cooling setpoint) and melting range was kept constant at 0.1°C. Although the savings are insignificant, the results show that savings are marginally better than the previous case as demonstrated in **Figure 8**.

In Summary for Muscat city, the optimal melting temperature was found to be 1°C above the cooling setpoint with very tight melting temperature range ~ 0.1°C. For continuously operated dwellings, application of low latent heat is appropriate when no external discharging mechanisms are available.

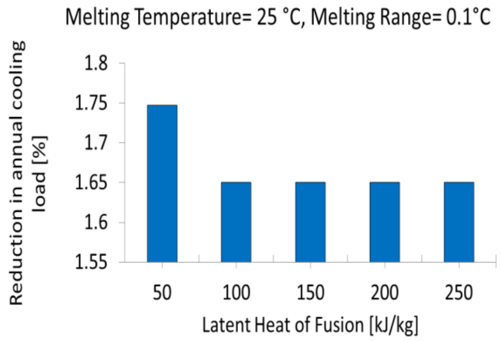

Figure 8 Simulation trial-4 (latent heat varies) for Muscat when cooling setpoint changed to 24°C

Salalah City

The latent heat behavior from the simulation trials in Muscat city was considered for Salalah city to reduce unnecessary simulation runs. **Figure 9** shows the results for Salalah city when the latent heat is 50 kJ/kg and melting range is 0.1°C and melting temperature varies between 23°C and 30°C. Regardless of the melting temperature, the saving in annual cooling load is between 0.9 to 1%. The optimal melting temperature is located at 2-3°C above or below the cooling setpoint. This is different than the case of Muscat which was found to be a 1°C above the cooling setpoint. This is pertained to the summer monsoon climate in Salalah where the outside temperature rarely rises above 28°C and the city is cloudy in almost all summer months. The climate difference drives the PCM discharge mechanism. Consequently, the PCM's optimal property is characterized by the outdoor climatic conditions rather than the indoor environment.

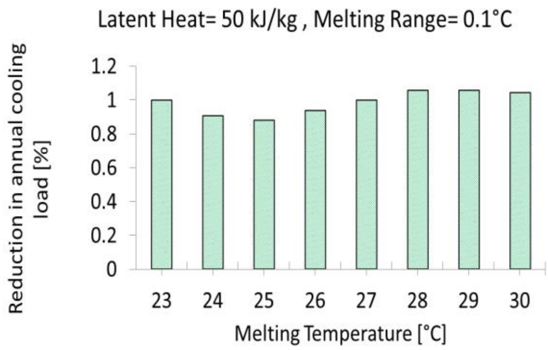

Figure 9 Simulation trial-1 (latent heat=50 kJ/kg, melting temperature varies) for Salalah

Increasing the latent heat by a factor of six, however, does not significantly help to reduce the cooling load as shown in **Figure 10**.

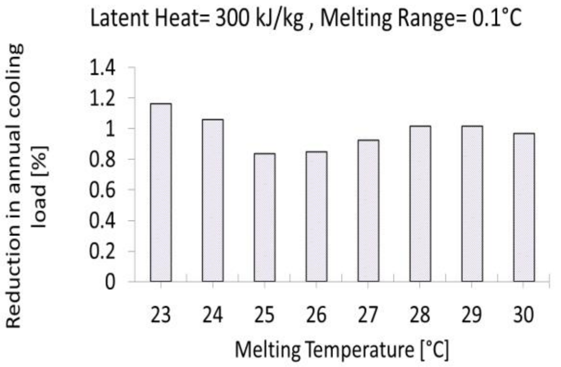

Figure 10 Simulation trial-2 (latent heat=300 kJ/kg, melting temperature varies) for Salalah

CONCLUSION

The simulation study for a typical dwelling in Oman shows that PCM-enhanced layer has a poor energy performance (i.e., being less than 2% in all cases) when embedded into exterior wall systems. This finding is in agreement with literature reported on PCM's performance in hot climate. Chan for example indicated that a reduction of 2.9% in annual cooling is achieved when PCM is integrated into the walls of a residential flat in Hong Kong (Chan, 2011).

The optimal thermal properties of PCMs are determined for two cities in Oman. For Muscat city (hot-humid climate), the optimal melting temperature is found to hover around the thermostat set-point with tight melting range; ~0.1°C. For Salalah city (warm tropical climate), the optimal melting temperature is found to be 2-3°C above or below the cooling setpoint.

Further research is still needed to understand the dynamic thermal behavior of PCM and optimize the energy storage utilization of this technology when integrated into building envelopes under hot climates. In particular, it will be useful to explore its performance when coupled with natural ventilation.

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