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PCM-to-Air Heat Exchangers for Free Cooling Applications

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ABSTRACT
Applications of PCM-to-air heat exchangers (PAHXs) were discussed in literature for free cooling application due to their latent thermal storage abilities. This paper aims to justify the generalization of a numerical model of PAHX and to compare the thermal performance of two different configurations of PAHX system. A generalized numerical model is developed and validated based on general apparent heat capacity method. The validation results show good agreement of the generalized approach in terms of averaged error with the experimental data. Model potential and limitations are discussed, and further recommendations are proposed to improve model accuracy. The paper ensures the significant potential of a PAHX ventilated façade configuration in free cooling applications.

KEYWORDS
Latent thermal storage, PCM-to-air heat exchangers, phase change materials, free cooling.

INTRODUCTION
The general awareness of using latent heat thermal energy storage (LHTES) systems has been growing widely due to their increased storage capacity, system efficiency and durability. Phase Change Materials (PCMs) are being used in building applications due to their latent thermal storage abilities. One of the efficient passive cooling concepts is utilizing night cold energy to be re-supplied at hot period of the next day; this needs involving a thermal storage process. Integrating this free cooling concept with a LHTES system can provide an acceptable indoor environment for building occupants. Applications of PCM-to-air heat exchangers (PAHXs) have been widely discussed in literature for free cooling applications. Those applications can be classified into two main configurations: system equipment as a part of ventilation systems, and ventilated facades as improved building envelopes. Both types involve convective heat transfer process between air and PCM.

It can be inferred from literature of integrated PAHX ventilation system configuration that maintaining supplied air temperature that achieves indoor thermal comfort is a current system limitation. Several studies reported that insufficient difference between phase change temperature (PCT) range and inlet temperature during charging affects system storage abilities and overall thermal performance (De Gracia et al. 2015; Waqas and Kumar, 2011). Using a hybrid system of PAHX and a direct evaporative cooling unit, Panchabikesan et al. (2017) experimentally found that the hybrid system increased the cooling potential by reducing the inlet air temperature during PCM solidification. Some studies confirmed the potential of using multiple PCMs in free cooling systems to satisfy workability under high inlet temperatures (Mosaffa et al. 2013). Regarding long-term applications, applying same PCM affects the annual system performance due to changing of ambient temperature profiles in various seasons, consequently, standalone PAHX system cannot maintain indoor thermal comfort all year-round; thermal management is required in such cases (Osterman et al. 2015). On the other hand, PAHX ventilated envelope configuration showed some achievements in free cooling applications, De Gracia et al. (2013) showed that direct free cooling had a high potential in reducing the cooling loads, however, insufficient difference between night temperature and PCT during solidification results in low system energy storage. Some other studies assured the system cooling potential when combined with night ventilation strategy (Jaworski, 2014; Evola et al. 2014, El-Sawi, et al 2013).

It can be inferred from the literature that PAHX ventilated façade configuration has lower performance than the ventilation system configuration. This paper investigates the performance of the two configurations of PAHXs. By monitoring system outlet air temperature, the current work investigates PAHX system parameters of both configurations that achieve same thermal performance. The main goal of this paper is the justification of a general numerical model of PAHX to be used efficiently in both configurations by designers and building developers. Also, this paper investigates the effect of numerical model generalization on the overall PAHX thermal behavior.

METHODS

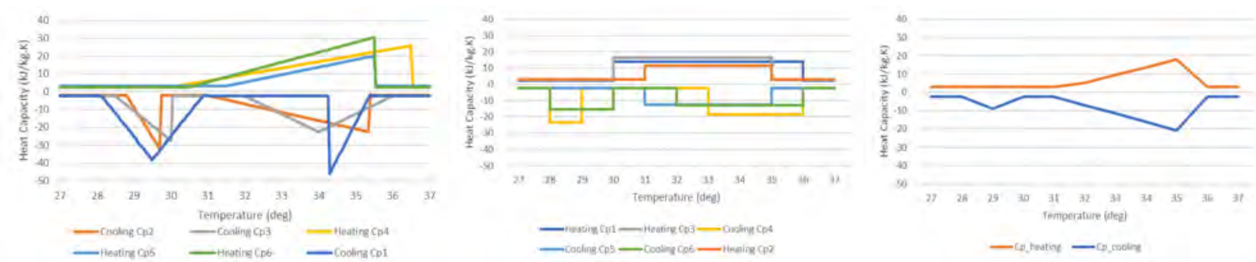
In this study, a generalized numerical model for PAHX is proposed and validated based on developments of an earlier version of the model. The model proposes an energy balance approach over number of control volumes to represent the system three media of heat transfer: air flow, encapsulation material and PCM. Full model nodal discretization and heat balance equations are described in detail in (Stathopoulos et al. 2016). Expression of latent heat storage during the phase change of the PCM is achieved by monitoring the change of heat capacity (c_p) values over the temperature range for each control volume. This apparent c_p method assumes fixed rate of heating/cooling during the latent heat transfer process. An earlier version of the numerical model was proposed by Stathopoulos et al. (2016) based on an improved apparent c_p method that proposes multiple values of c_p due to different heating/cooling rates. This method is based on measurements data using Differential Scanning Calorimetry (DSC). Using a developed version of model, this study is performing a comparison between general apparent c_p model and improved apparent c_p model proposed by Stathopoulos et al. (2016) to test the thermal performance of the two configurations of PAHXs: integrated ventilation system configuration, and ventilated envelope configuration.

Model potential and limitations

The model has good potential in terms of predicting the outlet air temperature due to the accurate evolution of c_p values over temperature. PCM thermal conductivity, density and volume are interpolated over temperature through phase change range. The model can auto-generate air density value according to air temperature. However, the early version of model discussed by Stathopoulos et al. (2017; 2016) showed some limitations in terms of its dependency on experimental data. Inlet air temperature and volume flow rate were represented to model every time step; these values were obtained from experimental data. Also, both cooling and heating curves for c_p were determined based on different cooling/heating rates of DSC measurements. Although these procedures provided better model accuracy, the dependency on experimental data obstructed the model applicability for broad investigations instead of single case study. Moreover, the model used a fixed input value for convective heat transfer coefficient, *h*. As mentioned by authors, the model also neglected the natural convection inside PCM, and long-wave radiation heat transfer between PCM plates. In this paper, further developments are made in terms of generalization of the model to be applicable for broad investigations. Also, the developed model promotes the applications of different PAHX configurations.

Justification of general apparent heat capacity method

Heat capacity value is a key factor in model accuracy. Stathopoulos et al. (2017) proposed the improved apparent c_p model using the experimentally obtained values of c_p, shown in figure 1-a, as model input. They also divided the system to three consequent parts (inlet, middle and outlet) assigning different cooling/heating curve for each part. Towards model generalization, the c_p values are reconsidered as average values for each curve maintaining the same approach of multiple curves for c_p, as presented in figure 1-b. In this case, an average value of c_p is introduced for each curve. Moreover, this approach still requires knowledge and access to the measured values of c_p to calculate the average values. Towards tackling the model limitation of obstructing the broad applications, current model developments assume having two curves for heating and cooling, as shown in figure 1-c. This approach assumes one fixed rate for cooling/heating along the system, which is the original assumption of apparent heat capacity method. This assumption was previously discussed by Stathopoulos et al. (2017) and was claimed to have less accuracy than the improved apparent c_p method due to the differences in heat transfer rate along the PCM plate. Despite the expected less accuracy, this approach can be beneficial to formulate a platform for system designers based on data sheets of c_p cooling and heating curves provided by PCM suppliers. In this paper, investigations for the general apparent c_p approach will be conducted to justify its acceptability and validity with experimental data.



a) b) c)

Figure 1. Heat capacity heating and cooling curves for PCM Microtek 37D a) improved apparent c_p method, b) c_p average values, c) general apparent c_p method

Experimental installation

The experimental investigation of PAHX ventilation system type (configuration 1) was illustrated in-detail in (Stathopoulos et al. 2016). A flat plated encapsulation of 16 aluminum PCM plates were investigated under various airflow rates. Microtek 37D paraffin was used as PCM (melting temperature 37.0˚C and latent heat of 230 kJ/kg). The total dimensions of the heat exchanger were 1.05m in length, 0.75m in width and 0.25m in height; it contained 31.8kg of PCM. Airflow and air temperature were actively regulated and controlled to the desired velocity and temperature. Inlet temperature varied from around 44.0˚C during melting phase and 26.0˚C during solidification phase. The available experimental data are for around 15 hours (1.0 hour introductory – 9.0 hours for melting – 5.0 hours for solidification). Sensors were installed within the heat exchanger to measure: PCM and encapsulation surface temperatures in three locations (inlet, mid, and outlet parts), inlet and outlet air temperatures, and airflow rate.

RESULTS

Figure 2 presents the results of the validation for different numerical models with the experimental results. The results show the evolution of system outlet air temperature under volume airflow rate of around 300 m^3/h during both melting (discharging) and solidification (charging). There are three presented numerical models based on the different c_p values discussed earlier: 1- the improved apparent c_p model tested by Stathopoulos et al. (2016) with experimentally obtained values of c_p, 2- the model that is based on developed average values of c_p, and 3- the generalized apparent c_p model that is based on simplified c_p values. The results show that considering an average value for each c_p curve is very close to the improved apparent c_p model. The generalized apparent c_p model shows some discrepancy with the original model and experimental results due to the simplified approach of c_p. For investigating the discrepancy level of the generalized model, a percent error test is performed for both improved and generalized apparent c_p models. Figure 3-a shows the percentage of error of both models compared to experimental data. The results show that both models exceed 10% of error percentage with the experimental data only at the start of each phase changing. Otherwise, the error for both models remains below 10% with the experimental data. In terms of the average error, improved apparent c_p model shows average errors of 3.2% and 3.7% during melting and solidification respectively with the experimental data. While the general apparent c_p model shows average errors of 3.9% and 4.6% during melting and solidification respectively with the experimental results. In comparison with the improved model, the generalized apparent c_p model shows up to 7% of percent error.

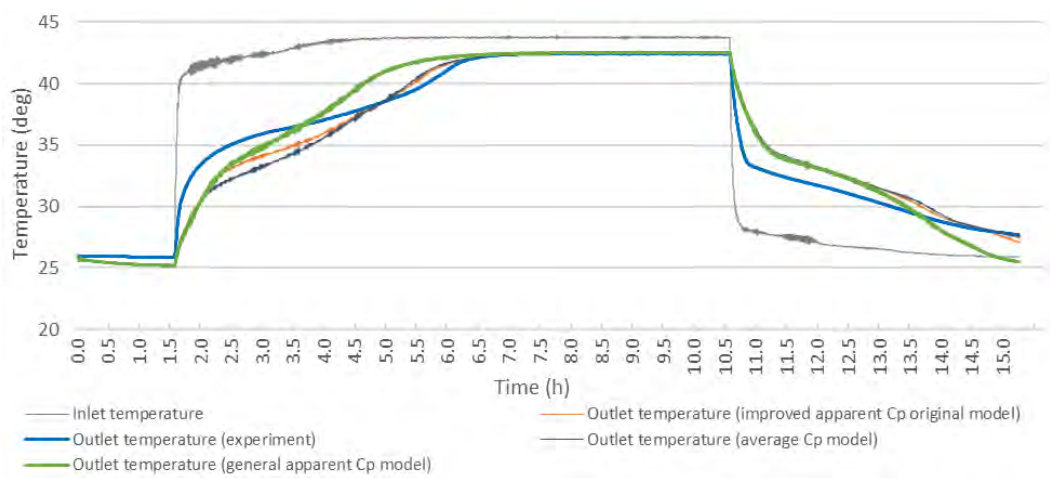
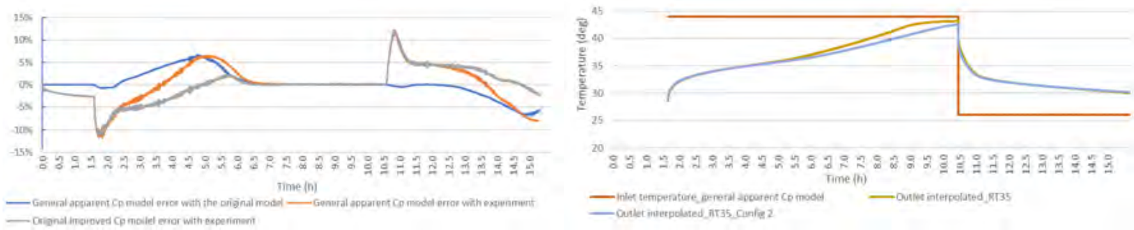


Figure 2. Validation of different models with experimental data

Comparison to ventilated envelope configuration

Using the generalized apparent c_p model, a comparison between the previous investigated PAHX ventilation system unit (configuration 1) and a ventilated envelope PAHX type (configuration 2), shown in figure 4, is held to monitor the thermal performance of the two configurations. In both configurations, inlet air temperature is fixed to two values: 44.0˚C during melting and 26.0˚C during solidification. Airflow rate is fixed to 300 m^3/h. RUBITHERM RT35 is used as a storage medium with thermal properties mentioned in table 1. Two curves for heating and cooling for c_p values are applied and presented at figure 5. The total PCM volume is 0.052 m^3. PAHX ventilated façade configuration variables are mentioned in figure 4, with total PCM volume of 0.064 m^3. It is worth mentioning that the objective of this investigation is the comparison between the two configurations and not obtaining the best thermal performance of the system. The results, shown in figure 3-b, prove that with almost the same volume of PCM, both configurations show significant conformity with values of outlet air temperature profile.



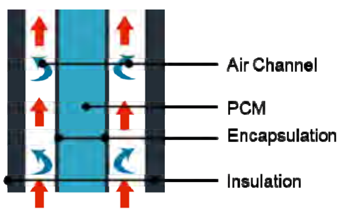
a) b)

Figure 3. a) Percent error analysis of original and generalized models b) Outlet air temperature of PAHX different configurations

Table 1. Thermal properties of PCM RUBITHERM RT35

Melting range	Solidification range	Heat Storage Capacity	Specific heat capacity	Density	Thermal conductivity	Volume expansion
29-36 ˚C	**36-31 ˚C**	**160 kJ/kg**	**2.0 kJ/kg.K**	**0.86 *solid* / 0.77 *liquid***	**0.2 W/m.K**	**12.5%**

A complementary study is conducted to test the indoor thermal performance of a ventilated façade PAHX type with the given configuration using TRNSYS. A standalone test unit of volume 27.0m^3 (3.0*3.0*3.0) is proposed with a northern window of 1.0m^2 and a heavy construction of stone walls (0.3m thick) and concrete roof slabs (0.25m thick). Two systems are compared: the PAHX ventilated façade system, and a conventional ventilation system with the same airflow and inlet temperature as the numerical model. The results show that 4.6% of the cooling loads can be saved during 5.0 hours of PAHX system operation.



System length (airflow direction)	2.0m
System width	1.6m
PCM panel thickness	0.02m
Air channel	0.02m
No of air channels	2
PCM volume	0.064m^3

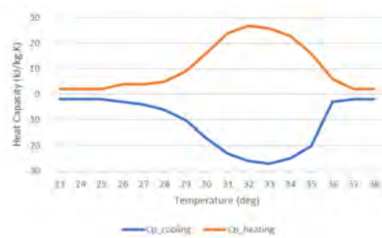


Figure 4. Ventilated envelope PAHX configuration

Figure 5. RT35 apparent c_p curves

DISCUSSIONS

With the validation of the general apparent c_p model, the discrepancy at the end of each phase change process is noticed. It means that with the simplified c_p approach the system tends to consume its storage capacity faster than the actual behavior. Accordingly, it can be noticed from the percent error analysis that the general apparent c_p model shows up to 10% as a level of discrepancy, and 3.9% and 4.6% as average errors during melting and solidification respectively with the experimental data due to consideration of system storage capacity. However, one of the advantages of the general model is its in-dependence of the spatial time constrains. Time step, discretization length and investigation duration can be adapted to desired conditions. Regarding general model limitations, the model still uses a fixed input value for convective heat transfer coefficient. Also, the natural convection inside PCM during melting and liquid phase is still neglected. It is expected that model accuracy can be enhanced when heat transfer coefficient is calculated according to airflow conditions. Also, it can be inferred from the results of comparison between the two configurations of PAHX system that the governing parameter in determining PAHX thermal performance is the volume of PCM. Both configurations have almost the same PCM volume and, as reported in results, the both outlet temperature profiles show the same behavior with great level of consistency, especially during solidification process. PAHX ventilated façade configuration shows promising potential for free cooling applications; it is recommended to improve the model by developing the convective and radiative heat transfer boundaries.

CONCLUSIONS

A generalized numerical model of PCM-to-air heat exchangers is developed and validated in this paper based on general apparent heat capacity method. A simplified approach for implementing heat capacity cooling and heating curves is presented and validated with experimental data. The general approach showed some discrepancies with experimental data. Using a percent error test, the average error of the general model was 3.9% and 4.6% during melting and solidification processes respectively. Referring to its ability of broad applications, the developed general model is very beneficial to building designers due to its in-dependence from experimental data as model inputs. Using the developed general model, a comparative analysis between PAHX ventilation system configuration and a ventilated envelope PAHX configuration is conducted. The study proved that PAHX ventilated façade type has promising potential for free cooling applications.

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