Enhancement in Free Cooling Potential through Evaporative Cooling Integrated with PCM Based Storage System: Experimental Design and Response Surface Approach

Saeedian, Abbas; Mohammadiun, Mohammad*+; Mohammadiun, Hamid; Dubaie, Mohammad Hosein; Sadi, Meisam

Mechanical Engineering Department, Shahrood Branch, Islamic Azad University, Shahrood, I.R. IRAN

ABSTRACT: *PCM-based thermal energy storage in conjunction with an electric air source is offered as a potential tool to support domestic energy demand reduction while at the same time minimizing supply challenges for the electricity utilities. This study is to advance the use of hybrid ventilation concepts in building design by assessment of PCM storage unit with an operation of the evaporative ventilation system. RSM CCD methods was employed to evaluate and optimize the individual/interactive effect of parameters on the cooling efficiency of the proposed system. Optimization results indicate that maximum efficiency can be achieved when inlet air temperature and velocity of 28 ºC and 1.2 m/s when PCM coils number was set to 28, respectively. This research compared the effectiveness of passive and free cooling application of PCM when applied to a duplex brick veneer building in Melbourne. It was observed that during the studied period, the free cooling application method is more effective than the passive application method in reducing the peak zone temperature.*

KEYWORDS: *Free cooling; Phase change material; Thermal comfort; Response surface methodology.*

INTRODUCTION

Worldwide energy consumption is on the rise. The main reason for this increasing growth can be traced to the growing trend of the world's population. Excessive energy consumption raises major concerns about resource supply [1, 2]. The exhaustion of energy sources and the adverse effects of environmental damage such as global warming, the depletion of the ozone layer, and serious climate change are direct consequences of increased energy consumption. In the past decades, there has been a direct relationship between the growth rate of energy consumption and the economic growth rate of countries. But in the last few years, due to the expansion of the use of new and environmentally friendly technologies, this trend has changed so that the decline in the growth rate of energy consumption per capita can be considered as one of the new indicators of development[3]. As such, energy intensity is considered one of the criteria for development as a ratio of wealth to energy consumption and unfortunately our country has one of the lowest energy intensity values in the world [4, 5].

** To whom correspondence should be addressed.*
+ E-mail: mmohammadiun@iau-sharood.ac.ir
1021-9986/2021/2/639-645 7/$/5.07

In recent years inactive solutions have received widespread attention. Passive passive systems are technolgies in which even electrical energy is consumed. One of the recently introduced passive methods is free cooling. In free cooling, a storage system is used to absorb and dispose of energy. Free-cooling storage systems are usually either tangible or intense. The main difference between free cooling and night ventilation cooling is that it acts as a storage system in the nighttime cooling of the body, such as walls, while a separate storage system is used for free cooling. It is used for energy storage and a mechanical device such as a fan during energy absorption and disposal researchers [5-11]. The advantage of free cooling over night cooling is that stored cold can be stored at any time. The desired time is released at any time by passing ambient or room air through the storage system[12-15].

The literature suggests that the implementation of the PCM-based free cooling concept is recommended in daily high-temperature climatic zones. HTF rate/ temperature, PCM phase transition temperature range, and enclosure geometry/ material are other parameters that affect the thermal performance of the free cooling system. Most research in the literature has been conducted in controlled conditions by simulating ambient conditions. There is little data available to address the function of the free cooling system in real-time environmental conditions. Also, all studies reported in the literature may be aimed at improving the thermal performance of thermal storage systems by adding balloon configurations and using heat transfer technologies such as nanomaterials in PCM. have seen. To the author's knowledge, no studies have been reported in the literature to increase thermal comfort in free cooling by incorporating PCM in evaporative cooling systems[16].

The aim of the research was to investigate the effectiveness of PCM in reducing the zone air temperature and improving thermal comfort in an experimental room under running direct evaporative cooling system. To do so, a direct evaporative cooling system was built and equipped with PCM coils. Experiments were performed using RSM approach with 3 independent factors including PCM content, inlet air temperature and velocity.

THEORITICAL SECTION

Materials

The ASHRAE (American Society of Heating, Refrigerating and Air Conditioning Engineers) has listed suggested temperatures and air flow rates in different types of buildings and environmental circumstances. Normally, the suggested room temperature is 23.5–25.5 °C in the summer. In the building applications, the PCMs with a phase change temperature (18–30 °C) are preferred to meet the need of thermal comfort [27].

Experimental setup

A direct evaporative system (HM170) was used as a laboratory setup. The laboratory system contained phase change material and operated under controlled environmental conditions. Hot air enters the phase shift system by passing a heater. Thermocouples were installed in the inlet and outlet of the air as well as in the phase shift system to measure the temperature. The energy storage system was made of copper coils with aluminum doors and a plate as a holder. Each coil contains 40 grams of PCM. Fig. 2 shows the PCM holder.

Design of experiment

In order to perform the tests, it is necessary to investigate the effect of important parameters in providing comfort and optimization of all factors. Since simultaneous testing with all factors requires a large number of tests, the need to use experimental design methods to reduce the number of trials and to carefully examine the effect of factors was used. Among the methods of designing experiments, the surface procedure has the advantage of simplicity and generality of the proposed model over other methods, and can also be applied in combination with optimization techniques which, due to its simplicity, speed up computation. . At all stages of the experiment design, the central cube design response procedure was used. Parameter levels were selected based on initial experiments. In this study, the design of the experiment was performed with Expert -Design software version 10 using response level method for data analysis and optimization. If all variables are assumed measurable, the response surface can be expressed as follows:

$$y = f(x_1, x_2, ..., x_k) \tag{1}$$

The aim is to optimize *y*. Second order polynomial is usually considered as a full model in RSM:

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_{ii}^2 + \sum_{i=1}^{k} \beta_{ij} x_i x_j + \varepsilon \tag{2}$$

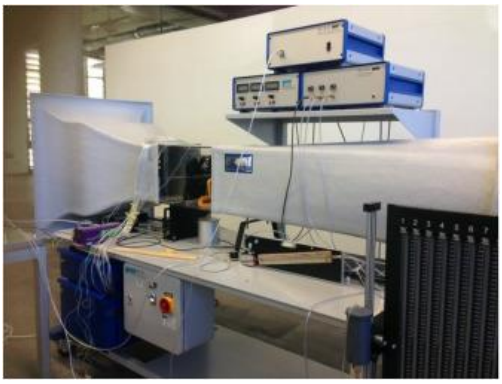

Fig. 1: Experimental setup.

Fig. 2: PCM holders.

Where y is the response (PPD), βs are regression coefficients, x_i is a coded independent variable, ε is the error and k is the number of factors. The most common response surface methodology is the central composite design[3].

The process variables investigated were inlet air temperature(X1), PCM coils number(X2), and fan speed (X3). Three responses were PPD % as mentioned above.

Calculations for performance analysis

The performance of the proposed system was evaluated according to the following equations:

The temperature difference between the inlet and outlet air is a common factor for evaluating the material performance as given in the following expression:

$$\Delta T = T_1 - T_2 \tag{4}$$

The cooling efficiency (saturation effectiveness) of eucalyptus is calculated with Eq. (5) given by ASHRAE (2001):

$$E = \frac{T_1 - T_2}{T_1 - T_1'} \times 100 \tag{5}$$

Where T_1 is the dry bulb temperature of inlet air, T_2 is the dry bulb temperature of outlet air and T'_1 is the wet bulb temperature of inlet air. From the equation, the efficiency of an evaporative cooling system could be calculated as the ratio of the difference between inlet-outlet DBT and the difference between inlet DBT - outlet WBT. The temperature levels of inlet air for testing in the laboratory were regulated according to the temperature of the days in summer when cooling is most needed.

RESULTS AND DISCUSSION

As discussed in the method section, preliminary experiments, the most influential variables which affected system efficiency were inlet air speed, temperature, and PCM coils number. CCD was conducted to identify the simple and combined effects of operating parameters on E. The following response equations were used to correlate removal efficiencies and independent variables n terms of coded factors regardless of the significance of coefficients:

Final Equation in Terms of Coded Factors: (6)

$$E = 0.6897 + 0.04A - 0.0675B + 0.041C - 1.52\times10^{-4}AB +$$

$$1.024\times10^{-5}AC - 8.65\times10^{-5}BC - 1.8\times10^{-3}B^2$$

The Lack of Fit F-value of 0.195 implies the Lack of Fit is significant[17]. There is only a 81% chance that a Lack of Fit F-value this large could occur due to noise.

Model summary statistic is listed in Table 2. The coefficient of determination (R^2) of the model for response was noted as 0.99 suggested that the fitted polynomial equations had a significant degree of fit of the model and only about 1% of the total variation cannot be explained by the fitted model. Another assumption considered in the regression is that the errors have a normal distribution with a mean of zero. Obviously, regression cannot be used if this assumption is not made. To do this, standard error values must be calculated and the data distribution graph and their normal diagrams drawn, and then a comparison between the two graphs is performed to check for the normality of the errors. Since errors in calculating regression tests as well as in calculating confidence intervals are assumed to be normal, large deviations from the normal distribution

Table 1: ANOVA results.

ANOVA for Response Surface Quadratic Model						
Analysis of variance table [Partial sum of squares - Type III]						
	Sum of		Mean	F	p-value	
Source	Squares	df	Square	Value	Prob > F	
Model	0.13	9	0.014	300.54	< 0.0001	significant
A-T	0.026	1	0.026	551.62	< 0.0001	
B-u	0.073	1	0.073	1570.81	< 0.0001	
C-N	0.027	1	0.027	579.54	< 0.0001	
AB	0.0495	1	0.0495	1061.215	0.084	
AC	0.05	1	0.05	1075.175	0.05333	
BC	0.03825	1	0.03825	820.3775	0.06481	
A^2	2.29E-05	1	2.29E-05	0.49	0.4983	
B^2	6.01E-05	1	6.01E-05	1.29	0.04818	
C^2	2.29E-05	1	2.29E-05	0.49	0.4983	
Residual	4.64E-04	10	4.64E-05			
Lack of Fit	3.62E-04	5	7.24E-05	3.55	0.1953	not significant
Pure Error	1.02E-04	5	2.04E-05			
Cor Total	0.13	19				

Table 2: Model summery statistics.

Std. Dev.	0.006812	R-Squared	0.996317
Mean	0.6913	Adj R-Squared	0.993001
C.V. %	0.985451	Pred R-Squared	0.975828
PRESS	0.003046	Adeq Precision	61.65523

can greatly affect the accuracy and reliability of the results. If the error distribution is normal, the points on the normal probability graph should be points along a straight line. Fig.3 shows the measured and predicted residual normal distribution of PPD. According to the figure, since the data were scattered around the straight line, so it can be said that they have normal distribution. Fig.4 shows the predicted values for PPD size versus the values obtained from the laboratory results. As can be seen, the graph data follows the line Y = X, which indicates that the grid has accurately predicted the PPD. In other words, when the predicted values are the same as their corresponding laboratory values, they must be in line with the 45 degree line. The lower the dispersion of the values around the Y = X line, the better the system performance.

The effects of the parameters on Efficiency

In Fig. 5, the variation in cooling efficiency is shown for different air velocities. For the variation of air velocity in the range of 1.7 → 1 m/s, cooling efficiency was calculated between 54% → 81%. This is due to the reduced contact time between air and wet evaporation pad and PCM coils which results with limited heat and mass transfer. In addition, Fig. 5 shows the number of coils effect on system efficiency. As the PCM amount increase, the efficiency was increased. Higher PCM load requires

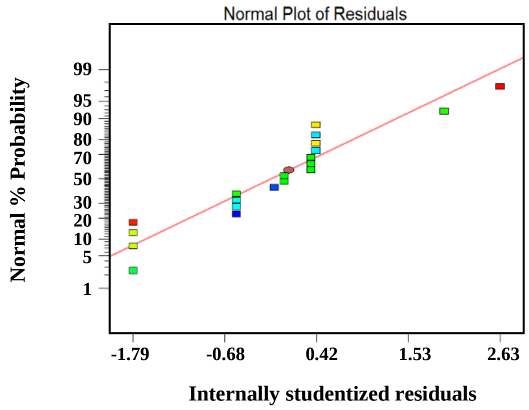

Fig. 3: Normal distribution probability plot.

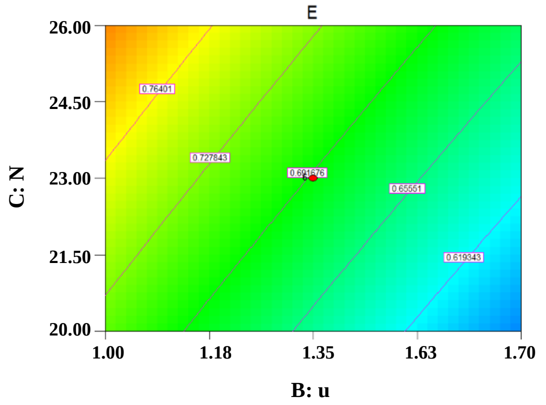

Fig. 5: Air velocity and coils number interaction effect on efficiency.

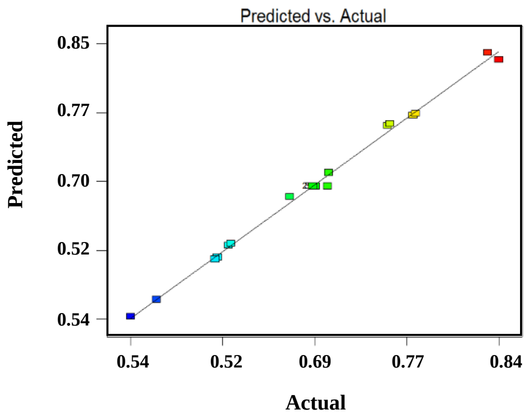

Fig. 4: Predicted vs Actual results.

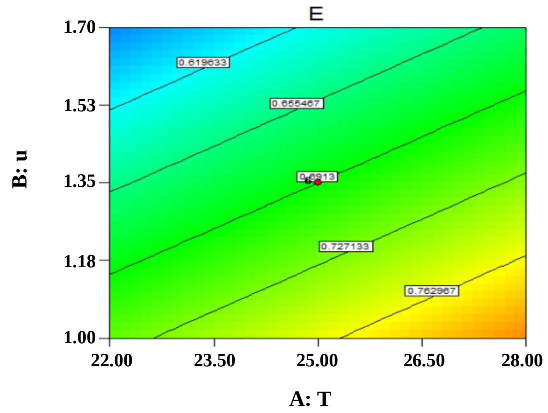

Fig. 5: Air velocity and temperature interaction effect on efficiency.

higher energy to be melted. This will results in higher heat transfer and consequently higher efficiency.

The interaction of inlet air speed and temperature was presented in Fig. 6. Higher air temperature will increase heat transfer rate into the PCM section and decrease room air temperature sharply. Moreover, when the indoor temperature is higher, the outdoor temperature is also higher under same temperature difference. The difference between dry-bulb temperature and wet-bulb temperature of the outdoor air is larger, which shows larger evaporative cooling potential. Therefore, increase of the indoor temperature is beneficial for proposed system.

Optimization and validation

To determine the optimum conditions for the proposed systems, the optimization tool of DesignExpert® 7.0.0 was utilized. The optimum process variables and the related response are presented in Table 3. Three confirmatory experiments were carried out under optimum condition. As shown in Table 3, good agreement between predicted and experimental values of efficiency was observed, with an Absolute Relative Error (ARE) of less than 4%.

Free cooling application

The experiment was run for five consecutive days, where the chamber temperature varied following a sinusoidal curve from 20 °C to 30 °C for 12 h and was kept constant at 20 °C for next 12 h. Fig. 6 shows the 2 zone air temperatures for No-PCM (only evaporative), PCM without evaporative cooling (passive application) and free cooling application of PCM during the studied period in Tehran. The figure shows that throughout the period of 6 consecutive days, free cooling application resulted in large temperature reduction compared to the evaporative method.

The temperature distribution at a different position of the free cooling unit is illustrated in Fig. 7. The average

Table 3: Optimized conditions.

Parameter	T	u	N	E_Pred	E_Exp
Optimum Value	28.00	1.20	24.00	0.773	0.75±4

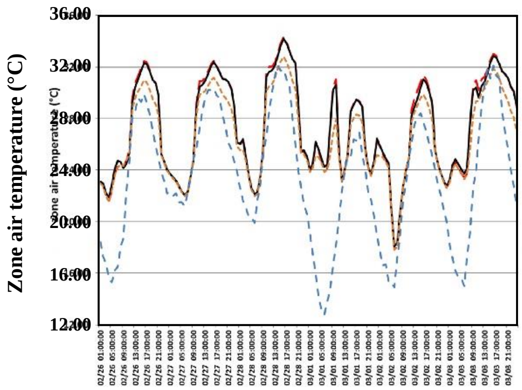

Fig. 6: Zone temperature during typical summer weather.

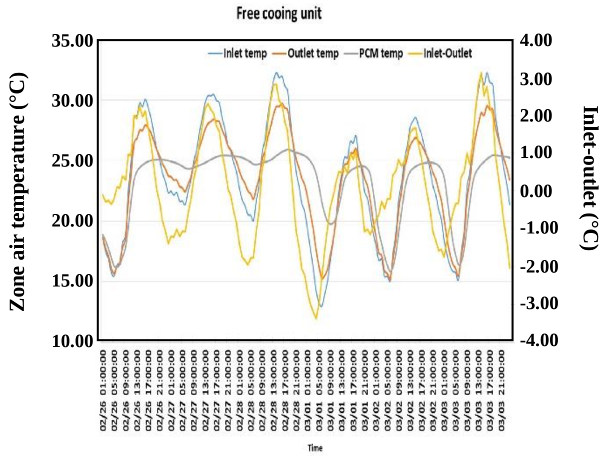

Fig. 7: Performance of Free cooling unit during typical summer.

the peak temperature of the outlet air from the free cooling unit is 2.2 °C cooler than the inlet air during the studied period with a maximum reduction of 3.12 °C. As mentioned earlier, the average reduction in peak zone air temperature due to free cooling is 1.63 °C which is only 26% lower compared to the reduction achieved in the free cooling unit. Hence, it can be said that the free cooling application method more effectively utilizes the cooling capacity of the PCM than the passive method.

CONCLUSIONS

A novel concept of integrating direct evaporative cooling with the PCM based free cooling system was investigated experimentally and the results are reported. According to the study results, it can be concluded that the proposed system at low air velocity provides better performance in terms of cooling efficiency. Also, higher inlet air temperature and PCM load increase cooling efficiency. RSM method was used to optimized system performance and the results showed that Maximum cooling efficiency of 77% can be achieved at inlet air velocity and temperature of 1.2 m/s and 28 C and PCM coil number of 24, respectively. This research compared the effectiveness of the passive and free cooling application of PCM when applied to a room in Tehran. It was observed that during the studied period, the free cooling application method is more effective than the passive application (PCM without evaporating system) method in reducing the peak zone temperature.

Received : Oct. 14, 2019 ; Accepted :Dec. 23, 2019

REFERENCES

[1] Zeinelabdein R., Omer S., and Gan G., Critical Review of Latent Heat Storage Systems for Free Cooling in Buildings, *Renewable and Sustainable Energy Reviews*, **82**: 2843-2868 (2018).

[2] Hosseinzadeh Helaleh A., Alizadeh M., Performance Prediction Model of Miscible Surfactant-CO_2 Displacement In Porous Media Using Support Vector Machine Regression with Parameters Selected by Ant Colony Optimization, *Journal of Natural Gas Science and Engineering*, **30**: 388-404 (2016).

[3] Alizadeh M. and Sadrameli S.M., Numerical Modeling and Optimization of Thermal Comfort in Building: Central Composite Design and CFD Simulation, Energy and Buildings, **164**: 187-202 (2018).

[4] Alizadeh M. and Sadrameli S.M., Development of Free Cooling Based Ventilation Technology for Buildings: Thermal Energy Storage (TES) Unit, Performance Enhancement Techniques and Design Considerations - A Review, *Renewable and Sustainable Energy Reviews*, **58**: 619-645 (2016).

[5] Wahid M.A., Hosseini S.E., Hussen H.M., Akeiber H.J., Saud S.N., Mohammad A.T., An overview of Phase Change Materials for Construction Architecture Thermal Management in Hot and Dry Climate Region, *Applied Thermal Engineering*, **112**: 1240-1259 (2017).

[6] Chandel S.S., Agarwal T., Review of Current State of Research on Energy Storage, Toxicity, Health Hazards and Commercialization of Phase Changing Materials, *Renewable and Sustainable Energy Reviews*, **67**: 581-596 (2017).

[7] Miliï¿½n Y.E., Gutiï¿½rrez A., Grï¿½geda M., Ushak S., A Review on Encapsulation Techniques for Inorganic Phase Change Materials and the Influence on their Thermophysical Properties, *Renewable and Sustainable Energy Reviews*, **73**: 983-999 (2017).

[8] Saffari M., de Gracia A., Ushak S., and Cabeza L.F., Passive Cooling of Buildings with Phase Change Materials Using Whole-Building Energy Simulation Tools: A Review, *Renewable and Sustainable Energy Reviews*, **80**: 1239-1255 (2017).

[9] Khoshraj B.M., Najafi F.S., Khoshraj J.M., and Ranjbar H., Microencapsulation of Butyl Palmitate in Polystyrene-co-Methyl Methacrylate Shell for Thermal Energy Storage Application, *Iranian Chemistry and Chemical Engineering (IJCCE)*, **37(3)**: 187-194 (2018).

[10] Saberimoghaddam A., Abadi M.M.B.R., Thermal Design Considerations and Performance Evaluation of Cryogenic Tube in Tube Heat Exchangers, *Iranian Journal Chemistry and Chemical Engineering (IJCCE)*, **38(1)**: 243-253 (2019).

[11] Djamila H., Indoor Thermal Comfort Predictions: Selected Issues and Trends, *Renewable and Sustainable Energy Reviews*, **74**: 569-580 (2017).

[12] Martinez-Molina A., Tort-Ausina I., Cho S., Vivancos J., Energy Efficiency and Thermal Comfort in Historic Buildings: A Review, *Renewable Sustainable Energy Rev.*, **61**: 70-85 (2016).

[13] Rathod M.K. and Banerjee J., Thermal Stability of Phase Change Materials Used in Latent Heat Energy Storage Systems: A Review, *Renewable and Sustainable Energy Reviews*, **18**: 246-258 (2013).

[14] Souayfane F., Fardoun F., and Biwole P.H., Phase Change Materials (PCM) for Cooling Applications in Buildings: A Review, *Energy and Buildings*, **129**: 396-431 (2016).

[15] Silva T., Vicente R., and Rodrigues F., Literature Review on the Use of Phase Change Materials in Glazing and Shading Solutions, *Renewable and Sustainable Energy Reviews*, **53**: 515-535 (2016).

[16] Alizadeh M. and Sadrameli S.M., Indoor Thermal Comfort Assessment Using PCM Based Storage System Integrated with Ceiling Fan Ventilation: Experimental Design and Response Surface Approach, *Energy and Buildings*, **188-189**: 297-313 (2019).

[17] Hazbehian M., Maddah H., Mohammadiun H., Alizadeh M., Experimental Investigation of Heat Transfer Augmentation Inside Double Pipe Heat Exchanger Equipped with Reduced Width Twisted Tapes Inserts Using Polymeric Nanofluid, *Heat and Mass Transfer/Waerme- und Stoffuebertragung*, **52(11)**: 2515-2529 (2016).