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Parameter optimization of free cooling using PCM filled air heat exchanger for energy efficiency in building

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ABSTRACT

The phase change process for energy storage is a complex heat transfer phenomenon and the solidification and melting process make the charging and discharging process entirely a transient heat transfer process. Analytical solutions are not available to evaluate the temperature of the PCM during the charging and discharging process. Hence, numerical methods are to be adopted to solve the governing equations involved during this transient heat transfer phenomenon. Further, the correlations are developed using the results obtained from the regression analysis using the experimental results to provide simple solutions to the practicing engineers. In this study, heat transfer experiments were conducted under different levels of air flow rate, inlet temperature, charging and discharging time according to the central composite rotatable design matrix. Within the design space, heat transfer variables were optimized using response surface methodology (RSM) concept to the required PCM melting temperature and room temperature. Further, optimized results show that the minimum PCM melting temperature of 29.8 °C and room temperature of 28.6 °C are obtained at the mass flow rate of 0.06 kg/s, inlet temperature of 31.4 °C, and discharging time 86 mins by optimizing process parameters.

1. Introduction

Researchers all over the world are in search of new and renewable energy sources. One of the options is to develop energy storage devices, which are as important as developing new sources of energy. Thermal Energy Storage [TES] technologies are very important in various fields of engineering applications. The most common TES technologies are sensible heat storage and latent heat storage.

It is essential to have a complete control over the relevant experimental parameters to enhance the solidification of PCM on which the quality of a cooling system is based in order to obtain the optimized heat transfer. Therefore, it is very important to select and control the heat transfer experimental parameters for obtaining maximum heat transfer. The efficient use of the statistical design of experimental techniques allows development of an empirical methodology, to incorporate a scientific approach in the experimental conditions. Hence, in this investigation, the design of experiments was used to conduct the experiments for exploring the interdependence of the experimental parameters.

Experiment and simulation studies for a free cooling system integrated to mechanical ventilation system were conducted by Arkar *et al* [1]. The experiments were conducted in four different cases. In first three cases, potential of natural ventilation system with different air exchange rate were analyzed and potential of integrated system (mechanical ventilation with LHTES unit) were analyzed. Due to solar and internal temperature gains weak cooling potential was experienced in natural ventilation. With effective five air exchanges per hour efficient cooling in case of natural ventilation was ensured, but whereas with two air changes per hour same cooling effect could be achieved using the LHTES system. From their investigations it was found that 6.4 kg of LHTES by means of PCM per m^2 floor area is optimum for the free cooling of low energy building of two floors with 191 m^2 of total living area and a heated volume of 430 m^3.

Raj *et al* [2] carried out heat transfer analysis for the fluid and PCM over a modular heat exchanger concept with air spacers between each module of heat exchangers. Their DSC analysis of the selected paraffin PCM showed that major phase change occurs in the temperature range of 26±2°C. For single module and two air spacers, transient / steady state CFD modelling was performed. Pressure drop characteristics were determined using the steady state CFD analysis and PCM solidification characteristics were analyzed using the transient analysis. In their CFD analysis, PCM domain was considered to be static, k – ε turbulence model was used and fully implicit method with PISO algorithm software as a solver option was adopted for transient simulation.

Lazaro *et al* [3] studied the efficacy of two real- scale prototypes air-PCM heat exchanger. Their study followed ANSI/ ASHRAE standards 94.1- 2002 (method of testing active latent heat storage devices based on thermal performance). Precision thermopiles were used to measure inlet/outlet air temperature and the air flow to obtain accuracy. Prototype 1 consists of aluminium pouches and Prototype 2 had aluminium panels. Higher cooling power was observed in heat exchanger with aluminium panels which could be attributed to fixed thickness of PCM layers and reduced heat transfer resistance inside PCM in these panels.

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PCM in aluminium pouches had disadvantage of leakages due to thermal expansion in liquid phase. Free cooling principle was explained by Stritih *et al* [4] in their experimental setup using RUBITHERM RT20 as energy storage medium with melting point of 22°C. A metal box with external and internal fins was filled with PCM. Air temperature and heat fluxes were studied for different air velocities and inlet temperature as a function of time. Their numerical model showed good agreement with experimental results. It was stated that the PCM could able to cool the air to a temperature below 24°C for more than 2.5 h when the air velocity is 1m/s and the inlet air temperature 26°C.

Yanbing *et al* [5] in their study proposed the Night Ventilation system with PCM packed bed storage (NVP) to cool the space during day time. They developed a mathematical model for the proposed system. Their experiments were carried in Beijing. In their study, night cool air is passed through the packed bed storage, by which the PCM gets charged. During day time, hot/used room air is passed to the PCM storage unit (where cool energy stored is transferred to the room air), and thus cold air is circulated inside the room. Their conclusion from the experimental results was, night ventilation system improved the indoor environment due to the integration of LHTES.

Mosaffa *et al* [6] performed the numerical investigations on optimizing the free cooling system using LHTES with multiple PCMs (Climsel 24 and $KF4H_2O$) and calculated the energy storage effectiveness, coefficient of performance (COP) of the system. The charging and discharging process of their flat multiple PCM slabs were predicted using effective heat capacity method. The authors also compared the energy storage effectiveness and other energy based optimization methods to find out the appropriate method of optimizing the free cooling operation using LHTES. One of their major observations was, due to the low thermal conductivity of liquid PCMs, time taken for the solidification is higher than the discharging process.

Chiu *et al* [7] carried out the techno-economic feasibility studies with multi objective optimization of active free cooling LHTES system for Swedish City in comparison to conventional air conditioning system. They used finned pipe heat exchanger where HTF circulates in the pipe and PCM is filled in between the fins. The authors calculated the cost of space cooling unit based on the Sweden statistics, where the cost / (m^2. year) were considered at 230 € for Stockholm.

Effect of PCM plate thickness, air flow rates, cooling power, Stefan number and inlet air temperature on a free cooling system was numerically investigated by Darzi *et al* [8]**.** They analyzed the performance of the free cooling system in two cases, (i) by changing the temperature gradient and (ii) by changing the air flow rates. PCM used was SP22A17 (from Rubitherm) because of its lower volume expansion and suitable phase transition temperature. Their major observations were, (a) conduction dominates during the start and later on natural convection has the more impact in the melted zone of the PCM, (b) with higher Stefan number and higher air flow rate PCM melts faster, (c) PCM thickness has the strong influence in the performance of PCM, (d) cooling power increases as airflow rate increases and (e) reduced airflow rate is advisable to the lower the outlet temperature so that the hot air has sufficient time to interact with the cold storage unit.

The various PCM integration and applications in buildings, free cooling is one of the novel concept in which the cool energy is stored in an external PCM based air- heat exchanger. A detailed review on phase change material storage for free cooling of buildings was carried out [9 – 16]. The free cooling potential for different climatic locations in Europe was studied and reported that the PCM with wider phase change temperature range (12ºC) was found to be most efficient. The optimal size of the LHTES for free cooling of building is between 1 and 1.5 kg of PCM per m^3/hr of fresh ventilation air [17].The free cooling potential for Bangalore and Pune cities was analysed and the appropriate technologies to provide comfort conditions within the temperature range of 25 ± 3ºC was suggested in order to reduce the energy requirement of the building [18-21].

The study was carried out in two steps. In the first step, second order quadratic model for the prediction of temperature of PCM and room temperature during discharging were developed from the data obtained by conducting the experiments. In the second step, the experimental parameters were optimized using response surface methodology (RSM) optimization technique, to obtain the maximum heat transfer to during charging and discharging process.

2. Experimental Conditions and Model Development

An initial step in the design of experiments is to select parameters for the experimental analysis. For economic (time requirements) and theoretical reasons (interdependence of parameters) it is not possible to control all possible parameter variations. From the literature [12 and13] the predominant factors which are having more influence on PCM temperature were identified. They are as follows:

1. Mass flow rate of heat transfer fluid
2. Inlet air temperature during charging
3. Inlet air temperature during discharging.
4. Charging time.
5. Discharging time.

A large number of experimental trials were conducted to identify the feasible working limit of the heat exchanger to transfer the heat from fluid medium to phase change material (PCM) temperature and PCM to fluid medium to reduce the temperature of the room. From the trials the following parameters were identified for the solidification of the PCM and given in Table 1 and for melting of the PCM and also room cooling temperature are given in Table 2.

Table 1. Important experimental parameters and their levels for charging.

No.	Parameters	Notations	Units	Levels				
				-1.682	**-1**	**0**	**1**	**+1.682**
1	Massflow rate	A	kg/s	.05	0.09	0.15	0.21	0.25
2	Inlet air temp.	B	ºC	24	25	27	28	30
3	Charging time	C	min	30	84	165	245	300

Table 2. Important experimental parameters and their levels during discharging.

No.	Parameters	Notations	Units	Levels				
				-1.682	**-1**	**0**	**1**	**+1.682**
1	Mass flow rate	A	kg/s	0.02	0.09	0.15	0.21	0.1
2	Inlet air temp.	B	ºC	26	27.6	30	32.4	34
3	Discharging time	C	min	10	57	125	193	240

In this work, central composite rotatable design was used which fits the second order response. The fitted regression equation to predict PCM temperature and room temperature are given below,

$$Y = b_0 + b_1(A) + b_2(B) + b_3(C) + b_{12}(AB) + b_{13}(AC) + b_{23}(BC) + b_{11}(A^2) + b_{22}(B^2) + b_{33}(C^2) \quad (1)$$

PCM Temp.during charging =

$$27.53-089A+0.68B-0.061C+0.088AB+0.51AC+0.41BC+0.85A^2+1.1B^2+0.64C^2 \quad (2)$$

PCM Temp.during discharging =

$$30.22+0.38A+0.11B+0.21C-0.089AB+0.013AC-0.013BC-0.96A^2-1.06B^2-0.75C^2 \quad (3)$$

Room Temp.during discharging =

$$29.16-0.55A-0.33B+0.89C+.58AB+0.31AC+0.28BC+0.49A^2+0.53B^2+0.1C^2 \quad (4)$$

All the coefficients were obtained applying central composite rotatable design using the Design Expert statistical software package (Version 8.07.1). The significance of each coefficient was determined by Student's t test and p values. In all the cases, A,B, C, AB, AC, BC, A^2, B2 and C^2 are significant model terms, values of "Prob>F" less than 0.05 indicates that model terms are significant. After determining the significant coefficients (at 95% confidence level), the final empirical relationships were constructed using only these coefficients. The adequacy of the developed model checked by ANOVA analysis and model aptness was checked by analyzing the R^2 and Adjusted R^2 values.

3. Optimizing the Experimental Parameters

To obtain the influencing tendency of the experimental parameters on early charging of the following conditions were adopted as shown in Table.3 show optimization criteria used in this study in graphical form with lower and upper limits. Response surface methodology (RSM) approach optimization results of solidification temperature of PCM with the possible combinations are shown in Table 4. Further, the three-dimensional and 2 dimensional diagrams are plotted under certain processing conditions.

Table 3. Optimization criteria used for PCM temperature during charging process.

Constraints		Specifications			
Lower	Upper	Lower	Upper		
Name	Goal	Limit	Limit	Weight	Importance
Mass flow rate	is in range	0.09054	0.20946	1	3
Inlet Temp.	is in range	25.2162	28.7838	1	3
Charging Time	is in range	84.7285	245.271	1	3
PCM Temp.	minimize	27.5	31.8	1	3

3D responses and 2D contour plots were drawn by using the equation (1), (Fig.1 and Fig.2) as surface plots and contour plots) for each of the experimental parameters. It is clear from response surface plots (Fig. 1) that the PCM temperature falls and increases with the increase in process parameters such as mass flow rate and inlet air temperature. The valley of the response plot gives the minimum PCM temperature. These response contours can help in the prediction of the response (temperature) at any zone of the experimental domain. A contour plot is produced to visually display the region of optimal factor settings. For second order response surfaces, such a plot can be more complex than the simple series of parallel lines that can occur with first order models. Once the stationary point is found, it is usually necessary to characterize the response surface in the immediate vicinity of the point. Characterization indicates to identify whether the stationary point found is a minimum response or a maximum response or a saddle point. To classify this, the most straightforward way is to examine through a contour plot.

Contour plots (Fig. 2) play a very important role in the study of the response surface. By solving Eqn. (1) and analyzing the profile of the response surface and the corresponding contour plot, the value of PCM temperature obtained is 27.28ºC, which is found to be minimum and is located at the mass flow rate of 0.19 kg/s, inlet temperature of 26.67ºC, and charging time 180.87 mins at the valley of the response surface plot and the corresponding domain in the contour plot. Three confirmation experiments were conducted to compare the experimental results with the prediction under the optimal conditions. The mean experimental PCM solidification temperature was obtained as 27.9. The error percentage of 4.24% showed an excellent prediction of the model.

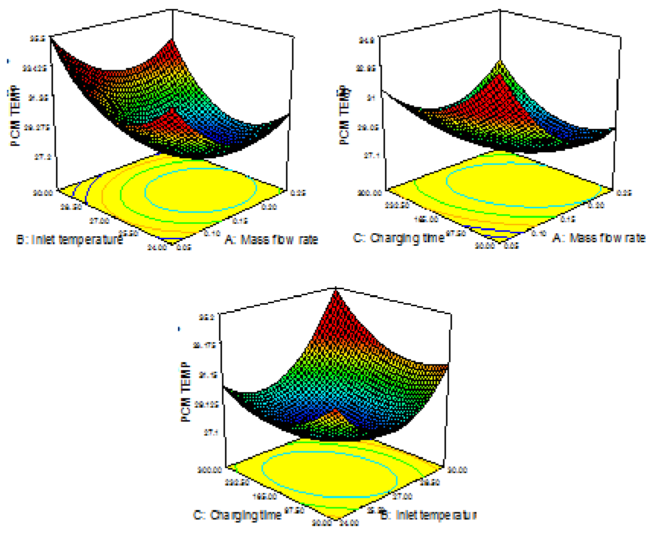

Fig .1Response surface plots for PCM temperature during charging process.

Table 4. Optimization results for PCM Temperature during charging process.

S.No.	Mass flow rate kg/s	Inlet Temp. ºC	Charging Time min	PCM Temp. ºC	Desirability	
1	0.19	26.67	180.87	27.2825	1	Selected
2	0.15	26.15	182.26	27.4115	1	
3	0.18	26.96	199.9	27.4817	1	
4	0.17	26.49	184.64	27.2628	1	
5	0.19	26.7	194.05	27.3697	1	

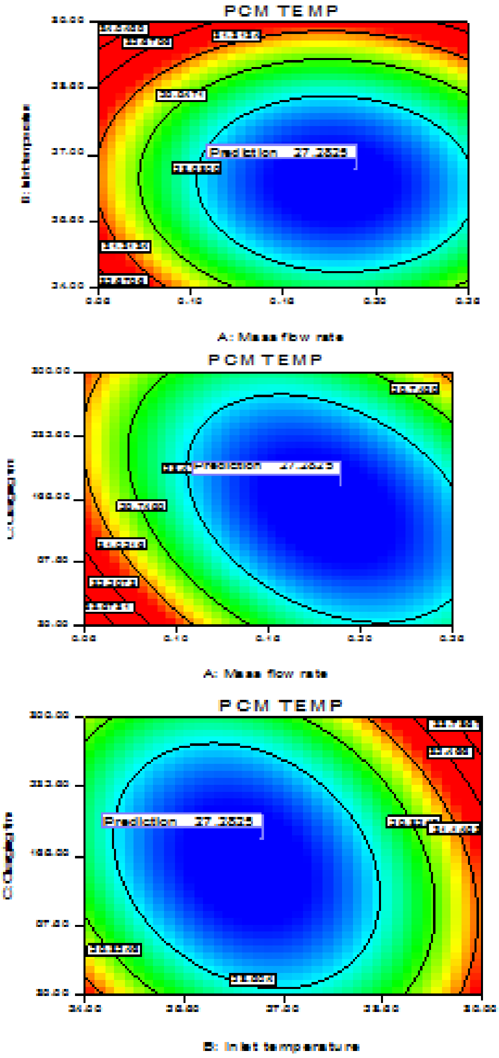

Fig 2. 2D Contour plots for PCM temperature during charging process.

Table 5 shows the different optimal settings used in this investigation to optimize and to obtain maximum PCM temperature and minimum room temperature during discharging RSM approach optimized results are presented. As discussed, by solving Eqns. (2 and 3) and analyzing the profile of the response surface and the corresponding contour plot (Figs.3-6), the value of PCM temperature obtained is 29.8ºC and room temperature 28.6ºC which are found to be optimized maximum PCM and minimum room temperature for the mass flow rate of 0.06 kg/s, inlet temperature of 31.4ºC, and discharging time 86 mins at the valley of the response surface plots and the corresponding domain in the contour plots. Three confirmation experiments were conducted to compare the experimental results with the prediction under the optimal conditions. The error percentage of 4.6% showed an excellent prediction of the model. Response surface methodology (RSM) approach optimization results of discharging with the possible combinations are shown Table 6.

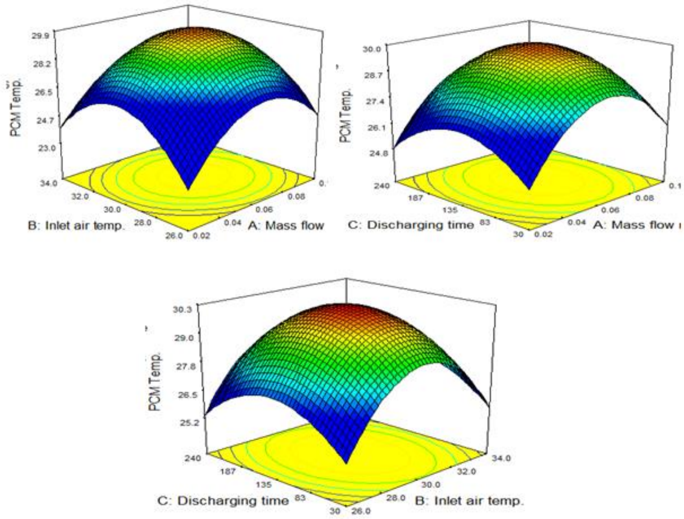

Fig 3. 3D response surface plots PCM temperature during discharging process.

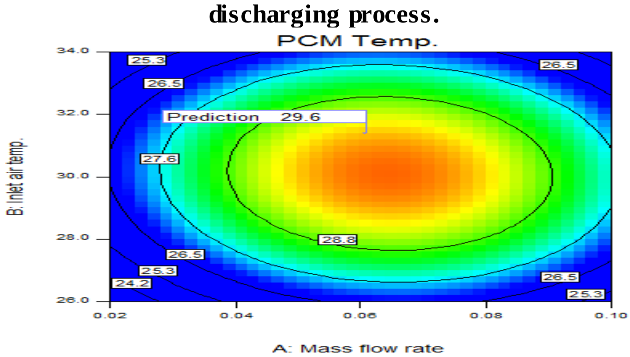

Table 5. optimization criteria used for discharging process

Constraints		Upper Limit	Lower Limit	Weight	Weight	Importance
Name	Goal					
Mass flow rate	is in range	0.1	0.0838	1	1	3
Inlet air temp.	is in range	34	32.39	1	1	3
Discharging time	is in range	240	193.379	1	1	3
PCM Temp.	maximize	26	30	1	1	3
Room Temp.	minimise	27.9	32	1	1	3

Table 6. optimization results for discharging process

S.No.	Mass flow rate kg\sec	Inlet air temp. ºC	Discharging time min	PCM Temp. ºC	Room Temp. ºC	Desirability	
1	0.05	29.9	80	29.13	29.33	1	
2	0.06	32.1	159	29.33	29.87	1	
3	0.04	31.5	76	28.12	29.29	1	
4	0.08	31.3	135	29.79	29.38	1	
5	0.08	29.8	108	29.79	28.76	1	
6	0.08	31.3	167	29.40	30.14	1	
7	0.04	30.3	93	29.24	29.39	1	
8	0.04	32.1	95	28.43	29.23	1	
9	0.07	28.6	140	29.83	29.51	1	
10	0.06	31.4	86	29.57	28.56	1	Selected

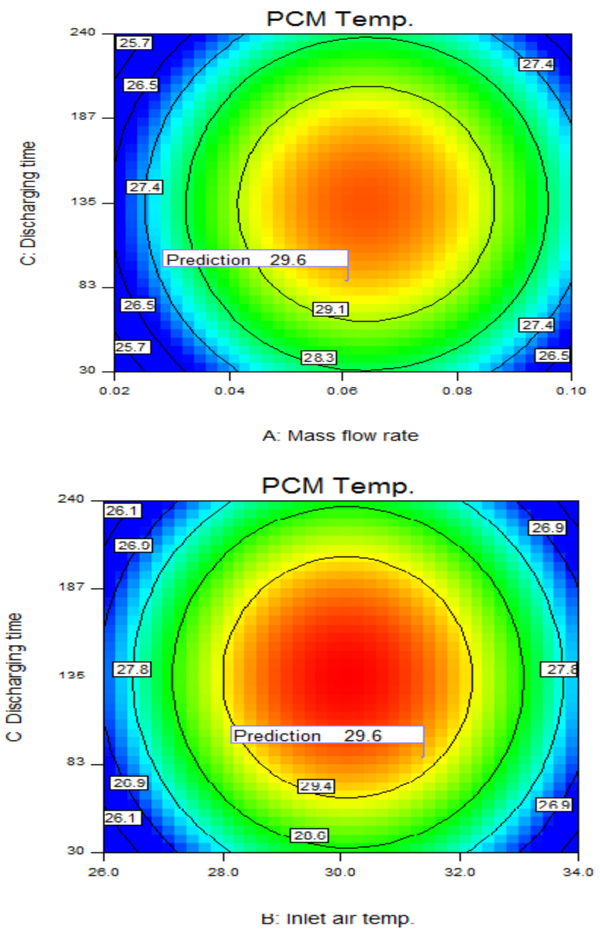

Fig 4. 2D Contour plots for PCM temperature during discharging process.

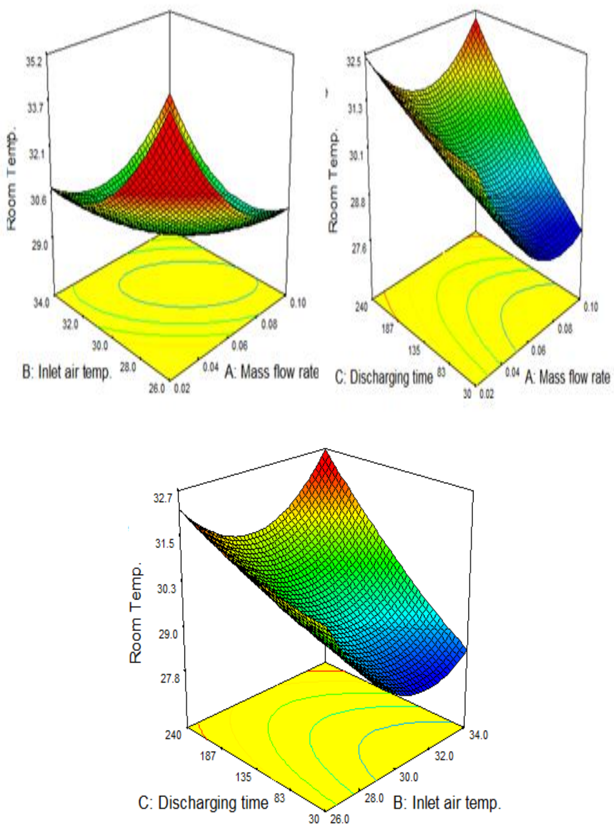

Fig 5. Surface plots for room temperature

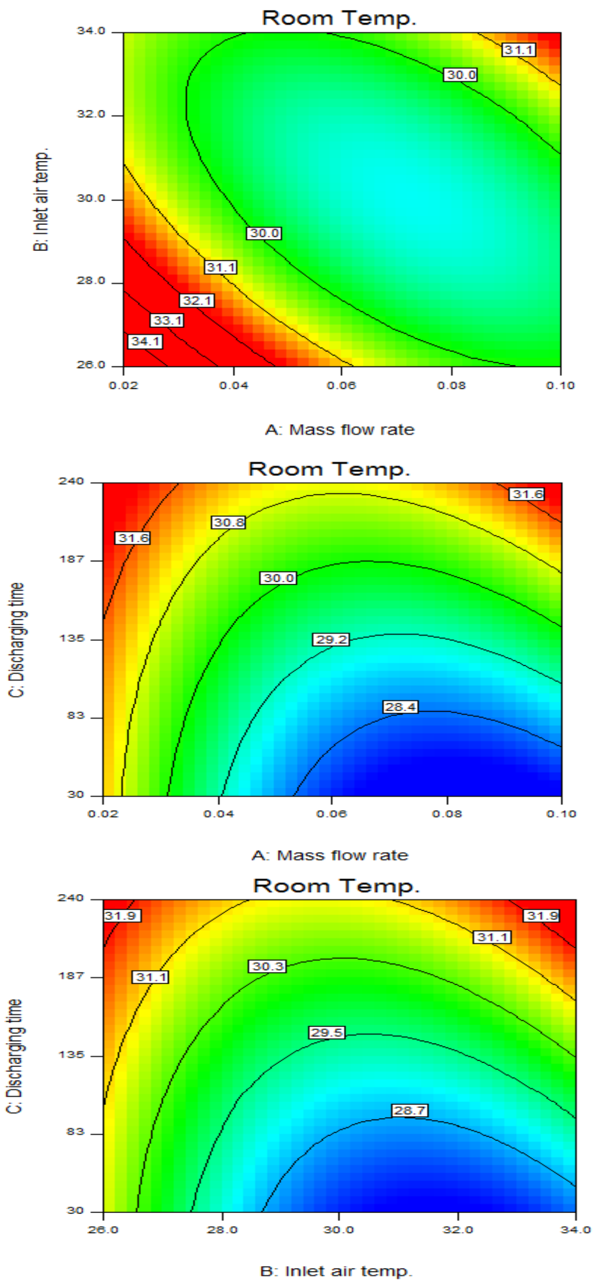

Fig 6. 2 D Contour plots for room temperature.

4 Graphical Optimization

Graphical optimization deals multiple responses and meets the requirements by superimposing or overlaying critical response contours on a contour plot. Then, the best possible results can be found by visual search. It is recommended to do numerical optimization first in the case of dealing with many responses; otherwise, one may find it difficult to uncover a feasible region. In the graphical optimization for each response, the criterion, which was proposed in the numerical optimization, was accommodated and the limits lower and / or upper have been chosen according to the numerical optimization results. The result of the graphical optimization are the overlay plots, this type of plots are extremely practical for quick technical use in the workshop to choose the values of the heat transfer parameters that would achieve certain response value for this type of equipment.

The issue of linking the PCM temperature and room temperature must be addressed as any increase in the PCM temperature is usually reflected in decreasing room temperature. As a consequence, both PCM temperature and room temperature are usually studied together. The graphical optimization result allows visual inspection to choose the optimum PCM melting condition. The shaded areas of the overlay plot are the regions that do not meet the proposed criteria. The graphical optimization plots are shown in Fig. 7. From this over lay plot one can easily find the required parameters to the desired response in with the design space.

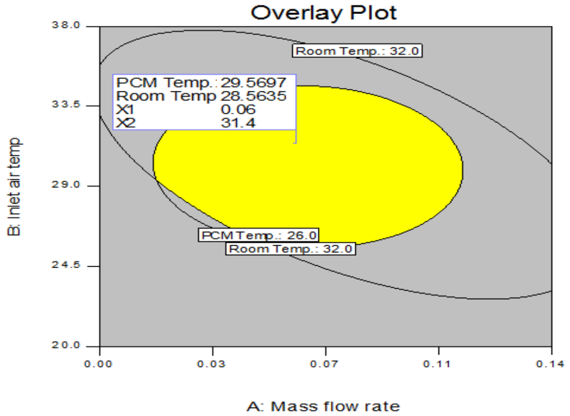

Fig 7. Graphical optimization result shows the optimized parameter for maximum PCM temperature and minimum room temperature for the given mass flow rate, inlet temperature and discharge time.

5 Conclusions

- The minimum PCM melting temperature of 29.8 °C and room temperature of 28.6 °C are obtained at the mass flow rate of 0.06 kg/s, inlet temperature of 31.4 °C, and
- discharging time 86 mins by optimizing process parameters.
- Graphical optimization shows the optimized region for the technical use which will provide the opportunity to identify the feasible region.
- A result of graphical optimization method has well agreement with the results found by the numerical optimization method.
- On PCM melting and room temperature drop both the mass flow rate of air and discharge time has significant effect and the marginal effect was observed in inlet temperature.

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