SSRG International Journal of Thermal Engineering
ISSN: 2395 – 0250 /doi:10.14445/23950250/IJTE-V7I2P101

Volume 7 Issue 2, 1-6, May-Aug 2021
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On Efficiency of Air-Phase Change Material Heat Exchanger for Free Cooling System

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Received Date: 20 May 2021
Revised Date: 23 June 2021
Accepted Date: 05 July 2021

Abstract **-** *Free cooling is a promising passive cooling technique that requires minimum or no energy for cooling the space. Free cooling can be achieved with the use of phase change material based thermal energy storage. An organic phase change material (PCM) with phase change temperature 35^{0}C is selected based on the climatic conditions of the selected location. A heat exchanger containing phase change material with selected geometry is tested by varying selected dependent variables, which are inlet airflow velocity and the orientation of the flat plates of the heat exchanger. In this paper, investigation results of an air-phase change material heat exchanger are presented along with its efficiency. It was observed that maximum heat exchanger efficiency of 74.07%was obtained.*

Keywords — *Air-PCM heat exchanger, Free cooling, Passive cooling, Phase Change Materials, Thermal Energy Storage*

I. INTRODUCTION

With increasing automation and industrialization, more and more machines entered into our lives. India, a developing nation, is the second-largest populous country in the world, and it is the third-largest consumer of energy after China and the United States of America, as per a study in 2019 [1]. Because of a growing population and their rising standard of living, energy consumption will continue to increase. Nearly 40% of energy is consumed by the domestic sector [2]. And the biggest fraction of energy consumption in the domestic sector is taken by space heating or cooling. Air-conditioners are extensively used for this purpose not only in residential buildings but also in commercial and industrial buildings. Apart from this, one more cause behind the ever-increasing trend in the use of air-conditioners is global warming. This results in an increase in the demand for electricity. Electricity production leads to the emission of greenhouse gases which causes a rise in the temperature of the Earth. This, in turn, pronounces more need to cool the space. Cooling the space without harming the environment can be done by either using renewable sources or using Passive cooling techniques. Passive cooling techniques are the methods that require minimum or no energy for cooling the space [3].

Free-cooling, one of the passive cooling techniques, is a process of storing outdoor coolness during the night and discharging this coolness during the day so as to maintain a comfortable indoor temperature [4]. Energy storage with the use of Phase Change Material (PCM) will reduce the mismatch between supply and demand and thereby plays an important role in conserving energy. Determinants of effective free cooling are; melting point of the PCM used, the Design of thermal energy storage, and the geographical location.

Present literature has given different theories regarding the first determinant, i.e., selection of suitable PCM for the free cooling [5-7]. Barreneche, C. et al. [8] have presented an innovative database of more than 300 PCMs. Iten M. [9] gave a review regarding various Thermal Energy Storage (TES) geometries for cooling as well as heating purposes. Various publications [10-15] gave different designs to test the free cooling phenomenon, which includes geometries like flat containers, shells, and tubes, Spherical encapsulated PCM beds, etc. The geographical location is also an important deciding factor as free cooling is applicable at the location where the diurnal temperature difference is larger than 15^{0}C. [16]

This publication focuses on finding the energy-saving potential of a Phase Change Material at a selected geographical location using an air-PCM heat exchanger. This heat exchanger is designed by Kolhekar et al. by solving a systematic non-linear optimization problem [17]. By carrying out discharging experiments with variable conditions, thermal comfort inside the selected location is monitored.

II. MATERIALS AND METHODS

For free cooling using PCM based heat exchanger, it is important to select the appropriate PCM and the container geometry. This section presents the methodology adopted for the selection of phase change material and for the investigations of the air-PCM heat exchanger to find out the cooling achieved.

A. Selection of Phase Change Material

The location selected to test the free cooling potential is Amravati, a city located in the central part of India, where winters are mild, but summers are very hot and dry. Temperature data for the past 4 years is collected at this location. After studying PCM properties and temperature data in the summer months, PCM HS29 having phase change temperature 29^{0}C was selected and tested by Kolhekar et al. [17]. It was found that PCM HS29 discharges in the temperature range of 27-30^{0}C. Also, for the calculated cooling load For the month of May, HS29 completely melts in the selected heat exchanger in 5 hours of discharging in the early morning hours.

At the selected location, May is the hottest month when day-long cooling is much needed. So, there is a need for cooling in the afternoon hours. So, for this work, we select a PCM whose phase change temperature is more than 30^{0}C. The aim is to extend the period of passive cooling. The study of PCM properties and the market survey gives us OM35 as the suitable PCM.

T-History test, which is used to measure thermal properties, is performed on 20 grams of OM35 sample in a test tube and placed in a temperature control bath. Temperatures are continuously monitored with a data logger. Thermophysical properties are measured with the help of the T-History method. It is found that OM35 discharges in the temperature range of 32^{0}C to 36^{0}C. OM35 is an organic compound bought from Palskem, Thane, which is white waxy flakes with a pink tinge in solid-state and freely flowing in the molten state. Relevant properties of OM 35 are tabulated as below, and the enthalpy curve derived from the T-history test is presented in the subsequent figure:

Table 1: Thermo-physical properties of OM35

Thermo-physical Property	Unit	Value
Melting Temp	^{0}C	35
Freezing Temp	^{0}C	34
Latent Heat	kJ/kg	202
Liquid Density	kg/m3	870
Solid Density	kg/m3	969
Liquid Specific Heat	kJ/kgK	2.78
Liquid Thermal Conductivity	W/mK	0.16
Solid Thermal Conductivity	W/mK	0.20

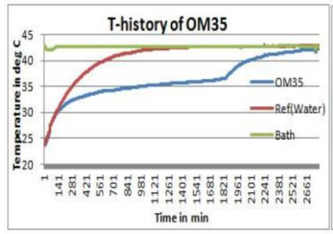


Fig 1: T-History of OM35

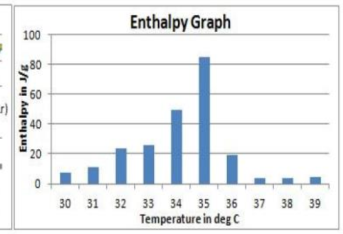


Fig 2: Enthalpy graph

B. Selection of the geometry of heat exchanger

Flat containers made up of Stainless-steel Grade-316 are considered for experimentation. To maintain the convective heat transfer area the same as that used in [17], the same geometry of the heat exchanger is used. As OM35 shrinks to 11.37% of its volume upon solidification, one side of the flat plate is available for heat transfer. There are 7 flat container plates each of dimension 0.32 x 0.19 x 0.009 m (L x W x Th). 3.33 kg of OM35 is filled in the molten state in 7 flat plates.

With PCM properties given in table 1, the optimization equations presented in [17], the optimum mass of the PCM OM 35 is calculated for 5 hours of experimentation as 3.33 kg. Each flat plate contains 475 grams of OM35.

$$\frac{m \times l}{t} = Q_{cool} = h \times A \times dT$$

Where, Q_{cool}= cooling load in the test room = 60 W

C. Selection of variants and their levels

Two key parameters are selected to investigate and understand the efficacy of the heat exchanger, inlet airflow velocity, and orientation of the heat exchanger with respect to the fan. These two input factors are tested with three and two levels, respectively.

D. Experimental Set-up details

The temperatures inside the test room were monitored with the data logger for 5 hours with the 60 W load without using the air-PCM heat exchanger. Heat stored in the air without using a PCM heat exchanger is measured. This experiment forms the basis for assessing the cooling achieved with an air-PCM heat exchanger. After this experiment, the heat exchanger consisting of frozen OM35 was kept inside the test room of dimension 0.95 x 0.75 x 0.75 m. A cooling load of 0.06 kW was simulated by putting a filament bulb of 60 W ON. A fan is installed at the inlet to ensure forced convention between the air and the PCM. The free cooling experiments were conducted at three different velocities; 2 m/s, 2.5 m/s, and 3 m/s. Each experiment was started with a PCM temperature of approximately 32˚C. So, the PCM was in a frozen state and fully charged with the cold.

For each air velocity, two orientations of the heat exchanger are tested. In the first orientation, the width of the flat plates (Shorter side) faces the fan, whereas, in the second orientation, the heat exchanger is rotated by 90^0 such that length (longer side) faces the fan.

Fig 3. Air-PCM Heat exchanger

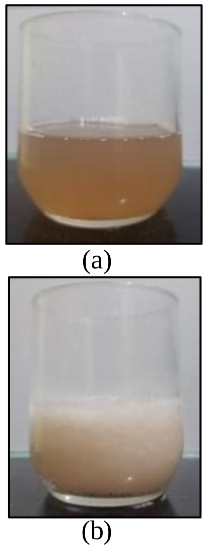
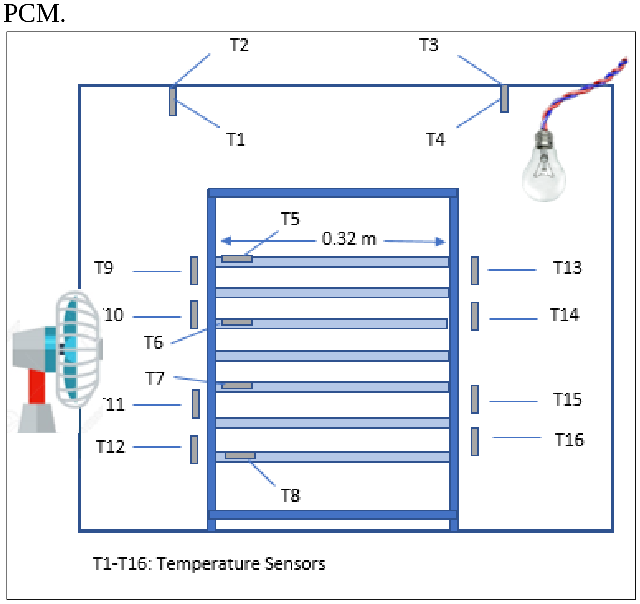
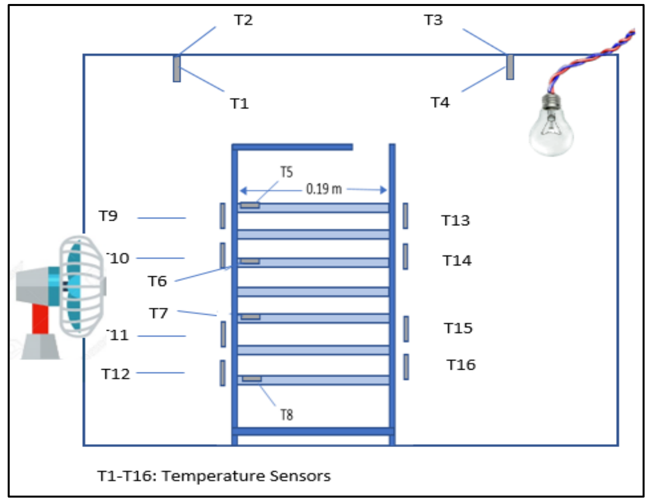


Fig. 4. OM35
(a) molten state
(b) frozen state

The following figure represents the schematics diagram of the experimental; setup in both orientations. The test room was containing the air-PCM heat exchanger, 16 temperature sensors at various locations, a filament bulb to simulate the cooling load at a location, and a fan installed at the inlet to ensure the convective heat transfer between the air and the PCM.



(a)



(b)

Fig. 5 Schematic Diagram of the experimental set-up (a) L: W (b) W:L

III. EXPERIMENTATION

Free cooling experimentation with three air velocities and two orientations is carried out in the simulated environment. Results of experiments are presented in the form of graphs below:

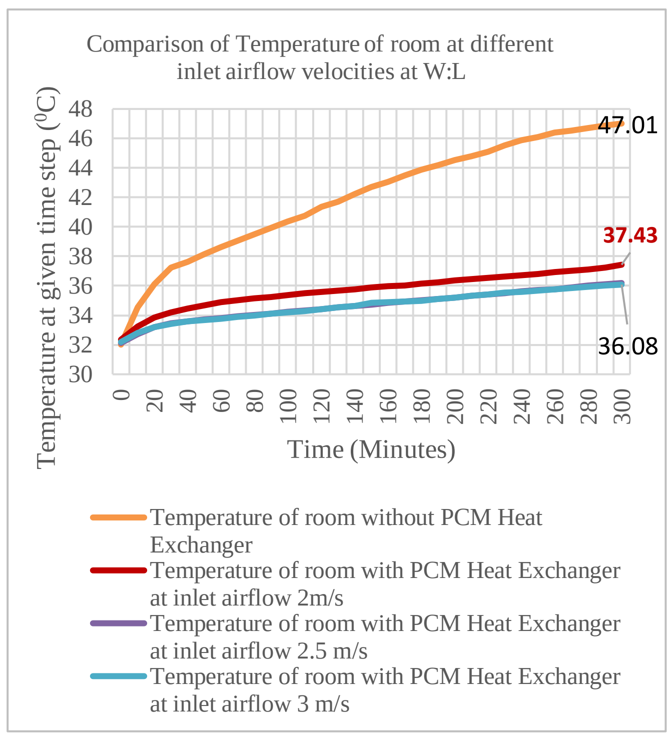


Fig 6. Comparison of the temperature of the room at different inlet airflow velocities at L: W orientation

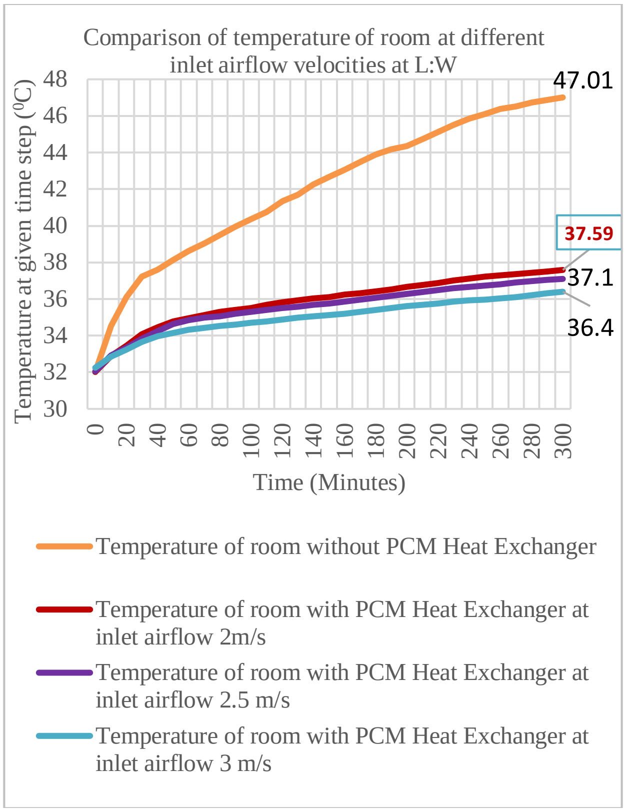
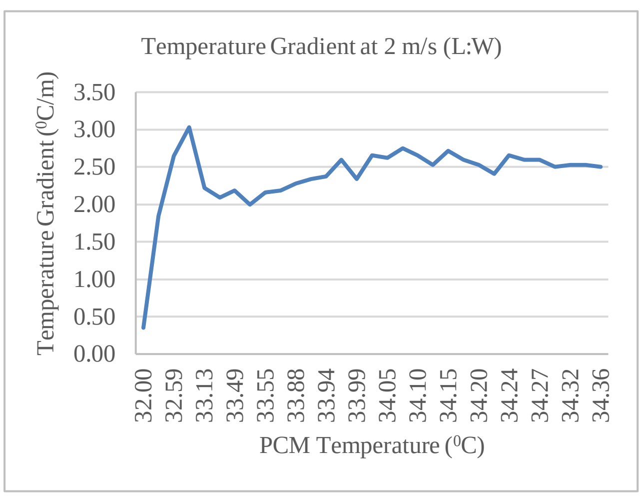
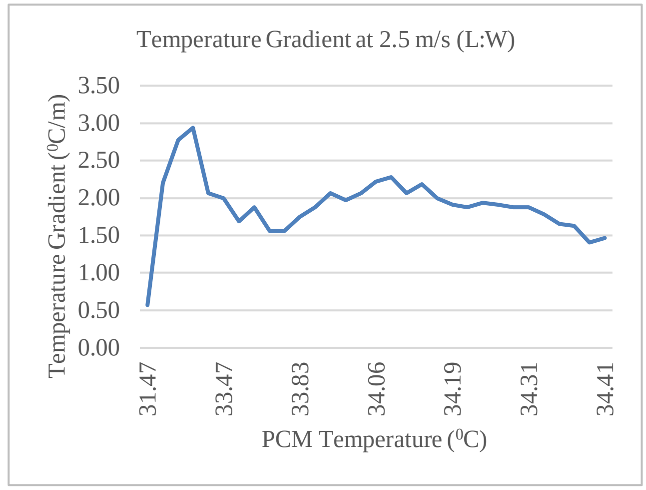


Fig 7. Comparison of the temperature of the room at different inlet airflow velocities at W:L orientation

The above graphs(Fig. 6 and 7) depict the temperature of the room without air- a PCM heat exchanger and with air-PCM heat exchanger for L: W and W:L orientation respectively at 3 different velocities.



(a)



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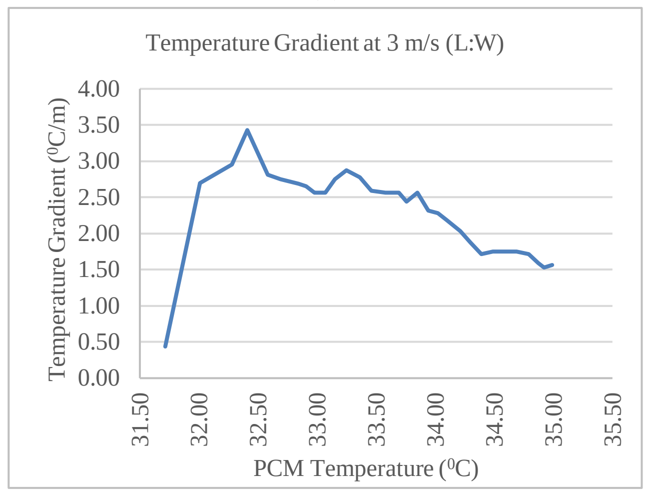

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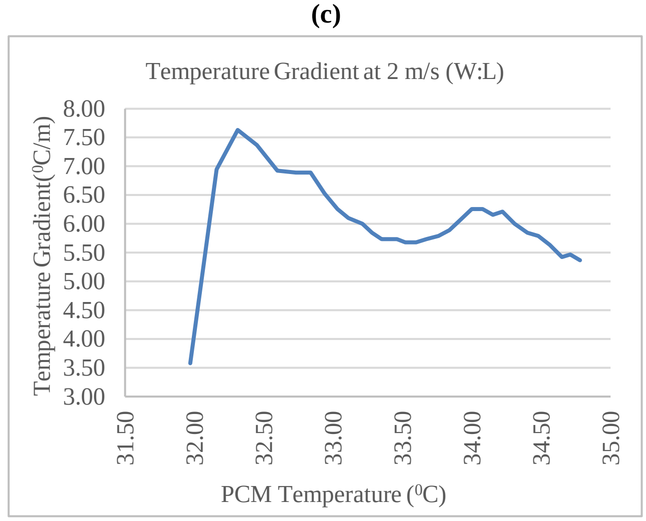

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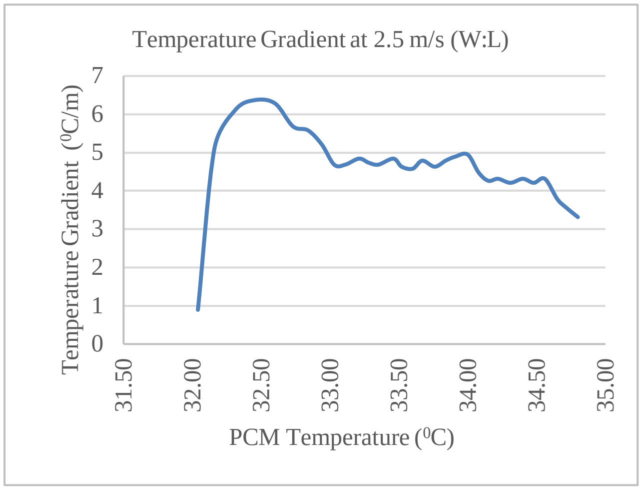
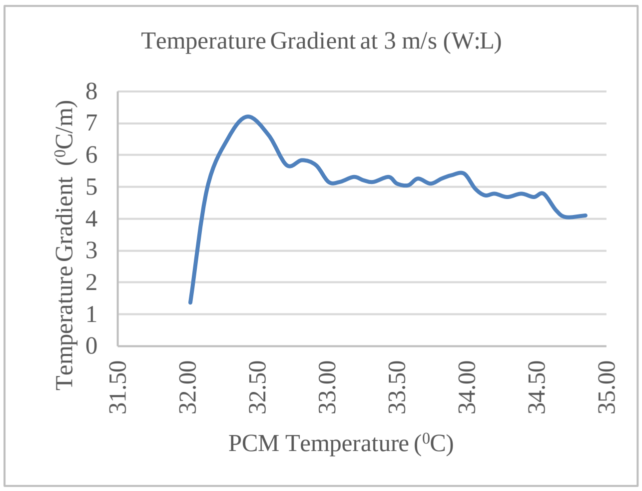


(e)



(f)

Fig. 8 (a-f) Temperature gradient vs. PCM temperature at different velocities and orientations.

Figure 8 (a-c) represents how the temperature gradient along the length varies with the PCM temperature for the L: W orientation of the heat exchanger. Figure 8 (d-f) shows how the temperature gradient along the width varies with the PCM temperature for the W:L orientation of the heat exchanger.

The temperature gradient increases initially, but it tends to decrease afterward. Until the temperature of the PCM reaches the saturation temperature, sensible heat transfer happens, whereas after the PCM temperature attains the saturation temperature, latent heat transfer starts, and the temperature gradient falls. PCM has a peculiar feature of changing the phase over an extremely smaller temperature range, and thus during this period, the temperature gradient is low.

Cooling achieved in each case is calculated and presented in the following graph, which shows an increasing trend with the increasing inlet airflow rate and also a change in orientation.

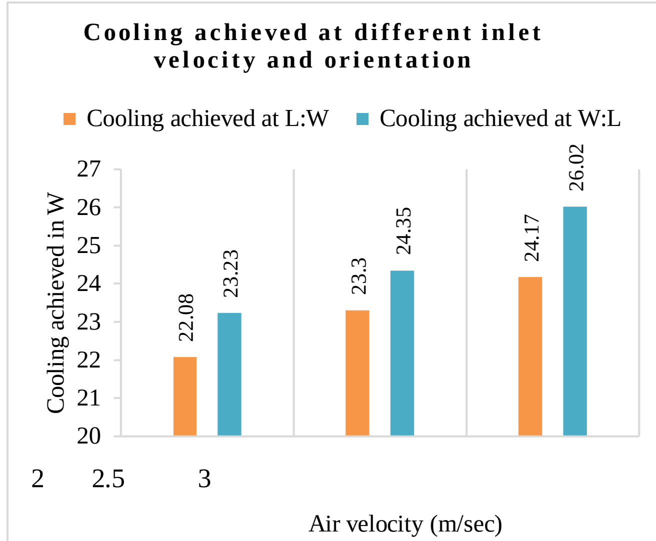


Fig 9. Effect of orientation and inlet airflow velocity on the cooling achieved

The efficiency of the heat exchanger is calculated as,

$$Efficiency of heat exchanger(\%) = \frac{\left(\begin{matrix} Heat\ generated without heat exchanger - \\ Heat\ generated with heat exchanger \end{matrix}\right) \times 100}{Heat\ generated without heat exchanger}$$

The following table shows the efficiency of the heat exchanger for the experiments performed with varying levels of the selected factors.

Table 2. Summary of the results

Experiment No.	Inlet air velocity (m/s)	Orientation	Molten Mass of PCM (kg)	The efficiency of the heat exchanger (%)	% Change inefficiency due to orientation
1	2	L:W	4.7	62.87	
2	2	W:L	4.9	66.13	5.19
3	2.5	L:W	5.6	66.33	
4	2.5	W:L	4.7	69.33	4.52
5	3	L:W	5.2	68.8	
6	3	W:L	5.86	74.07	7.66

IV. CONCLUSION

This work aims at finding the efficiency of the air-PCM heat exchanger used for the free cooling system. An experimental study was done with an air-PCM heat exchanger of designed geometry. The required mass of

PCM is calculated based on the cooling load requirement and latent heat of the PCM. Efforts are made to find the optimum combination of the selected variants and their levels so that total convective heat transfer from the air to the heat exchanger is maximized. Following conclusions are drawn from the study:

- The maximum efficiency of the air-PCM heat exchanger was found to be 74.07% at the highest selected level of the inlet airflow velocity, 3 m/s, and with W:L orientation.
- The efficiency of the heat exchanger increases with the air velocity.
- Efficiency increases for W:L orientation for the same air velocity as compared with L: W. This is because, in W:L orientation, air flows over the shorter length of the heat exchanger. This decreases Reynold's number and increases the convective heat transfer coefficient.
- Temperature gradient vs. PCM temperature graph shows that gradient increases initially which shows that there is sensible heating of the PCM. Temperature falls in the phase change range of the PCM, which shows that there is latent heating of the PCM and thus cooling of the air.
- To increase the duration of cooling, OM35 is effective in lowering room temperature, particularly for hot and dry climates.

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