Performance Evaluation of Phase Change Material Based Free Cooling System

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Session 2018-2021

Supervised by

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Abstract

Greenhouse emissions around the world are increasing day by day due to increase in demand of global energy utilization in buildings for different purposes. Large portion of energy is used for heating, cooling, and air conditioning purposes in buildings. Phase change material (PCM) can be used to store cold during night time which can be used during day time for lowering the temperature of buildings also known as free cooling. This paper presents the mathematical modelling under real time weather conditions (Islamabad) of PCM based free cooling system. Mathematical model was developed using MATLAB with Lauryl Alcohol as PCM. To analyze the performance of free cooling system three other PCMs were selected under suitable melting point range (22 to 28 ˚C) i.e., RT22HC, RT25HC & RT27. The performance evaluation of this system was done on two factors, varying air inlet velocity and air inlet temperature. The charging time for all PCMs can be reduced by 50 to 55% at higher air inlet velocity (3 m/s) and discharging time can be improved by 55 to 60 % at lower air inlet velocity (1 m/s). The optimum air inlet velocity was selected for charging and discharging process on the basis of above results. The effect of varying air temperature was analyzed for the selection of best suitable PCM for free cooling. Cost comparative analysis with conventional air conditioning system was also done to establish the setup for standard room.

Keywords: *Phase Change Material, Free Cooling, Mathematical Modelling*

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Muhammad Qaiser Bashir, Mariam Mahmood, Adeel Waqas. **“PERFORMANCE EVALUATION OF PHASE CHANGE MATERIAL (PCM) BASED FREE COOLING SYSTEM**”. International Conference on Energy, Water & Environment (ICEWE-2021) held on 31st March 2021 in UET Lahore (KSK Campus) (Published).

Abbreviation & Acronyms

PCM	Phase change material	T_m	Melting temperature of PCM
LHTES	Latent heat thermal energy storage	Q_{cold_abs}	Amount of cold absorbed by PCM
TES	Thermal energy storage	$\dot{m}_{air}$	Mass flow rate of air
HTF	Heat transfer fluid	C_{p_air}	Specific heat constant of air
ρ_{pcm}	Density of PCM	h	Convection heat transfer coefficient
λ	Latent heat of PCM	A_{HT}	Surface area of boundary node
H	Enthalpy of PCM	ΔT_{air}	Temperature difference between outlet and inlet air
C_{pcm}	Specific heat constant of PCM	T_{air_in}	Inlet temperature of air
T_{pcm}	Temperature of PCM	T_{air_out}	Outlet temperature of air

Chapter 1

Introduction

1.1 Background & Introduction

Buildings utilize more than 40% of the total global primary energy out of which 20 % is consumed by HVAC system [1], [2] contributing in the degradation of the environment. Researchers are working to minimize the energy demand for buildings which is consuming most of it on cooling and heating operations [3]. A lot of work is being done on free cooling as many phase change materials (PCM) can be used to store cold of night as latent heat of fusion and during day time this can be used to reduce the temperature of building [4], this energy storage is called as latent thermal energy storage [5] , [6].

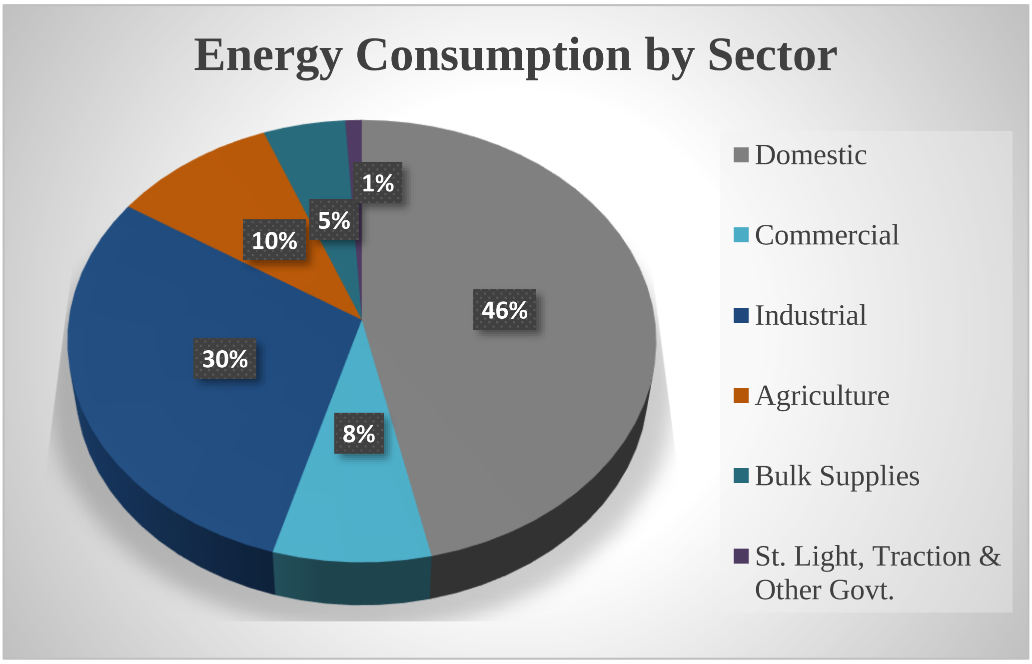


Figure 1.1: Energy consumption in different sectors of Pakistan [21]

PCM can be used more efficiently as heat storage as compared to cold storage [7]. Various problems have been faced during cold storage like encapsulation of PCM, suitable thermal physical properties of PCM and varying weather conditions [8]. Free cooling is most suitable for moderate climate zones and desert areas [9]. Due to more windy conditions in coastal areas temperature of those areas are moderate and greatly affects the efficiency of free cooling [10]. Having large surface area per storage volume can reduce the charging time of PCM during night time [11]. During charging process at night air inlet velocity should be higher and in last stage lower air. Air velocity plays a vital role in determining the capacity [12], [13] and power consumption of the fan so optimization of air inlet velocity must be regulated and optimized according to the conditions [14], [15].

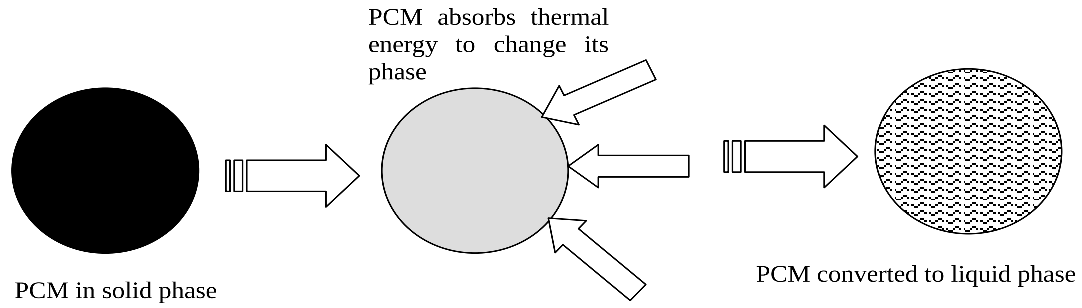
Climate conditions plays an important in selection criteria of ideal PCM for cooling purposes. Areas where temperature gradient of 10 °C is available between PCM and ambient air is most suitable for free cooling and if temperature gradient is less than 10 °C incomplete charging of PCM will be an issue during night time and if temperature gradient is more than 10 °C during day time discharging of PCM will be more rapidly [5]. Due to higher energy density PCMs can be used to store more energy as compared to its size and sensible heat storage system. However, due to lower thermal conductivity it is rather difficult to utilize the full capacity of the system [16]. This issue has been more prominent in which organic PCM has been used. To minimize effect of lower thermal conductivity on efficiency of PCM based system a lot of research has been done using different techniques [17]. Techniques which are used to address the issue are fins incorporation on heat exchanger, compound matrices, high conductivity materials addition and PCM encapsulation in smaller units which is called as micro-encapsulation [2]. Various techniques were adopted to overcome the issue of analyzing convection heat transfer in liquid phase and motion of solid in the melt due to density gradients [18].

1.2 Thermal Energy Storage

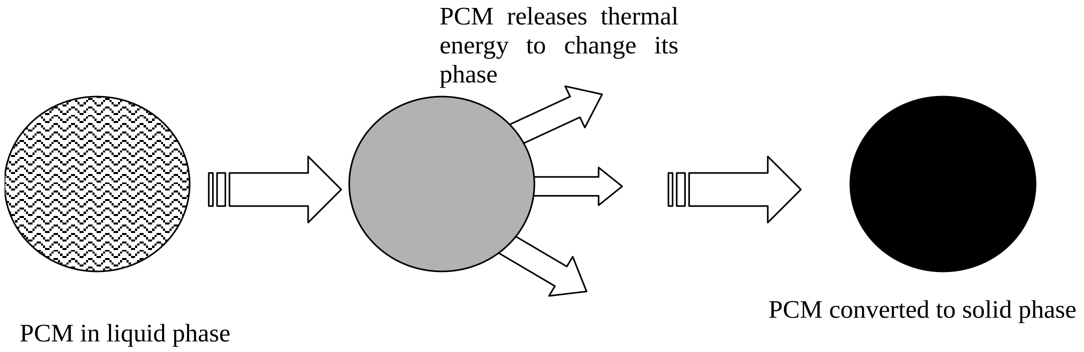
Due to usage of energy increases day by day, energy storage become an active field of research. Thermal energy storage system are incorporated into existing systems and are being integrated with free cooling system to increase the efficient utilization of ventilate cooling [17], [18]. Thermal energy storage may consist of sensible heat storage, latent heat storage or thermochemical heat storage. In recent decades latent heat storage get more focus owing to its durability, availability of various material for it and other silent performance indicators.

1.2.1 Phase Change Material

Phase change materials usually known as PCMs have a storage chamber to store the LHTE. These materials have changed the phase and the ability of store and release heat during their phase transformation.



Cooling affect



Heating affect

Figure 1.2: Latent heat thermal energy storage [2]

1.3 Scope

In recent past, different methods are being used to reduce cooling load of buildings and different methods and policies were introduced in designing buildings, apartments and houses which made them energy efficient. Evaporative cooling techniques using insulation, shades and other methods have been a great success in reducing fossil fuel consumption for electricity generation in buildings. These methods somehow utilize electricity in order to produce cooling effect [19]. Another technique which is gaining importance nowadays is cold storage using PCM. In this method cold air is utilized to capture cold in the PCM at night when atmospheric temperature is low then PCM temperature. This is called the charging procedure and during the day when temperature raises this cold is transferred to the atmosphere lowering the ambient temperature and reducing the air conditioning load.

1.4 Working Principle

The working principle of PCMs is firstly, the material is in liquid form at day time. The material at this stage have no energy stored as the ambient temperature decrease till the material starts to solidify as the material change its phase the energy stored is called latent heat [2], [11].

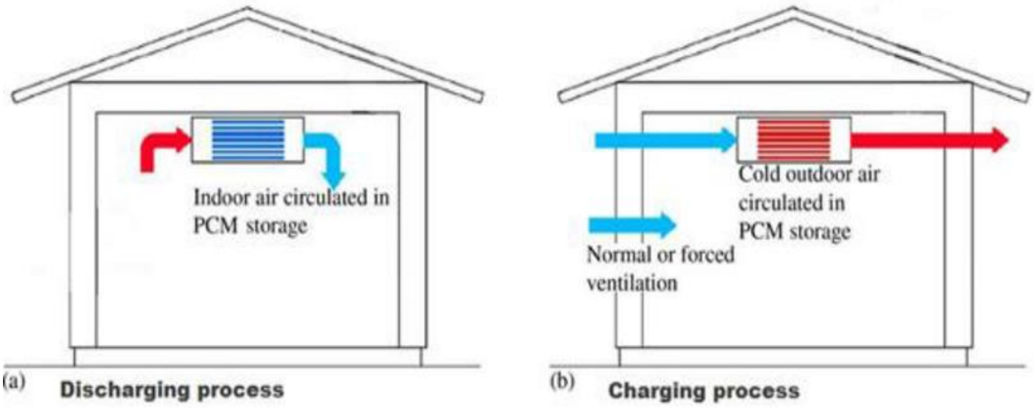


Figure 1. 3: Working principle of free cooling

(a) Day time, Discharging of PCM (b) Night time, Charging of PCM [17]

As from figure 1.3 charging cycle comprises of energy storing from the surrounding and leading to phase transition (liquid to solid), discharging cycle compromise release of stored energy when hot air pass through it during day time and it convert to solid to liquid. The endothermic and exothermic phase transition results in the charging and discharging of PCM [20].

1.5 Research Statement

The thermo-physical properties of PCM plays an important role for designing the free cooling system like melting point range, specific heat and thermal conductivity were evaluated through literature review. The performance of PCM based free cooling system also depends on differing operating parameters like air inlet velocity and temperature for charging and discharging of PCM. This study gives theoretical and experimental insight on the energy storage behavior of PCMs suited for free cooling.

Different PCMs are available in the literature with different melting points, however in the current study it is selected based on the desired temperature range for cold storage. Lauryl Alcohol and three other PCMs i.e., RT22HC, RT25HC and RT27 were selected for developing the numerical model and experimental validation and further performance evaluation of the system.

1.6 Objectives

- Designing and mathematical modelling of the PCM based free cooling system.
- Selection of PCMs on basis of their thermos-physical properties and required temperature range (22-28 ˚C).
- Comparative & parametric sensitivity analysis under different operating conditions.
- Sizing of the system and cost analysis of PCM based free cooling system in comparison with conventional AC system.

1.7 Organization of Thesis

Following pathway is adopted for studying the PCMs based free cooling system.

- **Chapter 1: Introduction**
  Background, Objectives, TES, PCMs, Working Principle, Research Statement
- **Chapter 2: Literature Review**
  Types of phase change materials, properties of phase change material, selection criteria, encapsulation, charging and discharging behavior and comparison of old investigations on PCM based system and relate them with new developments.
- **Chapter 3: Methodology**
  Brief introduction how to proceed, flow chart to achieve objectives
- **Chapter 4: Mathematical Modelling & Experimental Setup**
  Details of mathematical modelling, equations used to solve the problem, Details of selected PCMs, Design parameters of heat exchanger, Thermophysical properties of PCMs and air used in model, Boundary conditions identification, Experimental setup
- **Chapter 5: Results and Discussion**
  Validation of mathematical model with experimental results, Performance evaluation of TES at different air inlet velocity & temperature on charging and discharging process of selected PCMs.
- **Chapter 6: Sizing of system and Cost Analysis**
  In this chapter sizing of free cooling system was done for the standard room. Comparative analysis of cost and payback period for free cooling system was also calculated in this chapter.

- **Chapter 7: Conclusion and Recommendations**

  In the end conclusion were drawn on the basis of above results and PCM which was most suitable for free cooling selected. Recommendations were also suggested for future research in this field.

Summary

This section discusses the background of the problem that how buildings and residential sector share the major portion of around 40 % of energy utilization around the globe. Different techniques and methods and steps are being taken to resolve this issue which is discussed in the next chapter. One of the growing solutions to this problem is the notion of free/passive cooling via TES.

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Chapter 2

Literature Review

In this chapter method or techniques already available in literature are discussed. Material focuses on cooling techniques, types of PCM, encapsulation techniques and method to design system.

2.1 Techniques for Cooling

Different techniques are available in literature that set out for cheaper cooling of domestic buildings [1], [2].

Evaporative cooling utilizes evaporation principle to cool down ambient air. Air is cooled when water evaporates but this also adds humidity, which made this technique ineffective in areas of humid climate. **Soil cooling** works on passing air through a depth of 2-3 m and allowing it to cool. This technique also becomes ineffective for large buildings as it requires heavy mechanical devices like pump for circulating air. **Ventilating cooling** allows fresh cool air to enter buildings at high velocity and it forces hot air to leave the building thus cools the building [1].

Cold Storage also utilizes ventilation cooling technique. At night cold air that is used for ventilation, charges the PCM which gets discharge at day resulting in cooling of building [3] which also called as free cooling shown in figure 2.1.

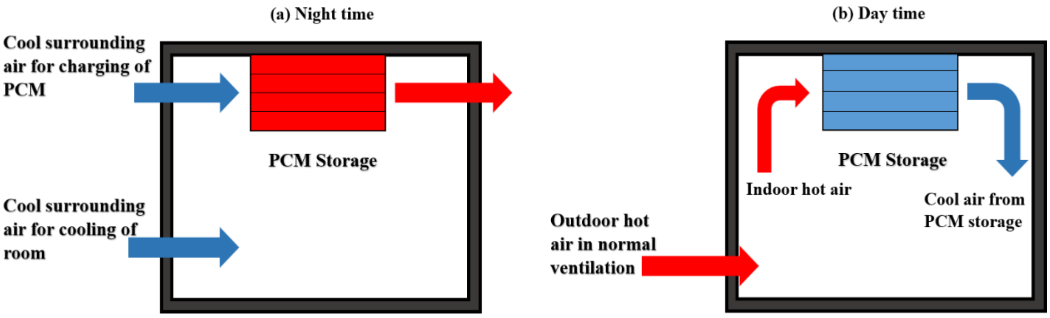

Figure 2.1: Working principle (a) Charging of PCM during night time (b) Discharging of PCM during day time [15]

2.2 Types of PCM

Phase change materials can be classified into three major groups Organic, Inorganic and eutectics as shown in figure 2.2.

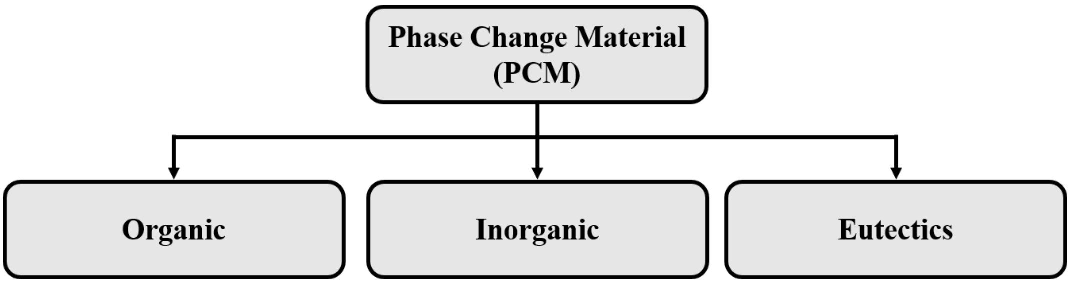

Figure 2.2: Types of PCM [1]

Organic PCMs are classified as paraffin and non-paraffin. Organic resources contain similar melting, self-nucleation and typically non-corrosiveness to the flask core. Generally organic PCMs consumed for cooling and heating in buildings have temperature between 20-32˚C.

Inorganic PCMs are more categorized as salt hydrate and metallic. An inorganic compound has a more latent energy per unit volume and mass, inexpensive associated to organic substances and is non-flammable. These materials get affected from decay and super cooling which further disturb their phase change characteristics. They are consumed for high temperature storages.

Eutectics are a minimum-melting alignment of more than two elements. Every component melt and freeze consistently making combination of the fundamental crystals at the time of crystallization [1].

Table 2.1: Advantages and disadvantages of different PCM groups [1]

PCM group	Advantages	Disadvantages
Organic PCMs	• No sub cooling and corrosion issues. • Chemically stable • Non-reactive with different type of PCM containers. • Available in desired temperature ranges meeting the application demand.	• Highly Flammable • Lower thermal conductivity issue. • Larger volume changes. • Technical grade PCMs are high in cost.

In Organic PCMs	• High latent heat along with higher thermal conductivity. • Volume changes are low during melting and solidification. • Non Flammable. • Low cost with ease in available.	• Highly corrosive • Large degree of super cooling and sub cooling that can affect the desired results. • Corrosive nature that can degrade the PCM container and capsulation. • Not compatible with micro and nano capsulation techniques.
Eutectic PCMs	• Sharp phase change temperature like a pure substance • Higher thermal conductivity compared to the other types • Thermal storage density per unit volume is very high	• Costly and limited availability

2.3 Selection of PCM

PCM is selected on the basis of its melting temperature and heat of fusion. Table 2.2 shows selection range of the parameter of material. Materials consumed as PCM in free cooling is shown in Table 2.2 [2] , [4]. Melting temperature range is chosen on the basis of ambient temperature. PCM temperature should be less than ambient temperature for cold storage, and min. temperature range of 4-5˚C is required [5]. Latent heat decides the charging and discharging time of PCM. High heat of fusion means high charging and discharging time and vice versa [6]. Properties which plays an important role in selection of PCMs are discussed below [1]

a. Thermo-Physical properties

- Suitable selection of PCM on the basis of their melting point which must be in desired range.
- Conductivity must be high
- Higher latent heat per unit volume
- High specific heat capacity

b. Chemical properties

- Chemical stability.

- Non-corrosive in nature.
- Non-toxic, non-flammable and non-explosive.

c. Kinetic properties

- No super-cooling or sub-cooling
- High crystallization rate.

Table 2.2: PCM selection properties

Properties	**Range**
Melting Point	22-28 °C
Latent Heat	150-200 kJ/kg
Thermal conductivity	0.2-0.6 W/m.K

Table 2.3: Properties of PCM [1]

PCM Name	**Nature**	**Melting Point**	**Latent Heat**	**Density**	**Thermal conductivity**
		(°C)	**(kJ/kg)**	**(kg/m^3)**	**(W/m.K)**
Lauryl Alcohol	alcohol/organic	24	200	830	0.2
$CH_3(CH_2)11OH$	Organic	26	200		
SP25 A8	Blend/hydratesalt	25	180	1350	0.5
S27	salt hydrate	27	183		0.48
Heptadecane	organic/paraffin	21.7	213		0.21
D-Lattic acid	Organic	26	184		
n-Octadecane	paraffin/organic	27	243	750	0.2
$LiBO_2 .8H_2O$	salthydrate/inorganic	25.7	289		
Paraffin RT27	paraffin/organic	27	179	800	0.2
STL27	salt hydrate/inorganic	27	213		
$Na_2CO_3.10H_2O$-$Na_2HPO_4.12H_2O$	Eutectic	24.9	182.7		
Paraffin C13–C24	paraffin/organic	24	189	760	0.21
RT22HC	paraffin/organic	22	200	760	0.2
RT25HC	paraffin/organic	25	230	880	0.2
RT27	paraffin/organic	27	189	800	0.2

On the basis of above selection criteria and thermo-physical properties four PCMs are selected for development of mathematical model and performance evaluation of the system. Lauryl Alcohol will be used to develop the mathematical model on MATLAB and experimentation to validate the model. To further analyze the performance of system three other PCMs i.e. RT22HC, RT25HC & RT27 are selected.

2.4 PCM Encapsulation Technique

Encapsulation includes covering of PCM with a suitable coating or covering like shell. Different techniques are used to encapsulate PCM for cold storage [7]. PCM encapsulation is executed due to following reasons [8], [9].

i. Reduction in PCM reaction with surroundings.
ii. Enhance in heat transfer rate.
iii. Enhancement in mechanical and thermal stability.
iv. This encapsulation also works as heat exchanger among air and PCM

2.4.1 Micro-Encapsulation Method

In this method, tiny specks of PCM are sealed off in small shells. The dimension of these shells ranges from 1 µm to 1000 µm. Micro-Encapsulation results in a higher heat transfer rates associated to macro-encapsulation. Also it provides better heat transfer zone, decreases PCM reactivity en route for the external environment and switches the volumetric change of PCM during phase change process. Normally micro encapsulation utilizes polymers for shell materials. Sari et al. shows microencapsulated PCM is more thermally reliable and chemically stable compared to macro encapsulated PCM [2], [7]. Major disadvantage of this techniques are:
i. Complex Manufacturing due to its small size

ii. Increase in the possibility of super cooling

2.4.2 Macro-Encapsulated Method

In this method, PCM is added in thicker container like tube or packets compared to microencapsulation. Thickness of these containers varies from 1 mm and above and also acts as heat exchanger [10]. Unlike micro encapsulation it is easy to manufacture but its major disadvantage is that it results in a temperature difference between PCM core and boundary, thus preventing effective heat transfer. It uses metallic material for shell if high heat transfer is required, else plastic material is normally used.

Table 2.4: Comparison between PCM encapsulation techniques [7]

Parameters	**Macro Encapsulation**	**Micro Encapsulation**	**Nano Encapsulation**
Encapsulation Thickness	1 mm and above	1 µm to 1000 µm	1 nm to 1000 nm
Heat Transfer	Temperature difference between PCM core and boundary	More efficient than macro-encapsulation	Efficient than both techniques
Manufacturing	Easy	Complex	Complex
Encapsulation Material	Mostly Plastic. Metallic material is used if high heat transfer is required	Polymer	Polymer
Thermal and Chemical Stability	Not stable	Stable	Stable
Structural Strength	Low	Low	Maximum
Commercial Availability	Available	Available	Not Available

2.4.3 Nano Encapsulation method

Nano encapsulation is an advanced emerging technique which is still in research phase. Thickness of this encapsulation is from 1 nm to 1000 nm. Sukhorukov et al. performed structural tests on a 10 nm and 10 µm poly electrolyte and found that 10 nm shell was less deformed. Nano-encapsulation is more structurally stable compared to former two techniques. But it is still in research phase and more work is required to bring it to commercial use like its former two techniques. It also utilizes Polymers to manufacture shell for encapsulation.

2.5 Methods available in Literature

Different techniques have been identified in research for PCM based cooling system. For better understanding, some of them are explained below along with their experimental setups.

Arkar et al. developed LHTES mathematical model in which PCM was assumed to be encapsulated in spheres. The mathematical model was assumed to be unsteady and 2D continuous solid phase packed bed model for PCM given in equation (1). The finite difference approximation method was used to solve the heat transfer problem between HTF (air) and PCM described in equation (2). In this study he analyzed the efficiency, suitable size, peak temperature of PCM [3].

$$\varepsilon(\mathrm{r})\rho \mathrm{c}\frac{\partial \mathrm{T}}{\partial t}+\mathrm{u}(\mathrm{r})\rho \mathrm{c}\frac{\partial \mathrm{T}}{\partial x}=k_{eff,x}\frac{\partial^2 \mathrm{T}}{\partial x^2}+k_{eff,r}\left(\frac{\partial^2 \mathrm{T}}{\partial r^2}+\frac{1}{r}\frac{\partial \mathrm{T}}{\partial r}\right)+\ h_{eff}a_p(r)(\theta-T) \quad (1)$$

$$\left(1-\varepsilon(\mathrm{r})\right)\rho_{PCM}c_{eff}(\theta)\frac{\partial \theta}{\partial t}=\ h_{eff}a_p(\mathrm{r})(\mathrm{T}-\theta) \quad (2)$$

The mathematical model was developed by Saman et al. to solve the heat transfer problem between air-PCM based thermal energy storage. This model is based on enthalpy as dependent variable instead of temperature [11], [1]. The total enthalpy of the storage unit is sum of sensible and latent heat of the PCM which can be expressed as follows:

$$\mathrm{H}=\begin{cases}\rho_{\mathrm{pcm}}.\mathrm{C}_{\mathrm{pcm}}(\mathrm{T}_{\mathrm{pcm}}-\mathrm{T}_{\mathrm{m}}) & \text{if } \mathrm{T}_{\mathrm{pcm}}<\mathrm{T}_{\mathrm{m}} \text{ Solid region}\\ \rho_{\mathrm{pcm}}.\mathrm{C}_{\mathrm{pcm}}\left(\mathrm{T}_{\mathrm{pcm}}-\mathrm{T}_{\mathrm{m}}\right)+\lambda.\rho_{\mathrm{pcm}} & \text{if } \mathrm{T}_{\mathrm{pcm}}>\mathrm{T}_{\mathrm{m}} \text{ Liquid region}\end{cases} \quad (3)$$

After calculating the enthalpy of PCM we can calculate the temperature of PCM using following equations:

$$\mathrm{T}_{\mathrm{pcm}}=\begin{cases}\mathrm{T}_{\mathrm{m}}+\dfrac{\mathrm{H}}{\rho_{\mathrm{pcm}}.\mathrm{C}_{\mathrm{pcm}}} & \text{if H } < 0\\ \mathrm{T}_{\mathrm{m}} & \text{if } 0 \le \mathrm{H} \le \rho.\lambda\\ \mathrm{T}_{\mathrm{m}}+\dfrac{\mathrm{H}-(\rho_{\mathrm{pcm}}.\lambda)}{\rho_{\mathrm{pcm}}.\mathrm{C}_{\mathrm{pcm}}} & \text{if H } > \rho.\lambda\end{cases} \quad (4)$$

After calculating the temperature of PCM from equation (2) liquid fraction of PCM was calculated. Liquid fraction can be defined as the amount of PCM which is either in liquid state, solid state and mushy region. Liquid fraction can be calculated using following equation:

$$L.F(H) = \begin{cases} 0 & if \quad H \leq 0 & solidphase \\ \frac{H}{\rho_{pcm}.\lambda} & if \quad 0 < H < \lambda . \rho_{pcm} & mushyregion \\ 1 & if \quad H \geq \lambda . \rho_{pcm} & liquidphase \end{cases} \tag{5}$$

Where ρ_{pcm} the density of PCM, λ is the latent heat of PCM, H is PCM enthalpy, C_{pcm} is specific heat constant of PCM, T_{pcm} is the Temperature of PCM and T_m is the melting temperature of PCM. Saman et al. solved the above equations by using finite difference method using implicit based numerical solving method.

Experimental setup was built by K. Panchabikesan et al. in which PCM was encapsulated in PCM RT 28HC encapsulated in high density polyethylene (HDPE) spherical balls and was integrated with direct evaporative cooling (DEC) system. Experiment was performed to analyze the effect of DEC system on charging and discharging of PCM [12].

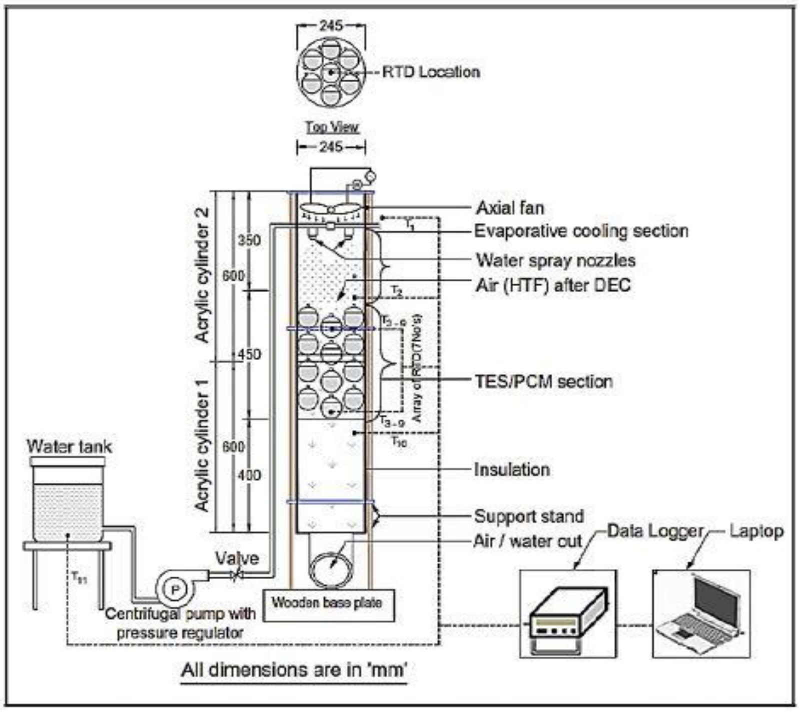

Figure 2.3: PCM based free cooling system integrated with DEC system [12]

Numerical study carried out by N.H.S Tay et al. shows the influence of tube in tank heat exchanger. The 3D model of tube in tank heat exchanger was developed in ANSYS to monitor the melting of PCM. This model was solved by using unsteady Navier–Stokes equations. Phase change time can be decreased by 36 % if mass flow rate of PCM is five times greater than the mass flow rate of HTF [13].

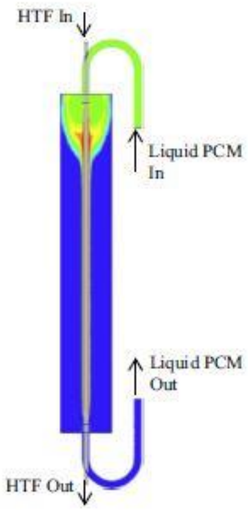

Figure 2.4: Tube in tank type storage device [13]

A.A. Rabienataj et al. developed physical and numerical model for plate type PCM storage. The temperature distribution was solved by thermal energy equations. The total enthalpy H of storage unit is calculated using following equation:

$$\mathrm{H} = h + \Delta H \tag{6}$$

$$h = h_{ref} + {}_{T_{ref}}^{\;\;T}\!\int C_p dt \tag{7}$$

Where h is the sensible enthalpy of storage unit and ΔH is latent heat enthalpy of the unit.

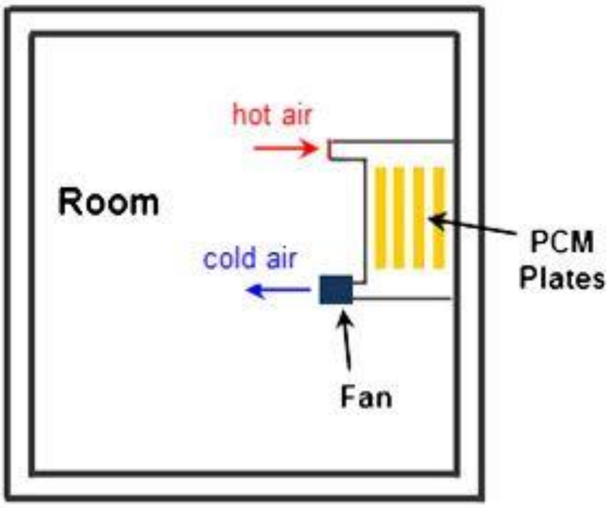

Figure 2.5: Plate type PCM storage [14]

Thickness of PCM plates were set to 1 mm and thermal conductivity of plate was 237 W/m.K. According to the results PCM melts faster at higher Stefan number and higher mass flow rate. By varying the Stefan number from 0.1 to 0.167 reduce the time required for melting by 37 %. By increasing the mass flow rate from 0.018 to 0.036 Kg/s reduce the melting time by 30 % [14].

Summary

This section comprises of literature review of different techniques available for cooling. Literature review shows that PCM for thermal storages are divided in three categories and based on literature, PCM selection criteria is developed. Lauryl alcohol was selected based on market survey and availability of PCM in desired range of properties. Three other PCMs i.e. RT22HC, RT25HC, RT27 were selected on the basis of their thermal-physical properties for performance evaluation of the system. In the end of this chapter different methods and PCM available in literature for thermal storage have been discussed.

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Chapter 3

Methodology

The methodology to meet the objectives is clearly defined in the process chart in figure 3.1. This study includes the theoretical design with mathematical modelling on MATLAB, validation through experimentation and performance evaluation of system.

Theoretical design of system includes the design of heat exchanger and selection of PCMs on the basis of their thermo-physical properties. Mathematical model of the system was developed on MATLAB and validation of model was done through experimentation. Thermo physical properties of the PCM are significant for design and performance evaluation of the PCM based free cooling system however it would be taken into account that it is noncombustible inexplosive and nature friendly. Melting point, latent heat, thermal conductivity and specific heat values must be in suitable range for this study.

Performance evaluation of this system is done by considering different parameters like air inlet velocity, selection of suitable air inlet velocity for charging discharging process and effect of different charging source temperature of air. Three PCMs will be selected on the basis of melting point, latent heat and thermal conductivity and performance of these PCMs will be analyzed through mathematical model developed in MATLAB and suitable PCM will be selected for best results for free cooling.

3.1 Methodology

Methodology to achieve these objectives is defined below in the process chart. Task performed in each phase are shown below.

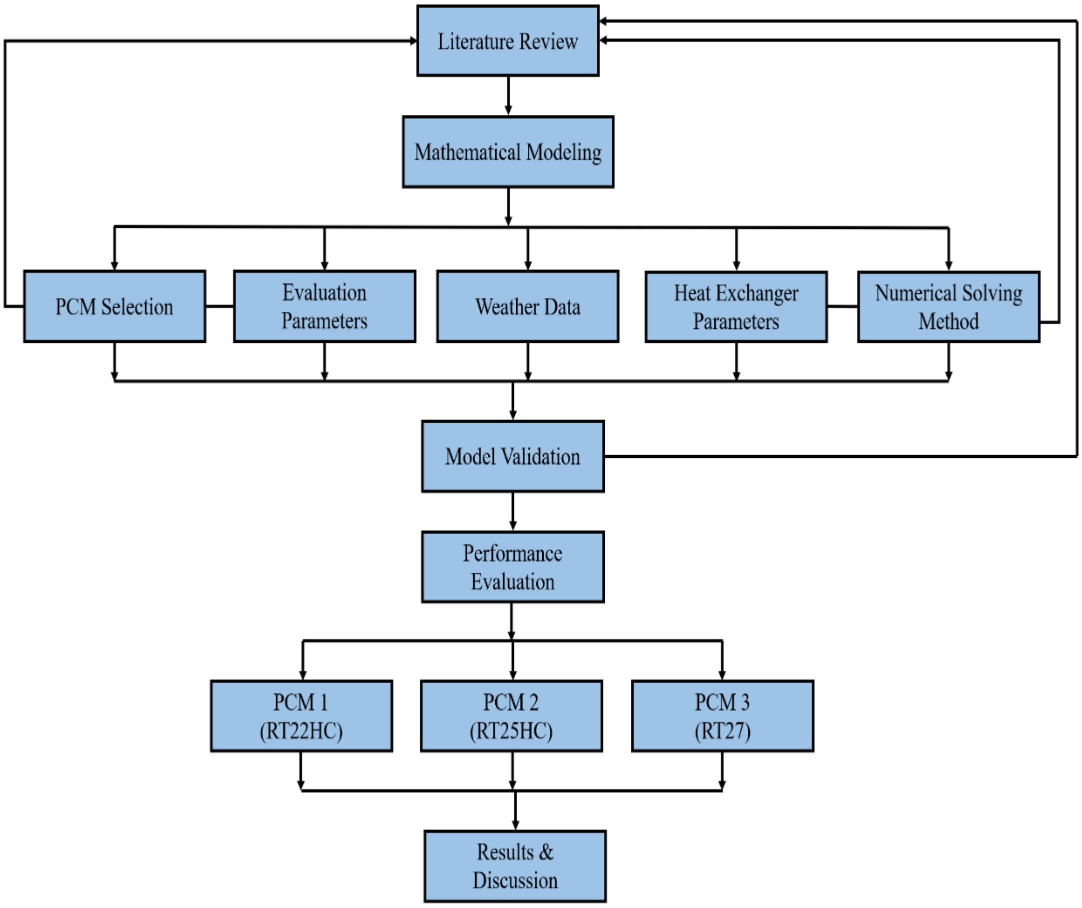

Figure 3.1: Methodology

Summary

In this chapter the methodology that defines how to carry out the work is properly discussed. The selection of PCM is depending on the local availability of material and its thermo physical properties. Theoretical design and mathematical Modelling of setup take place according to the detail study of literature review and the experimentation conducted at Solar Energy Research Laboratory at USPCAS-E NUST.

Chapter 4

Mathematical Modelling & Experimental Setup

4.1 Mathematical Modelling

1-D steady state mathematical model of heat exchanger was developed using MATLAB and explicit method was used to solve the equations. Enthalpy method was used to solve the heat transfer between HTF and different PCMs. Charging and discharging of all selected PCMs were analyzed under steady state for four hours. Total length and width of heat exchanger used in this setup was 0.3302 m and 0.3048 m respectively. Length of pipe in which PCM was encapsulated was 1.524 m. Table 4.1 shows the design parameters of the experimental setup established in Laboratory of USPCAS-E [1]. For analyzing length of PCM was divided into three parts, conduction & convection was studied in the first part while in second- and third-part conduction process was studied. Table 4.1 shows the design values of heat exchanger model used in mathematical modelling and experimentation and table 4-2 shows the thermophysical properties of air at 25 ˚C.

Table 4.1: Design values of heat exchanger [1]

Parameter	**Value (m)**
TES Device Width	0.3048
TES Device Length	0.3302
Length of Aluminum Tubes for PCM	1.524
Diameter of Aluminum Tubes	0.0127
Air Inlet & Outlet Diameter	0.0254
Slab Length	0.254
Slab Width	0.0762

Table 4.2: Thermo-physical properties of air at 25 ˚C

Property	Value
Thermal Conductivity	0.02588 W/m.℃
Density	1.27 Kg/m^3
Specific Heat	1.007 kJ/Kg. ℃
Viscosity	1.5 x 10^{-5} Kg/m. sec

Assumptions for this mathematical model are as follows:

- Air flow from the source was taken in 1-D
- Thermo-physical properties were assumed to be constant for complete cycle.
- Temperature of air was assumed to be steady state (constant) for complete cycle.
- Heat losses from heat exchanger to environment were neglected.
- Effect of turns of PCM encapsulation was neglected.
- HTF was assumed to be in contact with PCM as aluminum tube encapsulation was neglected.

4.1.1 Weather Data

Figure 4.1 shows the ambient temperature and relative humidity of year 2018 for the month of March and Figure 4-2 shows the ambient temperature of complete day of march which was collected from weather data system installed in USPCAS-E. On the basis of above data boundary conditions used for mathematical modelling at the inlet of heat exchanger i.e, temperature of inlet air for charging and discharging of PCM was 21 and 30 ˚C respectively and 2 m/s air inlet velocity was used for validation of results. For performance evaluation of system air inlet velocity of 1, 2 & 3 m/s and air inlet temperature of 18, 19 & 20 ˚C for charging and 32, 34 & 36 ˚C was used during discharging process of all PCMs.

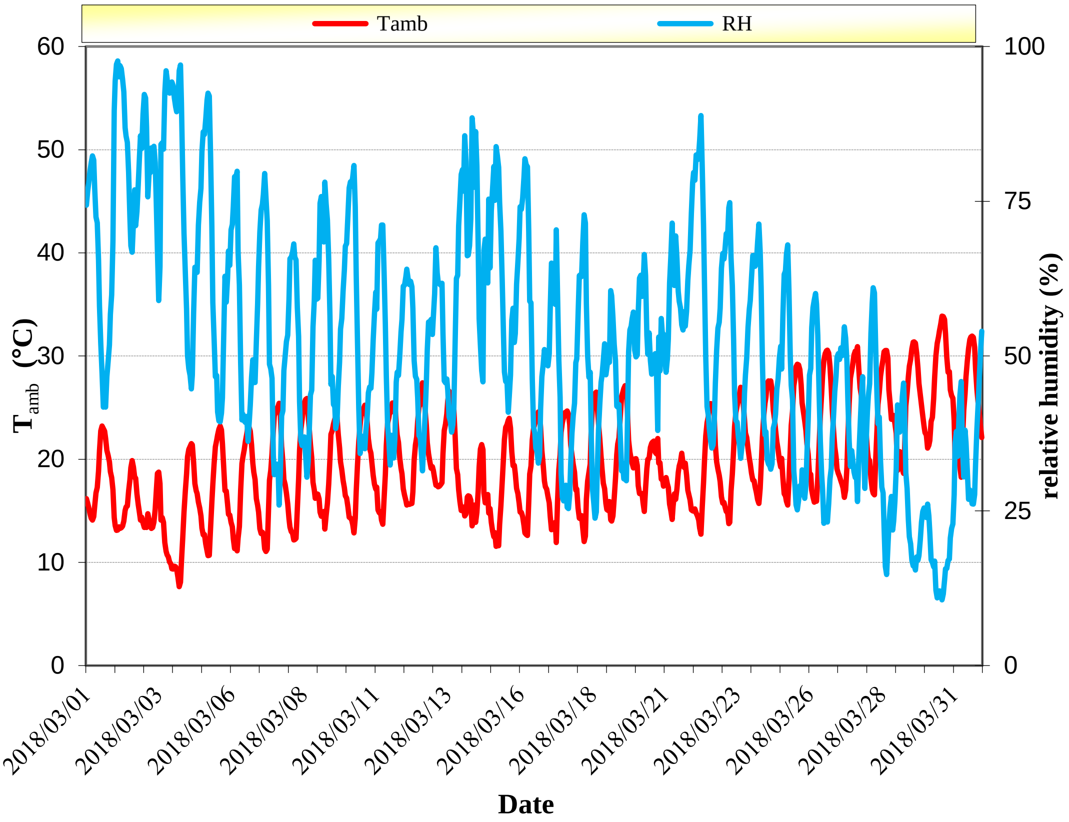

Figure 4.1: Ambient temperature and relative humidity of March 2018

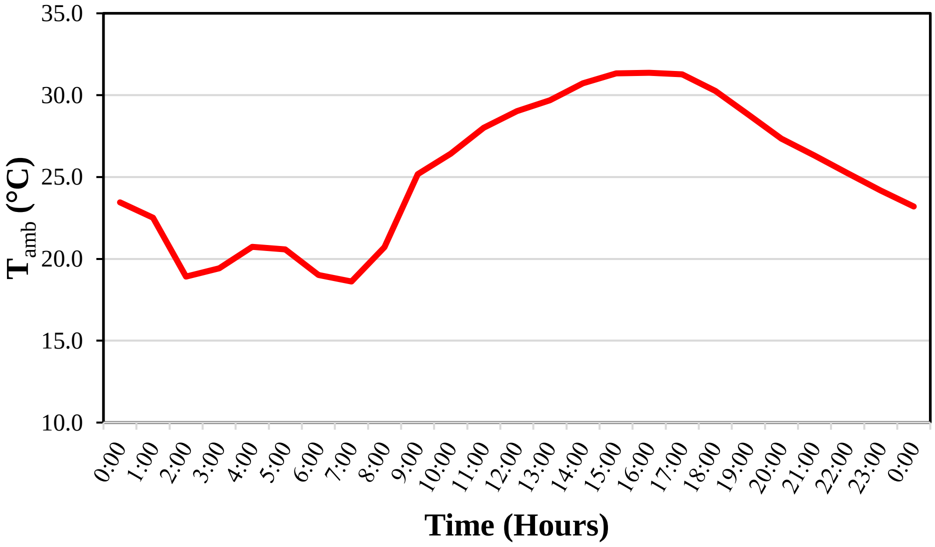

Figure 4.2: Hourly ambient temperature of air for complete day (30-03-2018)

4.1.2 PCM selection

PCM selection is the most important part in designing free cooling system and it depends on number of factors like thermo-physical, chemical and kinetic properties already discussed in section 2.3 of chapter 2. According to the literature review and these properties fours PCMs were selected. Table 4.3 shows the properties of Lauryl Alcohol used in experimentation and three other selected PCMs to evaluate the performance under different conditions. In mathematical modelling to analyze the performance of PCM, effect of encapsulation was not considered and it was assumed that PCM was placed as single slab and air was interacting with it directly.

Table 4.3: Thermo-physical properties of PCMs used in mathematical model [2]

Properties	**Density**	**Latent Heat**	**Melting Point**	**Thermal Conductivity**
PCM	**Kg/m^3**	**kJ/Kg**	**˚C**	**W/m.˚C**
Lauryl Alcohol	831	200	22-26	0.2
RT22HC	760	190	22	0.2
RT25HC	880	230	25	0.2
RT27	800	189	27	0.2

4.1.3 Governing Equations

The mathematical model for this system was developed using enthalpy method to solve the heat transfer between air and PCM [3], [2]. First of all convective heat transfer coefficient for air h_{air} was calculated using the following formula:

$$h_{air} = \frac{k_{air} * \mathrm{Nu}}{L} \tag{6}$$

where k_{air} is the thermal conductivity of air, Nu is Nusselt number and L is the hydraulic length. Nusselt number was calculated using following formula:

$$\mathrm{Nu} = 0.023 * {Re_{air}}^{0.8} * Pr^{0.3} \tag{7}$$

where Re_{air} is the Reynold number for air and Pr is the Prandtl number. Reynold and Prandtl number were calculated using following equations:

$$Re_{air} = \frac{\rho_{air} * v_{air} * \mathrm{L}}{\mu} \tag{8}$$

$$Pr = \frac{\mu * C_{air}}{k_{air}} \tag{9}$$

where μ is viscosity of air at 25 ˚C, v_{air} is the velocity of air and C_{air} is the specific heat constant of air. Nusselt, Reynold & Prandtl number was calculated using equation (7), (8) & (9). Heat transfer coefficient of air was calculated after putting the values of these numbers in equation (6).

Initially enthalpy of PCM storage H_0^i can be calculated using the following formula:

$$H_0^i = \begin{cases} \rho_{\mathrm{pcm}}.\,\mathrm{C}_{\mathrm{pcm}}(\mathrm{T}_{\mathrm{pcm}} - \mathrm{T}_{\mathrm{m}}) & \text{if } \mathrm{T}_{\mathrm{pcm}} < \mathrm{T}_{\mathrm{m}} \text{ Solid region} \\ \rho_{\mathrm{pcm}}.\,\mathrm{C}_{\mathrm{pcm}}(\mathrm{T}_{\mathrm{pcm}} - \mathrm{T}_{\mathrm{m}}) + \lambda.\,\rho_{\mathrm{pcm}} & \text{if } \mathrm{T}_{\mathrm{pcm}} > \mathrm{T}_{\mathrm{m}} \text{ Liquid region} \end{cases} \tag{10}$$

The energy balance technique was applied to calculate the enthalpy of PCM at initial node (m=0).

$$h_{air}A(T_{air}^i - T_0^i) + kA\frac{T_1^i - T_0^i}{\Delta y} = \rho_{pcm}A\frac{\Delta y}{2}C_{pcm}\frac{T_0^{i+1} - T_0^i}{\Delta t} \tag{11}$$

Above equation can be written in terms of enthalpy as:

$$H_0^{i+1} = H_0^i + \frac{2.\Delta t.k}{\rho_{pcm}.\Delta y^2}\left(T_1^i - T_0^i\right) + \frac{2.\Delta t.h_{air}}{\rho_{pcm}.\Delta y}(T_{air}^i - T_0^i) \tag{12}$$

Similarly, energy balance was applied at the inner nodes:

$$H_m^{i+1} = H_m^i + \frac{\Delta t.k}{\rho_{pcm}.\Delta y^2}\left(T_{m-1}^i - 2T_m^i + T_{m+1}^i\right) \tag{13}$$

The temperature of PCM at all nodes after every time step was calculated using following equations:

$$T_{pcm} = \begin{cases} T_m + \dfrac{H}{\rho_{pcm}.C_{pcm}} & \text{if } H < 0 \\ T_m & \text{if } 0 \leq H \leq \rho.\lambda \\ T_m + \dfrac{H - (\rho_{pcm}.\lambda)}{\rho_{pcm}.C_{pcm}} & \text{if } H > \rho.\lambda \end{cases} \qquad (14)$$

To calculate the amount of cold absorbed and temperature of air at every node after every time step following equations were used.

$$Q_{cold\_abs} = \dot{m}_{air} * C_{air} \int_0^t (T_{air\_out} - T_{air\_in}) \; dt \qquad (15)$$

$$Q = \dot{m}_{air} * C_{air} * \Delta T_{air} = h\, A_{HT} \,(T_{pcm} - T_{air\_in}) \qquad (16)$$

Where ρ_{pcm} the density of PCM, λ is the latent heat of PCM, H is PCM enthalpy, T_{pcm} is the Temperature of PCM and T_m is the melting temperature of PCM, Q_{cold_abs} is amount of cold absorbed from air to PCM, $\dot{m}_{air}$ is mass flow rate of air, A_{HT} is surface area of boundary node, Δy is the node thickness, Δt is the time step, k is the thermal conductivity of PCM.

4.2 Experimental Setup

Experimental setup for PCM based free cooling was established in laboratory of USPCAS-E at NUST Islamabad, Pakistan [1].. Figure 4.4 demonstrates the location of main parts and photograph of setup during experimentation. Main components of setup are wooden box, channels, PCM filled aluminum pipe, nozzles for air inlet into heat exchanger, air blower, anemometer, regulator, k type thermocouples, insulation and data logger.

Figure 4.3 shows the design of heat exchanger in which PCM was encapsulated in aluminum tubes. PCM used for this setup was Lauryl Alcohol whose melting point range is 22-26 ˚C and latent heat is 200 kJ/Kg. Figure 4.3 shows the real time U-shaped aluminum tubes filled with Lauryl Alcohol. O rings were used on both ends of aluminum tubes to avoid any leakages during experimentation. K-type temperature sensors were placed in wooden box along with aluminum tubes connected with data loggers to measure temperature of PCM at start and end of PCM tube and after every turn. Temperature sensor is represented by symbol ▲ in figure 4.3.

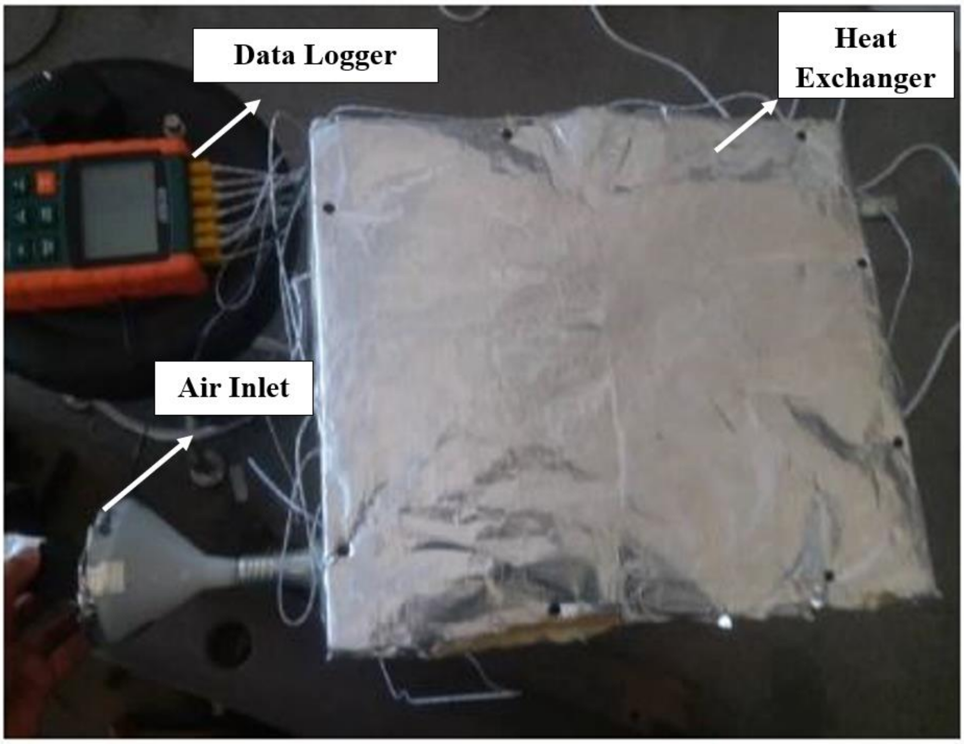

Figure 4.4 : Main components and real time photograph of setup [1]

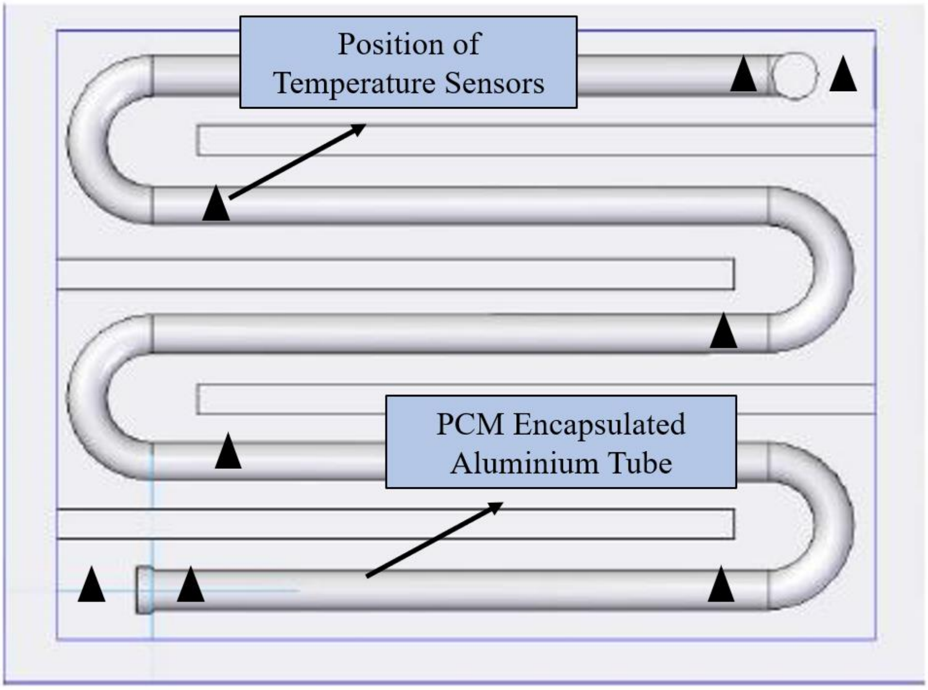

Figure 4. 3 : Design of heat exchanger & positioning of temperature sensors [1]

Summary

First portion of this chapter includes the details of Mathematical Modelling and design parameters of heat exchanger and equations used to solve the problem. Second part explains the parts of experimental setup used for experimentation.

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Chapter 5

Results and Discussion

This setup is divided into two parts, validation of mathematical model with experimental results and performance evaluation of the system by using PCMs RT22HC, RT25HC, RT27 in mathematical model. In performance evaluation first parameter is air inlet velocity which is varied from 1, 2 & 3 m/s to analyze its effect on charging and discharging process. On the basis of these results optimum air velocity will be chosen for charging and discharging process. Second parameter is air inlet temperature which is varied from 18, 19 & 20 ˚C for charging process and 32, 34 & 36 ˚C for discharging process at selected optimum air velocity. Analyzing the results will help understand the effect of these varying conditions on charging and discharging process and amount of coldness produced by selected PCMs.

5.1 Model Validation

Mathematical Model was developed by using thermos-physical properties of PCM (Lauryl Alcohol) and heat exchanger for both charging and discharging process as described in table 1 & 3. Experimental results were obtained by running the setup at night for charging process and during day time for discharging process of the system. PCM temperature was recorded with k type temperature sensors attached to PCM tubes and data loggers after regular interval of time. These temperature readings are recorded with respect to time to calculate charging and discharging time of PCM.

Figure 5.2 shows that in Experimental results Lauryl Alcohol phase transition from sensible to latent heat is around at 22.5 ˚C whereas in MATLAB results phase transition of PCM is at 23.5 ˚C. Phase transition from latent to sensible heat can be observed at 150 to 160 min for both experimental and MATLAB results. After 200 min PCM attained around 22 ˚C in both cases and the temperature of PCM will remain same as it nearly approaches the surrounding temperature.

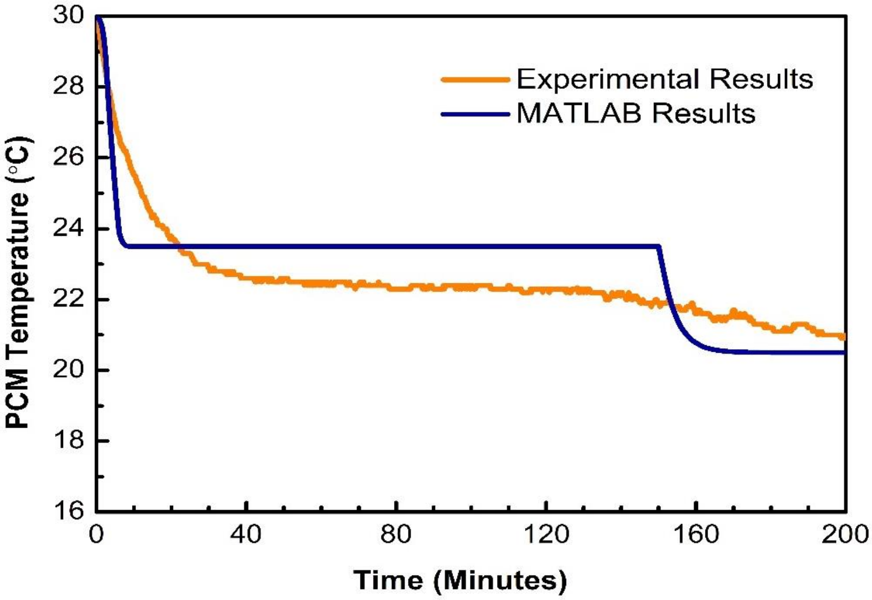

Figure 5.1: Comparison of experimental and numerical result during charging process

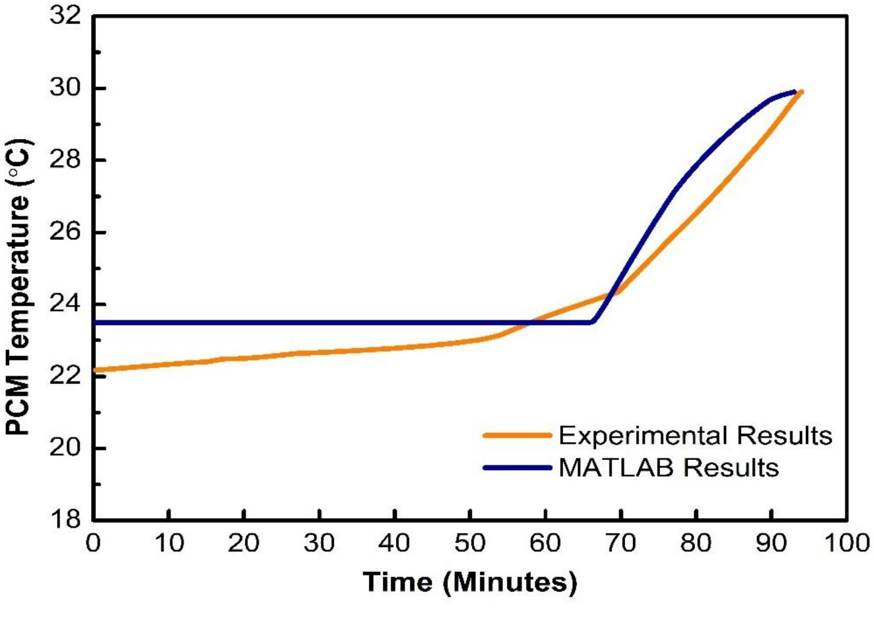

Figure 5.2: Comparison of experimental and numerical result during discharging process

Figure 5.1 shows that in experimental results Lauryl Alcohol start discharging at 22 ˚C and 23.5 ˚C for MATLAB results. Phase transition of PCM from latent to sensible heat for experimental results can be observed at 65 to 70 min whereas in MATLAB results phase transition can be observed at 67 min and attained temperature of 30 ˚C after 90 min in both cases which was the surrounding temperature during experimentation.

Difference between the temperature values of experimental and MATLAB results were due to following reasons.

- During experimentation conditioned air was also used for complete phase transition of PCM.
- During experimentation temperature sensors used to indicate the temperature of PCM were placed on outside surface of PCM encapsulated tubes so that leakages can be avoided. So, temperature sensors were not directly in contact with PCM.
- In mathematical model PCM encapsulation pipes were not considered rather it was supposed that PCM was placed in wooden box and directly in contact with air. So, effect of aluminum tube was not incorporated in this model.

Error between experimental and MATLAB results shown in Figure 5.1 and Figure 5.2 was calculated and it was nearly 3 to 4 % by using percentage error calculation formula.

5.2 Performance evaluation of selected PCMs

Performance evaluation PCM based free cooling was done on the basis of parametric analysis with different air inlet temperature and air inlet velocity.

5.2.1 Effect of air inlet velocity

Performance evaluation of selected PCMs was done by varying the speed of inlet air velocity in this model. To analyze the performance of all three PCM three different velocities i.e, 1, 2 & 3 m/s were used. Properties of PCM as described in Table 3 were used in same mathematical model to compare the performance of PCM.

Figure 5.3 demonstrates PCM RT22HC at inlet air velocity 1 m/s was completely charged after 240 minutes during night time, at 2 m/s it was fully charged after 140 minutes and at 3 m/s charging process is completed after 100 minutes.

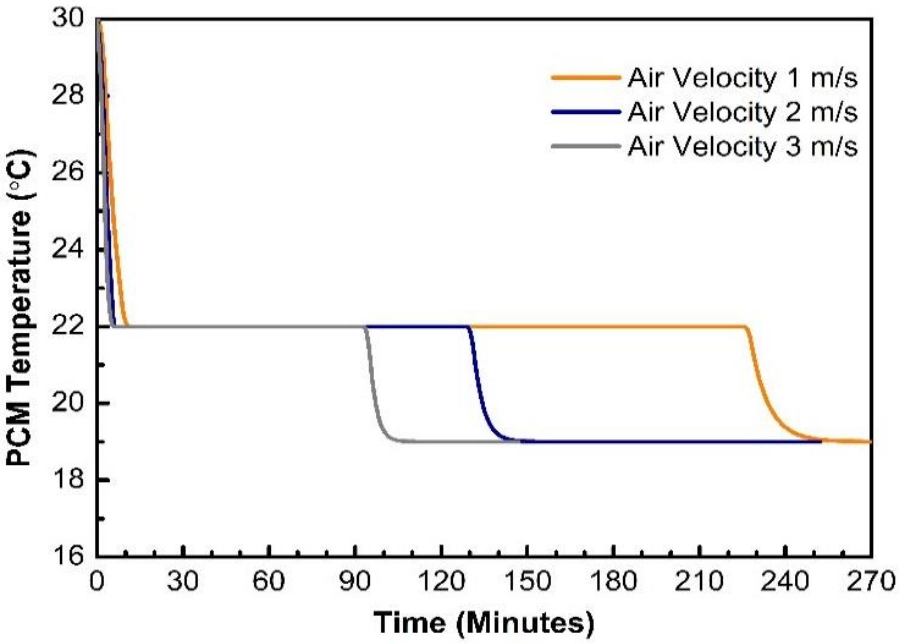

Figure 5.3: Charging process of RT22HC at 1,2 & 3 m/s

Figure 5.4 demonstrates PCM RT22HC at inlet air velocity 1 m/s was completely discharged after 110 minutes during day time, at 2 m/s it was completely discharged after 60 minutes and at 3 m/s it was completely discharged after 45 minutes.

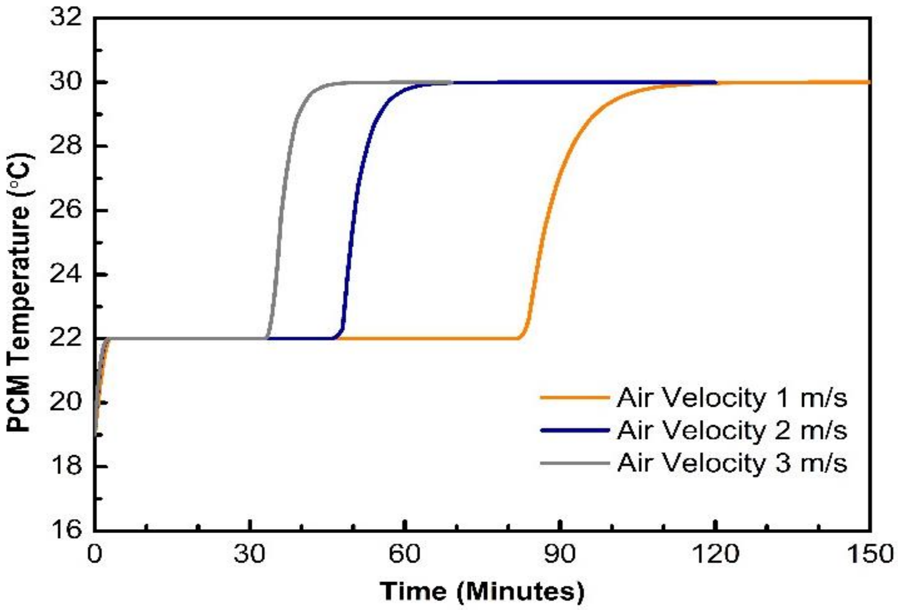

Figure 5.4: Discharging process of RT22HC at 1,2 & 3 m/s

Figure 5.6 demonstrates PCM RT25HC at inlet air velocity 1 m/s was completely charged after 190 minutes during night time, at 2 m/s it was fully charged after 110 minutes and at 3 m/s charging process was completed after 85 minutes.

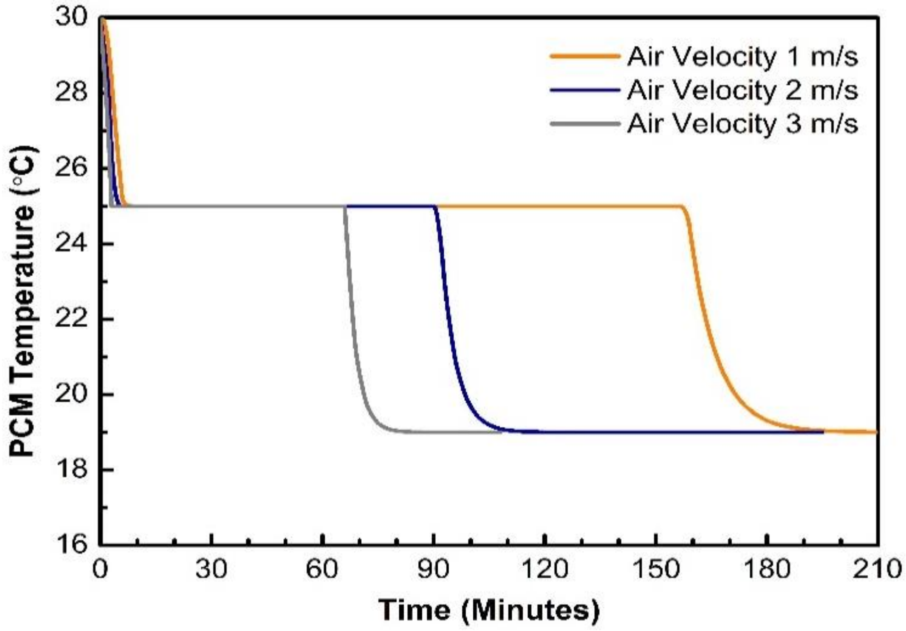

Figure 5.6: Charging process of RT25HC at 1,2 & 3 m/s

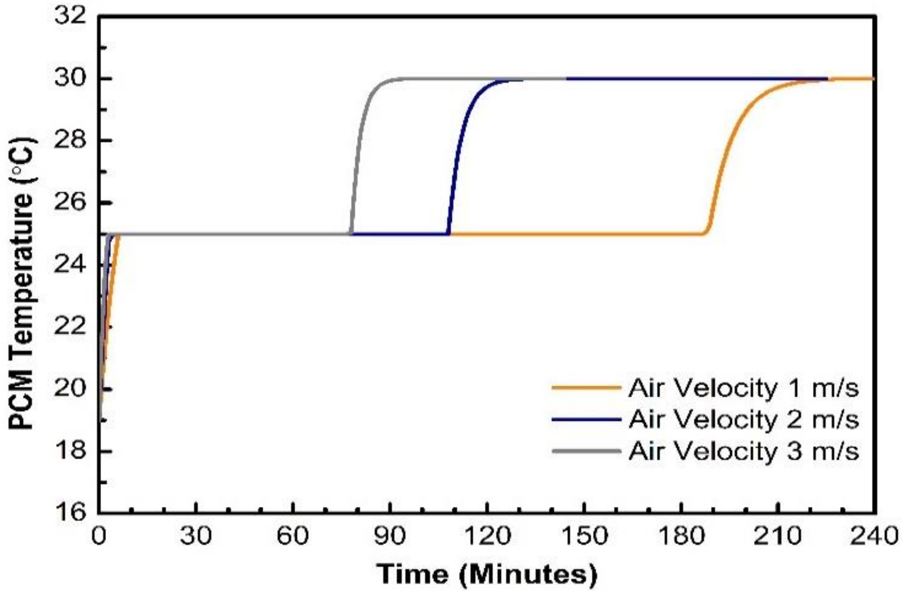

Figure 5.5: Discharging process of RT25HC at 1,2 & 3 m/s

Figure 5.5 demonstrates PCM RT25HC at inlet air velocity 1 m/s was completely discharged after 210 minutes during day time, at 2 m/s it was completely discharged after 120 minutes and at 3 m/s it was completely discharged after 80 minutes.

Figure 5.7 demonstrates PCM RT27 at inlet air velocity 1 m/s was completely charged after 110 minutes during night time, at 2 m/s it was fully charged after 70 minutes and at 3 m/s charging process was completed after 55 minutes.

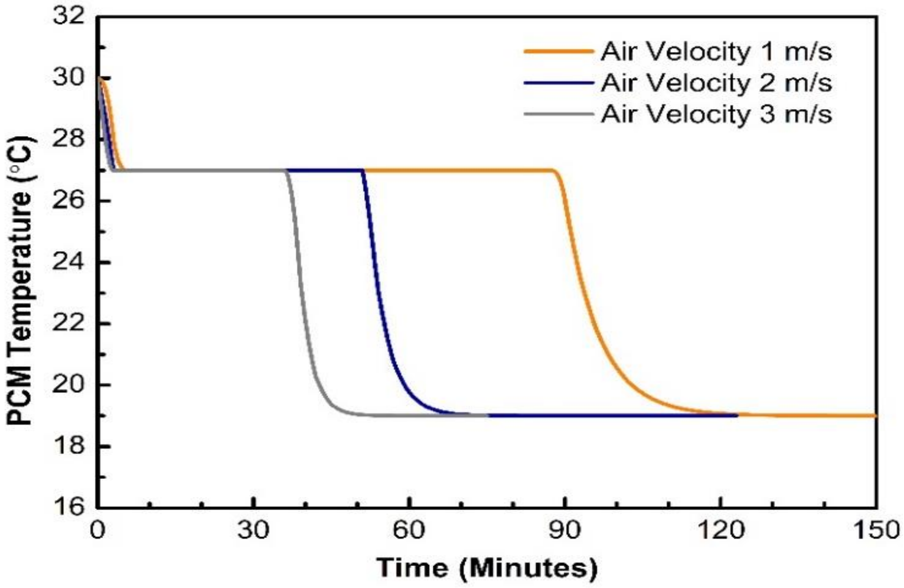

Figure 5.7: Charging process of RT27 at 1,2 & 3 m/s

Figure 5.8 demonstrates PCM RT27 at inlet air velocity 1 m/s was completely discharged after 250 minutes during day time, at 2 m/s it was completely discharged after 145 minutes and at 3 m/s it was completely discharged after 105 minutes.

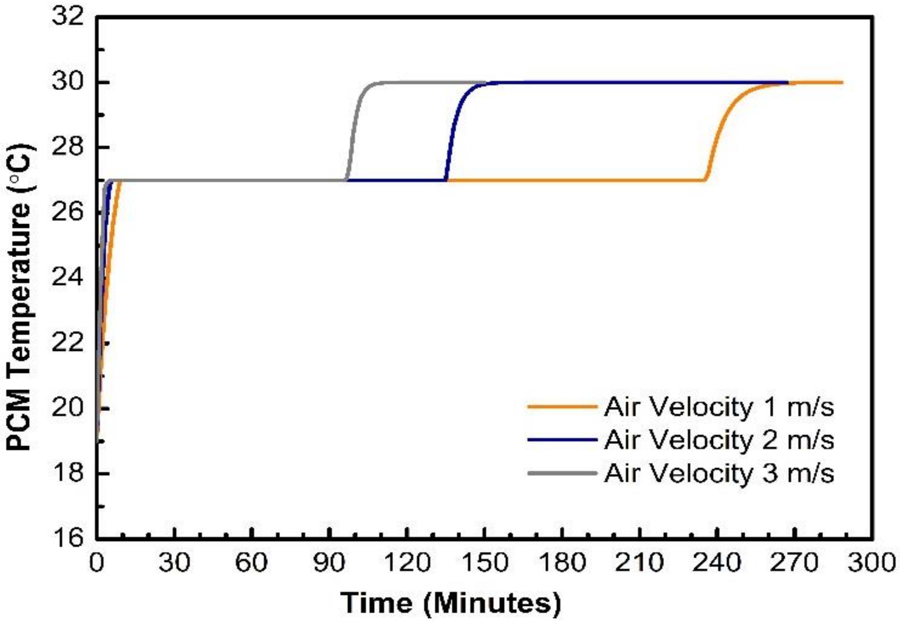

Figure 5.8: Discharging process of RT27 at 1,2 & 3 m/s

5.2.1.1 Selection of Optimum Velocity

On the basis of these results optimum velocity was selected to compare the results of selected PCMs, so that charging time during night time can be decreased and discharging time during day time can be increased. Above results shows that charging time of PCM can be decreased at higher air inlet velocity while discharging time of PCM can be decreased at lower air inlet velocity. Therefore, for charging process air inlet velocity of 3 m/s whereas for discharging process 1 m/s is selected as optimum velocity of air to analyze performance of all selected PCMs.

Figure 5.9 demonstrates that at selected optimum velocity for charging process i.e, 3m/s PCM RT27 was completely charged after 50 minutes whereas charging time required for RT25HC and RT22HC was 80 and 100 minutes respectively. Figure 5.10 demonstrates that at selected optimum velocity for discharging process i.e, 1m/s PCM RT22HC and RT25HC were completely discharged after 120 and 210 minutes respectively while RT27 was completely discharged after 250 minutes during day time.

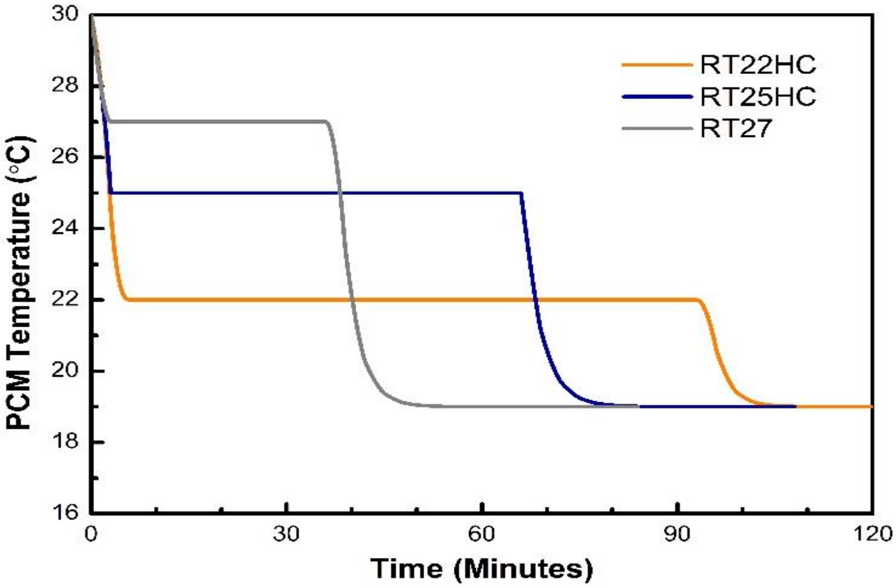

Figure 5.9: Charging process at air velocity of 3 m/s

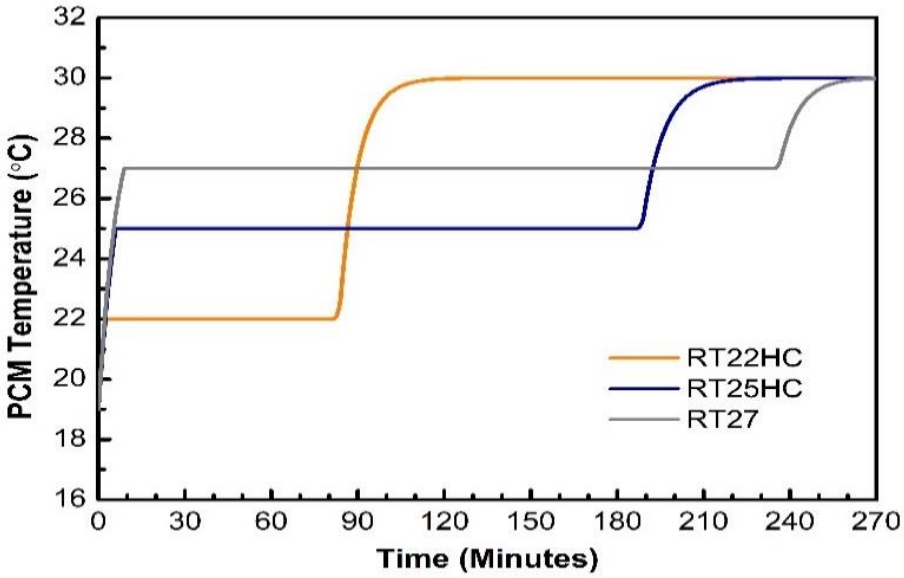

Figure 5.10: Discharging process at air velocity of 1 m/s

5.2.2 Effect of air inlet temperature

In this section effect of changing source temperature of air is analyzed for selected PCMs for both charging and discharging process. Effect of air temperature 18 ˚C, 19 ˚C & 20 ˚C for charging while 32 ˚C, 34 ˚C & 36 ˚C for discharging process was analyzed. Air velocity of 3 m/s for charging process while 1 m/s for discharging process was used as selected in previous section.

Figure 5.11 demonstrates that when air temperature of 18 ˚C was used PCM RT27 was completely charged after 45 minutes whereas charging time required for RT25HC and RT22HC was 70 and 85 minutes respectively.

Figure 5.12 demonstrates that when air temperature of 19 ˚C was used PCM RT27 was completely charged after 50 minutes whereas charging time required for RT25HC and RT22HC was 85 and 105 minutes respectively.

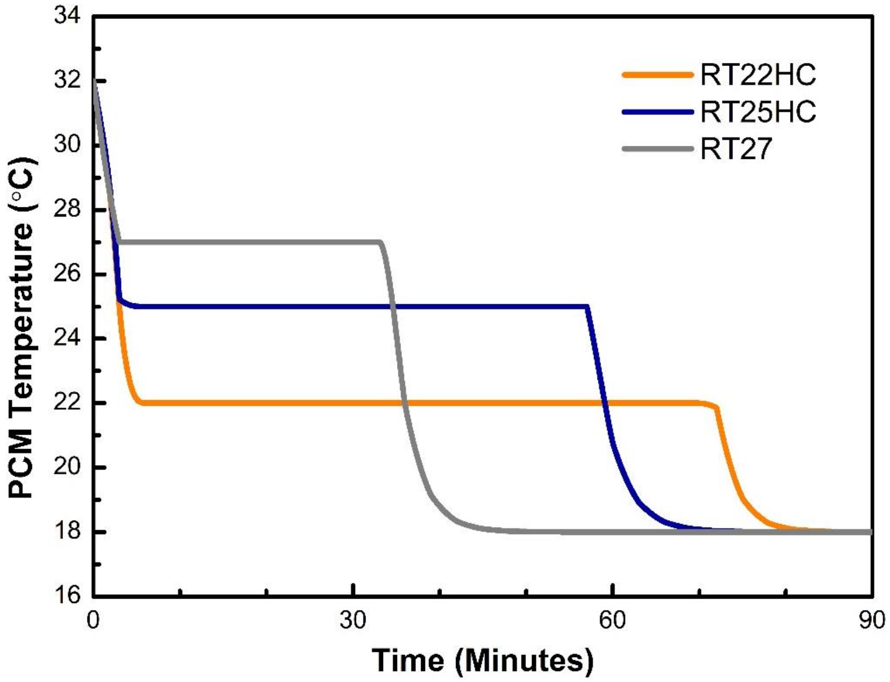

Figure 5.11: Charging process at air inlet temperature 18 ˚C

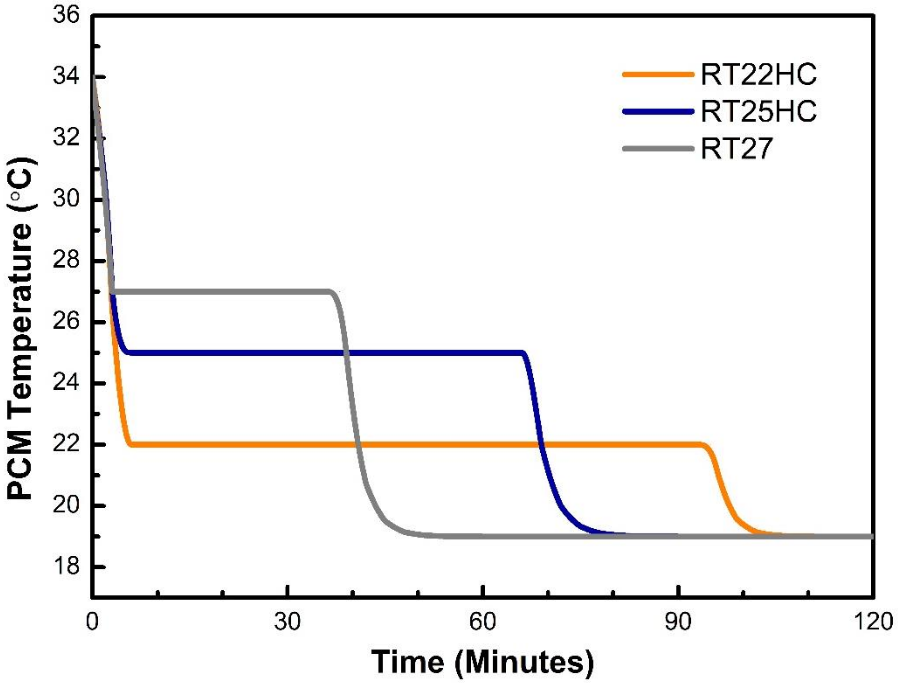

Figure 5.12: Charging process at air inlet temperature 19 ˚C

Figure 5.14 demonstrates that when air temperature of 20 ˚C was used PCM RT27 was completely charged after 60 minutes whereas charging time required for RT25HC and RT22HC was 100 and 160 minutes respectively.

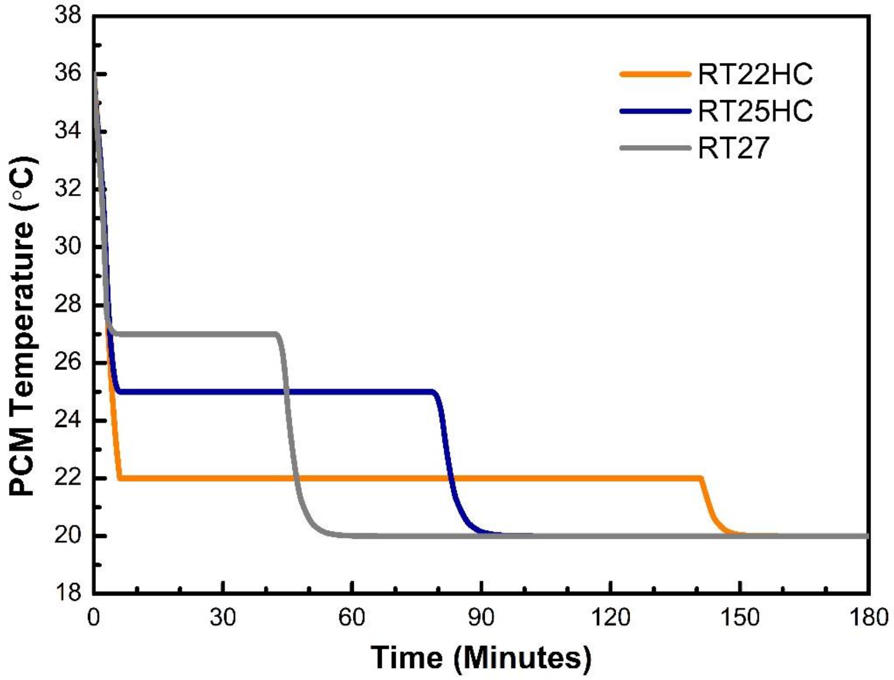

Figure 5.14: Charging process at air inlet temperature 20 ˚C

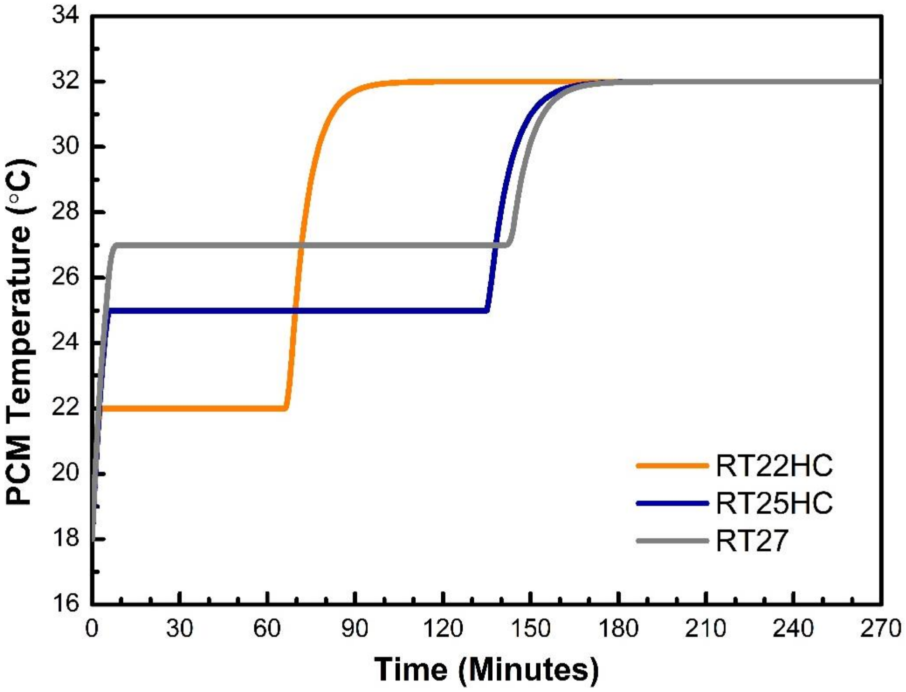

Figure 5.13: Discharging process at air inlet temperature 32 ˚C

Figure 5-13 demonstrates that when air temperature of 32 ˚C was used PCM RT27 was completely discharged after 160 minutes whereas charging time required for RT25HC and RT22HC was 155 and 100 minutes respectively.

Figure 5.15 demonstrates that when air temperature of 34 ˚C was used PCM RT27 was completely discharged after 130 minutes whereas charging time required for RT25HC and RT22HC was 130 and 85 minutes respectively.

Figure 5.16 demonstrates that when air temperature of 36 ˚C was used PCM RT27 was completely discharged after 110 minutes whereas charging time required for RT25HC and RT22HC was 120 and 80 minutes respectively.

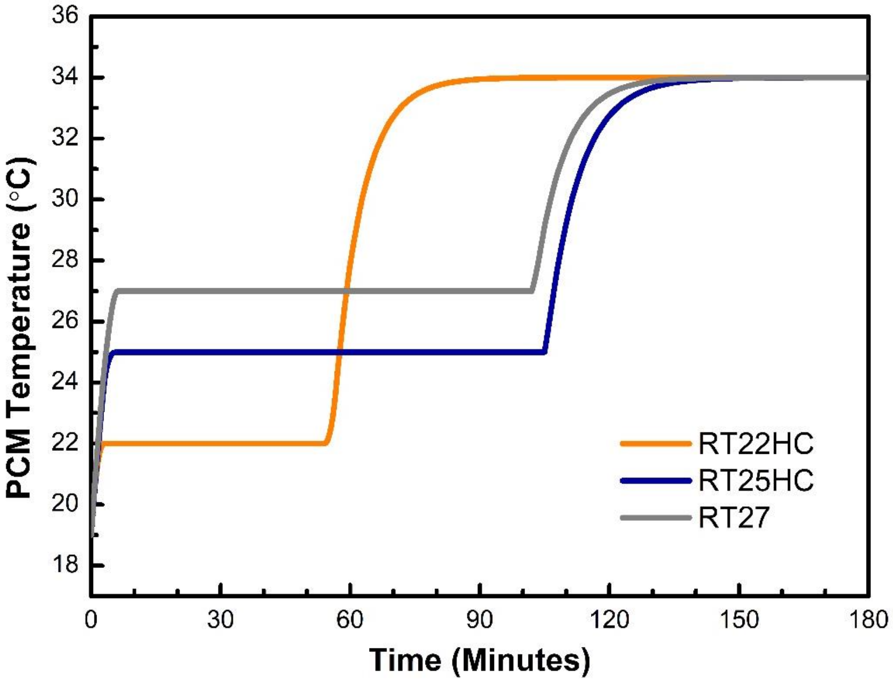

Figure 5.15: Discharging process at air inlet temperature 34 ˚C

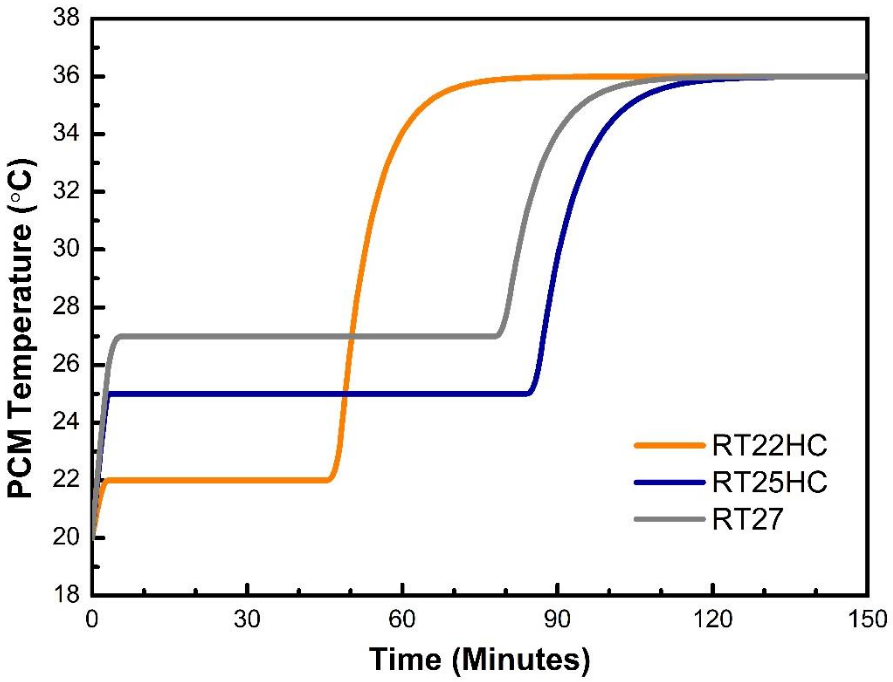

Figure 5.16: Discharging process at air inlet temperature 36 ˚C

After analyzing these results, we can see that RT27 at air inlet temperature of 18, 19 and 20 ˚C takes shortest time to completely solidify at air inlet velocity of 3 m/s during charging process. During discharging process RT25HC at air inlet temperature of 32, 34 and 36 ˚C takes longest time to discharge at low inlet air velocity of 1 m/s.

5.2.3 Heat / Cold Absorbed

Amount of cold absorbed by the PCMs can be calculated using equations (3) & (4) discussed in chapter 4 during complete charging cycle. Results shows that all PCMs are charged with less time at air inlet temperature of 18 ˚C and air inlet velocity of 3 m/s. On these optimum condition's calculations were performed using above mentioned equations to calculate amount of cold absorbed by all PCMs. During complete charging cycle amount of cold absorbed by RT22HC, RT25HC and RT27 was 0.320, 0.432 and 0.365 kW and it will be available during discharging process of PCMs if we ignore the heat loses to the surroundings.

On the basis of these results RT25HC will be most suitable for free cooling application as it takes less time for charging during night time and discharged in longer time span during day time and also the amount of cold absorbed by RT25HC is more than other PCMs due to suitable melting point temperature according to weather conditions & higher latent heat capacity.

5.3 Discussion

The major findings of the investigation are summarized below:

- During charging and discharging of PCM effect of air inlet velocity was analyzed. Results shows that at higher inlet velocity charging time of all PCMs was reduced and at lower inlet velocity discharging time of all PCMs was enhanced at lower inlet velocity as show in table 5.1. On the basis of these results 3 m/s and 1 m/s was selected for further evaluation of the system.

Table 5.1: Comparative results for varying air velocity

PCM	**Time Req. for Charging (min)**			**Time Req. for Discharging (min)**		
	1 m/s	**2 m/s**	**3 m/s**	**1 m/s**	**2 m/s**	**3 m/s**
RT22HC	240	140	100	110	60	45
RT25HC	190	110	85	210	120	80
RT27	110	70	55	250	145	105

- Effect of changing air temperature for charging and discharging process was also analyzed and results shows that at lower inlet air temperature charging time required for all PCMs was decreased due to increase in temperature gradient between PCM and air temperature. Similarly at lower inlet air temperature discharging time was more than at higher temperature due to higher temperature gradient as shown in table 5.2.

Table 5.2: Comparative results for varying air temperature

PCM	**Time Req. for Charging (min)**			**Time Req. for Discharging (min)**		
	18 ˚C	**19 ˚C**	**20 ˚C**	**32 ˚C**	**34 ˚C**	**36 ˚C**
RT22HC	45	50	60	160	130	110
RT25HC	70	85	100	155	130	120
RT27	85	105	160	100	85	80

- Passive techniques display favorable circumstances due to low running expenses but on the other hand the storage of energy is limited which is problem in hot climate zones due to non-availability of adequate energy to cool the room for longer period of time.

Summary

This section discusses the results of mathematical modelling and validation of model with experimental results. The PCM based free cooling system was then analyzed on the basis of different operating conditions i.e. air inlet velocity and air inlet temperature. The PCMs used for this parametric study were RT22HC, RT25HC and RT27. On the basis of these results RT25HC was selected as most suitable for PCM based free cooling system and cost analysis.

Chapter 6

Sizing of the System and Cost Analysis

This section discusses the sizing of the system and cost analysis with conventional AC system.

6.1 Sizing of the system

Results in previous section shows that RT25HC is best suitable for free cooling. Based on these results cooling load supplied by the thermal energy storage for RT25HC can be calculated from equations (3) & (4) discussed in chapter 4.

Results show that during complete charging cycle system absorbed 0.432 kW. 80 % of this absorbed cold is in useful region. So, the available cold after a charging cycle is 0.345 kW. Based on this data we can size the system according to our room cooling load requirements.

6.2 Calculation for mass of PCM

The standard room in Pakistan utilizes an air conditioning unit with a capacity of 5.6 kW to maintain room temperature in comfort level during summer. The mass of PCM required for complete room can be calculated using linear proportional method which is as follows:

For 0.345 kW; mass of PCM used = 160 gm

For 1 kW; mass of PCM used = 160 / 0.345 kW

For 5.275 kW; mass of PCM used = (160 / 0.345 kW) * 5.275 kW

For 5.275 kW; mass of PCM used = 2446 gm

So, from above calculation 2.5 kg of PCM is required to keep the room in comfort level during summer.

6.3 Cost calculation

Cost calculation for the standard room is as follows:

For 0.345 kW; cost of system = 9000 PKR (PCM Cost + Encapsulation Cost + Heat Exchanger Cost)

For 1 kW; cost of system = 9000 PKR / 0.345 kW

For 5.275 kW; cost of system = (9000 / 0.345) * 5.275

For 5.6 kW; cost of system = 137,603 PKR

So, from above calculation system cost is 137,603 PKR for a room of 17X10 sq. foot.

6.4 Payback period

The method to calculate the payback period of PCM based free cooling system is as follows.

Total capital cost required for PCM based free cooling system = 137,603 PKR

Cost of electricity units per month till June = 120 x 30 = 4620 PKR / month

Electricity cost during summer season = 4620 x 4 = 18,480 PKR

Payback period for capital investment = 137,603 / 18,480 = 7.4 years.

So, payback period on PCM based free cooling system is 7 years approx. and will be profitable after this time frame.

Summary

This chapter determines the actual load calculation and sizing of the system. It is concluded from results that the system will deliver 0.357 kW of energy for air conditioning. From the calculated data it is measured that for the room 2.5 kg of PCM is required and the total amount for the installation is 137,603 PKR.

Chapter 7

Conclusion and Recommendations

7.1 Conclusion

Numerical evaluation was drawn based on comprehensive study and experimentation on performance of PCM based Free Cooling. Results indicates the impact of different parameters on overall performance and to choose the best suitable PCM for free cooling applications in moderate climate zones. Following deductions can be obtained from above results:

a. Performance of three PCMs was evaluated using the same numerical model & at three different air velocities. During charging process air velocity was varied from 1 m/s to 3 m/s, time required was reduced by 50 to 60 % and in discharging process air velocity was varied from 3 m/s to 1 m/s, time required was improved by 60 %.
b. The effect of varying air temperature was analyzed for charging and discharging process. Lower temperature of ambient air can help PCM to charge in less time and discharge in extended time period.
c. Higher inlet velocity & lower air temperature can help to reduce the time required for charging process & lower inlet velocity and lower air temperature can help to improve the time required for discharging process.
d. The complete analysis and performance evaluation of PCM based free cooling system shows that PCM RT25HC is most suitable free cooling application.

7.2 Recommendations

- Latent heat thermal energy storage (LHTES) should be used as passive technique to offset cooling load.
- Micro Encapsulation of PCM will help in complete phase transition and promises better results.
- Low Thermal conductivity of PCM can be addressed using fins on heat exchanger or addition of high conductivity material like Cu and Al in PCM.
- Temperature gradient plays an important role in charging and discharging process which can be obtained using direct evaporative cooling system.

If we could use these systems which work on renewable energy rather than conventional air condition systems, we can drastically decrease the usage of fuels burning for building comfort and in turn decrease the amount of COx emissions in environment which is our sustainable development goal.

Acknowledgements

Allah is the Most Gracious and The Most Merciful and without Him I would not be able to complete this task. I would like to show my gratitude to my father as he motivated me to go for higher studies and supported me throughout my life.

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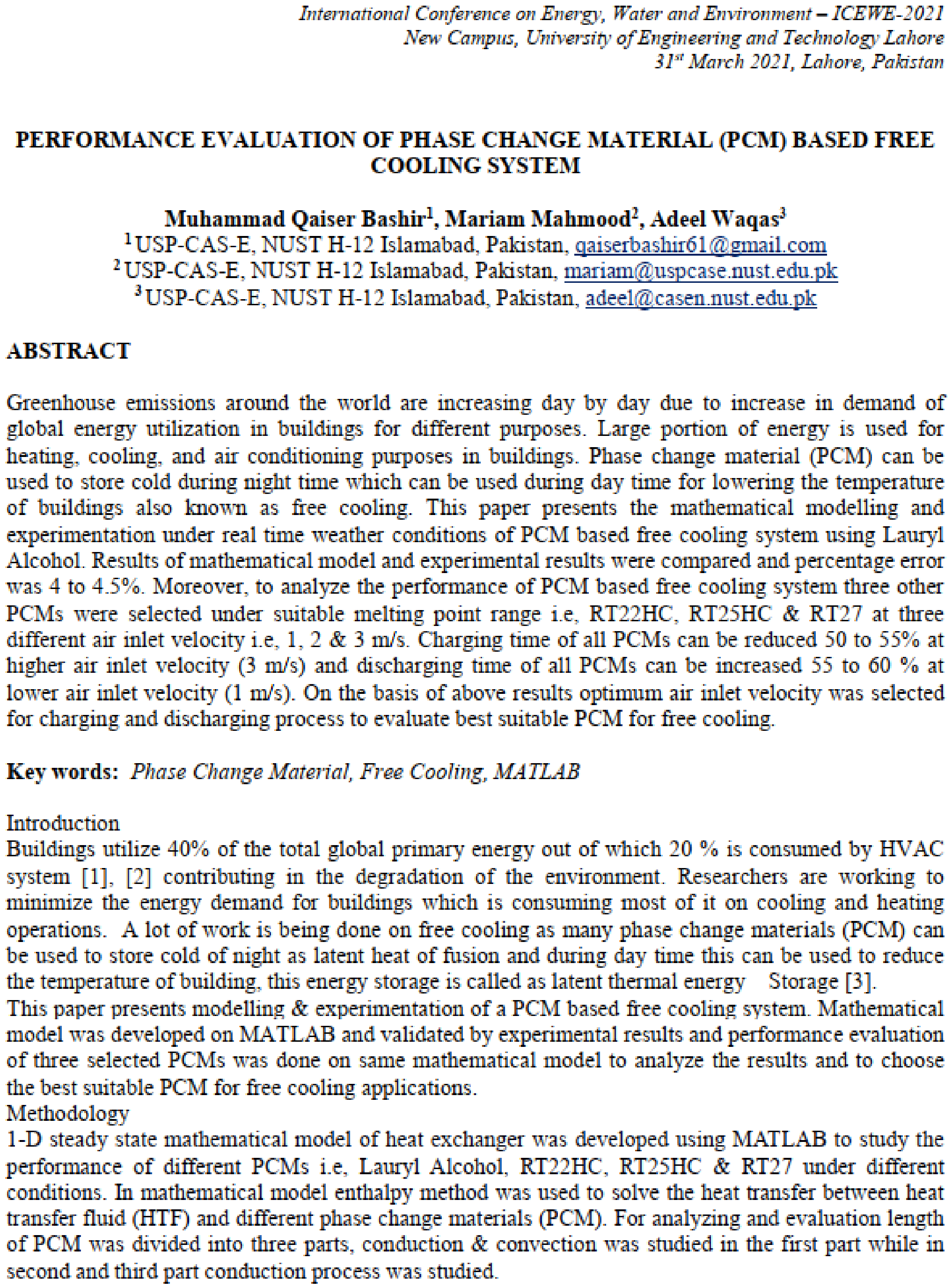
APPENDIX-PUBLICATIONS

1. **Muhammad Qaiser Bashir**, Mariam Mahmood, Adeel Waqas. **"PERFORMANCE EVALUATION OF PHASE CHANGE MATERIAL (PCM) BASED FREE COOLING SYSTEM"**. International Conference on Energy, Water & Environment (ICEWE-2021) held on 31st March 2021 in UET Lahore (KSK Campus) (Published).



International Conference on Energy, Water and Environment – ICEWE-2021
New Campus, University of Engineering and Technology Lahore
31st March 2021, Lahore, Pakistan

PERFORMANCE EVALUATION OF PHASE CHANGE MATERIAL (PCM) BASED FREE COOLING SYSTEM

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ABSTRACT

Greenhouse emissions around the world are increasing day by day due to increase in demand of global energy utilization in buildings for different purposes. Large portion of energy is used for heating, cooling, and air conditioning purposes in buildings. Phase change material (PCM) can be used to store cold during night time which can be used during day time for lowering the temperature of buildings also known as free cooling. This paper presents the mathematical modelling and experimentation under real time weather conditions of PCM based free cooling system using Lauryl Alcohol. Results of mathematical model and experimental results were compared and percentage error was 4 to 4.5%. Moreover, to analyze the performance of PCM based free cooling system three other PCMs were selected under suitable melting point range i.e, RT22HC, RT25HC & RT27 at three different air inlet velocity i.e, 1, 2 & 3 m/s. Charging time of all PCMs can be reduced 50 to 55% at higher air inlet velocity (3 m/s) and discharging time of all PCMs can be increased 55 to 60 % at lower air inlet velocity (1 m/s). On the basis of above results optimum air inlet velocity was selected for charging and discharging process to evaluate best suitable PCM for free cooling.

Key words: *Phase Change Material, Free Cooling, MATLAB*

Introduction

Buildings utilize 40% of the total global primary energy out of which 20 % is consumed by HVAC system [1], [2] contributing in the degradation of the environment. Researchers are working to minimize the energy demand for buildings which is consuming most of it on cooling and heating operations. A lot of work is being done on free cooling as many phase change materials (PCM) can be used to store cold of night as latent heat of fusion and during day time this can be used to reduce the temperature of building, this energy storage is called as latent thermal energy Storage [3].

This paper presents modelling & experimentation of a PCM based free cooling system. Mathematical model was developed on MATLAB and validated by experimental results and performance evaluation of three selected PCMs was done on same mathematical model to analyze the results and to choose the best suitable PCM for free cooling applications.

Methodology

1-D steady state mathematical model of heat exchanger was developed using MATLAB to study the performance of different PCMs i.e, Lauryl Alcohol, RT22HC, RT25HC & RT27 under different conditions. In mathematical model enthalpy method was used to solve the heat transfer between heat transfer fluid (HTF) and different phase change materials (PCM). For analyzing and evaluation length of PCM was divided into three parts, conduction & convection was studied in the first part while in second and third part conduction process was studied.