Design and Development of Lauryl Alcohol Based Thermal Energy Storage System for Cooling Purpose

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Abstract

Renewable energy technologies gained substantial importance in recent years which reduced the use of conventional hydrocarbon fuels significantly, since they are sustainable, green and environment friendly. Large amount of energy is utilized by buildings especially for cooling purpose. It is assessed that 40 percent of the world’s total energy is used by the buildings, resulting in 33 percent increase of the greenhouse gas (GHGs) emissions every year. To overcome the excessive energy used by the cooling equipment, free cooling of the buildings using latent heat thermal energy storage (LTES) technologies via phase change materials (PCMs) is one of feasible option to fulfill the energy demand of the building in an economical and efficient way. A “free cooling” technique uses PCMs as cold accumulators during night time ventilation of buildings. In this concept, cold air at night is consumed to freeze PCM to a lower temperature and this stored cold energy is used during the day time. “Lauryl alcohol” encapsulated into aluminum tube serpentine shape placed in a wooden box is used as PCM in experiments for free cooling technique. Airs enters from a nozzle and flow over a tube in a properly designed channel to store and release the energy during charging and discharging. The amount of lauryl alcohol filled in tube is 160g which store 37 kJ and recovered 35 kJ of energy during phase change. The transfer of heat during charging and discharging is 9.6W and 9.37W respectively.

Keywords*: Encapsulation, Thermal Energy Storage, Free cooling, Phase Change Material*

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- **Syed Shahzor Raza Bukhari,** Majid Ali, Adeel Waqas, **"Low Temperature Thermal Energy Storage for Passive Cooling using Lauryl Alcohol,"** 3rd IEEE International Conference on Energy Conservation and Efficiency (ICECE) 23-24 October 2019 at UET Lahore Pakistan.

Chapter 1

Introduction

1.1 Background

Conventional hydrocarbon fuels are responsible for worldwide environmental concerns especially global warming and climate change effects and are influencing over the global energy market. They have raised alarming situation regarding lessen their utilization ultimately in financial areas of the world because of their usage and limited reserves [1]. Globally, about (30–40)% of the entire energy is utilized by the buildings including commercial, residential and other buildings and is liable for one third of greenhouse gas emissions, which cause global warming every year. A huge extent of energy is consumed for heating and cooling purposes especially of the buildings and it is assessed that about (10–20)% of this energy is consumed by HVAC applications [2, 3]. Consumption of energy in different sectors of Pakistan is shown by pie chart in Fig.1.1. In order to overcome the environmental influences caused by the conventional fuels, researchers encouraged their interest to use some passive techniques for HVAC equipment. A passive technique termed as free cooling using LTES through PCMs, which exists one of feasible option to fulfill the energy demands in an efficient way [2].

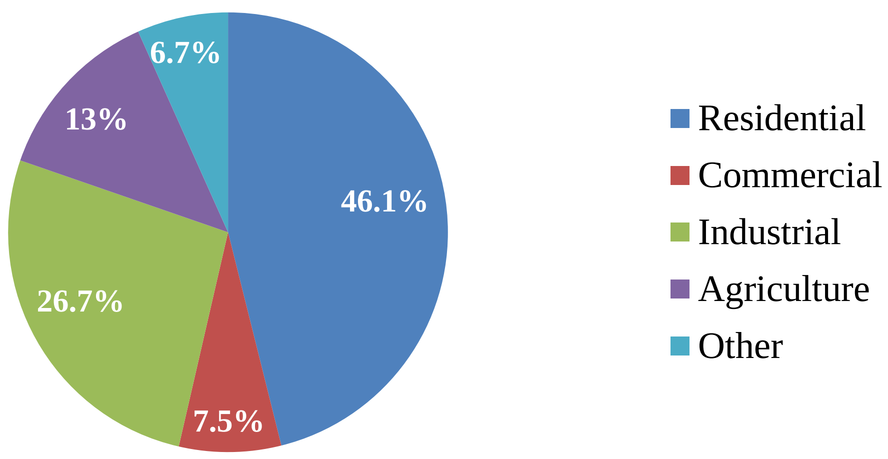

Figure 1.1: Energy consumption in different sectors of Pakistan [4]

In free cooling, the ambient temperature is lowered as compared to melting point of the material and the cold is capture in a storage medium. Furthermore, the stored energy is extracted from the storage chamber when it is required. In this technique, sensible and latent states of energy are used as a storage media. In this concept, cold air in night time is consumed to freeze PCM to a lower temperature. Later on, at day time this stored cold energy is utilized for cooling purposes [4]. Free cooling coupled with PCM based TES system is deemed an effective cooling techniques [5]. The selection of an ideal PCM for this purpose is mainly reliant on the natural environment conditions. These systems are usually suits the areas where the day to day temperature range is above 15°C. However, if its range is less than 15°C suitable design is needed for the areas because PCM charging and discharging problems may arise [6–10]. The inappropriate selection of PCM will results in incomplete solidification and liquefaction, leading to deficient cold storage. Therefore, PCM selection is the major task that linked with the free-cooling concept for storage purpose [11–14]. Different types of experimental as well as numerical investigations are conceded on the PCM based TES units to enhance energy storage, heat transfer by varying mass flow rate and adding impurities and by addition of fins. World energy consumption by some of the different fuels is mention in Fig.1.2.

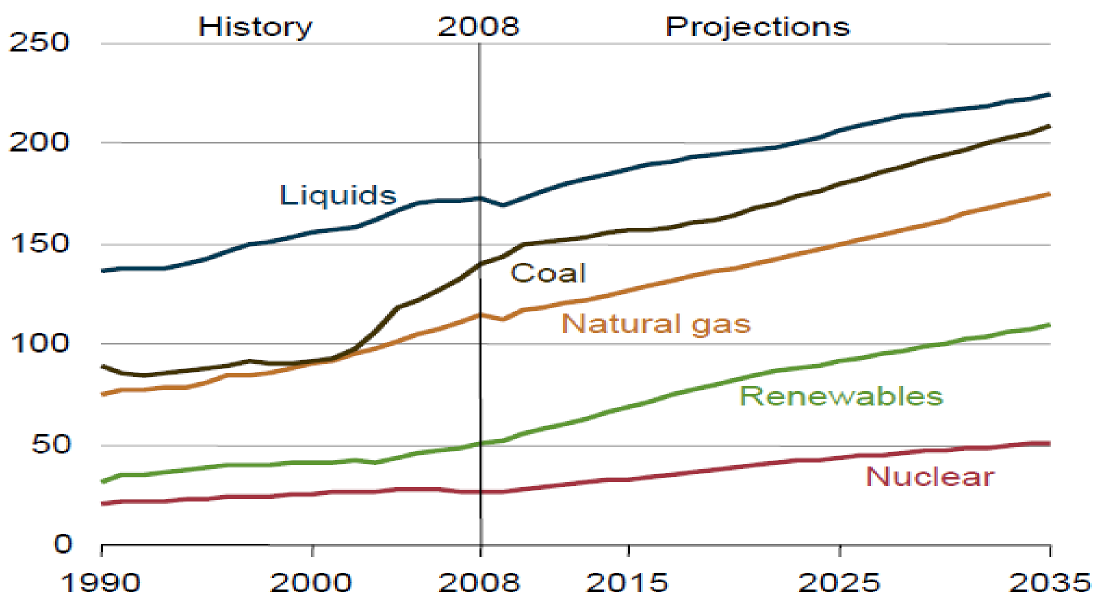

Figure 1.2: World energy consumption by different fuels [7]

1.2 Thermal Energy Storage

Due to increase of energy demand 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 [15]. 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.

1.3 Phase Change Material

Phase change materials usually known as PCMs have a storage chamber to store the LHTES. These materials have changed the phase and the ability of store and release heat during their phase transformation. Fig.1.3 determines the behavior during sensible and latent heat of energy as the phase of material changes from one form to another.

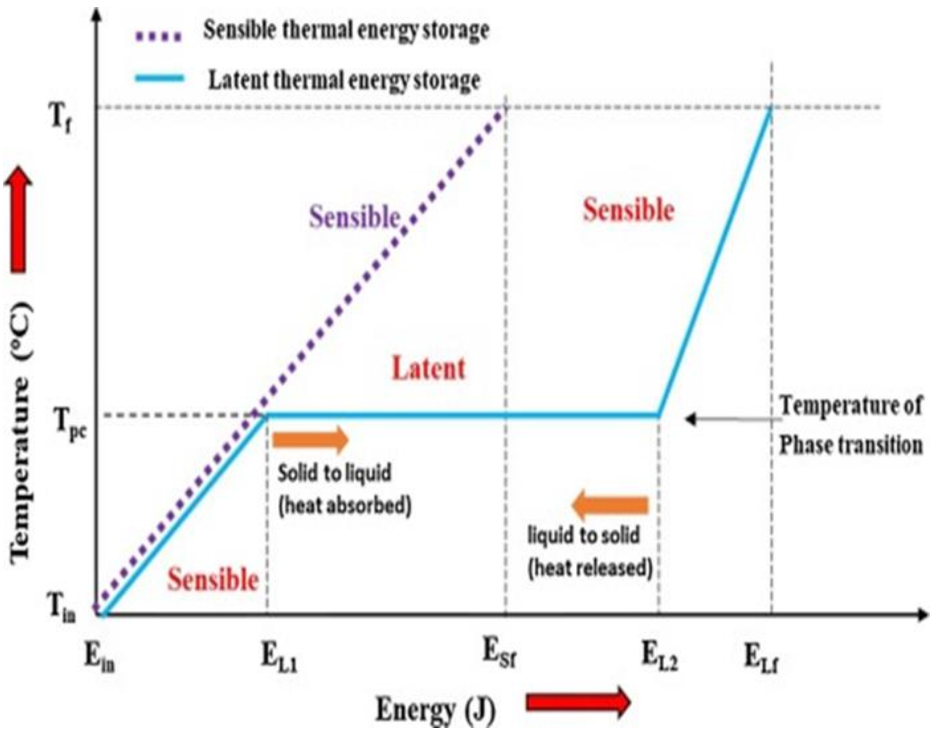

Figure 1.3: Energy storage phenomena [3]

1.4 Scope of Study

The scope of this research work is to carried out by PCM using TES system to store energy and reduce cooling load of buildings. Different methods and frameworks introduced for designing buildings, apartments and houses to make them energy efficient. Ventilative cooling in term of free cooling is an efficient technique in which PCM is used as cold accumulators during night time ventilation of buildings. This method is passive technique to produce cooling effect [16–21]. The working mechanism of this method includes PCMs, such that the material is in liquid form during day time. At this stage, PCM has no stored energy. Cool air is utilized to capture cold in the PCM when atmospheric temperature is low down than PCM temperature, the material starts to solidify. This is charging of the system. During discharging, at day time when temperature of ambient air raises this cold is transferred to the atmosphere lowering the ambient temperature and reducing the air conditioning load [22, 23].

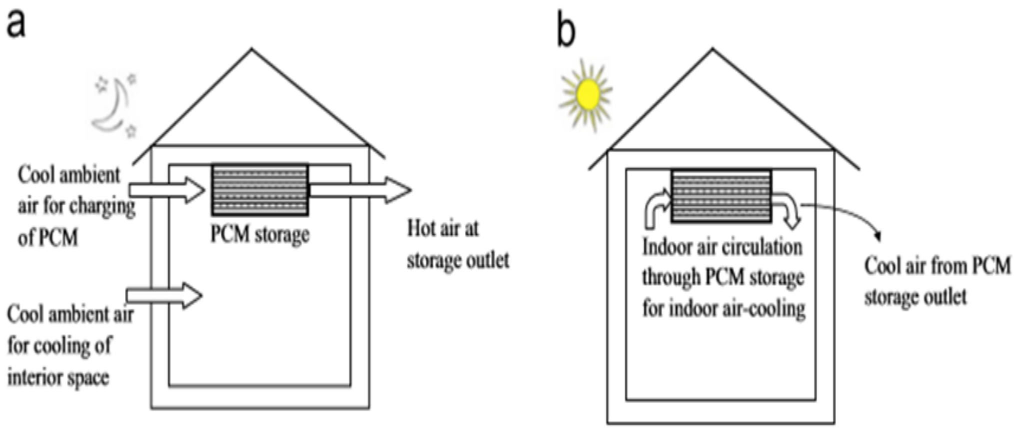

Figure 1.4: Principle functions of PCM cooling [6]

(a) Night time, charging of PCM (b) Day time, discharging of PCM

In Fig.1.4, charging cycle of PCM starts when the energy is stored from the surrounding during night and leading to phase transition from liquid to solid while discharging cycle compromise of releasing stored energy during day time and convert from solid to liquid state. The endothermic during which energy absorb and exothermic during which energy release results in the charging and discharging of PCM [24, 25].

1.5 Research Statement

The demand of energy is increasing day by day due to lack of conventional fuels. Their shortage creates an alarming situation to reserve them in an efficient way. GHGs emissions are another factor which makes our environment polluted. In order to overcome all this, a new method is proposed to obtain clean and efficient energy based on PCM based TES system. To design appropriate LHTES system, thermo physical properties need to be accurate for efficient utilization of technology. This study gives theoretical and experimental insight on the energy storage behavior of PCMs.

Different materials are available in literature but the desired range for cold storage is to be taken about 20°C to 30°C. An organic PCM namely Lauryl alcohol based LHTES system designed, fabricated and experiments take place to analyze the consequence of operating parameters of the system.

1.6 Objectives

The main objectives of this research work are as given below:

- To select the low temperature PCMs for cooling purpose.
- To design and fabricate of the TES Device.
- To study the charging/discharging of PCM in TES.
- To perform the economic analysis of passive cooling of buildings.

1.7 Organization of Thesis

Following pathway is adopted for studying the PCMs based TES system

Chapter 2. Literature Review

This chapter comprises of literature review of different sort of work done previously. Types, properties, selection criteria, encapsulation, charging and discharging behavior of PCMs. Comparison of old investigations on PCM based system and relate them with new developments.

Chapter 3. Methodology

Methodology of TES system for cooling purpose is to carry out through the process flow chart in this chapter.

Chapter 4. Design and Fabrication of Experimental setup

This chapter consists of two different sections: Design and Fabrication of system and explained briefly in relevant section.

Chapter 5. Results and Discussion

The experimental results obtained from the setup are discussed in the chapter. Furthermore, the discussions regarding charging and discharging are mentioned.

Chapter 6. Load calculation and sizing of system

In this chapter, load calculation and sizing of system for a desired room is briefly explained.

Chapter 7. Conclusion and Recommendations

This chapter discusses conclusion and future recommendations of the research work.

Summary

This section discuss 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 LHTES.

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Chapter 2

Literature Review

In this chapter, method and techniques available in literature are analyzed and discussed. The 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 for cooling of domestic buildings. These techniques include [1-9].

i. Evaporative cooling which 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.
ii. Soil cooling works on passing air through a depth of 2 to 3m and allowing it to cool. This technique also becomes ineffective for large buildings as it requires heavy mechanical devices like pump for circulating air.
iii. 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.

Cold Storage also utilizes ventilation cooling technique. At night, cold air is used for ventilation, charges the PCM which gets discharge at day resulting in cooling.

2.2 Types of PCM

There are major three types of PCM which is explained below

2.2.1 Organic PCM

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.

2.2.2 In-Organic PCM

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

2.2.3 Eutectics

Eutectics are minimum-melting alignment of two or more than two elements. Every component melts and freeze consistently making combination of forming a necessary base or core crystals at the time of crystallization.

2.3 Selection of PCM

PCM is selected on the basis of its melting temperature and heat of fusion. Table 2.1 shows selection range of the parameter of material. The materials utilized as PCM in free cooling is shown in Table 2.2. Melting temperature range is chosen on the basis of ambient temperature. PCM temperature should be less than ambient temperature for cold storage, and minimum temperature range of 5˚C is required. Heat of fusion decides the charging and discharging time of PCM. High heat of fusion means high charging and discharging time and vice versa [4, 5].

Table 2.1: PCM Selection properties

Properties	**Range**
Melting Point	20-26 °C
Latent Heat	150-200kJ/kg
Thermal conductivity	0.2-0.6W/m.K

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. PCM encapsulation is implemented due to following reasons [8-10]

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

Some of the encapsulation techniques are briefly discussed below.

Table 2.2: Properties of PCM [3-7]

PCMs	MP (°C)	HF (kJ/kg)	Nature	Density (kg/m^3)	Thermal conductivity (W/m.K)	Weight	Cost (Rs)
Lauryl Alcohol	24	200	Alcohol/ Organic	831	0.2	1kg	15000
ClimSel C24	24	216	Salt hydrate/ Inorganic			----	
$CH_3(CH_2)11OH$	26	200	Fatty acid/ Organic			----	
SP25 A8	25	180	Blend/ Hydrate salt	1380	0.6	----	
S27	27	183	Salthydrate/ Inorganic		0.48	----	
Heptadecane	21.7	213	Organic/ Paraffin		0.21	25gm	13800
D-Lattic acid	26	184	Fatty acid/ Organic			1kg	15500
n-Octadecane	27	243	Paraffin/ Organic	750	0.2	25gm	14500
$LiBO_2 .8H_2O$	25.7	289	Salt hydrate/ Inorganic			100gm	35000
Paraffin RT27	27	179	Paraffin/ Organic	800	0.2	----	
STL27	27	213	Salt hydrate/ Inorganic			----	
$Na_2CO_3.10H_2O$-$Na_2HPO_4.12H_2O$	24.9	182.7	Eutectic			1kg per	2800 /4800
48% $CaCl_2$ 4.3% NaCl 0.4% KCl47.3% H_2O	22	188	Eutectic			1kg per	3200 /1800 /3800
RT22HC	22	200	Paraffin/ Organic	760		----	
RT25HC	25	230	Paraffin/ Organic	880		----	
Paraffin C13–C24	24	189	Paraffin/ Organic	760	0.21	1ltr	6500

2.4.1 Micro-Encapsulation Method

In this method, tiny particles 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 are more thermally reliable and chemically stable compared to macro encapsulated PCM [4-7]. Major disadvantage of this techniques are complex manufacturing due to small size of PCM and increase in the possibility of super cooling of material at the time of phase change.

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. Unlike micro encapsulation, macro encapsulation is easy to fabricate but its major drawback is that it results in a temperature difference between PCM core and boundary of encapsulated material, thus preventing effective heat transfer. For high heat transfer usually metallic part is used for shell formation, else plastic material is normally used for encapsulation purpose.

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. [8] 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. Some progressive work has done for this 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.

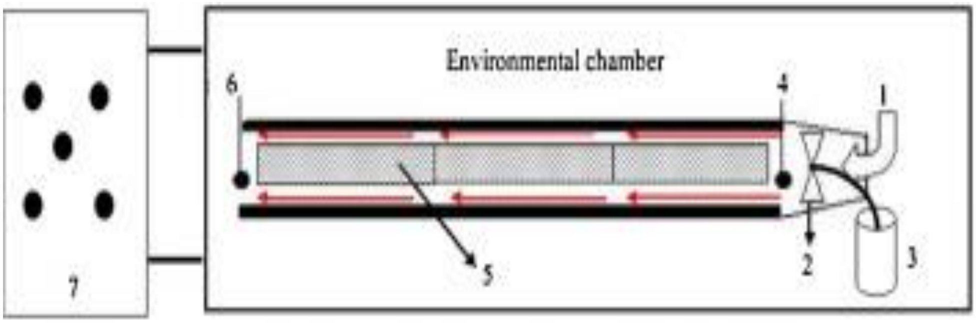
Table 2.3: Comparison between PCM Encapsulation Techniques

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 differ 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

2.5 Experimental study

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

A. Waqas et al. shows a prototype storing component was manufactured and mounted in a precise chamber to mimic the ambient circumstances of hot and dry atmosphere to examine the enactment of the PCM capturing unit. The environmental chamber comprises of a cooling unit (4.3 kW) to chill the chamber off to 10 °C. This could be handled by digital sensors. A heating system of 2 kW capabilities was utilized to warm the chamber up to 50 °C, and was handled physically by the control unit positioned outside the chamber. A dehumidifier handled the moisture inside the chamber.



1: Air inlet to storage unit. 2: Fan. 3: Fan speed controller. 4: Air inlet temperature sensor. 5: Storage material (PCM). 6:Air outlet temperature sensor. 7: Control panel for chamber AC, heater and fan.

Figure 2.1: PCM filled port [4]

The study done by Ana Lazaro et al. shows that that increasing thermal conductivity also increases PCM cost whereas economical method is to enhance heat exchanger design[16].

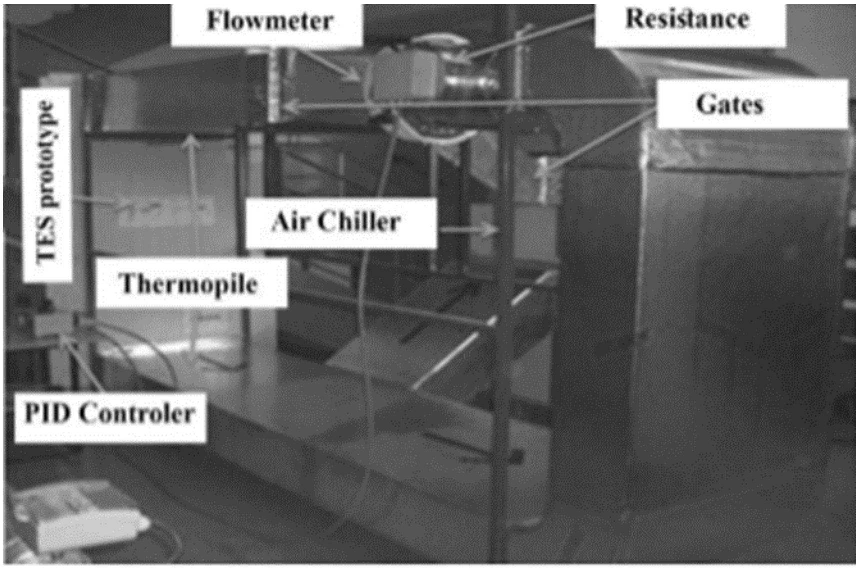


Figure 2.2: Experimental Setup to enhance heat exchanger design [11]

T. Karlessi et al. shows the effects of building tile, coated in cool PCM and its effect on reducing cooling load in building. His study shows that due to cooling coating on PCM, tiles absorb the excess heat and reduce the building temperature [9].

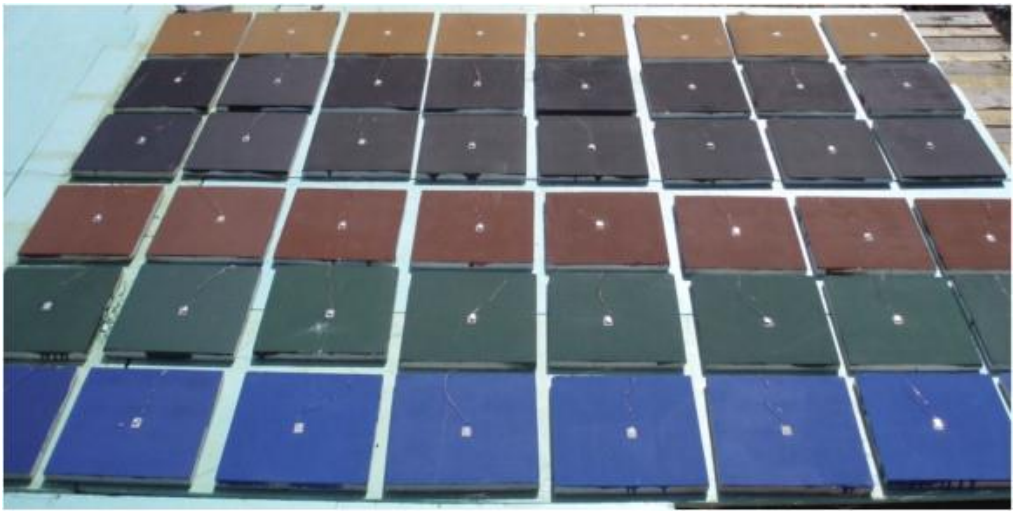


Figure 2.3: Testing tiles coated with PCM [6]

The experimental Study had done by Albert Castel et al. shows the influence of external fins on heat transfer from PCM surface to its module. Study shows that PCM module without fins required 17 min for charging, that reduced to 13 min (reduction of 23.52%) by 20 mm fins and to 7 min (reduction of 58.82%) by 40mm fins [7].

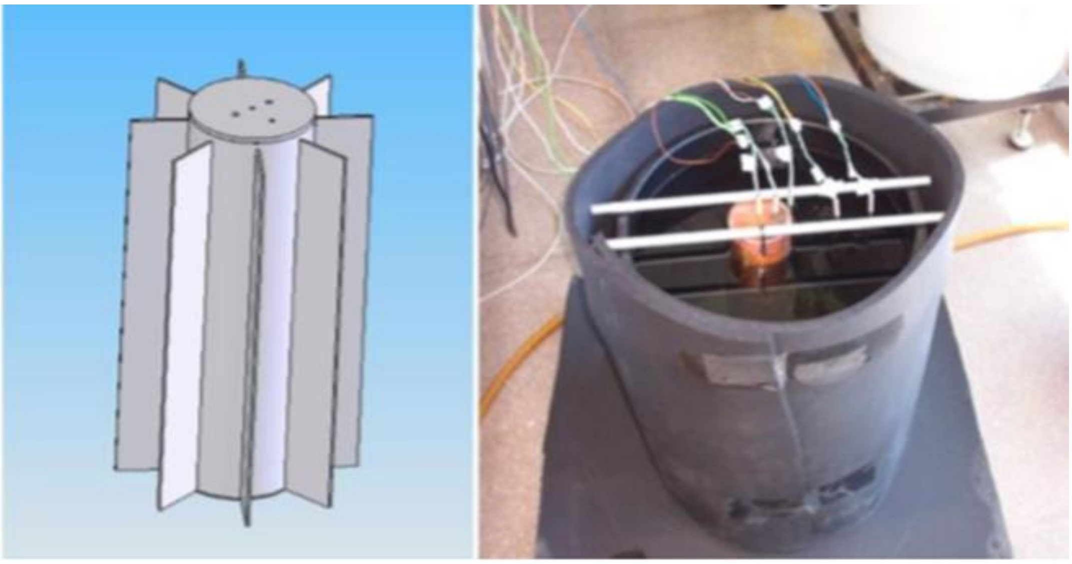


Figure 2.4: PCM Heat Exchanger with External Fins [9]

Numerical study carried out by N.H.S Tay et al. shows the influence of tube in tank heat exchanger. The study shows that if PCM flow rate is five times more than flow rate of heat transfer fluid then dynamic melting decreases the phase change time by 36-39 % [8].

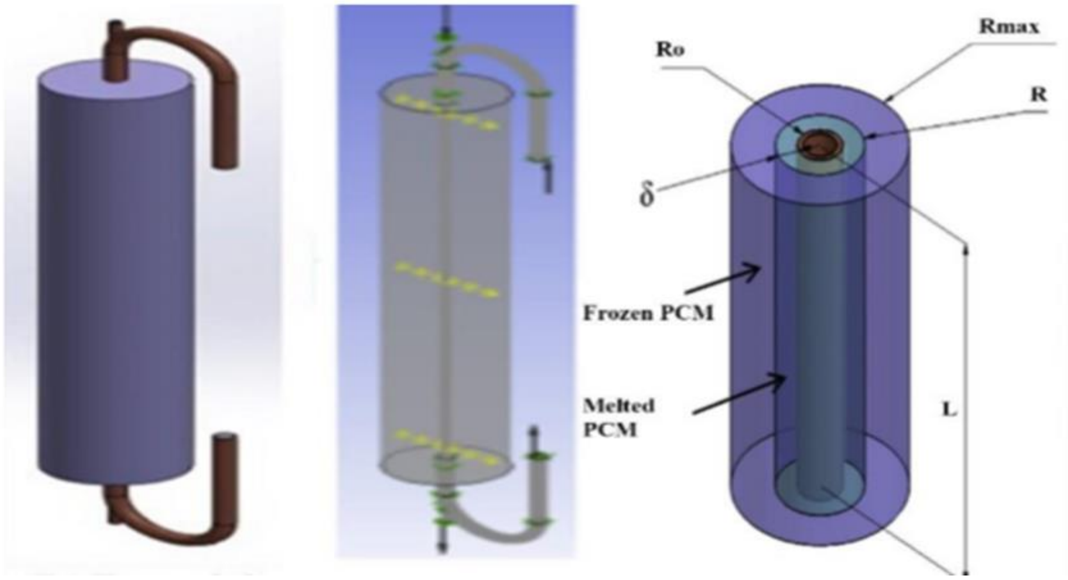


Figure 2.5: Tube in tank type heat exchanger [21]

Alvero de Gracia in his study shows that night cooling is the best solution for reducing cooling load. The system incorporates a façade which is being used as cold storage. Skin of the façade must be made of material having low thermal conductivity to enhance system efficiency [18].

Figure 2.6: Ventilated Facade with PCM cold storage [14]

F. Frusteri in his study displays the influence of carbon fibers on thermal conductivity of PCM and experimentally studied the effect of size of the fibers on the PCM thermal conductivity[19].

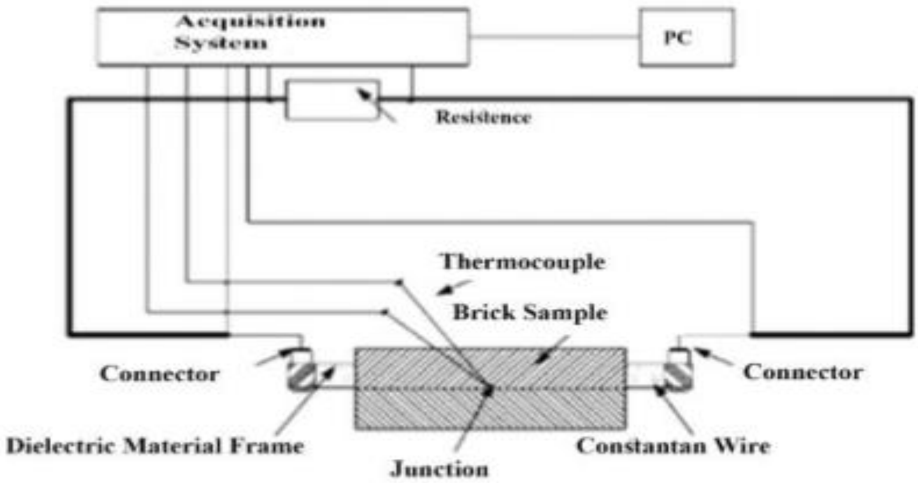


Figure 2.7: Experimental setup used to investigate PCM thermal conductivity [22]

Different experimental as well as theoretical studies mention above has been studied for literature review out of which different problems are sort out for our experimentation and fabrication.

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 PCM selection criteria is developed. Low temperature PCM was selected on the basis of detail study of literature and availability of PCM in desired range of properties. For PCM encapsulation macro encapsulation technique was used due to local manufacturing facility. In the end of this chapter, different methods and PCM available in literature for thermal storage have been discussed.

Chapter 3

3.1 Methodology

The methodology of TES system for cooling purpose is discussed in the process flow chart as shown in Fig. 3.1. The research work is divided in two phases: theoretical work and experimental work. Different tasks performed in each phase are identified. The framework of the study for the selection of PCM is totally depends on detail study of literature review, availability and its cost. Furthermore, thermo physical properties play a vital role to define the nature of material. However, the safety data sheet clearly mentions that it is noncombustible, inexplosive and friendly to nature so that an experimentation done in harmless environment. The melting point, latent heat and the specific heat capacity are also obtained from safety data sheet [1,2]. The experimentally determined values provide useful information for incorporating PCM based TES system.

The initial study for the design and development of LHTES system comprises of chosen of a suitable PCM for TES medium, box, heat transfer carrying channels, insulations and formation of the heat exchanger. Selection of pipe, material cooling/heating strategy and DC air blowers and readings are measured from data logger.

The experimental setup is fabricated and k-type temperature sensors are incorporated inside the TES tank to analyze temperature at different points of pipe. Moreover, for evaluating the charging/discharging of the PCM and for studying the influence of operating constraints such as flow rate of air on the implementation of LHTES system, anemometer and DC air blower are configured, while the inlet temperature of the air provided by the ambient air source. The process chart of research work is shown in figure 3.1.

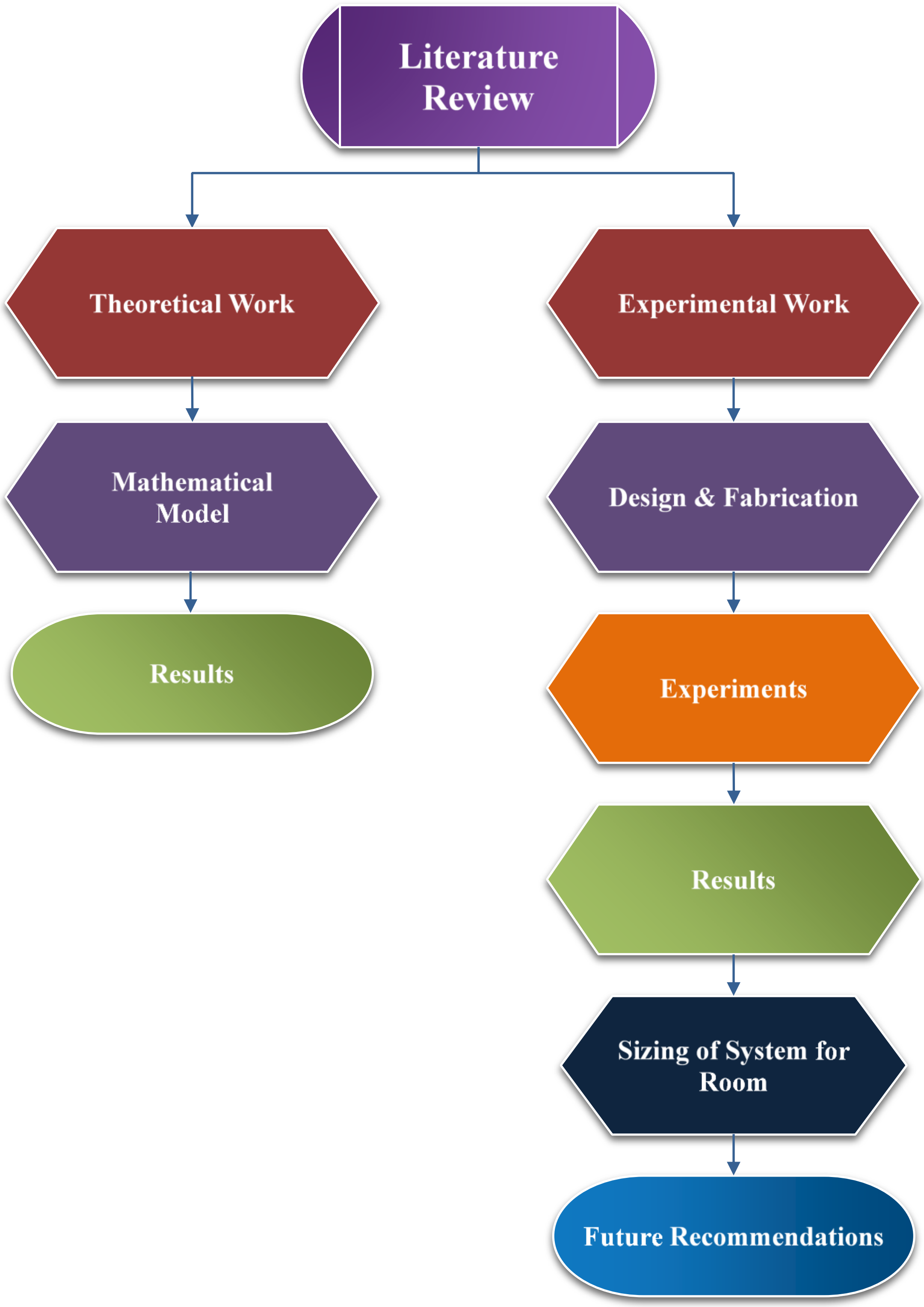


Figure 3.1: Process flow chart for TES system

3.2 Energy Storage and Heat Transfer Equations

The amount of energy of the PCM (sensible and latent) was calculated using equation (3.1)

Q = [Sum of energy stored as sensible in solid phase of PCM] +

[Sum of energy stored as Latent heat] +

[Sum of energy stored as sensible in liquid phase of PCM]

$$Q = m\,[(C_p\Delta T)_{solid} + \Delta h + (C_p\Delta T)_{liquid}] \tag{3.1}$$

where, Q is the quantity of stored energy in joules (J), C_p is amount of specific heat of PCM, m is the mass of PCM and ΔT indicates temperature difference [10–12].

The quantity of heat transfer from air to PCM and PCM to air during charging and discharging can be calculated by the following relationships;

$$D_h = \frac{2ab}{(a+b)} \tag{3.2}$$

where, D_h is the hydraulic diameter of air channel.

$$A_s = \pi . D_o . L \tag{3.3}$$

where, A_s is the surface area of pipe.

$$Re = \frac{(\rho . v . D_h)}{\mu} \tag{3.4}$$

where, Re is the Reynold number of air.

$$Nu = 0.023\, Re^{0.8} . Pr^{n} \text{, for heating n=0.4 and for cooling 0.3} \tag{3.5}$$

where, Nu is the Nusselt number of air.

$$h = \frac{(k.Nu)}{D_h} \tag{3.6}$$

where, h is the convection heat transfer coefficient.

$$\Delta T_m = \frac{(Ti - Te)}{ln[(Ts - Te)/(Ts - Ti)]} \tag{3.7}$$

where, ΔT_m is the LMTD of pipe.

$$Q = h.A_s.\Delta T_m \tag{3.8}$$

where, Q is amount of heat transfer through the system.

3.3 Uncertainty factor

Standard uncertainties u are Temperature u(T) = 0.5°C , Mass u(m) = 1mg, Speed u(v) = 0.1m/s and Latent heat u(Δh) = 8%.

The uncertainty factor can be determined by calculating u(Q) which is the amount of uncertain energy that is calculated from following relation

$$Q = m\,[(C_p\Delta T)_{solid} + \Delta h + (C_p\Delta T)_{liquid}] \pm u(Q) \tag{3.9}$$

$$u(Q) = C_p\sqrt{[u(T_{solid})]^2 + [u(h)]^2 + [u(T_{liquid})]^2 + [u(m)]^2}$$

$$Q = h.A_s.\Delta T_m \pm u(Q) \tag{3.10}$$

$$u(Q) = A_s\sqrt{[u(T)]^2 + [u(h)]^2 + [u(v)]^2}$$

Energy stored by the PCM during charging process was calculated 37 kJ and during discharging the amount of energy recovered is 34 kJ.

The heat transfer during charging and discharging is 9.6W and 9.37W respectively.

Summary

In this chapter, the methodology that defines the framework of research work is properly discussed. The selection of PCM is depending on the local availability of PCM and its thermo physical properties. Design and fabrication of setup take place according to the detail study of literature review and the experimentation conducted at USPCAS-E NUST Islamabad.

Chapter 4

Design and Fabrication of Experimental Setup

4.1 Model of TES Device

TES Device is demonstrated on the basis of calculation of mass and energy balance criteria. According to mass balance, the typical amount of mass is sufficient to release the desired amount of energy. A pipe as a sample is use in which sufficient amount of mass is filled with estimated expansion due to freezing so that there is no cracking take place.

On the basis of easy availability of PCM, Lauryl Alcohol is selected for the experimental study. The thermo physical properties of Lauryl Alcohol are as shown below:

Table 4.1: Thermophysical properties of Lauryl Alcohol

Property	**Description**
Commercial name	Lauryl Alcohol
Type	Fatty acid
Melting Temperature	22-26 ℃
Latent Heat	200kJ/kg
Thermal conductivity	0.2W/m.℃
Appearance	Liquid
Density	831kg/m^3
Boiling Point	393℃

Table 4.2: Thermophysical properties of Air

Properties	**Value**
Density	1.27kg/m^3
Thermal Conductivity	0.2588W/m.^{o}C
Specific heat	1.007kJ/kg.^{o}C
Viscosity of Air	1.5.11x 10^{-5}

4.1.1 Mass Based Criteria

In order to design a TES Device, we must designs a pipe which is easily fitted in a storage device for transfer of heat between air and material.

To testing take a material of about (150-160) gm of Lauryl Alcohol

$$\boldsymbol{\rho = \frac{m}{V}} \qquad (4.1)$$

ρ is density and V is the volume of pipe

Expandable factor up to 15% is considered for pipe

V = total volume – expanded volume

$$\boldsymbol{V = \pi . r^2 . L} \qquad (4.2)$$

r_o = 0.008 m, r_i = 0.007 m depends on the availability of pipe

r_o is outer diameter of pipe and r_i in inner diameter and L is the length of pipe.

L=1.524 m

We calculated the length of pipe including the expanded volume of material for 0.160kg of material i.e. 1.524m

To bend a pipe in such a way that proper passage of air through channels is to be provided the bending of pipe after every 0.254 m. In this way 5 bends refer to pipe and a serpentine shape is accomplished now on this basis the design of wooden box take into account to develop a properly channelized heat exchanger to fit the pipe and transfer of heat. A box is designed in such a way to leave a distance of 0.0127 m to pipe from each side and the thickness of wooden slab fitted in between and outsides of the box.

4.2 Design of a TES Device

Initially, software was used to design heat exchanger. Designed model is shown in figure 4.1 and the parameters of the TES Device are presented in table 4.3.

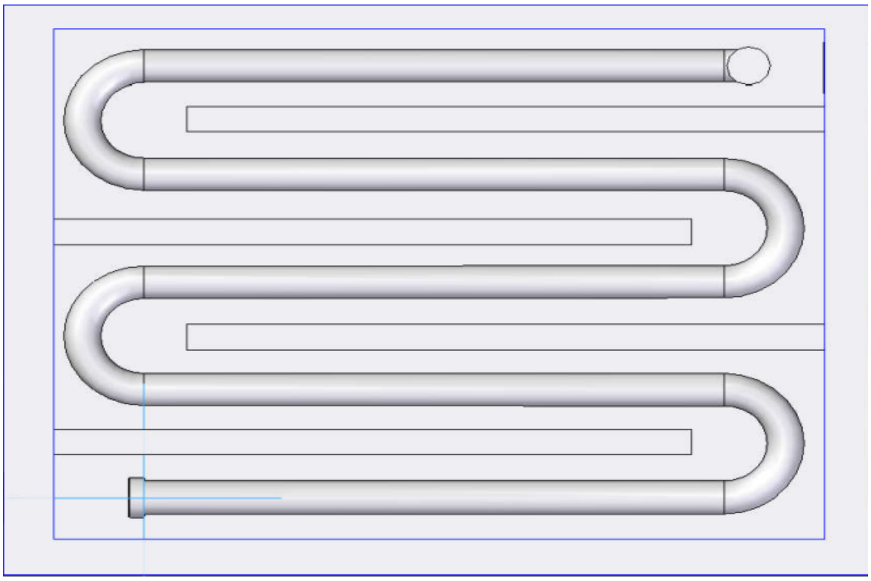


Figure 4.1: TES Device Design

Table 4.3: Design parameters of TES Device model

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
Slabs Length to place PCM filled tubes	0.254
Slab width	0.0762
Slab thickness	0.0254

4.3 Fabrication of the Setup

Experimental setup was fabricated in three stages which discussed below

4.3.1 Fabrication of TES Device

TES Device box was fabricated and assembled in the wood work shop at NUST. Wood has been utilized for the fabrication of heat exchanger and it does not require any other specific insulation.

Table 4.4: Parameters of box

Geometry	Height (m)	Width (m)
Model	0.3302	0.3048
Aluminum Encapsulation	0.381	0.058
Pipe Slab	0.254	0.04
Inlet, Outlet	0.01524	0.01524

One face of box was made removable due to experimentation requirements. For air inlet and outlet, 1 inch nozzle is used at both ends.

4.3.2 PCM Encapsulation

On the basis of available local resources, macro-encapsulation is selected for manufacturing of encapsulation. PCM is stored in aluminum tubes to avoid any leakage during experimentation of the system.

Figure 4.2: Aluminum pipe for encapsulation

4.3.3 Dimensions for Encapsulation

After many trials, aluminum pipes were used for encapsulation. No leakage was observed in this encapsulation. Specification of this encapsulation is given below:

Table 4.5: Parameters of pipe encapsulation

Parameters	**Values (m)**
Pipe length	1.524
Pipe thickness	0.00508
Pipe diameter	0.0127

These pipes were closed from both ends using aluminum caps which can be opened or closed. Threading on caps and pipes provided better fit. To avoid any leakage O-rings were used as a seal at both ends. They are shown in following figure 4.3.

Figure 4.3: Encapsulation of pipe

4.4 Components of the Test Setup

4.4.1 Air Circulation Setup

Air blowers of 12 V were selected to provide air flow required in experimental setup for heat transfer. Components of airflow circuit are briefly explained below.

4.4.2 Cold Air Source

Night time ventilation using free cooling technique takes into account as a cold source. An ambient air at night time is used to pass from box so that cold can be extracted from air and deliver to material to solidify it.

4.4.3 Air blower

12 V DC blowers connected with funnel constituted air duct. It collects the air from ambient source and supply to heat exchanger setup. Air is expelled in atmosphere from the air duct at outlet of heat exchanger setup.

Figure 4.4: Air blower attached with a funnel

4.4.4 Nozzles at inlet and outlet

Two nozzles of diameter 1 inch are punched at inlet and outlet of the box to provide air flow through the channels.

Figure 4.5: Nozzle

4.4.5 Wooden box

A rectangular box sizing 12x13 in made of wood is used for placing of pipe and act as a heat exchanger later. This box is fabricated in such a way that proper dimensioning of air passage channels are made on this box, as it provide passage to air to flow over the pipe with in the box.

Figure 4.6: Wooden box

4.4.6 Channels for air passage

In wooden box, proper channels are design in which pipe is placed and proper air is flow over the pipe. These channels provide passage to air which easily passes through it and exchange heat from material.

Figure 4.7: Channels for air passage

4.4.7 Thermocouples

K type thermocouples as shown below are attached with pipe to evaluate the temperature at different points of pipe.

Figure 4.8: Thermocouple

4.4.8 Anemometer

The purpose of anemometer is to measure the speed of air at inlet as well as outlet. It can measure the temperature of air and prescribed speed of air shown in fig.4.9.

Figure 4.9: Anemometer

4.4.9 Regulator

The regulator controls the speed of air blower. It prescribed the range to which air can be passed through it.

Figure 4.10: Regulator

4.4.10 Insulation

The TES Device is insulated from outside as well as inside including the channels with the help of glass wool for long lasting the storage of energy.

Figure 4.11: Glass wool

4.4.11 Data Logger

To measure temperature, k-Type sensor are selected and placed at sixteen different locations of experimental setup.

Data logger stored the measured temperature directly in PC using Excel format. Data logger was made using Arduino mega 2560 which is a microcontroller and integrates hardware with computer via LABView software. This software then store the data into excel file. Complete data logging setup is shown in following figure;

Figure 4.12: Data logger used during reading measurement

4.5 Piping and instrumentation diagram of setup

The working model is shown in fig. 4.13. For better experimental results, whole setup was covered with glass wool and it ensures better insulation as well. Glass wool is an insulation material consists of fiber glass covered with aluminum foil sheet.

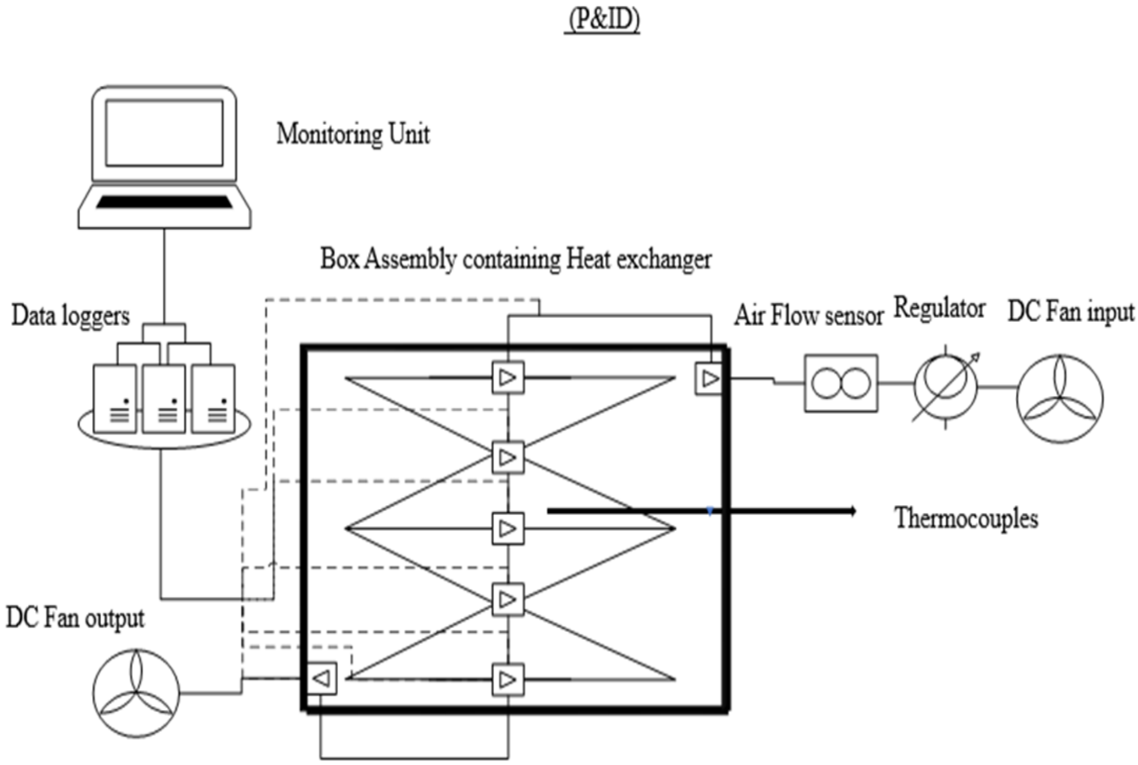


Figure 4.13 Piping and instrumentation diagram of setup

4.6 Experimental Setup

An experimental setup for the current study was established in the Laboratory for Solar Energy at U.S.-Pak Centers for Advance Studies in Energy at National University of Sciences and Technology, H-12 Islamabad. The design of a heat exchanger containing aluminium tube filled with PCM is shown in Fig. The piping and instrumentation diagram of setup is shown in Fig. 4.13. It consisted of two direct current (DC) powered air blowers, a wooden box, a data logger system and a personal computer (PC). The major components of the setup contain a wooden box, PCM filled pipe and temperature sensors. The PCM used here was lauryl alcohol having melting range 22–26 °C and heat storage capability of 200 kJ/kg. Some of the thermophysical characteristics of PCM are presented in Table 4.1. The material was encapsulated in U shaped aluminum tube, and the tube was placed in the wooden box. O-rings were used at both ends of the aluminum tubes to avoid any leakage of the PCM through the pipe during the freezing and liquefaction procedure. Fig.4.14 demonstrates the location of sensors on aluminum tubes in the wooden box setup and its real time photograph.

Figure 4.14: Experimental setup of TES Device

4.7 Experimental Procedure

DC-powered air blowers were used at the inlet and outlet to force the airflow through the air channel in the wooden box. K-type sensors were attached in the box to record the temperature of the air and PCM at different points.

During night time charging process take place and cool ambient air is delivered to PCM in the wooden enclosure, which led to PCM solidification. Ambient air is used as a source medium with the help of blower to freeze the material. Relatively hot ambient air was used to extract the accumulated cold during the discharging process from cold storage, which led to PCM liquefaction. The wooden box coupled with the PCM encapsulated pipe was isolated to reduce the cold transaction with the atmospheres [3,9]. The experimental setup was operated for 5½ h on a daily basis. The charging process, during which the PCM solidified, was run for 3½ h, whereas the discharging process was carried out for 2 h. Measurements were recorded after every 5 s.

Summary

The fabrication of experimental setup and results obtained has been briefly discussed in this chapter. Initially in this chapter description of all parts of experimental setup with complete fabrication details is discussed. In second portion of chapter, experimental results obtained have been briefly discussed. In addition it provided detail of flow rate effect on PCM charging and discharging, metal addition influence on PCM charging and discharging at high temperature.

Chapter 5

Results and Discussions

5.1 Experimental Results

5.1.1 Setup Analysis

During experimentation, the following parameters were observed and analyzed:

- Ambient temperature on the system ~20 to 30 °C.
- Mass flow rate of ambient air is 0.02 kg/s with speed of 5 m/s constant at inlet.

About 160g of PCM was encapsulated into aluminum tube. Initially material was in the liquid form and kept in the temperature of 30 °C more than its melting point. The data measured system and PC were respectively utilized to analyze and display the results of the system. The profile of temperature sensors at different location of pipe is shown in Fig. 5.1. The initial charging of PCM at different location of pipe is shown in Fig. 5.2 and the comparison of inlet, outlet and ambient air temperature is shown by graph in Fig. 5.3.

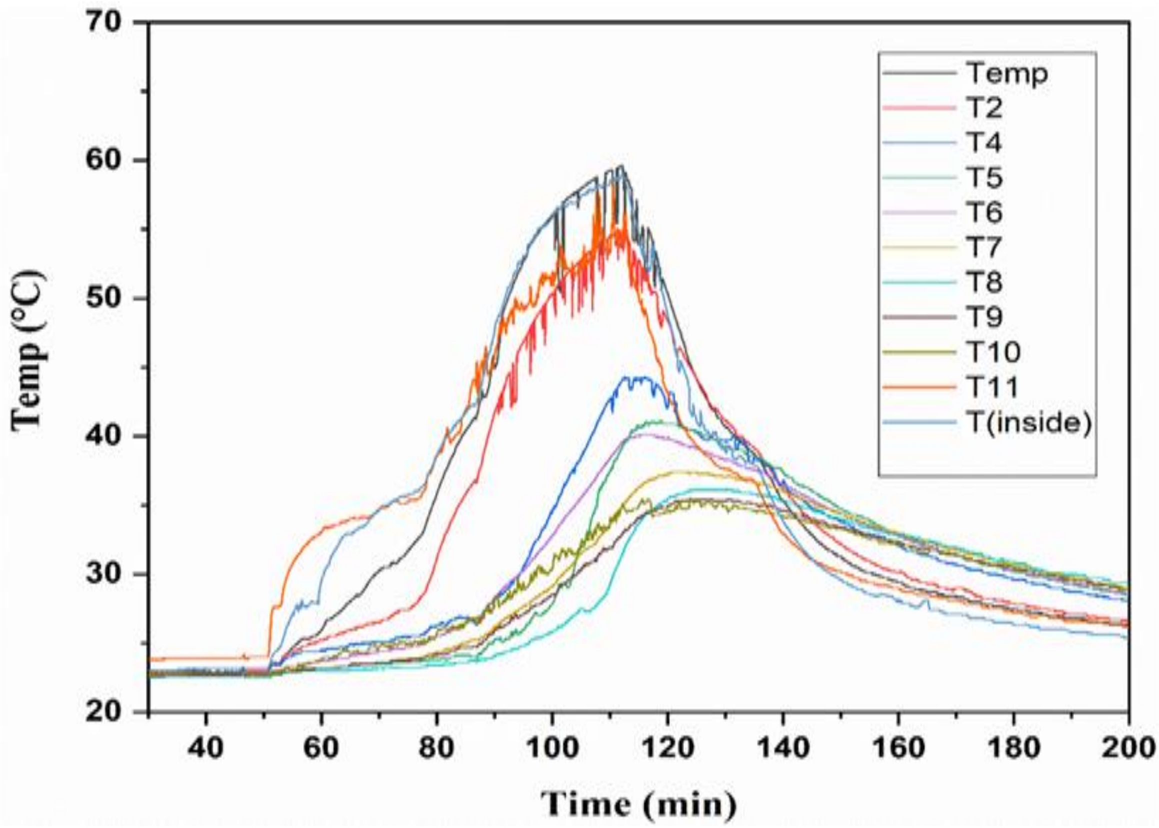


Figure 5.1: Profile of temperature sensors at different location

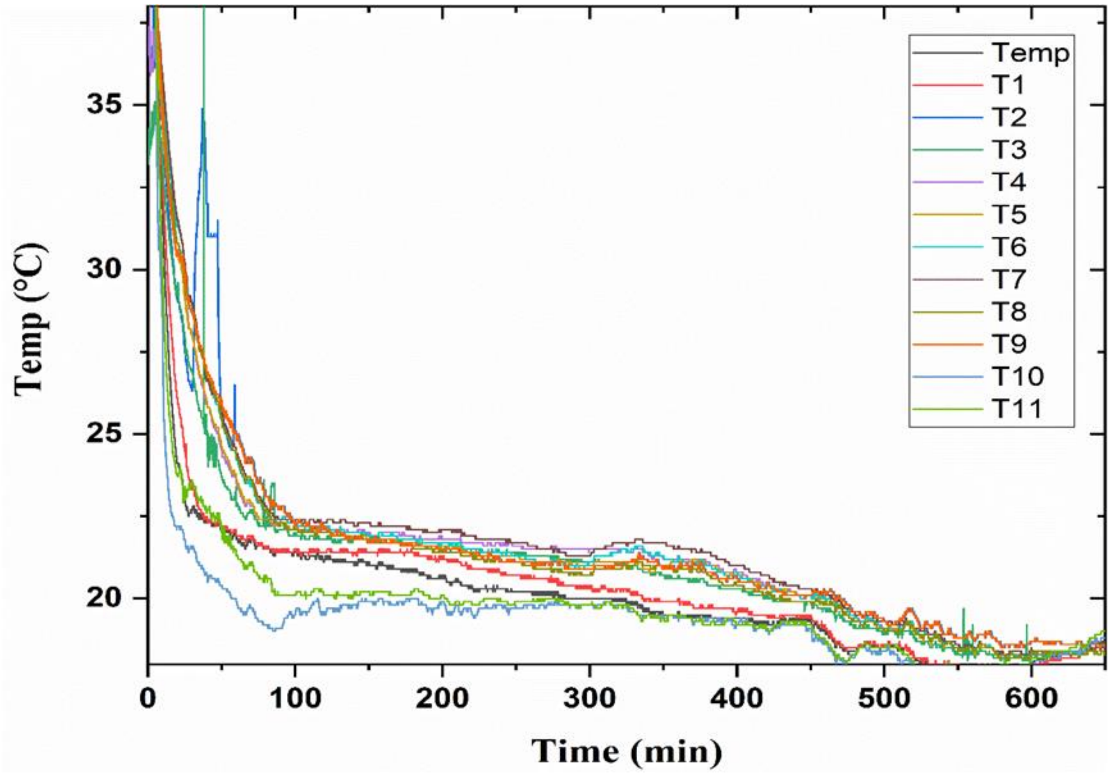


Figure 5.2: Profile of PCM charging temperature at different location of pipe

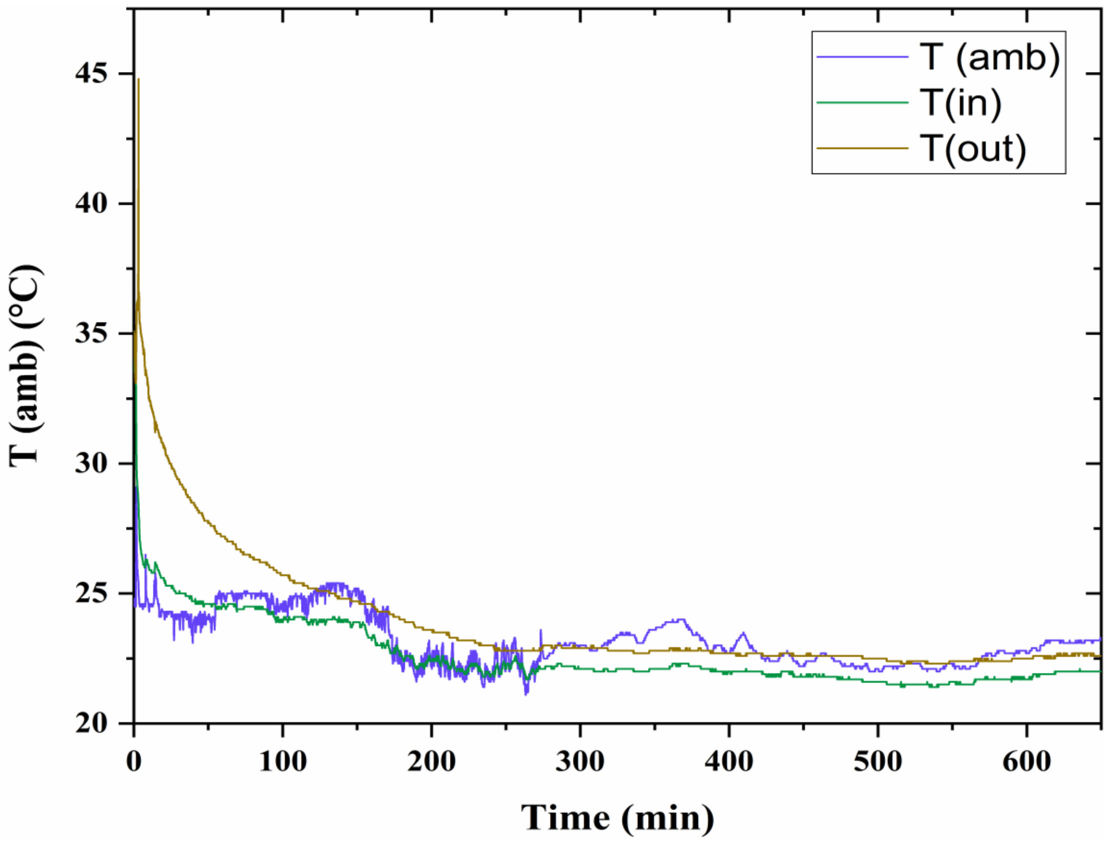


Figure 5.3: Profile of temperature at inlet, outlet and ambient air

5.1.2 Charging of PCM

The charging of PCM is studied by circulating ambient air flow at inlet temperature throughout the heat exchangers. The inlet temperature of 20^{o}C is maintained at mass flow rate of 0.02kg/s. The gradient curve shows that total amount of sensible energy stored during this phase of charging. The curve shows sharp decline as the PCM starts to solidify towards the lower temperature.

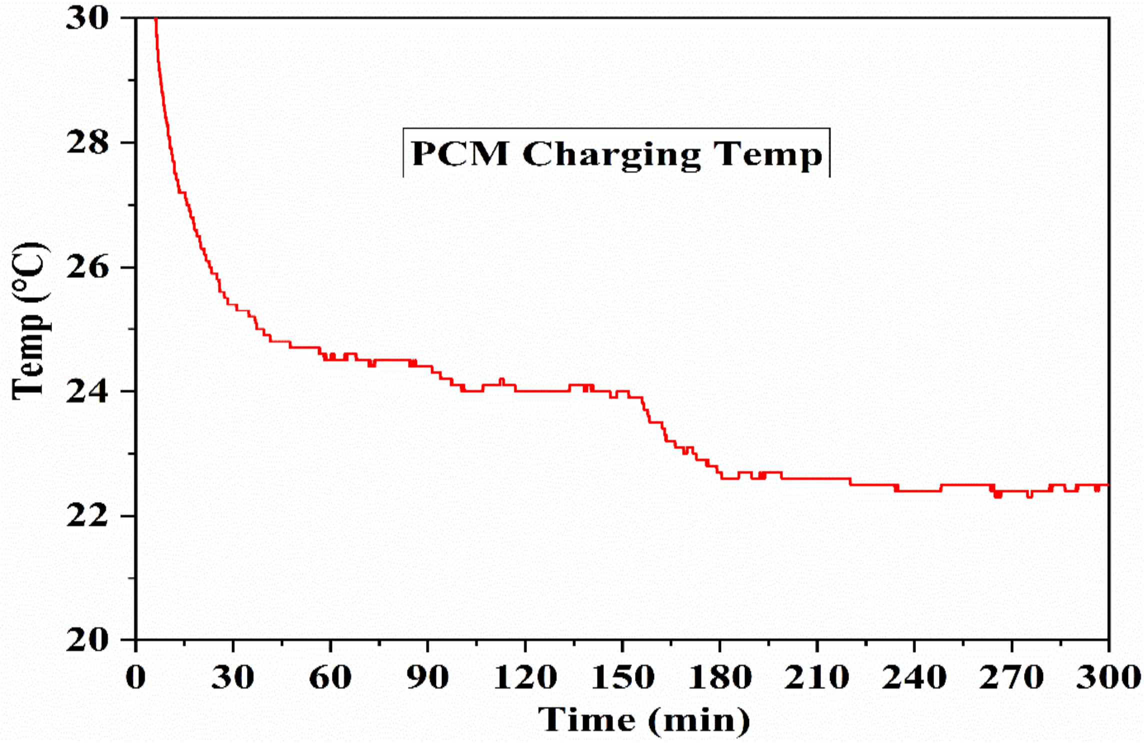


Figure 5.4: Profile of PCM during charging

5.1.3 Discharging of PCM

During the discharging of PCM the air is circulated through the nozzle at inlet with temperature of 30 ^{o}C and flow rate of 0.02kg/s. As the curve originated at time 0 PCM is in solid form. As the temperature increases the PCM start to melt and sharp curve occur which shows gradual slope until the material melts completely and release all of its stored energy.

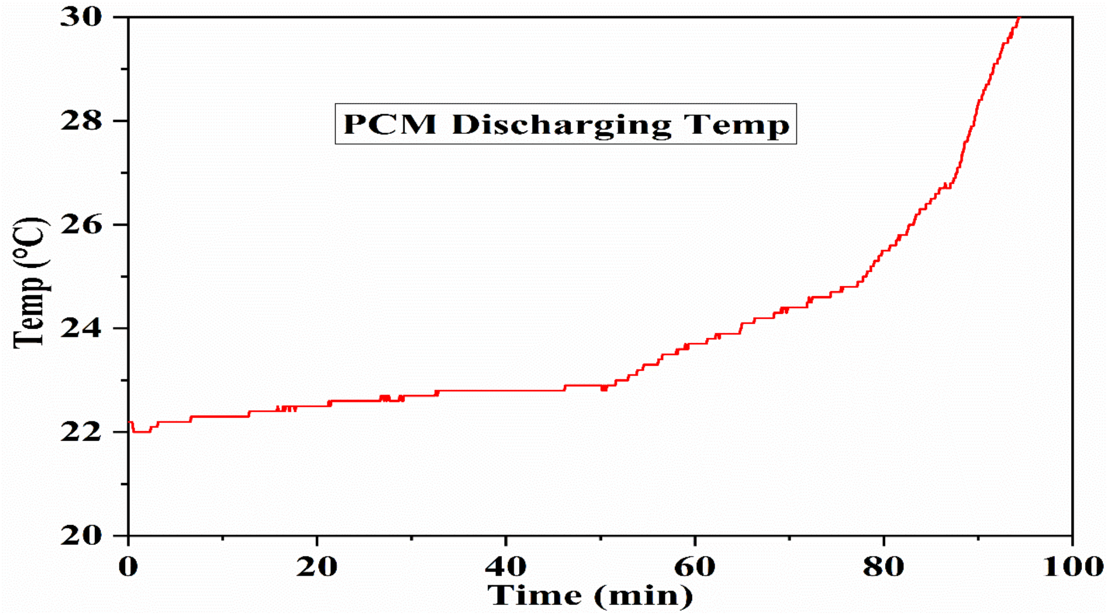


Figure 5.5: Profile of PCM during discharging

5.1.4 Air inlet and outlet flow

As the charging take place, air at inlet kept to 20 °C lower the melting point of PCM liquefaction of material convert to solidify until both graphs meet at a point and the outlet temperature fall below the inlet temperature. The graph explains that initially the temperature at outlet is 30 °C which fall down below the ambient temperature at appropriate time.

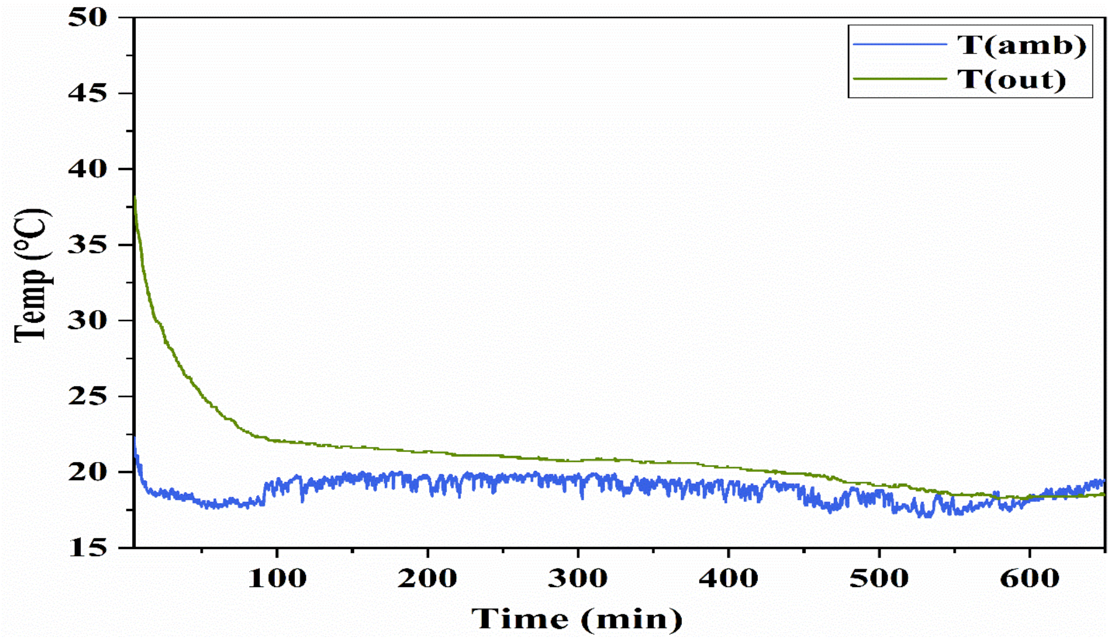


Figure 5.6: Profile of ambient inlet and outlet air

5.1.5 Complete profile of TES system

A series of experimentation take place to study the behavior of PCM. Fig. 5.7 shows a complete profile of TES system in which experimentation take place for a whole day. As the ambient temperature changes the charging and discharging of PCM occurs and the latent heat absorbed and released. The working of PCM shows that it is suitable for energy storage as maximum amount of energy is stored in it.

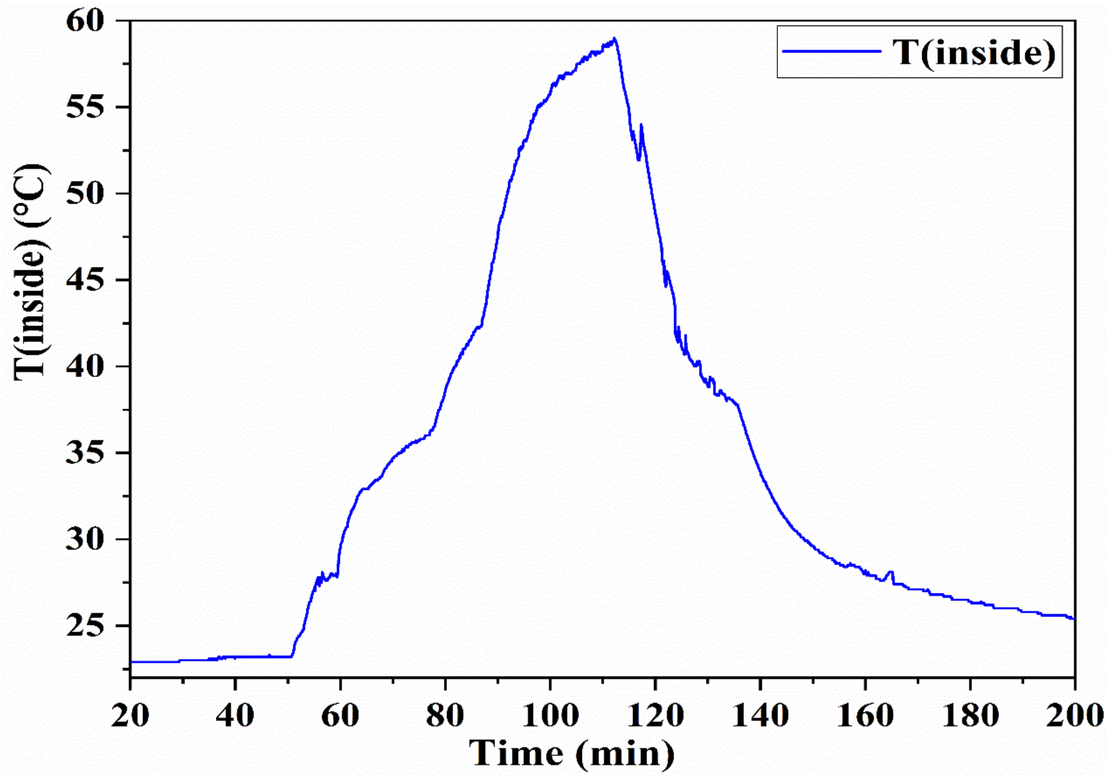


Figure 5.7: Complete profile of TES system

Chapter 6

Load Calculation and Sizing of the System

This section discusses the sizing of the system based on experimental results.

6.1 Sizing of the system

Experimental results discussed in previous section shows that during discharging process inlet air was at 30°C and outlet air was at 20°C. Based on these results cooling load supplied by the storage can be calculated using following equation;

$$Q_{abs} = m_{PCM}\, C_{p,air}(T_{out} - T_{in}) \int dt \qquad (6.1)$$

Q_{abs}= Energy absorbed, m_{PCM}= Mass of PCM, C_{pair}= Specific heat of air, T_{out}= Temperature at outlet, T_{in}=Temperature at inlet and ∫dt=Max time required to flow from inlet to outlet

Experiments show that during complete charging cycle system absorbed 0.323 kW. 80 % of this absorbed cold is in useful region. So the available cold after a charging cycle is 0.257 kW. According to our results we can size the system for our room cooling load requirements.

A room of 17x10 sq. foot utilizes an air conditioning unit with a capacity of 5.6 kW to maintain room temperature in comfort level during summer [9].

Using linear proportionality method

6.2 Calculation for Mass of PCM

For 0.257 kW; mass of PCM used = 160gm

For 1 kW; mass of PCM used = 160gm/0.257 kW

For 5.6 kW; mass of PCM used = (160gm/0.257 kW)*5.6 kW

For 5.6 kW; mass of PCM used = 3486gm

From above calculation 3.48 kg (approx. 3.5 kg) of PCM is required to keep the room in comfort level during summer.

6.3 Cost calculation

For 0.257 kW; cost of system = 6,500 PKR

For 1 kW; cost of system = 6,500 PKR/0.257 kW

For 5.6 kW; cost of system = (6,500/0.257 kW)*5.6kW

For 5.6 kW; cost of system = 1, 41,634 PKR

The system cost is 1, 41,634 PKR for a room of 17x10 sq. foot.

Table 6.1: Economic Analysis of System

Energy (kW)	Mass (g)	Cost (PKR)
0.257	160	6,500
1	622	25,291
5.6	3,486	1,41,634

Summary

This chapter determines the actual load calculation and sizing of the system. It is concluded from the experiment that the system is 80% efficient and deliver 0.257 kW of energy for air conditioning. From the calculated data it is measured that for the room 3.5 kg of PCM is required and the total amount for the installation is 1,41,634 PKR.

Chapter 7

Conclusion and Recommendations

Conclusion

Our goal is to develop low cost passive cooling system based on phase change material for human comfort during off-peak hours. For this purpose, the passive technique using PCM based on thermal energy storage system is one of the progressive and efficient techniques to store energy. Although its depend on diurnal temperature but its capability to store energy initiate researchers to perform further numerical and experimental investigations. After series of experimentation on TES Device the following conclusion:

- Lauryl alcohol was evaluated as one of the phase change material for storage of energy specifically consumed for passive/free cooling applications mainly in buildings.
- 160g of PCM takes 3½ h for charging and provide cold air within comfort range for almost 55 min.
- By using LA for cooling, reduces CO_2 emissions and cooling load of buildings during peak hours.
- Affordable and clean energy is achieved.

Recommendations

- Further pilot scale testings of system may point out any problems with the test instructions, instances where items are not clear, and formatting and other typographical errors and/or issues.
- Experimentation by adding impure materials and compare them with pure material may shows efficient results.
- Analysis at different flow rates, improvements in heat exchanger design and experimental setup shows even better results.
- Installation of system in building reduce off peak hours of building and save the energy as well as reduction in utility bills.

ANNEXURE