DIRECT PHOTO-THERMAL ENERGY STORAGE USING NANOPARTICLES LADEN PHASE CHANGE MATERIALS

A THESIS SUBMITTED IN FULFILLMENT OF THE REQUIREMENT FOR THE AWARD OF THE DEGREE OF

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CERTIFICATE

I hereby declare that the dissertation entitled "**Direct Photo-Thermal Energy Storage Using Nanoparticles Laden Phase Change Materials**: "Experimental Investigations" is an authentic record of my work carried out as requirements for the award of the degree of **Master of Engineering in Thermal Engineering** at **Thapar Institute of Engineering and Technology, (A Deemed to be University), Patiala** under the supervision of **Dr. Vikrant Khullar (Assistant Professor, Mechanical Engineering Department).** No part of the matter embodied in this report has been submitted to any other university or institute for the award of any degree.

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ABSTRACT

Thermal energy storage provides an efficient means of storing energy (during peak production period) and utilizing the stored energy during the peak load duration (particularly for heating and cooling household/industrial requirements). In other words, thermal storage ensures clean and uninterrupted energy supply at minimal additional operating costs. Storing solar energy is a clean and advantageous proposition. In this realm, we propose that seeding nanoparticles into pristine paraffin wax (due to their improved thermo-physical optical characteristics) could significantly enhance the charging rate and thus the thermal energy produce. In the present work, we have performed experiments to predict the charging rates when paraffin wax/nanoparticles dispersion directly (volumetrically) interacts with the sunlight. Broad absorption-based nanoparticles (amorphous carbon) have been seeded into the pristine phase change material (paraffin wax) to enhance photo-thermal conversion efficiency. In order to clearly identify the effects of adding nanoparticles, two systems of top heating have been studied (i.e. the one with surface heating and the other volumetric heating with nanoparticles dispersed in paraffin wax) and two systems of bottom heating have been studied (i.e. the one with surface heating and the other volumetric heating with nanoparticles dispersed in paraffin wax) under similar operating conditions. To understand the role of nanoparticles; samples of pristine paraffin wax and nano-PCMs (i.e. different concentrations of NPs) have been optically heated. Furthermore, optical charging has been compared with the conventional thermal charging process. As per experimental results, the optical charging scheme significantly improves the thermal charging rate (by more than 157% during top heating) at optimum nanoparticle concentration (0.2%, in the present study), in the same way the optical charging scheme significantly improves the thermal charging rate (by more than 81% during bottom heating) at optimum nanoparticle concentration (0.2%, in the present study) as compared to conventional thermal charging. The temperature distribution and thermal profile measurements of the Nano-PCMs collected through aforesaid process reveals that optical heating of PCM in presence of nanoparticles could definitely prove to be an improved method of charging.

Keywords: optical charging; phase change material (PCM); nanoparticles.

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NOMENCLATURE

English symbols

c_p	Specific heat [kJ/kg ^oC]
dT	Temperature to charge the PCM [^oC]
m	Mass [gm]
Q	Amount of energy stored [kJ]
T	Temperature [^oC]
V	Volume [m^3]

Greek Letters

λ	Latent heat of fusion [kJ/kg]
ρ	Density [kg/m^3]

Subscripts

atm	Atmospheric
avg	Average
f	Fraction
m	Melting
l	Liquid
p	Pressure
s	Solid
1	Lower
2	Higher

Abbreviations

ACNs	Amorphous carbon nanoparticles
IR	Infrared image
NPs	Nanoparticles
OC	Optical charging
PCM	Phase change materials
PID	Proportional integral derivative
LHS	Latent heat storage
SHS	Sensible heat storage
TC	Thermal charging
TC	Thermocouple
TES	Thermal energy storage

CHAPTER 1
INTRODUCTION

1.1. MOTIVATION

1.1.1 ENERGY STORAGE

Thermal energy storage provides an efficient means of storing energy (during peak production period) and utilizing the stored energy during the peak load duration (particularly for heating and cooling household/industrial requirements). Unremitting growing demand of supply is the main reason of energy deficiency. The demand of energy supply is continuously increasing day by day and in India; in the coming years energy demand in industrial sectors and other sectors shall escalate. In addition to the energy supply and demand mismatch; we are facing problems of global warming, air pollution, forest destruction, and emissions of radioactive substances. The risk of environmental degradation has become increasing high due to anthropogenic activities In presence of these environmental problems, energy from the sun is a sustainable and green option; particularly solar energy could be stored in various forms and could then be used during non-sunshine hours.

1.1.2 THERMAL ENERGY STORAGE

In today ‘s world energy storage is necessary to use it for a particular application, either it used for household purposes or it is used for industrial/agricultural purposes and its demand vary on daily, weekly and seasonal basis. Thermal energy storage (TES) provides a simple an economic means of utilizing solar energy even during non-sunshine hours to satisfy our heating and cooling needs. As a whole, thermal energy storage involves three processes: charging, storing and discharging. The TES systems could be broadly classified into sensible TES, latent TES, and thermo-chemical reactions. The effectiveness of sensible heat storage (SHS) depends on the specific heat, volume and density of the storage material. Whereas; in latent heat storage (LHS) system, the storage material undergoes a phase change at a constant temperature. Latent and sensible TES may also happen in similar storage material. Waste energy systems must be developed according to the requirement of the application in hand; chemical, industrial applications and agricultural applications etc., all have different requirements. There are many techniques which can be used to store thermal energy such as latent heat storage, sensible heat storage, steam accumulator, thermo-chemical energy storage, packed bed storage and non-convecting solar pond etc.
Technical standards required for TES i.e. resources used, environmental standards, size, cost, life, storage capacity etc. TES is indispensible in relation to utilization of solar energy, the highly intermittent nature of the solar energy. A variety of active and passive storage systems have been developed for efficient use of solar energy. Passive systems are those systems which do not require any pumps and are appropriate for household applications. Active systems are divided into direct and indirect systems. In some systems which do not require storage like solar distillers. Large numbers of organic compounds (such as paraffins) are suitable as storage media as these are nontoxic and are easily available at low cost.

1.2 METHODS OF TES

1.2.1 SENSIBLE HEAT STORAGE (SHS)

Sensible heat storage (SHS) material stores energy by increasing its temperature, i.e., sensible heat gain. The quantity of energy stored and effectiveness depends upon the temperature change of the material, specific heat of material, its volume and density. It can be expressed in the form

$$Q = \int_{T_2}^{T_1} mC_p dT \tag{1}$$

$$= \int_{T_2}^{T_1} \rho V C_p dT \tag{2}$$

where m is the mass and c_p specific heat at constant pressure, Q is the stored energy. T_1 and T_2 represents the upper and lower temperature of PCM or storage media.

1.2.2 LATENT HEAT STORAGE (LHS)

Latent heat storage (LHS) refers to storage in which the material undergoes phase transition at constant temperature.
In latent heat storage four types of phase transformations are useful such as: solid ↔ solid, solid ↔ liquid, liquid ↔ vapor, solid ↔ vapor. In latent heat the energy storage depends upon the mass and latent heat of fusion of the material. If a material changes its phase is heated from T_1 to T_2 that includes the melting temperature T_m. ($T_1 < T_m < T_2$) The amount of energy stored can be expressed in form

$$Q = \int_{T_1}^{T_m} mC_p dT + m\lambda + \int_{T_m}^{T_2} mC_p dT \tag{3}$$

For solar energy storage most common PCMs used undergo solid ↔ liquid transformation and this may be mathematically expressed as

$$Q = mC_{ps}\left(T_m - T_1\right) + \lambda + mC_{pl}\left(T_2 - T_m\right) \tag{4}$$

where m is the mass of material, T_1 and T_2 represents the upper and lower temperature of PCM or storage media, T_m is the melting temperature of material, c_{ps} and c_{pl} specific heat of solid and liquid phases.

1.2.3 THERMOCHEMICAL ENERGY STORAGE

In this type of storage system, chemical reactions are used to store energy, forward direction reaction is endothermic (i.e. storage of heat) and in reverse direction is exothermic (i.e. release of heat). Small quantity of material can store large amount of heat and amount of energy stored depends upon the heat of reaction. The main benefit of thermo-chemical storage is that the reactants can be stored at room temperature, i.e., no need of insulation. Reactions can also operate

isothermally [26]. For the medium and high temperature storage the bond energy storage system can be used for various applications.

1.3 ECONOMIC AND ENVIRONMENTAL IMPACTS

Intermittent nature of the solar energy resource lends TES to be an integral part of any solar thermal system. This allows excess of solar energy to be stored and subsequently the stored energy could be supplied during non-sunshine hours; hence leading to more economic and efficient utilization. TES could prove to be beneficial in mitigating thermal pollution as well as reduce the usage of fossil fuel-based technologies. The economic aspect is one of the key factors impacting the deployment of thermal energy storage systems.

1.4 CHARACTERISTICS OF TES

The storage system could be either long term or short term depending upon the requirement i.e. buffering, delivery period displacement, delivery period extension and seasonal storage. The buffering is used for short periods (few minutes to a 2-3 hours). The delivery period displacement is the collection of energy during the day which will be used for delivery during peak load period of evening hours. The delivery period extension energy is collected during day time and which have been used for longer times of non-sunshine hours of a day to a number of days. The Seasonal Storage, which have been stored heat during summer and used in winters.

1.5 LIMITATIONS OF TES

In TES system, the storage size contains a range of capacities. The storage size of the system depends upon the quantity of energy stored and the duration for which it is to be stored (for few hour/days or months). On the other hand, there are some limitations in thermal energy storage from societal point of view which consist of issues related to the energy storage and release of thermal energy at constant temperature, space requirements and disposal of the chemically derived PCMs and thermochemical reactive materials into the environment without any treatment. Thermal stability of the storage material is very important factor as it dictates its productive life span. As compared to other TES materials, phase change material can store three to four times more energy per unit volume. The chemical and physical stability of phase change material gives the longer life. The storage system performance depends upon the criteria which will be technique use for TES, selection of PCMs, size of storage capacity, time for storage (i.e. for an hour to a number of days) etc. There are different types of TES method and storage media available in the form of organic and inorganic PCMs but, TES by using solar energy is more cost effective and it can handle range of storage capacities.

1.6 THESIS OUTLINE

In the present work, the role of nanoparticles in enhancing the charging rate of nano-PCM has been experimentally studied. It has been found that the present technique is effective in thermal energy storage which represents improved charging rate through direct interaction with solar irradiance. Chapter 1 gives the motivation behind the present thesis work. It consists of reasons, method and

necessity of the present work that is thermal energy storage through optical charging mode. Chapter 2 is the review of the literature which I have gone through during my thesis work. This process has given me diverse viewpoints, data and much useful information related to my present work. From useful information I have found the research gaps. Chapter 3 is about experimental material and methods. It describes in detail the testing equipments used, methods, and materials used. Chapter 4 reveals the experimental results and outcomes. It shows the graphs of charging rate and temperature distributions of four cases with volumetric heating and surface heating. It also shows the thermal profile of four cases in IR images which is captured during experimentation and shows the result of different concentrations of nano-PCMs. Chapter 5 details the conclusion of the present work and future scope.

CHAPTER 2
LITERATURE REVIEW

2.1 INTRODUCTION

TES through usage of solar energy is clean, non-polluting and renewable resource of energy. TES essentially involves: charging, storage and discharging. Furthermore, thermal storage process could be either sensible TES or latent TES. In sensible heat storage (SHS), the material (concrete, rock, etc.) undergoes temperature change during charging and discharging processes; whereas in latent TES, the material (ice, salts, etc.) undergoes phase transformation during the charging and discharging processes [1]. Latent TES (employing PCMs) in particular offers range of capacities (quantity of energy stored) and capability of storing energy ranging from few hours to a few days at relatively high energy stored to volume ratio. PCMs could be classified into three basic types: organic (paraffins, fatty acids), inorganic (salt hydrates), eutectics (organic, inorganic) [2]. Conventionally, the charging process (melting of PCM) involves bleeding a part of the heated fluid from the outlet of solar thermal system and circulating it in a pipe through the PCM containing storage tank. Herein, the heat of the fluid gets transferred to the PCM primarily through conduction and therefore the pipe material is invariable a highly conducting material (such as copper). Furthermore, researchers have used pipes with fins and employed various agitation techniques to enhance the heat transfer.

2.2 APPLICABILITY OF NANOPARTICLES

Nanoparticles have a particle size in the nano-range (10^{-9}), they could be considered to be as lumped systems (uniform temperature distribution). The use of nanoparticles and nano-composites in thermal energy storage enhance the rate of heat transfer. When nanoparticles are mixed with the phase change materials it enhances the charging and discharging rate of PCMs [3] (see Table 1). The charging and discharging of PCMs depends upon the volume fraction of nanoparticles. In literature; researchers have used different types of nanoparticles and composites as per requirement. The following are the reasons the use of nanoparticles:

- Tunable optical properties.
- Enhanced thermal conductivity.
- Very small size, therefore could efficiently transfer the absorbed energy to the surrounding medium.

Recently, the photon-transport based optical charging (OC) wherein, the solar irradiance directly interacts with the PCM has proven to significantly improve the charging process. Herein, nanoparticles have been seeded in the conventional PCMs to enhance its absorption capability; and the nanoparticle-laden PCM directly interacts with the incident sunlight through absorption and scattering mechanisms. Although, seeding nanoparticles into a transparent PCM is the most effective proposition but researchers have revealed that photon-transport based optical charging can still be applicable to nanoparticles-laden opaque PCMs [3]. To enhance the charging rate researchers have dispersed various nanoparticles in PCMs (Cu NPs, Au NPs, Al_2O_3 NPs, metal foam copper, carbon nanotubes sponge, hybrid NPs etc.) - these could be broadly classified into plasmonic metallic nanoparticles or carbon-based broad absorption nanoparticles. With the objective of optimizing the optical charging process, there have been efforts to understand the

photon-nanoparticle laden PCM interaction mechanism and subsequently the melting process. Richardson et al., studied the light interaction with gold nanoparticles dispersed in ice matrix [4]. Chen et al., enhanced the enthalpy and thermal conductivity of PCM through usage of deformable carbon nano-tube sponge wherein energy storage is driven by illumination [5]. Lin and Al-Kayiem used copper NPs to improve the thermophysical properties of PCMs for thermal energy storage [6]. Usage of copper NPs in solar pond has proven to reduce the charging and discharging time significantly [7]. Alumina NPs dispersed into PCM to form a nano-PCM which has been used to increase the charging rate as compare to pure PCM [8]. Hybrid nanoparticles have been used in solar heating systems to enhance the storage and nanofillers of graphene NPs have been found to enhance the thermal conductivity with increase in loading of NPs [9-10].

Ultra-thin foam dispersed into PCM have shown to significantly increase (up to 18 times) the thermal conductivity at even low volume fractions and PCM filled spherical capsules have also been used to increase the thermal storage, cyclohexane with copper nanoparticles have been dispersed into PCM with porous medium to increase the energy storage [11-17]. The addition of metal foams has shown to increase the overall heat transfer up to 3-10 times. Researchers have also shown that usage of liquid metal gallium as nano-PCM reduces the melting time and improves thermal storage [17-23].

The present work is essentially an attempt to further understand the optical charging and discharging processes. This shall help in identifying the key parameters and processes impacting the melting rate of nanoparticle-laden PCMs. Firstly, we prepare the samples of nano PCM by using ultra-sonication method. Two set of experimental set-ups have been designed, which are similar in all respects except that one simulates the surface heating i.e. the conventional charging mechanism and the other simulates the optical charging mode. Subsequently, charging rate of nano PCM at different concentrations have been carefully measured under optical charging mode.

2.3 LITERATURE REVIEW STRATEGY

Type of heating source

- Optical heating (Solar simulator)
- Thermal heating
- Electrical heating
- Heat transfer fluid (HTF)

Type of base-PCM used

- Paraffin wax, ice, emulsions etc.

Material and morphology of nanoparticles used

- Material: Metallic, Carbon-based, composite.
- Shape: spherical, core shell etc.

Temperature range

- High, medium, low

Table 1: List of the notable researchers along with their affiliation who are actively working in enhancing the charging rates with nanoparticles seeded PCMs. (International status)

Author(s); (Year)	**Nanotube/ Particle /Size/fluid**	**Heating Source**	**Temperature**	**Time period**	**Surface modification**	**Phase change materials (PCMs)**
Hugh H. et al., (2006)	Au NPs (gold) [50nm]	Focused Laser beam [0.2 to 50 mW]	[-2.5 to -24] ˚C	30s	----------	Ice matrix
Zhao et al., (2010)	Metal foam Copper	Electrically heated	48-59 ˚C	4000s	----------	Paraffin wax RT58
Chen et al., (2012)	Carbon Nanotube sponge [20-30nm]	Electric potential PW-CNTS [1.5-1.75V] Solar simulator With intensity 58, 70, 90 w/cm^2	Up to 32 ˚C & Up to 50 ˚C	EP 2000s Light [400-500s]	----------	Paraffin wax
Lin et al., (2012)	CuO powder CuNPs [20nm]	----------	Up to 60.45˚C & Up to 59.57˚C & Up to 59.14˚C Sample [1,2,3]	----------	----------	Paraffin wax
Fan et al., (2013)	SMWCNTs LMWCNTs , GNPs, CNFs [20, 50, 64, 150] nm	Aluminum holder [Temperature bath]	Up to 40-60 ˚C & Up to 35-50 ˚C	3 hrs.	----------	Paraffin wax
Hengxing Ji et al., (2013)	UTGFs [500μm] & Erthritol Composites	Electrical heating & Laser flash method	Up to 58.9 ˚C & Up to 120.2˚C	600s	----------	Paraffin wax
Wang et al., (2014)	Au (NPs) [10.5±1.5nm] Au (NRs) [17±2.2nm]	Green laser light and sun light [Plasmonic heating] 36.3 w/cm^2	Up to 160˚C & Up to 48 ˚C	600s	Oleylam-ine	Paraffin based transparent gel wax

Table 1 Continued

Author (s); (Year)	**Nanotube/ Particle /Size/fluid**	**Heating Source**	**Temperature**	**Time period**	**Surface modification**	**Phase change materials (PCMs)**
Rakib et al., (2014)	CuO NPs and aluminum porous matrix	Thermal energy source	----------	3000s	---------	Cyclo-hexane
Wang et al., (2017)	Fe_3O_4 Graphene NPs [7±2nm]	Green Laser light With intensity 4 W/cm^2	Up to 130 ˚C [TC], Up to 120 ˚C [OC], [27-117 ˚C] [MOC]	900s	----------	Paraffin wax
Alomair et al., (2017)	CuO NPs [50nm] & Al_2O_3 NPs [50nm]	Polystat temperature regulator with 115V and 250W power input	Up to [5-80 ˚C]	58 min	----------	Paraffin Wax RT18
Mahdi et al, (2019)	Al_2O_3 NPs With Cu fins	Heat transfer fluid	Up to [80-90 ˚C]	120 min	----------	Paraffin wax (RT82)

Table 2: List of the notable researchers along with their affiliation who are actively working in enhancing the charging rates with nanoparticles seeded PCMs. (National status)

Author(s); Year	**Nanotube/ Particle /Size**	**Heating Source**	**Temperature**	**Time period**	**Surface modification**	**Phase change materials (PCMs)**
Murthy et al., (2012)	CuO Nano-Particles	Simulated solar pond with heater [2000W]	Up to [52-55 ˚C] & salt Water 65 ˚C	----------	----------	Paraffin (n-docosane)
Pise et al., (2013)	Al_2O_3 NPs nanopowder [20nm]	Water heater with heat transfer fluid	Up to 90 ˚C [HTF] & 60.45 ˚C [PCM]	300 min	----------	Paraffin wax

Khot et al., (2013)	Multiple spherical capsules PCM ball [75nm]	Solar simulation unit	Up to Water [64.45 ˚C] & PCM [63.4˚C]	80 min	----------	HS-58 Inorganic chemical based PCM
Krishnan et al., (2013)	Hybrid CuO and TiO_2 NPs (Powder) [21nm]	Heat transfer fluid HTF (water)	HTF [20-90 ˚C] & Up to 72 ˚C	720s	Sodium dodecyl benzene Sulfonate	Paraffin wax
Sankaret al., (2018)	NiO Nickel Oxide [100nm]	Water heater [2000W]	Up to 63 ˚C	30 min	----------	Paraffin wax n-Tricosane

2.4 GAPS IN THE LITERATURE

- Limited work using broad spectrum white light source which simulates sunlight.
- Limited studies that take care of the effect of direction of heating.
- Only a few studies have compared their work with the conventional storage devices.
- Limited work has been done which accounts for impact of nanoparticles on both charging and discharging modes.

2.5 THESIS OBJECTIVES

The present work investigates the impact of seeding nanoparticles on the charging rate of PCMs during optical charging. Following are the specific objectives of the thesis:

- Experimental investigation of thermal energy storage with nanoparticles laden phase change materials to enhance the charging rate of phase change materials. (in terms of typical temperatures reached)
- Investigation of thermal effect during Charging of phase change materials from both top and bottom side.
- Identification of the key operating parameters and performance of thermal energy storage with nanoparticles.

CHAPTER 3
EXPERIMENTAL MATERIAL AND METHODS

3.1 MATERIALS

In order to clearly understand the heat transfer mechanisms involved during thermal and optical heating; four sets of experiments have been carefully designed. In the present work paraffin wax has been used as PCM and amorphous carbon nanoparticles (<100nm SIGMA ALDRICH) of desired amount have been dispersed into PCM to form nano-PCM. All materials have been used without any further purification. For temperature measurements, K-type thermocouples were employed. In experiments, glass and solar selective surface (black chrome coated copper sheet, 0.019 cm thick, Solchrome) were used as interface in four set of experiments. The enhancement depends upon the type of the nanoparticles used and particle size.

For measuring temperature, we use K-type thermocouple because they give widest range of operating temperatures. It consists of two junctions one is positive and non-magnetic, other is negative which is magnetic. One of the constituent metals is nickel which is magnetic in nature. The major reason for using these thermocouples is that they can work in rugged environmental conditions and in different atmospheres [24]. It has composition of chromel and alumel and has an operating range between -270^{o}C to 1260^{o}C.

3.2 PREPARATION OF AMORPHOUS CARBON NANOPARTICLES BASED PCM

Various nano-PCMs containing paraffin wax (10g) and amorphous carbon nanoparticles (ACNs) with different mass fractions have been prepared and thermal conductivity has been measured using heat flow method (P.A Hilton Ltd., H112N) [see Table 3]. Weighing balance (METTLER TOLEDO XSE1) is used to measure the quantity of paraffin wax (in grams) and ACNs. Thermal conductivity set-up with PID controller is shown in Fig. 1.

Table 3: Nano-PCMs with different concentrations

Phase Change Material	**Mass fractions, m_f %**	**Thermal Conductivity($Wm^{-1}K^{-1}$)**
Paraffin wax (10g)	**0%**	**0.278± 0.011**
Paraffin wax (10g) + ACNs (**0.005g)**	**0.05%**	**0.324± 0.010**
Paraffin wax (10g) + ACNs (**0.01g)**	**0.1%**	**0.388± 0.013**
Paraffin wax (10g) + ACNs (**0.02g)**	**0.2%**	**0.359± 0.014**
Paraffin wax (10g) + ACNs (**0.04g)**	**0.4%**	**0.329± 0.012**

Fig. 1 Shows the thermal conductivity measurement setup with PID controller.

3.3 ULTRA-SONICATION PROCESS

Sonication is a process in which such disruptions can be used to mix solutions, speed up the mixing and agitate particles in solution by using sound waves. In water bath, sound waves are produced by sonicator, where samples are placed or probe can be put directly into the sample to be sonicated. The frequency of ultra-sonication process is usually greater than 20 kHz.
Initially, paraffin wax has been melted in water bath and subsequently amorphous carbon nanoparticles of desired mass have been added to melted paraffin wax as shown in Fig. 2. Paraffin wax and amorphous carbon has been mixed by ultra-sonication process. All samples are prepared by using sonication process in which ultra-sonic waves leads to uniform mixing of the nanoparticles into the melted medium. Sonication method is indirect method and, in this method, sonic energy is transmitted from horn through the water and into multiple samples i.e. a large number of nano-PCM samples could be prepared simultaneously. We use ultra-sonicator bath model SU-323 with load 3A by filling ¾ liquid in the tank (water). The process has been carried out for 15 minutes, subsequently; the as-prepared nano-PCM samples were cooled down to atmospheric conditions. Figure 2(b) shows the picture of as-prepared nano-PCM samples after the ultra-sonication process.

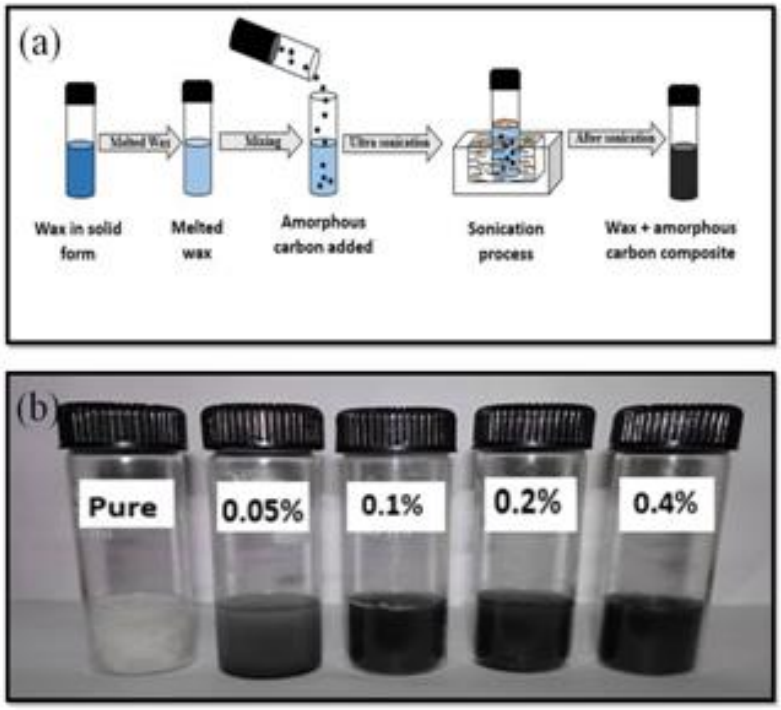

Fig. 2 (a) Schematic showing ultra-sonication process for preparing nano-PCM (b) showing prepared samples of nano-PCM after ultra-sonication process.

3.4 EXPERIMENTAL SET-UPS

Figure 3 shows the experimental set up consisting of 0.8cm diameter optical light guide [25] transporting the light from halogen lamp (250W, 24V Philips) connected with transformer and power supply. Intensity of light as measured by thermopile detector and power meter (1918-R, Newport) is 12.5W/cm^2. Holding clamp is used to hold the optical light guide and the cylindrical

tube housing the PCM is fixed at the base of the stand. Four equally spaced (0.5cm apart) and calibrated K-type thermocouples have been placed in the cylindrical tube (1.7cm X 1cm) housing the PCM and fifth thermocouple is kept in open to record ambient temperature.

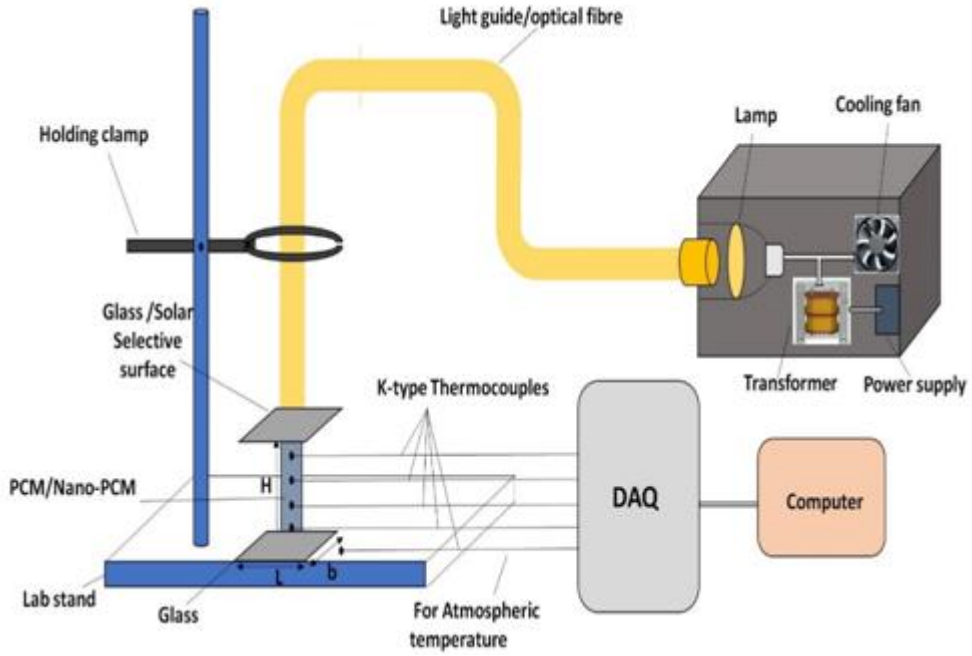

Fig. 3 Schematic shows experimental set-up of top heating for charging process of nano-PCM

As mentioned earlier, four sets of experimental were carried out i.e. volumetric (simulating optical charging) and surface (simulating thermal charging) heating from top and in similar way volumetric (simulating optical charging) and surface (simulating thermal charging) heating from bottom. In volumetric heating, the cylindrical tube is covered with glass (2.5cm X 2.1 cm) from both sides and in surface heating one side is covered by solar selective surface (2.5cm X 2.1 cm), and the other is covered with glass for all set of experiments.

Firstly, we calibrate these five thermocouples; check these thermocouples by dipping in hot and cold water baths, if all thermocouples give the same temperature it means they are ready for use. The tolerance of K-type thermocouples is $\pm 1^{o}C$. In four set of experiments, we fix the cylindrical tube at the base of the stand and also fix the positions of the thermocouples and optical light guide (see Fig. 3).

Tube is filled with PCM/nano-PCM. Heating or charging process has been carried out for 1800 seconds, after which the power supply is turned off and the melted PCM/nano-PCM is allowed to cool for 1380 seconds (to ensure that the solidification process is completed and the PCM/nano-PCM is in equilibrium with the atmospheric conditions). Figure 4 shows changed position of heating source and one holding clamp is used to hold the experimental setup and other clamp is used to hold the optical light guide system. Each experiment has been performed for at least three times (to ensure repeatability of the results). The temperature field as measured by the thermocouples was logged using data acquisition (DAQ) system (NI).

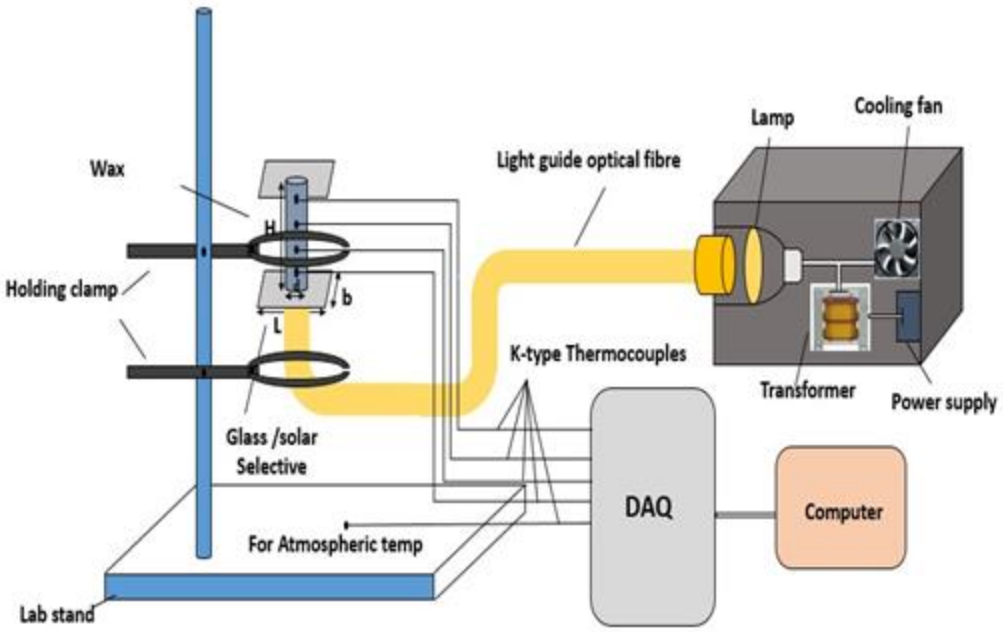

Fig.4 Schematic shows experimental set-up of bottom heating for charging process of nano-PCM

From experimental point of view the seasonal variations plays very important role in thermal energy storage. According to changes in season the atmospheric temperature may vary which gives the changes in absolute temperature. We have performed our experiment in winter season and storage tank requires a proper insulation because in seasonal variations energy losses may increase. We have recorded all data in terms of typical temperature reached.

The reason behind the use of solar selective material is that it absorbs most of the sunlight incident on it but emits very little of heat as thermal radiation. Different types of solar selective materials are used for different types of applications. All experiments of prepared samples are performed under similar conditions. Figure 5 shows the schematics of set-ups employed for surface and volumetric heating from top.

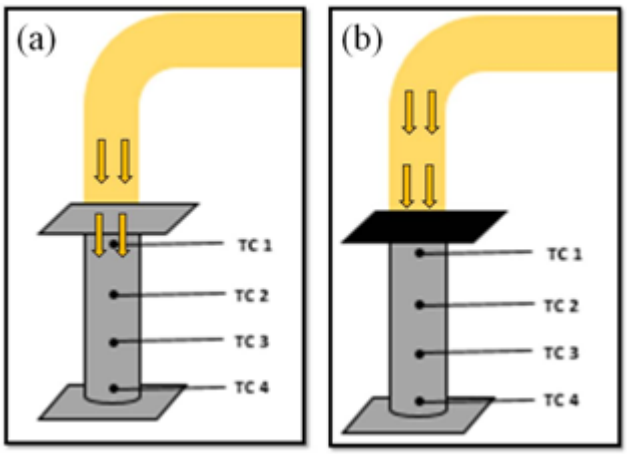

Fig. 5 Schematics showing the position of optical light guide and thermocouples heating from top for (a) volumetric heating, and (b) surface heating

Figure 6 shows the schematics of set-ups employed for surface and volumetric heating from bottom side. In our experiment we store energy at small scale but for using it at a commercial scale we require large storage systems. However, irrespective of the size, the heat transfer mechanisms dictating the charging and discharging rates shall essentially remain the same.

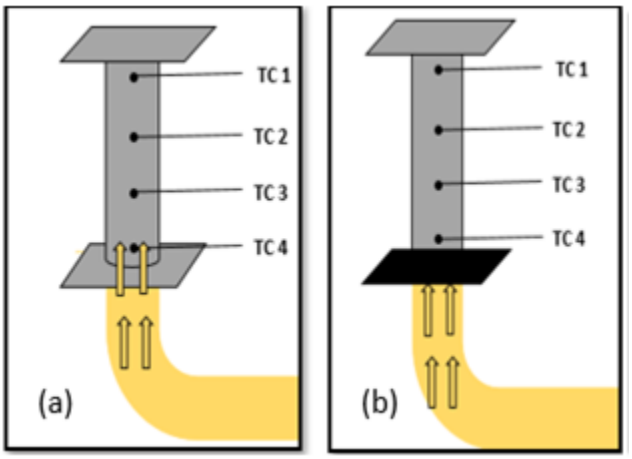

Fig. 6 Schematics showing the position of optical light guide and thermocouples heating from bottom for (a) volumetric heating, and (b) surface heating

CHAPTER 4
EXPERIMENTAL RESULTS

Charging rates for two cases i.e. heating from top (namely interface-glass and interface-solar selective material) at various concentrations of the nanoparticles have been plotted in Figs. 7 and 8.

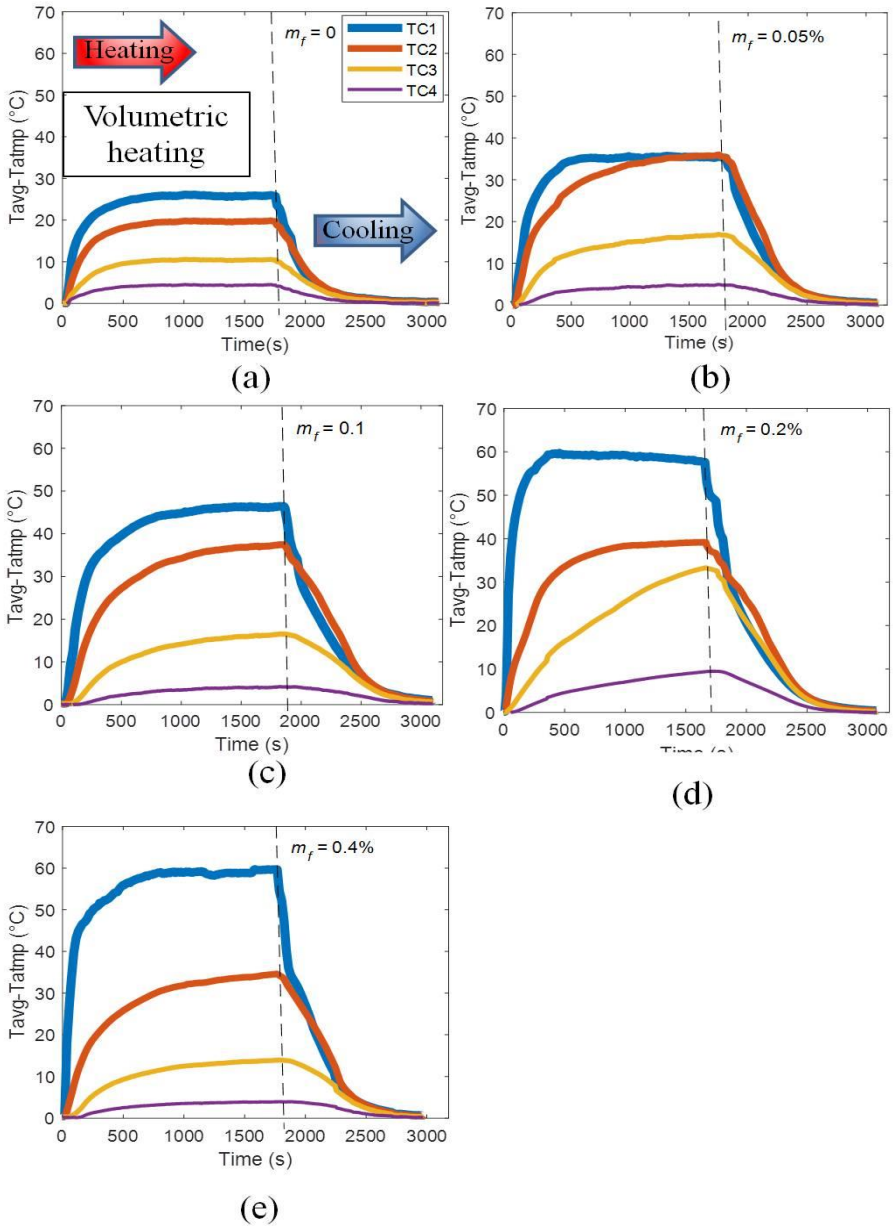

Fig. 7 Temperature field under OC mode (i.e. heating from top) as a function of time for four different concentrations of nanoparticles (a) pure paraffin wax, (b) NPs with concentration 0.05%, (c) NPs with concentration 0.1%, (d) NPs with concentration 0.2%, and (e) NPs with concentration 0.4%.

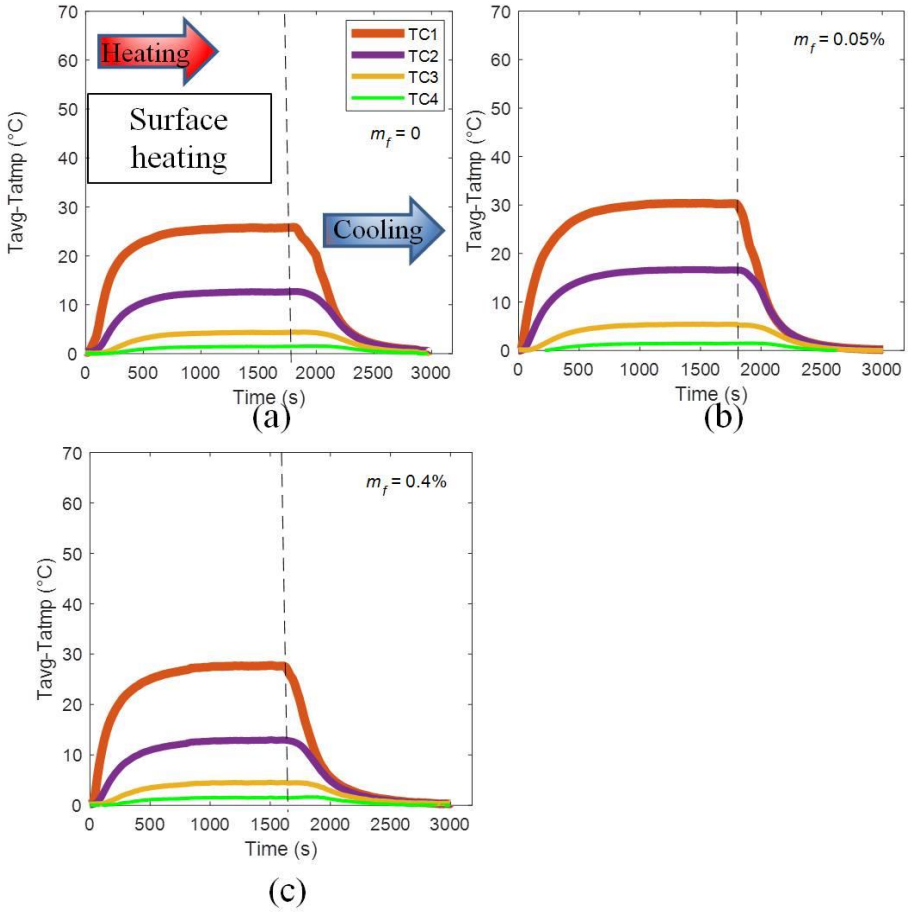

Fig. 8 Temperature field under TC mode (i.e. heating from top) as a function of time for two different concentrations of nanoparticles (a) pure paraffin wax, (b) NPs with concentration 0.05%, and (c) NPs with concentration 0.4%.

Graphs clearly reveal that for a given illumination period (30 minutes in the present study), charging rate increases with increase in concentration of nanoparticles. Furthermore, volumetric heating is more effective as compare to surface heating. All graphs show charging process from its initial state to final state. The melting time and solidification time have been kept same in all the cases.

Charging rates for the other two cases i.e. heating from bottom (namely interface-glass and interface-solar selective material) at various concentrations of the nanoparticles have been plotted in Figs. 9 and 10.

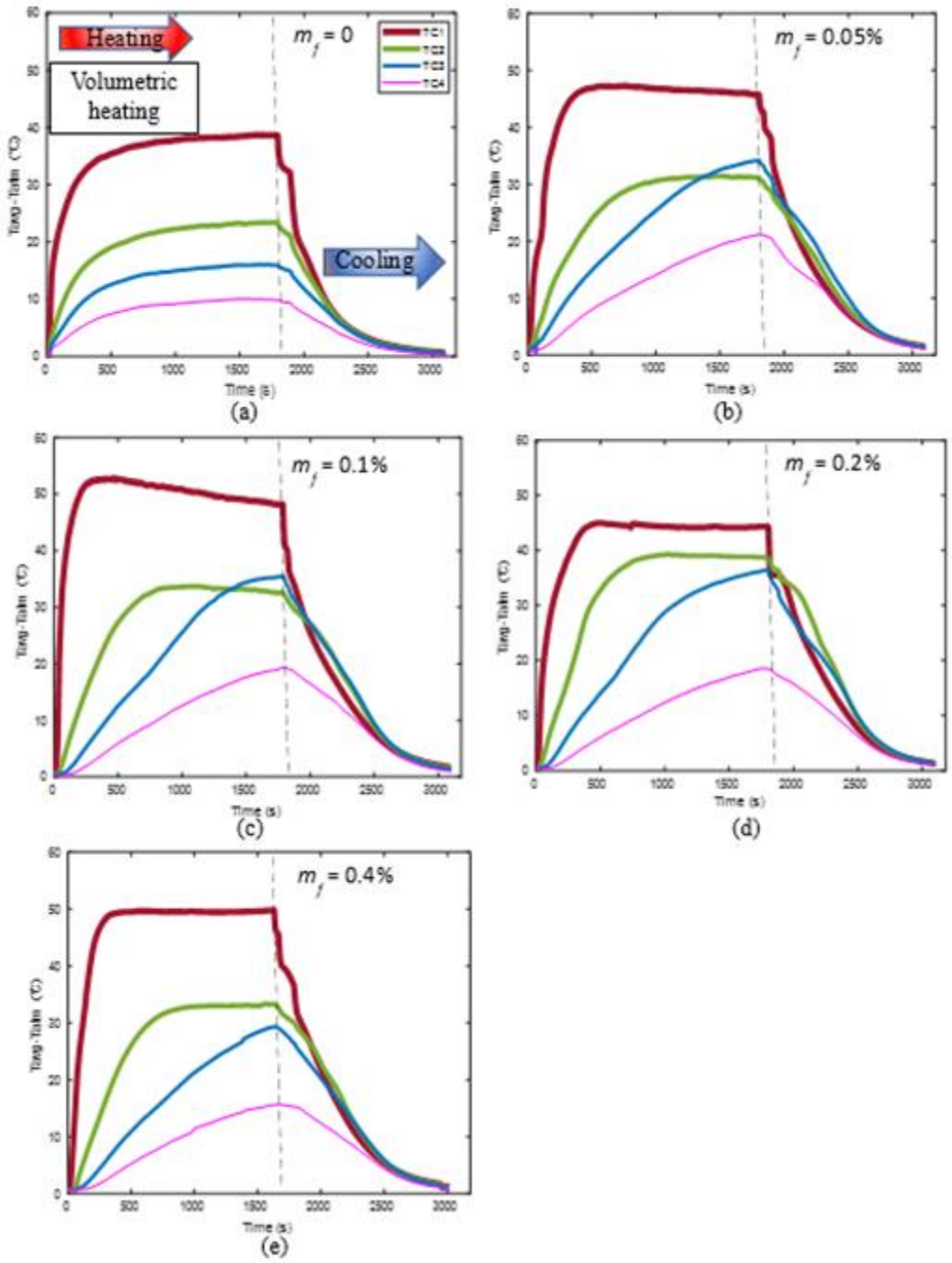

Fig. 9 Temperature field under OC mode (i.e. heating from bottom) as a function of time for four different concentrations of nanoparticles (a) pure paraffin wax, (b) NPs with concentration 0.05%, (c) NPs with concentration 0.1%, (d) NPs with concentration 0.2%, and (e) NPs with concentration 0.4%.

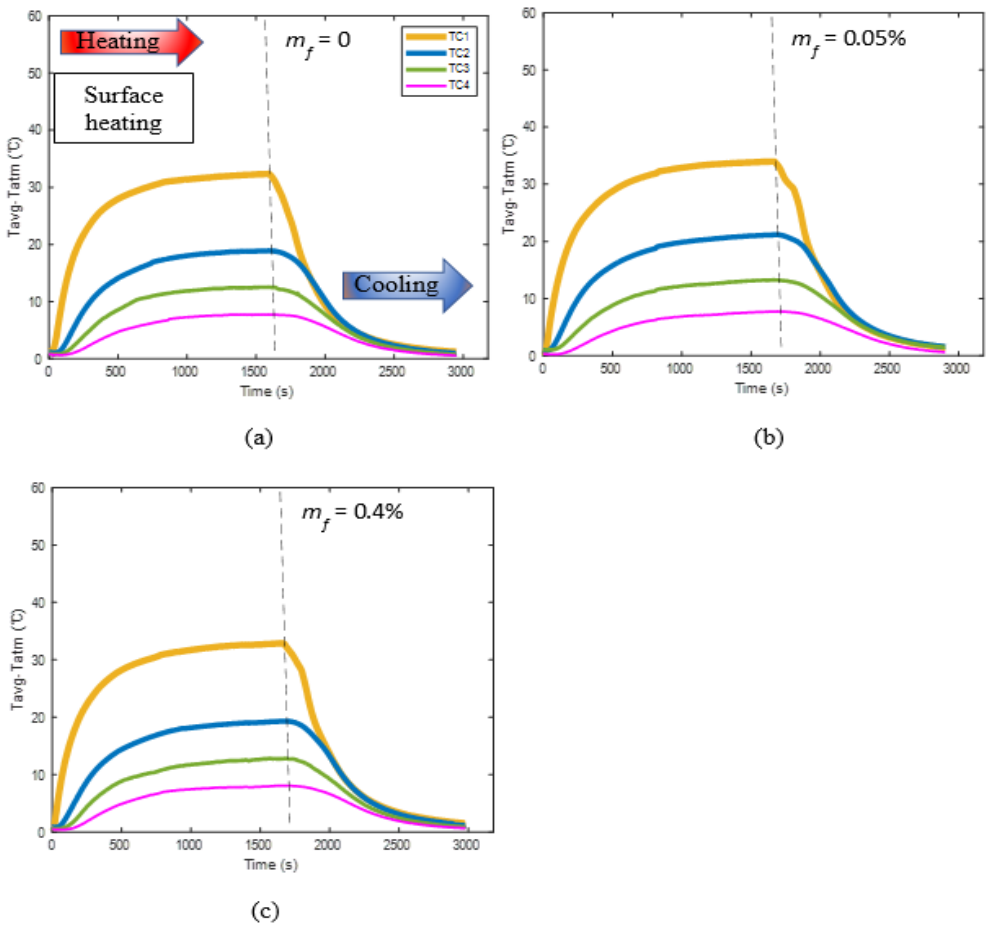

Fig. 10 Temperature field under TC mode (i.e. heating from bottom) as a function of time for two different concentrations of nanoparticles (a) pure paraffin wax, (b) NPs with concentration 0.05%, and (c) NPs with concentration 0.4%.

In order to clearly understand the reasons for charging rate enhancements temperature distribution in each case was also analyzed. To understand the effect of nanoparticles in volumetric heating; samples of pristine paraffin wax and nano-PCMs [different concentrations of nanoparticles (0.05%, 0.1%, 0.2%, 0.4%, weight %) have been optically heated. From experimental observations we note that charging rate enhances, with increase in concentration. To understand the effect of nanoparticles in surface heating; samples of pristine paraffin wax and nano-PCMs [different concentrations of nanoparticles (0.05%, 0.4%, weight %) have been heated. In case of surface heating (solar selective material used as interface) overall temperature distribution is less as compare to volumetric heating.

The temperature difference between the initial state and final state shows the charging process of nano-PCM. Four thermocouple positions give the temperature profiles to understand the thermal behavior of nano-PCM. These observations of top heating reveal that, the optical charging scheme significantly improves the thermal charging rate (by more than 157%) at optimum nanoparticle concentration (0.2%, in the present study) as compared to conventional thermal charging.

It may be noted that in case of thermal charging for top heating (surface heating), the light does not interact directly with the nanoparticles, instead it is absorbed by the solar selective surface and subsequently transferred to nanoparticle laden PCM through conduction. Thermal conductivity being nearly insensitive to the addition of nanoparticles, we need not carry out experiments for all mass fractions in case of surface heating. This is also confirmed through careful observation of the temperature distribution curves for various nanoparticle laden PCMs in case of surface heating (see Figs. 8 and 10). Similarly, the optical charging scheme significantly improves the thermal charging rate (by more than 81% i.e. bottom heating) at optimum nanoparticle concentration (0.2%, in the present study) as compared to conventional thermal charging. The temperature distribution and thermal profile measurements of the nano-PCMs collected through aforesaid process reveals that optical heating of PCM in presence of nanoparticles could definitely prove to be an efficient and reliable method for improved charging process.

Finally, thermal images of various samples both under optical charging as well thermal charging modes for top and bottom heating have been captured using IR camera (Keysight U5855A TrueIR thermal imager) (see Fig. 11 and 12). First image in each row shows the initial state and next image shows charging after 360 seconds, third image shows charging after 720 seconds. The all images are recorded after every 360 seconds and the same procedure should be followed in case of bottom heating.

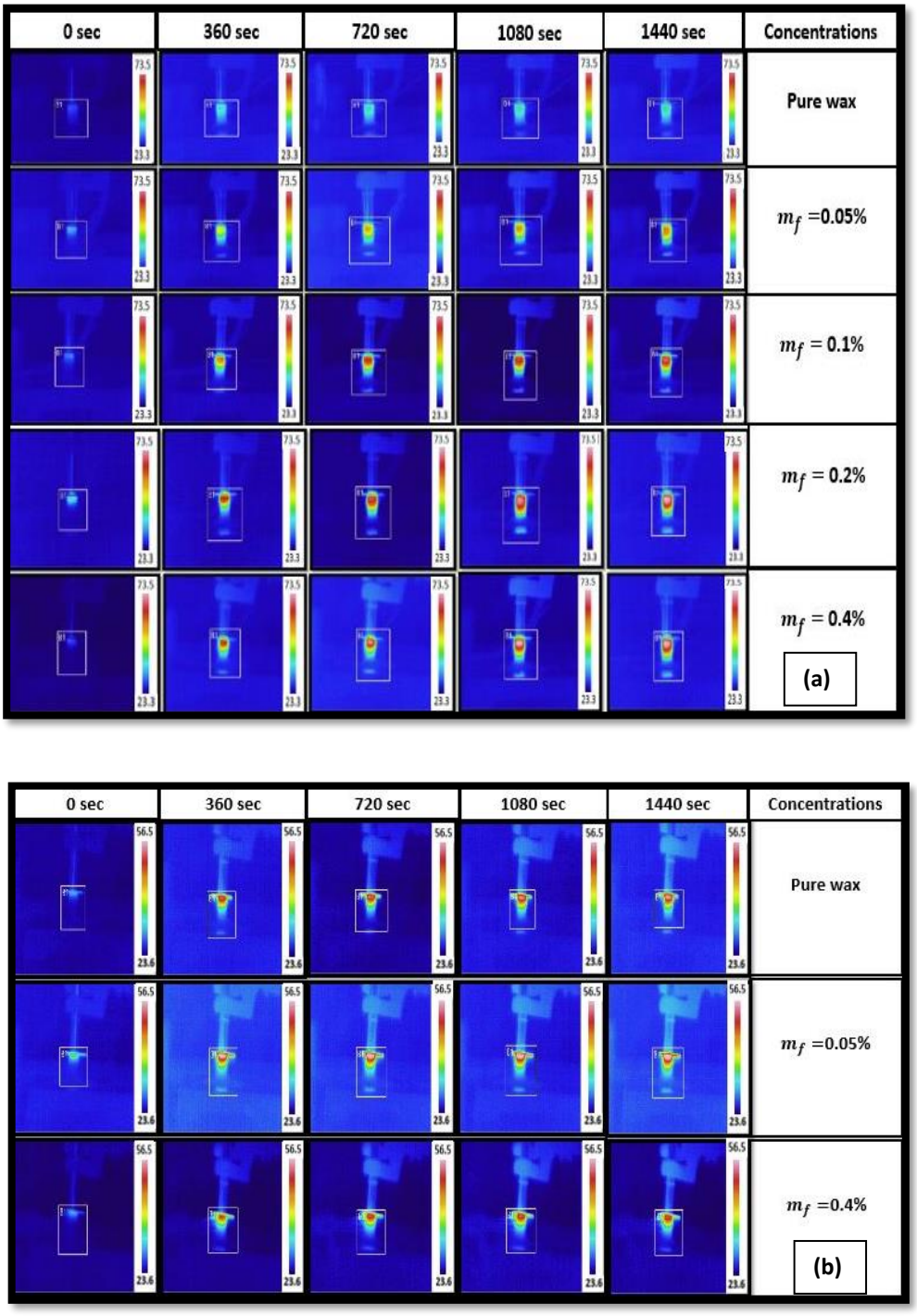

Fig. 11 Time-sequential thermal IR images of (i.e. heating from top) (a) pure paraffin and four different concentrations of nanoparticles [volumetric heating], and (b) pure paraffin and two different concentrations of nanoparticles. [Surface heating].

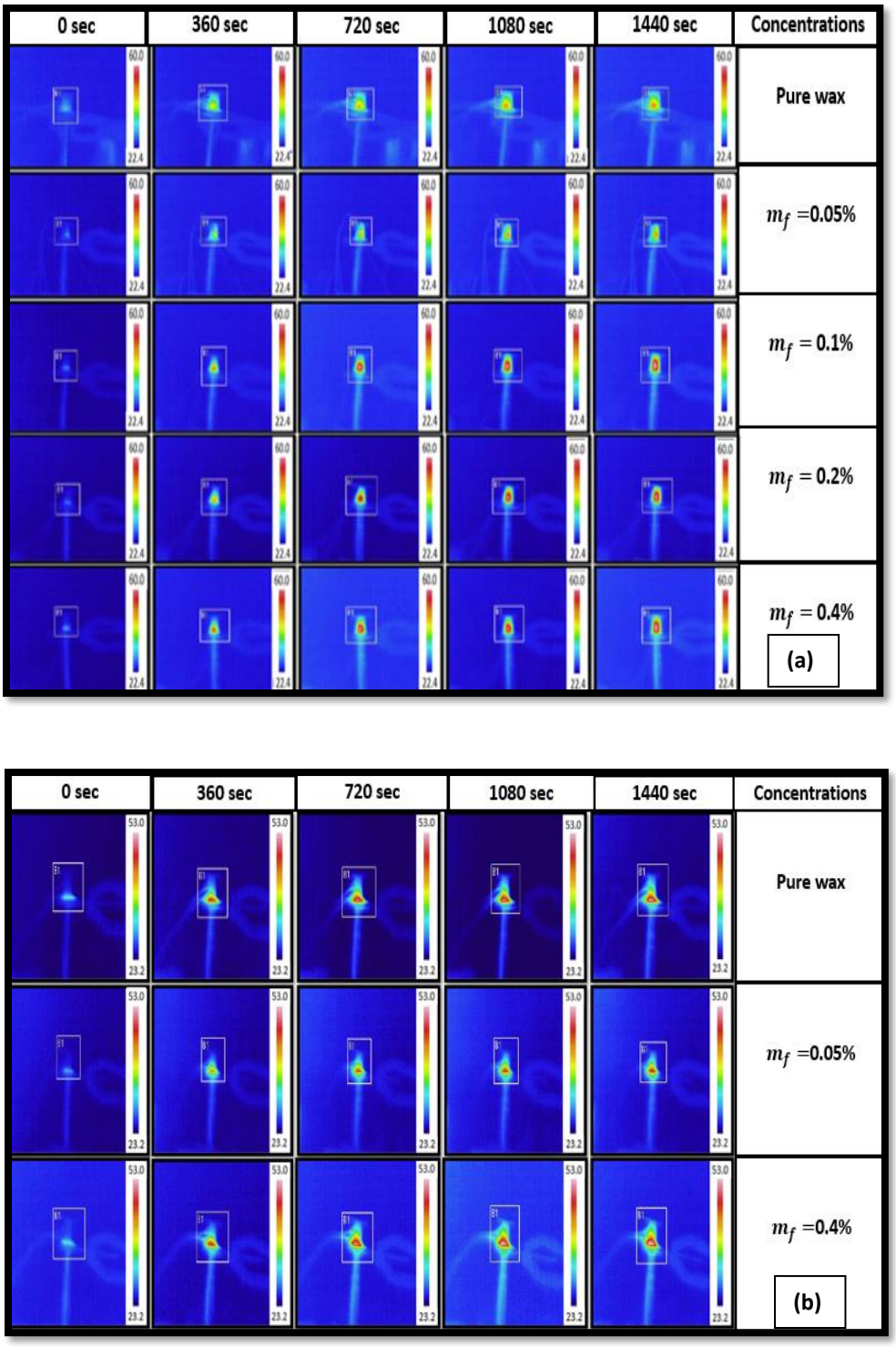

Fig. 12 Time-sequential thermal IR images of (i.e. heating from bottom) (a) pure paraffin and four different concentrations of nanoparticles [volumetric heating], and (b) pure paraffin and two different concentrations of nanoparticles. [Surface heating]

In order to clearly understand the melting rate and temperature distribution we compare the results of heating from top and bottom. Figs 13 (a) and 14 (a) clearly reveal the melting rate for four different cases (i.e. Volumetric heating) heating from top and bottom. These graphs clearly show in case of volumetric heating the top heating gives higher temperature distribution and melting rate as compare to heating from bottom. Figure 13 (b) and 14 (b) show the meting rate for two different cases (i.e. Surface heating) heating from top and bottom. In case of surface heating melting rate is higher in bottom heating as compare to top. These observations reveal that the temperature distribution and melting rate enhancement have been found at optimum concentration (m_f = 0.2%) in both cases as compare to conventional thermal charging.

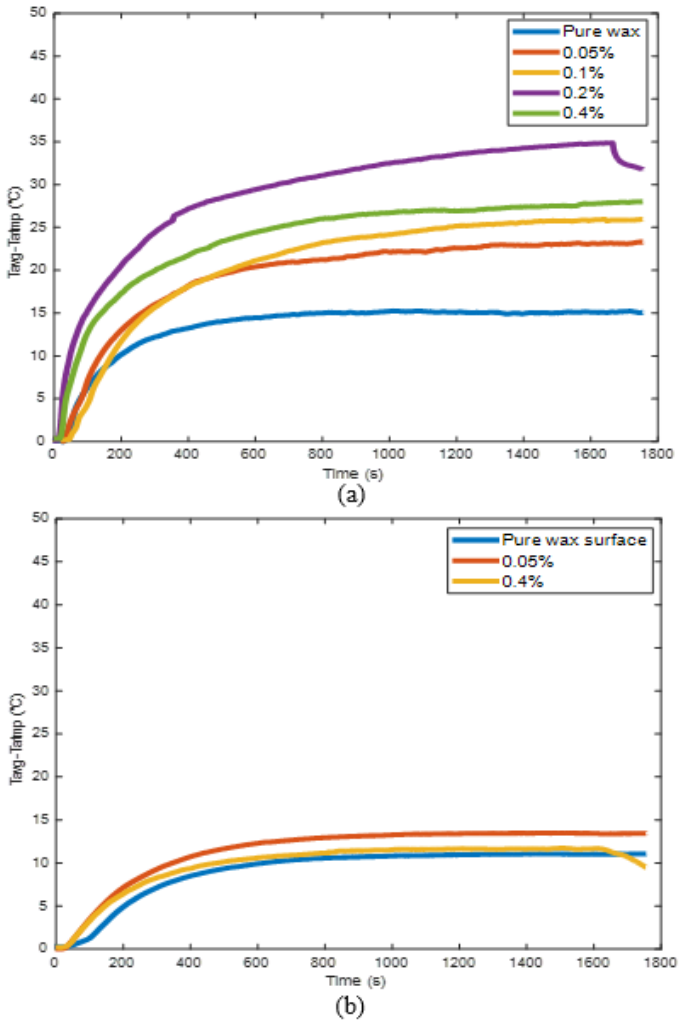

Fig. 13 Shows melting rate (i.e. heating from top) (a) under OC mode as a function of time for four different concentrations of nanoparticles (b) under TC mode as a function of time for two different concentrations.

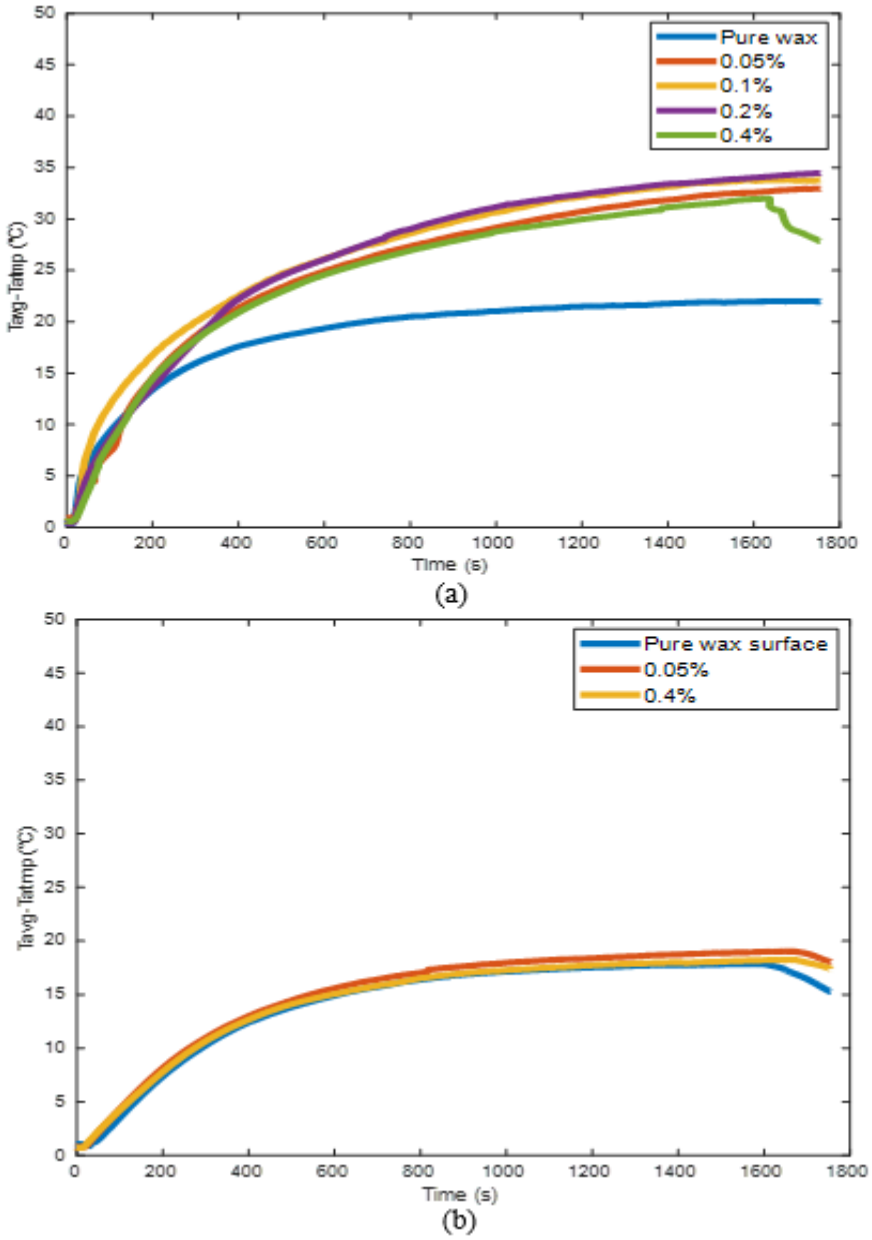

Fig. 14 Shows melting rate (i.e. heating from bottom) (a) under OC mode as a function of time for four different concentrations of nanoparticles (b) under TC mode as a function of time for two different concentrations.

CHAPTER 5
CONCLUSIONS AND FUTURE WORK

An experimental set-up has been developed to predict the charging rate when light directly interacts with nanoparticle laden PCM. Experimental results show that seeding ACNs can significantly increase the charging rate (~157% higher in case top heating at optimum concentration (m_f = 0.2%) and 81% higher in case of bottom heating at same concentration). Furthermore, temperature distribution measurements show that optical heating of PCM in presence of nanoparticles could achieve more distributed energy absorption and hence proving to be an efficient and reliable method for charging PCMs. Volumetric heating gives more effective results as compare to conventional thermal charging under similar operating conditions. Mass fraction of nanoparticles to be seeded should be carefully chosen, as after a certain limit the effect of increasing mass fraction does not enhance the charging rate further.

As a part of the future work, we intent to develop a comprehensive theoretical model simulating the optical charging process.

REFRENCES

[1] Dincer, I. and MA, T.E.S., 2002. Systems and Applications, New York.
[2] Paksoy, H.Ö. ed., 2007. Thermal energy storage for sustainable energy con Sumption: fundamentals, case studies and design (Vol. 234). Springer Science & Business Media.
[3] Wang, Z., Tong, Z., Ye, Q., Hu, H., Nie, X., Yan, C., Shang, W., Song, C., Wu, J., Wang, J. and Bao, H., 2017. Dynamic tuning of optical absorbers for accelerated solar-thermal energy storage. Nature communications, 8(1), p.1478.
[4] Richardson, H.H., Hickman, Z.N., Govorov, A.O., Thomas, A.C., Zhang, W. and Kordesch, M.E., 2006. Thermotical properties of gold nanoparticles embedded in ice: characterization of heat generation and melting. Nano letters, 6(4), pp.783-788.
[5] Chen, L., Zou, R., Xia, W., Liu, Z., Shang, Y., Zhu, J., Wang, Y., Lin, J., Xia, D. and Cao, A., 2012. Electro-and photo driven phase change composites based on wax-infiltrated carbon nanotube sponges. ACS nano, 6(12), pp.10884-10892.
[6] Lin, S.C. and Al-Kayiem, H.H., 2012. Thermophysical properties of nanoparticles-phase change material compositions for thermal energy storage. In Applied Mechanics and Materials (Vol. 232, pp. 127-131). Trans Tech Publications.
[7] Karunamurthy, K., Murugumohankumar, K. and Suresh, S., 2012. Use of CuO nano-material for the improvement of thermal conductivity and performance of low temperature energy storage system of solar pond. Digest Journal of Nanomaterials and Biostructures, 7(4), pp.1833-1841.
[8] Pise, A.T., Waghmare, A.V. and Talandage, V.G., 2013. Heat transfer enhancement by using nanomaterial in phase change material for latent heat thermal energy storage system. Asian J. Eng. Appl. Technol, 2(2), pp.52-57.
[9] Harikrishnan, S., Deepak, K. and Kalaiselvam, S., 2014. Thermal energy storage behavior of composite using hybrid nanomaterials as PCM for solar heating systems. Journal of Thermal Analysis and Calorimetry, 115(2), pp.1563-1571.
[10] Fan, L.W., Fang, X., Wang, X., Zeng, Y., Xiao, Y.Q., Yu, Z.T., Xu, X., Hu, Y.C. and Cen, K.F., 2013. Effects of various carbon nanofillers on the thermal conductivity and energy storage properties of paraffin-based nanocomposite phase change materials. Applied Energy, 110, pp.163-172.
[11] Ji, H., Sellan, D.P., Pettes, M.T., Kong, X., Ji, J., Shi, L. and Ruoff, R.S., 2014. Enhanced thermal conductivity of phase change materials with ultrathin-graphite foams for thermal energy storage. Energy & Environmental Science, 7(3), pp.1185-1192.
[12] Khot, S.A., Sane, N.K. and Gawali, B.S., 2012. Thermal energy storage using PCM for solar domestic hot water systems: a review. Journal of The Institution of Engineers (India): Series C, 93(2), pp.171-176.
[13] Hossain, R., Mahmud, S., Dutta, A. and Pop, I., 2015. Energy storage system based on nanoparticle-enhanced phase change material inside porous medium. International Journal of Thermal Sciences, 91, pp.49-58.
[14] Zhao, C.Y., Lu, W. and Tian, Y., 2010. Heat transfer enhancement for thermal energy storage using metal foams embedded within phase change materials (PCMs). Solar energy, 84(8), pp.1402-1412.

[15] Wang, Z., Tao, P., Liu, Y., Xu, H., Ye, Q., Hu, H., Song, C., Chen, Z., Shang, W. and Deng, T., 2014. Rapid charging of thermal energy storage materials through plasmonic heating. Scientific reports, 4, p.6246.

[16] Alomair, M.A., Alomair, Y.A., Abdullah, H.A., Mahmud, S. and Tasnim, S., Nanoparticle Enhanced Phase Change Material in Latent Heat Thermal Energy Storage System: An Experimental Study.
[17] Salyan, S. and Suresh, S., 2018. Liquid metal gallium laden organic phase change material for energy storage: an experimental study. International Journal of Hydrogen Energy, 43(4), pp.2469-2483.
[18] Khan, I., Saeed, K. and Khan, I., 2017. Nanoparticles: Properties, applications and toxicities. Arabian Journal of Chemistry.
[19] Abhat, A., 1983. Low temperature latent heat thermal energy storage: heat storage materials. Solar energy, *30*(4), pp.313-332.
[20] Posthuma-Trumpie, G.A., Wichers, J.H., Koets, M., Berendsen, L.B. and van Amerongen, A., 2012. Amorphous carbon nanoparticles: a versatile label for rapid diagnostic (immuno) assays. Analytical and bioanalytical chemistry, 402(2), pp.593-600.
[21] Hossain, R., Mahmud, S., Dutta, A. and Pop, I., 2015. Energy storage system based on nanoparticle-enhanced phase change material inside porous medium. International Journal of Thermal Sciences, 91, pp.49-58.
[22] Mahdi, J.M., Lohrasbi, S., Ganji, D.D. and Nsofor, E.C., 2019. Simultaneous energy storage and recovery in the triplex-tube heat exchanger with PCM, copper fins and Al2O3 nanoparticles. Energy Conversion and Management, 180, pp.949-961.
[23] Amy S. Fleischer, "Thermal Energy Storage Using Phase Change Materials Fundamentals and Applications.
[24] Tempsens Instruments (I) Pvt. Ltd "ISO 14001 and OHSAS 18001 certified company with NABL accredited laboratory".
[25] Khullar, V., Tyagi, H., Hordy, N., Otanicar, T.P., Hewakuruppu, Y., Modi, P. and Taylor, R.A., 2014. Harvesting solar thermal energy through nanofluid-based volumetric absorption systems. International Journal of Heat and Mass Transfer, 77, pp.377-384.
[26] O. Ercan Ataer, (2006), Storage of Thermal Energy, in Energy Storage Systems, [Ed. Yalcin Abd [ullah Gogus], in Encyclopedia of Life Support Systems (EOLSS), Developed under the Auspices of the UNESCO, Eolss Publishers, Oxford, UK, [http://www.eolss.net]

LIST OF PUBLICATIONS FROM THE PRESENT WORK

- Direct Photo-Thermal Energy Storage Using Nanoparticles Laden Phase Change Materials (accepted for publication as book chapter for the monograph entitled “Advances in Solar Energy”, Springer Nature, Singapore)

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