A

Dissertation Report

On

PERFORMANCE ANALYSIS OF PERSONALIZED RADIANT COOLING SYSTEM INTEGRATED WITH PCM THERMAL STORAGE SYSTEM

Submitted in partial fullfilment for the award of

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In
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By

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CERTIFICATE

This is certified that the dissertation report entitled "**Performance Analysis of Personalized Radiant Cooling System Integrated with PCM Thermal Storage System**" prepared by **C.P.Chandra Sekhar** (2015PTE5073), in the partial fulfillment for the award of **Master of Technology** in **Thermal Engineering,** of Malaviya National Institute of Technology Jaipur is a record of bonafide research work carried out by him under my supervision and is hereby approved for submission. The contents of this dissertation work, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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DECLARATION

I **C.P.Chandra Sekhar** hereby declare that the dissertation entitled **“Performance Analysis of Personalized Radiant Cooling System Integrated with PCM Thermal Storage System”** being submitted by me in partial fulfillment for the award of **Master of Technology** in **Thermal Engineering** is a research carried out by me under the supervision of **Dr.Ing-Jyotirmay Mathur** and the contents of this dissertation work, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma. I also certify that no part of this dissertation work has been copied or borrowed from anyone else. In case any type of plagiarism is found out, I will be solely and completely responsible for it.

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(C.P.Chandra Sekhar)

ABSTRACT

The major purpose of the building is to provide the indoor conditions that best match the occupant's activities. This goal becomes necessary to deploy HVAC systems in order to provide a comfortable environment for occupants. With population and economic growth global energy consumption is expected to increase significantly. The most of the energy used in buildings derived from fossil fuel, and there is growing concern about the issues of sustainability and environment. Because of this efficient operation of buildings becomes an important objective. The incorporation of energy efficient technology in building HVAC systems must be done in such a way that ensures reliable performance, reduced energy consumption, and cost-effective energy savings achieved.

Personalized conditioning systems emerged as a new technology to reduce the building energy consumption and to improve the thermal comfort to the occupant by deploying the energy where it actually needed and creating the micro climate zone around the occupant according to his/her comfort respectively. Thermal energy storage integration to the building HVAC systems provides several alternatives for efficient energy use and conservation. Among the different types of thermal energy storage, PCM latent thermal energy storage exhibits superior efficiency and dependability due to its high storage capacity and nearly constant thermal energy. This study presents the personalized conditioning system (personalized radiant cooling system) combined with PCM thermal energy storage system. The objectives of the study are to supply the cooling energy to personalized radiant cooling system from PCM thermal energy storage system and investigate the performance of personalized radiant cooling system and thermal energy storage system with respect to thermal behavior and energy consumption analysis. In order to supply cooling energy to personalized radiant cooling system, a thermal energy storage system has been designed and fabricated based on shell and finned tube heat exchanger concept to overcome the low heat transfer problem between PCM and heat transfer fluid in latent thermal energy storage systems. An experimental setup of the personalized radiant cooling system integrated with PCM thermal energy storage system has been located at the old administrative block, Center for Energy and Environment, Malaviya National Institute of Technology, Jaipur.

In order to know the thermal performance of the personalized radiant cooling system and PCM thermal energy storage system, several experiments were conducted. The energy was stored in thermal energy storage system from the chiller (energy source) by utilizing the low ambient conditions and low electricity utility rates (off–peak hours). The night time stored energy in thermal energy storage system was supplied to personalized radiant cooling system during daytime (specifically, peak hours) and personalized radiant cooling system created comfortable microclimate zone around the vicinity of the occupant. Thermal behavior of the thermal energy storage system was described by charging and discharging characteristics, and thermal performance of the personalized radiant cooling system was described by annual thermal energy consumption, electrical energy consumption, and operational cost.

It was observed that thermal energy storage system using PCM (OM–21) efficiently supplied cooling energy between 20°C and 22°C (HTF temperature) to personalized radiant cooling system and this personalized system created microclimate zone around the vicinity of occupant and maintained standard effective temperature between 25.7°C and 26°C. Thermal energy storage system efficiently shifted cooling load (electricity demand) of personalized radiant cooling system from peak hours to off–peak hours and 5.5% power cost savings achieved when compared with personalized radiant cooling system without thermal energy storeg system. There is no savings occurred in power consumption by integrating the thermal energy storage system to personalized radiant cooling system. Thermal energy storage system supplied cooling energy to personalized radiant cooling system at an average effectiveness greater than 90% and at nearly constant temperature, so the heat exchanger design is efficient for thermal energy storage applications using PCM as a storage medium.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

ASHRAE	American Society of Heating Refrigeration and Air– Conditioning Engineers
BEE	Bureau of Energy Efficiency
CFD	Computational Fluid Dynamics
COP	Coefficient Of Performance
DBT	Dry Bulb Temperature
DOAS	Dedicated Outdoor Air System
DPT	Dew Point Temperature
DV	Displacement Ventilation
ESCS	Embedded Surface Cooling System
ET	Effective Temperature
FCU	Fan Coil Unit
HC	Heated Chair
HTF	Heat Transfer Fluid
HVAC	Heating Ventilation and Air Conditioning
HX	Heat Exchanger
LPM	Litre Per Minute
LH	Latent Heat
MRT	Mean Radiant Temperature
OM	Organic Mixture

OT	Operative Temperature
PCM	Phase Change Material
PCS	Personalized Conditioning System
PRCS	Personalized Radiant Cooling System
PEC	Personalized Evaporative Cooler
PMV	Predictive Mean Vote
PPD	Predicted Percentage of Dissatisfaction
PU	Poly Urethane
RC	Radiant Cooling
RCCS	Radiant Cooled Ceiling System
RH	Relative Humidity
RTD	Resistance Temperature Detectors
SET	Standard Effective Temperature
SH	Sensible Heat
TABS	Thermally Activated Building Systems
TES	Thermal Energy Storage
TR	Ton Refrigeration
TSV	Thermal Sensation Vote
TSS	Thermal Sensation Scale
VAV	Variable Air Volume
VRF	Variable Refrigerant Flow

NOMENCLATURE

m	Mass of storage medium (kg)
$T_{initial}$	Initial temperature of storage medium (°C)
T_{final}	Final Temperature of storage medium (°C)
Q	Heat stored in storage medium (kJ)
Δh	Change in enthalpy (kJ)
$\dot{m}_{ch}$	Mass flow rate of HTF during charging process of TES system (kg/minute)
$T_{ch,\ out}$	Outlet temperature of HTF during charging process (°C)
$T_{ch,\ in}$	Inlet temperature of HTF during charging process (°C)
t_{ch}	Time duration of charging process (seconds or hours)
C_p	Specific heat of HTF at constant pressure (kJ/kg–K)
E_{ch}	Thermal energy supplied to TES system during charging process (kWh$_{Thermal)}$
$\dot{m}_{ds}$	Mass flow rate of HTF during discharging process of TES system (kg/minute)
$T_{ds,\ out}$	Outlet temperature of HTF during discharging process (°C)
$T_{ds,\ in}$	Inlet temperature of HTF during discharging process (°C)
t_{ds}	Time duration of discharging process (seconds or hours)
E_{ds}	Thermal energy utilized from TES system during discharging process (kWh$_{Thermal)}$
η_{ch}	Charging efficiency of TES system (%)

η_{ds}	Discharging efficiency of TES system (%)
η_{cyclic}	Cyclic efficiency of TES system (%)
P	Power consumption ($kWh_{Electrical}$)
$T_{avg, PCM}$	Average temperature of Phase change material (°C)
ε_{ch}	Effectiveness of TES system during charging process
ε_{ds}	Effectiveness of TES system during discharging process
h_r	Radiative heat transfer coefficient (W/m^2K)
h_c	Convective heat transfer coefficient (W/m^2K)

1 – INTRODUCTION

1.1 Back Ground

The energy consumption in buildings has been steadily increasing and became major energy consuming sector (Al-Mosawi 2011). In India building sector accounts 33% of the total country electricity consumption, and it significantly increases due to construction sector is expected to grow significantly in coming years (BEE 2015). In recent year's substantial amount of energy used in buildings for conditioning the space, in India conventional air conditioning systems consume 32%–55% of total building electricity consumption for conditioning the space depending on type of building and operating hours of the building. The conventional air conditioning systems contributes substantially to the peak power demand of the buildings (Y. K. Vibhav Rai Khare 2014). The current trends in energy supply and use are economically, environmentally and socially unsustainable since energy related emissions of CO_2 will be doubled by 2050 (Jaume Gasia 2016). Hence, the researchers from industry and academic organizations are moving towards efficient HVAC technologies, efficient thermal energy storage technologies, etc. to reduce the energy consumption and peak power demand in buildings Building industry nowadays facing two major challenges: 1. Increased concern of reduction in energy consumption due to energy crisis and global warming; 2. Thermal comfort enhancement to occupant due to increased living standards and to work efficiently in an office In order to reduce the energy consumption of the buildings researchers proposed and implemented several alternative air conditioning systems such as radiant conditioning systems, personalized conditioning systems, etc. for space conditioning in buildings. Radiant cooling systems and its usage increased in recent years in building space conditioning applications due to its unique advantages like less energy consumption and better thermal comfort. Personalized conditioning is new research area to reduce the energy consumption of buildings and enhancing the thermal comfort to the occupant. Radiant cooling systems and personalized conditioning systems can be effective solution for building industry to improve thermal comfort and to reduce the energy consumption.

A radiant cooling system refers to a temperature controlled surface or radiant surface consists either radiant panels or tubes embedded in structure to exchange the heat from conditioned space, that cools the indoor temperatures by removing sensible heat and where more than half of heat transfer occurs through thermal radiation. Temperature controlled surfaces on the floor, wall, or ceiling maintained indoor temperatures by circulating the water through a hydronic circuit embedded in panels or structure (ASHRAE 2007). Personalized conditioning systems aims to create microclimate zone around a single work place, deploying the energy where it actually needs and individual thermal comfort need also fulfilled. They can be as simple as having movable fan to direct the air flow towards the occupant or targeted cooling done to foot, body contact portions with chair, air stream flowing to the face etc. (Ravi Garg 2016).

Thermal energy storage systems remove heat from or add heat to a storage medium for use at another time. Thermal energy storage for HVAC applications can involve various applications associated with heating or cooling. Energy can be stored, charged, and discharged daily, weekly, annually or in seasonal process (ASHRAE 2007). Thermal energy storage provides several alternatives for effective energy conservation and use (Alessandro Beghi 2014). Thermal energy storage arises as key technology to reduce the mismatch between energy supply and energy demand and reducing the energy peak demand (Jaume Gasia 2016). Thermal energy storage improves the performance of HVAC system by utilizing night low ambient temperatures for storing of energy and shifting the peak energy demand to off peak energy, therefore power cost savings can avail through thermal energy storage.

The aim of this thesis is to supply the cooling from thermal energy storage to PRCS and analyzing the performance of complete system includes thermal energy storage and PRCS. PRCS is one type of personalized conditioning system. To achieve this aim thermal energy storage has been developed by using aluminum finned copper tube and stainless steel rectangular tank as shell and finned tube heat exchanger concept. This thermal energy storage design can be utilized for effective operation of the personalized radiant cooling system.

1.2 Terminology

Storage media: “The material or substance may liquid, solid, or phase change material used for storing of heat in the form of sensible or latent heat for later use in thermal energy storage” is termed as storage media.

Energy source: Chiller, generator, cooling tower or environment etc. from which the energy is transferred to the storage system.

Energy user: The thermal zone or to the building technical systems which are intended to use the energy.

Charging: "Storing cooled energy by removing heat from cool storage media or storing heated energy by adding heat to heat storage media" is termed as charging of the TES.

Discharging: "Utilizing stored cool energy by adding thermal energy to cool storage media or heat energy by removing thermal energy from heat storage media" is termed as discharging of the TES.

Full storage: A cool storage design strategy that meets the entire cooling load with discharge from thermal storage system from some period, typically hours when loads are high and electric power is expensive.

Fully charged condition: State of thermal storage system at which, no more heat removed in cool storage media or no more heat added in heat storage media. This state is generally reached when the control system stops the charging cycle as part of its control sequence or when the maximum allowable charging period has elapsed.

Fully discharged condition: State of thermal storage at which, no more useable cooling energy from cool storage media or heating energy from heat storage media can be delivered from thermal storage system.

Ice-on-coil (Ice-on-pipe): Ice storage technology that forms and stores ice on the outside of pipes or tubes submerged in an insulated tank.

Ice-on-coil, external melt: Ice storage technology in which pipes (coil) are immersed in water and ice is formed on the outside of the tubes or pipes by circulating colder secondary medium or refrigerant inside the tubes or pipes, and is melted externally by circulating unfrozen water outside the tubes or pipes to the load.

Ice-on-coil, internal melt: Ice storage technology in which pipes (coil) are immersed in water and ice is formed on the outside of the tubes or pipes by circulating colder secondary medium or refrigerant inside the tubes or pipes, and is melted internally by circulating same secondary coolant or refrigerant to the load.

Latent energy storage: A thermal storage technology in which energy is stored with in a medium, normally associated with phase change (usually between solid and liquid states), for use in cooling or heating the secondary liquid being circulated through the system.

Sensible energy storage: A thermal storage technology in which energy is stored with in a medium, normally associated with temperature gradients and heat capacity of medium, for use in cooling or heating the secondary liquid being circulated through the system.

Load profile: Compilation of instantaneous thermal loads over a period of time, normally 24 hours.

Maximum usable cooling supply temperature: Maximum heat transfer fluid supply temperature at which the cooling load can be met. This is generally determined by the requirements of the air-side distribution system or the process.

Maximum usable discharging temperature: Highest temperature at which beneficial cooling can be obtained from the thermal energy system.

Phase change material (PCM): A material that undergoes change of state, normally from solid to liquid or liquid to solid, while absorbing or rejecting thermal energy at a constant temperature.

Storage cycle: A period in which a complete charge and discharge of a thermal storage system has occurred, beginning and ending at the same state.

Storage inventory: amount of usable heating or cooling energy remaining in a thermal storage system.

Storage priority: A control strategy that uses stored cooling to meet as much of the load as possible. Chillers operate only if the load exceeds the storage system's available cooling capacity.

Chiller priority: A control strategy that uses chiller to meet as much of the load as possible, normally by operating at full capacity most of the time. Thermal energy storage is used to supplement chiller operation only when the load exceeds the chiller capacity.

Load leveling: A partial storage strategy that minimizes the storage equipment size and storage capacity. The system operates with refrigeration equipment running at full capacity 24 hours to meet the normal cooling minimum load profile and, when load is less than the chiller output, excess cooling is stored. When load exceeds the chiller capacity, the additional cooling requirement is obtained from the thermal energy storage.

Thermal energy storage capacity: A value indicating the maximum amount of cooling (or heating) that can be achieved by the stored medium in the thermal energy storage system.

Discharging capacity: The maximum rate at which cooling can be supplied from a thermal storage system

Nominal storage capacity: A theoretical capacity of the thermal storage system. In many cases this may be greater than usable storage capacity. This measure should not be used to compare usable capacities of other storage technologies.

Usable storage capacity: total amount of beneficial cooling able to be discharged from thermal storage system. This may be less than the nominal storage capacity because the distribution header piping may not allow the discharging the entire cooling capacity of the thermal storage system.

Depth of discharge (DOD): this describes how deeply the storage can be discharged providing usable energy (considering the application conditions which it is designed for) and without negatively affecting its properties (i.e. permanent damages), It is expressed as a percentage storage capacity. It must be referred to specific boundary conditions if they significantly influence the DOD, normally thermal storages referred to the nominal working temperature of the storage and the temperature of medium to be heated or cooled.

Charging period: The period of time during which the energy is intentionally transferred from the energy source to the storage system.

Discharging period: The period of time during which the energy is intentionally transferred from the storage system to the energy user

Stand by period: Period of time during which the storage system intentionally not in the charging or discharging period.

Working cycle: It is a process that includes a complete charge of the storage system, the discharge of the storage system to the DOD and eventually a certain inactive time (normally stand by period, few storage systems discharge starts after immediately after charging).

Standard Effective Temperature (SET): SET is defined as the temperature of an imaginary environment at 50% relative humidity (RH), average air speed is less than 0.1 m/s and MRT is equal to air dry bulb temperature (DBT) in which the total heat loss from the skin of an imaginary occupant with an activity level of 1.0 **met** and a clothing level of 0.6 **clo** is the same as that from person in the actual environment, with actual clothing and activity level.

Sub-cooling effect: Sub cooling is the effect where by the PCM temperature decreases below the melting temperature beyond which heat will be released and, as a result, the material solidifies, reaching the melting temperature again. This happens because when materials solidify they create regions for solidification that rejects heat to the surrounding liquid this increases the temperature, re-melting the solid regions (PCM nucleation) again.

Mean Radiant Temperature (MRT): MRT is defined as the uniform temperature of an imaginary enclosure in which the radiant heat transfer from human body is equal to the radiant heat transfer in the actual non-uniform enclosure.

Operative temperature (OT): OT is defined as the temperature of a uniform isothermal black enclosure in which person exchange heat by radiation and convection at the same rate as in the given non-uniform environment.

The reduction in energy consumption and impact can be achieved in many ways, including the use of low carbon building materials, enhanced insulation, low energy lighting, embedded renewable technologies, energy efficient technologies such as radiant cooling or heating, personalized conditioning, thermal energy storage, etc. and the use of low carbon fuels. Typical energy efficient technologies such as radiant systems, personalized systems and thermal storage systems explained in next sections.

1.3 Radiant Conditioning Systems

A temperature controlled surface which removes thermal load from conditioned space through radiation (>50%) and convection heat transfer modes is known as "radiant conditioning system" and shown in figure 1.1. Temperature controlled surfaces on the floor, wall, or ceiling maintained indoor comfort temperatures by circulating the chilled water through a hydronic circuit embedded in panels or structure.

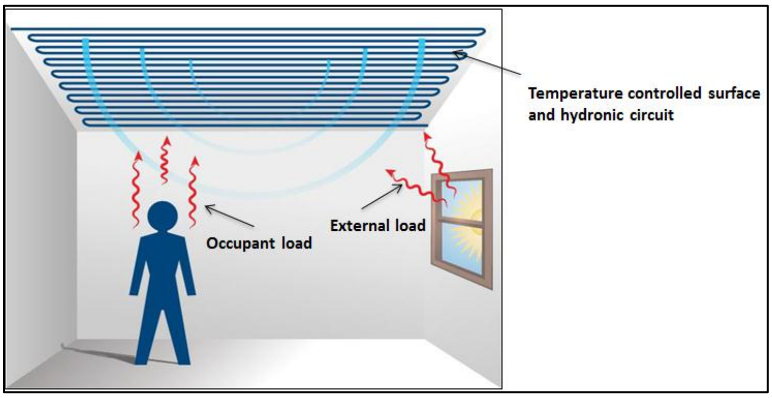


Figure 1.1 Simple radiant Conditioning System (Vivek Kumar 2016)

Radiant conditioning systems classified into several types, according location of controlled surface (ceiling radiant system, floor radiant system, or wall radiant system) and type of system or structure arrangement used for temperature controlled surface; typical classification of radiant conditioning systems are

1. Radiant cooling and heating panel system
2. Embedded surface heating and cooling systems
3. Thermally activated building systems (TABS)

Radiant cooling and heating panel system have panels with integrated pipes, suspended from ceiling, mounted on walls or floor. The thermal energy exchanged between the people & equipment present in conditioned space and heated or cooled radiant panel surface. Embedded surface heating and cooling system minimizes thermal coupling of the emitting element with the main building surface (ceiling or wall). A separating layer of thermal insulation is placed between the building structure and the pipe layer to reduce the heat exchange from the back side. TABS have the opportunity to store heat and transfer the cooling to a different time with respect to thermal load. The purpose of TABS is to transfer the cooling load to night time, operate that load in the night time and utilizing the lower electricity utility rates. Figure 1.2 shows the three different types of radiant systems

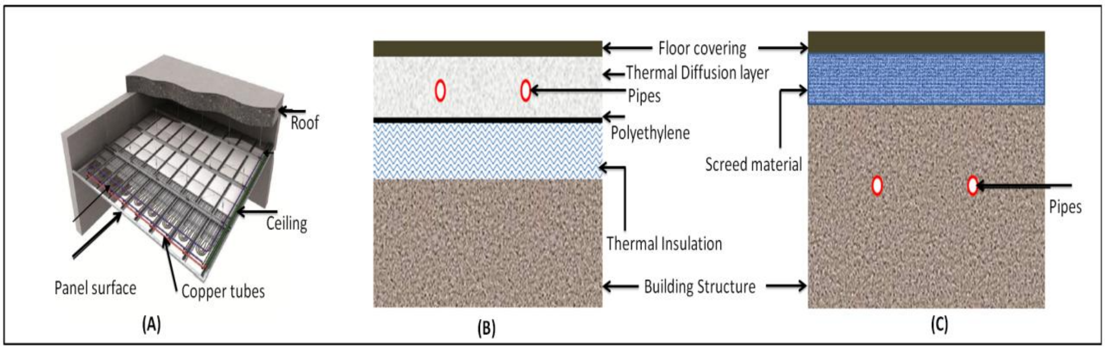


Figure 1.2 Types of radiant systems; A) Radiant panel heating and cooling system, B) Embedded surface heating and cooling system, C) Thermally activated building system (TABS); (Vivek Kumar 2016)

Radiant systems are energy efficient and more comfortable with additional advantage of less operating cost, enhancement of chiller efficiency due to usage of high temperature chilled water than conventional air systems, less noise, draft-free, maintain comfortable indoor environment at high cooling set points and lower heating set points. Radiant conditioning systems do not handle the latent loads, separate air systems (small capacity) are required to maintain humidity level inside the conditioned space.

1.4 Personalized Conditioning Systems

Personalized conditioning is new research area that emerged in buildings to optimize energy consumption and to improve thermal comfort. Personalized conditioning systems "aims to create microclimate zone around the vicinity of the occupant/person by deploying the energy where it actually needed at workplace only, energy optimization and comfort of the person happens". Occupants individual comfort can also achieved through personalized conditioning systems. This personalized conditioned technology is promising solution to the major problems of building industry; high energy consumption of conventional HVAC systems for conditioning the space and improving the thermal comfort to the occupants individually because thermal comfort requirement is different for different persons.

1.4.1 Different types Personalized conditioned systems

Personalized conditioning systems are classified based on the primary equipment used for conditioning the work place or particular zone, they are generalized as follows

- Head/face/upper body local air jets: this type of systems includes desk fans, small USB fans, slot diffusers, and nozzles in desks and workstation partitions. Flow of air usually frontal or from the side. Specific personalized system products incorporating these features included the personal environment module (PEM), ClimaDesk, and Exhausto personal ventilation systems. All these systems yet to reach market or to mass production.
- Overhead/ceiling fans: these systems provide vertical air stream under the fan, converting to a parallel stream outside the air jet. A large variety of fans are commercially available. Their power efficiency and sound quality has been significantly improved in recent years due to improvement in their motors and fan blade designs.
- Side large area air flows (including window ventilation): these systems consist large box fans that produce such bulk air flow, typically seen industrial, gymnasium, or lobby sittings. Natural air flow through windows or open designs may resemble such flows.
- Chairs, heated or cooled; or ventilated: chairs have been heated using electric resistance heating elements in the seat surface, the warm side of thermo electric devices or hot water tubes. Chairs have been cooled using isothermal air convection through or behind the heat surface, contact surfaces connected directly

to the cool side of thermoelectric devices, and through cooled water tubes. Typical examples are in automotive industry, where cooling is convective using cooled air from thermoelectric devices or the automobile's central HVAC.

- ❖ Personalized radiant cooling system; this systems works on the principle of radiant cooling, thermal load of occupant and equipment removed by temperature controlled surface or surfaces located at single workplace like walls of typical office cubicle in IT buildings. Chilled water is circulated in hydronic circuit of temperature controlled surface to maintain suitable surface temperature. Simple table fans can also use for the air circulation and dehumidifier

Typical advantages of the PCS: Individual thermal comfort requirements can achieve. Thermal comfort requirement is different for different people, because of variation in gender, body mass, age, clothing habits and metabolic rate. Mostly PCS have control so that one can change their surrounding thermal environment as per the requirement. And this system offers significant amount of energy saving in buildings because it provides comfort by targeting a relatively small amount of energy directly onto the occupants. In this way energy is deployed only the place where it is required.

1.5 Thermal comfort

"The condition of mind that express satisfaction with the thermal environment and is assessed by subjective evaluation" **or** "the state in which a person will judge the environment to be neither too cold nor too warm, a kind of neutral point defined by the absence of any feeling of discomfort" is known as thermal comfort. Standard effective temperature (SET) and Operative temperature (OT) are two important indices used to measure the thermal comfort of an indoor/conditioned space. Many factors influence the thermal comfort level, some are

- ❖ Personal factors: conditions of the occupant
  - Activity
  - Clothing insulation
  - Metabolism
- ❖ Environmental factors: conditions of thermal environment
  - Mean radiant temperature
  - Air temperature
  - Relative humidity

- Air movement

Two different models are typically used for describing thermal comfort; they are predicted mean vote (PMV) & predicted percentage of dissatisfied (PPD) model; and adaptive comfort model.

The PMV refers to a 7 pointer thermal sensation scale that runs from -3 (Cold) to +3 (Hot) developed using principles of heat balance and experimental data collected in a controlled climate chamber under study state conditions. The recommended acceptable PMV range for the thermal comfort from ASHRAE-55 is between -0.5 to +0.5 for an interior space. PPD predicts the percentage of occupants dissatisfied with the thermal conditions. It depends on PMV, as PMV moves further from 0 or neutral, PPD increases. The recommended percentage range for thermal comfort from ASHRAE-55 is less than 10% persons dissatisfied for an interior space. This method treats all occupants the same and disregards location and adaption to the thermal environment. It basically states that the indoor temperature should not change as the season do. Rather there should be one set temperature year around. This is taking a more passive stand that humans do not have to adapt to different temperatures since it will always constant.

Adaptive thermal comfort is a theory that suggests a human connection to the outdoors and control over the immediate environment allow them to adapt to (and even prefer) a wider range of thermal conditions than is generally considered comfortable. Adaptive model was developed based on hundreds of field studies with the idea that occupants dynamically interact with their environment. Occupants control their environment by means of clothing, operable windows, fans, personal heaters, sun shades, etc. This model especially applies to occupant controlled, naturally conditioned spaces, where the outdoor climate can actively affect the indoor conditions and so the comfort zone. According to ASHRAE Standard 55, which defines thermal comfort in commercial buildings, success means that a building meets the needs of 80% of occupants. The conventional way to meet that threshold is to create a highly predictable, controlled environment using energy-intensive mechanical equipment. The theory also takes into account that people’s perceptions of the environment around them changes based on seasonal expectations of temperature and humidity, as well as their ability to control the conditions of their personal space.

1.6 Thermal energy storage (TES)

Thermal energy storage is a temporary storage of thermal energy at high or low temperatures in different storage substances for later utilization. Energy storage can reduce time or rate mismatch between energy supply and energy demand, and it plays an important role in energy conservation. Energy storage improves performance of energy systems by smoothing supply and increasing reliability. The higher efficiencies would lead to energy conservation and improve cost effectiveness. Different types of thermal energy storage technologies are explained below;

1.6.1 Types of thermal energy storage technology

Thermal energy can be stored in a material or substance by changing the internal energy of the material i.e. sensible heat, latent heat, combination of sensible and latent heat, or thermochemical heat. Figure 1.3 shows the various methods of energy storage.

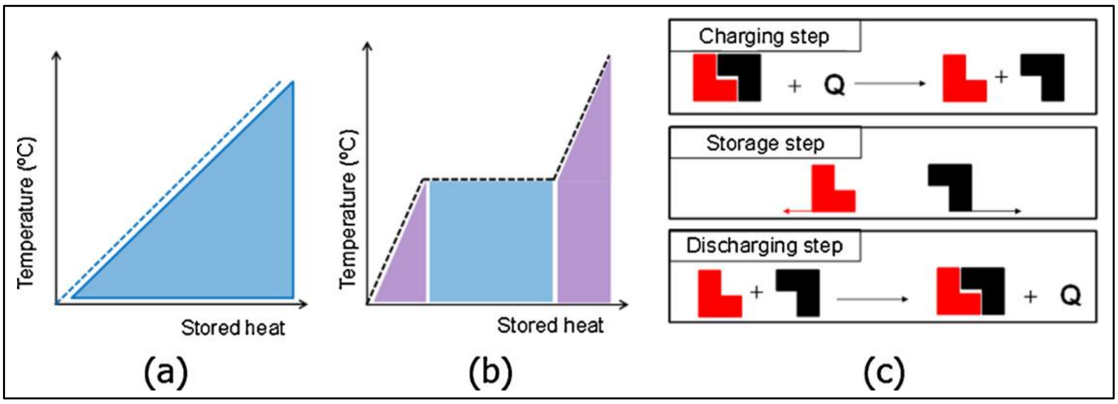


Figure 1.3 Methods of thermal energy storage, (a) Sensible heat storage, (b) Latent heat storage, (c) Thermochemical heat storage (Alvaro de Gracia 2015)

A) Sensible thermal storage

Sensible heat storage, a material's temperature changes during the process of charging and discharging without phase change. The choice of the material purely depends on the temperature range of the application. Sensible thermal storage systems are simpler in design than other storage systems. The storage size that depends on the mass of the heat storage medium (m), its specific heat (C_p) and temperature change.

$$\text{Heat stored, } Q = m \cdot C_p \cdot (T_{final} - T_{initial})$$

Oil and water are two substances that are normally used as sensible heat storage liquid types, while rock, concrete, brick, earth, and iron are the main solid types. The main disadvantages of the sensible heat storage are the large system size and cannot deliver or store energy at constant temperature (Al-Mosawi 2011).

B) Latent thermal storage

Latent heat storage, a material capture or releases heat during its phase change from solid to liquid or liquid to gas; such materials are termed as phase change materials (PCM). Unlikely sensible energy storage materials, PCMs absorb and release heat at a constant temperature, a process that is completely reversible. PCMs have significantly higher energy densities than non-PCMs. PCMs store 5 – 14 times more heat per unit volume than sensible storage materials. After completion of melting or solidification, any further heat stored will manifest as a temperature change (rise or drop) of the PCM. The latent heat stored during the phase change is equal to the enthalpy differences between the solid and liquid phases and is termed as melting enthalpy, solid liquid phase enthalpy change, or heat of fusion. (Al-Mosawi 2011)

$$\text{Heat Stored, } Q = \Delta H = m \cdot \Delta h$$

Different type of PCMs used in different thermal energy storage application and details are listed in section 1.6. Latent thermal storage is mainly used in limited storage space applications, constant temperature energy applications, etc. High initial cost, corrosive, and/or flammability etc. are disadvantages of latent thermal storage systems.

C) Thermo-chemical energy storage

This technology stores energy in the form of chemical bonds. A reversible chemical reaction which absorbs heat is used to be stored. Then this chemical reaction reversed for the utilization of stored heat. The most common reactions used for this process is the hydration of salts. The energy storage is based on the release of the heat of hydration. Hence, a salt hydrate storage system is changed by the endothermic thermal dehydration of the respected higher hydrated salt.

High energy storage and high storage efficiency are two major advantages of the thermo–chemical storage. High investment cost is the major issue of this storage technology.

Depending on application the different types of thermal storages widely being used in buildings and industries are chilled water sensible storage that includes thermal stratification tanks, flexible diaphragm tanks, multiple tanks, etc.; latent storage that includes internal ice on coil, external melt ice on coil, encapsulated ice, ice harvesters, ice slurry systems, PCM systems, etc.; The detailed explanation of all these types is listed in chapter 34, ASHRAE handbook 2007 HVAC applications.

1.7 Phase change materials (PCM)

PCM are the substances that absorb and release thermal energy during the process of melting and freezing. When a PCM freezes/melts, it releases/absorbs a large amount of energy in the form of latent heat at a relatively constant temperature.

1.7.1 Classification of PCM

There are many organic and inorganic materials that can classified as PCM and these are organized according to their melting temperature and latent heat of fusion. Normally, inorganic materials have almost doubled volumetric latent heat storage capacity (240–400 kJ/m^3) of organic materials (128–200 kJ/m^3). Based on their distinct chemical and thermal behavior; PCMs are divided into subgroups. The behavior of each subgroup helps in design considerations of an energy storage system using a PCM.

- **Salt hydrates:**

Salt hydrates are an important PCM group which exhibits attractive cost and behavior characteristics, some of the salt hydrates characteristics

- Massive latent heat of fusion per unit volume (~ 350MJ/m^3)
- Relatively high thermal conductivity (normally 0.5 W/m^2)
- Lower volume change on melting
- Low corrosive action and slight toxicity
- Moderate costs compared to organic PCMs

Sub cooling is the major disadvantage of the salt hydrate PCM group. Salt hydrates general formula $AB.nH_2O$, where A is acid, B is base, and n is number of water molecules. Addition of different salts to the water for producing the new salt hydrates to attain different phase change temperatures, and same salt can be used in different concentrations in water to produce both positive and negative temperature phase change materials. Different salt hydrates are using for different applications.

Examples: $Na_2SO_4{\bullet}10H_2O$, $NaCl{\bullet}Na_2SO_4{\bullet}10H_2O$, $Na_2SiO_3{\bullet}5H_2O$, etc.

❖ Organic materials:

Organic materials are defined as paraffin and non-paraffin and some exhibit congruent melting, meaning that the melting/freezing cycle can occur indefinitely without phase and consequent degradation of performance. Self-nucleation means that they crystallize with little or no super cooling and are usually non-corrosive. Some characteristics of organic materials

- High heat of fusion
- Inflammable
- Low thermal conductivity
- Low flash point
- Varying level of toxicity
- Instability at high temperatures

Paraffin PCMs are available for use over a large temperature range. Due to cost considerations, however, technical grade paraffin may be used in latent heat storage systems. Paraffin PCMs are safe, predictable, reliable, inexpensive, and non-corrosive. They show little volume change on melting, are stable below 500°C, have low vapor pressure in the melted form, provide wide range of melting temperatures, are chemically inert with no phase segregation and have minimal sub-cooling. Low thermal conductivity of paraffin PCMs limits their application. Metal matrix structures, metallic fillers and fins have been used to improve conductivity.

Organic non-paraffins are most numerous of the PCMs and possess highly varied properties. Each such material has its own unique set of properties, unlike the paraffins, which have similar properties. Fatty acids, glycols, and alcohols are appropriate for energy storage because they have high heat of fusion values compared to those of paraffin. They also exhibit reproducible melting and freezing behavior and freeze with no super cooling.

Examples: Paraffin, fatty acid, glycols, alcohols, etc.

1.7.2 Application of PCM

Applications of PCM include thermal energy storage, solar cooking, conditioning of buildings, cold energy battery, cooling of heat and electrical engines, transportation applications (food, blood, milk products, etc.), waste heat recovery, off-peak power utilization, heat pump systems, solar power plants, thermal comfort in vehicles, thermal protection of electronic devices, etc.

Thermal energy storage of the walls and ceilings can be improved by incorporating PCM. In buildings increased thermal mass decreases temperature variation, which can improve occupant comfort and reduce peak cooling/heating loads and accordingly reduce energy consumption.

With TES, shifting of electrical demand from peak hours to off-peak hours can realize significant primary energy savings, because lower ambient temperatures increases air conditioning unit efficiency and utility sources (generators, chillers etc.) operating at night typically have higher electricity efficiencies.

Heat storage at power plants typically is in the form of steam or hot water and is usually for short time. Oils having high boiling point and high heat of fusion at high temperatures can be used as heat storage substances for the electric utilities.

1.8 Factors influencing the storage design and selection:

Heat exchanger design and method of encapsulation in case of PCMs are two important problems of TES system. The heat exchanger should be designed to operate with as low temperature difference as possible to avoid ineffectiveness. Latent heat TES systems using PCM to store heat or coolness have many applications. Some factors should be considered in design and selection of storage system,

- The temperature range over which the storage has to operate.
- The capacity of the storage has a significant effect on the operation of rest of the system.
- Heat losses from the storage to be kept to a minimum
- Cost of the storage unit; includes initial cost of the storage medium, containers, insulation and the operating cost.
- Time duration which stored energy can be preserved with acceptable losses
- Length of time during which can be kept stored energy with acceptable losses.
- Volumetric energy capacity

Some factors influence the selection of storage medium i.e. PCM,

- Lower change of volume during phase change

- High change of enthalpy near temperature of use
- Little or no under cooling during the freezing process
- No chemical decomposition
- Non-corrosive to construction material
- Long term chemical stability
- High density with low density variation
- Favorable phase equilibrium
- Non-explosive, non-dangerous, non-flammable
- Low vapor pressure
- Non-poisonous, non-toxic
- High thermal conductivity would assist the charging and discharging of the storage high specific heat that provides additional sensible TES effect and also avoid sub cooling

A good storage system should have a long storage time and a small volume per unit of stored energy. The amount of energy storage provided is dictated by cost, the cost of floor space or volumetric space should be one of the parameters in optimizing the storage size.

1.9 Research Objective

The main objective of the thesis is to supply cooling energy from a PCM latent thermal energy storage system to the personalized radiant cooling system and investigating the performance of both thermal energy storage system and personalized radiant cooling system with respect to thermal behavior of latent thermal storage (charging and discharging characteristics), thermal comfort study of PRCS and comparison of energy consumption of the complete system with and without thermal energy storage.

To achieve this objective, thermal energy storage has been designed and fabricated using stainless steel sheets and cooling coils as shell and finned tube heat exchanger concept. This thermal storage is integrated to air cooled chiller (energy source) and PRCS (energy consumer) with CPVC and PU pipe fittings. Performance of complete system evaluated using different type of sensors, data logger, and energy meter installed in the system and various experiments were carried out to analyze complete system performance.

The complete experimental facility PRCS and TES is located at personalized cooling lab in 2nd floor and air cooled chiller located at roof top of Old administrative building, MNIT Jaipur. This thesis consists of performance of PRCS and PCM thermal storage in terms of thermal analysis include charging and discharging behavior of TES and thermal comfort analysis of PRCS, and energy analysis include comparison of energy consumption of complete system with and without PCM thermal storage.

1.10 Organization of thesis

This study is presented in five chapters.

Chapter 1: INTRODUCTION

The first chapter is composed of introduction, background, terminology, objective, and overview on radiant conditioning systems, personalized conditioning systems, thermal energy storage technology, thermal comfort, and PCM technology. It concludes with the disposition of subject matter that follows in the remaining part.

Chapter 2: LITERATURE REVIEW

The second chapter is composed of literature review on radiant conditioning systems, personalized conditioning systems, thermal energy storage systems, and PCMs. This chapter concludes with scope of present work.

Chapter 3: EXPERIMENTAL STUDY

The chapter presents the methodology of experimental study, design, fabrication, and installation of thermal energy storage system. This chapter explained various equipment used in experimental study such as PRCS, chiller, pumps, fan, etc., instrumentation details includes calibration and installation of various temperature sensors. It also describes experimental procedure, measurements and observations during the experimental study.

Chapter 4: RESULTS AND DISCUSSION

Chapter four explain the different results which were acquired from various experiments and the observations. It also describe thermal behavior of PRCS and TES system, and compared energy consumption with and without TES system.

Chapter 5: CONCLUSIONS AND FUTURE SCOPE

Chapter five concludes the study by summarizing the findings of present work and with a discussion on the future scope.

2 – LITERATURE REVIEW

This chapter consists the study of different research journals and papers to find out the type of work that has been carried out and the future scope or possibilities. Literature review on various ongoing research topics like personalized conditioning, radiant conditioning, thermal energy storage and phase change materials helps in finding the past work that has been done in recent years. The findings from the journals helps in the current study and practical data helps in improving the reasoning as well. This literature review illustrates some theoretical and experimental work that has been done in recent years. This chapter is subdivided into three parts to understand the topics clearly, there are

- Studies on radiant cooling systems
- Studies on personalized conditioning systems
- Studies on thermal energy storage

2.1 Studies on radiant conditioning systems

(Kyu-Nam Rhee 2015) presented a 50 year review of basic and applied research in radiant heating and cooling (RHC) systems for built environment in terms of thermal comfort, thermal analysis including heat transfer model, CFD analysis, heating/cooling capacity, system configuration, energy simulation and control strategies. This review explains the research trend of RHC systems, RHC system understating issues, and future research possibilities of RHC systems. The results are indicating that the RHC systems has been continuously developed, improved, and modified for achieving energy efficiency and better thermal comfort. The RHC systems implemented in many countries have been proved to be a better solution for energy efficiency and improved thermal comfort Single RHC system design and control for both cooling and heating applications, addition of the current advanced control strategies into multiple zone control, direct or indirect use of renewable energy (geothermal, solar, etc.) as a heat production source, etc. are some future research topics of RHC systems.

(Koichi Kitagawa 1999) experimentally investigated local parts and whole body thermal comfort in a radiant cooling system including impact of relative humidity and small air movements by using different subjects. Experiments were performed in a climate chamber using radiant cooling panel system as three distinct cases. Case1: to know the impact of humidity on thermal comfort, climate chamber maintained at various humidity levels (85%, 65% & 45%), panel temperature also varied between 27°C and 17°C. Case 2: to know the impact of air movement on thermal comfort, air velocity 0.1 m/s was maintained near to occupant in a climate chamber varying humidity between 85% and 65% and radiant panel temperature ranging between 27°C and 17°C. Case 3: to know the impact of air movement fluctuations on thermal comfort, air movement was fluctuated between 0.1 m/s and 0.3 m/s near to occupant in a climate chamber maintained at 65% humidity level and radiant panel temperature maintained at 25°C. Subjects were seated on chair under the radiant cooling panel system and voted their comfortable sensation and thermal sensation. Results indicated that increasing the humidity in radiant cooling system thermal sensation was warm even at same level of operative temperature. Small air movement shifts the thermal sensation fell approximately one scale cooler than still air conditions in same level SET* in radiant cooling systems. This study indicated that the most comfortable feeling of occupants was at –0.5 thermal sensation vote conditions instead of neutral thermal sensation vote conditions.

(Jyotirmay Mathur 2017) performed simulation and experimental study to find the load capacity and thermal performance of radiant cooling system. Series of experiments were conducted and simulations were performed on Energy Plus building energy modeling tool to know the capacity and performance a radiant cooling system. A building model was developed in simulation tool (Energy Plus) and calibrated with experimental results of a radiant cooling panel system in a composite climate of Jaipur, India. The results are shown that cooling capacity of the radiant panel depends on the temperature at which chilled water supplying to the radiant system, if the chilled water supply temperature is 15°C then panel capacity is 72 W/m^2 and at 20°C chilled water supply temperature panel capacity reduced to 25 W/m^2. Thermal performance of the system indicating that radiative heat transfer coefficient varies from 5.15 to 5.26 W/m^2-K, and the convective heat transfer coefficient ranges from 4.12 to 3.12 W/m^2-K as the chilled water supply temperature increases from 15°C to 20°C.

(M. B. Jyotirmay Mathur 2016) performed simulation study of an information technology office building to know the energy saving potential of radiant cooling system when compared with conventional variable air volume (VAV) system. Energy model of the building was developed in Energy Plus simulation software. This model was calibrated with the measured data of a radiant cooling system installed in the Infosys campus building SDB–1 in a composite climate of Hyderabad, India to the component level. And a base case model also developed by using calibrated model to know the energy saving potential of radiant system. The energy saving potential of the radiant system estimated by comparing the two wings of the building one is served by VAV system and other is served by radiant system. Results are shown that radiant cooling system integrated with dedicated outdoor air system (DOAS) consumes 28% less energy than conventional VAV system. Building orientation impact on cooling energy use also tested by rotating the building by 180°, and the results indicated that building orientation impact on energy savings was very less.

(Xiaozhou Wu 2015) proposed a new simplified model to calculate heat transfer and surface temperature of a radiant floor cooling and heating system and was developed on the basis of conduction shape factor. The proposed model was calibrated with the help of measured data from the references and numerical simulated data of this study also used to validate the simplified model. The effect of pipe space, average water temperature, and the thickness of the screed layer on the heat transfer and surface temperature of radiant floor system were quantitatively investigated using the proposed model. The results indicated that maximum difference between the calculated heat transfer and surface temperature using proposed model and measured data were 8.1 W/m^2 and 0.8°C for radiant floor heating system when the average water temperature between 60°C and 40°C and these values were 2 W/m^2 and 0.3°C for radiant floor cooling system when average water temperature between 20°C and 10°C. The calculated data of heat transfer and surface temperature using proposed model very well agreed with numerically simulated data when average water temperature changes from 10°C to 20°C for radiant cooling system and 25°C to 45°C for radiant heating system. The heat transfer and surface temperature of the radiant floor system profoundly influenced by average water temperature and pipe space while screed layer thickness influence was negligible on heat transfer and surface temperature of radiant floor system.

(M. B. Jyotirmay Mathur 2016) carried out a simulation study feasibility of cooling tower application for supplying chilled water in radiant cooling system under different climatic conditions of India. Three different configurations of radiant cooling systems were considered in this study to compare the energy consumption and to achieve energy saving potential. The designed building model consisting of radiant system on walls, ceiling, and floor and a DOAS also coupled in building for dehumidification and ventilation. Case 1: chilled water from cooling tower supplying to complete radiant system (wall, ceiling, and floor), case 2: cooling tower chilled water supplied to wall and ceiling radiant system and 16°C chilled water from separate chiller supplying to floor radiant system, case 3: cooling tower chilled water supplied to wall system and 16°C chilled water supplying to floor and ceiling systems.. The simulation results of the study indicated that the different configurations are suitable for various climatic conditions like case 3 most efficient for warm and humid climate zone, case 2 most appropriate for hot and dry and composite climate zones, case 1 suitable for temperate climate conditions. Energy consumption of all these cases was compared with conventional baseline scenario; case 1 was found to be efficient in mild climatic conditions than other cases. Composite and temperate climates are most suitable for the cooling tower integration with radiant cooling system, and warm and humid climates are least preferable for cooling tower integration to radiant cooling systems.

(Yasin Khan 2015) carried out a simulation study to estimate the energy saving potential of a radiant cooling system. To investigate the thermal performance and energy consumption of a radiant cooling system, simulations were performed in FLUENT and Energy Plus software respectively. The developed building model was calibrated with measured data of a commercial building installed with radiant cooling system in India. This calibrated model was used in simulation study to know the energy consumption of a building which is connected with conventional all-air system to find the potential energy savings of radiant system. The results are indicating that the energy consumption of a building with radiant system is 17.5% less than the conventional air system. This energy use is approximately 30% less than conventional air system when the system integrated with DOAS to handle latent load as advanced case. The radiant cooling system maintained uniform and stable indoor air temperature in the zone, hence better thermal comfort achieved while less energy consumption than conventional systems. This study also explained that more energy saving options available in radiant system when it integrated with DOAS under different operational control strategies.

(Anuj Sharma 2015) experimentally investigated thermal performance of radiant cooling system in terms of energy saving opportunities and effective temperature at different supply chilled water flow rates and temperature range. Thus study also explained the optimum combinations of the basic parameters (supply water flow rate and temperature) for radiant cooling system in composite climate. Experiments were conducted to know the performance and optimum parameter combinations radiant cooling system as six different cases; Case 1: supply chilled water temperature is between 15°C and 18.5°C, and flow rate is low (25% less than designed flow rate); Case 2: supply chilled water temperature is between 15°C and 18.5°C, and flow rate is high (25% more than designed flow rate); Case 3: supply chilled water temperature is between 15°C and 18.5°C, and flow rate is standard (designed flow rate); Case 4: supply chilled water temperature is between 14°C and 17.4°C, and flow rate is low, Case 5: supply chilled water temperature is between 14°C and 17.4°C, and flow rate is high, Case 6: supply chilled water temperature is between 14°C and 17.4°C, and flow rate is standard. During experiments panel temperature, energy consumption, indoor temperature and humidity, chilled water temperature, chilled water flow rate, and MRT were measured for system performance analysis. From the results it is concluded that there can be one optimum parameter either flow rate or water temperature and set of parameters may not be the optimum combination for similar energy savings and thermal comfort. Case 3 was an optimum combination in terms of low effective temperature and energy consumption, case 2 was an optimum combination in terms of least kW/TR, etc. are different optimum combinations indicated in this study.

2.2 Studies on personalized conditioning systems

(W. Michal Vesely 2014) presented a review study of different personalized conditioning systems and their impact on thermal comfort and building energy performance. Personalized conditioning systems emerged as new research area in buildings to improve the occupant thermal comfort and reduce the energy consumption of building conditioning systems. Personalized conditioning systems create micro-climate zone around the single workplace, and hence energy deploying only where it is actually needed, and the individual needs of thermal comfort are fulfilled. This study indicated that the thermal comfort can be maintained well even at higher temperatures up to 30°C when personalized cooling is applied. Among different elevated air movement methods, personalized ventilation has more advantages over personal fans. Among the different personalized heating methods heated chair systems by conduction preferred by the users. The energy saving potential of these personalized systems is up to 60% due to optimum usage of energy i.e. deploying the energy where it actually needed.

(Vaibhav Rai Khare 2015) carried out a simulation study to investigate the performance of personalize radiant cooling system integrated with conventional air system in terms of thermal comfort. ANSYS Fluent, CFD simulation tool used to know the air temperature around the occupant to investigate the effect of air temperature and temperature distribution for workspace. This work includes an office cubicle made up of aluminum radiant panels structured with copper pipe looping to circulate heat transfer fluid. The results indicating that the PRCS improves the thermal environment near the workplace and allows conventional air system to work at higher thermostat temperature for the same thermal comfort conditions and hence reduces energy consumption. Individual thermal comfort requirement of occupants can fulfill through PRCS.

(Ricardo Forgiarini Rupp 2015) theoretical study presented review of last 10 years of research related to human thermal comfort in built environment along with various sub areas of thermal comfort. This study examines standards, indoor experiments in semi-controlled and controlled environments, indoor field studies in office, educational, residential, and other building types, and outdoor and semi-outdoor field studies. Also explained influence of naturally ventilated, mixed mode and air conditioned buildings, personalized conditioning systems, personal factors (age, gender, weight, thermal history) and environmental factors (controls, air movement, layout, humidity, etc.) on thermal comfort. This study is indicating that a large number of thermal comfort studies are using adaptive thermal comfort models, remaining are using PMV/PPD models. Thermal comfort studies on personalized conditioning systems, mixed mode buildings, etc. are emerged as new research topics in built environment.

(Ravi Garg 2016) developed personalized radiant conditioning system to analyze the performance in terms of thermal comfort and compared with conventional air conditioning system. A PRCS designed and fabricated with aluminum radiant panels supported by wooden structure as a typical office cubicle of commercial building. Experiments were performed for both heating and cooling conditions by supplying hot water from small boiler and chilled water from air cooled chiller respectively to the PRCS. During the experiments, feedback of the occupant thermal sensation was taken through questionnaire and air temperature was measured for thermal comfort analysis and to determine the comfortable range of standard effective temperature (SET). The results shown that inlet water flow rate does not influence the performance of PRCS (i.e. SET). PRCS maintains thermally comfortable environment to the occupant and provide sufficient cooling for supplying water temperature range within 15°C to 21°C. This study shows that PRCS improves thermal comfort to the occupant and occupants individual thermal comfort needs can also be fulfilled by PRCS.

(P. M. Michal Vesely 2017) experimentally investigated personalized heating system in terms of effectiveness of different heaters and influence of various control modes. This personalized heating system consists of a heated desk mat, a heated chair, and a heated floor mat in a climate chamber under 18°C operative temperature. This experimental study investigated performance of all heaters (heated chair, heated desk mat, etc.) individually as well as combination of two or more heaters as user or occupant controlling the heaters according to comfort conditions. The results indicated that the complete system improves thermal comfort significantly under mild conditions. A heated desk mat and heated chair improve thermal comfort among the single components, and heated chair is most energy efficient. The user control of personalized system can be replaced by automatic control without loss of thermal comfort or increased energy consumption.

(Qihong Deng 2017) performed experimental study to know the thermal sensation and comfort of human regional- and whole-body in a cool environment with personalized heating system. Experiments were conducted in two different chambers one is uniform at 18°C, and another is non-uniform at 16°C having heated seat (chair) as personalized heating system with the involvement of 36 subjects (males and females) including children, elders, and adults. Regional and whole body thermal sensation and comfort of subjects analyzed through questionnaire and their skin temperatures. The results are indicated that personalized heating in non-uniform environment improved thermal sensation and comfort than the uniform environment without personalized heating; it may be due to the increased skin temperature in personalized heating.

2.3 Studies on thermal energy storage systems

(Abduljalil A. Al-Abidi 2014) experimentally investigated melting and solidification of PCM using triplex tube heat exchanger having internal and external fins, as thermal energy storage. PCM charging process examined with study and un–study HTF inlet temperature and the influence of the mass flow rates and the PCM melting & solidification. The melting and solidification process of PCM under different mass flow rates and the PCM temperature variation in the radial and angular directions were analyzed. The results shown that the HTF inlet temperature has high influence than the HTF mass flow rate, the charging time is reduced to 86% for HTF inlet temperature and 58% for HTF mass flow rate.

(Tay N.H.S 2012) proposed a simplified numerical tool for the characterization of the PCM thermal storage system. The effectiveness–NTU technique is basis for the simplified mathematical model to design, analysis and optimization of PCM thermal storage systems. A simplified mathematical representation for a cylindrical tank filled with PCM and HTF flowing through tubes inside the tank was developed by using effectiveness–NTU technique. Experiments were also carried out on a cylindrical tank filled with PCM with different number coils of tubes (such as one, two and four coils of tubes) to validate the proposed numerical technique. Experimental outcomes for the systems with a high heat transfer area comparable with those calculated results from the mathematical model. The results indicated that proposed model can be readily use as a design tool for sizing and optimizing a thermal storage system with PCMs. This simplified model based on effectiveness–NTU technique also predicts the average heat exchange effectiveness of the thermal energy storage system with a high heat transfer area during charging and discharging.

(Alessandro Beghi 2014) carried out a simulation study to design efficient control strategies for thermal energy storage systems. A model based approach is developed for increasing the performance of HVAC systems which ice cold TES on Matlab/Simulink simulation environment. Thermal behavior of the plant was analyzed by a lumped formulation of conservation equations on simulation environment. The ice CTES was modeled as a hybrid system in which the water phase transitions (liquid-freezing-solid and solid-melting-liquid) were described by combining continuous and discrete dynamics, and considered both latent and sensible heat. The proposed nonlinear model predictive control (NLMPC) approach is compared with standard control strategies. The results of the extensive dynamic simulations indicated that NLMPC exhibits better performance in terms of demand satisfaction and energy efficiency than the conventional procedures. The control strategies or operations are crucial in order to ensure load demand satisfaction and energy efficiency.

(Mohamed El Mankibi 2015) studied optimization of PCM–Air heat exchanger and proposed some load shifting methods in which thermal comfort of the occupants and the indoor air quality are constraints. This study aimed to shift the space heating demand from peak to off-peak period. The heat exchanger contains paraffin macro encapsulated PCM and is constructed in a way that facilitated its integration in a ventilation system. An experimentally validated numerical model developed on the basis of heat balance approach, and the apparent heat capacity method was used to perform this study. Heat exchanger dimensions, PCM quantity and properties, optimum charging and discharging time, etc. are different parameters were investigated during the optimization process. The results of the two different optimization approaches shown that a smaller and lighter heat exchanger was able to provide good air quality and indoor thermal conditions.

(Akash Shah 2016) experimentally investigated the efficient thermal storage system for PCM with different prototype models. A series of experiments conducted on 4 different thermal storage system designs such as tube in tank, single cooling coil in tank, multiple cooling coils in tank (parallel connection), and multiple cooling coils in tank (series connection). Organic mixture (OM–21) PCM is used as energy storage media having average melting temperature of 21°C. In this study thermal energy storage charged during night time and discharged during day time for free cooling of buildings. The experimental results have shown an increase in the effectiveness of the TES system with finned tube heat exchangers (cooling coils), since increased contact area through fins enhances heat transfer happen between PCM and heat transfer fluid. Among the all prototype setups, the cooling coils in tank connected in series ensures uniform charging and discharging of the thermal energy storage. This configuration with large number of cooling coils can be an excellent thermal storage system for high capacity storage systems used in HVAC applications or industrial applications.

2.3.1 Studies on Phase Change Materials

(Muthuvelan Thambidurai 2015) listed a detailed review of the PCMs for free cooling of building applications. Free cooling is a concept through which building cooling demands can meet without compromising the indoor air quality, free cooling stores the atmospheric night cold energy in PCM and uses the stored energy during day time to achieve the desired room comfort conditions. This study reviewed the work carried out in past years on free cooling using PCMs in latent heat thermal energy storage systems by various researchers. This study also discussed future potential of free cooling technologies, scope for further improvement, policies required to ensure market penetration of free cooling technology towards sustainability in detail. The primary outcomes of this review are: suitable PCM with optimum melting temperature and high heat storage capacity calculates the effectiveness of free cooling systems; free cooling suitable for less humid and maximum diurnal temperature range regions rather than warm and humid climatic conditions; commercialization and mass implementation of free cooling technology in residential sector restrict the air conditioner running hours and corresponding greenhouse gas emissions.

(Jingjing Shao 2015) carried out a review on phase change material emulsions (PCME) to establish their limitations in HVAC applications as thermal energy storage and an alternative heat transfer fluid for future research. PCMEs are multifunctional fluids consisting of carrier fluids and PCMs. PCMEs can take advantage of its high capacity to reduce flow rate and thus to save the pump power while delivering the same amount of cooling effect. PCME also used as cold storage to shift peak-load to off-peak time and improve the COP of the systems. Energy cost saving, peak load shifting and pump power reduction have also been reported from short-term experimental studies on PCMEs. Long-term experimental studies are required to evaluate the overall performances of PCMEs. The issues of higher viscosities in PCMEs, thermal stability of PCMEs and level of sub-cooling are the scientific barriers of the PCMEs application in large scale.

(Jaume Gasia 2016) experimentally analyzed the thermal behavior of a commercial paraffin as a PCM for industrial waste recovery and domestic hot water applications which is having melting temperature of 58°C. Complete characterization of this PCM is performed based on two different methods: a laboratory characterization (small quantity, milligrams) and an analysis in a pilot plant (large quantity, kilograms). In the laboratory analysis, PCM thermal and cyclic stability, enthalpy, specific heat and its thermal health hazard, as well as its phase change thermal range are analyzed using differential scanning calorimeter, thermocycling, infrared spectroscopy and thermogravimetric analysis respectively. In pilot plant characterization, paraffin thermal behavior was investigated in shell and tube heat exchanger under different mass flow rates of heat transfer fluid in terms of temperature, energy rates, and power. Results of laboratory analysis showed that this paraffin is suitability up to 80°C and for 2000 cycles. Results of pilot plant analysis revealed that geometry of the tank influence the PCM melting and/or solidification during charging and discharging process in shell and tube heat exchanger.

(Uros Stritih 2016) numerically studied innovative PCM room ventilation storage system in buildings. This system stores cold energy during night time and delivers it during the day time and thus reduces the cooling load. This system is connected with solar air collector in winter and heat is stored for heating during evening and morning hours. This storage unit consists of 30 plates filled with PCM (paraffin), and air is circulated between plates known as air gap for storing energy (cold or heat) in PCM. Results indicated that small air gap; thick plate is best configuration of storage unit design due to significant amount of PCM in the TES volume.. By using this best configuration PCM thermal storage in buildings there can be improved annual energy savings in overall system.

(Alvaro de Gracia 2015) reviewed applications of thermal energy storage in buildings using sensible, latent, and thermochemical energy storage to achieve thermal comfort and to reduce cooling and heating demand in buildings. Peak shaving and increase of energy efficiency in HVAC systems are also be obtained through TES in buildings. This study explained existing and explored active and passive TES technologies integrated in the buildings as well as the materials developed and used in the active and passive TES systems. This study indicated that passive techniques are used to reduce active heating and cooling devices and to maintain a thermal stability in buildings. The use of PCM in building envelope reduces the volume requirement in building than sensible thermal storage material and normally volume is limitation in the building sector. Thermal stability and leakage are the important design factors that should be consider in case of PCM passive TES systems. Active technologies are used for implementation of renewable energies for space heating and cooling, for improving the performance of existing installations, and for peak load shifting strategies. TES is a key technology to reduce the energy demand of buildings and to improve the energy efficiency of their energy systems. Few challenges of the TES technology are to reduce the cost, to increase the energy density of the materials, to enhance the compactness of the systems, to develop new materials, especially fluids that can act as heat transfer fluids and storage material at same time, and to increase thermal conductivity of the materials.

(Whiffen T.R 2012) extensively reviewed the PCM technology for the application of thermal energy storage within the built environment. Thermal storage systems offer attractive properties and enabling economical energy utilization within built environment. This research work explained the state of TES technology, PCM design, PCM selection, and performance enhancement methods of PCMs. This study indicated that PCMs are high energy storage density materials and only surpassed by methanol and hydrogen. A large number of PCMs were tested around indoor comfort temperature region. Organic PCMs mainly paraffins appear to be most feasible due to their long term stability. Inorganic PCMs are hindered by unwanted toxicity and sub-cooling. Improved methods of PCM encapsulation have enhanced performance and opened new way of research.

2.4 Summary of the literature

There is need to know about ongoing research topics like radiant cooling systems, personalized conditioning systems, thermal energy storage systems, phase change materials, etc. Following are some important points drawn from the literature review

- Research on radiant cooling and heating systems has been increased due to several advantages of these systems such as reduced energy consumption, high thermal comfort, quiet operation, space saving, etc. Investigation on thermal performance of radiant systems widely studying to implement these systems in practical applications.
- Personalized conditioning is new research area in buildings to reduce energy consumption and improve thermal comfort for occupants.
- Personalized chair/component heating, personalized ventilation, personalized conditioning, personalized fan systems, etc. are new technologies of

personalized conditioning systems, which shows the increasing interest on the personalized conditioning in recent years (hardly from five years)

- All different personalized conditioning systems are in research stage only; not a single technology has come in market till date.
- Multiple personalized systems are still to be analyzed in laboratory to know the performance of different systems at different thermal conditions in same climate chamber or room.
- Comparison of different personalized conditioning systems is still missing in terms of energy efficiency and thermal comfort.
- Thermal energy storage usage in buildings, process applications, heat recovery, etc. was increased in recent years, in order to minimize the supply and demand gap, energy conservation, etc.
- Increased research on phase change materials for the application of latent heat thermal energy storage due to its several advantages over other materials like high storage densities, wide range of availability, constant temperature heat storage, etc.
- New researches are going on PCMs to enhance thermal conductivity, heat transfer, thermal stability, etc.
- PCMs usage in buildings has increased in recent years to enhancing the energy system efficient by integrating passive or active technologies to the buildings.
- New researches are going on heat exchanger designs which are suitable for PCM storage systems to improve the heat transfer between HTF and heat storage medium, like triplex tube heat exchanger, finned tube heat exchangers, etc.
- Personalized conditioning systems operated through thermal energy storage to know the performance and energy saving opportunities is still missing.

These research gaps motivated to design a thermal energy storage that improves the heat transfer between HTF and heat storage material (PCM) and this TES unit used for the operation of PRCS to maintain thermally comfortable environment to occupants.

3 –EXPERIMENTAL STUDY

For this experimental study, thermal energy storage system made up of stainless steel material, and cooling coils was set up in personalized cooling lab at center for energy and environment, Malaviya National Institute of Technology (MNIT), Jaipur, India. The whole work has been divided into several phases described below;

Phase 1: Design and fabrication of TES system; the following steps were completed in this phase

- Selection of PCM (depending on requirement and availability)
- Design of TES (sizing of the system, volume, number of storage tanks)
- Procurement of materials (construction material, insulation, cooling coil, etc.)
- Fabrication of system (development of shell and finned tube heat exchanger)
- Installation of TES system (integration of TES to existed PRCS)
- Testing of the system (pressure testing of TES)
- Instrumentation (calibration and installation of sensors)

Phase 2: Experiment process; the following steps were completed in this phase

- Experiment planning (design of experiments and experimental procedures)
- Experiments to know the performance of whole system
- Experiments to understand the corrosive resistance of nickel coated copper strip.

Phase 3: Experimental analysis, the following steps were completed in this phase

- Measurement, calculation and calculated data analysis
- Results and discussion
- Conclusions of the experimental study

All these steps followed in experimental study are explained in later sections.

3.1 Methodology

Several steps have been identified and analyzed to complete whole experimental study. Figure 3.1 explains the adopted methodology to investigate the performance of PRCS that has been integrated with PCM thermal energy storage system.

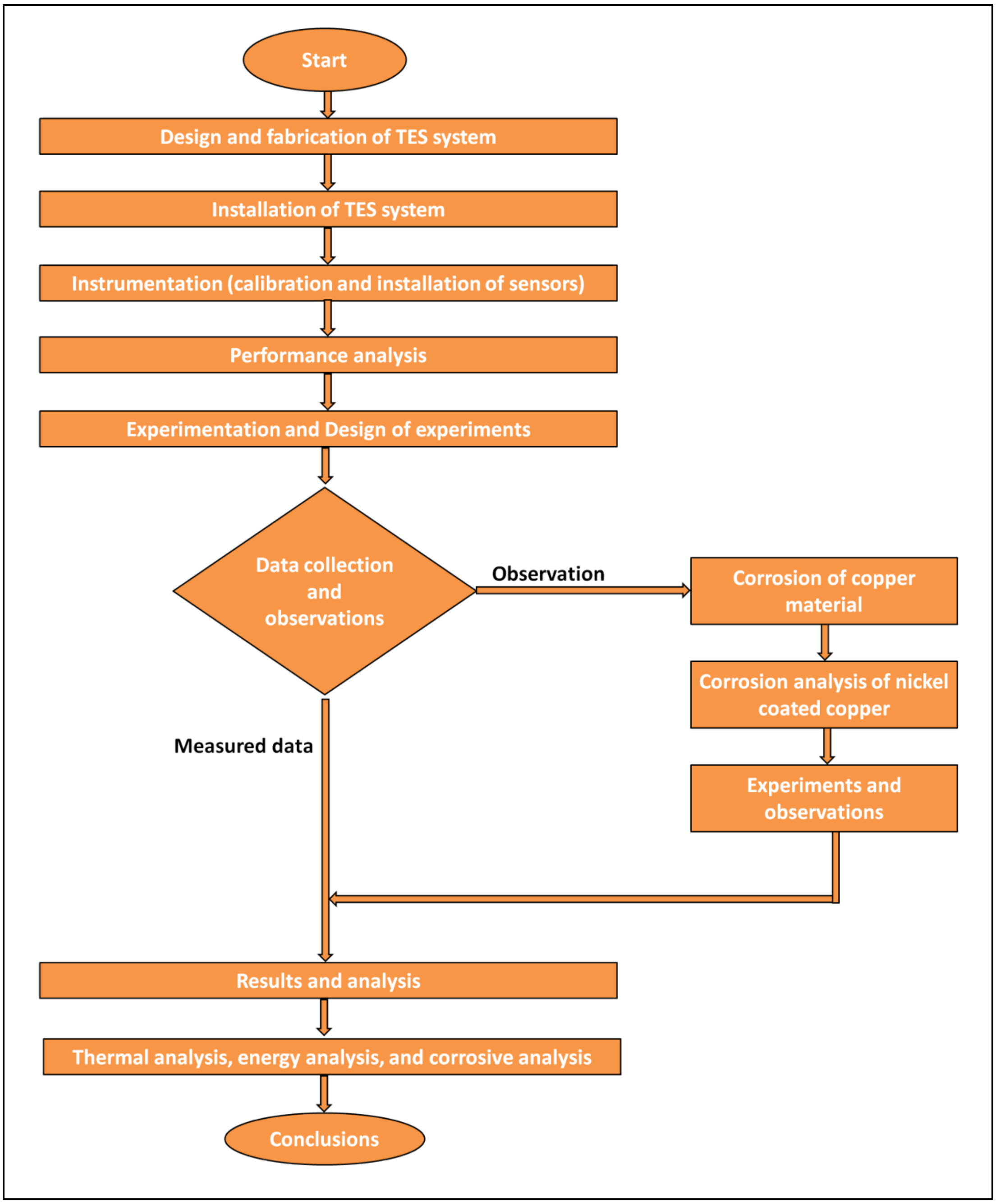


Figure 3.1 Methodology of Experimental work

3.2 Building Description

Thermal energy storage system has been installed in personalized cooling lab, center for energy and environment, second floor of old administrative building, MNIT, Jaipur. The first floor of the building is integrated with conventional HVAC system. Figure 3.2 shows the layout of 2nd floor of the building. This floor has radiant ceiling panels fitted in few rooms (highlighted – light blue). The room has been selected for experimental study, have radiant ceiling panels, personalized radiant cooling system, and its south wall is exposed to the sun.

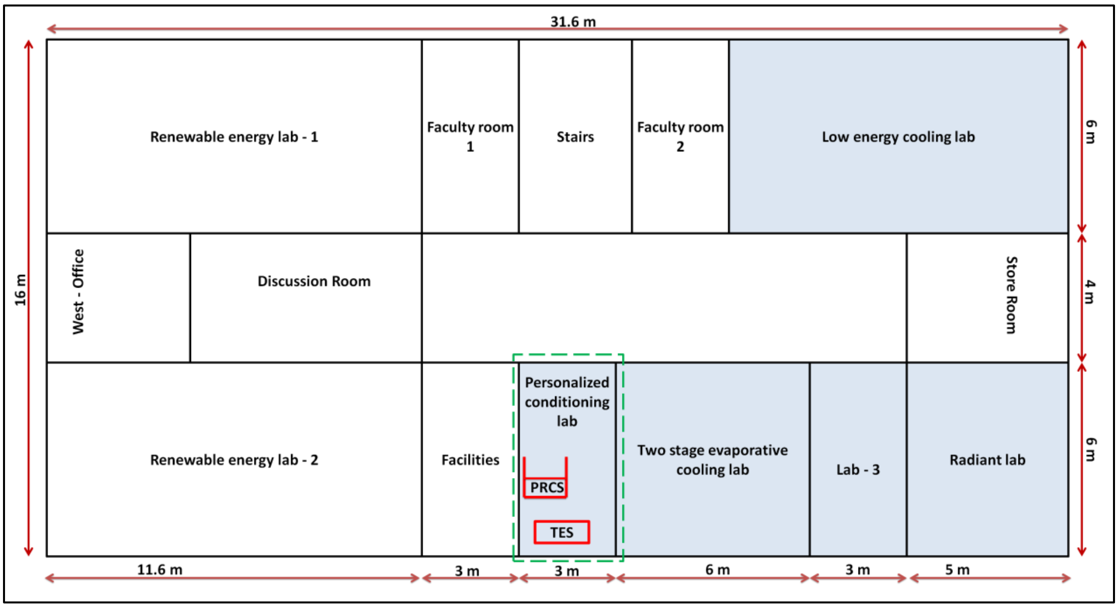


Figure 3.2 Second floor layout of the building

3.3 Description of experimental room

The room in which experiment is performed has the size of 6m × 3m × 3.5m (length × breadth × height). The room is north facing, and it has two south facing windows of size 1.3m × 1.18m (l × h). There is no provision for direct sunlight from the window because of overhangs. Figure 3.3 shows the detailed room layout.

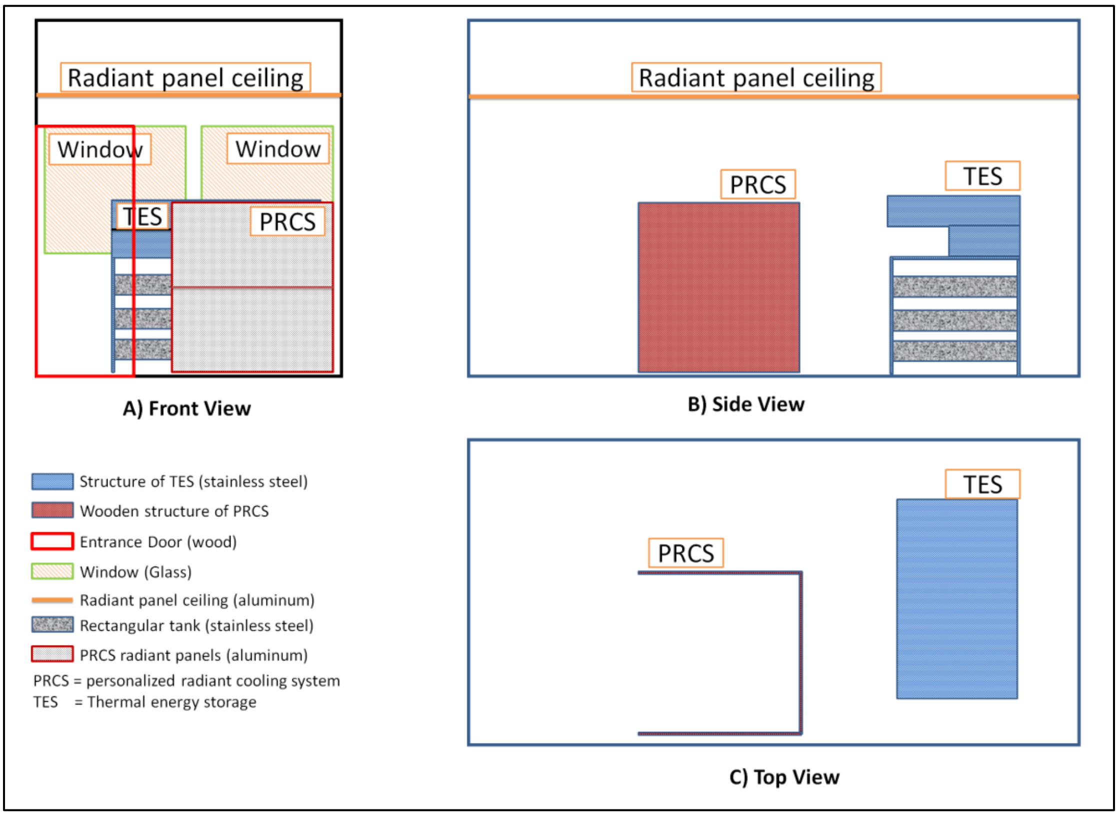


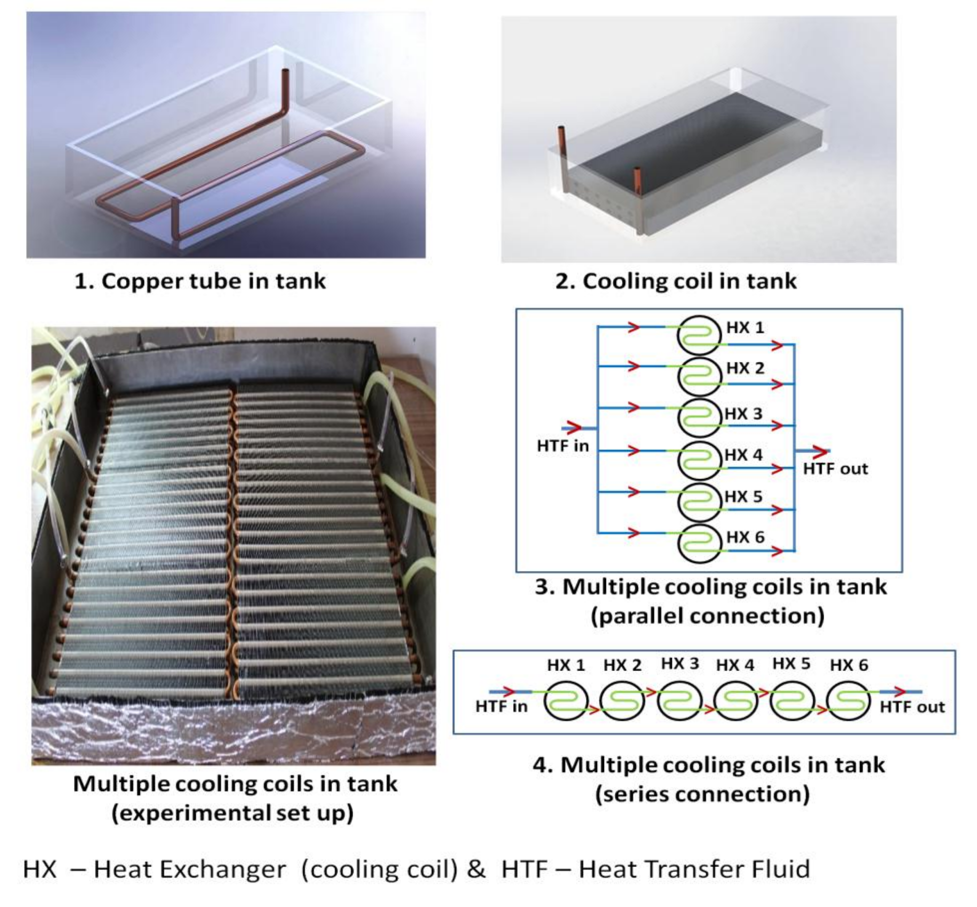
Figure 3.3 Experimental room layout

3.4 Design and fabrication of PCM thermal storage system

From the literature, it was observed that low thermal conductivity of phase change material (PCM) and less heat transfer between heat transfer fluid (HTF) and PCM heat storage media were two important challenges in PCM thermal storage system. There are different approaches followed by researchers to overcome these two challenges of PCM usage in thermal energy storage systems. Increasing the heat transfer area between HTF and PCM is one efficient way to improve heat transfer between HTF and PCM by utilization of finned tube heat exchangers, application of multiple tube heat exchangers, etc. Improving the thermal conductivity of PCM by addition of other materials such as metal matrix into PCM, utilization of bubble agitation in the PCMs by impregnation of porous materials, etc. are other methods to increase heat transfer between HTF and PCM storage medium. The other enhancement methods for heat transfer process by maintaining a contact temperature difference between the PCM and the HTF involves the use of multiple PCM families, which are packed in the decreasing order of their melting points in the flow direction of thermal energy storage.

The most considerable efficient method to enhance the heat transfer in PCM thermal storage system is use of fins embedded in the PCM. This particular method for increasing the heat transfer area has been extensively investigated by researchers recently. Particularly PCMs in thermal storage systems as energy storing material has been grown in research and industrial applications due to advancement in technology and various advantages over other storage materials. By integrating the thermal energy storage systems in buildings, the efficiency enhancement of energy systems (like HVAC systems, electricity generation systems, etc.) can observed in terms of operational cost, direct reduction in energy use, etc.

In this experimental study, shell and finned tube heat exchanger has been developed on the basis of prototype experiments carried out by (Akash Shah 2016) using cooling coils placed in rectangular tank. The experiments performed to know the cooling coils application as heat exchanger in thermal energy storage using PCM storage medium. The results explained that the cooling coils in rectangular tank can be used as thermal energy storage system for building applications. Among all prototype models cooling coils in series connection showed favorable thermal energy storage characteristics. The figure 3.4 shows the different prototype models used in experimental study.



1. Copper tube in tank

2. Cooling coil in tank

Multiple cooling coils in tank (experimental set up)

3. Multiple cooling coils in tank (parallel connection)

4. Multiple cooling coils in tank (series connection)

HX – Heat Exchanger (cooling coil) & HTF – Heat Transfer Fluid

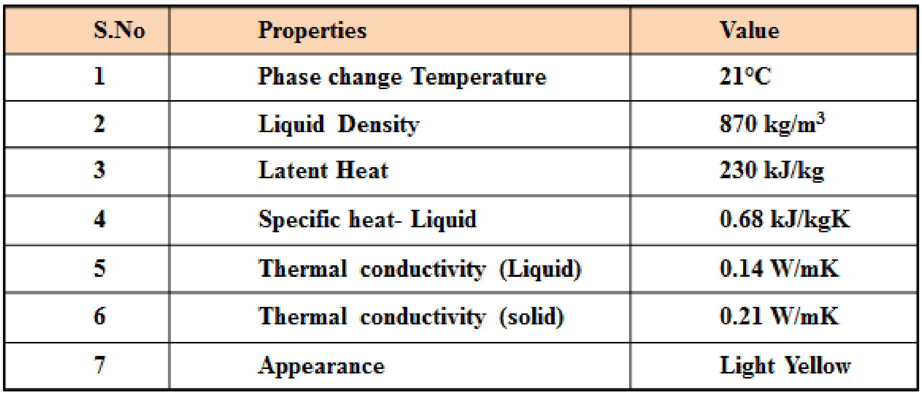
Figure 3.4 Prototype models used in experiments

3.4.1 Selection of PCM

Latent heat TES using PCM has found to be nowadays more attractive than sensible TES despite the fact that, in terms of cost, sensible TES materials cheaper than PCM because of their narrower operating temperatures and high thermal storage densities. Paraffins and fatty acids are widely used organic PCMs for both domestic and industrial applications. The advancement in PCM technology makes sure that the availability of PCM at more temperature ranges for various applications. PCM is used as thermal storage medium for cooling and heating applications, and reduces the energy demands of building sector during peak hours.

The operating temperature required for the operation of PRCS is the basis for the selection of PCM, which is in the range from 15°C to 21°C (Ravi Garg 2016). Organic mixture PCM, OM–21 with an average 21°C melting temperature satisfies the operating temperature required for PRCS. This is the only PCM available in this range in India as per the requirement of experimental study. Table 3-1 shows the thermo-physical properties of OM–21 Phase change material.

Table 3-1: Properties of Phase Change Material (OM–21)

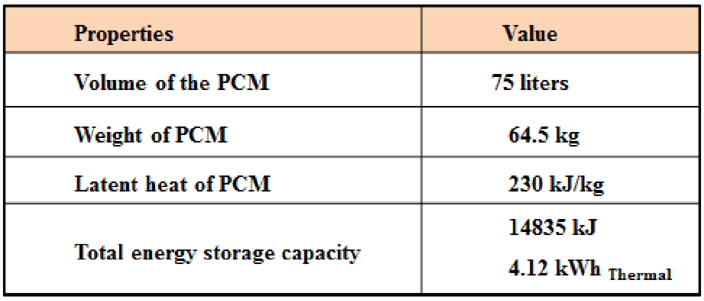


S.No	Properties	Value
1	Phase change Temperature	21°C
2	Liquid Density	870 kg/m^3
3	Latent Heat	230 kJ/kg
4	Specific heat- Liquid	0.68 kJ/kgK
5	Thermal conductivity (Liquid)	0.14 W/mK
6	Thermal conductivity (solid)	0.21 W/mK
7	Appearance	Light Yellow

3.4.2 Design of the TES system

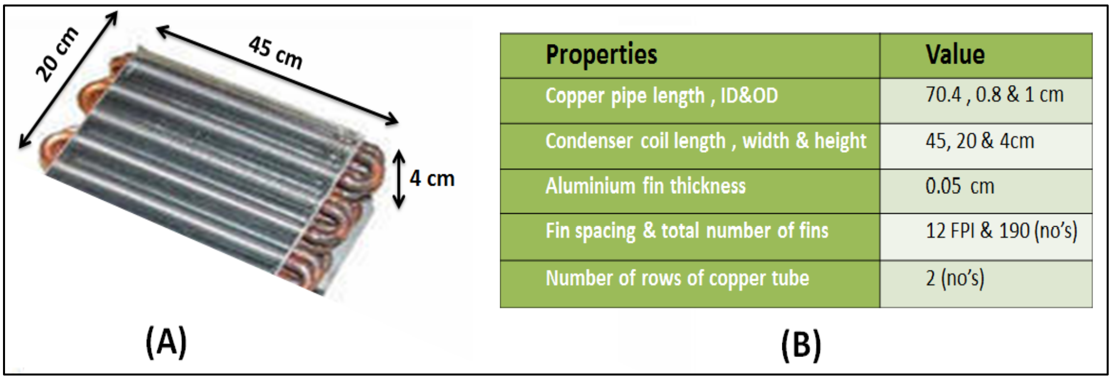
Latent heat thermal energy storage system using PCM as storage medium was designed to supply cooling energy to personalized radiant cooling system during day time. The sizing of the TES system was purely on the basis of operational hours of PRCS. The PRCS has capacity of 1.2 kW (including pumping losses) and 3.5 hours continuous operation of PRCS requires 4.2 kWh thermal energy from TES system. From the table 3-1 (properties of PCM, OM–21) the required amount is 76.5 liters, so the roundup value is 75 liters of PCM. Therefore the capacity of PCM thermal storage system is 75 liters and complete details of capacity shown in table 3-2.

Table 3-2: Specifications of TES system



Properties	Value
Volume of the PCM	75 liters
Weight of PCM	64.5 kg
Latent heat of PCM	230 kJ/kg
Total energy storage capacity	14835 kJ 4.12 kWh $_{Thermal}$

Shell and finned tube heat exchanger concept was used to design the TES system for heat transfer enhancement between PCM and HTF. Multiple cooling coils (finned tube heat exchanger) placed in rectangular tank (shell) used as TES system. In order to improve the effectiveness of the TES system total designed volume divided into three equal parts and hence the TES system has three storage tanks. Cooling coil specification and cooling coil used in storage system shown in figure 3.5. Cooling coil height and number of cooling coils in tank were two constraints used to divide the storage system into three tanks.



Properties	Value
Copper pipe length , ID&OD	70.4 , 0.8 & 1 cm
Condenser coil length , width & height	45, 20 & 4cm
Aluminium fin thickness	0.05 cm
Fin spacing & total number of fins	12 FPI & 190 (no's)
Number of rows of copper tube	2 (no's)

Figure 3.5 (A) Cooling coil; (B) Specification of cooling coil

If the amount of PCM inside the tank greater than cooling coil height, the heat transfer area will be less, therefore, system performance may reduce. And the number of cooling coils in tank depends on pressure drop across the coils, length of the shell (or space), and charging and discharging characteristics of TES system. The optimum number of cooling coils in tank is six as per the above constraints; it may vary to other applications. Figure 3.6 shows the expected model of the single storage tank i.e. shell and finned tube heat exchanger having 25 liters capacity.

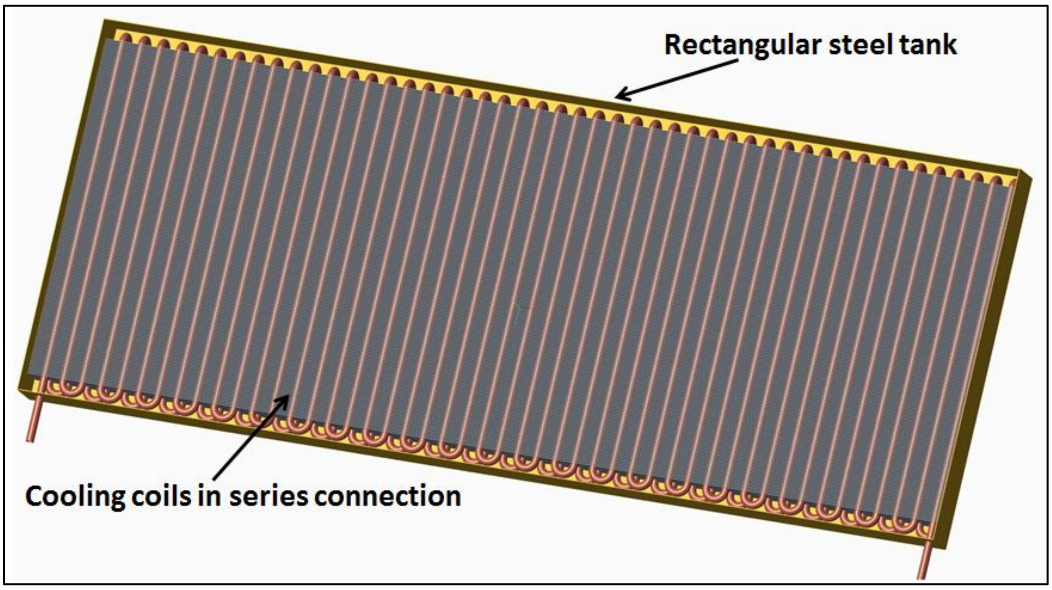


Figure 3.6 Imaginary model of storage tank during design stage

3.4.3 Fabrication of TES system

According to TES design, three storage tanks of each 25 liters capacity was fabricated using stainless steel sheets (rectangular tank/ shell) and cooling coils (finned tube heat exchanger). Figure 3.7 shows three distinct layers of storage tank such as inside steel tank, PUF (polyurethane foam) insulation layer, and outside steel supporting layer (or tank).

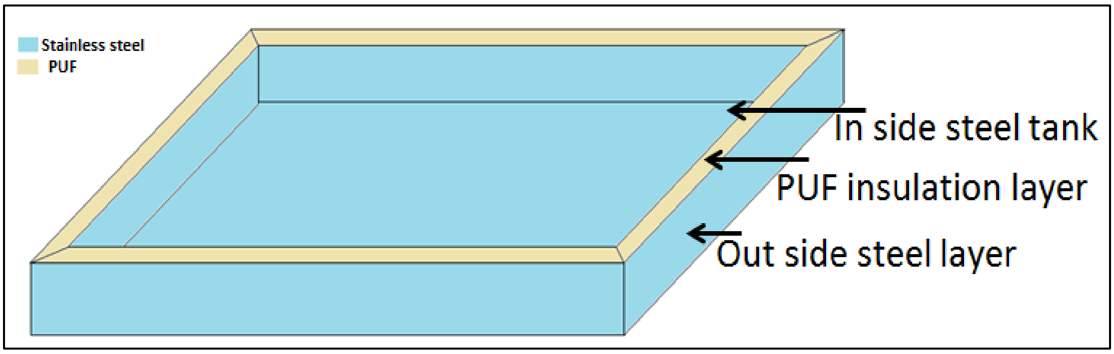


Figure 3.7 Different layers of TES tank

Each tank of size 122 × 48 × 6 cm^3 was built by using 1 mm thick stainless steel sheets. Six cooling coils horizontally mounted in tank connected in series by welded joint. An insulation of 25 mm thick PUF was wrapped around the inside steel tank to minimize the heat losses.

Stainless steel sheets are covered on the PUF insulation layer for structural support and good appearance like experimental equipment shown in figure 3.8 (A). The three storage tanks placed parallel in a stainless steel structure to minimize the space requirement and different experimental configurations like parallel or series configurations of thermal storage tanks. Figure 3.8 (B) shows the thermal energy storage system after completion of fabrication process.

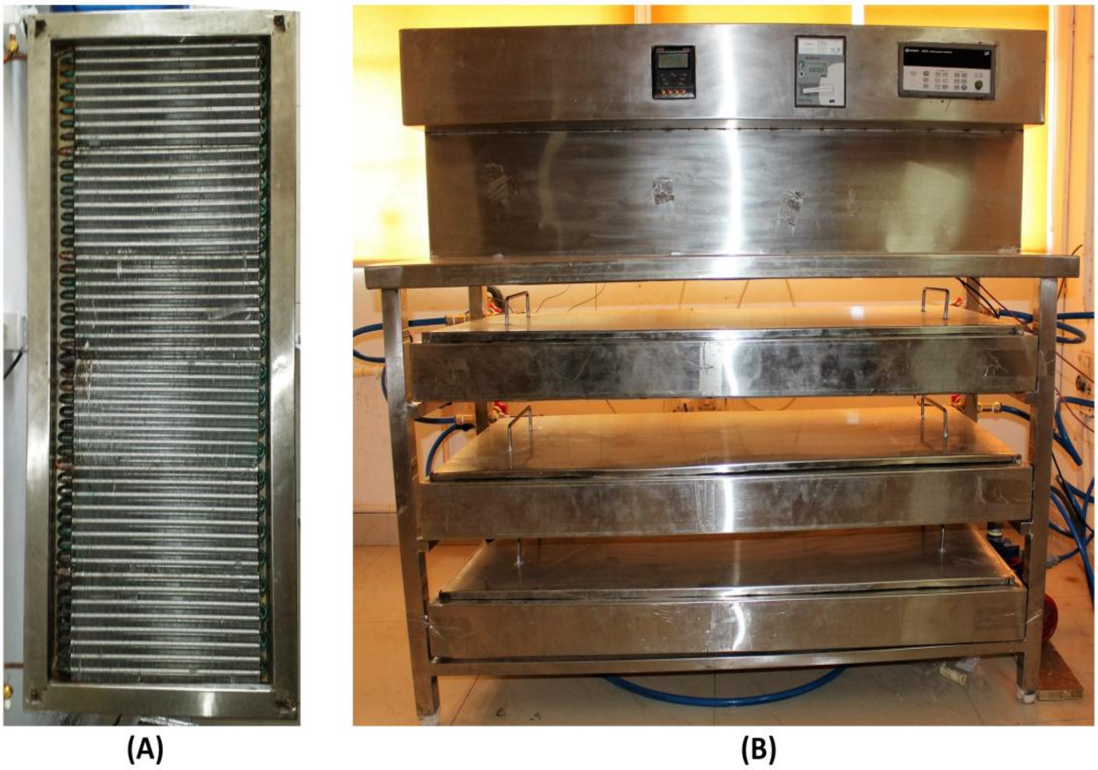


Figure 3.8 (A) Storage tank (heat exchanger), (B) TES system

3.5 Experimental facility

The fabricated TES system was installed in the experimental room and was integrated with existing PRCS and chiller by using both CPVC and PU pipes and its fittings to perform experimental study. Figure 3.9 shows the complete experimental setup. The experimental setup consists of PRCS, TES system, chiller, water circulation pumps, piping connections and flow meter. All components of experimental setup are discussed in detail in following sections.

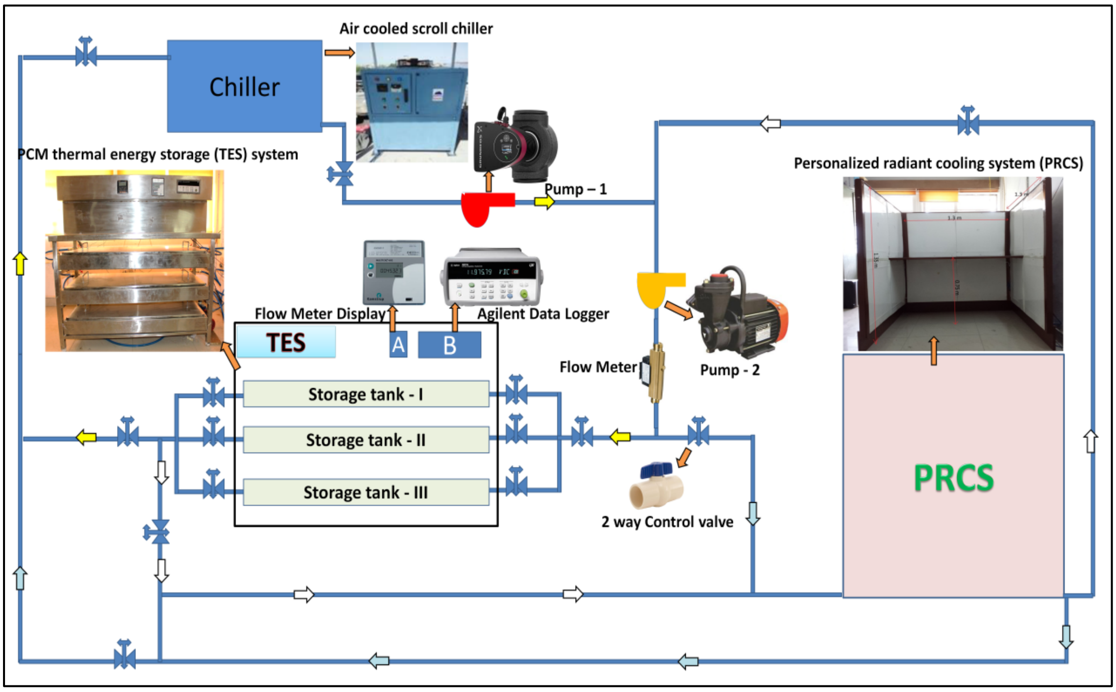


Figure 3.9 Layout of experimental facility

3.5.1 Chiller

An air cooled vapor compression type chiller of 4 TR cooling capacity equipped with scroll compressor and having 3 COP was used to supply chiller water (HTF) to TES system and PRCS for energy storage during night time and for providing cooling energy respectively.

3.5.2 Personalized radiant cooling system (PRCS)

PRCS is a type of personalized conditioning system which works on the principle of radiant cooling system. PRCS aims to create micro-climate zone around the vicinity of occupant instead of cooling entire space. It provides thermally comfortable environment to the occupant between 24°C and 27°C when chilled water supply temperature range from 15°C to 21°C. Thermal sensation of the occupant can be increased (feel better) by increasing air movement around the occupant.

This PRCS was developed by using 12 radiant panels (aluminum) supported by wooden structure. Radiant panels were connected in series (P_1 – P_6 one series connection & P_7 – P_{12} another connection, shown in figure) by using PU pipes to ensure sufficient flow to each panel. An insulation of 9 mm thick nitrile rubber applied between radiant panel and wooden structure to minimize heat losses. Figure 3.10 shows the schematic of radiant panel and PRCS.

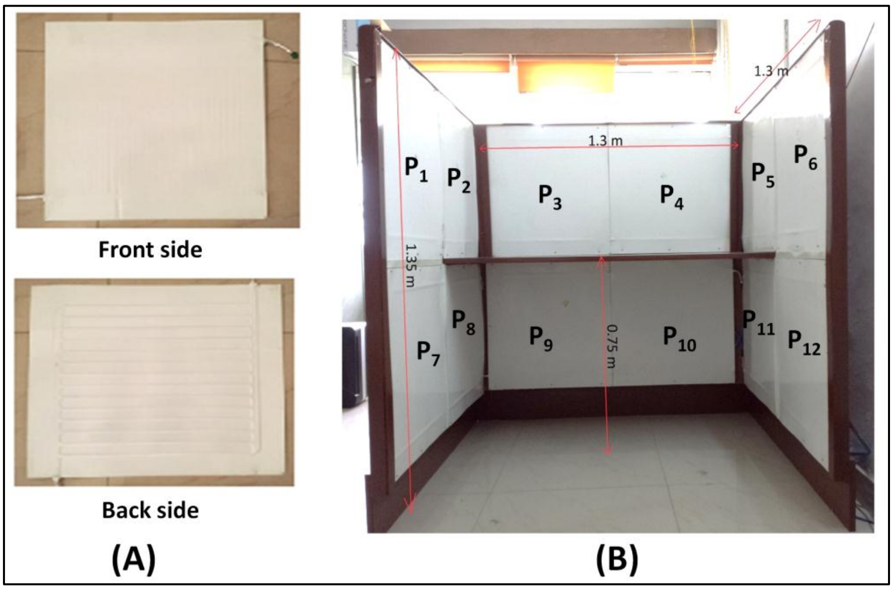


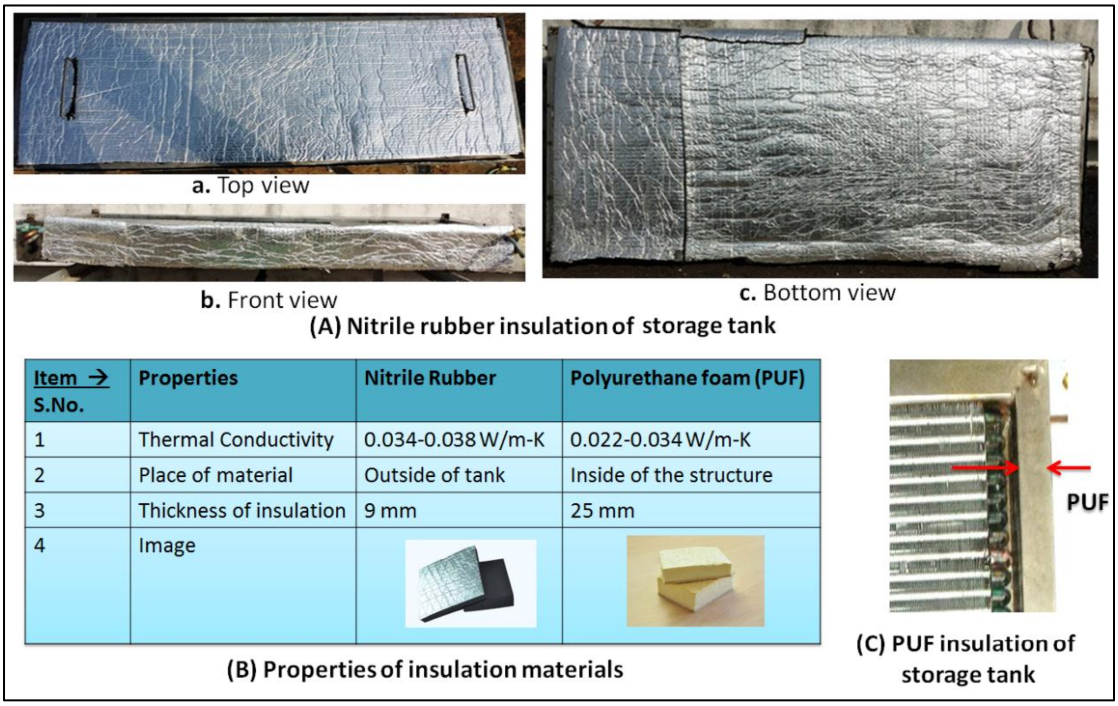
Figure 3.10 (A) Radiant panel, (B) schematic of PRCS

3.5.3 Water (HTF) circulation pumps

Two circulation pumps were used to circulate water in the flow loops of experimental setup. Pump–1, it circulates the chilled water from chiller to various experimental rooms in the 2nd floor of building, and it also supply the chilled water to personalized radiant cooling lab (experimental room). Pump–2 mainly to circulate the water inside the experimental room, such as circulation of water between TES system and chiller i.e. taking water from main flow line and flows inside the TES system and send back to main flow return line, water circulation between PRCS and chiller, and water distribution between PRCS and TES system. Depending on the flow requirement of other experimental rooms in building operational strategies of pumps were changed i.e. operate single pump (pump–1 or pump–2) or run both the pumps to perform the experimental study.

3.5.4 TES system

The TES system integrated with existing PRCS and chiller in such a way that the three storage tanks can be charge or discharge in series combination or parallel combination using control valves at entry and exit of the HTF in each storage tank. These thermal storage tanks again insulated with 9 mm thick nitrile rubber to minimize further heat loss from storage tanks. Figure 3.11 shows the complete insulation details of TES system.



Item → S.No.	Properties	Nitrile Rubber	Polyurethane foam (PUF)
1	Thermal Conductivity	0.034-0.038 W/m-K	0.022-0.034 W/m-K
2	Place of material	Outside of tank	Inside of the structure
3	Thickness of insulation	9 mm	25 mm
4	Image		

Figure 3.11 Insulation of thermal storage tank and properties of insulating materials

3.5.5 Pipes and pipe fittings

Both CPVC pipes and PU pipes and its fittings were used to integrate the complete experimental setup. PU pipes were used to connect PRCS and TES system due to its flexibility and durability for different temperature range. CPVC pipes were used to connect main chilled water flow line (standard to all experimental rooms) and TES system in experimental room i.e. both, from supply chilled water main flow line to PRCS and TES connections, and from PRCS and TES connections to return chilled water flow line. Two-way ball valves were used in experimental set up to control and divert the flow between different flow loops like charging loop, discharging loop and direct PRCS loop.

3.5.6 Tower fan

Tower fan is a simple blower which provides air at very low speed without consuming much power. It was used to create air movement near to occupant from the radiant cooling system.

3.5.7 Dehumidifier

Radiant systems cannot cater latent load, so a dehumidifier is used for handling latent load. It reduces the level of humidity of surrounding without adding or removing sensible heat. It can control the humidity level in between 40% to 80%. The effective temperature range of the system is 5-37°C, and air flow rate is 120 m^3 per hour.

3.5.8 Flow meter

A BTU meter used to measure water flow rate in the system. It measures the thermal energy of the system by measuring flow rate of HTF and the change in its temperature (ΔT) between inlet and outlet of system. But in this experimental study only flow rate measured through this BTU meter. Multical–402–energy meter of kamstrap was used, it measures flow rate from 0.6 – 15 m^3/h and temperature 2°C – 50°C with an accuracy of ± 1.5%.

3.5.9 Data logger

A data logger is an electronic device that records data over time via external instruments and sensors. Agilent data logger was used in this experimental study for data acquisition. All temperature sensors (thermocouples and RTDs) were coupled with data logger for continuous measurement of temperature values.

3.6 Instrumentation

In this experimental study, different sensors were used to measure air temperature, water temperature, PCM temperature and indoor environmental variables. Details of various sensors used in experiment and calibration of sensors explained in next section.

3.6.1 Temperature measuring sensors

K–type thermocouples and RTDs (PT–100) were used to measure temperature in this experimental study. K–type thermocouples were used to measure the air temperature and wall temperature inside the experimental room, PCM temperature inside the TES system, and PRCS radiant panel temperature. RTD (PT–100) probe type sensors were used to measure the HTF (water) inlet and outlet temperatures at various locations of experimental setup. Total 42 thermocouples and 5 RTDs were used in this experimental study for accurate measurement of temperature.

3.6.2 Calibration of sensors

Before installation of sensors, they were calibrated by using a thermal calibrator. Fluke Calibration 1586A super – DAQ temperature scanner was used to calibrate the sensors. Figure 3.12 shows the calibration of sensors and various components of thermal calibrator.

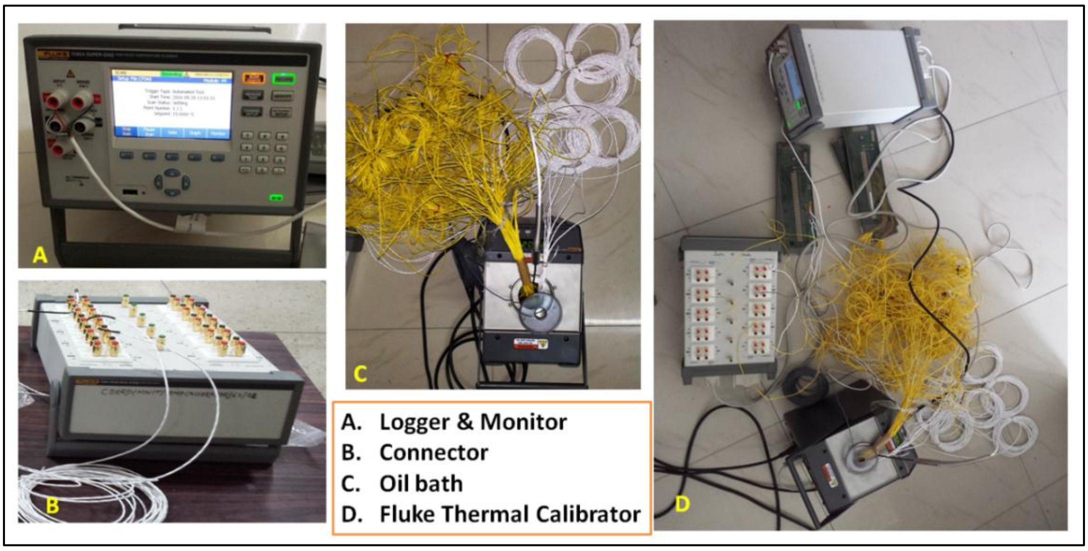


Figure 3.12 Calibration of sensors using thermal calibrator

Calibration of sensors was done at eight different temperatures i.e. 10°C, 15°C, 20°C, 25°C, 30°C, 40°C, 50°C and 60°C. A graph was plotted to compare the measured temperatures with actual temperature (master sensor reading) and all the sensors were close to ± 0.5°C accuracy. Calibration result of selected temperature sensors was shown in the figure 3.14 and figure 3.15, because of large number of sensors and calibration set points, particular sensors (shown in figure 3.13) and appropriate calibration set points (20°C and 15°C) only; where thermocouple 1, thermocouple 2, and thermocouple 3 are K–type thermocouples at different lengths i.e. 3 m, 4 m, and 5 m respectively.

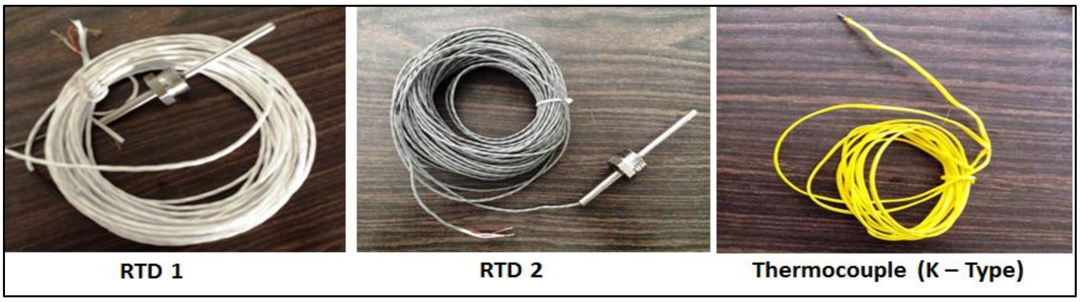


Figure 3.13 Various temperature sensors used in experimental study

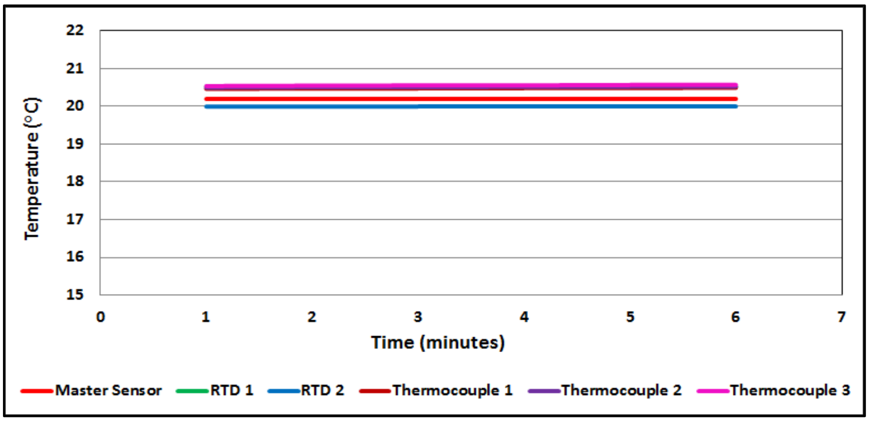


Figure 3.14 Calibration result of various temperature sensors at 20°C

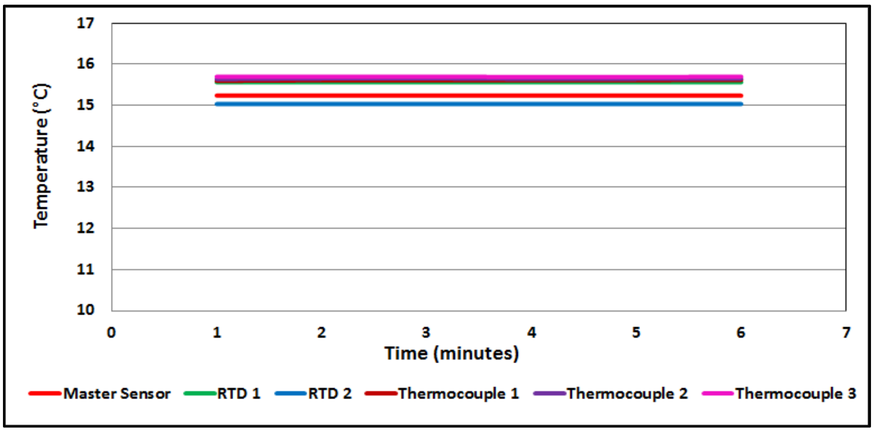


Figure 3.15 Calibration result of various temperature sensors at 15°C

3.6.3 Installation of sensors

All temperature sensors were placed in room, walls, flow loops, inside TES system, and near to personalized radiant cooling system to measure temperature at different locations. Figure 3.16 shows the location of the temperature sensors in experimental setup.

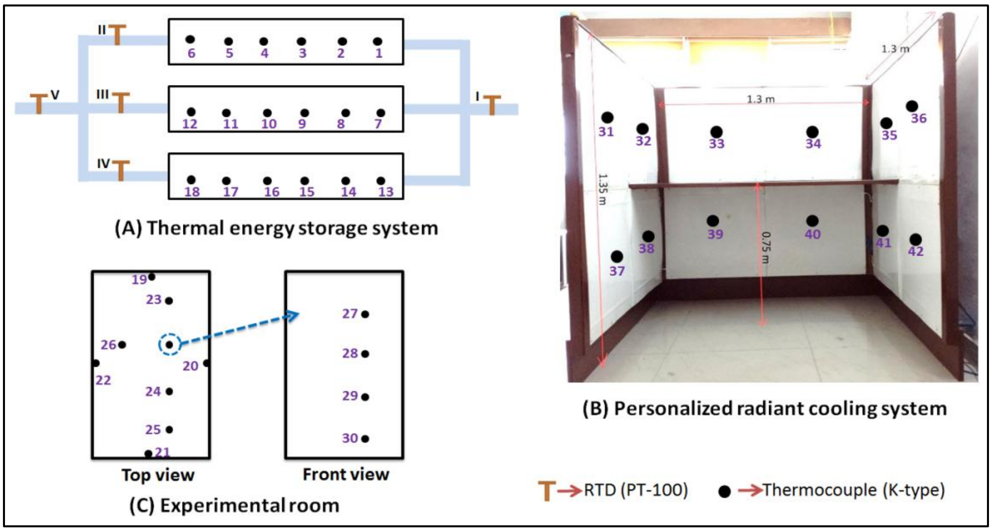


Figure 3.16 Installation of various sensors in experimental room

18 Thermocouples (1–18) were placed in TES tanks to measure the PCM temperature, 4 thermocouples (19–22) were placed on inside surface of walls, 4 thermocouples (23–26) were placed in room to measure air temperature, 4 thermocouples (27–30) placed near to occupant to measure vertical temperature difference inside PRCS, 12 thermocouples (31–42) attached to radiant panels to measure surface temperature, and 5 RTDs (I–V) were placed in fluid flow pipes to measure HTF temperature at various locations of flow loop. Thermocouples inside the room and near to occupant to measure air temperature at different locations placed as per ASHRAE standard–55.

3.6.4 Instruments used to measure thermal environment variables

Testo–480 high-end ventilation and air conditioning measuring instrument setup was used to measure thermal environmental variables such as relative humidity, air temperature, globe temperature, air velocity, and air quality. Figure 3.17 shows the different components of testo–480 setup. The instruments chosen for the study met the accuracy and response time as per the requirement of ASHRAE Standard–55 and ISO 7730. These measuring sensors and probes were mounted on tripod at a height of 1.1 m from floor level; measurements were recorded after showing steady readings.

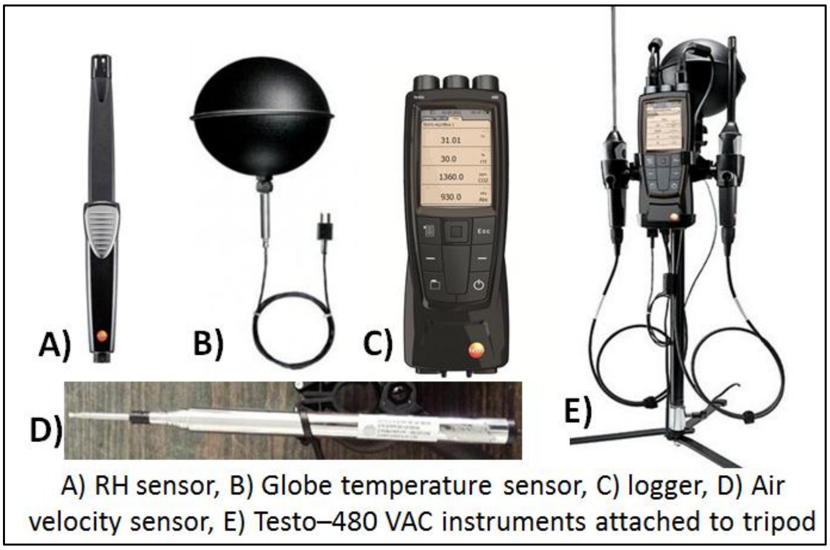


Figure 3.17 Testo–480 instrument setup

3.7 Design of experiments (DOE)

The DOE is a method to determine the relationship between factors affecting a process and the output of that process. It deals with planning, conducting, analyzing, and interpreting controlled tests to evaluate the factors that control the value of parameter or group of parameters. This experimental design involves the selection of input variables and operational time based on the normal output conditions of experimental study i.e. better thermal performance and enhancement in energy savings of overall system.

3.7.1 Experimentation for performance analysis of PRCS operated with TES

For the investigation of performance of PRCS integrated with PCM thermal energy storage following operations charging operation of TES system, discharging process of TES and operation of PRCS during discharging operation of TES system should perform sequentially.

- **Charging operation of TES system**

In order to utilize low ambient atmospheric conditions and low electricity rates, the charging process of TES system carried out in night time normally between 11.00pm and 5.00am. The charging of TES mainly depends on two parameters– HTF inlet temperature and HTF flow rate. Chilled water from thermostat controlled air-cooled chiller used as HTF to charge TES system i.e. storing of energy in PCM. From the literature, HTF inlet temperature significantly influences the charging operation of TES system than HTF flow rate. HTF flow rate in this charging operation depends on duration of charging process, uniform charging of storage tank, and time period of constant temperature chilled water from chiller (like 50minutes or 1 hour), since single point location of thermostat in a 250 liters chilled water tank of chiller, automatic on/off operation of chiller after sensing of desired set point temperature and tolerance of set point such as 2°C. Therefore the optimum input variables of HTF depending on the above constraints for charging of TES system are 15°C HTF supply temperature lower than PCM melting temperature (21°C), and HTF flow rate is 7 kg/min.

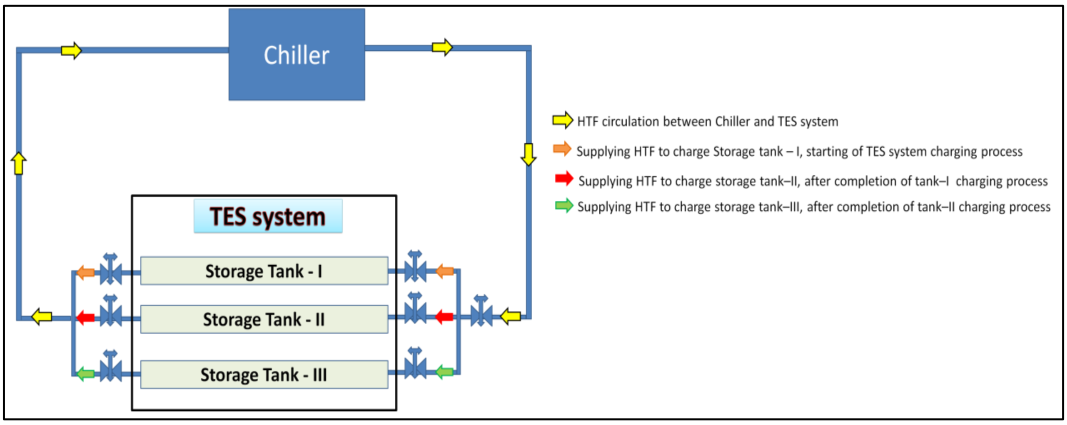


Figure 3.18 line diagram for Charging of TES system

During charging process HTF initially supplied to storage tank–I shown in figure 3.18 to charge it completely. The completion of storage tank indicated by the inlet and outlet HTF temperature difference, this difference less than 0.5°C hence the energy supply to the PCM storage medium became very less and the charging process of storage tank completed. Similarly charging of storage tank–II will start after complete charging of storage tank–I and then charging of storage tank–III start after complete charging of storage tank–II. The charging process of the TES system is said to be completed after complete charging of three storage tanks.

- **Discharging operation of TES system**

In order to utilize the stored energy in TES system and to reduce operational cost of the PRCS by reducing the peak load demand of system, TES system discharging operation carried out in day time normally between 2.00pm and 5.00pm. The discharging operation mainly depends on energy consumer i.e. PRCS and its limiting conditions such as minimum flow rate and maximum supply HTF temperature. The discharged cooling energy is supplying to PRCS for its efficient operation in typical daytime. From the experimental analysis of conventional PRCS (Ravi Garg 2016) the minimum flow rate required for PRCS operation is 3 kg/min, so the HTF flow rate during discharging is varies between 3 and 3.5 kg/min due to the manual operation of control valves. During discharging process HTF is circulated between TES system and PRCS only shown in figure 3.19.

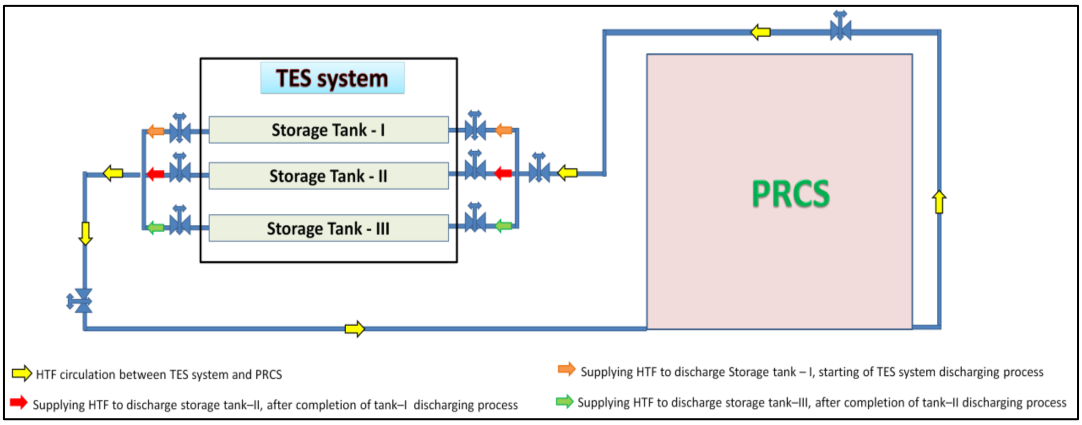


Figure 3.19 Line diagram of TES system discharging process

High-temperature HTF (25–28°C) is supplied to storage tank, and the outlet of the low-temperature HTF is supplied to PRCS, high-temperature HTF from PRCS is re–circulated to storage tank–I until complete discharge of storage tank–I. The outlet low-temperature HTF from TES system is indication of completion of discharging process of storage tank. The outlet low-temperature HTF is greater than 21°C; it means that discharging process of the particular storage tank is completed. Since supplying of high-temperature HTF to PRCS will not provide sufficient cooling to the occupant. Similarly, the discharging process of storage tank–II and storage tank–III will continue one after another i.e. after complete discharge of storage tank–I, discharging of storage tank–II will start. The discharging process of the TES system is said to be completed after full discharge of three storage tanks.

- **Supplying cooling energy to PRCS**

To maintain thermally comfortable environment for the occupant, cooling energy supplied to the PRCS in the form HTF (chilled water) from energy source either chiller or TES system. The HTF temperature should be between 15°C and 21°C to supply sufficient cooling energy to PRCS (Ravi Garg 2016). In order to know the performance of PRCS when it operated through TES system, discharged energy from TES system i.e. outlet low-temperature HTF is supplied to PRCS at constant flow rate and the return HTF from PRCS supplying back to TES system.

The operational hours of the PRCS are 8 hours from 9.00am to 5.00pm (regular working hours). From 9.00am to 2.00pm cooling energy supplied from chiller and from 2.00pm cooling energy supplied from TES system until complete discharge of the TES system and the remaining time PRCS operated by the chiller.

All the experiments were conducted in month October 2016. For this duration, ambient temperature varies between 25°C and 36°C (25°C – 30°C, night time; 30°C – 36°C, daytime). Repeated number of experiments was performed for accurate analysis of complete system.

3.7.2 Experimentation for corrosive analysis of copper material in PCM

During the experiments the change of PCM colour from light yellow to green was observed. After detailed observation and discussion with PCM manufacturer, it was finalized that the copper material (cooling coil) in the storage tank was reacting with PCM (OM–21). Hence the change of PCM colour happened in TES system. Therefore the copper material is showing corrosive nature in PCM (OM–21) storage media. This is a unique problem because of copper tube/ material for heat exchanger with this PCM not used, and there is no literature to address this particular issue. Regular corrosive resistance techniques such as zinc coating, Nickel coating, etc. can be a solution to stop the corrosion of copper tube. These methods were also suggested by the PCM manufacturer on the basis of related literature.

Nickel coating on copper material can be a solution to stop the corrosion in PCM because nickel material tested in PCM bath by the manufacturer and nickel was not corroded with PCM (OM–21). To test the corrosive nature of nickel coated copper material with PCM experiments were conducted in simple test PCM bath with two copper strips one is simple copper strip, and another is nickel coated copper strip. The nickel coating on copper strip was done with dip-coating process, and the thickness of the nickel layer is approximately 4 microns. The test samples and PCM bath shown in figure 3.20. The test samples was planned to keep in PCM baths over 15 days for detailed study of corrosive nature. These experiments were conducted in the month February 2017.

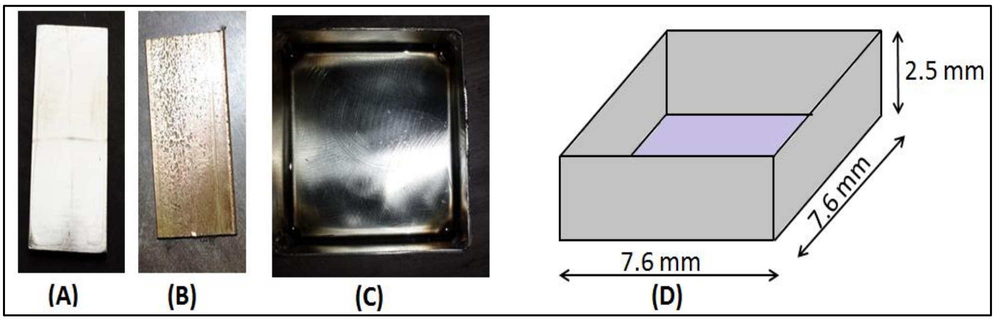


Figure 3.20. (A) Nickel coated copper strip, (B) Simple copper strip, (C) PCM test bath, (D) Schematic view of PCM test bath

3.8 Experimental procedure

To study the performance of complete system various experiments were performed. The schematic diagram of the whole experimental procedure is shown in figure 3.21 that includes two primary circuits– charging circuit and discharging circuit. The charging circuit consists of chiller, circulation pump and PCM thermal storage system. The discharging circuit comprises of PRCS, circulation pump, PCM thermal storage system.

The complete experimental procedure consists of charging process and discharging process of TES system. During charging process the chilled water (HTF) from the chiller at roof top of experimental room was supplied to the TES system in charging loop to solidify the PCM storage media with the help of charging circulation pump.

The charging of TES system started at 12.00am with the chilled water flow rate of 7 kg/min and chilled water supply temperature setpoint is 15°C. Approximately 2 hours and 30 minutes time required to complete charging process of TES system. After completion of the charging process, the uniform temperature of the PCM in TES system achieved 19°C after stability or some time.

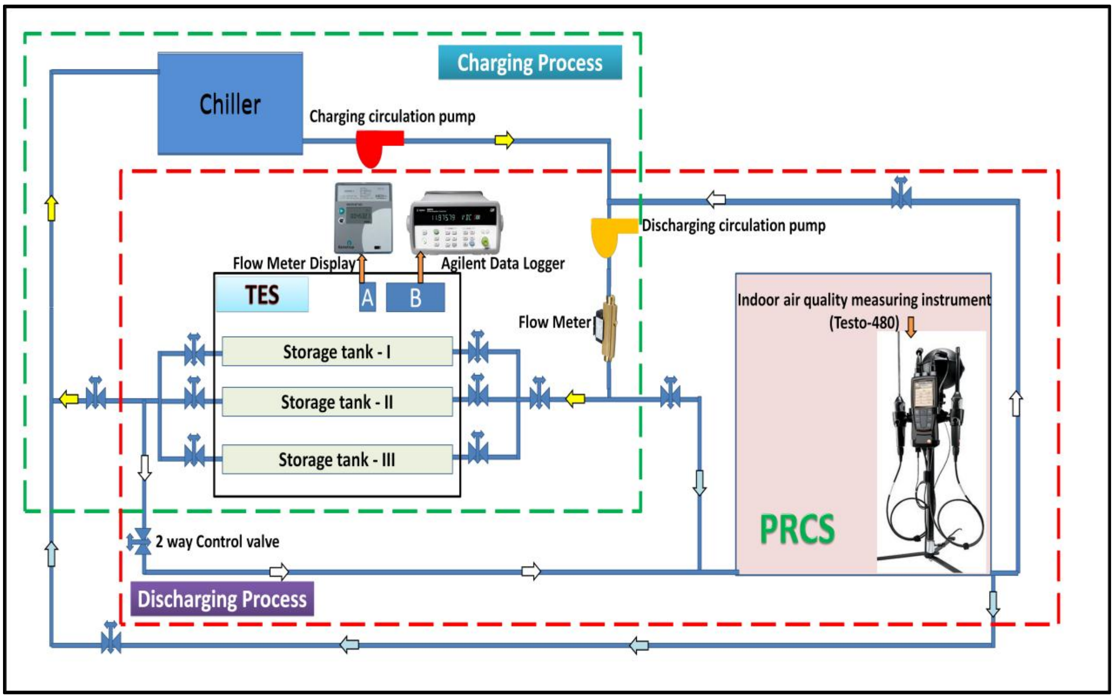


Figure 3.21 Schematic diagram of the experimental procedure

During discharging process the HTF circulated between TES system and PRCS by using discharging circulation pump in discharging loop to use stored energy. The discharging of TES system started at 2.00pm with HTF flow rate 3.36 kg/min and HTF initial temperature at inlet of the TES system is 25°C, low-temperature HTF between 20°C and 22°C from outlet of TES system supplied to PRCS for providing the conditioned environment to occupant. The high-temperature HTF from outlet of PRCS is re–circulated to TES system and the process continues till complete discharge of the TES system. Approximately 2 hours and 15 minutes required to discharge whole TES system. Here the TES system operated PRCS by supplying stored cooling energy for the efficient operation of complete system. The respective control valves were used to change the flow between two circuits and within the circuit i.e. between storage tanks.

Different temperature sensors thermocouples and RTDs were installed in experimental set up for the accurate measurement of PCM temperature, air temperature, HTF temperature, etc. and all the sensors were connected with data acquisition system to record the all temperature readings at every one–minute time interval. Testo–480 ventilation and air quality instruments were used to measure indoor environmental variables such as relative humidity, air velocity, globe temperature, etc. and all values were recorded in data logger at every one-minute interval. The measured data was used for the analysis of the performance of the complete system.

3.9 Measurements and observations

Measurement plays vital role in the experimental analysis and is important step that what to measure, how to measure, and when to measure. To investigate the performance of complete system, various parameters were measured, and some are calculated on the basis of measured values.

3.9.1 Measured parameters

During the experimental study, various parameters were measured to study the thermal behavior of TES system, thermal comfort study of PRCS, and the energy consumption of complete system. All the measurements were recorded by using Agilent data logger.

- HTF inlet and outlet temperature during charging and discharging operation of TES system
- HTF flow rate
- PCM temperature at different location of each storage tank
- Room air temperature at various heights and directions
- PRCS environmental variables (globe temperature, Relative Humidity, air velocity, air temperature)
- Panel surface temperature

3.9.2 Calculated parameters

Energy supplied to TES system:

During charging process the amount of energy supplied to TES system was calculated using measured mass HTF flow rate ($\dot{m}_{ch}$), inlet and outlet HTF temperature difference ($T_{ch,out} - T_{ch,in}$), and charging time (t_{ch}). The energy supplied to the TES system,

$$E_{ch} = \mathring{m}_{ch} \times C_p \times (T_{ch,out} - T_{ch,in}) \times t_{ch}$$

Energy utilized from TES system:

During discharging process the amount of stored energy utilized from TES system was calculated using measured discharging flow rate (m_d), inlet and outlet HTF temperature difference ($T_{ds,out} - T_{ds,in}$), and discharging time (t_{ds}). The energy utilized from TES system,

$$E_{ds} = \mathring{m}_{ds} \times C_p \times (T_{ds,out} - T_{ds,in}) \times t_{ds}$$

Cyclic efficiency of the TES system:

The cyclic efficiency of the TES system (η_{cyclic}) is simple product of charging efficiency (η_{ch}) and discharging efficiency (η_{ds}).

$$\eta_{cyclic} = \eta_{ch} \times \eta_{ds}$$

Where, $\eta_{ch} = \dfrac{\text{Energy stored in TES system}}{\text{Energy supplied to TES system}}$

$$\eta_{ds} = \frac{\text{Energy utilized from TES system}}{\text{Energy stored in TES system}}$$

Then, $\eta_{cyclic} = \dfrac{\text{Energy utilized from TES system}}{\text{Energy supplied to TES system}} = \dfrac{\mathring{m}_{ds} \times C_p \times (T_{ds,out} - T_{ds,in}) \times t_{ds}}{\mathring{m}_{ch} \times C_p \times (T_{ch,out} - T_{ch,in}) \times t_{ch}}$

Power consumption:

Electrical chiller is only power consuming device in the experimental study. The circulation pump power consumption was neglected. Electric power consumption was calculated by using thermal energy consumption and COP of the chiller. Power consumption of the chiller,

$$P = \frac{\text{Thermal energy consumption}}{\text{COP of chiller}}$$

Operative Temperature (OT):

Operative temperature provides satisfactory thermal environmental conditions in terms of the combinations of air temperature and Mean Radiant Temperature that people find thermally acceptable. It is calculate by the average of MRT and DBT weighted by their respective transfer coefficients, i.e. the following expression

$$OT = \frac{(h_r \times MRT) + (h_c \times DBT)}{h_r + h_c}$$

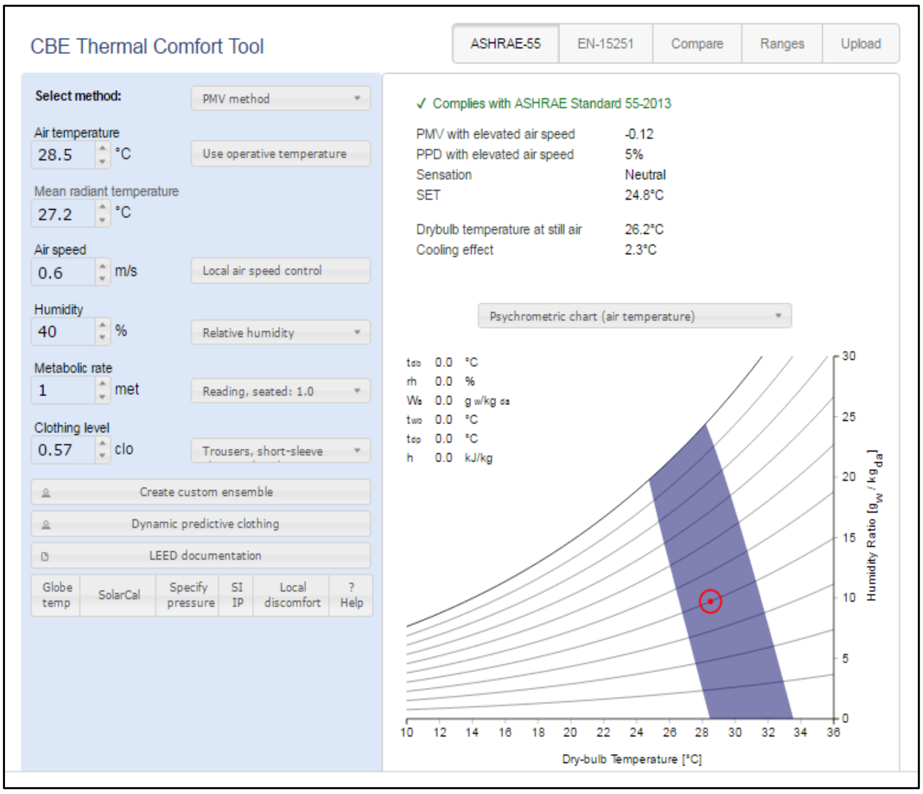
Where h_c and h_r are convection and radiation heat transfer coefficients respectively.

A simplified formula suggested by the ASHRAE to finding the operative temperature and it gives acceptable results,

$$OT = \frac{MRT + DBT}{2}$$

Standard Effective Temperature (SET):

SET is the one of the effective parameter to study thermal comfort. SET considered both environmental and personal factors. In this experimental study, SET was calculated by using CBE Thermal Comfort Tool (http://comfort.cbe.berkeley.edu/). This tool has six input parameters which are air temperature, Mean Radiant Temperature, air speed, Humidity, Metabolism rate and Clothing level. All the input parameters were measured during experiment except MRT, but this MRT also calculated from this thermal comfort tool by using globe temperature. Figure 3.22 shows the sample of the CBE thermal comfort tool. SET and Thermal sensation can be obtained as an output from this tool.



CBE Thermal Comfort Tool

Select method: PMV method

Air temperature 28.5 °C

Mean radiant temperature 27.2 °C

Air speed 0.6 m/s

Humidity 40 % (Relative humidity)

Metabolic rate 1 met (Reading, seated: 1.0)

Clothing level 0.57 clo (Trousers, short-sleeve)

✓ Complies with ASHRAE Standard 55-2013

PMV with elevated air speed	-0.12
PPD with elevated air speed	5%
Sensation	Neutral
SET	24.8°C
Drybulb temperature at still air	26.2°C
Cooling effect	2.3°C

Psychrometric chart (air temperature)

tdb 0.0 °C
rh 0.0 %
Wa 0.0 g w/kg da
twb 0.0 °C
tdp 0.0 °C
h 0.0 kJ/kg

Figure 3.22 Sample calculation of CBE thermal comfort tool (http://comfort.cbe.berkeley.edu/)

3.10 Challenges faced during experimental study

Different problems were occurred at various stages of the experimental study. All the problems were listed as follows

3.10.1 During installation of the system

The control valves fitted on the TES tanks for the circulation of HTF inside TES system have been specified with thread size in millimeter (mm), but the fittings and assemblies available in the market were specified thread size in inches (inch) i.e. diameter of the thread. To overcome this challenge different set of connectors were used and to prevent the leakages from the connections thread locker adhesive was used.

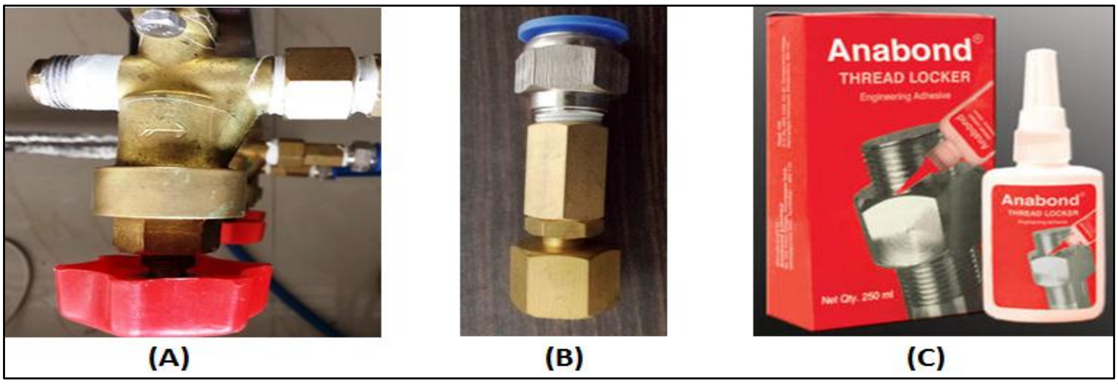


Figure 3.23 (A) Control valve of TES tank, (B) Assembly of different connectors, (C) Thread locker adhesive

3.10.2 During pressure testing of the TES system

Leakages in the cooling coil joints were found at two separate locations in a TES tank shown in figure 3.24. Leakage–1 indicates HTF leakage from copper pipe joint between two cooling coils; similarly Leakage–2 was HTF leakage from copper pipe joint between cooling coil and outlet copper pipe. The leakages in the system were rectified through welding process.

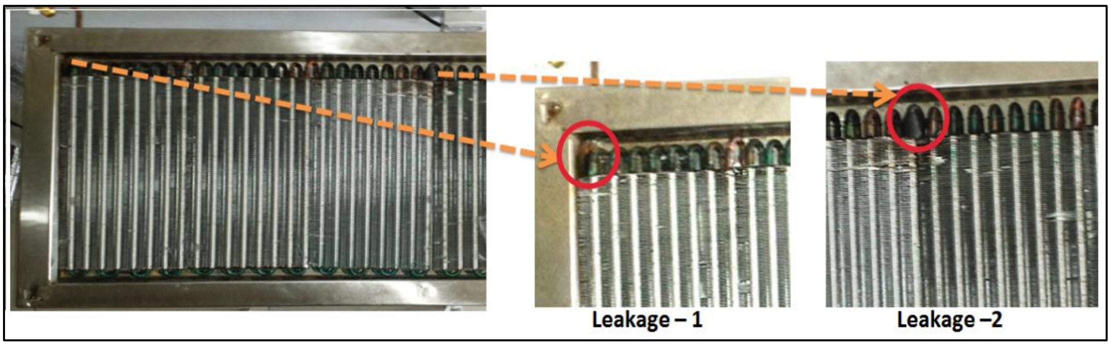


Figure 3.24 HTF leakages in a TES tank

The leakage–2 was fixed at experimental room only by using portable brazing blow torch shown in figure 3.25(A). The leakage–1 was fixed at factory location by using standard welding equipment (figure 3.25(B)) because it was not fixed by the portable torch. The leakage joint was very near to the structure of the tank which was filled with PUF insulation material. The flame from the brazing blow torch was wider, not concentrating on the leakage joint and heat highly conducting or transferd into the PUF material filled in structure, then burning of the PUF started i.e. smoke came out from the tank. Hence the tank was shifted to factory and leakage was fixed by using gas welding technique.

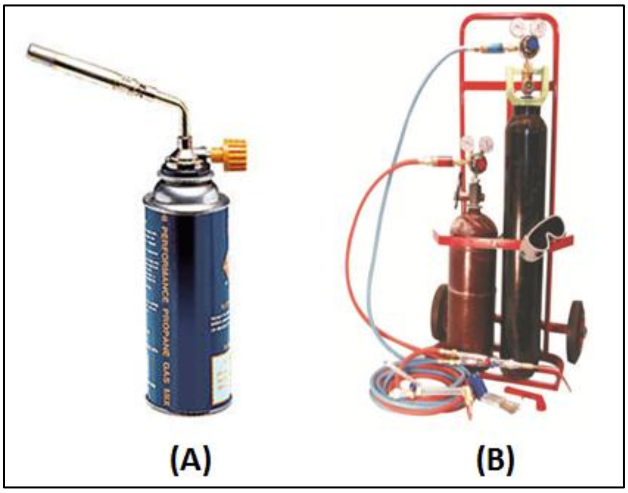


Figure 3.25 (A) Brazing blow torch, (B) Gas welding equipment

3.10.3 During nickel coating of cooling coil

Nickel coating on the copper tube will restrict the corrosion of copper with PCM (OM–21). So the nickel coating of complete cooling coil was planned by using dip coating technique. The aluminum fins on the cooling coil will completely react with nickel solution mixture present in the dip coating bath, and only copper tube will come out after the dip coating process. To overcome this challenge development of new cooling coil was planned with nickel coated copper tube and aluminum fins.

3.10.4 During new cooling coil manufacturing process

Simple copper tube which is used to make cooling coil was coated with nickel and tested for making cooling coil. Cooling coil making includes various mechanical operations such as bending, heat treatment, joining, and expansion of copper tube. During this process the nickel layer on the copper tube was removed which is not suitable for experimental study. In order to overcome this challenge copper nickel

(90/10) alloy tubes available in market were planned to use in the cooling coil manufacturing process.

The existed copper nickel (90/10) tubes were hard tubes, but for cooling loop applications soft tubes are required. For the soft tubes, it has to be order in a large quantity (minimum of 500 kg), but for the research purpose, small quantity (< 100 kg) is required. Few suppliers indicated that the semi-hard copper nickel tubes are available and these tubes can be used for cooling coil applications after heat treatment process i.e. heating and tube bending for coil making, etc. The less number of cooling coil manufacturers are in Jaipur and were not ready to help in new cooling development using semi-hard copper nickel tubes, because of manufacturing setup existed and technique helps to produce standard cooling coils with smooth copper pipe only. The cooling coil with semi hard pipe requires continuous heating equipment during mechanical operations (bending, etc.) and they are not aware of other methods.

The copper nickel pipes for cooling coil application definitely restrict the corrosion problem of standard copper tube with PCM (OM–21). Since copper nickel alloys are mainly using in marine applications, cooling coil applications. For the large capacity TES systems using PCM (OM–21) can be used cooling coils manufactured from copper nickel tubes without any corrosive problems.

4 – RESULTS AND DISCUSSION

The complete study performed on PRCS and TES system is represented in the form of two primary results – thermal analysis and energy analysis. There were various experiments conducted to analyze the performance of overall system. The results are represented for the performance analysis and corrosive analysis of copper material in PCM (OM–21).

4.1 Thermal analysis of TES system

In order to evaluate the thermal behavior of TES system, several experiments has been conducted with constant HTF flow rate and constant HTF inlet temperature. Thermal analysis of the TES system has been presented and discussed in terms of charging and discharging characteristics of TES system.

4.1.1 Charging characteristics of TES system

Following are the experimental results for the charging process with HTF supply temperature of 15°C and initial average PCM temperature inside storage tank is 25°C. Figure 5.1 shows the temperature evaluation of the HTF at the inlet and outlet of the tank and the average temperature profile of the PCM inside the storage tank during charging process at a HTF mass flow rate of 7 kg/minute.

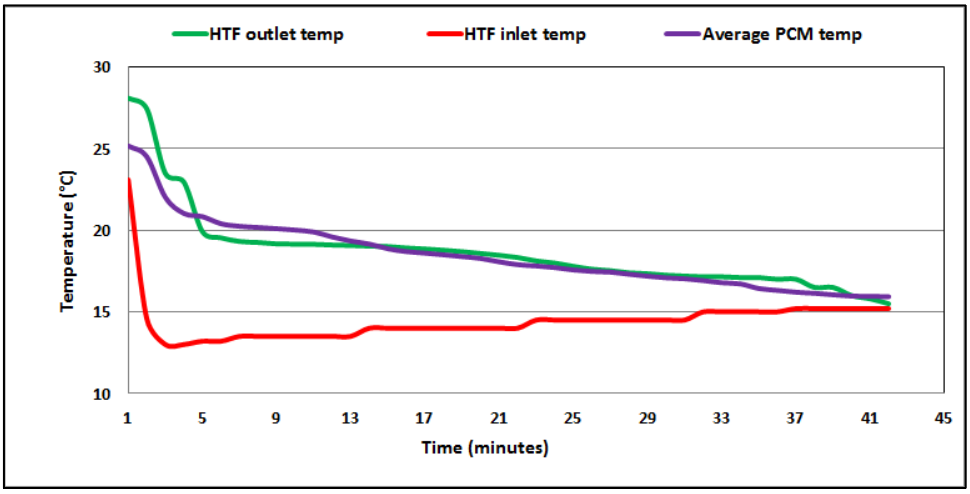


Figure 4.1 Average temperature profile of PCM inside storage tank and temperature profile of the HTF at an HTF mass flow rate of 7 kg/minute during charging process

The time recorded for the complete charging of storage tank is 42 minutes. The average PCM temperature at the end of charging process is 15.9°C (~16°C). The locations of sensors are in the middle of tank, and near to the heat exchanger tubes, so the PCM surrounding to the heat exchanger tubes is lesser temperature than PCM at distance from heat exchanger tubes. An hour after from end of charging process the PCM inside tank reached 19°C because the PCM self-adjustment of the temperature entire tank. Figure 5.2 shows the temperature variation of the PCM at different locations inside the storage tank during charging process.

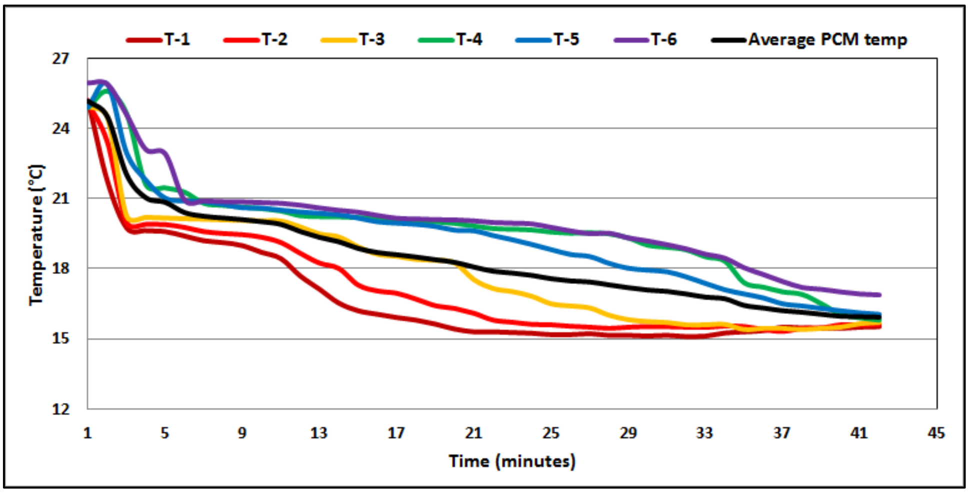


Figure 4.2 Temperature variation of PCM at various locations inside the storage tank during charging process

The PCM nearer to the inlet of the HTF in storage tank controlled by the temperature sensor, thermocouple 1 (shown in figure 3.16), named as T–1 achieved lower temperature with less time. Since the energy supplied by the HTF is received first by the PCM nearest to the inlet of HTF fluid and therefore solidification and charging process started and finished before the rest of the PCM located along the tank. The PCM near to outlet of the HTF in storage tank controlled by the temperature sensor, thermocouple 6 (shown in figure 3.16), named as T–6 had the opposite behavior for similar reason. The charging process of the single storage tank was finished in 42 minutes.

The same thermal behavior was shown by the remaining two storage tanks because of the same HTF inlet conditions, same storage capacity etc. Total 135 to 150 minutes time required to complete charging of the three storage tanks of TES system, extra charging time required in manual operation (adjustment) of control valves and keeping the constant HTF temperature in chilled water tank of chiller (temperature layers formed inside the chilled water tank; lower temperature HTF at bottom of tank and high-temperature HTF at top of the tank), this is the reason for temperature deviation in supply HTF i.e. 15 ± 2°C during charging process.

4.1.2 Discharging characteristics of TES system

Following are the experimental results for the discharging process with HTF inlet temperature between 25°C and 28°C and the initial PCM temperature between 19.5°C and 20°C. Figure 5.3 shows the temperature evaluation of the HTF at the inlet and outlet of the tank and the average temperature profile of PCM inside the tank during discharging process at a HTF mass flow rate of 3.36 kg/minute.

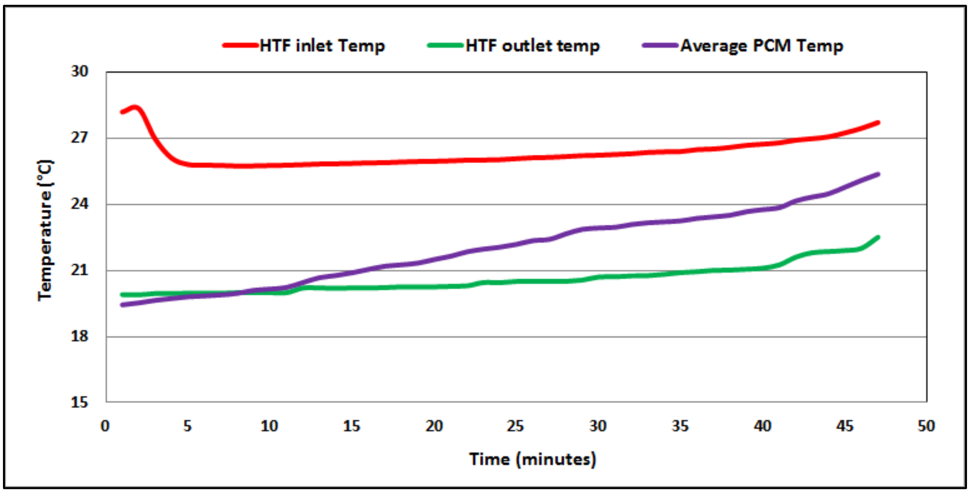


Figure 4.3 Average temperature profile of PCM inside storage tank and temperature profile of the HTF at an HTF mass flow rate of 3.36 kg/minute during discharging process

The time recorded for the complete discharge of storage tank was 47 minutes. The outlet HTF temperature at the end of discharging process was approximately 22°C. The discharged energy was supplied to PRCS (energy user) for its efficient operation. The supply HTF temperature to PRCS is limited by thermal comfort conditions of occupant and is 21°C., So the discharging of storage tank was said to be completed after higher HTF outlet temperature (i.e. >21°C). Figure 5.4 shows the temperature of the PCM at different locations inside storage tank during discharging process.

The PCM near to the inlet of the HTF inside storage tank controlled by T–1 thermocouple achieved higher temperature with less time. Since energy received by the HTF is supplied first by the PCM nearest to inlet of HTF and therefore melting and discharging of process started and finished before the rest of the PCM located along the tank. The PCM near to outlet of the HTF in storage tank controlled by T–6 thermocouple had the opposite behavior for similar reason. The single thermal energy storage tank was discharged completely in 47 minutes.

The similar thermal behavior was shown by the remaining storage tanks because of same HTF inlet conditions, same storage capacity, etc. The complete discharge of three storage tanks was done in 143 minutes and continuously supplied this discharged energy to PRCS to maintain thermally comfortable conditions to the occupant. The outlet HTF temperature range from 20°C to 22°C during discharging process was very suitable temperature range of HTF to operate PRCS effectively without significant fluctuations in the PRCS performance. The TES system (heat exchanger design) which gives outlet temperature range of 2°C approximately is very useful or economical in HVAC or heat recovery applications compared with other TES system design.

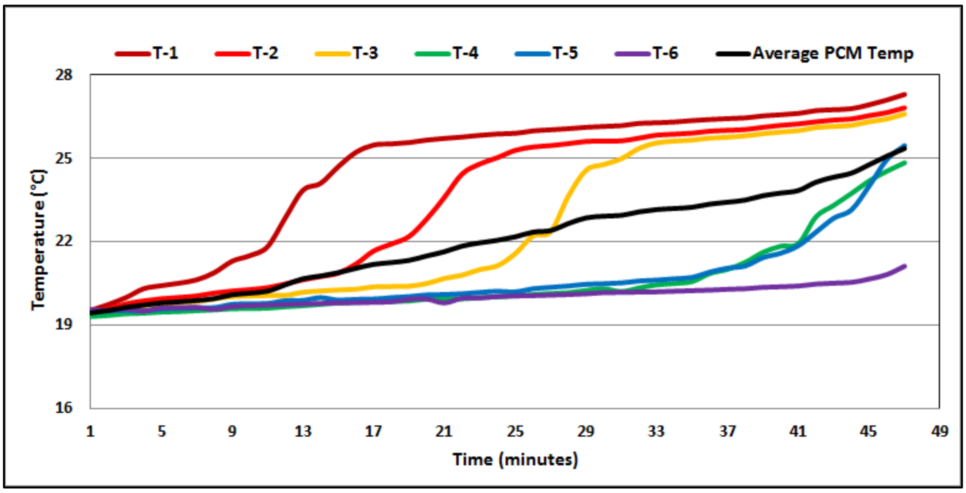


Figure 4.4 Temperature variation of PCM at different locations inside the storage tank during discharging process

4.1.3 Effectiveness of TES system

Generally, for the effectiveness calculations in TES systems average PCM temperature inside the storage tank is considered. Figure 4.1clearly indicated the average PCM temperature is lesser than outlet HTF temperature (at large number of points) during charging process i.e. actual heat transfer is more than the maximum heat transfer, it is impossible characteristic of heat transfer. Similarly, figure 4.3 indicating the average PCM temperature is higher than outlet HTF temperature during discharging process.

$$\text{Effectiveness, } \varepsilon = \frac{\text{Actual heat transfer between HTF and PCM}}{\text{Maximum possible heat transfer between HTF and PCM}}$$

$$\varepsilon_{ch} = \frac{(T_{ch,\,out} - T_{ch,\,in})}{(T_{avg,\,PCM} - T_{ch,\,in})}$$

$$\varepsilon_{ds} = \frac{(T_{ds,\,in} - T_{ds,\,out})}{(T_{ds,\,in} - T_{avg,\,PCM})}$$

So the effectiveness of TES system will be greater than one if the average PCM temperature considered in the effectiveness calculations and is theoretically not possible i.e. actual heat transfer is greater than maximum possible heat transfer.

During discharging process the outlet HTF temperature mainly depended on the PCM near to outlet of the HTF in storage tank, so the effectiveness of the TES system was calculated by considering the PCM temperature as T–6. The figure 4.5 shows the effectiveness of the storage system (heat exchanger) and varies from 0.96 to 0.79; average effectiveness is 0.91 (> 90%). Therefore the heat exchanger design is effectively worked as TES system with high effectiveness.

$$\varepsilon_{ds} = \frac{(T_{ds,\,in} - T_{ds,\,out})}{(T_{ds,\,in} - (T\text{–}6))}$$

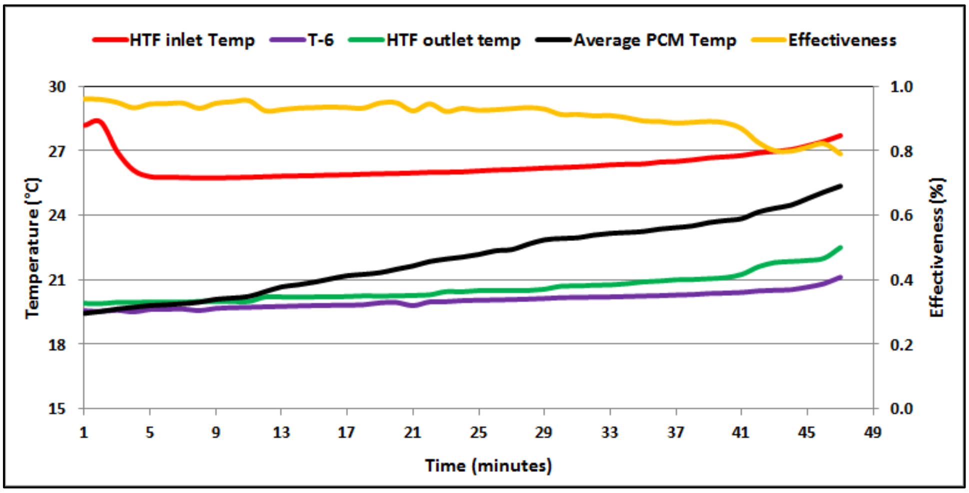


Figure 4.5 Effectiveness of TES system during discharging process

4.1.4 Thermal comfort analysis of PRCS

In order to study the thermal comfort conditions of PRCS operated with TES system, several experiments were conducted with supplying HTF temperature range between 20°C and 22°C at constant HTF flow rate. Thermal comfort analysis was explained with the help of SET maintained by PRCS.

During the discharging process of TES system, the low-temperature outlet HTF supplied to the PRCS for the maintenance of the comfort environment to the occupant and the return water from PRCS was re-circulated to the TES system for producing the low-temperature HTF. During the experiment indoor environmental parameters air temperature, air velocity, globe temperature, relative humidity, etc. measured and

MRT, SET, and OT were calculated. A graph has been plotted between time and temperature for various indoor environmental parameters shown in figure 4.6.

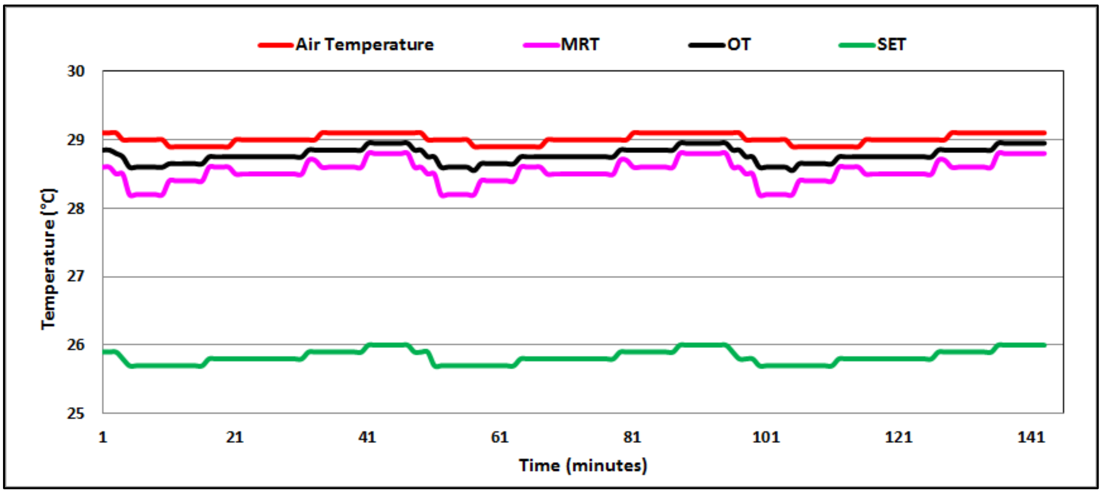


Figure 4.6 Temperature variation of various thermal comfort parameters of PRCS

The PRCS maintained thermally comfortable environment to the occupant when energy was supplied from TES system. The low-temperature outlet HTF between 20°C and 22°C continuously provided cooling energy to the PRCS over 143 minutes. It has been observed from the figure that the SET, OT, etc. shown similar trend in first 47 minutes, from 48 to 95 minutes, and from 96 to 143 minutes because of three similar storage tanks of TES system and the second storage tank is started after complete discharge of first storage tank. Initial 47 minutes the SET varies between 25.7°C and 26°C because the supplied HTF temperature (outlet low-temperature HTF during discharging process) ranging between 20°C and 22°C from the storage tank –I. Similarly from 48 to 95 minutes the energy supplied from storage tank–II and from 96 to 143 minutes the energy supplied from storage tank–III.

The difference between MRT and air temperature was found to be less than 1°C, which indicates the better thermal comfort within the microclimate zone around the occupant. The occupant wearing normal office clothing with insulation of 0.57 CLO (0.50 – 0.60) feels neutral thermal sensation with the above operating temperatures. During the experiments, the required air velocity and relative humidity was maintained by using tower fan and dehumidifier respectively. Table 4-1 explains the indoor environmental parameters of micro climate zone created by PRCS. It was observed that the thermal environment in the vicinity of the occupant was well within the thermal comfort range i.e. SET between 23.5°C and 26°C. Therefore the PRCS effectively maintained thermally comfortable environment to the occupant when it was operated with TES system.

Table 4-1: Indoor environmental variables surrounding to the occupant

Indoor environmental variables	Value
Air Velocity	0.6 m/s
Relative Humidity	40 %
Air Temperature	28.6°C – 29.1°C
Mean Radiant Temperature (MRT)	28.2°C – 28.8°C
Operative Temperature (OT)	28.6°C – 28.95°C
Standard Effective Temperature (SET)	27.5°C – 26°C

4.2 Energy analysis

Energy consumption analysis has been carried out for overall system i.e. PRCS integrated with TES system. Energy consumption of the conventional PRCS was also calculated to compare energy consumption of PRCS integrated with TES system. Energy analysis of the overall system represented in two parts – thermal energy consumption and operational cost (power cost).

4.2.1 Thermal energy consumption

Thermal energy was measured by using basic energy equation and was converted into electric energy taking the COP of the chiller. Assuming the COP of the chiller during night time is 3.5 and during day time is 3.

❖ Energy supplied during charging process of TES system:

The energy supplied from the chiller to the TES system to store the energy during night time for later use.

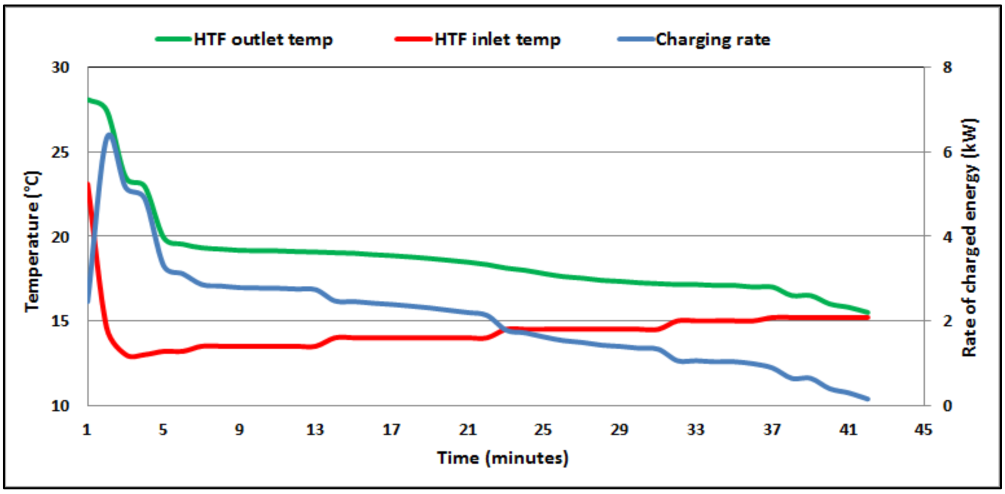


Figure 4.7 Energy rate profile of thermal storage tank during charging process

Figure 4.7 shows the rate of energy supplied by the HTF and HTF inlet and outlet temperature profiles during charging process at an HTF mass flow rate of 7 kg/minute. At the beginning of the charging process the energy rate is high due to the maximum heat transfer between HTF and PCM located around the tubes of HTF because of the maximum temperature gradient between HTF and PCM. The rate of charging energy was decreased continuously till the complete charging of the storage tank. The thermal energy supplied to the storage tank was 1.45 kWh $_{\text{Thermal}}$. The similar behavior was shown by the remaining storage tanks and same thermal energy supplied to the tanks. Therefore total thermal energy supplied to the TES system was 4.35 kWh. The electrical energy consumed by the chiller during charging process to store energy in TES system was 1.24 kWh $_{\text{Electrical}}$ (COP = 3.5). Table 4-2 shows the energy details of TES system during charging process.

Table 4-2: Energy supplied to TES system during charging process

Properties	Value
Energy supplied to each storage tank	1.45 kWh $_{\text{Thermal}}$
Energy supplied to TES system	4.35 kWh $_{\text{Thermal}}$
COP of the chiller (night time)	3.5
Electrical energy consumed by the chiller	1.24 kWh $_{\text{electrical}}$

❖ Energy utilized during discharging process of TES system

The stored energy in TES system was utilized to operate PRCS instead of using chiller during daytime (peak hours). Figure 4.8 shows the rate of energy utilized by the HTF and HTF inlet and outlet temperature profiles during discharging process at an HTF mass flow rate of 3.36 kg/minute.

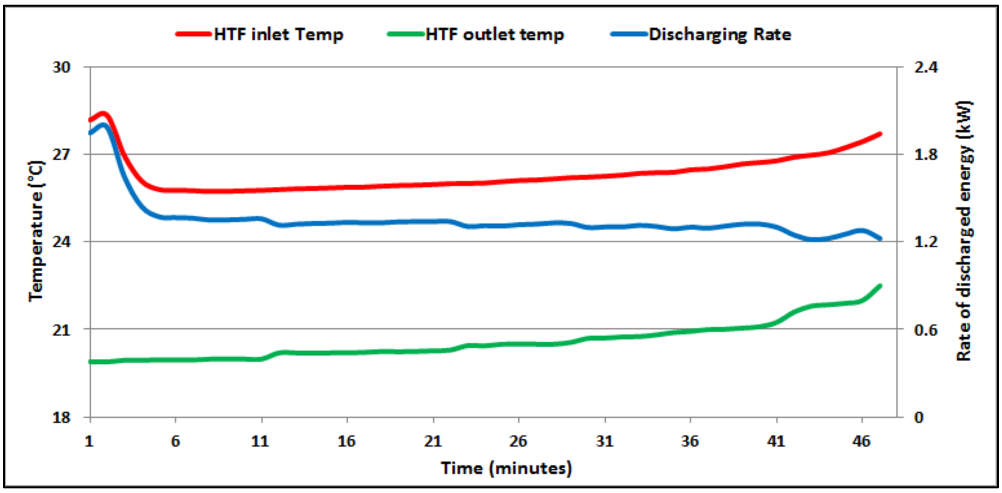
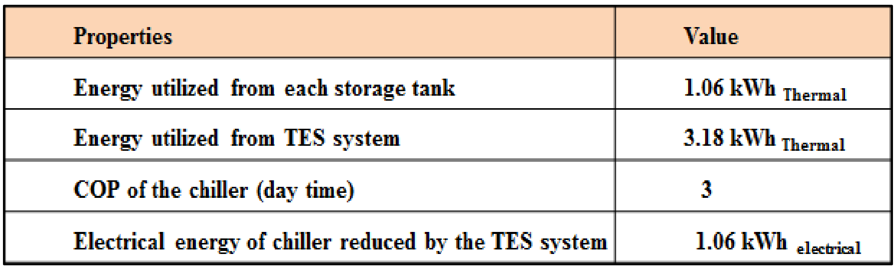


Figure 4.8 Energy rate profile of thermal storage tank during discharging process

At the beginning of discharging process the rate of discharged energy is higher due to the maximum heat transfer between HTF and PCM inside tank because of maximum temperature gradient between PCM and HTF. After that the discharged energy rate was nearly constant and less at the end of discharging process because the HTF from outlet of the PRCS was re-circulating to the TES system i.e. inlet to the storage tank. The thermal energy utilized from the storage tank was 1.06 kWh $_{\text{Thermal}}$. The similar behavior was shown by the remaining storage tanks and thermal energy utilized is also same. Hence the total thermal energy utilized from TES system was 3.18 kWh $_{\text{Thermal}}$. Total electrical energy consumption of chiller reduced by supplying the cooling energy from TES system to PRCS in day time was 1.06 kWh $_{\text{Electrical}}$ (COP = 3). Table 4-3 shows energy details of TES system during discharging process.

Table 4-3: Energy utilized from TES system during discharging process



Properties	Value
Energy utilized from each storage tank	1.06 kWh $_{\text{Thermal}}$
Energy utilized from TES system	3.18 kWh $_{\text{Thermal}}$
COP of the chiller (day time)	3
Electrical energy of chiller reduced by the TES system	1.06 kWh $_{\text{electrical}}$

❖ Efficiency of TES system

The cyclic efficiency of the PCM thermal energy storage system was calculated using the total thermal energy supplied to the system and total energy utilized from the system. From table 4-3 and table 4-4 the total thermal energy supplied and total energy utilized are 4.35 kWh$_{\text{Thermal}}$ and 3.18 kWh$_{\text{Thermal}}$ respectively. Therefore the cyclic efficiency of the PCM thermal energy storage system is 73 %. The losses in the system are due to large standby duration of the stored energy. The efficiency of the TES system can be increased by reducing the losses in system by using proper insulation in terms of thickness and low conducting material.

4.2.2 Power cost analysis

Thermal energy storage technology mainly adopted as peak load shifting technology, storing thermal energy at night and discharging thermal energy during day (peak load periods) which always leads to more energy consumption than the conventional air conditioning system (Hu Lina 2014). Annual operating cost of PRCS integrated with TES system was compared with annual operating cost of conventional PRCS.

Assuming the electricity utility rates in Jaipur is similar to the Delhi time of use electricity tariff shown in table 4-4, and just used for the power cost analysis of overall system; because Jaipur electricity utility rates are flat and in future it may change to differential tariff.

Table 4-4: Time of use power tariff (Delhi, India)

S.No	Time period (hours)	Power price (INR/kWh $_{\text{electrical}}$)
1	0.00 – 6.00	6.30
2	7.00 – 14.00	8.40
3	15.00 – 23.00	10.08

Conventional PRCS having capacity 1.2 kW (thermal energy) and operating 8 hours (9.00 – 17.00) per day, energy supplied from chiller only, the conventional PRCS is consumed 9.6 kWh Thermal energy per day to provide comfortable thermal environment to the occupant. Therefore electrical energy consumed by the chiller to operate PRCS was 3.2 kWh $_{\text{electrical}}$ (chiller COP = 3, during daytime). Considering the 200 operating (working) days in year and the total power consumption of conventional PRCS was 640 kWh $_{\text{electric}}$. The operational cost of the conventional PRCS is 5780 (INR) per year. Table 4-5 shows the energy consumption and power cost details of conventional PRCS.

Table 4-5: Annual energy consumption and power cost of conventional PRCS

S.No	Time period (hours)	Thermal energy (kWh $_{\text{Thermal}}$)	Electrical energy (kWh $_{\text{Electrical}}$)	Power cost (INR)
1	0.00 – 6.00	0	0	0
2	7.00 – 14.00	1200	400	3360
3	15.00 – 23.00	720	240	2420
Total		1920	640	5780

PRCS integrated with TES system also operated 8 hours per day and the energy supplied to PRCS from chiller and TES system. TES system stored energy during night off-peak hours and that stored energy used for providing the energy to PRCS during daytime peak hours. Chiller provided energy to TES for storing energy in PCM during night hours (0.00 – 6.00) with COP 3.5. This stored energy was utilized to supply cooling to PRCS during day time (14.00 – 16.20) and in the remaining time (9.00 – 14.00 & 16.20 – 17.00) energy supplied to PRCS directly from chiller.

Table 4-6: Annual energy consumption and power cost of PRCS integrated with TES system

S.No	Time period (hours)	Thermal energy ($kWh_{Thermal}$)	Electrical energy ($kWh_{Electrical}$)	Power cost (INR)
1	0.00 – 6.00	870	249	1569
2	7.00 – 14.00	1200	400	3360
3	15.00 – 23.00	160	53	534
Total		2230	702	5463

The total annual power consumption of overall system is 702 $kWh_{electrical}$. The operational cost of overall system is 5463 (INR) per year. Table 4-6 shows the annual energy consumption, and power cost of PRCS integrated with TES system. It has been observed that the electrical energy consumption of the conventional PRCS 640 $kWh_{electrical}$ was lesser than PRCS integrated with TES system 702 $kWh_{electrical}$, but the annual power cost of PRCS integrated with TES system 5463 (INR) was lower than conventional PRCS 5780 (INR) i.e. 5.5 % cost savings shown in table 4-7. There is no savings occurred in power consumption by integrating the TES system to personalized radiant cooling system (conventional)

Table 4-7: Comparison of annual energy consumption and power cost between PRCS with and without TES system

S.No	Parameter	Conventional PRCS	PRCS with TES system	Savings (%)
1	Thermal energy consumption ($kWh_{Thermal}$)	1920	2230	– 16
2	Electrical energy consumption ($kWh_{Electrical}$)	640	702	– 8.8
3	Power cost (INR)	5780	5463	5.5

The total thermal energy consumption of PRCS integrated with TES system was 310 $kWh_{Thermal}$ about 16 % more than the conventional PRCS. The PRCS with TES system was added thermal energy consumption for energy storage in TES system during night time about 870$kWh_{Thermal}$ and reduced thermal energy consumption of chiller by utilizing stored energy from TES system during daytime peak hours about 560 $kWh_{Thermal}$ shown in figure 4.16. Therefore the cost of power consumption of overall system reduced to 5463 (INR) by shifting the thermal load from peak hours to off–peak hours shown in figure 4.17 i.e. 5.5% power cost savings occurred through PRCS integrated with TES system.

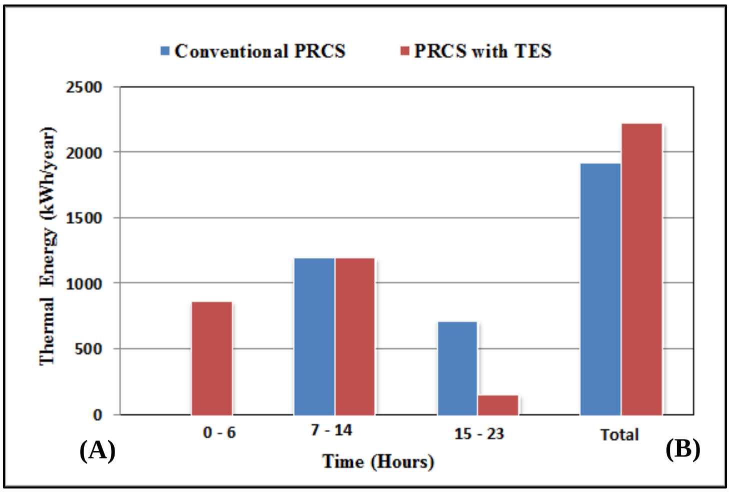


Figure 4.9 Thermal energy comparison between conventional PRCS & PRCS with TES system

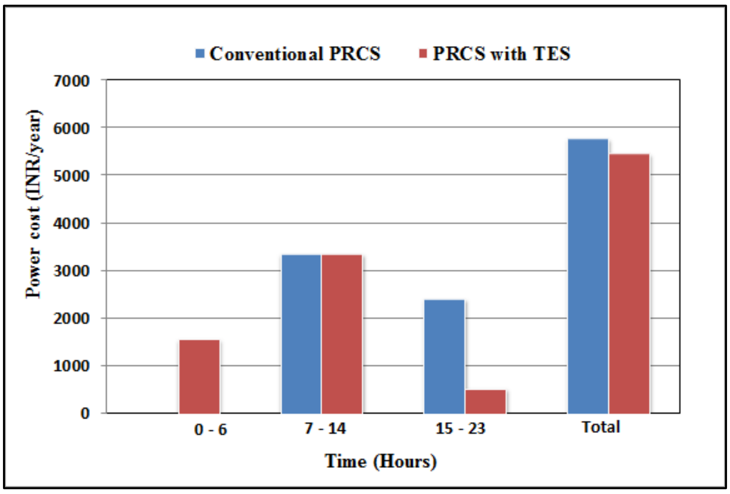


Figure 4.10 Power cost comparison between conventional PRCS & PRCS with TES system

4.3 Corrosive analysis of copper material in PCM (OM–21)

Following are the experimental observations for the corrosive behavior of copper material with and without nickel coating on it, when it was placed in PCM (OM–21) bath. Figure 4.18 shows the corrosive nature of both nickel coated copper strip and simple copper strip over 15 days in PCM bath.

It has been observed that the simple copper strip started reacting with PCM after 2 days i.e. the colour of PCM surrounded by the simple copper strip was changed. The nickel coated copper in other PCM bath not shown any corrosive behavior after 2 days. After 8 days the PCM having simple copper strip was completely changed into some light colour and the PCM having nickel coated copper strip was in same colour as initial. After 15 days the PCM having simple copper strip was appear in dark colour i.e. changed from light colour to dark colour, implies the corrosive behavior of simple copper strip was increased continuously. The PCM having nickel coated strip has not shown any corrosive behavior even after 15 days.

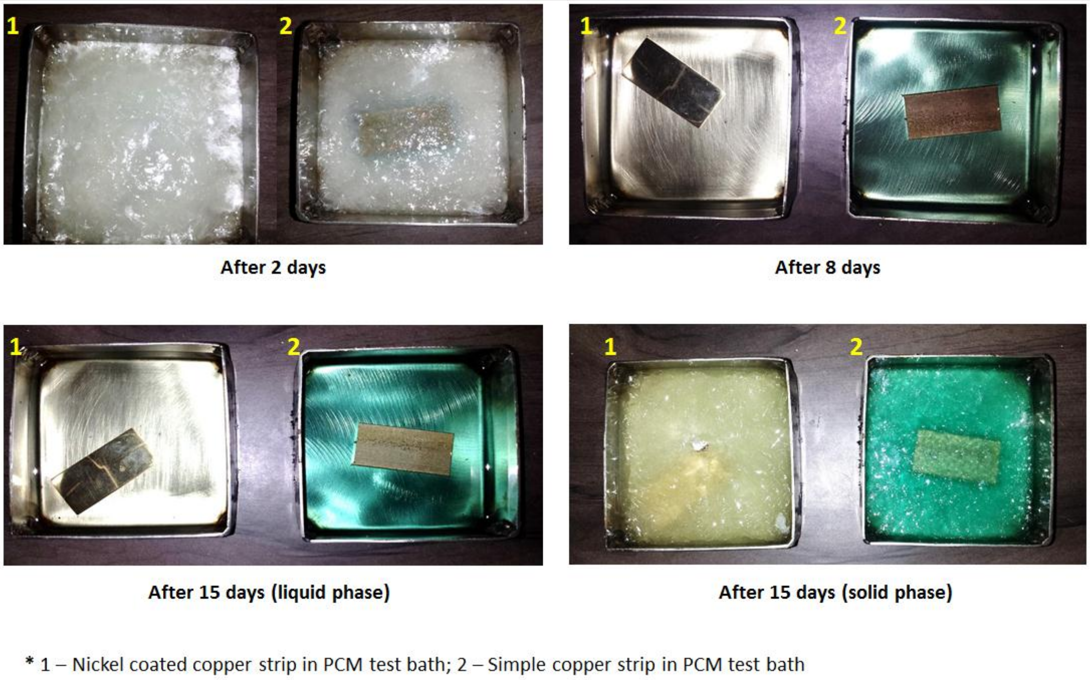


Figure 4.11 Corrosive behavior of simple copper strip and nickel coated copper strip (15 days)

From the experimental observations, the nickel coated copper material cannot react with PCM (OM–21), and it can be a good solution for corrosive problem with copper material to use in PCM (OM–21) applications. Therefore the nickel coated copper tubes, copper nickel alloy tubes, etc. can be used in PCM (OM–21) large scale applications.

5 – CONCLUSIONS AND FUTURE SCOPE

The aim of this work is to supply the cooling energy from PCM thermal energy storage system to personalized radiant cooling system and to study the performance of personalized radiant cooling system and thermal energy storage system. Thermal energy storage system was designed to improve the heat transfer between PCM and HTF on the basis of shell and finned tube heat exchanger concept.

Thermal behavior of thermal energy storage system, (charging and discharging characteristics), thermal analysis of personalized radiant cooling system (thermal comfort study), energy consumption analysis of personalized radiant cooling system with and without PCM thermal energy storage, and power cost analysis are examined.

5.1 Conclusions

Several experiments were conducted to evaluate the performance of personalized radiant cooling system and thermal energy storage system. It is found that PCM thermal energy storage system efficiently supplied constant temperature cooling energy to the personalized radiant cooling system in order to maintain comfortable thermal environment around the occupant. Following are the conclusions that could be drawn from this thesis;

- During discharging process, the average effectiveness of thermal energy storage system is greater than 90% and energy discharged at nearly constant temperature i.e. HTF outlet temperature range is 2°C only. Hence the heat exchanger design is efficient for thermal energy storage applications using PCM as storage medium.
- The design of thermal energy storage system (shell and finned tube heat exchanger) enables the system to continuously supply the energy at constant temperature to end energy user (HVAC system, Heat recovery system, etc.) i.e. this design can be used in building HVAC applications, industrial heat recovery applications, etc.
- Thermal energy storage system using PCM (OM–21) efficiently supplied nearly constant temperature cooling energy between 20°C and 22° (HTF temperature range) for continuously 2 hours and 20 minutes to personalized radiant cooling system in order to maintenance comfortable thermal environment to the occupant.

- Personalized radiant cooling system created micro-climate zone around the vicinity of occupant and maintained standard effective temperature between 25.7°C and 26°C (comfortable thermal conditions for occupant) when it operated with PCM thermal energy storage system .
- There is no savings achieved in power consumption by integrating the thermal energy storage system to personalized radiant cooling system and the overall system increases operational cost than conventional personalized radiant cooling system if the city electricity utility rates are flat (constant).
- Thermal energy storage system integrated with personalized radiant cooling system reduced the operational cost of overall system than conventional personalized radiant cooling system if the city electricity utility rates are different (assuming the Delhi city tariff rates), i.e. 5.5% power cost savings achieved by shifting the cooling load from peak hours to off–peak hours.
- From corrosive analysis study it was found that the nickel coated copper material cannot react with PCM (OM–21) unlike simple copper material; nickel coated copper tubes, copper nickel alloy tubes can be used in heat exchanger design of thermal energy storage system without any corrosion problem in PCM (OM–21) applications.

Finally, this study shows that the new design of heat exchanger improved the heat transfer between PCM and HTF in latent heat thermal energy storage applications. And personalized radiant cooling system efficiently operated with PCM thermal energy storage system, maintained thermal comfort conditions to the occupant, and power cost savings are achieved by integration of PCM thermal energy storage system to the personalized radiant cooling system.

5.2 Future scope

More research work is needed in this field of personalized radiant cooling system (personalized conditioning systems) to implement this technology in real building cooling applications, and thermal energy storage systems using PCMs to increase the heat transfer between PCM and HTF. Following are recommendations for future research

- Investigation on performance of thermal energy storage system using other PCMs and HTFs for various cooling and heating applications.

- Investigation on performance of thermal energy storage system made of copper nickel alloy tube or nickel coated copper tube heat exchanger using PCM (OM–21) as energy storage medium, and study the corrosion behavior of heat exchanger material with PCM (OM–21)
- It is possible to provide Instrumentation control for performance parameters (flow rate and temperature of supply HTF), for changing the HTF flow among various loops such as charging circuit, discharging circuit, etc. during different processes of experiment, and for changing HTF flow among the storage tanks during charging and discharging process of thermal energy storage system. And investigate the performance of overall system.
- Multiple personalized radiant cooling systems in a large office area can be operated by large capacity thermal energy storage system for shifting the cooling load from peak hours to off–peak hours and for supplying it is also possible for supply the cooling energy at different temperatures to particular personalized radiant cooling systems in order to fulfill the individual thermal comfort needs in same office.

PUBLICATIONS:

C.P.Chandra Sekhar, Jyotirmay Mathur, Mahabir Bhandari, Prateek Srivastava, Yasin Khan, Rana Veer Pratap Singh. “**Performance Analysis of Personalized Radiant Cooling System integrated with PCM Thermal Energy Storage**.” IHMTC 2017, Hyderabad. (Abstract accepted)

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Appendix – Sample Experimental Readings

Charging Process of TES System:

Time (min)	HTF inlet temp (°C)	T–1 (°C)	T–6 (°C)	Average PCM temp (°C)	HTF outlet temp (°C)	HTF Flow rate (kg/minute)	Energy (kWh)
1	23.10	25.20	25.95	25.17	28.10	7	0.04095
2	14.60	21.77	25.90	24.52	27.46	7	0.105323
3	13.00	19.75	24.59	22.03	23.49	7	0.085913
4	13.00	19.63	23.10	21.04	22.96	7	0.081572
5	13.20	19.59	22.92	20.84	19.92	7	0.055037
6	13.20	19.40	20.94	20.41	19.54	7	0.051925
7	13.50	19.20	20.90	20.25	19.32	7	0.047666
8	13.50	19.12	20.87	20.18	19.25	7	0.047093
9	13.50	18.99	20.86	20.11	19.17	7	0.046437
10	13.50	18.70	20.83	20.02	19.15	7	0.046274
11	13.50	18.43	20.80	19.90	19.14	7	0.046192
12	13.50	17.69	20.72	19.59	19.10	7	0.045864
13	13.50	17.12	20.60	19.34	19.07	7	0.045618
14	14.00	16.53	20.50	19.16	19.03	7	0.041196
15	14.00	16.20	20.42	18.87	19.00	7	0.04095
16	14.00	16.05	20.28	18.70	18.92	7	0.040295
17	14.00	15.91	20.16	18.60	18.86	7	0.039803
18	14.00	15.80	20.13	18.50	18.78	7	0.039148
19	14.00	15.63	20.10	18.39	18.69	7	0.038411
20	14.00	15.42	20.09	18.28	18.58	7	0.03751
21	14.00	15.30	20.05	18.07	18.47	7	0.036609
22	14.00	15.30	19.98	17.90	18.33	7	0.035463
23	14.50	15.27	19.95	17.81	18.12	7	0.029648
24	14.50	15.24	19.92	17.72	17.99	7	0.028583
25	14.50	15.18	19.77	17.57	17.79	7	0.026945
26	14.50	15.18	19.62	17.48	17.62	7	0.025553
27	14.50	15.22	19.50	17.43	17.53	7	0.024816
28	14.50	15.15	19.52	17.31	17.40	7	0.023751
29	14.50	15.15	19.32	17.19	17.34	7	0.02326
30	14.50	15.12	19.19	17.09	17.25	7	0.022523
31	14.50	15.15	19.03	17.03	17.20	7	0.022113
32	15.00	15.10	18.85	16.92	17.15	7	0.017609
33	15.00	15.12	18.62	16.79	17.15	7	0.017609
34	15.00	15.25	18.45	16.72	17.10	7	0.017199
35	15.00	15.30	18.04	16.43	17.10	7	0.017199
36	15.00	15.35	17.75	16.32	17.00	7	0.01638
37	15.20	15.50	17.45	16.21	17.00	7	0.014742
38	15.20	15.47	17.20	16.14	16.50	7	0.010647
39	15.20	15.46	17.12	16.05	16.50	7	0.010647
40	15.20	15.45	17.01	15.97	16.00	7	0.006552
41	15.20	15.50	16.92	15.95	15.80	7	0.004914
42	15.20	15.52	16.88	15.93	15.50	7	0.002457
						Total Energy	1.450

Discharging Process of TES System:

Time (min)	HTF inlet Temp (°C)	T–1 (°C)	T–6 (°C)	Average PCM Temp (°C)	HTF outlet temp (°C)	HTF flow rate (kg/minute)	Energy (kWh)
1	28.18	19.53	19.56	19.44	19.90	3.36	0.032446
2	28.34	19.74	19.53	19.53	19.89	3.36	0.033104
3	26.96	19.99	19.58	19.64	19.95	3.36	0.027464
4	26.09	20.31	19.51	19.72	19.95	3.36	0.024061
5	25.80	20.42	19.62	19.80	19.96	3.36	0.022877
6	25.77	20.51	19.63	19.84	19.96	3.36	0.022775
7	25.75	20.63	19.64	19.89	19.96	3.36	0.022712
8	25.73	20.89	19.57	19.96	19.99	3.36	0.022493
9	25.73	21.30	19.67	20.09	19.99	3.36	0.022516
10	25.75	21.50	19.70	20.15	19.99	3.36	0.022579
11	25.77	21.82	19.72	20.22	19.99	3.36	0.022642
12	25.79	22.85	19.74	20.45	20.20	3.36	0.021917
13	25.82	23.85	19.76	20.67	20.20	3.36	0.022023
14	25.83	24.10	19.78	20.77	20.19	3.36	0.022109
15	25.85	24.70	19.80	20.89	20.20	3.36	0.022136
16	25.87	25.22	19.81	21.05	20.20	3.36	0.022234
17	25.88	25.48	19.82	21.19	20.22	3.36	0.022179
18	25.91	25.52	19.84	21.25	20.25	3.36	0.022187
19	25.93	25.57	19.93	21.33	20.24	3.36	0.022305
20	25.94	25.66	19.94	21.49	20.25	3.36	0.02232
21	25.97	25.72	19.80	21.64	20.27	3.36	0.022324
22	25.99	25.77	19.97	21.84	20.30	3.36	0.02232
23	26.00	25.83	19.98	21.96	20.45	3.36	0.021756
24	26.02	25.88	20.03	22.05	20.44	3.36	0.021858
25	26.06	25.90	20.05	22.18	20.50	3.36	0.021807
26	26.10	25.99	20.06	22.35	20.50	3.36	0.021968
27	26.12	26.03	20.08	22.41	20.50	3.36	0.02203
28	26.16	26.07	20.10	22.65	20.50	3.36	0.022179
29	26.20	26.12	20.13	22.86	20.56	3.36	0.022105
30	26.22	26.15	20.17	22.92	20.70	3.36	0.021638
31	26.25	26.18	20.18	22.95	20.71	3.36	0.021713
32	26.29	26.26	20.19	23.08	20.75	3.36	0.021705
33	26.35	26.28	20.20	23.16	20.76	3.36	0.021901
34	26.37	26.31	20.22	23.20	20.82	3.36	0.021756
35	26.39	26.36	20.24	23.24	20.90	3.36	0.021501
36	26.47	26.40	20.26	23.36	20.94	3.36	0.021685
37	26.50	26.43	20.29	23.43	21.00	3.36	0.02156
38	26.58	26.46	20.31	23.50	21.01	3.36	0.021815
39	26.67	26.53	20.36	23.66	21.05	3.36	0.022026
40	26.72	26.57	20.38	23.75	21.10	3.36	0.02203
41	26.78	26.62	20.41	23.85	21.25	3.36	0.021678
42	26.90	26.72	20.48	24.15	21.60	3.36	0.02078
43	26.97	26.75	20.51	24.33	21.80	3.36	0.020266
44	27.05	26.79	20.54	24.47	21.85	3.36	0.020396
45	27.23	26.93	20.66	24.78	21.90	3.36	0.020898
46	27.44	27.10	20.82	25.08	22.00	3.36	0.021317
47	27.70	27.30	21.12	25.36	22.50	3.36	0.020396
						Total Energy	1.060

Thermal performance of PRCS:

Time (min)	Air Temp (°C)	Globe Temp (°C)	air velocity (m/s)	MRT (°C)	OT (°C)	SET (°C)	Room air temp (°C)
1	29.10	28.90	0.60	28.60	28.85	25.90	31.5
2	29.10	28.90	0.60	28.60	28.85	25.90	31.5
3	29.10	28.80	0.60	28.50	28.8	25.90	31.5
4	29.00	28.80	0.60	28.50	28.75	25.80	31.5
5	29.00	28.70	0.60	28.20	28.6	25.70	31.5
6	29.00	28.70	0.60	28.20	28.6	25.70	31.5
7	29.00	28.70	0.60	28.20	28.6	25.70	31.5
8	29.00	28.70	0.60	28.20	28.6	25.70	31.5
9	29.00	28.70	0.60	28.20	28.6	25.70	31.5
10	29.00	28.70	0.60	28.20	28.6	25.70	31.5
11	28.90	28.70	0.60	28.40	28.65	25.70	31.5
12	28.90	28.70	0.60	28.40	28.65	25.70	31.5
13	28.90	28.70	0.60	28.40	28.65	25.70	31.5
14	28.90	28.70	0.60	28.40	28.65	25.70	31.5
15	28.90	28.70	0.60	28.40	28.65	25.70	31.5
16	28.90	28.70	0.60	28.40	28.65	25.70	31.5
17	28.90	28.80	0.60	28.60	28.75	25.80	31.5
18	28.90	28.80	0.60	28.60	28.75	25.80	31.5
19	28.90	28.80	0.60	28.60	28.75	25.80	31.5
20	28.90	28.80	0.60	28.60	28.75	25.80	31.5
21	29.00	28.80	0.60	28.50	28.75	25.80	31.5
22	29.00	28.80	0.60	28.50	28.75	25.80	31.5
23	29.00	28.80	0.60	28.50	28.75	25.80	31.5
24	29.00	28.80	0.60	28.50	28.75	25.80	31.5
25	29.00	28.80	0.60	28.50	28.75	25.80	31.5
26	29.00	28.80	0.60	28.50	28.75	25.80	31.5
27	29.00	28.80	0.60	28.50	28.75	25.80	31.5
28	29.00	28.80	0.60	28.50	28.75	25.80	31.5
29	29.00	28.80	0.60	28.50	28.75	25.80	31.5
30	29.00	28.80	0.60	28.50	28.75	25.80	31.5
31	29.00	28.80	0.60	28.50	28.75	25.80	31.5
32	29.00	28.90	0.60	28.70	28.85	25.90	31.5
33	29.00	28.90	0.60	28.70	28.85	25.90	31.5
34	29.10	28.90	0.60	28.60	28.85	25.90	31.5
35	29.10	28.90	0.60	28.60	28.85	25.90	31.5
36	29.10	28.90	0.60	28.60	28.85	25.90	32
37	29.10	28.90	0.60	28.60	28.85	25.90	32
38	29.10	28.90	0.60	28.60	28.85	25.90	32
39	29.10	28.90	0.60	28.60	28.85	25.90	32
40	29.10	28.90	0.60	28.60	28.85	25.90	32
41	29.10	29.00	0.60	28.80	28.95	26.00	32
42	29.10	29.00	0.60	28.80	28.95	26.00	32
43	29.10	29.00	0.60	28.80	28.95	26.00	32
44	29.10	29.00	0.60	28.80	28.95	26.00	32
45	29.10	29.00	0.60	28.80	28.95	26.00	32
46	29.10	29.00	0.60	28.80	28.95	26.00	32
47	29.10	29.00	0.60	28.80	28.95	26.00	32
48	29.10	28.90	0.60	28.60	28.85	25.90	32
49	29.10	28.90	0.60	28.60	28.85	25.90	32
50	29.00	28.80	0.60	28.50	28.75	25.90	32
51	29.00	28.80	0.60	28.50	28.75	25.70	32
52	29.00	28.70	0.60	28.20	28.6	25.70	32

53	29.00	28.70	0.60	28.20	28.6	25.70	32
54	29.00	28.70	0.60	28.20	28.6	25.70	32
55	29.00	28.70	0.60	28.20	28.6	25.70	32
56	29.00	28.70	0.60	28.20	28.6	25.70	32
57	28.90	28.70	0.60	28.20	28.55	25.70	32
58	28.90	28.70	0.60	28.40	28.65	25.70	32
59	28.90	28.70	0.60	28.40	28.65	25.70	32
60	28.90	28.70	0.60	28.40	28.65	25.70	32
61	28.90	28.70	0.60	28.40	28.65	25.70	32
62	28.90	28.70	0.60	28.40	28.65	25.70	32
63	28.90	28.70	0.60	28.40	28.65	25.70	32
64	28.90	28.80	0.60	28.60	28.75	25.80	32
65	28.90	28.80	0.60	28.60	28.75	25.80	32
66	28.90	28.80	0.60	28.60	28.75	25.80	32
67	28.90	28.80	0.60	28.60	28.75	25.80	32
68	29.00	28.80	0.60	28.50	28.75	25.80	32
69	29.00	28.80	0.60	28.50	28.75	25.80	32
70	29.00	28.80	0.60	28.50	28.75	25.80	32
71	29.00	28.80	0.60	28.50	28.75	25.80	32
72	29.00	28.80	0.60	28.50	28.75	25.80	32
73	29.00	28.80	0.60	28.50	28.75	25.80	32
74	29.00	28.80	0.60	28.50	28.75	25.80	32
75	29.00	28.80	0.60	28.50	28.75	25.80	32
76	29.00	28.80	0.60	28.50	28.75	25.80	32
77	29.00	28.80	0.60	28.50	28.75	25.80	32
78	29.00	28.80	0.60	28.50	28.75	25.80	32
79	29.00	28.90	0.60	28.70	28.85	25.90	32
80	29.00	28.90	0.60	28.70	28.85	25.90	32
81	29.10	28.90	0.60	28.60	28.85	25.90	32
82	29.10	28.90	0.60	28.60	28.85	25.90	32
83	29.10	28.90	0.60	28.60	28.85	25.90	32
84	29.10	28.90	0.60	28.60	28.85	25.90	32
85	29.10	28.90	0.60	28.60	28.85	25.90	32
86	29.10	28.90	0.60	28.60	28.85	25.90	32
87	29.10	28.90	0.60	28.60	28.85	25.90	32
88	29.10	29.00	0.60	28.80	28.95	26.00	32
89	29.10	29.00	0.60	28.80	28.95	26.00	32
90	29.10	29.00	0.60	28.80	28.95	26.00	32
91	29.10	29.00	0.60	28.80	28.95	26.00	32
92	29.10	29.00	0.60	28.80	28.95	26.00	32
93	29.10	29.00	0.60	28.80	28.95	26.00	32
94	29.10	29.00	0.60	28.80	28.95	26.00	32
95	29.10	29.00	0.60	28.80	28.95	26.00	32
96	29.10	28.90	0.60	28.60	28.85	25.90	32
97	29.10	28.90	0.60	28.60	28.85	25.80	32
98	29.00	28.80	0.60	28.50	28.75	25.80	32
99	29.00	28.80	0.60	28.50	28.75	25.80	32
100	29.00	28.70	0.60	28.20	28.6	25.70	32
101	29.00	28.70	0.60	28.20	28.6	25.70	32
102	29.00	28.70	0.60	28.20	28.6	25.70	32
103	29.00	28.70	0.60	28.20	28.6	25.70	32
104	29.00	28.70	0.60	28.20	28.6	25.70	32
105	28.90	28.70	0.60	28.20	28.55	25.70	32
106	28.90	28.70	0.60	28.40	28.65	25.70	32
107	28.90	28.70	0.60	28.40	28.65	25.70	32
108	28.90	28.70	0.60	28.40	28.65	25.70	32
109	28.90	28.70	0.60	28.40	28.65	25.70	32
110	28.90	28.70	0.60	28.40	28.65	25.70	32

111	28.90	28.70	0.60	28.40	28.65	25.70	32
112	28.90	28.80	0.60	28.60	28.75	25.80	32
113	28.90	28.80	0.60	28.60	28.75	25.80	32
114	28.90	28.80	0.60	28.60	28.75	25.80	32
115	28.90	28.80	0.60	28.60	28.75	25.80	32
116	29.00	28.80	0.60	28.50	28.75	25.80	32
117	29.00	28.80	0.60	28.50	28.75	25.80	32
118	29.00	28.80	0.60	28.50	28.75	25.80	32
119	29.00	28.80	0.60	28.50	28.75	25.80	32
120	29.00	28.80	0.60	28.50	28.75	25.80	32
121	29.00	28.80	0.60	28.50	28.75	25.80	33
122	29.00	28.80	0.60	28.50	28.75	25.80	33
123	29.00	28.80	0.60	28.50	28.75	25.80	33
124	29.00	28.80	0.60	28.50	28.75	25.80	33
125	29.00	28.80	0.60	28.50	28.75	25.80	33
126	29.00	28.80	0.60	28.50	28.75	25.80	33
127	29.00	28.90	0.60	28.70	28.85	25.90	33
128	29.00	28.90	0.60	28.70	28.85	25.90	33
129	29.10	28.90	0.60	28.60	28.85	25.90	33
130	29.10	28.90	0.60	28.60	28.85	25.90	33
131	29.10	28.90	0.60	28.60	28.85	25.90	33
132	29.10	28.90	0.60	28.60	28.85	25.90	33
133	29.10	28.90	0.60	28.60	28.85	25.90	33
134	29.10	28.90	0.60	28.60	28.85	25.90	33
135	29.10	28.90	0.60	28.60	28.85	25.90	33
136	29.10	29.00	0.60	28.80	28.95	26.00	33
137	29.10	29.00	0.60	28.80	28.95	26.00	33
138	29.10	29.00	0.60	28.80	28.95	26.00	33
139	29.10	29.00	0.60	28.80	28.95	26.00	33
140	29.10	29.00	0.60	28.80	28.95	26.00	33
141	29.10	29.00	0.60	28.80	28.95	26.00	33
142	29.10	29.00	0.60	28.80	28.95	26.00	33
143	29.10	29.00	0.60	28.80	28.95	26.00	33

- Room air temperature is the average temperature of the air inside room other than microclimate zone created by the PRCS.
- Remaining parameters (OT, SET, Air Velocity, etc.) are representing the conditions of microclimate zone created by PRCS.

DOCUMENT

Chapter 1 and Chapter 2

SCORE

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Chapter 3, Chapter 4 and Chapter 5

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