Design and Development of 10 kWh Solar Thermal Space Heating with Thermal Energy Storage

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Abstract. Solar space heating presents a sustainable solution for maintaining indoor thermal comfort by utilizing solar thermal energy. This technology is broadly categorized into active systems, which use fluid-based solar collectors and distribution mechanisms, and passive systems, which rely on architectural features to naturally capture and retain solar heat. The present study focuses on an active solar space heating system that integrates heat pipe-based evacuated tube collectors (ETCs) with a paraffin-based thermal energy storage (TES) unit to enable nighttime space heating in remote, cold regions. The system architecture comprises three key components: the solar collector unit, thermal energy storage unit, and space heater. Field implementation demonstrated an energy storage capacity of approximately 16 kWh under an average Global Horizontal Irradiance (GHI) of 2.4 kWh/m², effectively maintaining consistent indoor temperatures throughout the night. The simplicity of installation, minimal maintenance requirements, and reliable performance under low solar input conditions underscore the system's suitability for off-grid applications in regions such as Leh. The results affirm the viability of this integrated solar thermal system as an efficient, cost-effective solution for domestic space heating in sun-rich, high-altitude cold climates.

Keywords: Solar Thermal Heating, Solar Collectors, Thermal Energy Storage, Paraffin wax

Abbreviations:

Thermal Energy Required = Q_{th}
Melting Temperature of PCM = T_l
Water Inlet Temperature = T_{w1}
Water Outlet Temperature = T_{w2}
Inner Diameter of Tube = D_{in}
Outer Diameter of Tube = D_o
Change in temperature of Thermic Fluid = ΔT_{TF}
Heat Required from Thermic Fluid / hr = Q_{TF}
Heat Transfer Coefficient of TF = HTC_{TF}
Logarithmic mean temperature difference = LMTD
Heat Transfer / length= Q

Phase Change Material = PCM
Thermic Fluid = TF
Enthalpy of PCM = H_{PCM}
Density of PCM = ρ_{PCM}
Density of TF = ρ_{TF}
Viscosity of TF = μ_{TF}
Velocity of TF = V_{TF}
Specific Heat capacity of TF = Cp_{TF}
Reynolds number = Re
Prandtl number = Pr
Thermal Energy Storage = TES

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1 Introduction

Solar space heating is one of the more intuitive use of solar thermal energy by using the sun's heat to subsequently heat spaces within buildings, drying of agricultural products etc. Technology within space heating can be separated into two distinct categories: passive and active [1]. Active space heating captures energy from sunlight, either as heat or electricity, to augment heating systems, while passive space heating captures heat from the sun as it comes into home through windows, roofs and walls to heat objects in the room. Active space heating uses large flat-plate or evacuated tube collectors on a rooftop or ground mounted to absorb the thermal energy and redistribute it to the fluid. Solar thermal space heating systems, when integrated with TES, offer a sustainable solution to address the intermittent nature of solar energy, particularly in regions with significant diurnal temperature variations. A broad range of technologies and systems are currently available for capturing solar energy. These systems are generally categorized into direct and indirect methods, both of which are continually advancing in terms of efficiency, cost-effectiveness, and versatility of use [2]. Latent Heat Storage utilizes phase change materials (PCMs) that absorb or release heat during phase transitions, such as from solid to liquid. Numerous experimental and simulation studies have assessed the thermal performance of phase change materials. Results have shown that incorporating PCMs into wall systems can lead to energy savings of up to 30%, while also reducing peak indoor temperatures by 3–5°C in hot climates [3,4]. Combining PCMs with insulation materials has demonstrated synergistic improvements in energy efficiency [5]. These outcomes highlight the effectiveness of PCM integration, particularly in regions with significant diurnal temperature fluctuations. There is also a growing focus on PCM retrofitting methods and dynamic thermal modeling to further enhance energy savings [6].

PCMs offer higher energy densities compared to Sensible Heat Storage and maintain a constant temperature during the phase change process [7]. However, challenges include issues related to material stability, heat transfer rates, and cost. The combination of solar collectors and TES enables the storage of excess thermal energy generated during the day for use during nighttime or cloudy periods, thereby enhancing the reliability and efficiency of space heating applications.

Passive space heating uses organic PCMs that store thermal energy during melting and release it during solidification. This latent heat storage helps buffer indoor temperature fluctuations. When integrated into building components such as walls, roofs, ceilings, or floors, PCMs can delay heat transfer, reduce HVAC loads, and stabilize indoor temperatures. Organic PCMs are more commonly used in building applications due to their reliability and compatibility with construction materials [8].

The present manuscript discusses the process and method for design and development of an active mode of space heating system utilizing a PCM material, keeping in mind a volume of 100 ft^3, and harnessing solar heat with a daily average GHI of 2.4 kWh/m^2.

1.1 System Brief:

An innovative active solar space heating system is customized to meet the requirement of 10 kWh of thermal energy for heating a space volume of 10 X 10 X 10 cubic feet during non-sunshine hours. Highly efficient heat pipe based solar energy collector arrangement of 6.25 m^2, was deployed to harvest the solar energy. To deliver the heat energy for space heating during non-sunshine hours, an efficient and cost-effective paraffin-based thermal storage system was envisaged [2]. Collector support structure was designed and fabricated to suit the geo location of colder region to realize maximum annual yield. The system was designed to transfer heat using water & ethylene glycol [9]. All the components in the system are designed keeping in mind of easy installation and maintenance.

1.2 Process Description:

The solar thermal heating system utilized in this study comprises ETCs integrated with heat pipes for efficient solar energy absorption and transfer. Each heat pipe is sealed and partially filled with a working fluid, housed within a vacuum-sealed glass tube to minimize thermal losses. The condenser end of the heat pipe is embedded into a top manifold header, through which a water-based heat transfer fluid is circulated. During solar irradiation hours, a circulation pump actively drives water into the hot header of the collector array. As the heat pipes absorb incident solar energy, the internal working fluid vaporizes and conveys heat to the manifold through condensation. This thermal exchange raises the water temperature to approximately 70 °C [1,2].

The heated water is subsequently directed to TES. The TES unit incorporates paraffin wax as PCM, selected for its favorable thermal stability, cost-effectiveness, and melting point suitable for low-temperature applications [2,7]. Upon contact with the 70 °C water, the paraffin wax undergoes a solid-to-liquid phase transition, storing latent heat. During this heat exchange process, the water cools to around 60 °C before being recirculated to the solar collector system for reheating, thus forming a closed-loop thermal cycle. This setup allows for continuous and reliable energy storage during peak solar hours and ensures thermal availability during non-sunshine periods, improving the overall efficiency of the space heating system. A schematic representation of this thermal process is illustrated in Figure 1(a).

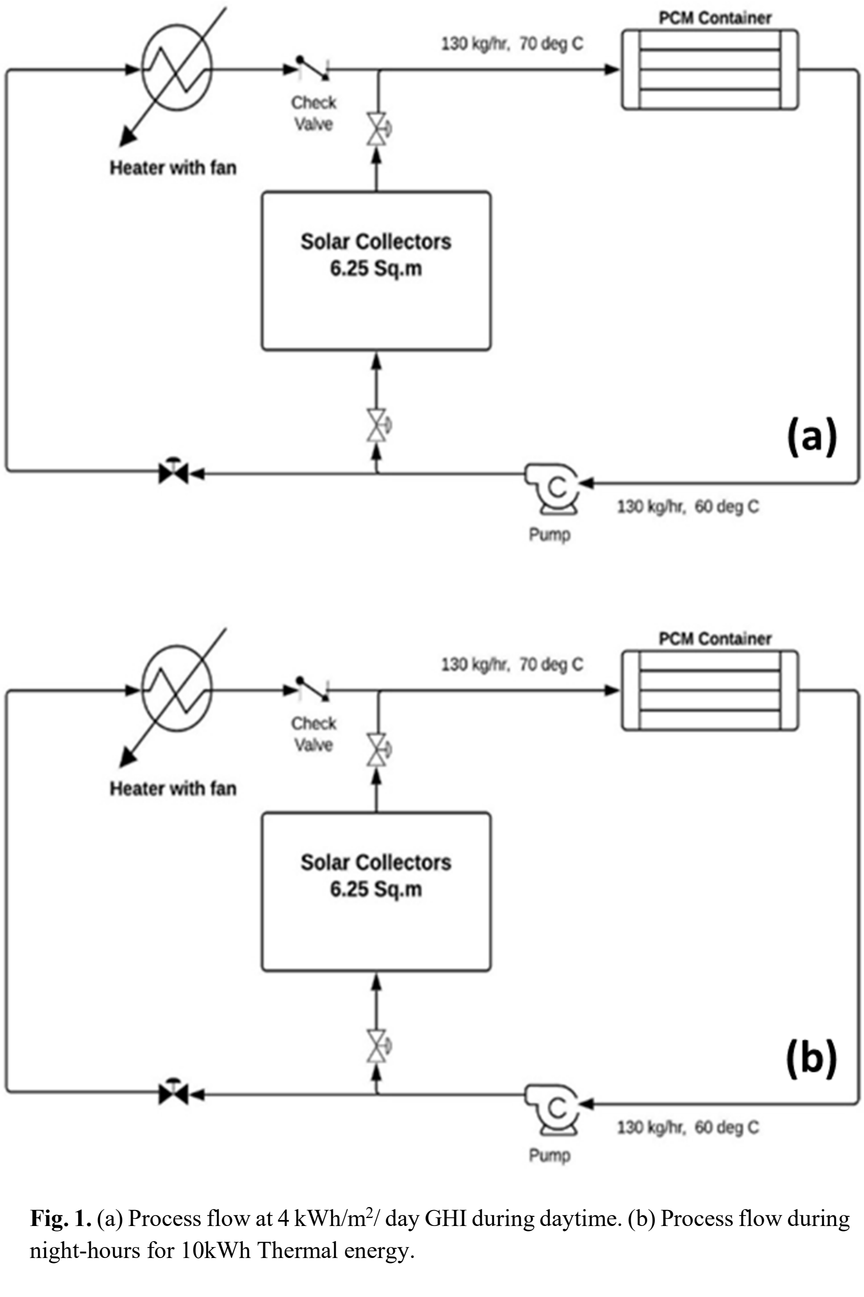


Fig. 1. (a) Process flow at 4 kWh/m^2/ day GHI during daytime. (b) Process flow during night-hours for 10kWh Thermal energy.

During nighttime or low solar radiation periods, the water in the circulation loop cools down to approximately 40 °C. As it enters the TES unit, it is reheated to around 50 °C by drawing on the latent heat stored in the molten paraffin wax from the daytime charging phase. This thermally upgraded water is then directed to a heat dissipator unit, where it transfers thermal energy to the surrounding air via a heat exchanger, effectively providing space heating.

Following heat exchange, the water temperature decreases back to 40 °C, completing the thermal cycle. It is then recirculated into the TES unit for reheating, thereby maintaining a continuous closed-loop operation. This process ensures thermal buffering and indoor temperature regulation during non-sunshine hours. A schematic of the nighttime heat delivery cycle is illustrated in Figure 1(b).

1.3 Description of the system:

The major components of the space heating system are Evacuated tube collectors, PCM heat exchanger and radiator.

1.3.1 Solar Thermal Collector:

The solar thermal heating system operates on the principle of GHI and comprises of ETC integrated with a heat pipe configuration, designed to meet a thermal load of 1 kW for 10 hours per day, equivalent to 10 kWh of energy. The solar collector field is dimensioned to supply this thermal requirement based on an average GHI of 4 kWh/m²/day, as recorded at NETRA, Greater Noida.

Each evacuated tube measures 1.8 m in length and 0.047 m in diameter and is coupled to a heat pipe that facilitates efficient thermal transfer from the absorber to the working fluid. A single header connects 20 evacuated tubes, and the system comprises a total of four (4) such headers, as shown schematically in Figure 2(a).

The headers are fabricated using rectangular cross-section tubing with dimensions 50 mm × 25 mm, into which the condenser sections of the heat pipes are inserted. This configuration enhances the effective heat transfer area, promoting efficient conduction from the heat pipes to the circulating fluid.

Table 1. Specifications of the system

1.	Heat required in the room	1 kW
2.	Hours of Operation	10 hours
3.	Total Energy to heat the room	10 kWh
4.	Average Solar Radiation	4 kWh/m^2/ day
5.	Solar collector optical to thermal energy conversion Efficiency	40%
6.	Solar Thermal Collector Area	6.25 m^2

Water flows through the headers at a velocity of 0.15 m/s, ensuring uniform heat pickup and minimal thermal stratification. The heat pipe-to-header assembly is illustrated in Figure 2(b).

This ETC based heat pipe configuration offers modular scalability, high thermal efficiency, and reliable performance across a range of climatic conditions. By operating on GHI, the system can effectively capture diffuse and scattered solar radiation, eliminating the need for sun-tracking mechanisms. This makes it particularly suitable for regions with variable or fluctuating solar availability. Furthermore, the integration of CPCs enhances the thermal collection efficiency of ETCs under non-ideal radiation conditions [10], making them an excellent choice for low- to medium-temperature thermal applications [1,11].

1.3.2 Thermal Energy Storage System:

The PCM employed in the TES unit is paraffin wax, selected for its low melting point, high latent heat capacity, chemical stability, and wide availability [2,7]. The paraffin wax used in this system has a melting temperature of 57 °C and a latent heat of fusion of 176 kJ/kg, making it highly suitable for low- to medium-temperature thermal applications [2].

During solar charging hours, water heated to 70 °C circulates through copper tubes embedded in the TES module. As the hot water flows through these tubes, it transfers thermal energy to the surrounding paraffin wax, causing it to melt and store energy in the form of latent heat. This stored heat is subsequently utilized during night hours to raise the temperature of return water from 40 °C to 50 °C, thereby maintaining consistent thermal output.

The heat exchanger system is designed to transfer a total of 10 kWh of thermal energy. To achieve this, a total heat transfer area of 17 m^2 was calculated and realized using copper tubing with an outer diameter of 15.87 mm. The paraffin wax layer is assumed to have a thickness of 21 mm per meter of tube length. Accordingly, a total of 93 meters of copper tubing was coiled and immersed within the liquid PCM, optimizing the surface area for heat transfer. The modular heat exchanger assembly is housed within a storage tank with dimensions of 710 mm × 550 mm × 950 mm, as depicted in Figure 2 (c) and Figure 2 (d). This design ensures effective thermal charging and discharging while maintaining system compactness and efficiency, critical for residential or off-grid thermal management applications [7, 12].

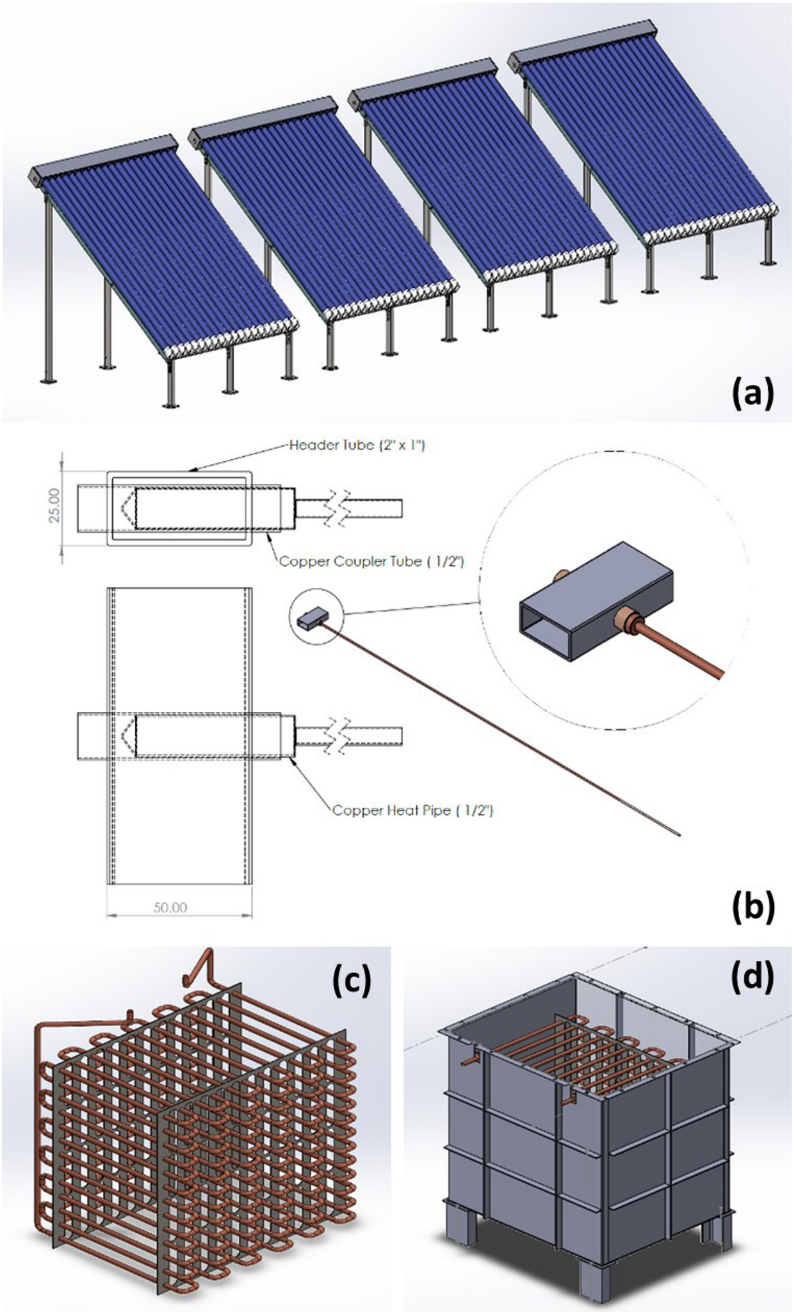


Fig. 2. (a) Evacuated Tube collectors with heat pipe configuration. (b) Heat Pipe Assembly with Header Tube. (c) Heat Exchanger Unit of TES (d) Covered PCM Heat Exchanger

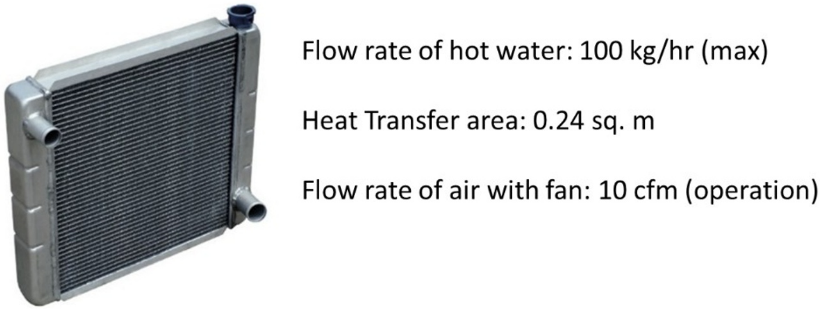


Fig. 3. Photograph of the Room Heater

1.3.3 Water Circulation System:

The water circulation system comprises a pump and solenoid valves to selectively route flow between the solar collectors and PCM module, alongside hand-operated valves for system isolation. Monitoring of critical fluid parameters is achieved via pressure gauges and flow meters [13]. All components are neatly organized within a plumbing panel, arranged as per the P&ID layout. Flexible hoses connect the solar collectors, PCM unit, and room heater to the panel, providing modular flexibility and ease of maintenance [14,15].

Operated as a closed-loop at a nominal 1.5 bar, the system incorporates a 24-liter bladder-style expansion tank to accommodate thermally induced volume variations and stabilize pressure [16]. Such tanks are widely used in solar thermal and hydronic systems to prevent overpressure and extend component life [13].

Daytime operation channels the working fluid between the PCM module and solar collectors, charging thermal energy into the PCM [14,15]. During nighttime, circulation switches between the PCM module and space heater, enabling heat release for ambient heating. This day/night switching is controlled by solenoid valves activated via time or temperature signals [17].

1.3.4 Room Heater:

A forced convection mode of heat transfer is employed to transfer thermal energy from hot water to room air. In this system, hot water flows through a finned-tube heat exchanger, which increases the effective surface area for heat transfer. A fan forces air across the heat exchanger fins, significantly enhancing convective heat transfer efficiency [18,19]. The use of extended surfaces (fins) facilitates efficient energy exchange even at relatively low fluid temperatures [20]. Such water-to-air heating modules are compact, reliable, and suitable for applications involving solar thermal or PCM-based energy storage systems [12, 21]. The schematic of the heating module is shown in Figure 3.

2 Design Methodology for PCM-Based TES Systems

The appropriate selection of PCM is a critical factor in enhancing the efficiency and performance of any TES system. In this project, paraffin wax was selected due to its moderate melting temperature, high latent heat capacity, chemical stability, and non-corrosive nature, making it highly suitable for nighttime heat delivery in low-temperature space heating applications [2, 7].

The design and thermal modelling of the PCM-based heat exchanger system involve determining the thermal load required for the maximum water mass flow rate, from which the required heat transfer area and PCM thickness are derived. These parameters are calculated considering the standard tube diameters available for fabrication. The resulting heat transfer coefficient is then used to estimate the total tube length and number of tubes required, which in turn guides the selection of the optimal tank geometry and module configuration.

In the thermal design process, the following assumptions were made:

1. Only conduction occurs between the molten PCM and the tube surface, representing the worst-case scenario for heat transfer [12].
2. Water is always present inside the tubes and serves as the heat transfer fluid, consistently transferring energy to the PCM surface.

The volume of paraffin wax required is computed based on the total thermal energy demand of the TES system. A summary of the key design parameters for the TES unit employing paraffin wax is presented in Table 2.

$$\text{Volume of PCM}=\frac{Q_{th}}{H_{PCM}}\times\frac{1}{\rho_{\,PCM}} \tag{1}$$

Using energy balance, the maximum mass flow rate inside the tubes is calculated.

$$Volume\ of\ TF=\frac{Q_{TF}}{Cp_{TF}\times(\mathrm{T}_{w2}\text{-}T_{w1})}\times\frac{1}{\rho_{TF}} \tag{2}$$

$$Velocity\ of\ TF=\frac{Volume\ of\ TF}{\frac{\pi}{4}(D_{in})^2} \tag{3}$$

Table 2. Design parameters for required PCM

1.	Enthalpy of Paraffin Wax	176 kJ / kg
2.	Mass of PCM required	204.55 kg
3.	Density of Paraffin wax	820 kg / m^3
4.	Volume of PCM required	0.25 m^3
5.	Maximum water flow	0.0239 kg /s

2.1 Charging of TES

During daytime charging, the melting point of paraffin wax was considered to be 57 °C, a value that aligns well with its typical thermal operating range in low-temperature latent heat thermal energy storage (LHTES) systems [12]. The inlet and outlet temperatures of the circulating water were observed to be 40 °C and 50 °C, respectively. Using these values, the LMTD, a key parameter for assessing heat exchanger performance was calculated to be 11.27 °C. This value provides a basis for the heat transfer rate estimation between the heat transfer fluid and the PCM. The use of paraffin wax in such applications is supported by its relatively narrow melting range, chemical stability, and high latent heat capacity, which contribute to effective energy storage and retrieval [2, 22].

$$\mathrm{LMTD} = \frac{\triangle \mathrm{Ta} - \triangle \mathrm{Tb}}{ln \triangle \mathrm{Ta} - ln \triangle \mathrm{Tb}} \tag{4}$$

$$(\triangle T_a = T_1 - T_{w1}, \triangle T_b = T_1 - T_{w2}) \tag{5}$$

2.2 Discharging of TES

In the discharging phase of the TES system, heat stored in the paraffin wax during the charging cycle is released to raise the temperature of circulating water. Assuming a worst-case thermal condition, the temperature difference (ΔT) used in the heat transfer calculation is 11.27 °C, which corresponds to the LMTD determined during system operation.

To evaluate the heat transfer rate between the PCM and the circulating water, the thermal resistance model is applied. The overall thermal resistance is the sum of three individual resistances encountered during the process:

- Case 1: Convective resistance due to water flow inside the copper tubes (internal surface)
- Case 2: Conduction resistance across the tube wall (copper material)
- Case 3: Conductive resistance through the paraffin wax (PCM module) surrounding the tubes

The total thermal resistance, as detailed in Table 3, forms the basis for computing the overall heat transfer coefficient (U-value) of the TES module. This U-value is critical for determining the thermal discharge capacity and response time of the system under varying loads and ambient conditions [12,23].

This resistance-based approach is commonly employed in the thermal modeling of PCM heat exchangers, particularly in worst-case (pure conduction) scenarios where natural convection in the PCM is negligible or absent [24].

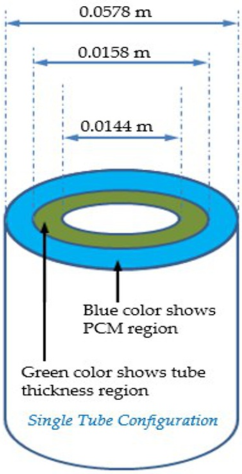


Fig. 4. The dimensions of the tube are based on salt thickness.

Fig. 5. Photograph of the Installed system.

$$PCM\ Outer\ Diameter = (2\ X\ Thickness\ of\ PCM) + D_o \tag{5}$$

$$\text{Re} = \frac{\rho_{TF} \times V_{\text{TF}} \times D_{in}}{\mu_{TF}} \tag{6}$$

$$(HTC_{TF}) = \frac{k \times 0.023 \times R_e^{0.8} \times P_r^{0.4}}{D_{in}} \tag{7}$$

$$Total\ Resistance = Resistance\ by\ PCM + Resistance\ by\ Tube + Resistance\ by\ TF \tag{8}$$

$$\text{Q} = \frac{LMTD}{Total\ Resistance} \tag{9}$$

$$Length\ of\ Tube\ = \frac{Total\ Heat\ Required}{Q} \tag{20}$$

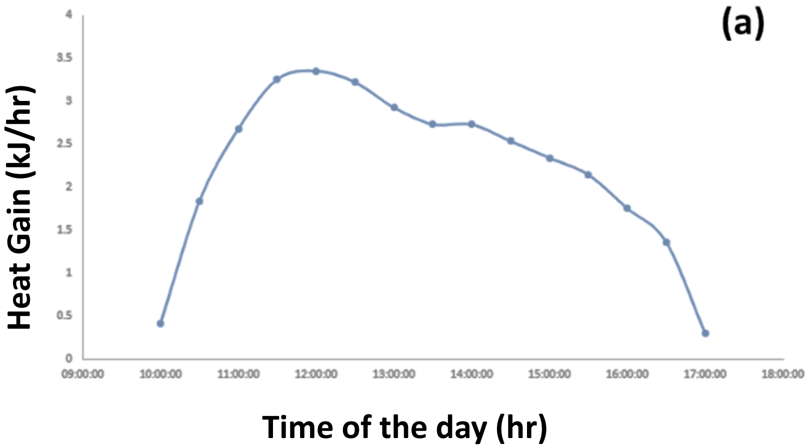
3 Result & Discussion

The system was installed and tested at NTPC NETRA, Greater Noida, during the month of December, when the daily average GHI was 2.4 kWh/m² shown in Figure 5.

The charging-discharging cycle of the system was thoroughly evaluated. During the day, solar thermal energy was collected using heat pipe-based evacuated tube collectors and stored in a paraffin-based TES unit. The TES charging period spanned from 10:00 AM to 5:00 PM. On average, approximately 16 kWh of thermal energy was stored in the TES, which was later utilized during nighttime to maintain a consistent indoor temperature. This highlights the system's improved efficiency and strong potential for practical application. Figure 6 (a) illustrates the average energy stored during the TES charging period.

Table 3. Design parameters for heat transfer

1.	Melting point temp. of Paraffin Wax	57°C
2.	Inlet temperature of Water	65 °C
3.	Outlet temperature of Water	75 °C
4.	Delta T (LMTD)	12.33 °C
5.	Tube Outlet Diameter (Standard size available, Figure 4)	0.0158 m
6.	Tube Inlet Diameter (Based on pipe schedule)	0.0144 m
7.	Reynolds number for water	2647.8
8.	Conductivity of water	0.5 W/mK
9.	Heat transfer	914.6 W/m^2K
10.	Convective heat transfer resistance (per unit length)	0.0242 mK/W
11.	Thermal conductivity of tube	398 W / mK
12.	Tube resistance (per unit length)	3.76×10^{-5}mK/W
13.	Paraffin wax thickness (based on weld gap required)	0.021 m
14.	Diameter with PCM thickness	0.0578 m
15.	Thermal conductivity of Paraffin Wax	0.2 W/mK
16.	Paraffin wax resistance	1.0323 mK/W
17.	Total resistance	1.0566 mK/W
18.	Outer diameter (based on PCM thickness)	0.0578 m
19.	Heat Transfer rate, Q	10.666 W/m
20.	Length of tube for 1 kW heat transfer	93.5 m



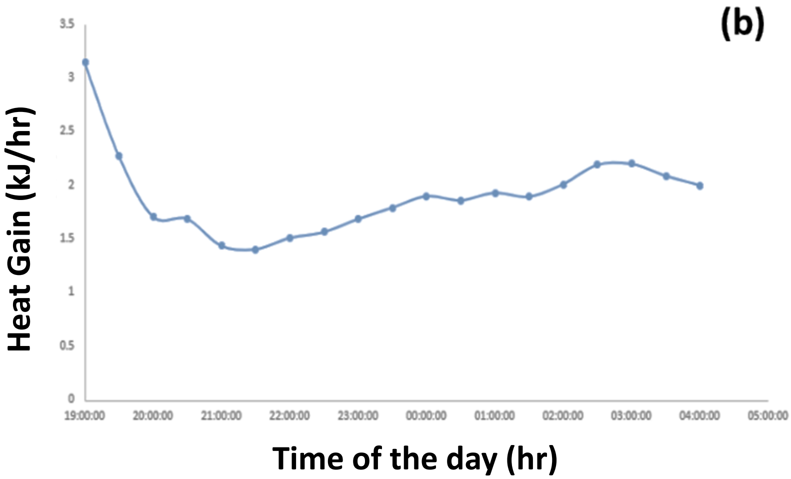


Fig. 6. (a) Plot during Charging of the system (Heat Gain v/s Time) (b) Plot during Discharging of the system (Heat Loss v/s Time).

TES heat was utilized for heating a space of 10 X 10 X 10 cubic feet during the nighttime i.e from 7:00 pm to 4:00 am to maintain the room temperature of 15 °C. Figure 6b shows the average energy released during the discharging process. Considering the charging and discharging cycle of the system, it is concluded that system would be very beneficial for the remote locations where an abundance of sunlight is available during daytime e.g., Leh etc. and nights are very cold. The system is very easy to install and maintain, which makes it feasible for domestic use in such regions. TES-enhanced solar thermal systems can play a significant role in reducing energy consumption and greenhouse gas emissions in buildings.

The successful demonstration of the prototype system, extending this system as a broader adoption of heat pump-based cooling and heating technologies across its townships to substantially reduce overall electricity consumption is under consideration. As an initial strategic move in this direction, developing and demonstrating a 140 TR solar thermal and thermal energy storage-based 24x7 air conditioning system for a hospital is being envisaged. The system will comprise of a CPC, positioned beneath the ETC to improve thermal energy capture efficiency. The new project aims to establish a sustainable and energy-efficient HVAC solution that utilizes solar energy and advanced thermal storage to provide continuous operation both day and night.

4 Conclusion

i. Solar space heating presents a sustainable solution for maintaining indoor thermal comfort by utilizing the solar thermal energy.
ii. The present study has demonstrated a cost effective active solar space heating system that integrates heat pipe base evacuated tube collectors and uses paraffin wax as working fluid. The system has successfully demonstrated night time space heating.
iii. Field implementation demonstrated an energy storage capacity of approximately 16 kWh under an average Global Horizontal Irradiance (GHI) of 2.4 kWh/m², effectively maintaining consistent indoor temperatures throughout the night.

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