

Utilizing PCM-Based Thermal Energy Storage System for Developing Sustainable HVAC Solution[#]

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ABSTRACT

Buildings account for around 40% of the world's primary energy consumption. The growing energy demand from the building sector highlights the critical need for sustainable heating, ventilation, and air conditioning (HVAC) systems that can maintain occupant thermal comfort at a lower energy cost. This study focuses on utilizing a PCM-based thermal energy storage (TES) system for developing a sustainable HVAC solution. For this, the thermal performance of the shell-and-multi-tube TES system was evaluated experimentally during HVAC operation. The TES achieved mean temperatures of 117-124°C and 55-67°C at the end of subsequent charging and discharging cycles, respectively. With the application of the TES system and proper water flow rate regulation, the heating capacity of the HVAC system can be varied between 4.12 kW and 2.76 kW, based on load requirement. The thermal comfort analysis of the TES coupled fan coil unit (TES-FCU) system showed that higher FCU water flow rates improve heat transfer and help in achieving indoor temperatures of up to 23.42°C, with 40.86% relative humidity. Out of the 5 operating cases tested, case 1 (PMV: -0.09, PPD: 5%) and case 2 (PMV: -0.39, PPD: 8%) complied with ASHRAE 55 thermal comfort standards for Delhi's winter climate. The results demonstrated the importance of the TES system, FCU speed, and water flow rate for achieving thermal comfort and sustainable heating solutions for cold regions.

Keywords: phase change material, thermal energy storage, sustainable, cold regions, HVAC.

NONMENCLATURE

Abbreviations

LPM	Liter per minute
PMV	Predicted Mean Vote
PPD	Percentage of People Dissatisfied
VFD	Variable Frequency Drives

Symbols

M	Metabolic rate (W/m ²)
o	Outdoor
in	Indoor
avg	Average

1. INTRODUCTION

The building sector is responsible for nearly 40% of global primary energy use [1,2]. Heating, ventilation, and air conditioning (HVAC) systems account for approximately 54% of the total energy demand from the building sector [3]. Household thermal comfort needs contribute to around 6.7% of the world's energy demand [4], making the optimization of HVAC systems a central focus in energy-saving strategies [5,6]. This study contributes to the global discourse on the growing energy demand and aims to develop low-carbon, energy-efficient, sustainable HVAC solutions for providing thermal comfort to the occupants across the world at lower energy levels.

Despite the widespread use of HVAC systems in buildings and the recognized potential of Fan Coil Units (FCUs) in enhancing energy efficiency [7], there remains a significant research gap in evaluating their performance when integrated with TES systems. This study addresses the critical gap in practical research and develops a TES-coupled FCU system that reduces reliance on conventional heating systems and improves energy efficiency and thermal comfort.

The study focuses on providing a sustainable space heating solution for cold climate regions. Delhi falls in the composite climate zone, experiencing extreme seasonal variations with cold, dry winters and hot, dry summers. The winter season of Delhi provided a realistic context for testing the space heating potential of the newly designed TES-coupled HVAC system. For this purpose, a lab-scale experimental setup was designed and tested at

IIT Delhi (Latitude: 28.55°N, Longitude: 77.11°E), as shown in Figure 1. The room measurements are 20 ft × 15 ft × 12 ft (length × width × height). The thermal properties of the room envelope are as follows: wall (2.28 W/m²K), roof (1.76 W/m²K), floor (0.8 W/m²K), and window (5.27 W/m²K).

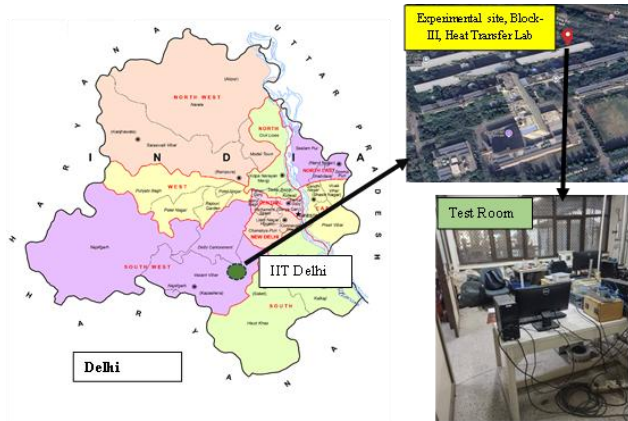


Fig. 1 Location of the experimental test room.

1.1 Research Objectives

This study experimentally analyzes the performance of a novel TES-FCU system and explores the combined effects of design and control parameters, such as TES temperature, flow rate, and the temperature difference (ΔT) between the supply and return water, on energy efficiency and occupant comfort, using real-time data collection. It also aims to enhance thermal comfort under dynamic heating loads.

2. MATERIALS AND METHODS

The TES-FCU system integrates several advanced components and technologies to improve indoor thermal comfort and energy efficiency in space heating applications. The layout of the installed TES-FCU system is shown in Figure 2.

The heat transfer fluid (Dowtherm™ RP) was used to circulate heat between the oil heater and TES system due to its high thermal stability and superior heat exchange characteristics. A shell and multi-tube type TES system has been utilized to store thermal energy in latent form using paraffin wax (PCM). This PCM has a high latent heat of 117 kJ/kg, a melting temperature of 80°C, which enables it to absorb and release substantial energy during phase transitions, thereby reducing the peak energy demand and enhancing indoor temperature stability. Fan Coil Units (Carrier 40HP18) were selected due to their wide heating capacity range up to 6.3 kW, and compatibility with hot water temperatures of 30°C–70°C. FCUs allowed zonal heating, making the system more responsive and efficient compared to all-air systems. The control panel was equipped with safety switches, VFDs, relays, and indicators, enabling precise system monitoring and automated control of the pumps, heaters, and FCUs. This central control system helped maintain the desired heat transfer fluid and hot water temperatures while minimizing manual intervention. Other key components included oil and water pumps with VFDs to control flow rates and pressure heads, and expansion tanks that managed volumetric changes in fluid due to thermal expansion.

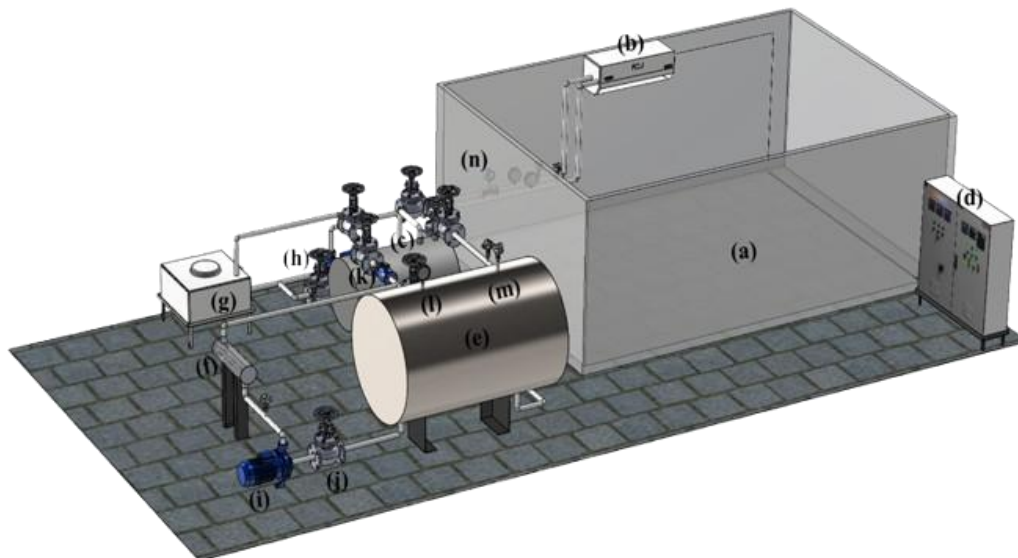


Fig. 2 3-D drawing of the installed TES-FCU system: (a) Test room, (b) FCU, (c) PCM-based thermal energy storage, (d) Control Panel with Pump VFDs, (e) Oil Expansion Tank, (f) Heater, (g) Water Tank, (h) Water Pump, (i) Oil Pump, (j) Globe valves, (k) Non-return valves, (l) Diaphragm gauge, (m) Thermocouple, (n) Flowmeter.

Overall, the TES-coupled FCU system was designed to:

- Achieve efficient charging and discharging cycles of the TES system.
- Provide precise control and design parameters for indoor temperature control.
- Lower operational energy demand.
- Enhance the thermal comfort in space heating applications.

2.1 Testing and Performance Tuning

The system was designed with a focus on integrating latent heat thermal storage with hydronic heating. Therefore, various subcomponents required for developing the TES-FCU system were selected based on compatibility, thermal load, heating capacity, and operating temperature range requirements. A TES system was fabricated using SS316 stainless steel. It included 20 charging and 17 discharging tubes of 12.5 mm diameter, strategically designed for optimal heat transfer during charging and discharging cycles. The TES system was integrated with the oil heater and fluid circulation circuit. The PCM (192 kg of paraffin wax) was filled into the TES system. A wall-mounted FCU system was selected for space heating applications in the test space. Then, the control panel was installed and connected with all electrical components for achieving centralized control operation.



Fig. 3 Installed TES-FCU system at the heat transfer lab, IIT Delhi.

The system was charged by heating the oil using a heater. The hot oil was transferred to the TES during the charging phase. In the discharging phase, the stored heat of TES was used to supply hot water to the FCUs for space heating. Various variable frequency drives (VFDs) were employed to dynamically adjust pump speeds and maintain consistent flow, pressure balance, and operating temperature. Compact layout and rockwool insulation material were used to minimize heat losses in the circuit. For safety concerns related to high-

temperature fluid handling, emergency push buttons, safety relays, and auto-shutoff valves were incorporated within the control panel. The picture of the installed TES-FCU system is shown in Figure 3. The TES-FCU system was operated continuously for 5 hours per day, with data recorded at 5-minute intervals. System performance was evaluated across five test cases, each corresponding to a High FCU speed (1000 m³/h) and a different water flow rate, decreasing from 7 LPM in Case 1 to 3 LPM in Case 5. The experimental study demonstrated the feasibility of integrating TES with hydronic FCUs in high-performance space heating.

3. MEASUREMENT AND CALCULATION

To evaluate the performance of the TES-FCU system, several precise measuring instruments were employed. These instruments recorded parameters such as air velocity, water flow rate, temperature, relative humidity, pressure drop, and power consumption, as shown in Figure 4. Each instrument was selected based on its range, resolution, and measurement uncertainty to ensure high accuracy and reliability in the data collection process.



Fig. 4 Measuring instruments: (a) Hot wire anemometer, (b) Vane-type anemometer, (c) Turbine flowmeter, (d) Thermal hygrometer, (e) T-type thermocouple, (f) K-type thermocouple, (g) Wi-Fi smart plug, (h) Diaphragm gauge, (i) Air quality probe.

Air velocity was measured using two instruments: a hot-wire anemometer (Testo 405i) with a measurement range of 0 to 30 m/s and an uncertainty of ± 0.1 m/s, and a vane-type anemometer (Testo 410i) covering 0.4 to 30 m/s with ± 0.2 m/s uncertainty. The water flow rate in the system was recorded using a turbine-type flowmeter

(Rockwin make) with a range of 0 to 35 LPM and an uncertainty of ± 0.1 LPM. Indoor temperature and relative humidity were monitored using thermal hygrometers (Testo 174H), which operate within a range of -20°C to 70°C for temperature and 0 to 100% for RH, with uncertainties of $\pm 0.5^{\circ}\text{C}$ and $\pm 3\%$ RH, respectively. For detailed thermal mapping, both T-type and K-type thermocouples (Tempens) were employed. T-type thermocouples measured indoor air and FCU delivery air temperatures within the range of 0 to 250°C , while K-type thermocouples, used for thermal energy storage and heat transfer fluids, covered up to 500°C . Both types had a measurement uncertainty of $\pm 0.5^{\circ}\text{C}$. Electrical power consumption of system components was tracked using a Wi-Fi smart plug, which measures loads up to 2000 W with a resolution of 0.1 W. Pressure values in the supply and return lines were monitored using diaphragm gauges with a range of 0 to 100 psi and an uncertainty of ± 1 psi. Indoor air quality was assessed using a Testo air quality probe, capable of measuring temperature and RH with uncertainties of $\pm 0.5^{\circ}\text{C}$ and $\pm 1.8\%$ RH, and $\pm 3\%$ of the measured value. These instruments enabled accurate and reliable data collection for performance analysis.

3.1 Data Acquisition System

A comprehensive monitoring system with thermocouples, flow meters, pressure gauges, and control sensors was implemented to ensure real-time data acquisition during operation.

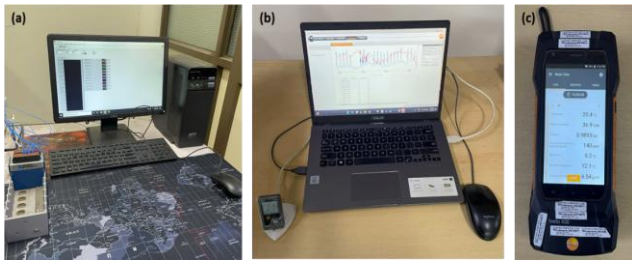


Fig. 5 Data Acquisition System: (a) National Instruments (NI) Data acquisition (DAQ) system, (b) Thermal hygrometer data logger, (c) Indoor air quality measuring probes data logger.

All thermocouples were interfaced with a National Instruments (NI) Data Acquisition (DAQ) system for temperature logging. Testo 174H sensors were used with an integrated data logger for humidity monitoring. Data was processed using the ComSoft Basic software. The Testo 400 multi-probe system was utilized for indoor environmental monitoring, which captured air velocity, temperature, humidity, and pressure. Real-time data was logged at 5-minute intervals. The recorded data

were systematically analyzed using time-series plotting and performance benchmarking, as shown in Figure 5. Temperature trends from thermocouples were correlated with flow, velocity, and indoor air quality to assess the TES-FCU system's performance under various conditions. Instrument calibration and adherence to international standards ensured the validity and reproducibility of the experimental outcomes.

3.2 Performance Indicators

The efficacy of the TES-FCU system was studied using different performance indices: operative comfort temperature (T_{comfort}), PMV and PPD values, heating capacity of fan coil units (Q_{FCUs}), and standard deviation (SD) of indoor temperature during operating hours. The fundamental equation for various performance indicators is defined as [8]:

$$T_{\text{comfort}} = 0.31 \times T_O + 17.8 \quad (1)$$

$$PMV = (0.303e^{-0.036M} + 0.028) \times L \quad (2)$$

$$PPD = 100 - 95e^{-(0.3353PMV^4 + 0.2179PMV^2)} \quad (3)$$

$$Q_{\text{FCUs}} = \dot{m}(h_1 - h_2) \quad (4)$$

$$SD = \sqrt{\frac{\sum_{i=1}^{i=5} (T_{\text{in},i} - T_{\text{avg}})^2}{n}} \quad (5)$$

Where, T_O is the outside average air temperature ($^{\circ}\text{C}$); L is the thermal load on the body of an occupant (W/m^2); \dot{m} is the supplied air mass flow rate of FCUs in kg/s ; h_1 is the enthalpy at the supply air outlet in $\text{kJ}/(\text{kgK})$; h_2 is the enthalpy at the return air in $\text{kJ}/(\text{kgK})$; $T_{\text{in},i}$ is the indoor air temperature ($^{\circ}\text{C}$) at the i^{th} hour of the test; T_{avg} is the average indoor temperature ($^{\circ}\text{C}$) during the test; and n is the population size of the measurement.

4. RESULTS AND DISCUSSION

4.1 Thermal performance analysis of TES system

The TES-FCU system uses paraffin RT 80 (PCM) for space heating and operates for a 5-hour discharging and 4-hour charging cycle every day, followed by a 15-hour idle period. Because of PCM's low thermal conductivity, temperature readings showed non-uniform phase transitions because of buoyancy effects. The thermal behavior of the TES was studied at every time step during the subsequent charging and discharging cycles, as shown in Figure 6.

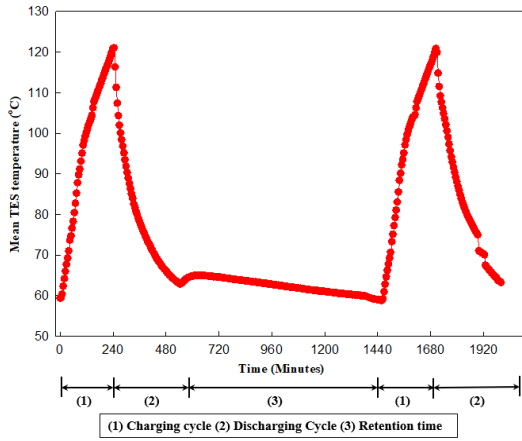


Fig. 6 Mean temperature variation of the TES system during cases 4 and 5.

The TES achieved a mean temperature in the range of 117-124°C at the end of the charging cycles, and 55-67°C after the end of the discharging cycles. A very small temperature drop of less than 5°C occurred during the idle phase, suggesting low losses and adequate insulation. The system's capability for long-duration room heating in cold areas is confirmed by its stable thermal behavior, effective heat retention, and repetitive charging/discharging cycles.

4.2 Thermal comfort analysis of the TES-FCU system

According to the performance analysis, variations in water flow rates caused notable variations in indoor air temperature and relative humidity. The TES coupled FCU system exhibited faster and more efficient heat transfer at higher water flow rates, resulting from increased Logarithmic mean temperature difference values at higher flow rates. Case 1 (7 LPM) had the greatest mean interior temperature of 23.42°C, while case 5 (3 LPM) had the lowest mean interior temperature of 20.16°C. Additionally, drier air was provided by higher flow rates, which decreased relative humidity (RH). Case 1 had the lowest mean relative humidity of 40.86%, whereas Case 5 had the greatest mean relative humidity of 54.19%. These findings underscore the importance of optimizing water flow rates to strike a balance between energy efficiency, humidity control, and efficient space heating. The indoor air temperature and relative humidity variation with time are shown in Figures 7(a) and 7(b), respectively. These findings highlight the necessity of water flow rate optimization to strike a balance between energy economy, humidity control, and efficient space heating.

The thermal comfort indices values were evaluated using Fanger's PMV and PPD models. The findings show

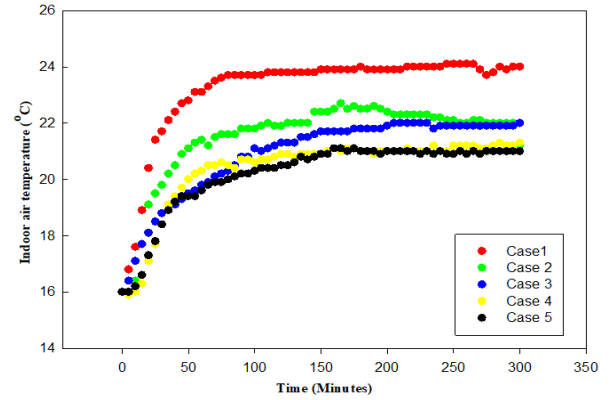


Fig. 7(a) Indoor air temperature.

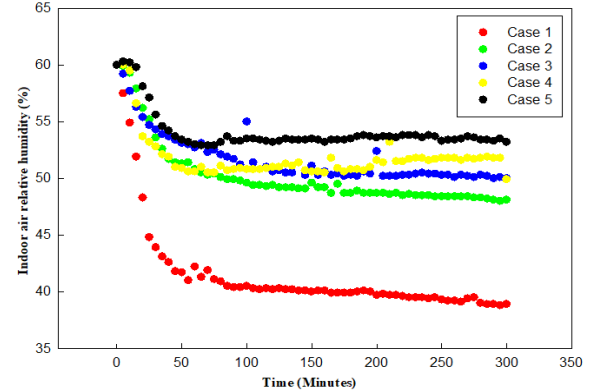


Fig. 7(b) Relative humidity variation with time.

that the water flow rate has a major impact on the thermal comfort of the occupants (as shown in Figure 8). Out of the 5 different cases, only Case 1 (PMV: -0.09, PPD: 5%) and Case 2 (PMV: -0.39, PPD: 8%) satisfied ASHRAE 55 requirements, indicating neutral comfort. Case 5 had a slightly cooler thermal comfort sensation (PMV: -0.75, PPD: 17%) as compared to the other cases. Across a range of flow rates, the room temperature standard deviation varied from 0.4°C at 7 LPM to 0.7°C at 3 LPM. Smaller SD values at higher flow rates show thermal uniformity, greater temperature stability, and less fluctuation as compared to lower flow rate cases.

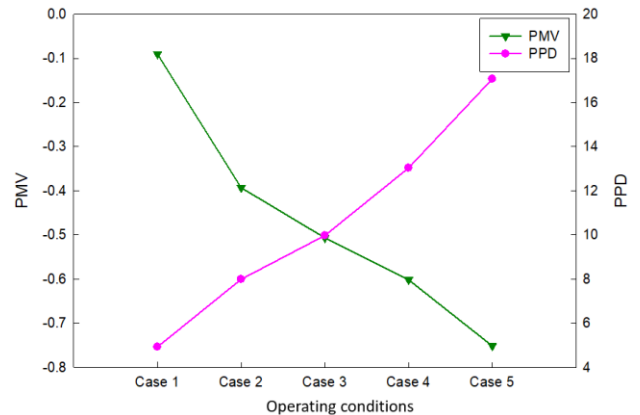


Fig. 8 PMV and PPD values variations under different operating conditions.

Figure 9 highlights the heating capacity variations of the TES-FCU system under different operating conditions. It was discovered that the water flow rate increased the heating capacity. The heating capacity was reduced by 12.13% when the flow rate decreased from 7 LPM to 6 LPM at high FCU speed (1000 m³/h). Case 1 (7 LPM) has the highest capacity of 4.12 kW, while Case 5 (3 LPM) has the lowest heating capacity of 2.76 kW. These results demonstrate that heating performance may be efficiently controlled based on heating demand by varying FCU speed and hot water flow rate. The novel TES-coupled HVAC system offers a viable foundation for sustainable space heating in cold regions.

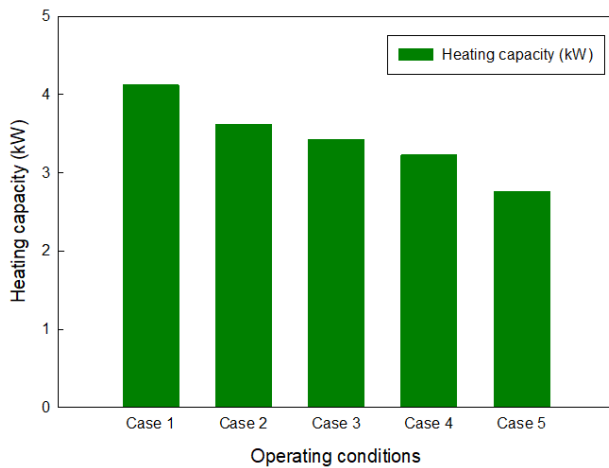


Fig. 9 Heating capacity variations under different operating conditions.

4.3 Future Scope and Recommendation

To improve energy efficiency and thermal comfort, future research can concentrate on incorporating intelligent control systems that dynamically adjust water flow, supply temperature, and FCU speed based on occupancy patterns and outdoor conditions. Performance and adaptability can be further enhanced by incorporating air circulation and alternate phase change materials (PCMs) with greater heat storage capacity. The TES coupled system can become more resilient, tackling issues like decreased relative humidity during heating and using solar energy for thermal storage during the day and heat transmission during non-sunshine hours. The system's wider application can be supported by numerical optimization studies that consider energy consumption, cost-effectiveness, and environmental effects into account. This will assist the system's long-term survivability, scalability, and reproducibility.

ACKNOWLEDGMENT

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