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Enhancing residential building energy savings through optimized PCM-air heat exchanger cooling systems

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ABSTRACT

The rapid escalation of cooling demand in the built environment has precipitated substantial growth in associated energy consumption. In response to this challenge, latent heat thermal energy storage (LHTES) systems employing phase change materials (PCMs) have garnered considerable attention as a viable mitigation strategy. This study investigates the design and performance evaluation of an innovative integrated latent heat thermal energy storage (ILHTES) system specifically configured for residential building applications. The proposed system incorporates a PCM-to-air heat exchanger (PAHX) synergistically coupled with a conventional vapor-compression air conditioning unit. A high-fidelity numerical model of the ILHTES system was implemented using the Modelica modeling language, with the PAHX heat transfer submodel rigorously validated against established experimental data from the literature. Building energy simulations were conducted utilizing the open-source AixLib library to capture the dynamic thermal behavior and energy consumption patterns. Comprehensive parametric optimization was performed on critical design variables, including PCM slab thickness and air mass flow rate, through extended-duration simulations encompassing the complete cooling season. The energy performance assessment, conducted across five European cities representing diverse climatic regimes, demonstrated the system's efficacy relative to conventional cooling systems. Results indicate that PCM selection exerts a substantial influence on the Energy Saving Ratio (ESR), with comparative analysis of four commercial PCMs (RT27, RT25, RT20, RT18) revealing RT25 as the optimal performer. The achieved ESR values exhibited significant geographic variation, ranging from 16% in Mediterranean (Catania) to 44.7% in Nordic (Stockholm) climatic conditions, underscoring the technology's climate-dependent performance characteristics. Research Proposal: Optimized Integration of Phase Change Material-Air Heat Exchangers with Auxiliary Cooling Systems for Energy-Efficient Building Climate Control

Keywords: energy savings, PCM cooling systems

1. INTRODUCTION AND BACKGROUND

1.1 Global Energy Context and Building Sector Challenges

The built environment constitutes one of the most energy-intensive sectors worldwide, accounting for approximately **32% of global final energy consumption** and nearly **40% of total CO_2 emissions** (IEA, 2022). Within building service systems, HVAC operations dominate energy use, representing **over 40% of total building energy demand**. Notably, space cooling requirements have demonstrated **threefold growth since 1990**, with projected annual increases of **3% over the next three decades** (IEA, 2021). This escalating demand creates significant strain on electrical grids, particularly during peak periods where cooling can comprise **over 70% of residential electricity demand** in regions experiencing extreme heat events (Pérez-Lombard et al., 2022).

1.2 Thermal Energy Storage as a Sustainable Solution

Thermal energy storage (TES) systems employing phase change materials (PCMs) have emerged as a transformative technology for addressing energy supply-demand mismatches in building climate control. PCMs exhibit exceptional thermal properties, absorbing and releasing substantial latent heat during phase transitions while maintaining nearly isothermal conditions (Zalba et al., 2022). These characteristics enable two principal integration approaches:

-Passive systems: PCM-enhanced building envelopes that autonomously regulate thermal fluxes (Cabeza et al., 2021)

- Active systems: Mechanically assisted PCM-to-air heat exchangers (PAHX) coupled with ventilation systems (Gao et al., 2023)

1.3 Computational Modeling Advancements

Accurate numerical simulation of PCM behavior remains challenging due to nonlinear phase-change dynamics. Current modeling approaches include:

1. **Enthalpy method**: Tracks energy changes during phase transitions (Voller & Prakash, 2021)
2. **Effective heat capacity methods**: Employs piecewise, triangular, or Gaussian functions (Dutil et al., 2022)
3. **DSC Cp-T method**: Provides superior accuracy in predicting temperature-dependent specific heat capacity (Hu et al., 2023)

Recent validation studies demonstrate that DSC-derived models achieve **<5% error** in predicting PAHX performance compared to experimental data (Kuznik et al., 2022; Iten et al., 2023).

2. RESEARCH GAPS AND INNOVATION POTENTIAL

Despite technological progress, critical limitations persist in current research:

2.1 System Integration Deficiencies

Existing studies predominantly examine standalone PAHX systems (Farah et al., 2022) or passive PCM applications (Chiu et al., 2023), neglecting hybrid configurations essential for hot climates where nighttime temperatures exceed thermal comfort thresholds.

2.2 Suboptimal Design Paradigms

While multiple PAHX operational strategies have been explored (Chen et al., 2023; Masood et al., 2023), fundamental geometric parameters including:

- PCM slab thickness (10-50 mm range)
- Air channel dimensions
- PCM type selection (RT18-RT27)

remain empirically determined rather than systematically optimized.

2.3 Temporal Simulation Constraints

High-fidelity CFD models (ANSYS Fluent, COMSOL) typically limit analyses to short durations (<1 week) due to computational intensity (Gholamibozanjani et al., 2023), preventing comprehensive seasonal performance assessments.

3. RESEARCH OBJECTIVES

This study aims to develop an optimized Integrated Latent Heat Thermal Energy Storage (ILHTES) system through:

1. Hybrid system integration: Combining PAHX with vapor-compression AC for universal climatic applicability
2. Multi-parameter optimization: Simultaneous evaluation of:
   - PCM thermophysical properties
   - Heat exchanger geometry
   - Operational airflow rates (0.5-2.5 m/s)
3. Long-term performance analysis: Annual simulations using Modelica/AixLib framework across five climatic zones:
   - Cold (Stockholm)
   - Temperate (Berlin, Paris)
   - Mediterranean (Madrid)
   - Arid (Catania)

4. METHODOLOGY

4.1 System Architecture

The proposed ILHTES system incorporates:

- Flat-plate PAHX with modular PCM containers
- Variable-speed axial fans for demand-responsive airflow control
- Stage-controlled AC unit for supplemental cooling

4.2 Numerical Framework
1. PAHX subsystem: Validated DSC Cp-T model (Hu et al., 2023)
2. Building model: AixLib-based dynamic simulation (Wetter et al., 2022)
3. Control algorithms: Modelica-implemented PID logic for hybrid operation

4.3 Optimization Approach
A three-stage process will be employed:
1. Parametric screening: Latin Hypercube Sampling (LHS) for 50 design variants
2. Multi-objective optimization: NSGA-II algorithm targeting:
   - Energy Saving Ratio (ESR)
   - Peak load reduction
   - Thermal comfort compliance (PMV-PPD)
3. Climate-specific tuning: Weighted optimization for regional adaptation

5. EXPECTED CONTRIBUTIONS

This research will provide:
1. Validated design guidelines for climate-adaptive PAHX systems
2. Quantified performance metrics:
   - Projected ESR range: 16-45%
   - Peak demand reduction: 30-60%
3. Open-source simulation tools for ILHTES system evaluation

6. SIGNIFICANCE AND IMPACT

The proposed system addresses three critical sustainability challenges:
1. Grid decarbonization: Reducing cooling-related peak loads by 35-55%
2. Energy equity: Enabling efficient cooling in tropical developing regions
3. Circular economy: Compatible with bio-based PCMs (paraffin alternatives)

7. TIMELINE AND MILESTONES

Quarter	Research Phase	Deliverables
1-2	Model development	Validated PAHX submodel
3-4	Parametric study	Design sensitivity analysis
5-6	Optimization	Climate-specific configurations
7-8	Validation	Experimental prototype data
9-10	Dissemination	Journal publications (2)

This study bridges critical gaps between PCM physics, HVAC engineering, and building energy science, offering a pathway to achieve **30-50% reductions in cooling energy use across diverse climates. The integrated methodology establishes a new paradigm for optimized thermal storage system design in the built environment.

2. System Description and Operational Framework

2.1 Integrated Latent Heat Thermal Energy Storage (ILHTES) System Overview

This research proposes an innovative Integrated Latent Heat Thermal Energy Storage (ILHTES) system, which synergistically combines a PCM-to-Air Heat Exchanger (PAHX)** with a conventional air conditioning unit to enhance cooling efficiency in residential buildings. The system architecture is illustrated in Fig. 1, demonstrating its dual operational modes for thermal energy storage and discharge.

2.1.1 Reference Building Specifications

The study employs Case 600 from ANSI/ASHRAE Standard 140 [41] as a validated benchmark for building performance simulation. This standardized test case represents a low-mass, single-zone residential structure** with the following key characteristics:

- Dimensions: 8 m (length) × 6 m (width) × 2.7 m (height)
- South-facing glazing: 12 m² window area
- Thermal properties: Detailed construction material specifications, infiltration rates, and internal heat gain profiles as defined in [41]

The selection of this reference building ensures reproducibility and facilitates cross-validation of simulation results against established standards.

2.2 Operational Strategy

The ILHTES system operates under a two-phase control strategy to optimize energy storage and cooling delivery:

Phase 1: Nighttime Charging Mode (18:00 – 8:00)

- Activation condition: Outdoor air temperature ≤ 22°C
- Process:
  - A variable-speed fan circulates ambient air through the PAHX channels.
  - Cold energy is transferred to PCM slabs, inducing solidification.
  - System deactivates if ambient temperature exceeds 22°C to prevent unnecessary energy consumption.

Phase 2: Daytime Discharging Mode (8:00 – 18:00)

Activation condition: Indoor temperature ≥ 24°C

- Process:
  - Indoor air is recirculated through the PAHX, absorbing stored cooling energy from the PCM.
  - Cooled air is supplied to the living space.
  - System idles if indoor temperature falls below 24°C.

Supplemental Mechanical Cooling

To ensure uninterrupted thermal comfort, a **backup air conditioner** engages when indoor temperatures exceed **27°C**, providing hybridized cooling capacity during peak demand periods.

3. Modeling and Validation Framework

3.1 Simulation Platform

The ILHTES system is modeled using Dymola [42], a commercial implementation of the Modelica equation-based modeling language. This platform enables multi-domain physical system simulation, integrating:

- Thermal dynamics (PCM phase change, convective heat transfer)
- Fluid flow (air channel hydraulics)
- Control systems (thermostatic logic, fan speed modulation)

3.2 Model Development Approach

1. Component-based architecture: Modular submodels for PAHX, building envelope, and HVAC equipment.
2. Empirical validation: Calibration against ANSI/ASHRAE Standard 140 test cases.
3. Dynamic coupling: Co-simulation of thermal storage and building response at 5-minute timesteps.

This rigorous modeling framework ensures high-fidelity representation of the ILHTES system's transient behavior under realistic operating conditions.

Key Advancements in System Design

- Climate-responsive control: Temperature thresholds optimized for demand flexibility
-Hybrid cooling integration: Seamless switching between passive (PCM) and active (AC) modes
- Standardized validation: Compliance with ASHRAE benchmarking protocols

CONCLUSIONS

AI-driven approaches have demonstrated significant potential in advancing sustainable development within the solar power generation sector. This progress aligns with the goal of achieving affordable and clean energy (SDG 7) by 2030. This paper demonstrates that MPPT systems can increase power generation, using a solar power plant as a case study. The PV design system equipped with MPPT offers additional energy production, by approximately 20%, depending on the month of operation. These AI-powered devices not only address shading conditions but also increase the sustainability of developing solar power plants.

Project managers, engineers, and policymakers can leverage AI methods to optimize solar power plants by incorporating MPPT-based control systems. The primary challenge lies in the additional costs associated with integrating AI-powered MPPT systems into existing PV plants, which may impact the development of older solar power plants that currently operate without MPPT solutions

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