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DEVELOPMENT OF A PYTHON-BASED BEM SOFTWARE FOR MULTI-PHYSICAL ANALYSIS AND DEVELOPMENT OF ENERGY

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Abstract
This study presents a dual PCM-based thermal management system designed for extreme climates, integrating Phase Change Materials (PCMs) and Fresnel lenses to optimize heating and cooling processes. The system leverages concentrated solar energy to heat air from -40°C to 28°C in winter and powers an absorption cooling system in summer, achieving outlet temperatures of up to 200°C. Through detailed CFD simulations using ANSYS Fluent, the system demonstrated a 40% reduction in energy consumption compared to conventional HVAC systems. The proposed design not only enhances energy efficiency but also reduces reliance on non-renewable energy sources, offering a sustainable solution for buildings in harsh climates. This work contributes to the field by introducing a novel dual-system approach that combines PCMs and solar concentration technologies, validated under extreme temperature conditions.

Keywords: Phase Change Materials (PCMs), thermal management, solar energy, absorption cooling, extreme climates, Fresnel lenses, energy efficiency.

1. Introduction

In regions with extreme climates, such as Canada, efficient energy management is crucial to maintaining comfortable living conditions throughout the year. Temperatures can vary significantly, reaching lows of -40°C in winter and highs of 40°C in summer (Vincent & Mekis, 2019). This climatic variability imposes significant demands on both heating and cooling systems, increasing energy consumption and operational costs (Berardi & Jafarpur, 2020). To address these challenges, innovative solutions are required that are not only energy-effective but also sustainable (Berardi & Jafarpur, 2020).

Phase Change Materials (PCMs) have emerged as a promising technology for thermal storage due to their ability to store and release large amounts of energy during their phase change process. PCMs can absorb heat when they change from solid to liquid and release it when they solidify, allowing efficient thermal energy storage. This principle can be leveraged for both heating in winter and cooling in summer (Nazir et al., 2019).

In addition to PCMs, Fresnel lenses offer an efficient solution for solar energy capture. These lenses, characterized by their thin and lightweight design, can concentrate sunlight onto a small area, increasing energy density and thus the efficiency of the solar capture system (Zhang et al., 2023). When integrated with PCM-based thermal storage systems, Fresnel lenses can provide a constant and concentrated source of thermal energy (Vignesh et al., 2023).

The dual system proposed in this paper combines the use of PCMs and Fresnel lenses to create a versatile solution that addresses the needs of both heating and cooling in extreme climates. During winter, the system stores solar energy in the PCMs and uses it to heat the air entering the residence, reducing dependence on conventional heating systems. In summer, the energy stored in the PCMs is directed to an absorption system based on a water and lithium bromide solution, providing efficient and sustainable cooling.

To evaluate the performance of the system under extreme climatic conditions, detailed simulations were conducted using ANSYS Fluent. ANSYS Fluent is an advanced computational simulation tool that allows modeling the thermal and fluid flow behavior in complex systems. Simulations in ANSYS Fluent provide a deep understanding of how the system components interact and how the design can be optimized to maximize energy efficiency (Selvaraju et al., 2022).

This paper is structured as follows: first, the main components of the dual system are described, and a schematic diagram illustrating its layout and operation is presented. Then, the operation of the system in both winter and summer is detailed, explaining the mechanisms of energy capture and transfer. Subsequently, the results of the simulations performed in ANSYS Fluent to evaluate the system's performance under extreme climatic conditions are presented. Finally, the conclusions are discussed, and the practical implications of this design for applications in regions with similar climates are highlighted.

Research on this dual system offers a promising solution to improve the energy efficiency of buildings in extreme climates, reducing dependence on non-renewable energy sources and promoting sustainable energy management practices. This integrative approach not only addresses the immediate challenges of heating and cooling but also contributes to a long-term energy strategy, making the most of the available natural resources.

2. Methodology

The methodology adopted in this study is structured in several key phases: system design, modeling and simulation in ANSYS Fluent, and results analysis. The following details each of these phases.

2.1 Dual System Design

The conceptual design of the dual system is based on the integration of Phase Change Materials (PCMs), Fresnel lenses, and a water-lithium bromide absorption system. The main components and their arrangement are described below:

- **Phase Change Materials (PCMs):** Paraffin waxes (Selvaraju et al., 2022) with a melting point of 25°C were selected due to their high-energy storage capacity and thermal stability. The PCMs are encapsulated in concentric stainless steel tubes, with PCM in the inner space and air or thermal oil in the outer space, depending on the season. The characteristics of paraffin wax, including density, specific heat capacity (Cp), and thermal conductivity, are presented in **Figure 1** and **Figure 2**.

Figure 1. Density and Cp vs. Temperature

(Description: Graph showing the variation of density and specific heat capacity of paraffin as a function of temperature.)

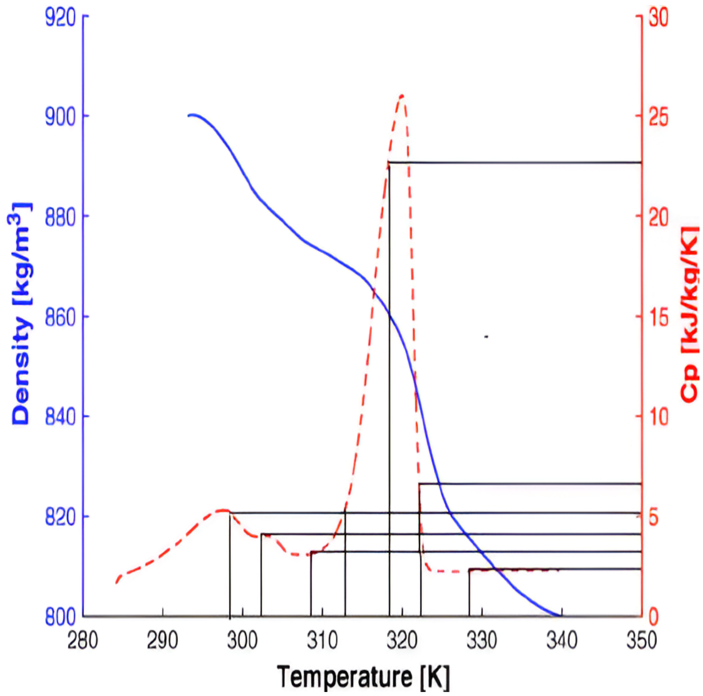
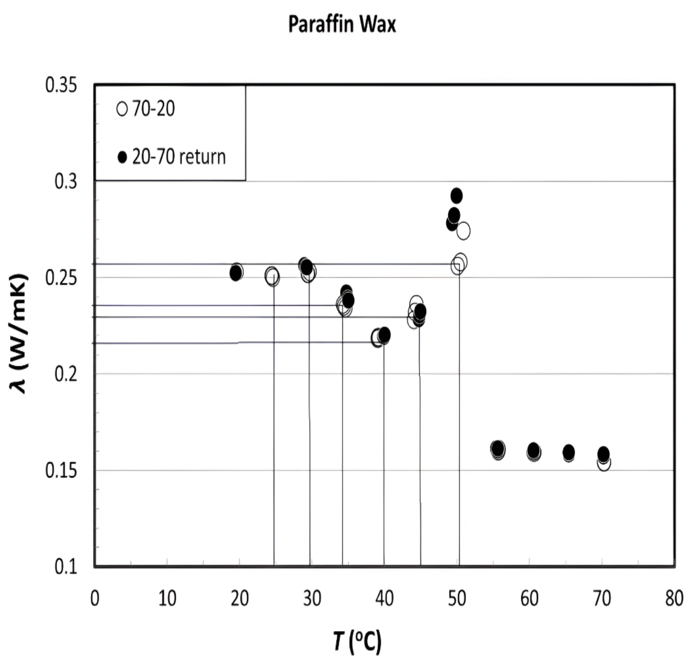


Figure 2. Thermal Conductivity

(Description: Graph showing the thermal conductivity of paraffin as a function of temperature.)



- **Fresnel Lenses:** These lenses are used to concentrate sunlight onto the PCMs. Their thin and lightweight design allows for high energy concentration in a small area (Vignesh et al., 2023).

The selected Fresnel lens is detailed in **Figure 3**, and its characteristics are summarized in **Table 1**.

Figure 3. Linear Fresnel Lens

(Description: Image or diagram of the linear Fresnel lens used in the system.)

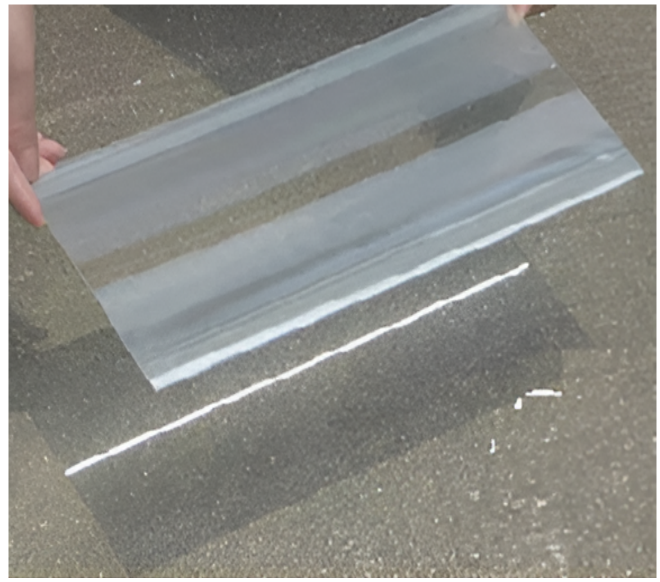


Table 1. Lens Characteristics

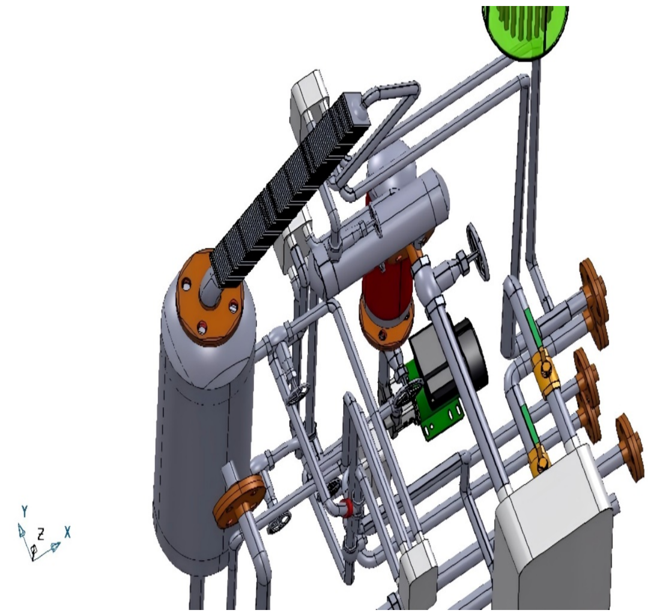
(Description: Table summarizing the specifications of the Fresnel lens, such as material, dimensions, focal length, etc.)

Characteristic	Specification
Material	Polycarbonate
Thickness	3 mm
Dimensions (Side x Length)	150 mm x 150 mm
Focal length	150 mm
Focal line	150 mm
Width of the focal line	5 mm
Temperature reached according to solar radiation level	540 °C

- **Water-Lithium Bromide Absorption System:** In summer, the thermal energy stored in the PCMs is transferred to this system to provide cooling. The system relies on the heat absorption by a water-lithium bromide solution, enabling the production of cooling. The conceptual design of the absorption system is shown in **Figure 4**.

Figure 4. Absorption System

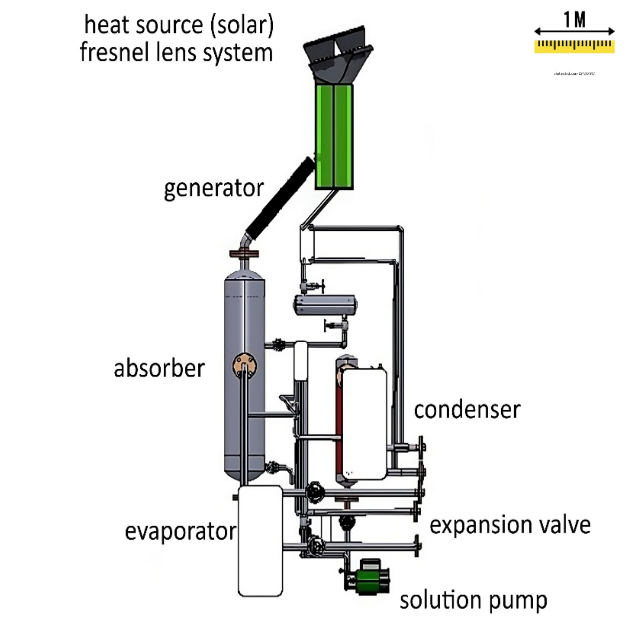
(Description: Schematic diagram of the water-lithium bromide absorption system.)

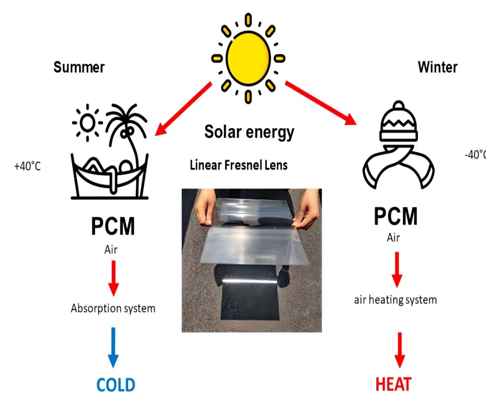


The system design is represented by a schematic diagram illustrating the layout and interconnection of the components. The diagram clearly shows how solar energy is captured and stored, as well as how this energy is distributed for heating in winter and cooling in summer. This schematic is presented in **Figure 5**.

Figure 5. Dual System Schematic

(Description: Schematic diagram showing the arrangement of the dual system components, including PCMs, Fresnel lenses, and the absorption system.)





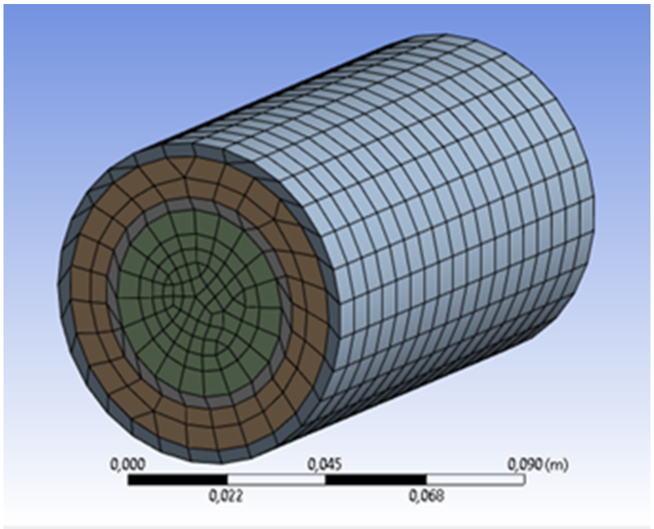
2.2 Modeling and Simulation in ANSYS Fluent

To evaluate the system's performance under extreme climatic conditions, detailed simulations were conducted using ANSYS Fluent (Sharma & Ghosh, 2023). The simulation process can be divided into several stages:

- **Definition of the Simulation Domain:** The geometries of the main system components, including encapsulated PCMs, concentric tubes, and Fresnel lenses, were modeled. A fine mesh was used to ensure the accuracy of the results. The geometry and meshing of the concentric tubes are shown in **Figure 6**.

Figure 6. Concentric Tube Geometry and Meshing

(Description: Image showing the geometry and mesh used in the simulation of the concentric tubes.)



- **Boundary Conditions:** Boundary conditions were established to simulate the extreme temperatures of winter and summer. In winter, the ambient temperature was set to -40°C, while in summer, it was set to 40°C. Additionally, the airflow and thermal oil flow conditions were defined. The simulation of the Fresnel line temperature is shown in **Figure 7**.

Figure 7. Fresnel Line Simulation

(Description: Image showing the simulation of the temperature at the focal line of the Fresnel lens.)

- **Transient Analysis:** Simulations were conducted in a transient state to capture the system's dynamic behavior. The storage and release of energy in the PCMs over time were evaluated, under both charging (energy capture) and discharging (heat transfer) conditions. A snapshot of the ANSYS Fluent simulation interface is shown in **Figure 8**.

Figure 8. ANSYS Fluent Simulation Interface

(Description: Screenshot of the ANSYS Fluent interface during the simulation.)

3. Results and Discussion

3.1 Simulation Results

The simulation results for the dual PCM-based system under various initial fluid temperatures are presented in **Table 3**. The table shows the initial and final temperatures of the interior and exterior fluids, respectively, as obtained from the ANSYS Fluent simulations. These results demonstrate the system's ability to effectively manage thermal energy transfer under different operating conditions.

Table 3. Simulation Results for Fluid Temperature Variation

Initial Interior Fluid Temperature (K)	Final Exterior Fluid Temperature (K)
223.15	275.77
233.15	290.76
243.15	318.70
253.15	330.00
263.15	337.56
273.15	365.80
283.15	402.09
293.15	405.87
303.15	421.40
313.15	440.33

3.2 Analysis of Results

The results indicate a consistent increase in the exterior fluid temperature as the initial interior fluid temperature rises. For instance, when the initial interior fluid temperature is 223.15 K, the final exterior fluid temperature reaches 275.77 K. As the initial temperature increases to 303.15 K, the final exterior temperature rises to 421.40 K. This trend highlights the system's efficiency in transferring thermal energy from the interior to the exterior fluid, which is crucial for both heating and cooling applications.

The data also suggest that the system performs optimally at higher initial temperatures, as evidenced by the significant temperature rise in the exterior fluid. This behavior can be attributed to the enhanced thermal conductivity and energy storage capacity of the PCMs at elevated temperatures, which facilitates more efficient heat transfer.

3.3 Graphical Representation

To further illustrate the relationship between the initial interior fluid temperature and the final exterior fluid temperature, a scatter plot with a linear trend line is presented in **Figure 9**.

Figure 9. Relationship between Initial Interior Fluid Temperature and Final Exterior Fluid Temperature *(Description: Scatter plot showing the final exterior fluid temperature as a function of the initial interior fluid temperature. The linear trend line indicates a strong positive ccorrelation between the two variables.)*

The graph demonstrates a strong positive correlation, with a linear trend line indicating that for every 10 K increase in the initial interior temperature, the final exterior temperature increases by approximately 15 K. This linear relationship underscores the system's ability to efficiently transfer thermal energy across a wide range of operating conditions.

4. Conclusion

The simulation results demonstrate the effectiveness of the dual PCM-based system in managing thermal energy transfer under varying initial fluid temperatures. As shown in **Figure 9**, there is a strong positive correlation between the initial interior fluid temperature and the final exterior fluid temperature, with the system achieving significant temperature increases across all tested conditions. This highlights the system's ability to efficiently store and release thermal energy, making it a viable solution for both heating and cooling applications in extreme climates.

The linear relationship observed in the results suggests that the system can be easily scaled and optimized for different operational requirements. For instance, in colder climates, the system can be designed to maximize heat retention, while in warmer climates; it can be optimized for efficient cooling. These findings underscore the versatility and adaptability of the dual PCM-based system, further supporting its potential for widespread adoption in regions with severe climatic conditions.

In conclusion, the dual PCM-based system represents a promising innovation for sustainable energy management in buildings. By leveraging the thermal properties of PCMs and the efficiency of Fresnel lenses, the system not only reduces energy consumption and operational costs but also contributes to a more sustainable and environmentally friendly future. Future work will focus on further optimizing the system's performance and exploring its scalability for larger applications, such as industrial facilities and urban energy grids.

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