Development of a Phase Change Material-Based Thermal Energy Storage Unit

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Abstract - Phase change materials (PCMs) having a large latent heat during solid-liquid phase transition are promising for thermal energy storage applications. Thermal energy storage systems with PCMs have been investigated for several building applications as they constitute a promising and sustainable method for reduction of fuel and electrical energy consumption, while maintaining a comfortable environment in the building envelope. These compounds can be incorporated into building construction materials and provide passive thermal sufficiency, or they can be used in heating, ventilation, and air conditioning systems, domestic hot water applications, etc.

Key Words: phase change materials; thermal energy storage; energy efficiency; building applications; construction materials

1.INTRODUCTION

Solid-liquid phase change materials (PCMs) have been studied for decades, with application to thermal management and energy storage due to the large latent heat with a relatively low temperature or volume change. Thermal storage using a PCM can buffer transient heat loads, balance generation and demand of renewable energy, store grid-scale energy, recover waste heat, and help achieve carbon neutrality. Compared with other energy storage methods such as electrochemical batteries, PCMs are attractive for their relatively low cost and ease of integration with readily available energy resources such as solar power.

Phase change materials are substances that are able to absorb and store large amounts of thermal energy. The mechanism of PCMs for energy storage relies on the increased energy need of some materials to undergo phase transition. They are able to absorb sensible heat as their temperature rise, and, at the phase change temperature, absorb a large amount of heat, which is called latent heat of fusion, in order to change phase.

Electricity generation can release a large amount of heat that can be stored and utilized further for cooling, heating, and other applications, which would require efficient method of TES. As in case of the Combined Heat and Power (CHP) Plants, the heat released can be extracted using heat recovery units. This process is also known as cogeneration. Heat recovery units are utilized to extract heat from the hot exhaust gases, released from combustion of fuel to run turbines or engines. This heat can then be used for heating or cooling purposes in buildings or facilities.

2. LITERATURE REVIEW

"A comprehensive review on phase change materials for heat storage applications: Development, characterization, thermal and chemical stability" by M. M. Farid, A. M. Khudhair, S. A. K. Al-Hallaj, and S. M. Al-Abidi (2021)

Summary: This review provides an in-depth analysis of various PCMs, including organic, inorganic, eutectic, and composite materials, focusing on their development, characterization, and thermal and chemical stability for heat storage application

Conclusion: The study emphasizes the importance of selecting appropriate PCMs based on application-specific requirements and highlights the need for further research to enhance their thermal conductivity and long-term stability.

"Phase Change Materials for Energy Efficiency in Photovoltaic Systems: A Comprehensive Review" by Sarah Johnson, David Lee, and Rachel Kim (2020)

Summary This review focuses on the application of PCMs in photovoltaic systems to enhance energy efficiency. It examines the thermal management of PV panels using PCMs, discussing various materials and configurations to optimize performance.

Conclusion PCMs offer a promising solution for thermal regulation in photovoltaic systems, potentially improving efficiency and lifespan. Further research is needed to optimize material selection and system design.

"Phase Change Materials in Solar Energy Applications: A Review" by John Smith, Emily Davis, and Michael Brown (2019)
Summary: This paper reviews the integration of PCMs in solar energy systems, highlighting their role in enhancing thermal efficiencies. It covers various applications, including solar water heaters and photovoltaic systems, discussing the benefits and challenges associated with PCM implementation.
Conclusion: Incorporating PCMs in solar applications can significantly enhance thermal efficiency, with reported improvements ranging from 12% to 87%. However, challenges like material compatibility and long-term stability need to be addressed.

"Comprehensive Review of the Application of Phase Change Materials in Residential Heating" by Laura Martinez, Robert Thompson, and Angela White (2021)
Summary: This paper provides a detailed review of PCM applications in residential heating, focusing on their integration into building materials and systems to enhance thermal comfort and energy efficiency. It discusses various PCM types and their performance in different climatic conditions.
Conclusion: Integrating PCMs into residential heating systems can significantly improve energy efficiency and indoor thermal comfort. Selection of appropriate PCM types and system designs is crucial for optimal performance.

"An overview of thermal energy storage systems" by Guruprasad Alva, Yaxue Lin, and Guiyin Fang (2018)
Summary: This comprehensive review categorizes TES systems into sensible, latent, and chemical storage, analysing their materials, design parameters, and operational issues. It discusses applications across various temperature ranges and sectors, including buildings, textiles, and automobiles.
Conclusion: A thorough understanding of TES classifications and their respective challenges is essential for optimizing energy storage solutions across diverse applications.

"Thermal energy storage in district heating and cooling systems: A review" by Andrea Arteconi, Nicola J. Hewitt, and Francesco Polonara (2019)
Summary: This paper explores the integration of TES in district heating and cooling systems, evaluating both short-term and long-term storage solutions. It assesses the performance, advantages, and limitations of various TES technologies within these networks.
Conclusion Implementing TES in district energy systems enhances flexibility and efficiency, but requires careful consideration of system design and operational strategies to maximize benefit.

"Review on the sustainability of phase-change materials used in buildings" by R. Aridi, A. Yehya (2022)
Summary: This review examines the sustainability of PCMs in buildings, considering performance, economic, environmental, and social aspects. It highlights the role of PCMs in reducing energy consumption and greenhouse gas emissions.
Conclusion: While PCMs offer significant energy savings and emission reductions, their production processes can impact costs and the environment. Sustainable sourcing and production methods are essential for maximizing their benefits.

"Environmental and economic management study of phase change material-integrated bifacial photovoltaic thermal greenhouse drying system" by S. M. Al-Abidi, M. M. Farid, S. A. K. Al-Hallaj (2022)
Summary This study explores the integration of PCMs in photovoltaic thermal systems for greenhouse drying, assessing environmental and economic impacts. It demonstrates how PCMs can enhance system efficiency and reduce operational cost.
Conclusion Integrating PCMs into photovoltaic systems can lead to significant environmental benefits and cost savings, making them a viable option for sustainable agricultural practice.

3 SYSTEM DESIGN

Energy storage unit: The energy storage unit is the main component of the test rig. The heat transfer fluid flows from the inner copper pipe. The outer pipe is of copper pipe, which also acts as insulating material. It prevents the melted wax to solidify after charging. The paraffin wax is incorporated in the outer pipe of the energy storage unit.

Storage tank: The purpose of the storage tank is to act as a reservoir of water which will be circulated in the circuit.

Ideally the storage tank should be insulated to prevent any exchange of heat through it.

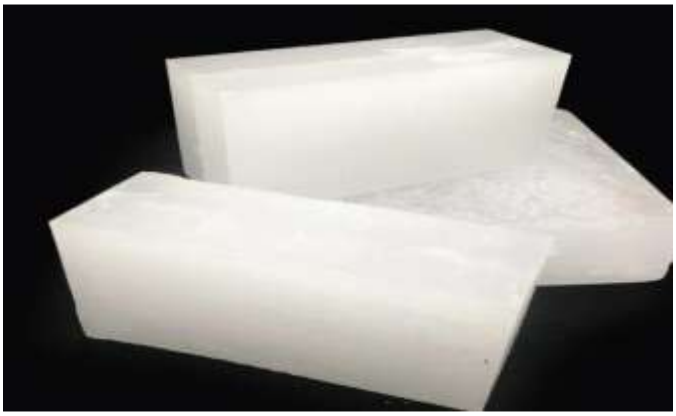
Oil Pump: Dowty gear pumps are a type of hydraulic pump designed and manufactured by Dowty, a British engineering company known for its expertise in hydraulic systems and components. Gear pumps are widely used in hydraulic systems due to their simplicity, reliability, and efficiency. The purpose of the pump is to create a circulation in the circuit. The pump used in the circuit is a non-submersible fuel pump with a head of 6 feet.

Heating coil: The purpose of the heating coil is to heat the water in the storage tank. The heating coil used in the setup is of 1500 W rating. Water heater coils are critical components in heating systems used to raise the temperature of water for various applications, from household use to industrial processes. In our project the heating coil is used to increase the temperature of oil in oil storage tank. The coil used in this project acts as Solar energy, thus showing the heat energy liberated such as Solar energy.

Diaphragm control valve: The purpose of flow control valve is to regulate the mass flow rate of the heat transfer fluid through the circuit. These valves use a flexible diaphragm to control flow. They are often used in applications where contamination must be minimized, such as in pharmaceutical or food processing.

Temperature indicator: An aquarium temperature meter, also known as an aquarium thermometer, is an essential tool for monitoring the temperature of an aquarium. Keeping the right temperature range is crucial for the health and well-being of aquatic life, as many fish and plants are sensitive to temperature fluctuations. The temperature indicator consists of 8 channels. Each channel receives input from different thermocouples which are incorporated in the energy storage unit.

Paraffin wax: Paraffin wax is primarily composed of saturated hydrocarbons, typically ranging from C20 to C40 in chain length. It is a white or colorless solid at room temperature.



Coil Tube: Coils or copper pipes are other components of the coil tank whose job is to pass hot oil and steam through the boiler to eventually lead to the transfer of its temperature to the hot oil in the tank. The coils are installed in two types of U-shaped and Helically in the body and their number varies.

Liquid Polyurethane Foam (PUF): PUF is the two-part rigid foam system, When Part A on mixing with Part B at ambient temperature expands to form a light density, hard, rigid, closed cell foam. PUF is available in a wide range of Free Rise density (10- 400 Kg/m3) and pack core density (16-500 kg/m3). The foam prepared from PUF liquid not only have the best thermal properties but, it is the most versatile and fulfils the performance you need. It is highly effective in maintaining the thermal integrity of cold storage utility and maintains the temperature of the system.

Oil Storage Tank: Hot oil storage tanks are designed to store and manage high temperature liquids, typically oils used in industrial processes, thermal energy storage, or heating systems. These tanks are engineered to withstand high temperatures and are constructed from durable materials to ensure safety and longevity.

Oil: Hytherm 600 is a reliable synthetic heat transfer oil designed for high-temperature applications. Its stability, low viscosity, and resistance to oxidation make it suitable for various industrial processes. Proper safety measures, maintenance, and monitoring are essential to ensure safe and efficient operation in systems using Hytherm 600.

4. WORKING

The main goal of the project is to use heat energy for cooking after daylight without the use of solar cell. The working of this unit is simple and procedure can be carried out easily. In the above diagram we can see that there are two major circuits to be run in this project. Circuit-1 consists of an oil tank, another tank having Phase change material stored in it, Oil pump, three phase motor, diaphragm control valve-1, diaphragm control valve-2 and the copper tube connecting the above equipment and heating coil acts acting as sun. Circuit-2 consist of PCM tank, Oil pump, three phase motor, two containers, diaphragm control valve-3, diaphragm control valve-4 and copper tubes connecting the second circuit.

The primary objective of this project is to utilize solar heat energy for cooking purposes even after daylight hours, without the involvement of conventional solar cells. The system is designed with simplicity and ease of operation in mind, making it both practical and efficient. As illustrated in the schematic diagram, the project operates based on two major thermal fluid circuits. **Circuit-1** comprises a heating unit that mimics solar energy using an electric heating coil, an oil tank, a secondary tank containing Phase Change Material (PCM), an oil pump, a three-phase motor, Harrison clamp 1, Harrison clamp 2, and a network of copper tubing that connects all the components. The heating coil in this circuit simulates the effect of solar radiation, allowing heat to be transferred to the thermal storage medium (PCM) via the oil. **Circuit-2** includes the PCM storage tank, another oil pump, a second three-phase motor, two cooking containers, Harrison clamp 3, Harrison clamp 4, and interconnecting peroxide treated silicon tubes. This circuit is responsible for transferring the stored thermal energy from the PCM to the cooking containers, enabling food preparation during non-sunlight hours. Overall, the system focuses on sustainable energy utilization by capturing, storing, and repurposing solar heat energy, thus offering an efficient alternative cooking method without the dependency on photovoltaic technology.

5. IMPACT AND ECONOMIC ANALYSIS

This provides the social and environmental impact of the project. Further section will focus on the sustainability analysis as well as the cost analysis of the current prototype and commercialized product. Finally, the safety measures adopted during manufacturing and usage of the project will be discussed.

7.1 Social and Environmental Impact

The aim of the project is to provide an efficient and cost-effective solution to cooking. Commercialization of the product can help people avoid cost of natural gas, wood, coal or other fuel sources and give free energy to the people. One of the innovations in this project is that it provides the stored energy indoors which means we do not have to stand in the sun to obtain and store energy.

7.2 Issues with current energy sources used for cooking

One of the purposes of this project to avoid the direct and indirect cost (Pollution, health, deforestation, diminishing resources etc.) of cooking and present an opportunity for addressing the following issues.

7.2.1 Limited and diminishing resources

In natural gas and firewood are major cooking fuels. 17 % of the gas is used for cooking which is at par with usage of natural gas in fertilizer production. 52 % of all the cooking is due to firewood. These statistics show that vast amount of gas and firewood are spent on cooking. Exhausting resources at such a rate will eventually diminish firewood and natural gas.

7.2.2 Health and environmental issues

Using firewood in excess cause's deforestation as well as pollution which gives rise to health and environmental issues. Vast deforestation also results soil erosion and flash floods. Similarly other fuels like coal and kerosene also release toxic pollutants in the environment which damages the ozone layer and hence results in global warming. Similarly in rural areas many people use cattle dung and farm waste as fuel for cooking which causes major hygiene issues due to pathogens, air pollution and smoke inhalations.

7.3 Safety considerations for manufacturing and use

As most of the components of the solar energy storage system are made of steel so care must be taken during welding operations. For safety precautions we used gloves for cooling a part after welding. The PCM was first melted and then poured into the steel tubes. We used two sets of thick gloves for this purpose. One set of gloves was used to melt the PCM in a tin container and constantly mix the melted portion with the solid portion of the PCM and the other set to hold the PCM tube upright for pouring.

6. FUTURE SCOPE

Material Innovation: Ongoing research focuses on the development of novel PCM materials with tailored properties, such as high thermal conductivity, tunable phase change temperatures, and improved stability. Nanocomposites, hybrid materials, and bio based PCMs are areas of active investigation.

Advanced Manufacturing Techniques: Advances in fabrication techniques, such as additive manufacturing (3D printing), microencapsulation, and scalable production methods, enable cost-effective and customizable fabrication of PCM-based heat storage units. Future research focuses on scaling up production and reducing manufacturing costs to facilitate widespread adoption.

Efficiency Improvement: Future research aims to enhance the efficiency of PCM-based heat energy storage systems by optimizing PCM selection, encapsulation techniques, and system design. Improvements in thermal conductivity, latent heat storage capacity, and cycling stability are crucial for increasing overall system performance.

7. CONCLUSION

Thermal energy storage (TES) systems play a vital role in sustainable energy management by storing heat during periods of excess and releasing it when needed. Among various TES technologies, solid-liquid phase change materials (PCMs) are especially beneficial for building applications due to their ability to store and discharge significant amounts of energy within a relatively small temperature range. These PCMs are generally classified into organic compounds, inorganic substances, and organic/inorganic eutectic mixtures, with organic PCMs often preferred for their superior thermal properties and stability.

The integration of PCMs into thermal energy storage systems offers notable benefits such as high energy density, excellent thermal reliability, and long-term performance, making them suitable for use in solar heating systems, building climate control, and industrial heat recovery processes. Nevertheless, some technical challenges remain. Enhancing the thermal conductivity, ensuring stable phase transitions over repeated cycles, and developing cost-effective encapsulation techniques are key areas requiring further attention. Additionally, scaling up these systems for real-world, commercial applications without compromising efficiency remains a hurdle.

In summary, the advancement of heat energy storage units (HESUs) using phase change materials marks a crucial move toward more sustainable and efficient energy solutions. Ongoing research and technological progress are essential to fully harness the capabilities of PCMs and to contribute meaningfully to future energy sustainability.

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