Design and Analysis of a Phase Change Material-based Thermal Energy Storage System for Enhanced Solar Energy Utilization

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Abstract: Solar energy is clean and sustainable but intermittent in nature. Efficient storage of solar thermal energy is critical for its wider applications. This paper presents design and research on a thermal energy storage unit using phase change material (PCM). A prototype of PCM heat exchanger with a helical coil tube was designed and fabricated for solar thermal energy storage, and was tested on a solar thermal experimental apparatus. This paper discusses the design concepts, selection of materials, as well as heat transfer analysis with the CFD tool Ansys Fluent.

Keywords: Solar energy, Solar thermal energy storage, Phase change material (PCM), Heat exchanger, Computational Fluid Dynamics (CFD).

1. Introduction

The energy supply from various sustainable sources, such as solar thermal or wind, is characterized by its intermittent nature. Therefore, the implementation of efficient energy storage solutions becomes crucial for the practical applications of these sustainable energies [1]. In the context of residential solar thermal applications, conventional hot water systems exhibit relatively low efficiency and limited capacity, particularly during night-time and days without sunshine. To address these challenges, the utilization of phase change materials (PCMs) has been proposed as a means to store thermal energy [2, 3]. PCMs offer advantageous features, including nearly isothermal solid-liquid phase change and high energy storage capacity attributed to the latent heat of fusion.

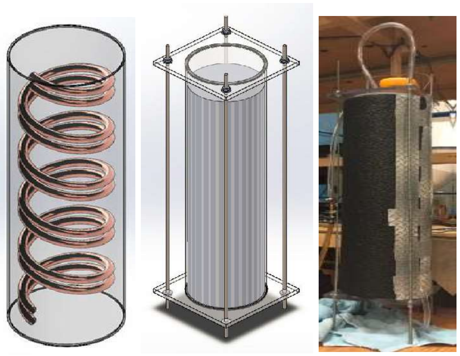
Diverse phase change energy storage systems have undergone extensive study [4,5]. Among the various designs explored, a tube and shell unit stands out as one of the simplest and widely employed configurations. The materials chosen for a latent heat storage tank must meet criteria such as ease of availability, cost-effectiveness, and environmental friendliness. Opting for an organic phase change material (PCM) offers advantages such as widespread availability, a high latent heat of fusion, chemical stability, and resistance to corrosion. However, drawbacks include flammability and low thermal conductivities [6]. Inorganic PCMs, typically employed in high-temperature applications, present challenges such as sub-cooling and corrosion of the containment material [6,7].

The objective of this paper is to conceptualize, create, and evaluate a solar thermal energy storage unit incorporating phase change materials. A prototype of a helical coil PCM heat exchanger was constructed and subjected to testing within a solar thermal apparatus. Thermal fluid characteristics of the PCM storage tank were analyzed using a Computational Fluid Dynamics (CFD) tool, and initial results from laboratory testing are presented.

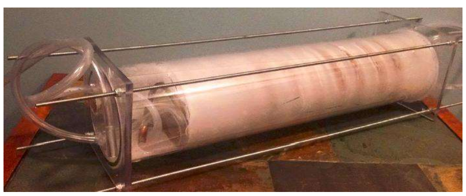
2. Methods and Materials

Solid Works models (a, b) and the fabricated prototype (c, d) of a phase change material (PCM) heat exchanger for thermal energy storage are illustrated in Figure 1. The heat exchanger comprises two end plates, a cylindrical shell, a spiral tube for heat transfer fluid (HTF), and four supporting struts.

Paraffin Wax was chosen as the phase change material (PCM) to fill the storage tank space between the heat transfer fluid (HTF) tube and the shell. Paraffin is readily available and cost-effective, offering an excellent latent heat of fusion. It operates within a desirable temperature range (~50°C) suitable for warm water applications. The heat transfer fluid selected is single-phase water.



(a) (b) (c)



(d)

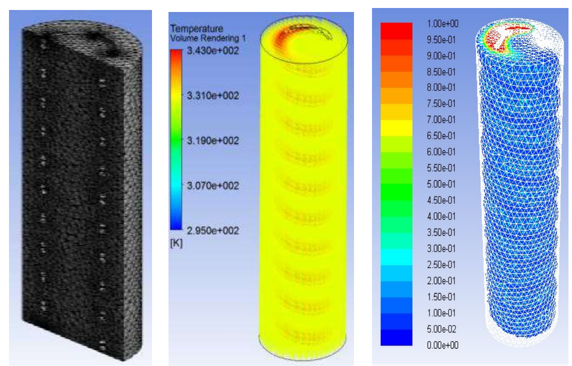
Fig. 1: Solidworks model and fabricated prototype of the PCM heat exchanger

The experimental prototype's tank shell is made of polycarbonate due to its durability, availability, and ease of use, coupled with excellent heat and corrosion resistance. Moreover, polycarbonate, with its low thermal conductivity, acts as a pseudo-insulator. Its transparency allows for monitoring the PCM melting and solidification process during testing.

While a straight tube was initially examined in heat transfer simulations, the final fabrication opted for a spiral tube design, as depicted in Fig. 1(a). Both Computational Fluid Dynamics (CFD) simulations and laboratory testing confirmed that the spiral tube exhibits superior heat transfer performance. Copper was selected for the heat transfer fluid (HTF) tube due to its exceptionally high thermal conductivity, cost-effectiveness, and widespread availability. Fig. 1(d) illustrates the complete assembly with the phase change material (PCM), while Fig. 1(c) showcases the final unit equipped with outer insulation for testing.

ANSYS Fluent CFD tools were employed to assess the heat transfer within the prototype spiral tube PCM heat exchanger, utilizing pure water as the working fluid and paraffin wax in the shell. The PCM's initial temperature is set at 295K, while the heat transfer fluid's inlet temperature is 343K. Given these relatively low temperatures, the PCM undergoes a gradual melting process, prompting an 8-hour simulation to capture its behaviour during operation.

Figure 2(a) illustrates the meshing for the prototype configuration. Figures 2(b) and (c) depict representative temperature and liquid fraction results. Melting is observed across all sections of the pipe, progressing outward as shown in Figure 2(c). Following an 8-hour heat transfer process, the unit achieves a relatively uniform temperature distribution at approximately 321K, which is the melting point of the phase change material (PCM). A significant portion of the volume either exists as fully liquid or is undergoing phase change, although the PCM has not completely melted at this stage.



(a) (b) (c)

Fig. 2: Melting of paraffin wax in a PCM heat exchanger with spiral tubes

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3. Results and Discussion

The fully assembled thermal energy storage unit with phase change material (PCM), as depicted in Fig. 1(c). The objective was to validate the charging time and the heat transfer process. The experimental setup comprises a solar collector, a water tank, a liquid flow pump, an air compressor (used during air-liquid two-phase flow testing), flow meters, temperature and pressure sensors, and a data acquisition system. The working fluid is heated while passing through the solar collector and then directed to the downstream water tank. A pump circulates the water back to the collector for reheating.

The PCM heat exchanger was integrated into the system between the water outlet of the solar collector and the inlet leading to the water storage tank, effectively substituting the traditional water tank. The inlet water temperature for the PCM tank was assessed approximately 0.6 meters upstream, the outlet water temperature was measured around 0.45 meters downstream, and a representative internal PCM temperature was monitored near the inlet of the shell. Measurements of these three points were conducted at five-minute intervals over a span of approximately one hour.

Figure 3 presents initial testing findings, featuring the temperatures of inlet and outlet water as well as the internal temperatures of the PCM throughout a 65-minute charging period.

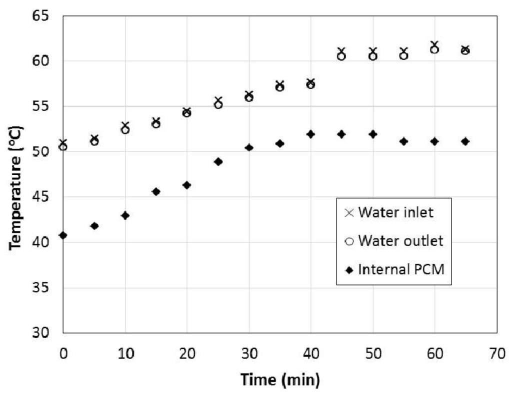

Fig. 3: Variation of Temprature in TES tank vs Time

The temperature differential consistently remains below one degree, validating the assumption of a constant surface temperature in the copper tubing. The paraffin wax temperature exhibits a steady rise, reaching approximately 51 degrees Celsius around the 40-minute mark of the charging period. This observation is crucial as it indicates a confirmed phase change occurrence, aligning closely with the measured melting point of the wax. Due to temperature constraints of the tubing, this test only reached the melting point and the early phase change period. A more extended-duration test will be conducted to investigate fully melted PCM.

4. Conclusion and Future Directions

We conceptualized, manufactured, and subjected a phase change material (PCM) heat exchanger to both numerical and experimental analyses for latent storage of solar thermal energy. The configuration incorporates paraffin wax, a cylindrical shell, and a spiral tube facilitating the flow of heat transfer fluid. Computational Fluid Dynamics (CFD) simulations offered essential insights into the impacts of various design parameters. A functional prototype of the heat exchanger was adeptly assembled for laboratory testing, serving as validation for our concepts, confirmation of assumptions made during simulations, and generating valuable preliminary data for refining future iterations of the design.

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