**Title: Experimental Investigation on the Effect of Tube Parameters on PCM Based Thermal Energy Storage System**

**Keywords:** Thermal Energy Storage (TES), Phase Change Material (PCM), Tube Geometry Optimization, Solar Parabolic Trough Collector, Heat-Transfer Enhancement, Volumetric Fraction Analysis

The use of thermal energy storage (TES) technology has become increasingly important in stabilizing the renewable energy systems, particularly in areas with discontinuous access to sunlight including Bangladesh. Phase change materials (PCMs) based latent heat storage are considered to be one of the most promising TES technologies because they have a high energy density, almost isothermal behavior during phase transition, and can be deployed in small-scale and decentralized systems. Non-value-added but PCM-based TES systems are also characterized by a fundamental limitation, i.e., the nature of PCMs that has very low thermal conductivity and thus delays the process of charging and discharging.

In order to eliminate this challenge, heat-transfer tubes are embedded into PCM tanks. However, there is a major effect on thermal performance influenced by the geometry and material of the tubes. The majority of the currently available studies are based on the use of PCM enhancement methods, including fins, nanoparticles or the variation of tube patterns. But a systematic experimental study that compares the tube diameter, tube number as well as tube material in the same PCM mass, tank size and heating conditions is deficient. Absence of such a systematic analysis inhibits the capability of coming up with cost-effective and high-performance TES units.

The existing literatures have executed extensive research on the impact of PCM properties and tube geometry modification but lack systematic experimental comparative analysis of the tube diameter, tube number, and the tube material of PCM-based multi-tube thermal energy storage systems at identical operating conditions. To address this gap the experimental work conducted during my undergraduate thesis assessed the combined influence of volumetric fraction, heat-transfer area, and tube material on TES behavior using consistent geometry and solar-based heat input. Furthermore, there is limited literature correlating stored energy with weighted heat-transfer area across multiple tube diameters which has been addressed in this project as well. And the primary objectives of this study lie in identifying the optimum tube configuration balancing storage capacity and heat transfer rate along with investigating the effect of different tube materials in the performance of MTES system.

Two identical latent heat TES units were constructed using commercial cylindrical storage tanks (18 L), each fitted with removable tube bundles filled with paraffin wax (melting range: 56–58°C). The tanks were insulated using polyethylene foam sheet coated with aluminum foil. Copper and aluminum tubes of identical dimensions were used to separately study material effects. Five tube-count configurations were tested for each diameter, ranging from high-density to low-density arrangements.

Tube numbers were selected so that each diameter set represented a decreasing PCM volumetric fraction while maintaining identical tube thickness and insertion height. All tubes were fully filled with identical PCM mass per unit length.

The TES units were charged using water heated by a solar parabolic trough collector. The heat-transfer fluid (HTF) entered the storage tank through a closed loop, with temperatures recorded hourly. Charging continued until HTF temperatures stabilized. A **3-hour retention** period followed the charging stage to evaluate thermal holding capacity. Afterwards, **discharge tests** were performed by replacing the hot water with room-temperature water until PCM temperature reached near equilibrium.

**Effect of Tube Material:** Copper consistently outperformed aluminum in all cases where material comparison was conducted (12.7 mm diameter set). Copper tubes enabled **1–2°C higher PCM temperatures** during the active charging stage due to their higher thermal conductivity. This led to **10–15% higher stored heat** under identical solar conditions. During retention, aluminum occasionally held slightly higher temperatures in dense configurations, but this advantage diminished in lower tube counts. Overall, copper demonstrated superior charging efficiency and total stored heat.

**Effect of Tube Diameter and Number:** Tube geometry was found to be the dominant factor influencing storage capacity.

The smallest diameter (9.5 mm, 71 tubes) offered the **fastest response** but **lowest stored heat**, leading to less than 10 minutes **discharge duration**. The largest diameter (15.9 mm, 18 tubes) offered **maximum stored energy** and **more than 40 minutes discharge duration**, but much slower charging. The **12.7 mm tubes** provided the **best compromise** between PCM volume and heat-transfer surface area.

Quantitatively, 12.7 mm copper tubes stored **18–30% more heat** than 15.9 mm tubes and **40–55% more** than 9.5 mm tubes.

**Combined Heat-Transfer-Area Correlation:** A unified regression analysis across all diameters showed an exceptionally strong second-order correlation between **heat-transfer area** and **stored energy resulting in** $R^2$ values ranged between **0.92 – 0.999** across all diameter groups

This indicates that stored energy does not increase linearly with area; instead, it follows a saturation curve where excessive tube density reduces net PCM volume, lowering energy storage despite high surface area. The 12.7 mm configuration exhibited the steepest curve and the highest coefficient of determination followed by the 15.9 mm and 9.5 mm tubes and thus emerged as the optimal configuration.

**Cost–Performance Trade-Off:** While copper exhibits a higher thermal storage range (up to approximately 6.4% – 17%) compared to aluminum, the increased material expense (60% more costly than aluminum) may outweigh the thermal performance benefits in large-scale applications. The 12.7 mm aluminum configuration still performed acceptably and delivered stable discharge durations, making it a cost-effective alternative.

These findings highlight the practical trade-off between cost, stability, and performance. Overall, the study has offered experimental results for the optimization of PCM-based TES systems, thus, closing the gaps in literature and guiding the development of cost-effective and high-performance thermal energy storage technologies.