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DEVELOPMENT OF A LOW-COST, SCALABLE SPHERICAL PCM STORAGE USING CORRUGATED PIPES: CONCEPT, DIMENSIONING AND PROTOTYPE DESIGN

Summary

Thermal energy storage with phase change materials (PCM) enables compact and efficient heat storage, crucial for decarbonizing heat supply. A novel low-cost concept embeds corrugated pipes in bulk PCM (PCM58), avoiding costly encapsulation and enhancing thermal performance. A 60-liter spherical prototype models a 12 m³ system for urban heating applications, using dimensionless analysis to ensure scalability. The design focuses on hydraulic performance. Two downscaling strategies are applied: one based on fluid residence time, the other on dynamic similarity. Corrugated pipes are modeled as helical coils, with pressure drops estimated using standard correlations. The analysis excludes detailed convective modeling, assuming sufficient heat exchange via conduction and natural convection. Preliminary results suggest DN16 pipes are optimal, balancing performance and feasibility. The prototype will validate the design and inform a generalized methodology. Future work includes transient thermal analysis and measurements of the 60 l prototype to refine assumptions. *Keywords: Thermal energy storage, phase change material, corrugated pipes, heat exchanger*

1. Introduction

Thermal energy storage is a key technology for decarbonizing heat supply, particularly in systems with variable generation such as solar thermal or heat pumps. Latent heat storage using phase change materials (PCM) enables high energy density and compact system designs, making it especially attractive for applications in space-constrained environments. Despite their advantages, current PCM systems remain limited in widespread application due to high costs and technical complexity. Systems that incorporate lamella structures to improve heat transfer as shown by Waser et al. (2020) are expensive to manufacture and integrate in a storage vessel. Alternative approaches, such as macro-encapsulated PCM systems as investigated by Krabben et al. (2024), Palacios et al. (2023) and Rehman et al. (2023), offer modularity but are associated with high production costs and potential leakage risks particularly when using salt hydrates such as sodium acetate trihydrate (SAT).

To address these limitations, a novel low-cost concept has been developed based on corrugated pipes embedded directly into bulk PCM. These pipes serve as internal heat exchangers through which water is circulated. This configuration eliminates the need for costly lamella or encapsulation structures, thereby reducing system complexity and failure points. The chosen PCM is PCM58, a salt hydrate produced by COWA Thermal Solutions (2025) with a melting point of approximately 58 °C. The storage tank is designed as a sphere to ensure uniform stress distribution, avoid deformation under hydrostatic pressure, and minimize surface area.

A 60-liter prototype is currently under development as a scaled-down representation of a spherical 12 m³ heat storage vessel designed by Energy4me (2025) for use in multi-family buildings or district heating substations, particularly in dense urban environments. To ensure meaningful comparison between scales, the design process applies dimensionless analysis to assess hydraulic and thermal similarity. The core research focus lies in developing a cost-effective method to integrate a heat exchanger directly into the PCM volume without compromising charging and discharging performance. At the same time, pressure losses must remain within acceptable limits to allow seamless integration into existing hydraulic systems typical of district heating or multi-unit residential buildings. The design approach proposed and the prototype will allow experimental investigation of these aspects across different tube geometries and materials, providing the basis for a scalable, generalisable design methodology for PCM storage systems.

2. Methodology

To validate the design approach and enable scalable system development, a systematic methodology was established in this study. The 60-liter prototype serves as a downscaled physical model of the 12 m³ full-scale storage and is used to test analytical assumptions under realistic boundary conditions. The system's thermal and hydraulic characteristics are compared using dimensionless analysis, with the Reynolds number as the key scaling parameter. Corrugated pipes embedded in the PCM are approximated as helically coiled tubes to apply standard pressure drop correlations.

The methodology includes geometric modeling of the pipe layout within the sphere, considering total pipe length, coil pitch, and spatial packing. Hydraulic behavior is estimated using the Zanke correlation for helical and rough-walled pipes, the Prandtl-Colebrook equation for turbulent flow, and the Blasius correlation for transitional regimes (Eismann, 2018). Two downscaling strategies were applied: the first assumes constant residence time of the fluid in the pipe between full-scale and prototype; the second maintains constant Reynolds number to ensure dynamic similarity. Design constraints such as allowable pressure loss, flow velocity (to avoid vibration or fatigue), and manufacturing feasibility were factored into the analysis.

Detailed modeling of convective heat transfer such as the use of Nusselt or Peclet numbers was intentionally omitted in this phase. The assumption is that water-side heat transfer is not the limiting factor, as the pipes contain a large water volume that is not fully exchanged in each cycle. Additionally, the system is expected to operate primarily during peak thermal loads, with extended idle periods that provide sufficient time for heat exchange via natural convection and conduction. This assumption will be evaluated in future stages, where transient thermal analysis may be incorporated to refine the model. The methodology provides a scalable framework for evaluating and designing spherical PCM storage systems across various sizes and applications.

3. Preliminary Results

Initial results show that the proposed methodology is effective in evaluating the hydraulic behavior of embedded corrugated pipes for spherical PCM storage. Corrugated pipes were modeled as helically coiled structures with known pitch and curvature, and pressure losses were calculated using established correlations. Two downscaling strategies were applied. In the first approach, which assumes constant residence time, the flow velocity in the prototype decreases compared to the full-scale system. This leads to a reduction in Reynolds number and a shift into laminar flow, which increases the friction factor. Nevertheless, due to the significantly reduced velocity, the resulting pressure drop remains within acceptable limits.

In the second approach, the Reynolds number was held constant by adjusting the flow velocity in the prototype, ensuring dynamic similarity across scales. Under practical constraints specifically a maximum allowable pressure drop of one bar and flow velocity below one meter per second a limited range of pipe diameters was found to be technically feasible. Within this range, DN16 and DN32 emerged as viable candidates. After evaluating factors such as bending radius, material availability, and mechanical stability, DN16 was selected for implementation in the prototype.

Two pipe materials were considered in this context. Stainless steel, which offers high thermal conductivity and structural robustness, and HDPE (RS321), a cost-efficient and highly flexible material suitable for curved layouts. RS321 was identified as a promising solution due to its low friction characteristics and ease of integration into spherical geometries. However, its limited production length may require modular assembly solutions for larger storage volumes.

Figure 1 summarizes the results for different pressure loss scenarios, assuming a pipe packing density of 20 %. Under this condition, a total pipe length of approximately 45 m can be installed within the spherical volume. Combined with a target flow velocity of less than one meter per second, the expected pressure drop remains below 1 bar meeting the boundary conditions defined for integration into district heating or residential building systems.

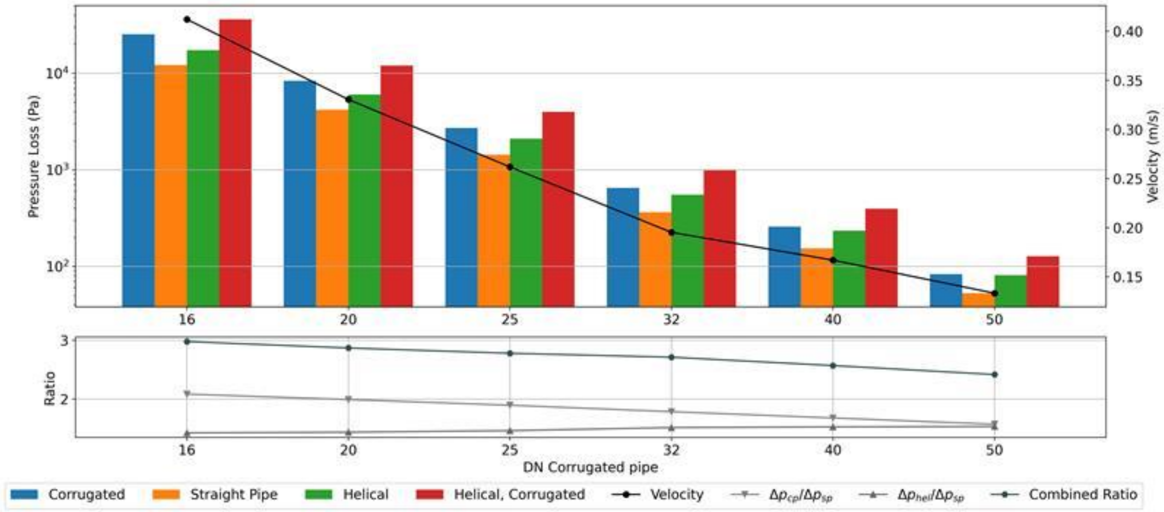

Fig. 1: Dimensioning results of the pressure losses for different pressure models and pipe shapes for the 60 litre prototype. In addition, the pressure ratios of different pressure models are shown.

4. Outlook

In the next phase of the project, the 60-liter prototype (Fig.2) will be constructed and tested under realistic boundary conditions. The system will undergo multiple charging and discharging cycles using water as the heat transfer fluid, replicating thermal loads typical of residential or district heating systems. During testing, pressure losses will be measured across various flow rates, and the hydraulic assumptions from the analytical model will be verified. Furthermore, the thermal and structural performance of the embedded pipe configuration will be assessed under dynamic operation, including system behavior during idle phases where passive heat transfer dominates. These experimental results will serve to confirm or refine the assumptions made in the current model and will support the further development and upscaling of the storage concept for larger applications. The full paper will include the dimensioning approach and measurement results of the prototypes.

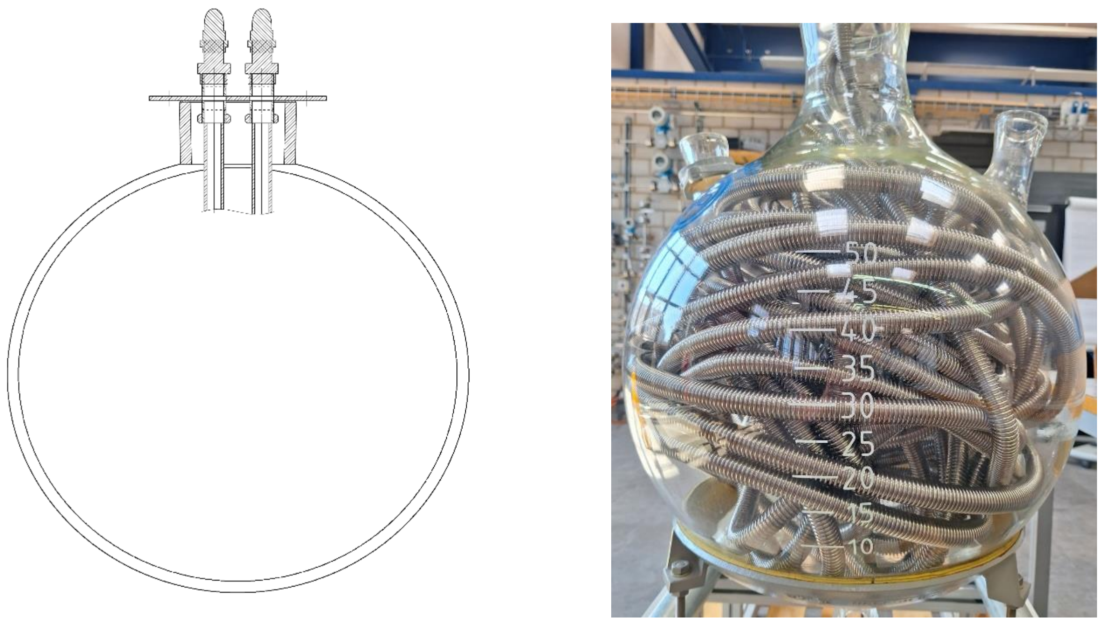

Fig. 2: Left: 60 l prototype design with pipe connection above. Right: 60 l prototype as the first version without PCM, filled with DN16 pipes and a packing density of 20%.

5. References

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6. Appendix

Table 1: Abbreviations

Name	**Abbreviation**
Nominal Diameter	DN
Phase Change Material	PCM
High Density Polyethylene	HDPE
Tightly and Annularly Corrugated Hose	RS321