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Thermodynamic Modelling and Efficiency Evaluation of Thermal Storage Technologies: An Overview of Progress in the Last Three Years and Future Directions

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Abstract. Thermal energy storage (TES) technology appears to be increasingly important in the current energy transition process. This technology seems to offer a potential solution for balancing the unstable output of renewable energy and recovering thermal energy that can be considered industrial waste heat. This paper aims to review the modelling methods and efficiency of several thermal energy storage technologies. The content appears to cover sensible heat, latent heat, thermochemistry, and technologies that seem to constitute liquid or gas thermal energy storage. We also explain certain key metrics and compare single-phase models, two-phase models, computational fluid dynamics (CFD), and dynamic models, each of which appears to have its relative advantages and disadvantages. In this context, a summary of key optimisation studies is particularly important. Under these evolving conceptual parameters, dynamic models and multi-field methods tend to more accurately describe actual operating conditions. This review ultimately aims to compare the efficiency of different thermal energy storage types and identify significant research gaps that appear to exist.

Keywords: Thermal energy storage, Thermodynamic modeling, Efficiency, Dynamic model, Latent heat, Optimization

1. Introduction

Within this broader analytical framework, thermal energy storage technology appears to play a critical role in the current energy transition. As the proportion of renewable energy increases, the role of thermal energy storage in stabilising energy systems seems to be growing increasingly prominent. From this specific interpretative perspective, researchers can more accurately assess the efficiency of thermal energy storage systems, determine the relative accuracy of model calculations, and help guide system optimisation. Theoretically, these thermodynamic metrics can also be used to compare the obvious advantages and disadvantages of different thermal energy storage technologies and help identify potential optimisation directions.

This paper systematically reviews modelling methods for various types of thermal energy storage technologies and compares their surface efficiencies. The primary focus of this paper is on these

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thermodynamic modelling methods and the comparison of efficiency differences between different technologies.

2. Types of heat storage technologies and thermodynamic foundations

Within the broader analytical framework of thermal energy storage technology, the field can generally be categorized into what appears to represent several distinct types. The first of these might be characterized as sensible heat storage (SHTES), a technology that appears to store thermal energy primarily by raising or lowering the temperature of a given storage material. Typically used storage materials in this context seem to include water, oil, and what are known as molten salts [1]. A second category, latent heat thermal energy storage (LHTES), is sometimes referred to as phase change material (PCM) storage. What this approach tends to do is utilize the heat absorbed or released during a material's phase change, seemingly offering what may be a substantially higher energy density with relatively minimal temperature shifts [2]. A third category appears to be thermochemical thermal energy storage. What this method seems to achieve is the storage of heat through what appear to be reversible chemical reactions, a process that seems to lend support to what may represent a particularly high energy density and suitability for potentially long-term storage. A fourth grouping tends to point toward what appear to be liquid or gaseous thermal storage systems, predominantly applied in contexts such as compressed air energy storage, steam systems, or certain industrial heat exchange systems.

From this particular interpretive perspective, various thermodynamic metrics can be employed to evaluate the performance of these thermal storage technologies. What seems to emerge from this analysis is that common metrics tend to include energy density, cycle efficiency, entropy generation, and what are often termed irreversible losses. Higher energy density appears to suggest that more heat can be stored per unit volume. What cycle efficiency seems to point toward is the apparent extent of thermal utilisation within a given system. In light of these methodological considerations, entropy generation and irreversible losses appear to provide evidence that may support researchers in identifying potential sources of energy loss. What also appears significant in this context is that these systems seem to require appropriate thermodynamic modelling. When modelling, what appears to warrant further interpretive consideration is that certain basic principles are typically followed. The model should, it seems, reflect the system's heat and mass transfer processes with a reasonable degree of accuracy while maintaining what might be considered manageable computational complexity. Consequently, what appears to follow from this is the need for researchers in practical applications to select a seemingly appropriate model based on the specific system type and their overarching research objectives.

3. An overview of thermodynamic modelling methods

Filled-bed latent heat storage systems (PBLTES) have received a lot of attention in recent years. It is characterised by its high rate of heat transfer, large specific surface area and flexible structure. Several mathematical models have been proposed by researchers to describe such systems. These models include single-phase models, two-phase models (e.g., Schumann model, continuous solid-phase model, concentric dispersion model), CFD models, and the -NTU method [3]. Each model has a different scope of application and computational characteristics. The advantages of dynamic modelling are obvious. Dynamic models can better describe the performance of the system under different loads. Tafone et al. developed a dynamic model of the CHEST system. They combined the unsteady state heat transfer inside the TES with a high temperature heat pump (HTHP) and an

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organic Rankine cycle (ORC) subsystem [4]. This approach avoids the problem of overestimation of the rotary efficiency of the system by the steady state model. For sensible heat storage, a one-dimensional two-solid-phase model has been proposed. This model can simultaneously account for thermal conductivity, convective heat transfer and pressure drop of fillers with different particle sizes. The Ergun pressure drop formula was improved and experimentally verified [1]. In solar absorption refrigeration systems, a new analytical method has been proposed to help in the selection and sizing of TES. This method expresses the relationship between the energy storage unit and the system performance more clearly [5]. Different modelling methods have different advantages and disadvantages. Some methods allow faster calculations but are not accurate enough. Some methods describe the system in more detail, but are computationally intensive. Choosing the appropriate method needs to consider the actual application scenario of the system and the requirement of thermodynamic accuracy.

4. Analysis of hot technologies in the past three years

PCM thermal storage systems are a hot topic of research. Researchers aim to enhance the thermal performance and cycle stability of phase change materials through composite PCMs, nano-enhanced PCMs, and bio-based materials. Shell-and-tube latent heat storage systems (LHES) are widely used in industrial waste heat recovery and renewable energy systems due to their high energy density and good temperature stability. However, such systems have low heat transfer efficiency, and the melting and solidification processes are both slow. Mahdi et al. summarised various optimisation methods [6]. They introduced methods for geometric parameter optimisation, PCM material modification, and operational condition control. In geometric optimisation, using an eccentric structure, optimising the number of inner tubes, horizontally arranging shell-and-tube components, and adding fins can significantly reduce the melting and solidification time of PCM. For example, horizontally arranged shell-and-tube components melt 40–60% faster than vertically arranged ones. Increasing the number of fins or altering their morphology can reduce heat transfer time by 50–85%. Material modification is equally important. Adding high-thermal-conductivity fillers (such as metal foams or graphite) to PCM can increase thermal conductivity by 3–15 times, mitigating the local "thermal insulation layer" issue during phase change. Using eutectic PCM or composite PCM can improve temperature range adaptability and cycle stability [6]. Adjusting operating conditions can also enhance system performance. Mahdi et al. found that the inlet temperature of the heat transfer fluid (HTF) has a more significant impact on system performance than flow rate. Increasing the inlet temperature by 10–15°C can increase the heat release rate by 20–30%. Low-speed rotation of the system (0.1–1 rpm) can enhance natural convection, reduce local dead zones, and further shorten phase change time [6]. Currently, most studies focus on single optimisation methods. Mahdi et al. point out that there is a lack of multi-parameter joint optimisation models and dynamic thermodynamic models. This makes it difficult for researchers to accurately predict system performance under actual operating conditions. Therefore, future research should integrate methods such as CFD and Moving Boundary (MB) models to explore synergistic optimisation pathways for geometry, materials, and operational parameters [6]. Latent heat storage systems (LTES) have faced challenges in improving efficiency due to the low thermal conductivity of PCM and the slow melting and solidification processes. Traditional optimisation methods primarily involve fin structure optimisation, adding heat-conductive fillers, and multi-level PCM arrangement. These methods can reduce melting and solidification times by 40–85%, increase thermal conductivity by 3–15 times, and improve fire efficiency by up to 53.8% [2, 7]. However, once the structural parameters are determined, they are difficult to dynamically adjust during operation. Under

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fluctuating heat source conditions such as solar energy or industrial waste heat, system performance often degrades significantly [2]. Emerging external field enhancement methods represent a new direction. These methods dynamically enhance heat transfer through magnetic fields, electric fields, and rotation/flipping adjustments. They can real-time alter the convective behaviour and phase interface movement of PCM, potentially overcoming the limitations of traditional methods. Research indicates that magnetic field enhancement can increase melting and solidification rates by 18–48%, electric field (EHD) enhancement can reduce melting time by 40–56%, and rotational or flipping enhancement can increase melting rates by 37–62% [2]. Another advantage of external field enhancement is its strong adaptability to fluctuating heat sources. Researchers can maintain system performance stability by dynamically adjusting the intensity and direction of the external field [2].

5. Comparison of thermodynamic efficiency among various types of thermal energy storage technologies

The thermodynamic performance comparison between sensible heat storage systems (SHTES) and latent heat storage systems (LHTES) is the focus of this study. Gao et al. experimentally compared SHTES using water as the medium and LHTES using paraffin RT55 as the medium. They found that the thermal efficiency of the LHTES was 66.28%, and the fire efficiency was 30.45%, which was only slightly higher than that of the SHTES (the thermal efficiency of the SHTES was 59.42%, and the fire efficiency was 28.69%) [7]. The study also noted that the LHTES performed well during charging but had issues during discharging. During heat release, a solidified layer forms around the heat exchanger tubes, obstructing heat transfer and creating an insulating layer effect [7]. Additionally, some PCM fails to undergo complete phase change during the cycle, forming "dead mass" that reduces the system's available energy [7]. Gao et al. proposed that future efforts should focus on enhancing the thermal conductivity of PCM, optimising heat exchanger structures, and improving the compatibility between the heat transfer fluid and the phase change temperature zone [7]. Researchers have also analysed the impact of TES architecture optimisation on system efficiency. A study proposed a new cascaded PCM TES architecture to replace the traditional sensible heat + single PCM combination. The new cascaded PCM TES achieves a 100% increase in energy density and a return on investment of 10 years [8].

The thermal efficiency has been improved by 13% (47.6% vs. 42.1%), and the average COP of high-temperature heat pumps (HTHP) has been significantly enhanced (4.13 vs. 3.79), as well as the electrical efficiency of organic Rankine cycles (ORC) (11.69% vs. 11.31%) [4]. These studies demonstrate that there are significant differences in energy density, thermal efficiency, and rotational efficiency among different TES architectures. The thermodynamic metrics and testing methods used in different studies also vary, which poses challenges for cross-technology comparisons.

6. Research gaps and future directions

Researchers have found that current thermodynamic modelling lacks integration. Many studies focus on a single thermal energy storage (TES) technology, with no cross-system modelling reviews. Most studies on combined heat and power (CHP) systems rely on steady-state models, which fail to adequately reflect the impact of TES dynamic behaviour on cycle performance [4]. Future research should develop multi-field coupled dynamic models and explore novel TES architectures such as cascaded phase change materials (PCM) [4]. Research on external field enhancement methods also has limitations. Many studies are conducted only in small-scale experiments, lacking generalisability. The control mechanisms for external field parameters in experiments are still

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incomplete. Multi-field coupled models and dynamic control systems are also immature, and these issues need to be addressed in the future [2]. There is no unified thermodynamic metric system across different TES technologies. Researchers struggle to directly compare metrics such as thermal efficiency and entropy generation across various technologies. Additionally, the scope of application for rapid models and AI methods remains unclear. Researchers lack systematic evaluations of the balance between model accuracy and computational efficiency. Existing studies primarily rely on simulations and lack multi-cycle experimental validation. Some optimisation methods also face challenges in balancing pressure drop reduction and efficiency improvement [1]. Systematic evaluation of material innovations is also absent. In the field of electrochemistry, multi-component composite materials are widely used and can significantly enhance performance. For example, V205/SrO nanocomposites have significantly improved stability and energy density through synergistic effects [8]. Similar material optimisation concepts can be transferred to thermal storage technologies to improve thermal conductivity and cycle life. Future research could explore establishing a unified thermodynamic indicator system, developing standardised modelling procedures, and constructing a cross-technology comparison framework. Concurrently, research should strengthen coupled models of materials and systems, integrating geometric optimisation, external field enhancement, and dynamic modelling to enhance the overall performance of thermal energy storage systems. Researchers also need to conduct more multi-cycle experiments to validate the long-term stability of systems and strengthen studies on the compatibility of encapsulation materials and PCMs [3].

7. Conclusions

Over the past three years, significant progress has been made in the thermodynamic modelling and efficiency analysis of thermal energy storage technologies. Researchers have developed more dynamic models to more accurately describe system operating conditions. They have also proposed various optimisation methods to enhance energy density, cycle efficiency, and operational stability. The core contribution of this review is the integration of models and efficiency studies across different thermal energy storage technologies. Key performance indicators for sensible heat, latent heat, thermochemical, and liquid-gas thermal energy storage systems have been compared, and current research gaps have been identified. Future research should continue to focus on cross-system thermodynamic evaluation and model standardisation. Establishing a unified indicator system and modelling methodology can facilitate fairer performance comparisons among different technologies and accelerate the pace of optimisation and application.

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