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Advanced Modeling Approaches for Latent Heat Thermal Energy Storage Systems

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ABSTRACT

This paper highlights the significance of modeling Latent Heat Thermal Energy Storage (LHTES), temperature-based and enthalpy in an understanding phase transitions, emphasizing their distinct insights based on the specific application. LHTES systems addresses the escalating demand for efficient and environmentally friendly energy management across various sectors. These systems leverage Phase Change Materials (PCMs) to store and release thermal energy during phase transitions, offering significant advantages in terms of energy storage capacity and temperature regulation. This research provides an overview of the methodologies, applications and challenges associated with modeling LHTES systems, which have gained prominence in diverse fields such as phase change modeling, temperature-centric modeling, enthalpy modeling, porous medium approach, conduction-dominated and convection-dominated phase change. This research critically reviewed heat transfer coupled with phase change in simple configurations, exploring fundamental principles and modeling of heat storage units like packed beds. This research finally highlights the crucial importance of modeling underscores its significant role in propelling the development of LHTES technology. These review paper recommended the design and development of accurate, predictive models improve LHTES systems to enhance energy efficiency and reduce ecological impacts across a wide range of applications.

Keywords: Phase change materials, Latent Heat Thermal Energy Storage, Packed beds and Porous medium approach

INTRODUCTION

In the contemporary era, where sustainability and efficient energy management are paramount, the adoption of advanced energy storage technologies has become imperative. Latent Heat Thermal Energy Storage (LHTES) systems, among these technologies, play a pivotal role in the pursuit of sustainable and energy-efficient solutions across diverse applications. These systems leverage the latent heat associated with phase transitions in materials to store and release thermal energy, offering distinct advantages in terms of energy storage capacity and precise temperature control [1][2][3]. This discourse delves into the realm of modeling LHTES systems, a discipline that has gained significant importance in recent years. LHTES systems have become indispensable across various sectors, including renewable energy integration, building heating, ventilation, and air conditioning (HVAC) systems, as well as industrial processes [4][5][6][7]. Hence, to grasp the significance of modeling in the context of LHTES, it is crucial to acknowledge the complexity and multifaceted nature of phase change problems, along with the diverse modeling techniques employed to address them. The spectrum of phase change problems encompasses a wide range of phenomena, from simple to highly intricate, including temperature-based models, enthalpy models, porous medium approaches, and scenarios dominated by either conduction or convection during phase change [8][9][10] [11]. Understanding and modeling heat transfer in simple geometries and comprehending the fundamental principles underlying heat storage units, particularly packed beds, are integral components of this domain. As we embark on an exploration of LHTES system modeling, it is essential to recognize the pivotal role this discipline plays in advancing LHTES technology [12][13]. Accurate and predictive modeling not only assists in system design but also facilitates optimization, ultimately contributing to enhanced energy efficiency and minimized environmental impact across a wide array of applications [14][15]. This comprehensive review seeks to shed light on the various modeling approaches, challenges, and the overarching significance of this field in steering LHTES systems toward greater efficiency and sustainability.

Related Work

Enhancing our comprehension of Latent Heat Thermal Energy Storage (LHTES) systems is crucial for addressing the increasing demand for efficient and sustainable energy management across diverse applications [16][17][18]. This section offers an insightful overview of pertinent research endeavors, concentrating on essential modeling approaches and the associated challenges within the realm of LHTES. Modeling Phase Change Phenomena stands out as a central focus in LHTES research. Scholars have delved into diverse modeling methodologies to accurately simulate and predict phase change behaviors. Among the prominent models, the Temperature-Based Model and the Enthalpy Model have emerged as key players [19]. The Temperature-Based Model places emphasis on tracking temperature variations within LHTES systems and comprehending thermal boundary conditions. This approach proves particularly valuable in systems characterized by well-defined phase transition temperatures [17][20]. Researchers have effectively applied this model to investigate heat transfer during phase change in uncomplicated geometries, such as melting and freezing processes [14]. The Enthalpy Model represents a significant advancement in the study of Latent Heat Thermal Energy Storage (LHTES) systems, offering a comprehensive perspective by incorporating both temperature and enthalpy as primary variables. By accounting for the total energy content of phase change materials, this model facilitates precise tracking of phase changes and allows for a thorough exploration of multi-phase interactions [1][21]. Its versatility is evident in its successful application to both conduction-dominated and convection-dominated phase change scenarios [14]. In addition to the Enthalpy Model, researchers have delved into the porous medium approach to simulate heat transfer and phase change within porous structures. This methodology has proven effective in analyzing LHTES in packed beds and other heat storage units, offering valuable insights for optimizing thermal performance [22] [11]. Despite the progress made in modeling LHTES systems, several challenges persist. Accurate characterization of phase change materials remains a critical aspect that requires further refinement. The modeling community is actively addressing the complexities associated with multi-phase interactions, aiming to enhance the overall accuracy of simulations [2] [23]. Another area for improvement is computational efficiency, as researchers strive to develop models that are not only accurate but also efficient in terms of computation time and resources. The modeling of LHTES systems is a dynamic and evolving field with diverse applications. Researchers are committed to refining existing models and exploring innovative approaches to deepen our understanding of phase change phenomena. The ultimate goal is to optimize LHTES systems, contributing to improved energy efficiency and sustainability in various applications. As advancements continue, the collaborative efforts of the scientific community promise a future where LHTES systems play a pivotal role in shaping a more sustainable and energy-efficient world [1][2][11].

Modelling of Phase Change Problems (Temperature and Enthalpy Based Model)

Phase change problems involving solid-liquid or liquid-gas transitions are ubiquitous in various scientific and engineering domains. Accurate modelling of these phenomena is indispensable for comprehending complex thermal processes, optimizing system designs, and enhancing energy efficiency. Phase change problems, encompassing phenomena like melting, freezing, and vaporization, are prevalent in applications ranging from energy storage to materials processing [14].

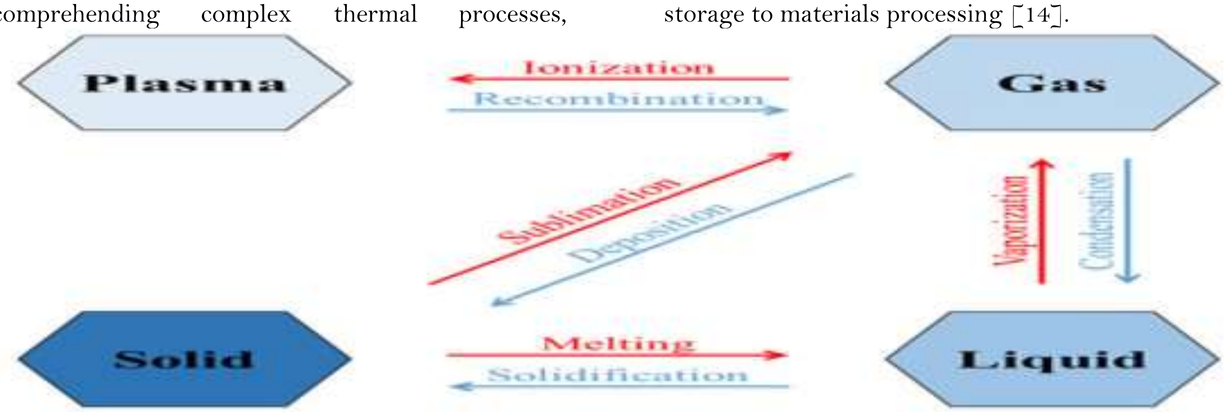

Figure 1: Phase Change Transitions

Figure 1 illustrates the essential modeling of phase change, a critical aspect for comprehending heat transfer, forecasting system performance, and refining energy management strategies. In this pursuit, two primary approaches, namely the Temperature-Based Model and the Enthalpy-based Model are employed [20].

Temperature-Based Model

The Temperature-Based Model places temperature as its central focus and leverages thermal boundary conditions to simulate phase change. It offers several notable characteristics such as:

- Thermal Boundary Conditions: The Temperature-Based Model emphasizes the significance of thermal boundary conditions in determining temperature variations within the system.
- Phase Change Temperature: Key to this model is the identification of the temperature at which phase change initiates or concludes, such as the melting point. This pivotal temperature threshold delineates the onset and conclusion of phase transitions.
- Simplicity: Renowned for its simplicity, the Temperature-Based Model is frequently employed in didactic settings and straightforward phase change problems.
- Limitations: Despite its utility, this model may lack the precision required to capture intricate phase change behaviors, particularly in cases involving multiple phases or nonlinear phase change materials.

Phase change problems occur across a broad spectrum of temperatures, from cryogenic conditions to high-temperature industrial processes. The Temperature-Based Model offers a versatile framework for simulating phase change phenomena and understanding thermal behavior. The temperature based application can occur in three forms known as: low temperature, medium temperature, and high temperature ranges [14][20].

- Low Temperature Range: In cryogenic and low-temperature applications, the Temperature-Based Model plays a pivotal role in predicting phase transitions, such as solid-to-liquid or liquid-to-gas, at extremely cold conditions. Applications include the storage of liquefied gases and cryopreservation. Accurate modelling ensures the safe handling and efficient utilization of cryogenic substances.
- Medium Temperature Range: In the medium-temperature regime, which encompasses ambient and moderate temperature conditions, the Temperature-Based Model finds wide application in fields like HVAC systems, electronics cooling, and food processing.
  Modelling focuses on thermal energy storage, phase change materials, and heat exchangers, offering insights into energy efficiency and temperature control.
- High Temperature Range: At high temperatures encountered in metallurgy, material processing, and power generation, the Temperature-Based Model remains indispensable. It facilitates the understanding of phase transitions, such as solid-state transformations or combustion processes. Applications span from optimizing industrial furnaces to designing advanced materials for extreme environments

Modelling phase change problems across different temperature ranges using the Temperature-Based Model presents challenges related to phase change kinetics, material properties, and computational complexity [14]. Advances in numerical techniques, coupled with experimental validation, contribute to overcoming these challenges and enhancing the accuracy of models. The Temperature-Based Model's adaptability across low, medium, and high-temperature ranges underscores its significance in diverse scientific and engineering applications. Its application enriches the understanding of phase change phenomena, enabling the optimization of systems and processes at varying thermal conditions [14].

Enthalpy Model

The Enthalpy Model adopts a comprehensive approach, considering both temperature and enthalpy, the latter representing the internal energy of the material. Key characteristics of the Enthalpy Model include:

- Enthalpy as the Primary Variable: In the Enthalpy Model, enthalpy takes precedence as the primary variable of interest. It accounts for the total energy content of the material, encompassing the energy associated with phase transitions.
- Precise Phase Change Tracking: The Enthalpy Model excels in the precise tracking of phase change phenomena by continuously updating the enthalpy field. This capability allows for the accurate determination of phase boundaries and behavior.
- Multi-Phase Applications: Well-suited for modelling complex scenarios involving multiple phases or materials with varying latent heat values, the Enthalpy Model adeptly handles simultaneous phase transitions.
- Complexity: Although more computationally demanding than the Temperature-Based Model, the Enthalpy Model offers unparalleled accuracy in capturing phase change dynamics.

Applications of the Enthalpy Model

The Enthalpy Model finds extensive use in various fields, including materials science, metallurgy, and energy storage. It is crucial for simulating and optimizing processes involving phase transitions, such as the heat treatment of materials, the performance of latent heat thermal energy storage systems, and the behavior of phase change materials in building insulation. Despite its accuracy and versatility, the Enthalpy Model can be computationally intensive, particularly for complex systems. Ongoing advancements in numerical techniques and high-performance computing have helped address these challenges, making it increasingly practical for a broader range of applications [19]. The Enthalpy Model stands as a robust and essential tool for modeling phase change problems across various scientific and engineering domains. Its capacity to accurately describe phase transitions by considering both temperature and enthalpy enriches our understanding of thermal processes and contributes to the optimization of energy-efficient systems and materials. Researchers and engineers continue to rely on the Enthalpy Model to tackle complex thermal challenges and drive innovation in diverse fields.

Porous Medium Approach in Conduction-Dominated and Convection-Dominated Phase Change

Phase change phenomena, involving the transition between solid, liquid, and gas states, are integral to numerous engineering applications. Understanding and modeling these processes is crucial for optimizing technologies like latent heat thermal energy storage (LHTES) systems. The Porous Medium Approach is a modeling technique employed in situations where the material undergoing phase change exhibits a porous structure. This technique considers the porous medium as a continuum with effective properties, simplifying the modeling process. In the context of phase change problems, porosity, permeability, and thermal conductivity of the porous medium play pivotal roles in shaping the overall behavior [15].

Conduction-Dominated Phase Change

In scenarios where heat transfer is primarily governed by conduction, such as in solid-liquid or solid-gas phase transitions, the Porous Medium Approach proves valuable. Key studies like that of Bear and Bachmat provide foundational insights into heat conduction in porous media, establishing principles used in contemporary models [24]. The effective thermal conductivity is a general parameter for characterizing porous media and is mainly affected by the components of the medium, more specifically, the distributions, proportions and properties of the components. When the solid, liquid and gas phases have a layered distribution and are connected in series, the thermal conductivity reaches its minimum; in contrast, when the layers are connected in parallel, the thermal conductivity reaches its maximum. When the layers are connected in series (superscript L) or in parallel (superscript U), the theoretical values of the effective thermal conductivity for a multiphase medium are

$$\begin{cases} \lambda^{L} = (\{\ \phi_n/\lambda_n)^{-1} \\ \lambda^{U} = \{ \quad \phi_n/\lambda_n \end{cases} \qquad (1)$$

Where λ is the thermal conductivity of the porous medium, the subscript n refers to different components, and ϕ denotes the volume proportion of each component. Conduction-dominated phase change is a common phenomenon in various engineering applications, influencing the behavior of materials transitioning between solid and liquid states. This work explores the fundamental principles and modeling techniques associated with conduction-dominated phase change, emphasizing the importance of accurate representation in technologies such as latent heat thermal energy storage (LHTES) systems.

Fundamental Principles

Conduction-dominated phase change occurs when heat transfer within a material is primarily governed by thermal conduction. During this process, energy is transferred through the material by the movement of heat from regions of higher temperature to lower temperature, resulting in phase transitions. Understanding the fundamental principles of heat conduction in such scenarios is crucial for designing efficient systems.

Modeling Techniques

The Porous Medium Approach is a widely used modeling technique in conduction-dominated phase change scenarios. This approach considers the material undergoing phase change as a porous medium with effective properties. Key parameters, such as porosity and thermal conductivity, play a vital role in shaping the overall behavior of the material. The effective thermal conductivity of the porous medium is particularly significant in accurately predicting temperature profiles during conduction-dominated phase change.

Principles of Convection-Dominated Phase Change

Convection-dominated phase change occurs when fluid motion, induced by temperature gradients, plays a dominant role in the heat transfer process. Understanding this phenomenon is essential for various applications, including boiling, condensation, and evaporative cooling [20][17]. Several key principles define convection-dominated phase change:

- Fluid Motion: Fluid motion, driven by buoyancy or forced convection, facilitates the transport of heat within the system. In natural convection, warmer, less dense fluid rises, while cooler, denser fluid descends, creating circulation patterns.

- Heat Transfer Modes: Convection-dominated phase change involves multiple heat transfer modes, including conduction, convection, and phase change. Heat is conducted through the fluid boundary layer, while bulk fluid motion enhances heat transfer rates.
- Heat Flux Distribution: The heat flux distribution across the fluid-solid interface is non-uniform, with higher heat transfer rates near the heated surface due to the enhanced convective heat transfer.

Applications

Convection-dominated phase change has numerous practical applications:

- Boiling: In heat exchangers and power generation, the understanding of boiling heat transfer is essential for efficient energy conversion.
- Condensation: In refrigeration and air conditioning systems, controlling condensation processes optimizes cooling efficiency.
- Evaporative Cooling: Evaporative cooling is widely used in HVAC systems and industrial processes for temperature control.

Heat Transfer with Phase Change in Simple Geometries

Heat transfer involving phase change in simple geometries is a fundamental phenomenon crucial in various engineering and industrial applications. This process occurs during the transition of a substance from one phase to another, like solid to liquid (melting) or liquid to gas (vaporization), often impacting systems with specific geometrical configurations [16][17].

Fundamental Principles

The transfer of heat during phase change in simple geometries is governed by principles of thermodynamics and heat transfer. Energy is absorbed or released during phase transitions, influencing the temperature and state of the material. This process follows the laws of conservation of energy and mass, impacting the overall thermal behavior of the system. The process of heat transfer with phase change in simple geometries is observed in scenarios like melting, freezing, evaporation, and condensation. Commonly, this occurs in materials with well-defined shapes or structures, allowing for a clear understanding of the heat exchange process within these configurations.

Understanding Phase Change in Simple Geometries

Melting and Solidification:

- Heat Absorption: During melting, a solid absorbs heat, which alters its state to a liquid while maintaining a constant temperature.
- Heat Release: Conversely, during solidification, a liquid releases heat to its surroundings to transform back into a solid state.

Vaporization and Condensation:

- Heat Absorption: Vaporization occurs when a liquid absorbs heat and transforms into a vapor without temperature increase.
- Heat Release: Condensation happens when a vapor releases heat, transitioning into a liquid state.

Applications in Simple Geometries

- Heat Exchangers: Phase change processes are used in heat exchangers for effective temperature control and energy transfer.
- Refrigeration and Air Conditioning: Evaporation and condensation processes in simple geometric configurations are the basis of refrigeration and air conditioning systems.
- Boilers and Condensers: Simple geometries facilitate heat transfer during the boiling and condensing processes in boilers and condensers.

Basic Concepts and Modeling of Heat Storage Units - Packed Beds

Modeling heat storage units, particularly packed beds, involves understanding the fundamental concepts of heat transfer and storage in a granular media arrangement. Packed beds are used extensively in various industries for thermal energy storage due to their high surface area and porosity, allowing efficient heat exchange [22].

Modeling Concepts

Basic Concepts

- Granular Media Arrangement: Packed beds consist of solid particles or granular material placed in a container or vessel, allowing the flow of a heat transfer fluid (commonly air or water) for heating or cooling purposes.
- Thermal Conductivity and Heat Capacity: The heat transfer in packed beds is determined by the thermal conductivity of the packing material and its heat capacity, affecting the efficiency of heat storage and release.

- Pore Structure and Void Fraction: Understanding the structure, arrangement, and void spaces within the packed bed is crucial for modeling. It affects fluid flow, heat transfer, and storage capacity.
- Mass and Heat Transfer Mechanisms: Modeling involves considering mechanisms such as conduction, convection, and radiation within the packed bed to predict the heat transfer and storage characteristics accurately.
- Heat Exchange Fluid Flow: The flow of the heat exchange fluid through the packed bed significantly influences the heat transfer efficiency and is a critical factor in modeling.

Modeling Approaches

- Mathematical Modeling: Involves the development of mathematical equations and computational models to simulate heat transfer, storage, and fluid flow through packed beds. Finite Element Analysis (FEA), Computational Fluid Dynamics (CFD), and other numerical methods are employed.
- Experimental Validation: Modeling often requires experimental data to validate and refine the theoretical models. Experimental setups with temperature sensors and flow meters help validate the accuracy of the models.
- Thermal Performance Prediction: Models are used to predict the thermal performance of packed beds under different operating conditions, aiding in the design and optimization of heat storage systems.

Key Factors in Modeling Packed Beds

- Material Properties: Thermal conductivity, specific heat, and density of the packing material.
- Boundary Conditions: Inlet and outlet temperatures, environmental conditions, and fluid flow rates.
- Bed Geometry: Consideration of the bed's dimensions, porosity, and particle size [22].

The modeling and understanding of heat storage in packed beds are crucial for various applications like solar energy storage, industrial processes, and HVAC systems. Research continues to enhance the efficiency and practical application of these heat storage systems.

FINDINGS

The temperature-based model concentrates on temperature variations during phase transitions, while the enthalpy model encompasses the entire energy change, incorporating latent heat. Both models provide distinct insights into phase change issues, with the selection contingent upon the specific application and desired level of detail. The porous medium approach proves advantageous in scrutinizing phase change problems within porous materials, where conduction, convection, and phase change processes intertwine. This methodology proves invaluable for examining heat transfer in intricate structures and materials exhibiting varying porosity. Conduction-dominated phase change predominantly occurs within the material itself, influencing phase transitions in solid materials. On the other hand, convection-dominated phase change involves the fluid movement around the material, a phenomenon commonly observed in liquids and gases. Analyzing heat transfer in simple geometries, such as slabs or cylinders, provides fundamental insights into material behavior during phase change. The simplicity of these geometries facilitates a better understanding of the fundamental principles governing heat transfer during phase transitions.

Packed beds play a crucial role in thermal energy storage, employing materials with high heat capacity to store and release thermal energy. Modeling heat storage in packed beds necessitates consideration of factors such as heat capacity, thermal conductivity, and the specific geometry of the bed. These advanced models and concepts are at the forefront of ongoing research and innovation, contributing significantly to the development of sustainable energy solutions and the optimization of thermal energy storage systems.

CONCLUSION

In conclusion, a profound grasp of heat transfers and phase change phenomena is essential in numerous engineering and energy applications. The amalgamation of diverse models and approaches forms a robust foundation for comprehending and predicting heat storage units, with a specific focus on packed beds. Concepts ranging from temperature-based modeling to convection-dominated phase changes play a pivotal role in advancing heat transfer studies. Two primary models, namely the temperature-based model and the enthalpy model, offer distinctive perspectives on heat transfer processes during phase change. The temperature-based model provides a fundamental understanding based on temperature variations, whereas the enthalpy model considers energy changes throughout the phase change, offering a more comprehensive analysis. The porous medium approach is crucial in understanding the impact of material structure on heat transfer within packed beds. This approach explores the interaction between solid matrices and fluid flow, significantly contributing to the accurate modeling of heat storage systems. Conduction and convection-dominated phase change models focus on different heat transfer mechanisms. Conduction-dominated models emphasize heat transfer through solid structures, while convection-dominated models address fluid flow and convective heat transfer, particularly relevant in systems involving fluid-filled packed beds. Analyzing heat transfer with phase change in simple geometries serves as a cornerstone in studying fundamental concepts before extending to complex systems. These simple geometries provide a practical foundation for understanding and testing theoretical models and concepts. Finally, the study and modeling of heat storage units, particularly packed beds, offer a comprehensive approach to understanding phase change problems. The diverse methodologies, ranging from basic to advanced modeling, equip researchers and engineers with the necessary tools to design efficient heat storage systems. Furthermore, these models serve as a framework for innovation and advancement in renewable energy, industrial processes, and environmental conservation.

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