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Thermodynamic Analysis of Thermal Efficiency and Entropy Production in Distributed Energy Storage Systems within Power Distribution Networks

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ABSTRACT

In the realm of electrical distribution networks, the integration of renewable energy sources has rendered Distributed Energy Storage Systems (DESS) indispensable for load regulation and enhancement of energy efficiency. Despite widespread research on their economic and electrochemical aspects, a comprehensive understanding of their thermodynamic properties, particularly thermal efficiency and entropy production, remains elusive. This study introduces a mathematical model designed to simulate transient heat transfer processes in DESS under non-thermal equilibrium conditions, addressing the existing research gap in transient behavior and non-equilibrium heat transfer mechanisms. The model incorporates the intricate physical structure and complex heat transfer mechanisms of these systems, establishing itself as an innovative tool for deepened insight and optimization of energy storage solutions. A thorough thermodynamic analysis, utilizing exergy analysis and system thermal efficiency evaluation, is conducted. This analysis quantitatively assesses energy conversion and losses during operational phases of the systems. Insights into critical factors influencing system thermal efficiency are unearthed, offering a scientific foundation for refining DESS design and operational efficacy. This investigation contributes novel theoretical and methodological perspectives to the advancement of green and low-carbon power distribution networks, bearing significant theoretical and practical implications.

1. INTRODUCTION

In the evolving global energy landscape, where renewable energy sources are rapidly advancing, DESS have emerged as increasingly pivotal in power distribution networks. Their capacity to balance grid loads, enhance energy utilization efficiency, and bolster grid stability and reliability is well-acknowledged [1-5]. However, the efficiency of these systems is not a constant factor; it is intricately linked to their thermal management capabilities [6-9]. Traditionally, research on DESS has been concentrated predominantly on their electrochemical characteristics and economic performance. The exploration of their thermal efficiency and entropy production has been relatively less explored, thus limiting the comprehensive understanding and optimization of their overall performance.

The thermal efficiency of energy storage systems is intrinsically tied to the effective utilization of energy and the economic operation of these systems [10, 11]. Systems exhibiting high thermal efficiency can mitigate thermal energy losses, thereby reducing operational costs and lessening environmental heat load. This enhancement in thermal efficiency contributes to the overall environmental friendliness of the systems [12-15]. The analysis of entropy production, crucial for quantifying irreversible losses in energy conversion processes, plays a pivotal role. It unveils the fundamental causes of energy losses, thereby guiding system optimization and elevating energy conversion efficiency. Consequently, the study of thermal efficiency and entropy production is not merely beneficial for deepening the understanding of DESS's thermodynamic characteristics but also holds substantial value for promoting the green and low-carbon evolution of power distribution networks [16, 17].

In contemporary thermodynamic examinations of DESS, the predominant focus is on steady-state processes, with transient behaviors and non-equilibrium phenomena in porous media often being overlooked [18, 19]. Prevailing heat transfer models, which generally presume a state of thermal equilibrium, are found to fall short in accurately predicting the thermal response and entropy production in storage systems under dynamic loading conditions [20, 21]. Therefore, the development of a mathematical model that accurately depicts the thermal dynamic behavior of storage systems in non-thermal equilibrium states is identified as crucial. Such a model is essential for refining the accuracy of predictive models and the efficiency of thermal management in these systems [22-25].

This paper introduces a novel heat transfer analysis and mathematical modeling approach, specifically designed for prevalent DESS in power distribution networks. The proposed model meticulously incorporates the physical structure of storage systems and their intricate heat transfer mechanisms. It is adept at delineating transient, non-thermal equilibrium flow and heat transfer processes within porous media. Following this, the paper embarks on a comprehensive analysis of the thermal efficiency and entropy production characteristics inherent in DESS. Utilizing thermodynamic methodologies such as exergy analysis and system thermal efficiency assessment, a quantitative evaluation of the energy conversion and loss processes within these systems is conducted. These analyses not only unveil pivotal factors impacting the thermal efficiency of storage systems but also furnish theoretical underpinnings and technical pathways for their design optimization and operational management. This endeavor significantly contributes to the technological progression and efficiency enhancement of power distribution networks, offering valuable insights for future advancements in the field.

2. HEAT TRANSFER ANALYSIS AND MATHEMATICAL MODEL OF ENERGY STORAGE MODULE IN DESS

In the domain of power distribution networks, the energy storage modules within DESS typically utilize highly efficient energy storage media, coupled with advanced thermal management techniques, to ensure effective energy storage and release. These modules predominantly comprise Phase Change Materials (PCM) as the energy storage medium, characterized by their ability to oscillate between solid and liquid states while absorbing or releasing heat, effectuating high-density energy storage and stable thermal output. Encircling the PCM, heat transfer fluid channels, strategically designed, facilitate the conversion of surplus electrical energy from the grid into thermal energy. This thermal energy is transferred to the PCM via mediums like water or air, or conversely, the stored thermal energy is swiftly converted back to electrical energy as necessitated. The exterior of the storage module is enveloped in an insulation material with low thermal conductivity to reduce thermal losses and prevent ineffective thermal energy leakage due to external environmental fluctuations, thereby preserving the overall thermal efficiency of the system.

In these networks, the DESS energy storage module is the central component for energy regulation and storage. Its heat transfer mechanism is critical to the thermal efficiency and energy management performance of the system. This study is dedicated to a detailed analysis of the heat transfer mechanism in the storage module, aiming to optimize its thermal efficiency and minimize entropy production. This analysis encompasses three key aspects:

- Heat exchange between the heat transfer fluid and the PCM surface: This process significantly influences the thermal efficiency of the storage module. The fluid, as it traverses the channels, engages in heat transfer with the PCM through convection. The efficiency of this interaction is contingent upon factors such as the fluid's flow velocity, the nature of contact between the fluid and PCM surface, the fluid's temperature, and the PCM's thermal conductivity. Optimizing the fluid's flow dynamics and surface properties enhances the heat exchange efficiency at this interface.
- Internal heat transfer within PCM: This involves both thermal conduction and phase change heat transfer mechanisms. Thermal conduction within the PCM pertains to heat propagation through molecular or lattice vibrations in its solid state. Phase change heat transfer pertains to the absorption or release of heat during the PCM's phase transition. The latent heat associated with PCM phase changes is substantial, making the efficiency of heat storage or release during these transitions vital to the overall module performance. Enhancing internal heat transfer efficiency in the PCM can be achieved by incorporating high thermal conductivity fillers or utilizing metallic framework structures to amplify internal heat conduction.
- Thermal exchange between the system and its environment: Operational storage modules inevitably engage in thermal exchange with their surroundings, often resulting in thermal energy losses and affecting the system's thermal efficiency. To mitigate undesired thermal exchange, the storage module is designed with insulation layers that limit heat transfer to the environment through radiation, convection, and conduction. The insulating performance, and thus the system's energy retention capability and stability, are influenced by the material choice and structural design of these insulation layers.

In the arena of power distribution networks, computational models for thermal analysis of DESS predominantly focus on accurately delineating the thermal response of storage materials and the system's thermal management behavior. These models extensively use complex partial differential equations for characterizing heat conduction, convection, and phase transitions, enabling the simulation of temperature distribution within storage materials and its temporal alterations. Integration of porous media models in some instances allows for considering the percolation effects of heat transfer fluids within the storage medium. Distinguished by their capacity to manage intricate boundary conditions, time-dependent heat sources, and the temperature-dependent non-linearity of material properties, these models are instrumental in design and optimization phases. They facilitate engineers in assessing thermal efficiency and thermal load response across varied design scenarios and support the development of operational strategies by simulating the system's thermal behavior under diverse operating conditions. Figure 1 depicts a schematic of the numerical computation for the energy storage module in DESS.

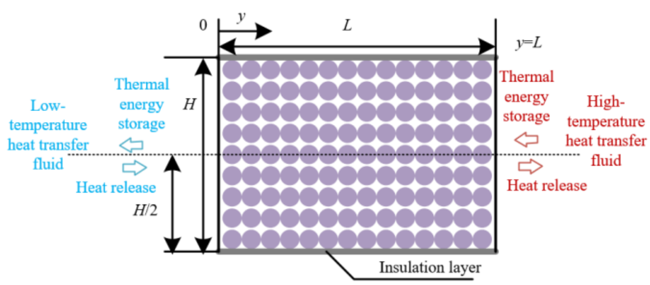

Figure 1. Schematic diagram of numerical computation for energy storage module in DESS

Current simulation models predominantly utilize a single-phase flow approach, presuming a consistent phase state during heat transfer processes, or a more elaborate two-phase flow paradigm. Despite their detail, these models incur high computational demands and necessitate precise parameterization, which may impede swift application in practical engineering settings. To more effectively capture heat conduction and convective heat transfer phenomena during phase changes, while circumventing the computational intensity of tracking phase interfaces in complete two-phase flow models, this study adopts a two-phase continuum model. Based on the local non-thermal equilibrium theory in porous media, a simplified transient flow and heat transfer model is established. Figure 2 presents the numerical calculation flowchart for the energy storage module in DESS.

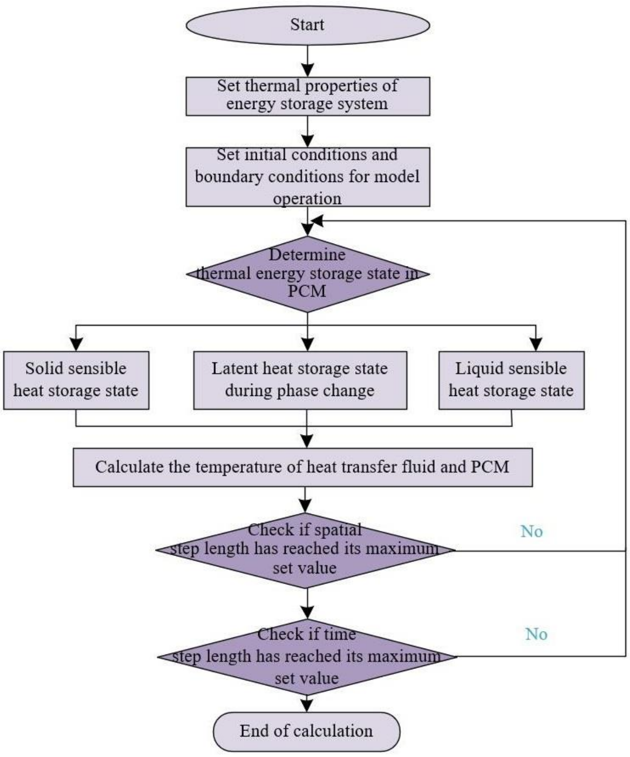

Figure 2. Numerical calculation flowchart for energy storage module in DESS

In the energy storage modules of DESS within power distribution networks, the formulation of conservation equations for mass, momentum, and energy in relation to the heat transfer fluid is imperative. Accurate modeling and resolution of these conservation equations are foundational for optimizing thermal management, enhancing the efficiency of energy storage, reducing energy losses, and augmenting the system's thermal stability.

The mass conservation principle dictates that the total mass within a specified control volume remains unchanged in the absence of material ingress or egress. For the heat transfer fluid within the energy storage module, this necessitates a balance between the inflow and outflow masses at any point, thereby ensuring no unaccounted disappearance or creation of the fluid. In developing the mass conservation equation, considerations include the fluid's velocity distribution across various directions and the fluid density fluctuations. Key parameters include the module's porosity (γ), the heat transfer fluid's density (ϑ_d), its constant pressure heat capacity ($v_{o,d}$), the fluid's velocity vector ($\vec{i}$), pressure (o), gravitational constant vector ($\vec{h}$), fluid's dynamic viscosity (ω), viscous resistance coefficient (J), inertial resistance coefficient (V_D), width per unit of PCM (f_o), convective heat transfer coefficient (g_c) between PCM and fluid, and effective thermal conductivity (j_{EFF}). The mass conservation equation for the heat transfer fluid is expressed as follows:

$$\frac{\partial(\gamma\vartheta_d)}{\partial y}+\nabla\cdot\left(\vartheta_d\vec{i}\right)=0 \tag{1}$$

Regarding momentum conservation within the energy storage module, it encompasses the fluid particles' velocity alterations due to internal friction, interaction with conduit walls, fluid mass changes, and external pressure gradients. The momentum conservation equation is established to ensure equilibrium between all forces exerted on a fluid element and its momentum change rate. The equation is articulated as follows:

$$\begin{aligned}&\frac{\partial\left(\vartheta_d\vec{i}\right)}{\partial y}+\nabla\cdot\left(\vartheta_d\frac{\vec{i}\vec{i}}{\gamma}\right)=-\gamma\nabla o+\nabla\cdot\left(\vec{i}\nabla\vec{i}\right)+\gamma\vartheta_d\vec{h}\\&+\gamma\left(\frac{\omega}{J}+\frac{V_D}{\sqrt{J}}\vartheta_d\left|\vec{i}\right|\right)\vec{i}\end{aligned} \tag{2}$$

$$V_D=\frac{1.75}{\sqrt{150\gamma^3}} \tag{3}$$

$$J=\frac{f_o^2\gamma^3}{150\left(1-\gamma\right)^2} \tag{4}$$

The energy conservation equation in the module captures the internal energy variations attributable to temperature changes in the heat transfer fluid and energy transfers due to the working substance's flow. In framing this equation, a balance is maintained between the energy absorbed, stored, converted, and lost by a fluid element at any moment. The energy conservation equation for the heat transfer fluid is formulated as follows:

$$\begin{aligned}&\frac{\partial\left[\left(\gamma\vartheta v_o\right)_d Y_d\right]}{\partial y}+\nabla\cdot\left[\left(\vartheta v_o\right)_d Y_d\vec{i}_d\right]=\\&\nabla\cdot\left(j_{EFF}\nabla Y_d\right)+g_c\left(Y_a-Y_d\right)\end{aligned} \tag{5}$$

In the DESS energy storage modules of power distribution networks, formulating energy conservation equations for PCM and their insulation layers is crucial. The equation for PCM delineates the dynamics of energy storage and release during heating and cooling processes, incorporating latent heat absorption and release during phase transitions. This aspect is critical for optimizing PCM's energy storage capacity, response rate, and overall thermal efficiency. For the insulation layer and system's external walls, the energy conservation equation is pivotal in minimizing energy loss to the external environment through radiation, convection, and conduction during operation, thereby elevating the system's energy utilization rate and stability. Precise formulation of these equations facilitates comprehensive control over intricate thermal transfer processes within the storage module, offering a robust foundation for enhancing system performance and understanding thermal management mechanisms.

The construction of PCM's energy conservation equation revolves around balancing energy changes during the material's phase transitions. In the heating phase, PCM transforms from solid to liquid, retaining a constant temperature while storing substantial latent heat. Conversely, during cooling, PCM reverts to solid, releasing stored latent heat. The equation is formulated to encapsulate this phase transition energy exchange and thermal interactions with the environment. The equation for PCM's energy conservation is formulated as:

$$\frac{\partial\left\{\left[(1-\gamma)\vartheta v_o\right]_a Y_a\right\}}{\partial y}=\nabla\cdot\left(j_a\nabla Y_a\right)-g_a\left(Y_a-Y_d\right) \tag{6}$$

For the insulation layer and system's external walls, the energy conservation equation aims to bolster thermal stability and efficiency. The insulation layer plays a vital role in impeding the thermal energy stored internally from dissipating to the outside environment, a crucial aspect when external temperature differences are significant. This equation factors in the insulation layer's thermal conductivity and potential convective and radiative heat losses from external walls, aiding in simulating and assessing the insulation layer's effectiveness. The energy conservation equation for the insulation layer and external walls is articulated as:

$$\frac{\partial\left[\left(\vartheta v_o\right)_{INS} Y_{INS}\right]}{\partial y}=\nabla\cdot\left(j_{INS}\nabla Y_{INS}\right) \tag{7}$$

In DESS modules, the efficient thermal exchange between heat transfer fluid and PCM is instrumental for system performance optimization. Precise calculation of the convective heat transfer coefficient is essential for ensuring effective heat transfer to or from PCM as the fluid flows through. This coefficient influences the PCM's energy absorption and release rates, impacting the module's response time and energy density. Likewise, determining the effective thermal conductivity of the heat transfer fluid is crucial, influencing the fluid's internal thermal energy transfer capability, an integral parameter for designing fluid channels and evaluating the system's overall thermal performance. Computing the natural convective heat transfer coefficient on external vertical walls is also vital, as it governs the thermal exchange rate between the module and the environment. In scenarios lacking forced convection, natural convection dominates module cooling, with its efficiency directly affecting the system's thermal stability and energy retention.

In this study, the focus on calculating the convective heat transfer coefficient between the heat transfer fluid and PCM in DESS energy storage modules reveals how fluid dynamics facilitate thermal exchange at the fluid-solid interface. This coefficient's value is influenced by the fluid's inherent properties, its flow behavior, and the characteristics of the solid surface. The principle underlying this calculation is the assessment of heat transfer efficiency from areas of higher temperature to lower temperature, propelled by the movement of the fluid under specific conditions. Variables considered include the Reynolds number (Er_o), the Prandtl number (Oe), thermal conductivity (j_d) of the heat transfer fluid, constant pressure heat capacity ($v_{o,a}$) of PCM, PCM temperature (Y_A), thermal conductivity (j_a) of PCM, constant pressure heat capacity ($v_{o,INS}$) of insulation material, insulation material temperature (Y_{INS}), and thermal conductivity (j_{INS}) of insulation material. The equation calculating the convective heat transfer coefficient g_c is presented as:

$$g_c=\frac{6(1-\gamma)\,j_d\left[2+1.1Er_o^{0.6}Oe^{1/3}\right]}{f_o^2} \tag{8}$$

$$Er_o=\frac{\vartheta_d f_o\left|\vec{i}\right|}{\omega_d} \tag{9}$$

$$Oe=\frac{V_{o,d}\,\omega_d}{j_d} \tag{10}$$

Determining the effective thermal conductivity of the heat transfer fluid centers on assessing the fluid's capability to disseminate internal thermal energy via molecular motion and collisions in the absence of substantial flow. This coefficient reflects the intrinsic thermal conduction attributes within the fluid, dependent on the fluid type, temperature, and pressure. The formula for calculating the effective thermal conductivity is:

$$j_{EFF}=\begin{cases}0.7\gamma j_d, Er_o<0.8\\ 0.5OeEr_o j_d, Er_o>0.8\end{cases} \tag{11}$$

The computation of the natural convective heat transfer coefficient on external vertical walls is based on the buoyancy effect caused by density variations in the fluid due to temperature differences. Heat transfer in this context relies on internal temperature differentials and subsequent density shifts, rather than external forces inducing fluid movement. The fluid's expansion upon heating and contraction upon cooling establish a natural convective cycle, driving heat transfer. The calculation factors in wall characteristics, fluid thermal properties, and the temperature gradient. Variables include the Nusselt number (B_i), Rayleigh number (Es), Prandtl number (Oe), fluid's volumetric thermal expansion coefficient (α), and kinematic viscosity (c). The natural convective heat transfer coefficient g_{OUT} on external vertical walls is calculated as follows:

$$g_{OUT}=\frac{Bi_{OUT}\,j_{INS}}{G}=\frac{\left[0.825+0.387\left(Es\cdot d(Oe)\right)^{1/6}\right]^2 j_{INS}}{G} \tag{12}$$

$$d(Oe)=\left[1+\left(0.492/Oe\right)^{9/16}\right]^{16/9} \tag{13}$$

$$Es=HeOe \tag{14}$$

$$He=h\alpha\Delta YG^3/c^2 \tag{15}$$

A significant pressure drop can escalate energy consumption and potentially result in non-uniform fluid flow. This non-uniformity can adversely affect the consistency of thermal exchange and the response of PCMs. Furthermore, the precise assessment of pressure drop is paramount for the reliability analysis of the system. Improper pressure distribution may induce fatigue in the equipment, consequently diminishing its operational lifespan. Therefore, the calculation of pressure drop within the energy storage units of DESS in power distribution networks holds critical significance. In determining the pressure drop, factors such as the fluid's density and viscosity, flow rate, as well as the conduits' length, diameter, and surface roughness are imperative. These elements collectively influence the magnitude of frictional forces encountered by the fluid in motion. Additionally, the specific geometric characteristics of each channel within the energy storage unit, along with the nature of fluid flow, substantially impact the overall pressure drop. An elaborate equation is formulated for the calculation of this pressure drop, encompassing these diverse parameters.

$$\Delta O = 150G\frac{(1-\gamma)^2}{\gamma^2}\frac{\omega_d i_d}{f_o^2} + 1.7G(1-\gamma)\frac{\vartheta_d i_d^2}{f_o} \tag{16}$$

3. THERMODYNAMIC ANALYSIS OF THERMAL EFFICIENCY AND ENTROPY PRODUCTION IN DESS

In DESS within power distribution networks, the analysis of thermal efficiency and entropy production is increasingly pivotal as these networks evolve towards smarter, more distributed frameworks with a greater integration of renewable energy sources. DESS play a fundamental role not only in optimizing energy distribution and enhancing grid stability and reliability but also in providing critical energy support during peak demand periods. The thermal efficiency and entropy production of these systems are intimately linked to their overall effectiveness and operational costs. An analysis of thermal efficiency is crucial for pinpointing and diminishing energy losses during system operation, particularly in energy conversion and storage processes. Enhanced thermal efficiency implies that a greater proportion of input energy is converted into usable electrical energy, thus elevating the effective utilization of energy. On the other hand, entropy production analysis sheds light on the root causes of irreversible processes and thermodynamic inefficiencies within the systems. This analysis is essential for guiding improvements in system design, such as refining heat exchanger designs, optimizing flow channel layouts, and selecting suitable materials, and for adjusting operational strategies to reduce irreversible losses.

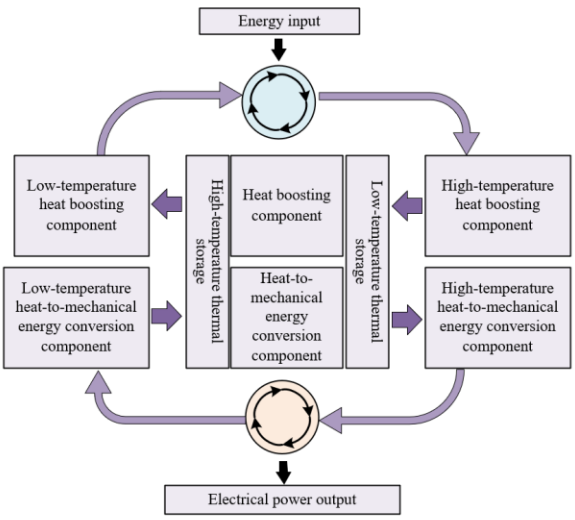

Figure 3. Energy transfer process in DESS

In the DESS within power distribution networks, Figure 3 serves as an illustrative guide to the energy transfer process. This study utilizes exergy analysis, underpinned by the second law of thermodynamics, to explore the energy conversion efficiency and irreversibility in DESS components. This approach quantifies total exergy destruction within each component during energy conversion and pinpoints specific stages and causes of energy loss, thereby playing a crucial role in system optimization. The exergy at each state point in the DESS is calculated, adhering to the fundamental principles of the second law of thermodynamics, which address the quality and efficiency issues of energy during mass and energy exchange processes. Key state points within the system are identified, signifying pivotal stages in energy conversion and material flow, such as the inlets and outlets of energy storage units, endpoints of heat exchangers, and other vital operational components. At each state point, the interplay of energy and materials is examined, taking into account discrepancies between actual and ideal conditions of energy conversion and material transfer. By comparing the actual state at each point with the environmental reference state, the irreversibility of energy transformation from one state to another is discerned. Ideally, the exergy of the system should be conserved if no energy loss occurs. Nevertheless, in practice, due to irreversible phenomena like friction, heat losses, and eddies, exergy destruction manifests, signifying a decline in energy efficiency. Calculating the exergy at each state point effectively evaluates the energy utilization efficiency at that juncture. The larger the exergy loss, the more irreversible and less efficient the energy conversion process at that state point. The exergy at each state point, considering entropy a, specified flow stock state k, and environmental state P, is calculated as follows:

$$Rz_k = l(g_k - g_0) - Y_0(a_k - a_0) \tag{17}$$

For dynamic systems like power distribution networks, real-time monitoring and optimization of exergy destruction levels are imperative for ensuring stable operation and enhancing the reliability of energy supply. Consequently, formulating exergy destruction equations is vital not only for improving the performance of individual energy storage components but also for achieving efficient and sustainable operation of the entire DESS. This research constructs exergy destruction equations for components engaged in both energy storage and release processes.

In the energy storage process components, power conversion components, which transform energy from one form to another (e.g., alternating to direct current or vice versa), are analyzed. In these processes, energy dissipation as heat, resulting from resistance losses, semiconductor losses, and electromagnetic losses, directly impacts energy conversion efficiency. The exergy destruction equations for these components are formulated to encompass these factors:

$$U_{VO} = \sum_u U_{VOu} = \sum_u \left\{ \left[Rz_{S2u} - Rz_{S(2u-1)} \right] y_{vo} - Q_{VOu} \right\} \tag{18}$$

For cooling components, exergy destruction is primarily linked to the thermodynamic cycle during the compression process. Due to friction, flow losses, and thermal leakage, these cycles do not achieve ideal Carnot cycle efficiency, thereby indicating efficiency loss represented by exergy destruction. A standardized exergy destruction equation is described as:

$$U=\left(\sum_{u}Rz_{IN}-\sum_{u}Rz_{OUT}\right)y \tag{19}$$

In the energy release process, voltage regulation components, responsible for adjusting the released energy from storage to meet the grid's voltage and frequency requirements, are examined. Energy losses in this process occur due to irreversible factors like electromagnetic losses, copper losses, iron losses, and potential harmonic losses, leading to exergy destruction. The exergy destruction equations for these components consider these aspects to assess their impact on the system's overall efficiency:

$$U_{YC}=(Rz_{IN}-Rz_{OUT})\,y_{YC} \tag{20}$$

In DESS within power distribution networks, components that directly contribute to energy release play a crucial role in converting stored energy into electrical or thermal energy for external consumption. For batteries during the discharge process, internal resistance and the irreversibility of electrochemical reactions result in power loss. In thermal energy storage systems, thermal losses and suboptimal heat transfer contribute to energy inefficiency. Exergy destruction equations for these energy release medium components are constructed to quantify these losses and irreversible processes, thereby identifying factors that reduce the system's overall thermal efficiency. The exergy destruction equations are formulated as follows:

$$U_{VO}=\sum_{u}U_{VOu}=\sum_{u}\left\{\left[Rz_{S2u}-Rz_{S(2u-1)}\right]y_{SYN}-Q_{SYN}\right\} \tag{21}$$

$$U_{EYN}=(Rz_{IN}-Rz_{OUT})\,y_{EYN}-Q_{EYN} \tag{22}$$

$$U_{NO}=(Rz_{IN}-Rz_{OUT})\,y_{NO}-Q_{NO} \tag{23}$$

Performance indices in DESS, such as net power, round-trip efficiency, exergy efficiency, and energy storage density, serve as crucial metrics for assessing system performance. These indices not only represent the system's thermal efficiency and entropy production characteristics but also hold considerable significance in understanding and optimizing the thermodynamic behavior of DESS. Enhancing the overall energy efficiency and reliability of the system, as well as minimizing its environmental impact, are key outcomes of these analyses.

Within DESS in power distribution networks, net power is defined as the power output during energy release by the energy storage system, subtracted by the power required for the system's own operation. This parameter represents the actual effective power provided externally by the system, accounting for internal energy consumption. The calculation formula for net power output during the energy release process is given by:

$$Q_{NET}=Q_{SYN}+Q_{EYN}-Q_{NO} \tag{24}$$

Net power is computed using the following formula:

$$RAR=\frac{Q_{NET}}{Q_{VO}} \tag{25}$$

Round-trip efficiency quantifies the efficiency of the complete process of storing electrical energy in the energy storage system and subsequently releasing it back into the grid. Specifically, it is the ratio of the electrical energy output during the release phase to the initial electrical energy input into the system. This efficiency metric reflects the energy losses occurring during both the storage and release phases, calculated as follows:

$$EYR=\frac{Q_{NET}+W_{QG}}{Q_{VO}+W_{AYV}} \tag{26}$$

Exergy efficiency assesses the quality conversion efficiency of energy during the system's energy release process. It represents the ratio of the actual useful work output by the system to the total exergy entering the system. Exergy efficiency considers the irreversibility in energy conversion and the degradation of energy quality, calculable through:

$$\lambda_{rz}=\frac{Q_{NET}+Rz_{QG}}{Q_{VO}+Rz_{AYV}} \tag{27}$$

Energy storage density indicates the amount of energy storable per unit volume or unit mass in an energy storage system, essential for applications with space or weight constraints, such as mobile applications. This parameter is calculated using:

$$ROC=\frac{Q_{NET}}{C_{SAV}} \tag{28}$$

These performance indices are instrumental in evaluating and optimizing the design of DESS in power distribution networks, aiding in comprehending the system's energy conversion and storage capacities and guiding enhancements in energy utilization and storage efficiency.

4. EXPERIMENTAL RESULTS AND ANALYSIS

Figure 4 depicts the variation in energy storage efficiency of DESS within power distribution networks, contrasting scenarios with and without insulation layers across multiple operational cycles. It was observed that, in the absence of an insulation layer, energy storage efficiency initiates at 57% and exhibits a gradual increase, achieving stability at 61% by the fourth cycle. This trend indicates an initial phase of substantial thermal losses due to significant temperature gradients, followed by the system attaining a more stable state characterized by reduced thermal losses and consistent energy storage efficiency. In contrast, the presence of an insulation layer results in a notable initial efficiency of 62.5%. This efficiency escalates rapidly with each cycle, stabilizing at 69.8% by the fourth cycle. Such findings underscore the efficacy of the insulation layer in diminishing thermal losses, thus facilitating a swifter attainment and maintenance of elevated energy storage efficiency.

Figure 5 illustrates the relationship between the pressure drops in DESS energy storage units and the corresponding energy storage efficiency across a range of temperatures (250K to 500K) over successive cycles. This analysis contributes to comprehending the impact of temperature and pressure drop on the efficiency of energy storage units. Data reveal that under all examined temperatures, an initial increase followed by a decrease in pressure drop is noted with each cycle. This pattern implies an association between pressure drop and the thermal balancing process within the energy storage unit. During the phase of increasing pressure drop, a reduction in energy storage efficiency occurs, attributed to the escalated energy loss inferred from the augmented pressure drop. Conversely, as pressure drop attains its maximum and subsequently decreases, an enhancement in energy storage efficiency is noted, attributed to the reduction in the system's internal resistance. At lower temperatures (250K and 300K), the system begins with a lower initial pressure drop; however, with temperature elevation, the initial pressure drop escalates due to the diminished fluid density and augmented flow resistance at elevated temperatures. Conversely, at higher temperatures (450K and 500K), not only does the peak pressure drop intensify with each cycle, but the post-decline stabilized pressure drop is also lower. This indicates that energy storage units more effectively achieve thermal equilibrium at higher temperatures, resulting in diminished energy losses during later cycles. Thus, it is deduced that the temperature-dependent characteristics of pressure drop in energy storage units significantly influence their efficiency. In designing and operating DESS within power distribution networks, the effect of temperature on pressure drop and energy storage efficiency warrants consideration. The design objective should encompass minimization of energy loss, involving thermal management and fluid dynamics optimization within energy storage units to achieve reduced pressure drops and augmented energy storage efficiency across varying temperatures.

Figure 6 elucidates the interplay between system efficiency and convective heat transfer temperature differences under varied pressure drops in energy storage modules of DESS within power distribution networks. The data enable an understanding of how operational pressure and temperature differentials impact the efficiency of energy storage systems. It has been discerned that at a constant convective heat transfer temperature difference, an increase in operating pressure corresponds to a gradual decrease in system efficiency. This phenomenon is attributable to augmented flow resistance at elevated pressures, thereby diminishing the efficacy of thermal transfer. Furthermore, at a given operating pressure, an escalation in the convective heat transfer temperature difference leads to a decrement in system efficiency, suggesting that augmented temperature differentials elevate thermal resistance, consequently impairing heat exchange efficiency. A consistent trend is noted: irrespective of the operating pressure, a negative correlation exists between convective heat transfer temperature difference and system efficiency, indicating that greater temperature differences result in lower efficiencies. The inference is that variations in operating pressures and convective heat transfer temperature differences substantially influence the efficiency of energy storage modules in DESS. Design and operational considerations of these systems should include the selection of suitable operating pressures and minimization of convective heat transfer temperature differences to enhance heat exchange efficiency. An optimal operational scenario is characterized by lower pressure and minimal temperature differences, thereby optimizing the system's overall thermal efficiency.

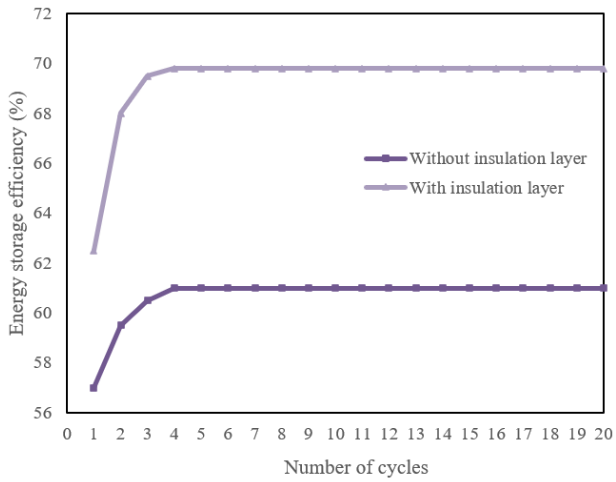

Figure 4. Variation in energy storage efficiency of DESS with and without insulation layers across multiple operational cycles

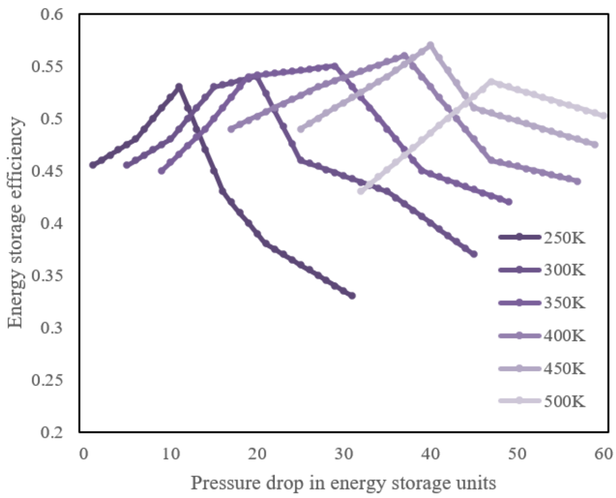

Figure 5. Relationship curves between the pressure drops in DESS energy storage units and the corresponding energy storage efficiency across a range of temperatures

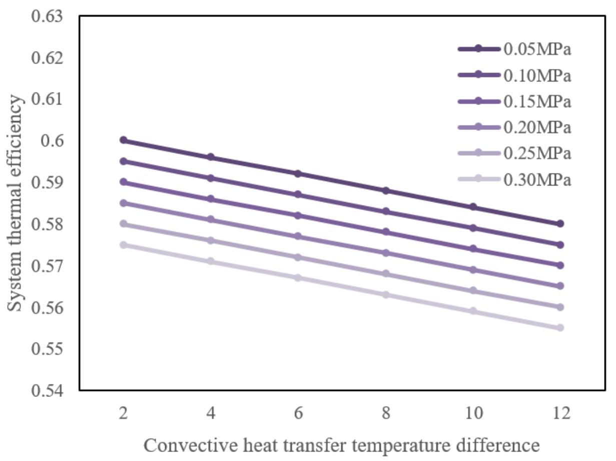

Figure 6. System efficiency curves corresponding to convective heat transfer temperature differences under different energy storage unit pressure drops

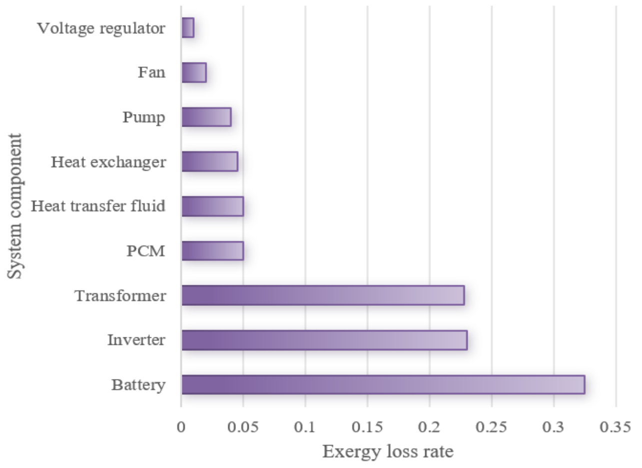

Figure 7. Exergy loss rates of different components in DESS for power distribution networks

Table 1. Experimental results of system performance indices for different DESS configurations in power distribution networks

Performance Index	Unit	Reference System	System in This Study	System in This Study
PCM		Paraffin	Paraffin	Fatty acid
Energy storage efficiency	%	88.9	114.2	87.9
Round-trip efficiency	%	56.8	67.8	62.3
Exergy efficiency	%	68.8	77.5	67.8

Table 2. Comparison of energy storage density and power density for different energy storage solutions

	Solution 1	Solution 2	Solution 3	Solution 4
PCM	Paraffin	Fatty acid	Fatty acid	Paraffin
Heat transfer fluid	Air	Water	Air	Water
Energy storage density	21	1.3	10	87
Power density	331	5000	1245	631

Table 1 presents the experimental results for various system performance indices of different DESS configurations within power distribution networks. The table compares the performance of systems utilizing paraffin and fatty acid as PCM against a reference system. The data indicate that the system in this study, when employing paraffin as PCM, exhibits a significant energy storage efficiency (114.2%) compared to the reference system (88.9%), suggesting the adoption of more effective thermal management strategies or advanced technologies that surpass conventional performance limits. Conversely, when fatty acid is used as PCM, the energy storage efficiency (87.9%) is marginally lower than that of the reference system, indicating that fatty acids may be less effective in this particular system configuration. Regardless of the PCM used, the round-trip efficiency of this study's system surpasses the reference system's 56.8%, with values of 67.8% and 62.3% respectively. This indicates that the system in this study incurs fewer losses during energy storage and release processes, effectively preserving the input energy. When utilizing paraffin, the system's exergy efficiency reaches 77.5%, and with fatty acid, it is 67.8%, both higher than the reference system's 68.8%. This demonstrates that the system in this study experiences lesser irreversible losses during energy conversion, leading to more efficient energy utilization. Consequently, the system in this study, particularly with paraffin as PCM, outperforms the reference system in terms of energy storage efficiency, round-trip efficiency, and exergy efficiency, while with fatty acid, despite a slight decrease in energy storage efficiency, round-trip efficiency and exergy efficiency still surpass the reference system. This signifies that the system proposed in this study has distinct advantages in design and performance, enabling more effective energy storage and conversion.

Table 2 offers a comparative analysis of energy storage density and power density across four distinct energy storage solutions within power distribution networks. These solutions incorporate either paraffin or fatty acid as PCMs, combined with either air or water as heat transfer fluids. The data illustrate that Solution 4, employing paraffin and water, demonstrates superior energy storage density, whereas Solution 2, combining fatty acid and water, excels in power density. The selection of an appropriate solution is contingent upon specific application requirements. For scenarios demanding high energy storage density, such as long-duration stable energy supply, Solution 4 emerges as the preferable choice. Conversely, for applications necessitating rapid response and high power output, Solution 2 is more apt. Solutions 1 and 3 present competitive alternatives for applications with intermediate performance demands. This underscores the pivotal role of selecting the appropriate PCM and heat transfer fluid in optimizing the performance of energy storage systems.

Figure 7 shows the exergy loss rates of different components in DESS for power distribution networks. The exergy loss rates, indicative of irreversibility and efficiency loss in each component during the energy conversion process, are critically examined. The analysis elucidates that batteries exhibit the highest exergy loss rate, quantified at 0.325. This significant loss rate is primarily due to internal resistance and the irreversibility inherent in electrochemical reactions during the charging and discharging cycles. This finding underscores that batteries are the predominant source of energy loss within the system, highlighting the necessity for advancements in battery technology to enhance overall system efficiency. In contrast, inverters and transformers demonstrate comparably substantial exergy loss rates, recorded at 0.23 and 0.228, respectively. These values suggest notable efficiency losses during the conversion of electrical energy, which are ascribed to electromagnetic and thermal losses, among other factors. PCM and heat transfer fluids, with exergy loss rates of 0.05 and 0.0498, respectively, show relatively higher efficiency in energy storage and thermal management processes. Nonetheless, these components still present opportunities for further efficiency improvements. Additionally, heat exchangers and pumps, with exergy loss rates of 0.045 and 0.04, benefit from relatively optimized designs, yet they still require enhancements in efficiency. Fans and voltage regulators, on the other hand, register the lowest exergy loss rates in the system, at 0.02 and 0.01, respectively. This indicates minimal energy loss in comparison to other components, attributed to their simpler operational principles and lower levels of irreversibility. Thus, within DESS for power distribution networks, batteries, inverters, and transformers emerge as principal contributors to exergy loss and demand focused attention for efficiency improvement. While PCMs and heat transfer fluids exhibit lower loss rates, indicating higher efficiency, there is still scope for further optimization. Fans and voltage regulators operate with the highest relative efficiency under the existing system configuration.

Figure 8 demonstrates the influence of ambient temperature on key performance indices in DESS within power distribution networks, encompassing energy storage efficiency, round-trip efficiency, exergy efficiency, and energy storage density. It is observed that as ambient temperature rises, a reduction in energy storage efficiency occurs, declining from 1.21 to 1.11. This pattern suggests enhanced energy storage capability at lower temperatures, whereas at elevated temperatures, efficiency suffers due to augmented thermal losses. Round-trip efficiency exhibits a decreasing trend with rising ambient temperature, moving from 0.76 to 0.6. This trend implies increased energy losses in both energy storage and release processes at higher temperatures, likely owing to heightened challenges in thermal management. Energy storage density displays a non-linear response to temperature changes, initially increasing, peaking at approximately 30°C, and subsequently decreasing. This behavior reflects the complexities in the performance of PCMs or storage media as a function of temperature. Exergy efficiency experiences a marginal decrease with increasing ambient temperature, shifting from 0.78 to 0.764. The decline in exergy efficiency signifies an escalation in irreversibility within energy conversion processes, attributed to intensified thermal stress and losses in system components under high-temperature scenarios. In conclusion, escalating ambient temperatures adversely affect the performance metrics of DESS in power distribution networks. The observed decrease in energy storage and round-trip efficiencies underscores the necessity for integrating effective thermal management strategies, such as utilizing superior insulation materials or refining cooling methodologies. These strategies aim to alleviate the impact of ambient temperature on system performance. A more nuanced analysis is warranted to elucidate the non-linear behavior of energy storage density and to guide the strategic selection and optimization of storage substances. Moreover, the slight reduction in exergy efficiency points to opportunities for augmenting the overall efficiency of energy conversion within the system, particularly in high-temperature environments.

Figure 9 elucidates the impact of the inlet temperature of the heat transfer fluid on several critical performance indices of DESS within power distribution networks. These indices include energy storage efficiency, round-trip efficiency, and exergy efficiency. The analysis indicates a progressive increase in energy storage efficiency, ascending from 1.05 to 1.17, as the inlet temperature rises from 490K to 550K. This elevation in efficiency is attributable to the enhanced thermal absorption promoted by the increased temperature differential at higher inlet temperatures. Conversely, the round-trip efficiency exhibits a declining trend with an elevation in inlet temperature, diminishing from 0.73 to 0.67. This pattern suggests an escalation in overall energy loss during the processes of storage and release, likely due to amplified internal or external thermal losses at elevated temperatures. Similarly, exergy efficiency undergoes a slight reduction as the inlet temperature increases, descending from 0.78 to 0.768. The decrease in exergy efficiency reflects an augmentation in the irreversibility of the energy conversion process at higher inlet temperatures. The data thus infer that the elevation of the inlet temperature of the heat transfer fluid profoundly influences the performance of DESS. Although higher inlet temperatures are associated with improved energy storage efficiency, they concurrently induce an increase in total energy losses, resulting in diminished round-trip and exergy efficiencies. This phenomenon is primarily due to the intensification of thermal losses within the system at higher temperatures, coupled with the potential degradation in the performance of materials and components under extreme temperature conditions. These findings underscore the need for meticulous design and operational strategies in DESS, especially considering the thermal dynamics influenced by inlet temperature variations.

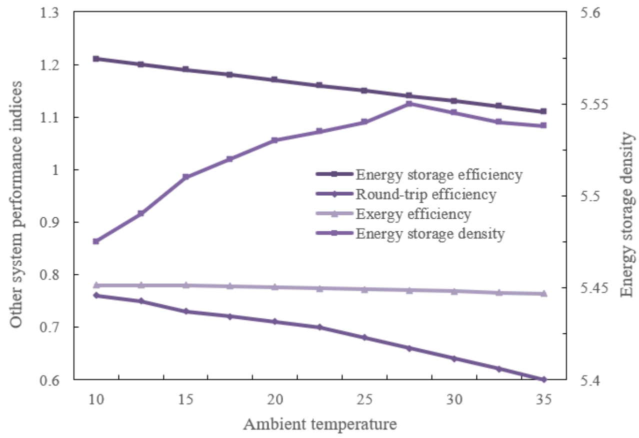

Figure 8. Impact of ambient temperature on performance indices of DESS in power distribution networks

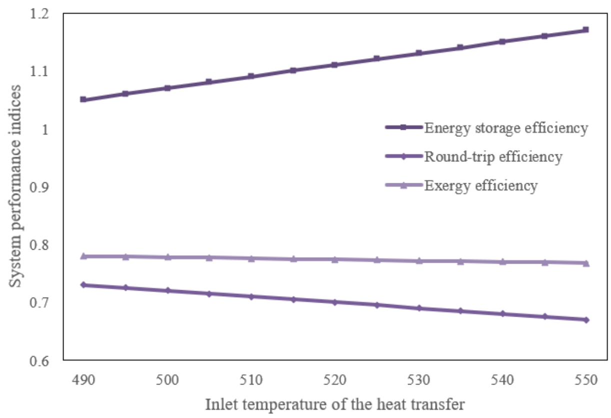

Figure 9. Influence of inlet temperature of the heat transfer fluid on performance indices of DESS in power distribution networks

5. CONCLUSION

This research introduces a groundbreaking mathematical model adept at analyzing the heat transfer processes in DESS within power distribution networks. Distinctive for its applicability to complex physical structures and dynamic thermal phenomena, the model excels in addressing transient behaviors and non-equilibrium states in porous media. Such an approach, scarce in the existing literature, contributes a novel theoretical framework to the realm of thermal management in energy storage systems.

Through rigorous experimental data analysis, employing thermodynamic techniques such as exergy analysis and thermal efficiency evaluation, the model's efficacy is substantiated. The results indicate that strategic selection of PCMs and heat transfer fluids substantially enhances energy storage efficiency. The model's capability to predict system performance variations due to external factors, such as ambient temperature and heat transfer fluid inlet temperature, is also established. This underscores the significance of considering these parameters in the design phase to ensure optimal energy storage and release efficiency. A comparative analysis of different energy storage solutions highlights their distinct energy storage density and power density profiles, underlining the necessity of tailored solutions based on specific application needs. Further, the exergy loss rate assessment of system components identifies batteries, inverters, and transformers as primary energy loss contributors, while fans and voltage regulators exhibit minimal losses. This insight is crucial for directing future system design optimizations toward minimizing energy losses in these key components. Moreover, the study reveals a decrement in exergy efficiency with increasing ambient temperatures and heat transfer fluid inlet temperatures, pointing to the impact of elevated temperatures on system performance. This finding is vital for developing strategies to mitigate temperature-induced performance degradation.

In conclusion, this study offers a comprehensive methodological approach for evaluating and enhancing the performance of DESS in power distribution networks. By providing a quantitative analysis of system performance across various components and conditions, the research paves the way for the design and operational optimization of practical DESS. This advancement is poised to significantly contribute to the progression and application of energy storage technologies, aiming for elevated energy storage efficiency and diminished energy losses, thereby fostering the sustainable evolution of power distribution networks.

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