Editorial: Thermal Management in Energy Systems –Technologies, Trends, and the Road Ahead

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1. Introduction

Thermal management plays a pivotal role in the design, efficiency, and safety of modern energy systems. As energy systems continue to diversify and expand, encompassing everything from electric vehicles to grid-scale energy storage and industrial electronics, the demand for efficient, adaptive, and scalable thermal management solutions has never been greater. This Special Issue of *Applied Thermal Engineering* presents cutting-edge research focused on innovative methods and technologies for thermal management, ranging from phase change materials (PCMs) to advanced cooling geometries and data-driven design methodologies.

In this editorial, we briefly present and contextualise the eight research articles included in the special issue. We further provide a forward-looking perspective by identifying key challenges and emerging trends in thermal management research. We aim to stimulate discourse, highlight research gaps, and encourage interdisciplinary collaboration across domains such as materials science, fluid dynamics, artificial intelligence, and systems engineering.

2. Overview of Contributions in This Special Issue

The eight papers accepted into this Special Issue represent diverse approaches to enhancing thermal performance in energy systems, with a focus on battery cooling, phase change heat storage, and computational optimisation.

2.1 Phase Change Material (PCM)-Based Thermal Management

Four papers in this issue focus on the integration and optimisation of PCMs as a key thermal storage and regulation medium:

- *Mingyang Yang et al.* [1] present a novel graphene aerogel composite that dramatically enhances the thermal conductivity of PCMs. This innovation addresses one of the longstanding challenges of PCM deployment: the low intrinsic thermal conductivity, which limits charging/discharging rates. The aerogel matrix not only facilitates rapid heat transfer but also ensures long-term mechanical and thermal stability.

- *Pengbo Sun et al.* [3] and *Subhan Ali Shaik et al.* [4] delve into geometric optimisation of fin structures to enhance heat transfer in PCM systems. Sun et al. propose a multi-objective optimisation framework for Y-type fins, while Shaik et al. offer advanced fin geometries (e.g., dendritic, fractal designs) that optimise surface area and conduction paths. These structural innovations significantly reduce melting time and improve thermal efficiency.

- *Yuanji Li et al.* [5] target structural integration of PCMs with nickel foam matrices. The metallic foam provides a 3D network that enhances the effective thermal conductivity and enables compact storage design. This work contributes towards scalable and high-power density thermal buffers for industrial applications.

2.2 Thermal Management for Lithium-Ion Batteries

Three articles focus on the pressing issue of thermal regulation in lithium-ion batteries – critical for EVs and stationary energy storage:

- *Hui Xu et al.* [2] introduce an innovative method of embedding microchannels in battery electrodes filled with ionic liquids. This strategy brings cooling mechanisms closer to heat sources, reducing thermal gradients and extending battery lifespan. It also introduces new hybrid cooling paradigms that combine conduction, convection, and electrochemical compatibility.

- *Han Yang et al.* [6] investigate the impact of inlet angles in air-cooling battery packs. Using both experimental and simulation data, they provide insights into flow dynamics and suggest optimal geometrical parameters that enhance uniform cooling.

- *Weiheng Li et al.* [7] propose a coupled computational fluid dynamics (CFD) and artificial neural network (ANN) approach to optimise PCM-based passive cooling. Their framework accelerates the design cycle by learning from CFD results, making it possible to explore vast parameter spaces in real time.

2.3 Liquid Cooling and Open-Source Design Frameworks

- *Raffaele De Rosa et al.* [8] introduce an open-source geometric optimisation tool for liquid cold plates used in railway electronics. Their algorithm, which optimises internal channel geometries, offers a reproducible and scalable method for improving liquid cooling efficiency and is a notable contribution to transparent and collaborative design methodologies.

3. Current Trends and Research Frontiers

The convergence of advanced materials, intelligent algorithms, and application-driven design is reshaping the thermal management landscape. As energy systems become more compact, efficient, and multifunctional, thermal solutions must evolve to keep pace with escalating demands on performance, safety, and sustainability. These emerging research frontiers are not only demonstrated within the contributions of this Special Issue but are also gaining momentum across the broader scientific community. By identifying these key trends—ranging from smart materials and geometric optimisation to AI-driven modelling and open-source collaboration—we aim to provide a roadmap for future research and innovation in thermal management science.

3.1 Functional Materials with Tunable Thermal Properties

The use of graphene aerogels and nickel foams illustrates the push toward next-generation materials that combine structural robustness with tailored thermal conductivity. For instance, Yang, M. et al. demonstrate thermal conductivity enhancements by nearly an order of magnitude using graphene aerogel scaffolds. This enables faster energy charging rates and a more compact system design. In parallel, Li, Y. et al. showcase how metallic foams, when properly structured, improve both heat dispersion and structural integration in latent heat storage units. These findings underscore the broader trend of using composite materials and nanostructures to overcome traditional thermal bottlenecks in energy systems. Future research may extend these materials into dynamic or adaptive domains, such as phase-adaptive composites or temperature-sensitive metamaterials that change properties in response to local thermal loads. Such functionalities could lead to self-regulating systems that automatically adapt to fluctuating environmental or operational conditions.

3.2 Integration of Geometry, Topology, and Flow

Several papers in the issue reflect an increasing awareness that performance is not only materials-dependent but also geometry-driven. Sun et al. and Shaik et al. both show that structured fin designs can substantially enhance PCM melting rates by reducing thermal resistance paths. This is consistent with physical principles, as geometric features can manipulate the temperature gradients and enhance convective patterns within confined volumes. Computational topology optimisation, as used by De Rosa et al., further demonstrates how fluid-thermal co-optimisation leads to significant gains in cooling efficiency. These approaches move beyond trial-and-error design and lean into algorithmically guided innovation. The convergence of simulation, optimisation, and additive manufacturing now allows for previously unfeasible thermal topologies to be realised in practice. This has far-reaching implications for embedded cooling in compact electronic devices, battery modules, and heat exchangers.

3.3 Data-Driven Modelling and Design Automation

AI-augmented tools are rapidly reshaping thermal design. Li, W. et al. leverage ANN surrogates trained on CFD data to explore wide design spaces at a fraction of the computational cost. These approaches are crucial for real-time control, especially in systems subject to dynamic thermal loading. Additionally, AI enables predictive maintenance and operational forecasting by identifying patterns in large thermal datasets. This allows for better integration of thermal subsystems into the broader energy infrastructure. The synergy of machine learning and physical modelling is also being increasingly seen in commercial applications, such as in the design of thermal management modules for EVs, servers, and industrial electronics. Furthermore, as regulatory pressures increase and design cycles shrink, data-driven methods offer the flexibility and responsiveness needed for next-generation product development.

3.4 Battery Safety, Efficiency, and Lifespan

Thermal issues are one of the primary causes of battery degradation and safety incidents. For example, temperature heterogeneity across a battery pack can accelerate local ageing, reduce capacity, and increase fire risk. Yang, H. et al. show how cooling configuration (e.g., inlet angle) can significantly affect airflow distribution and, thus, temperature uniformity. Meanwhile, embedded microchannels proposed by Xu et al. offer a promising direction by directly targeting high-temperature zones. These developments contribute to broader goals in battery thermal management: to prevent thermal runaway, extend operational life, and maintain safe conditions across diverse usage profiles. The significance of these innovations is amplified in the context of fast-charging applications, where intense thermal spikes must be quickly mitigated to avoid damaging electrochemical components. Ensuring thermal stability is also essential for improving battery energy density, a key performance metric in transportation and grid-scale storage.

3.5 Open-Source and Collaborative Frameworks

The introduction of De Rosa et al.'s open-source optimisation platform exemplifies a shift toward transparency and reproducibility in thermal design. With increasing complexity in thermal management systems, there is a growing need for standardised, community-vetted design workflows. Open-source tools reduce entry barriers, foster community validation, and encourage innovation by enabling researchers and engineers to build upon each other's work. This mirrors trends in adjacent fields, such as computational mechanics and energy systems modelling, where open platforms have catalysed research growth. In educational contexts, such frameworks also serve as valuable teaching tools, equipping the next generation of engineers with hands-on experience in advanced thermal design. Furthermore, open innovation enables faster adoption of emerging technologies in industrial settings, supporting the transition from lab-scale prototypes to commercially viable systems.

4. Challenges and Future Directions

Despite notable advancements, the field of thermal management continues to face fundamental challenges that must be addressed to enable next-generation energy systems. As applications grow in complexity and scale, researchers and engineers must navigate multifaceted design trade-offs, integrate across disparate physical scales, and incorporate sustainability

considerations from the outset. We outline several key areas where future research and development efforts should be concentrated to overcome existing limitations and unlock new technological possibilities.

4.1 Bridging Scales: From Materials to Systems

Achieving optimal thermal management requires bridging multiple physical scales, from nanoscale material properties to macroscale system-level performance. Future research must focus on developing robust multiscale models and simulation tools capable of capturing the complex interactions of conduction, convection, radiation, and phase changes. Experimental validation across these scales remains essential, as does the development of advanced characterisation techniques to accurately measure and interpret multiscale phenomena. Integrating these insights into coherent, predictive design frameworks will enable the creation of more efficient, reliable, and resilient thermal management systems.

4.2 Coupling with Lifecycle and Sustainability Metrics

Beyond thermal performance, future thermal management solutions must explicitly consider environmental impact, lifecycle sustainability, and economic feasibility. This includes assessing embodied energy, carbon footprint, recyclability, and material scarcity associated with thermal management technologies. Researchers and industry stakeholders should collaborate to develop standardised lifecycle assessment (LCA) frameworks tailored specifically to thermal management solutions. Such frameworks will inform more sustainable material selection, manufacturing processes, and disposal or recycling pathways, thus supporting global sustainability goals.

4.3 Hybrid Cooling Systems and Multi-Objective Design

As energy systems become increasingly complex, thermal management solutions must integrate multiple cooling strategies (active, passive, hybrid) to achieve optimal performance across diverse operating conditions. Hybrid approaches combining PCM storage, liquid cooling, and convective air cooling, for instance, offer great promise but require sophisticated multi-objective optimisation frameworks. Future research should emphasise developing scalable and computationally efficient optimisation methods that balance trade-offs between energy efficiency, cost, weight, reliability, and ease of maintenance. Additionally, the exploration of novel hybrid concepts, such as dynamically adaptable cooling solutions, will further enhance system adaptability and performance.

4.4 Smart and Adaptive Control

The integration of advanced sensing technologies, Internet-of-Things (IoT), and artificial intelligence (AI) into thermal management systems opens possibilities for real-time adaptive control and predictive maintenance. Future research should focus on developing robust control algorithms and machine learning models capable of interpreting real-time sensor data to dynamically optimise cooling performance. Such smart adaptive systems would significantly enhance energy efficiency, improve reliability, and reduce maintenance costs. Additionally, addressing cybersecurity concerns associated with connected thermal management systems will become increasingly important as adoption grows.

4.5 Application-Specific Innovation

Thermal management solutions must be increasingly tailored to the specific requirements of diverse applications, such as electric vehicles, grid-scale energy storage, data centres, industrial electronics, and renewable energy systems. Each domain poses unique thermal challenges, necessitating specialised approaches and bespoke designs. Collaboration between researchers, engineers, and industry stakeholders across disciplines is essential to co-create targeted solutions. Further investigation into domain-specific thermal profiles, operating conditions, and reliability requirements will enable the development of customised solutions that maximise performance and operational lifetime.

5. Concluding Remarks

The papers included in this Special Issue illustrate the vibrancy and diversity of research within the field of thermal management for energy systems. Together, they reveal a landscape where materials innovation, computational optimisation, and application-driven design converge.

As guest editors, we believe that future progress will require stronger coupling between disciplines, deeper integration of AI in thermal system design, and a more holistic view that includes lifecycle sustainability and system-level performance. We hope this Special Issue serves not only as a compendium of innovative work but also as a catalyst for new research directions.

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