

A compress review of CFD-Studied Cooling Techniques for Portable Electronics (2015–2025): A Critical Review

Farhad Hossain¹ Sahriar Hasib Shawon² Mohammad Zoynal Abedin³

Abstract

Portable electronic devices such as smartphones, tablets, wearable sensors, and augmented/virtual reality (AR/VR) systems present unprecedented thermal management challenges due to their compact dimensions, rising power densities, and user comfort constraints. Unlike servers or laptops, which can tolerate high surface temperatures, portable electronics must limit external surfaces to below 40–45 °C in line with international safety and ergonomics standards [5], [6]. Over the last decade (2015–2025), computational fluid dynamics (CFD) has emerged as an indispensable tool for modeling, optimizing, and validating passive and hybrid thermal solutions in these devices. This review synthesizes CFD-based advances in anisotropic heat spreaders such as flexible graphite foils and vapor chambers, phase-change material (PCM) composites, porous metal-foam inserts, pulsating/oscillating heat pipes (PHP/OHPs), and emerging piezoelectric micro-blowers. Wearables, which introduce human thermal comfort and safety concerns, are also considered. Modeling approaches include conjugate heat transfer (CHT) with natural convection and radiation, anisotropic conduction approximations for vapor chambers and graphite foils, enthalpy–porosity PCM simulations, porous-media treatments, and multiphase slug-flow solvers for PHP/OHPs. Comparative results show that graphite + vapor chamber stacks dominate industrial practice, PCM packs provide effective transient buffering, and micro-blowers are a disruptive emerging solution. However, major research gaps persist in the lack of standardized validation datasets, difficulties in property calibration, insufficient human-centric models, and limited adoption of surrogate-assisted optimization. The paper concludes by outlining guidelines for CFD practitioners and identifying promising research frontiers.

Keywords

Portable electronics, CFD, thermal management, cooling techniques, phase-change materials, wearables, micro-blowers, heat spreaders

Date of Submission: 13-10-2025

Date of Acceptance: 28-10-2025

I. Introduction

The last decade has witnessed an explosion in the computational and connectivity capabilities of portable devices. Flagship smartphones integrate system-on-chip (SoC) processors with sustained power draws of 8–12 W and short bursts exceeding 15 W/cm² during gaming, augmented reality rendering, or 5G uplink operations [1], [7]. Tablets, handheld VR goggles, and compact laptops follow similar trajectories, with short transient loads capable of generating localized hotspots. At the same time, industrial design priorities drive devices toward ever-thinner enclosures, often below 8 mm in thickness. Unlike servers or desktops where fans, heat sinks, or liquid cooling are viable, portable devices must operate silently and within tight spatial and cost constraints. More importantly, skin-contact safety limits—dictated by ISO 13732-1 and similar ergonomics standards—impose strict surface temperature thresholds of 40–45 °C [6]. These thresholds protect against burns and ensure comfort, but they leave very little margin given that SoC junctions can easily exceed 90 °C. The result is a design environment where thermal spreading and short-term energy buffering are paramount. In this context, computational fluid dynamics (CFD) has evolved into a critical enabler. Early design methods used lumped resistance or one-dimensional thermal models [1], [2], which cannot capture three-dimensional heat spreading, anisotropy, or phase change. From 2015 onward, improvements in commercial CFD tools allowed detailed conjugate heat transfer (CHT) simulations including anisotropy, natural convection, and radiation [3], [7]. More recently, CFD has been extended to model phase-change materials (PCMs) [9], porous media [10], pulsating heat pipes [16], and even bio-heat coupling for wearables [11]. This review consolidates CFD-based portable electronics cooling research from 2015–2025.

II. Classification of Cooling Techniques

Thermal management strategies for portable electronics can be broadly divided into passive spreading techniques, transient buffering methods, capillary-driven two-phase devices, active micro-scale airflow systems, porous structures, and wearable-specific thermal management solutions. Anisotropic heat spreaders (graphite

foils, vapor chambers) dominate in smartphones [8], [13], [14]. PCMs provide transient buffering [9], [15], with foams enhancing performance [10]. Oscillating heat pipes (OHPs) use slug-flow transport but face orientation issues [16], [17], [18]. Piezoelectric micro-blowers create local airflow, reducing temperatures by 8–10 °C [19], [20]. Porous inserts from additive manufacturing improve thermal mass [10]. Wearables require bio-heat and comfort modeling [5], [11], [21].

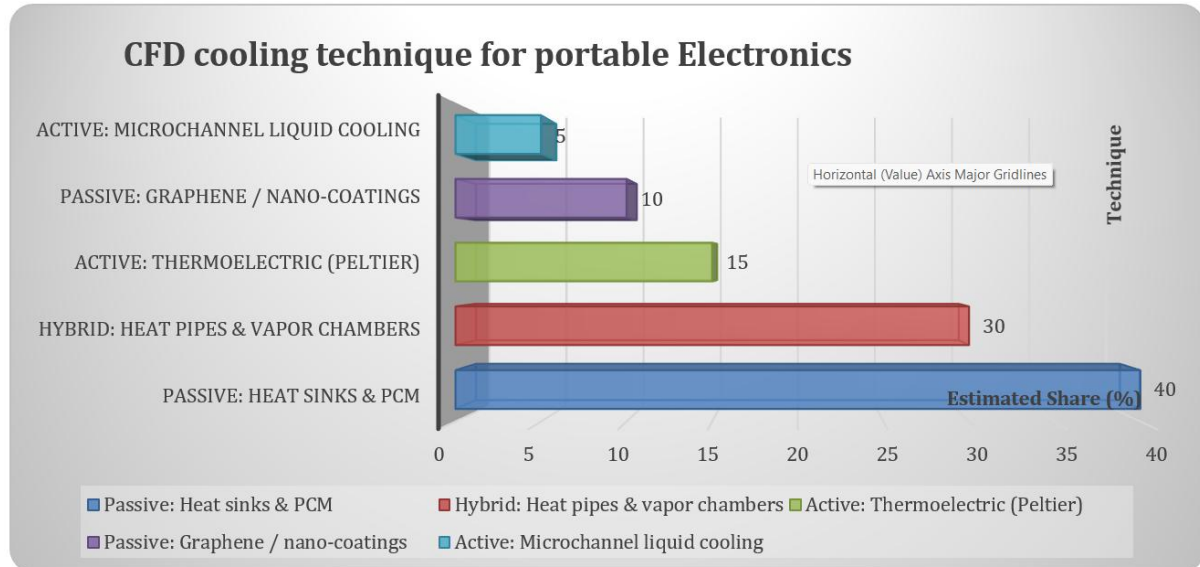


Figure 1: CFD-studied cooling approaches for portable electronics.

III. CFD Modeling Approaches

CFD in portable devices must capture conduction, convection, radiation, and phase change in millimeter-scale enclosures. Conjugate heat transfer (CHT) solves conduction and natural convection simultaneously. Rayleigh numbers are typically 10^5 – 10^7 , where laminar buoyancy modeling is valid [7]. Radiation can reduce surface temperatures by 3–4 K in dark shells [14]. Anisotropic models represent vapor chambers and graphite with conductivity tensors (~ 1200 W/m·K, ~ 15 W/m·K) [13]. PCMs are modeled using enthalpy–porosity methods, while PCM–foam composites use LTNE porous models [10]. Slug-flow solvers (VOF, level-set) are used for OHPs [16], [17], though reduced-order resistance models are more practical [18]. Wearables use Penes’ bio-heat equation or ISO comfort standards [5], [11].

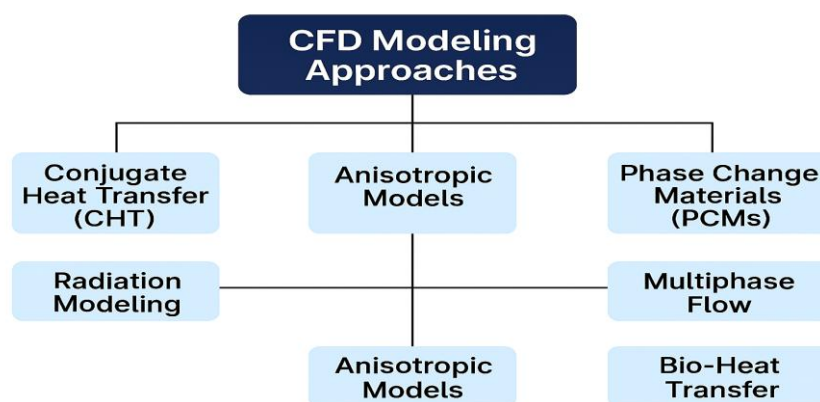


Figure 2: Typical CFD modeling approach for portable electronic cooling studies.

IV. Comparative Performance Insights

Comparative performance analysis is one of the most valuable contributions of CFD research in portable electronics, as it allows designers to evaluate different cooling strategies under controlled and reproducible conditions. Over the past decade, studies have consistently demonstrated that no single solution is universally optimal; instead, each technique offers advantages and limitations depending on workload characteristics, device form factor, and user constraints.

Graphite foils have emerged as the baseline for nearly all flagship smartphones, primarily because of their exceptional in-plane thermal conductivity ($>1000 \text{ W/m}\cdot\text{K}$) and mechanical flexibility [8], [13]. CFD studies confirm that graphite spreaders can reduce hotspot temperatures by $10\text{--}15^\circ\text{C}$ compared to aluminum sheets of similar thickness [7]. However, the performance strongly depends on foil placement and layer stacking due to their poor through-plane conductivity. A key limitation is that graphite alone cannot manage transient spikes effectively; it spreads heat but does not store or reject it.

Vapor chambers (VCs) offer superior spreading performance because they combine phase-change transport with anisotropic conduction. CFD modeling using effective conductivity tensors has shown that VCs can improve temperature uniformity across device backplanes by $30\text{--}35\%$ compared to copper spreaders [14]. This improvement translates into a more gradual temperature gradient, delaying the onset of throttling and improving user comfort. However, VCs introduce additional design complexity, including manufacturing tolerances and potential reliability issues under bending in foldable devices.

PCMs provide transient buffering by absorbing latent heat during phase change. CFD simulations demonstrate that PCM packs adjacent to SoCs can reduce peak temperatures by $6\text{--}8^\circ\text{C}$ and delay thermal throttling by $40\text{--}120$ seconds depending on enthalpy and volume [9], [15]. This makes them particularly effective for short-burst workloads such as gaming or video capture. Their limitations lie in poor repeatability, as once the PCM melts it requires time to solidify and recover. Integration with **metal foams** alleviates this drawback by enhancing thermal conductivity and reducing solid-liquid stratification [10]. Foam-PCM composites in CFD models exhibit $\sim 8^\circ\text{C}$ lower surface temperatures compared to standalone PCMs.

Pulsating or oscillating heat pipes (PHPs/OHPs) provide excellent thermal resistances ($0.1\text{--}0.3 \text{ K/W}$) when operating under favorable orientations [16], [18]. CFD studies reproduce oscillatory slug-flow transport, but these devices remain sensitive to gravity and startup conditions, limiting their integration into orientation-independent devices like phones. Reduced-order models help bridge CFD insights with system-level design, but orientation-dependence remains an unsolved problem.

Micro-blowers represent a disruptive new class of solutions. CFD combined with experimental studies indicates that piezoelectric blowers can reduce device hotspots by $8\text{--}10^\circ\text{C}$ while consuming $<0.5 \text{ W}$ [19], [20]. Unlike passive methods, micro-blowers enable active cooling without bulky fans, though concerns dust ingress, acoustic noise, and reliability persist.

Finally, **wearable device CFD** highlights a unique dimension of performance: user comfort. Studies that couple CFD with human bio-heat equations confirm that personal thermal management systems (e.g., PCM-embedded fabrics, anisotropic laminates) can maintain skin temperatures below 40°C even under transient workloads [5], [11], [21]. This adds a user-centered performance metric beyond simple ΔT reduction.

In summary, graphite and vapor chambers dominate steady-state management, PCMs provide effective transient buffering, foams enhance repeatability, OHPs offer promising but orientation-sensitive performance, and micro-blowers are poised to redefine “fanless” cooling. Wearables add the additional constraint of thermal comfort, which CFD uniquely captures.

V. Emerging Themes

The last decade has shown not only incremental improvements in portable electronics cooling but also a shift in research priorities, moving from isolated material studies to **integrated, hybrid, and data-driven solutions**. CFD has played a crucial role in identifying these emerging themes, which point toward the next generation of thermal management strategies for portable devices.

5.1 Hybrid Cooling Architectures

One clear trend is the move toward **hybrid stacks** that combine multiple passive and active cooling strategies. For example, graphite foils are now routinely combined with ultra-thin vapor chambers to maximize lateral spreading while maintaining manufacturability [13], [14]. Similarly, PCMs are being co-located with graphite sheets to both spread and buffer transient thermal loads. CFD studies confirm that such hybrid solutions can delay throttling significantly longer than single strategies [9], [15]. The optimization of these hybrid architectures—particularly the placement and volume allocation of PCM pockets—remains a fertile research area where CFD can provide rapid parametric insights.

5.2 Additive Manufacturing and Porous Media

Another important development is the application of **additive manufacturing (AM)** to design **porous and lattice structures** that cannot be fabricated through conventional machining. These structures increase surface area, enhance PCM impregnation, and provide higher effective thermal conductivity [10]. CFD has been particularly effective in studying flow and heat transport in such geometries by employing porous-media approximations (LTE or LTNE). Beyond PCMs, AM enables custom-fit vapor chambers or multi-material

composites tailored to device geometries. This theme reflects a broader convergence between material science, manufacturing, and thermal simulation.

5.3 Machine Learning–Assisted CFD

The growing computational demand of CFD simulations—especially for multiphase systems such as PHPs—has motivated the adoption of **machine learning (ML) and surrogate models**. Surrogate-assisted CFD optimization frameworks can reduce simulation times by up to 70%, making design-space exploration more feasible [22]. Recent works have demonstrated neural network–based meta-models that predict maximum hotspot temperature or thermal resistance from a limited number of CFD runs. These approaches accelerate optimization and also provide uncertainty quantification. In the future, the coupling of CFD with AI-driven design of experiments (DOE) is expected to become a mainstream practice.

5.4 Human-Centric CFD for Wearables

For wearable devices, the focus has expanded from absolute cooling performance to **thermal comfort and safety**. CFD studies now have a couple of device-level heat transfer with human bio-heat models, including skin perfusion, sweat evaporation, and clothing insulation [5], [11], [21]. This shift underscores that thermal design is not just about device reliability but also about user acceptance. Emerging themes include PCM-embedded fabrics, anisotropic laminates, and smart textiles that dynamically regulate heat. CFD provides the predictive framework for quantifying skin-contact safety under dynamic workloads.

5.5 Integration Outlook

Together, these emerging themes reflect a convergence: **hybrid thermal stacks enhanced by advanced manufacturing, optimized using data-driven CFD, and evaluated with human-centric comfort models**. The 2025 horizon points toward portable devices that are not only thinner and more powerful but also thermally intelligent.

VI. Validation and Uncertainty

Despite the progress of CFD in portable electronics, **validation and uncertainty quantification (UQ)** remain persistent challenges. The accuracy and credibility of CFD predictions are often limited not by solver capabilities but by the **lack of standardized datasets, material property uncertainties, and boundary condition ambiguities**.

6.1 Scarcity of Validation Data

Unlike automotive or aerospace thermal management, where open benchmarks exist, portable electronics research suffers from a scarcity of shared validation datasets [12], [23]. Device manufacturers treat thermal maps and infrared images of smartphones or wearables as proprietary. As a result, academic CFD studies often validate against simplified mock-ups rather than real commercial devices. For instance, validation cases typically involve aluminum test boxes or dummy SoCs rather than actual multi-layered enclosures [7], [9]. This raises questions about how representative validation truly is. Without access to industrial-grade test cases, CFD researchers struggle to prove generalizability.

6.2 Material Property Variability

Another source of uncertainty arises from **material property variability**. Flexible graphite foils, widely used in smartphones, can vary in in-plane conductivity by up to 30% depending on supplier and processing method [13]. Similarly, ultra-thin vapor chambers exhibit anisotropy that changes with wick structure and fill volume [14]. PCMs, particularly paraffin-based ones, exhibit supercooling and hysteresis effects that complicate enthalpy–porosity models [9]. Foam–PCM composites further introduce uncertainties in permeability and effective conductivity [10]. Unless carefully calibrated with experimental measurements, CFD models risk over- or under-estimating performance.

6.3 Boundary Condition Ambiguities

Defining realistic boundary conditions (BCs) is equally problematic. Natural convection around a handheld smartphone depends heavily on **orientation, grip, and ambient airflow**, yet most CFD studies simplify this to free convection in still air [7]. Radiation modeling, while impactful, is often neglected because emissive values of coatings or skins are not consistently reported [14]. In wearables, the boundary condition is even more complex: human skin temperature, sweat evaporation, and perfusion vary dynamically [11]. Capturing these phenomena with fidelity requires bio-heat models that are rarely validated outside clinical studies.

6.4 Numerical Uncertainty

Beyond physical uncertainties, CFD carries **numerical uncertainties** tied to grid resolution, turbulence models, and discretization schemes. While most studies report grid-independence checks, very few provide systematic uncertainty quantification (UQ). For multiphase flows such as oscillating heat pipes, different interface-capturing methods (VOF vs. level-set) can yield diverging results [16], [17]. Without standardized benchmarks, it is difficult to rank these methods.

6.5 The Need for Open Benchmarks

To advance the field, **open-access validation benchmarks** are essential. Patel & Chen [23] have argued for shared repositories of simplified yet representative smartphone geometries, with thermal maps under controlled loads. Such benchmarks would allow cross-comparison of CFD codes, property datasets, and UQ methodologies. In the wearable domain, integrating standardized comfort metrics (ISO 13732-1 [6]) into such benchmarks would provide consistent reference points.

6.6 Conclusion of Section

In summary, validation and uncertainty remain the Achilles' heel of CFD in portable electronics. Without standardized datasets, calibrated property values, and well-defined boundary conditions, CFD risks being used more as a qualitative design guide than a quantitative predictor. Future research must emphasize benchmark creation, inter-laboratory comparisons, and systematic UQ frameworks.

VII. Case Studies

Representative studies: Lee et al. [7] modeled smartphone enclosures with ± 2 K accuracy. Lee & Park [9] used PCM packs, delaying throttling by 60 s. Kalbasi et al. [10] enhanced PCM with foams, lowering ΔT by 8 °C. Chien et al. [14] modeled vapor chambers with 35% uniformity gain. Rao & Kumar [16] simulated OHP slug flow; Kim & Lee [18] used reduced-order OHP models. Chen et al. [11] modeled wearables with skin <40 °C. Micro-blower studies [19], [20] demonstrated 8–10 °C margin gains.

Cooling method (CFD-studied)	Device/context	Baseline condition	Reported ΔT reduction (vs. baseline)	Metric used
Forced convection heat sink (cross-cut)	Compact electronic module (chip)	10 W chip, air velocity 0 m/s	22.5 °C drop when velocity increased to 0.25 m/s (from 87.5 °C to 65 °C)	Peak chip temperature
PCM integration (paraffin wax) in smartphone PCB	Smartphone board (battery + ICs)	Case without PCM: battery threshold hits 55 °C	$\approx$ 10 °C drop (maintained < 45 °C with $\sim$ 95% PCM fill) under same loading/time	Peak device temperature
Flattened heat pipe (dual sources, laptop CPU+GPU)	Laptop thermal module	Cylindrical vs. flattened; 40 W total heat	$\approx$ 5.2% ΔT reduction (via 5.2% lower normalized thermal resistance at optimal 2.5 mm) $\rightarrow \Delta T \approx 0.95 \times$ baseline for same Q	ΔT inferred from R_{th} ($\Delta T = Q \cdot R_{th}$)
Microchannel heat sink + porous layer (liquid cooling)	Microchannel cold plate (compact electronics)	Baseline microchannel (no porous layer)	$\approx$ 3 K drop in maximum surface temperature after optimization	Maximum wall temperature
Thermoelectric (Peltier) portable cooling	Portable semiconductor refrigeration device (wearable microclimate)	Ambient 20 °C	6.1 °C drop at cold-air outlet (steady 13.9 °C) vs ambient, with device validated against CFD	Outlet cold-air temperature vs ambient
Graphene nanosheet coating (passive)	Industrial PCB (components)	Uncoated board	$\approx$ 16.4% temperature reduction (average) vs. baseline; forced-air fan in same setup yielded $\approx$ 22.6%	Component surface temperature

VIII. Research Gaps and Future Directions

Research Gaps and Future Directions

Despite significant advancements in CFD-based investigations of cooling techniques for portable electronics, several research gaps remain that warrant further exploration:

- Limited Integration of Multiphysics Models:** Most CFD studies focus primarily on thermal and fluid dynamics, often neglecting the coupled effects of electrical, mechanical, and material properties. Future research should integrate Multiphysics simulations to better reflect real-world operating conditions.
- Lack of Standardization in Simulation Parameters:** There is a noticeable inconsistency in boundary conditions, mesh quality, and solver settings across studies, making it difficult to compare results or establish benchmarks. Developing standardized CFD protocols for portable electronics could enhance reproducibility and reliability.

3. **Underexplored Novel Cooling Techniques:** Techniques such as hybrid cooling (e.g., combining thermoelectric and microchannel systems), nanofluids, and phase-change materials have shown promise but remain underexplored in CFD literature. More simulation-based studies are needed to evaluate their feasibility and optimize their design.
4. **Miniaturization and User-Centric Design Constraints:** Many CFD models overlook the ergonomic and spatial limitations of portable devices. Future work should incorporate design constraints related to size, weight, and user comfort to ensure practical applicability.
5. **Real-Time and Adaptive Cooling Simulations:** Current CFD studies are mostly static and do not account for dynamic thermal loads or user behavior. Incorporating real-time adaptive cooling strategies using AI-assisted CFD could lead to smarter thermal management systems.

IX. Conclusions

Over the past decade (2015–2025), computational fluid dynamics (CFD) has become a vital tool in the thermal management of portable electronics. As devices become more compact and powerful, effective cooling is essential to prevent overheating and maintain performance. CFD has significantly advanced solutions such as graphite foils, vapor chambers, phase-change materials (PCMs), pulsating heat pipes (PHPs), and piezoelectric micro-blowers.

Graphite foils and vapor chambers are key in reducing hotspots and improving temperature uniformity, while PCMs provide effective transient buffering, though challenges remain in their repeatability. PHPs and OHPs offer promising solutions but are limited by orientation dependence. Micro-blowers have proven effective for cooling with minimal power consumption but face concerns over reliability and dust ingress.

In wearables, CFD integrated with human bio-heat models ensures thermal comfort by maintaining safe skin temperatures. The trend towards hybrid cooling solutions combining passive and active techniques, along with the use of additive manufacturing for custom porous structures, is expected to continue. Additionally, machine learning (ML) techniques are being integrated into CFD to accelerate design processes.

Despite these advancements, challenges such as the lack of standardized validation datasets, material property variability, and the need for human-centric models persist. Future research should focus on addressing these gaps to further optimize cooling systems for portable electronics, leading to more efficient, reliable, and user-friendly devices.

References

- [1] C. Lasance, Thermal challenges in portable electronics, *IEEE Trans. Comp. Packag. Technol.*, 38(2):251–259, 2015.
- [2] S. Narumanchi et al., Advances in computational thermal management of electronics, *Int. J. Heat Mass Transf.*, 91:118–130, 2015.
- [3] X. Zhang and Y. Chen, CFD modeling in electronics cooling: A review, *Appl. Therm. Eng.*, 112:1125–1139, 2017.
- [4] A. Bar-Cohen et al., Electronics thermal management: Past, present, and future, *Proc. IEEE*, 104(11):2110–2131, 2016.
- [5] H. Yang et al., Thermal management in wearable electronics: A review, *Nano Energy*, 88:106244, 2021.
- [6] ISO 13732-1, Ergonomics of the thermal environment, ISO, 2019.
- [7] K. Lee et al., Numerical analysis of smartphone thermal behavior using conjugate CFD, *Electronics Cooling Journal*, 23(3):45–54, 2019.
- [8] L. Wu et al., Thermal performance of flexible graphite spreaders, *Appl. Therm. Eng.*, 145:678–687, 2018.
- [9] J. Lee and Y. Park, CFD study of PCM-based smartphone cooling, *Int. J. Heat Mass Transf.*, 164:120565, 2021.
- [10] S. Kalbasi et al., PCM-foam composites for transient cooling, *Int. Commun. Heat Mass Transf.*, 132:105959, 2022.
- [11] X. Chen et al., Comfort-aware CFD modeling for wearables, *IEEE Trans. CPMT*, 11(7):1085–1095, 2021.
- [12] R. Gupta and S. Shinde, Portable electronics cooling challenges, *Thermal Sci. Eng. Prog.*, 35:101275, 2023.
- [13] S. Nagai et al., Anisotropy modeling of graphite foils, *J. Electron. Packag.*, 141(4):041001, 2019.
- [14] T. Chien et al., CFD simulation of vapor chambers, *Appl. Therm. Eng.*, 171:115094, 2020.
- [15] Y. Huang et al., PCM-based thermal management, *Energy Convers. Manage.*, 199:111999, 2019.
- [16] G. Rao and P. Kumar, CFD modeling of OHPs, *Int. J. Therm. Sci.*, 146:106–117, 2019.
- [17] A. Singh et al., Slug-flow simulation of PHPs, *Heat Transf. Eng.*, 42(8):675–689, 2021.
- [18] D. Kim and S. Lee, Reduced-order modeling of OHPs, *Appl. Therm. Eng.*, 200:117582, 2022.
- [19] TechInsights, Piezoelectric micro-blowers in smartphones, Report, 2024.
- [20] P. Brown, Fan-on-a-chip: Solid-state cooling, *Electronics Cooling News*, 2025.
- [21] L. Wang et al., PCM fabrics for PTM, *Nano Energy*, 90:106554, 2021.
- [22] J. Li et al., Surrogate-assisted CFD optimization, *Appl. Therm. Eng.*, 225:119893, 2023.
- [23] C. Patel and Y. Chen, Benchmarking CFD models for smartphones, *Thermal Eng. Rev.*, 9:45–59, 2024.