American Journal of Advanced Multidisciplinary Innovation and Research (AJAMIR)

E-ISSN: XXXX-XXXX ● Website: www.ajamir.com ● Email: editor@ajamir.com

Passive Thermal Management for Compact Mechanical Systems

Prof. Elisabeth Mayer

Professor, Montanuniversität Leoben, Austria

Abstract

Compact mechanical and mechatronic systems increasingly combine motors, bearings, power electronics, sensors, actuators, batteries, control modules, and structural components within restricted packaging volumes. The resulting concentration of heat can generate local hot spots, lubricant degradation, thermal distortion, accelerated material aging, and reduced reliability. Active cooling can provide high heat-removal capacity, but fans and pumps add power consumption, acoustic noise, moving parts, maintenance requirements, packaging complexity, and additional failure modes. Passive thermal management therefore remains attractive where heat can be redistributed, stored temporarily, and rejected without continuous auxiliary power. This study develops a methodological framework for selecting and integrating passive thermal technologies for compact mechanical systems. Because authenticated prototype temperatures, heat-flux measurements, computational-fluid-dynamics results, and thermal-cycle records were not supplied, the quantitative component is explicitly simulation based. Three architectures are evaluated: a conductive metallic heat spreader with natural-convection heat rejection, a vapor-chamber-assisted spreader, and a hybrid vapor-chamber plus phase-change-material system for intermittent thermal loads.

A Passive Thermal Management Integration Index is developed from spreading resistance, heat-transport capability, transient buffering capacity, temperature uniformity, packaging efficiency, orientation robustness, and reliability. Simulated analysis indicates that passive architecture selection becomes increasingly important as heat density rises. At an intermittent 50 W heat load, modeled peak temperature decreases from 105 °C for the conventional conductive system to 87 °C using a vapor chamber and to 72 °C using a vapor-chamber/phase-change-material hybrid. The study emphasizes that phase-change materials should be treated primarily as transient energy buffers rather than continuous heat sinks, while vapor chambers and heat pipes are most effective when an adequate downstream heat-rejection path exists. The proposed framework supports passive thermal design as a system-level optimization problem involving conduction, spreading, storage, natural convection, component arrangement, mass, volume, and reliability.

Keywords: passive thermal management, compact mechanical systems, heat pipes, vapor chambers, phase-change materials, heat spreading, natural convection, thermal reliability

1. Introduction

Miniaturization has increased the functional density of modern mechanical and mechatronic assemblies. Compact robotic joints, precision actuators, embedded drives, portable machinery, autonomous platforms, instrument enclosures, and densely integrated electromechanical modules often place heat-generating components close to temperature-sensitive structures. Thermal management therefore becomes a mechanical-design problem as much as an electronics problem. Excessive temperature can alter lubricant viscosity, accelerate polymer and insulation aging, modify clearances, generate thermally induced deformation, reduce sensor stability, and lower the operating life of bearings, motors, batteries, and semiconductor components. Compact systems are particularly difficult to cool because the available surface area for heat rejection does not necessarily increase in proportion to internal heat generation.

Active cooling using fans, pumps, blowers, or liquid circulation can increase heat-transfer coefficients, but it introduces additional energy consumption and hardware. This can be undesirable in systems where silence, reliability, low maintenance, dust resistance, limited electrical power, or mechanical simplicity are important design priorities. Passive techniques instead rely on conduction, natural convection, radiation, capillary-driven two-phase heat transport, and latent-heat storage. Heat pipes are especially attractive because they can transfer heat through evaporation and condensation with very low effective thermal resistance while requiring no mechanical pumping. Reviews of small heat pipes emphasize their relevance to compact cooling because miniaturized heat pipes, loop heat pipes, and vapor chambers can redistribute heat from concentrated sources toward larger heat-rejection surfaces.

Vapor chambers extend this principle by providing planar two-phase heat spreading. Rather than transporting heat primarily along one axis, a vapor chamber distributes heat laterally across a broader surface, helping suppress hot spots in thin or spatially constrained packages. Its performance depends strongly on wick structure, working fluid, vapor-space dimensions, filling ratio, contact resistance, orientation, and the relationship between evaporator and condenser regions. Reviews of vapor-chamber technology identify wick optimization and capillary transport as critical to achieving high heat-flux capability in narrow spaces.

Phase-change materials provide a different passive mechanism. Instead of transporting heat continuously to the environment, a PCM absorbs thermal energy as latent heat while changing phase over a selected temperature range. This can delay peak temperature during intermittent operation and can be particularly useful for devices that operate through repeated high-power bursts followed by lower-power recovery periods. Experimental studies using paraffin-based PCM with pin-fin heat sinks show that properly selected fins and PCM volume can extend the time before a critical temperature is reached. Hybrid systems combining heat pipes with low-melting-point PCM have also demonstrated strong buffering against short high-power thermal shocks.

2. Objectives of the Study

2.1 To Develop an Integrated Passive Thermal Management Framework

The first objective is to develop a framework capable of evaluating several passive mechanisms simultaneously. Thermal design is frequently approached by selecting a heat sink, heat pipe, PCM, or other component individually. Such component-level selection can overlook the fact that passive thermal technologies perform different functions within the heat-flow path.

The proposed framework therefore separates heat acquisition, spreading, transport, temporary storage, and ultimate rejection. A high-performance vapor chamber provides little sustained benefit if the condenser region cannot reject heat effectively to the surroundings. Similarly, a PCM can delay temperature rise but eventually becomes fully melted unless the stored energy is subsequently discharged. Passive performance must therefore be assessed through the complete source-to-ambient thermal pathway.

2.2 To Compare Steady and Transient Thermal Control

The second objective is to distinguish steady thermal resistance from transient thermal buffering. Compact mechanical systems frequently experience variable workloads rather than constant heat generation. Motor acceleration, intermittent actuation, high-current battery discharge, short machining cycles, or temporary processor loads can produce peak thermal events that differ materially from average operating conditions.

The study therefore evaluates both peak temperature and capacity to absorb transient thermal energy. Conductive heat sinks are treated as continuous heat-rejection devices, vapor chambers as spreading and transport devices, and phase-change materials primarily as temporary storage media. This distinction avoids overstating the continuous cooling capacity of PCM-based systems.

2.3 To Evaluate Thermal Performance Against Packaging and Reliability Constraints

The third objective is to include compactness and reliability directly in passive thermal selection. Increasing fin area, PCM mass, or heat-pipe dimensions may improve thermal performance while creating unacceptable increases in system volume or mass. Thin devices may also impose strong orientation, bend-radius, contact-pressure, or manufacturing constraints.

The framework consequently evaluates thermal benefit together with volume efficiency, mass penalty, orientation sensitivity, mechanical simplicity, leakage risk, and absence of moving components. The preferred design is therefore the architecture providing sufficient thermal control with the lowest overall integration penalty rather than simply the lowest calculated temperature.

3. Review of Literature

3.1 Heat Pipes and Vapor Chambers for Compact Heat Transport

Heat pipes are passive two-phase devices in which a working fluid evaporates at the heat source and condenses at a cooler location. Capillary forces generated by a wick return the condensed liquid to the evaporator, allowing the cycle to continue without an external pump. Their high effective thermal conductance has made them established thermal links between concentrated heat sources and larger heat-rejection surfaces.

Miniaturization has produced flat heat pipes, micro heat pipes, loop heat pipes, and vapor chambers suitable for restricted packages. Reviews of small heat-pipe technology emphasize that thermal capability depends not only on geometric size but also on capillary, sonic, entrainment, boiling, and viscous limits. Very thin structures can experience competing requirements: a small thickness improves compactness while reducing vapor-flow area and liquid-return capability.

Vapor chambers are especially useful when several components share a compact structural surface or when a concentrated source must distribute heat across a broader chassis. Their principal advantage is reduction of spreading resistance. A conventional metal plate conducts heat through its finite thermal conductivity, creating a pronounced hot region near the source. A vapor chamber uses internal phase change to equalize temperature more effectively across the plane. Reviews of vapor-chamber performance identify evaporator wick design, capillary pressure, permeability, wettability, and wick manufacturing as critical determinants of maximum heat-transfer capability.

3.2 Phase-Change Materials for Transient Passive Cooling

Latent-heat storage provides a different solution to compact thermal management because heat can be absorbed with relatively limited temperature increase while the PCM undergoes phase transition.

The required storage capacity can be approximated as:

$$Q_{PCM}=m[c_{p,s}(T_m-T_i)+L+c_{p,l}(T_f-T_m)]$$

where m is PCM mass, $c_{p,s}$ and $c_{p,l}$ are the solid- and liquid-phase specific heats, L is latent heat, and T_m is the phase-transition temperature.

The major weakness of many organic PCMs is comparatively low thermal conductivity. Consequently, internal fins, porous metals, high-conductivity particles, and heat pipes are frequently used as thermal-conductivity enhancers. Experimental work with PCM-filled pin-fin sinks shows that fin dimensions, PCM quantity, melting temperature, and applied heat flux strongly affect the duration for which the system remains below a prescribed temperature.

Design should not maximize latent-heat capacity without considering thermal transport. Research on PCM-based electronics cooling emphasizes that maximizing conductivity alone is also insufficient; thermal storage geometry, operating time, source duty cycle, melting temperature, and heat-rejection conditions must be considered together. Hybrid PCM–heat-pipe systems are therefore attractive because the heat pipe spreads energy rapidly while PCM temporarily absorbs the transient load. Experimental thermal-shock studies demonstrate the potential of such integration for high-power intermittent operation.

3.3 System-Level Constraints in Passive Compact Cooling

Passive thermal technologies depend heavily on boundary conditions. A heat pipe can move heat efficiently but does not remove energy from the system by itself. Its condenser must couple to natural convection, radiation, a structural chassis, or another heat sink. Similarly, a PCM module stores rather than destroys heat, so repeated duty cycles require sufficient off-time or a secondary pathway for resolidification.

Compact packaging further introduces thermal-contact resistance.

The effective source-to-ambient resistance can be written conceptually as:

$$R_{th,total}=R_{contact}+R_{spreading}+R_{transport}+R_{rejection}$$

and the steady temperature rise is:

$$\Delta T=QR_{th,total}$$

Reducing one resistance produces limited benefit when another term dominates. This explains why advanced spreaders should be evaluated simultaneously with thermal-interface materials, mounting pressure, chassis conductivity, fin area, and natural-convection orientation.

Compact-system design therefore benefits from hybrid rather than isolated solutions. Heat pipes or vapor chambers can spread localized heat; high-conductivity frames can use the structural enclosure as an extended thermal path; fins can increase passive convection; and PCM can buffer short peaks. The engineering task is to select the smallest combination that maintains allowable component temperatures throughout the expected duty cycle.

4. Research Methodology

4.1 Simulation Design and Compact Thermal Architectures

The study adopts a simulation-based methodological design. No real compact-system prototype, embedded thermocouples, infrared thermography, heat-flux sensor data, or experimentally validated finite-element model was supplied. Accordingly, all numerical values are illustrative.

synthetic compact electromechanical module is assumed to contain a localized heat source mounted within a restricted aluminum enclosure. The module experiences intermittent heat loads from 10 to 60 W under a standardized duty cycle. Ambient temperature and available external surface area are held constant so that architecture effects can be compared.

Three passive configurations are investigated:

Configuration A — Conductive spreader and passive heat sink: heat is transferred through an aluminum spreading plate to external natural-convection surfaces.

Configuration B — Vapor-chamber-assisted spreader: a flat vapor chamber reduces lateral spreading resistance before heat reaches the passive external heat sink.

Configuration C — Vapor chamber with PCM buffer: the vapor chamber distributes heat to both the rejection surface and a PCM reservoir designed to absorb short thermal peaks.

Table 1: Variables Used in the Passive Thermal Management Framework

Design Dimension	Proposed Empirical Measure	Thermal Function	Principal Design Constraint
Spreading resistance	Source-to-spreader temperature difference per watt	Controls local hot-spot severity	Material conductivity and source footprint
Passive heat transport	Effective vapor-chamber/heat-pipe conductance	Transfers heat away from source	Capillary and orientation limits
Latent buffering	PCM latent capacity and utilization fraction	Delays transient temperature peaks	Saturation and resolidification time
Temperature uniformity	Maximum–minimum structural temperature difference	Limits distortion and localized aging	Heat-source concentration

Design Dimension	Proposed Empirical Measure	Thermal Function	Principal Design Constraint
Heat-rejection capacity	Natural-convection/radiation performance	Removes energy from system	Available surface area and orientation
Packaging efficiency	Thermal benefit per unit mass and volume	Supports compact integration	Geometrical restrictions
Reliability robustness	Moving-part count, leakage risk, mechanical complexity	Supports long-term operation	Manufacturing and sealing quality

Source: Author-developed simulation framework informed by passive heat-pipe, vapor-chamber, and PCM thermal-management literature.

4.2 Passive Thermal Management Integration Index

The proposed Passive Thermal Management Integration Index (PTMII) combines seven normalized dimensions:

$PTMII_i = w_s S_i + w_h H_i + w_b B_i + w_u U_i + w_p P_i + w_o O_i + w_r R_i$

where:

- S_i = spreading-performance score;
- H_i = passive heat-transport score;
- B_i = transient buffering capability;
- U_i = temperature-uniformity score;
- P_i = packaging-efficiency score;
- O_i = orientation robustness;
- R_i = reliability score.

For the baseline model:

$PTMII_i = 0.20S_i + 0.15H_i + 0.15B_i + 0.15U_i + 0.15P_i + 0.10O_i + 0.10R_i$

and:

$\sum w_j = 1$

Spreading performance receives the largest weight because severe local temperature can exist even when average enclosure temperature remains acceptable. The weighting remains illustrative and should be adapted to the specific mechanical system.

4.3 Thermal Resistance and Transient Energy-Balance Model

For the conductive system, source temperature is represented using:

$T_s = T_\infty + Q R_{th,total}$

where T_∞ is ambient temperature, Q is heat load, and $R_{th,total}$ includes contact, spreading, and heat-rejection resistance.

For the vapor-chamber configuration:

Rth,total=Rcontact+RVC+Rsink
where RVC is the effective resistance of the vapor-chamber spreading stage.
The hybrid PCM system is modeled through the transient balance:
Qin−Qout=meqceqdtdT+m˙PCML
during phase change, where the latent-heat term increases the apparent thermal capacity.
The PCM is considered effective only until its available latent storage is exhausted. During subsequent **low-power or off-load intervals:**
Qreject>Qgeneration
must hold sufficiently long for the PCM to release stored heat and resolidify. The model therefore penalizes PCM configurations that cannot recover between operating cycles.

5. Analysis

5.1 Thermal Performance Across Increasing Compact-System Loads

The synthetic analysis shows relatively small differences among the three architectures at the lowest heat inputs. At 10 W, peak component temperature is modeled at 46 °C for the conductive system, 43 °C for the vapor chamber, and 41 °C for the vapor-chamber/PCM hybrid.

The performance difference grows substantially as heat input rises because lateral spreading resistance and transient heat capacity become increasingly important. At 40 W, modeled peak temperature reaches 88 °C for the conventional system, compared with 74 °C using the vapor chamber and 63 °C using the hybrid architecture.

5.2 Comparative Passive Architecture Performance

Table 2: Simulated Performance of Passive Thermal Architectures

Thermal Architecture	Mean PTMII	Peak Temperature at 30 W	Peak Temperature at 50 W	Transient Buffering	Primary Limitation
Conductive spreader + passive heat sink	0.54	72 °C	105 °C	Low	Increasing spreading resistance and hot-spot concentration
Vapor-chamber-assisted spreader	0.76	62 °C	87 °C	Moderate	Downstream heat rejection remains limiting
Vapor chamber + PCM buffer	0.88	55 °C	72 °C	High during intermittent load	PCM saturation and required recovery interval

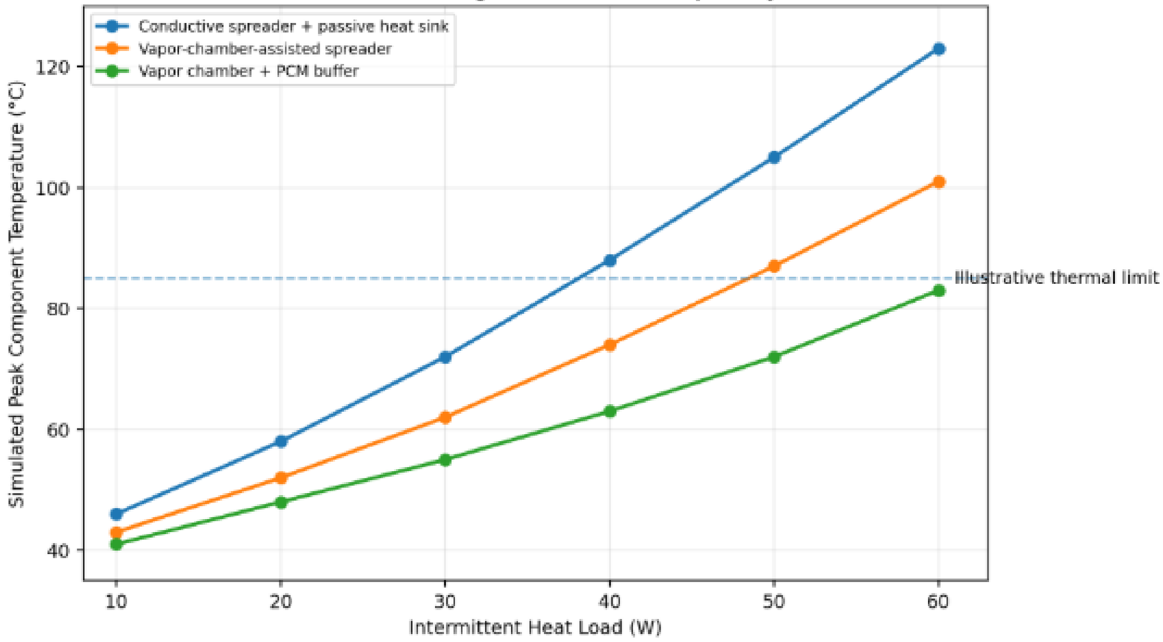
Note: All temperature and index values are synthetic and should not be interpreted as measured performance of a specific commercial assembly.

The vapor chamber produces a significant improvement without relying on temporary latent storage. This makes it comparatively robust where heat generation is continuous and the external enclosure can reject the transported heat.

The PCM hybrid produces the lowest peak temperature during intermittent operation because heat is both redistributed and temporarily absorbed. However, the advantage decreases if the duty cycle does not provide sufficient time for PCM recovery.

5.3 Peak Temperature Under Intermittent Heat Loading

Graph 1: Simulated Passive Thermal Management Under Compact-System Heat Loads



The graph demonstrates a nonlinear separation among architectures as thermal load rises. The conductive spreader exceeds the illustrative 85 °C thermal limit between 30 and 40 W. The vapor-chamber architecture remains below this reference limit through approximately 40 W but exceeds it at 50 W.

The vapor-chamber/PCM configuration remains below the illustrative thermal limit even at 60 W within the simulated intermittent duty cycle. This result should not be interpreted as unlimited passive cooling capability. The PCM is assumed to retain usable latent storage during the analyzed event.

The difference between the vapor chamber and PCM hybrid illustrates the distinction between thermal transport and thermal storage. The vapor chamber reduces source-to-sink temperature gradients, whereas the PCM reduces the rate at which system temperature rises during temporary overload.

Key Finding: Compact passive thermal management is strongest when heat spreading, heat rejection, and transient storage are assigned separate functions and then integrated according to the actual duty cycle.

6. Discussion

6.1 Heat Spreading Is Often the First Compact-System Bottleneck

The first implication is that reducing hot-spot concentration can be more valuable than increasing bulk heat-sink mass. A compact system may possess adequate total surface area but still overheat locally because heat cannot spread efficiently from a small source to that surface.

Vapor chambers are particularly effective under this condition because the two-phase internal mechanism provides high effective in-plane thermal conductance. Current reviews emphasize their ability to suppress hot spots within narrow packaging spaces, while wick research shows that performance ultimately depends on balancing capillary pressure with permeability and vapor transport.

This suggests a practical design sequence. Engineers should first identify whether source temperature is dominated by interface resistance, spreading resistance, or external heat rejection. Installing a vapor chamber is most valuable where spreading is important. If external natural convection is already the dominant resistance, improving the internal spreader alone will produce diminishing returns.

6.2 PCM Is Most Effective for Intermittent Rather Than Continuous Loads

The second implication is that phase-change materials should be selected according to duty cycle rather than maximum power alone. PCM creates a period of enhanced effective thermal capacity, but the stored energy remains inside the mechanical system until it is eventually rejected.

Experimental research on PCM heat sinks shows that melting temperature, PCM fraction, fin geometry, and heat flux determine the time before a critical temperature is reached. Design studies likewise emphasize that conductivity enhancement and storage capacity must be optimized together rather than independently.

This makes PCM particularly suitable for systems with burst-type operation. Intermittent actuators, portable tools, inspection robots, compact drives, and mission-specific devices may generate high heat for a limited interval followed by sufficient recovery time. For a continuously operating thermal source, increasing external heat rejection or using a passive two-phase transport loop may provide greater long-term benefit than simply adding more PCM.

Hybridization is valuable precisely because it addresses PCM's low-conductivity limitation. Heat pipes or metallic fins distribute heat rapidly into the storage material, while the PCM provides latent capacity. High-power experimental work with finned heat pipes and low-melting-point storage materials supports the viability of such combined architectures under transient thermal shock.

6.3 Compact Thermal Design Requires Thermal–Mechanical Co-Optimization

The third implication is that passive cooling should be integrated with mechanical packaging from the earliest design stage. Heat-spreader location, chassis thickness, contact pressure, fastener layout, surface coatings, orientation, PCM containment, and structural stiffness all influence the eventual thermal pathway.

A thermally excellent module can become mechanically impractical if it adds excessive mass or occupies space required by actuators, bearings, cables, or sensors. Conversely, the structural frame itself can become a useful thermal component when high-conductivity paths are intentionally integrated into load-bearing members.

Reliability is another advantage of passive systems. Eliminating fans and pumps reduces moving-part count, vibration, acoustic noise, and power consumption. This is particularly valuable in sealed or contaminated environments. However, passive does not mean failure-proof. Heat pipes can suffer from manufacturing defects, working-fluid loss, wick degradation, freezing constraints, or dry-out at excessive heat flux. PCM systems require containment, volume-change management, cycling stability, and chemical compatibility.

System design should therefore optimize a combined objective such as:

$\min[T_{peak}, \Delta T_{structure}, V_{thermal}, M_{thermal}, R_{failure}]$

subject to thermal, structural, packaging, and reliability constraints.

7. Conclusion

Passive thermal management offers a practical route for controlling temperature in compact mechanical and mechatronic systems where auxiliary power, maintenance, noise, or packaging complexity make active cooling undesirable. The principal passive mechanisms examined in this study—solid conduction and natural convection, vapor-chamber heat spreading, and phase-change thermal buffering—perform different functions and should therefore be integrated according to the dominant thermal bottleneck.

The proposed Passive Thermal Management Integration Index evaluates spreading resistance, passive heat transport, transient buffering, temperature uniformity, packaging efficiency, orientation robustness, and reliability. Within the synthetic analysis, the conventional conductive architecture produces a peak temperature of 105 °C at an intermittent heat input of 50 W, while the vapor-chamber-assisted system reduces the value to 87 °C. Combining vapor-chamber spreading with PCM buffering further reduces the simulated peak to 72 °C. These results illustrate system behavior and are not experimentally measured performance data.

The analysis further demonstrates that PCM should not be regarded as a substitute for sustained heat rejection. Its principal advantage is the ability to absorb temporary overload and delay temperature rise. Vapor chambers and heat pipes provide continuous transport but remain dependent upon an adequate condenser-side sink. Effective compact thermal design therefore requires a source-to-ambient perspective in which contact resistance, spreading, transport, storage, and final heat rejection are evaluated together.

Future experimental research should validate the framework using compact electromechanical prototypes instrumented with thermocouples, infrared thermography, heat-flux sensors, and controlled power inputs. Comparative studies should examine orientation, thermal-interface resistance, vapor-chamber thickness, wick design, PCM melting range, PCM cycling stability, enclosure natural convection, and recovery time between load pulses. Reliability testing should additionally consider vibration, shock, leakage, freeze–thaw behavior, and repeated thermal cycling. Passive thermal management will provide its greatest engineering value when thermal components are treated not as attachments added after mechanical design, but as integrated structural elements that distribute, store, and reject heat within the same compact architecture.

References

1. Zohuri, B. (2020). Functionality, advancements and industrial applications of heat pipes. Academic Press.
2. Pizzolato, A., Sharma, A., Ma, Z., & Liao, X. (2020). Small-sized pulsating heat pipes/oscillating heat pipes with low thermal resistance and high heat transport capability. Energies, 13(7), 1736.
3. Cataldo, F., Marcinichen, J., & Thome, J. R. (2021). Mini-scale pulsating heat pipe cooling systems for high-heat-flux electronic equipment. Journal of Physics: Conference Series, 1868, 012009.
4. Sun, B., & Huang, X. (2021). Seeking advanced thermal management for stretchable electronics. npj Flexible Electronics, 5, 12.
5. Zhang, S., Du, W., Chen, W., Dang, Y., Iqbal, N., & Ma, Y. (2021). Passive temperature management based on near-field heat transfer. arXiv preprint arXiv:2103.03903.
6. Bianco, V., De Rosa, M., & Vafai, K. (2022). Phase-change materials for thermal management of electronic devices. Applied Thermal Engineering, 214, 118839.
7. Liu, Y., Zheng, R., & Li, J. (2022). High latent heat phase change materials with low melting temperature for thermal management and storage of electronic devices and power batteries: Critical review. Renewable and Sustainable Energy Reviews, 168, 112853.
8. Sankara Subramanian, A. T., Subramaniya Siva, A., Ramesh, M., & Sabarish, P. (2022). Experimental analysis on passive thermal management system for electronic gadgets using inorganic phase changing material (PCM). Materials Today: Proceedings, 69, 1029–1033.
9. V. C., Midhun, Sivan, S., Akhil Krishnan, S. R., & Pandian, R. S. T. (2022). Effect of vacuum insulation panel integration in phase change material-based passive thermal management system for electronics package exposed to hot air environment. Journal of Energy Storage, 53, 105180.
10. Kurhade, A. S., & Murali, G. (2022). Thermal control of IC chips using phase change material: A CFD investigation. International Journal of Modern Physics C, 33(12).
11. Bianco, V., De Rosa, M., & Vafai, K. (2022). Phase change materials for thermal management and energy storage: A review. Journal of Energy Storage, 55, 105602.
12. Alqahtani, A. A., & Bertola, V. (2023). Polymer and composite materials in two-phase passive thermal management systems: A review. Materials, 16(3), 893.
13. Faraji, H., Yildiz, Ç., Arshad, A., Arıcı, M., Choukairy, K., & El Alami, M. (2023). Passive thermal management strategy for cooling multiple portable electronic components: Hybrid nanoparticles enhanced phase change materials as an innovative solution. Journal of Energy Storage, 70, 108087.
14. Experimental optimization of various heat sinks using passive thermal management system. (2023). Case Studies in Thermal Engineering, 49, 103262.
15. Phase change material integrated cooling for transient thermal management of electronic devices. (2023). International Journal of Heat and Mass Transfer, 213, 124263.
16. Elshaer, A. M., Soliman, A. M. A., Yousef, M. S., Kassab, M., & Hawwash, A. A. (2023). Experimental study about the impact of open cell aluminium foam insertion in salt-based phase change material for electronics thermal management. Thermal Science and Engineering Progress, 44, 102311.
17. Liu, H., Yu, J., Wang, C., Zeng, Z., Poredoš, P., & Wang, R. (2023). Passive thermal management of electronic devices using sorption-based evaporative cooling. Device, 1(6), 100122.

18. Liu, H., Yu, J., Wang, C., Zeng, Z., Poredoš, P., & Wang, R. (2023). Membrane-encapsulated, moisture-desorptive passive cooling for high-performance, ultra-low-cost, and long-duration electronics thermal management. Device, 1(6), 100121.
19. Song, Y., et al. (2023). Rationally tunable phase change material thermal properties enabled by three-dimensionally printed structural materials and carbon-based functional additives. International Journal of Energy Research.
20. A comprehensive review on thermal management of electronic devices. (2023). Journal of Engineering and Applied Science, 70, 140.