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Design and Performance Optimization of an Automobile Radiator: Means and Technologies

S. O. Onubaye [1,*], S. H. Eromi [1]

[1] *Mechanical Engineering Department, Confluence University of Science and Technology, Osara, Nigeria*

* **Corresponding author:** onubayeos@custech.edu.ng • ORCID: 0000-0002-8818-1154

Abstract

Radiators play a critical role in determining vehicle efficiency and continue to see improvements in heat dissipation capabilities while shedding weight. Radiators have shrunk from heavy copper-brass designs to lightweight aluminum radiators with intelligent cooling. These intelligent cooling designs are achieved through innovative technologies such as fin optimization, nanofluids, computational fluid dynamics (CFD) modeling, and additive manufacturing. Advancements in artificial intelligence (AI)-assisted radiator design and integrated sensor technologies will enable radiators of the future to become adaptive platforms with the intelligence to react and respond to changing conditions. Electric vehicles (EV) and hybrid electric vehicles (HEV) will use modular radiators capable of providing dynamic cooling based on the real time heat load of each subsystem. Marelli has developed a smart EV thermal management module called iTMM. Another way engineers are developing radiators at a faster pace is through AI algorithms paired with 3D printing that allows for user customizable radiator geometries. Integrated sensor networks within radiators allow for real-time condition monitoring, predictive maintenance, and even active manipulation of cooling channels to control heat transfer. Research is also being conducted outside of the automobile industry in areas such as eco-friendly machining, resource efficient convective cooling, and machine-learning based predictive control to reduce energy consumption and associated emissions. Developments in scalable organic photovoltaics and printable flexible graphene supercapacitors are other examples of how thermal management intersects with improving environmental impacts.

.**Keywords:** Automobile radiator; Radiator design; smart sensor; performance optimization; nanofluid

1. Introduction

The automobile radiator is an essential heat exchanger in automobile thermal management systems. It maintains the engine's optimum operating temperature range and prevents engine overheating while running [1]. Radiators were originally large, heavy copper-brass designs; modern radiators use lightweight aluminium constructions with superior heat transfer capabilities [2]. Automobile radiators have advanced through time to satisfy the demands for fuel economy, emission control, and better performance. As a result, significant developments have occurred in radiator materials, coolant flow rates, and hybrid cooling systems [3]. Electric and hybrid vehicles require radiator systems that can dynamically adjust cooling rates based on load, sensors, smart controllers, and module-based system design [4]. This article reviews automobile radiator design and performance optimization techniques. It also discusses traditional automobile radiator designs and compares them with future technologies.

2. Fundamentals of Radiator

2.1. Material Trends and Progression

Historically, radiator cores are made of copper-brass alloys, radiator material has evolved into aluminium as the prime alloy for mass and corrosion reduction [2]. Composite plastics are now used to construct radiator tanks as well to decrease mass and cost, though heat stabilization methods need to be used to ensure proper thermal properties [1]. Some radiator tanks use additional protection coatings like epoxy resins and nano ceramic thermal applications [3].

2.2. Design Pattern and Heat Transfer

Radiators most commonly operate under crossflow or downflow orientation. Tubes and micro-channels used in radiators are either flat or round to allow proper surface contact and air flow [5]. Fin arrangements were used to interrupt laminar flow such as Louvered or Offset strip fins [2]. All of these aspects affect the performance of heat exchange as observed by the Nu number [1].

2.3. Fluid Dynamics and Temperature Characteristics

Fluids used for cooling applications for automobiles are water-ethylene mixtures that are pressurized [1]. Flow rate, temperature difference, and fin parameters play large roles in thermal performances of these systems. Using Computational Fluid Dynamics (CFD) we can model flow channels and find hotspots [5].

3. Performance Optimization Strategies

3.1. Improving Fin/Tube Geometry

Adjusting fin pitch, louvers angle, and tube geometries can effectively increase heat transfer surface area and turbulence, leading to better heat dissipation [5]. Micro-channel tubes and offset strip fin allow radiators to run cooler while reducing size for optimum performance gains [1][3].

3.2. Coolant variation

Utilizing nanofluids (CuO or Al_2O_3) can improve heat transfer by up to 30%. Copper oxide or aluminum oxide nanoparticles used in conjunction with ethylene glycol have been proposed as potential coolant options [6]. However, the long-term stability and corrosion against radiator surfaces pose significant challenges for nanofluids [1].

3.3. Computational Fluid Dynamics (CFD) Analysis

CFD programs like ANSYS workstations or free software like Open FOAM allow developers to map airflow-coolant distribution, as well as pressure drops before building physical prototypes, allowing for predictive modeling [1][2][7]. Utilizing CFD tools can help designers develop more efficient radiator designs while reducing cost.

3.4. Improved Air Flow Technique

Active grille shutters and electronically-controlled variable speed fans allow the hood to adapt to changing conditions while reducing drag and improving airflow to the radiator when necessary [8]. Techniques using CFD to design ducting for better airflow distribution through the radiator core can also help minimize pressure drop (loss).

3.5. Intelligent Control

Networking sensors and controlling coolant flow with ECUs allows for real-time temperature tracking and predictive controls that can help prevent many problems [9]. By analyzing driving behavior, ambient temperature, and workload, coolants can be pumped through the radiator at the most optimal times while controlling fan speed to avoid being under or over-cooled [10].

4. Advanced Techniques in Radiator Design

4.1. Innovation in 3D Printing and Additive Manufacturing for Radiator Design

Thanks to additive manufacturing technologies, it is now possible to produce complex internal geometries for cooling channels as well as ultra-lightweight radiator frames that cannot be produced by traditional manufacturing processes [11]. Innovative materials including sintered aluminium and alumina-based ceramics are currently being developed for use in automobiles and aerospace applications due to their high thermal stability and strength when exposed to high temperatures [12][13].

4.2. Smart Sensors and Internet of Things (IoT) connectivity for Radiator Performance Monitoring

Integration of smart sensors within radiator cores allow for real-time monitoring of operating temperature, pressure, and flow rate to intelligently adapt cooling output and predict maintenance needs before failures occur [14]. Many of these smart radiator sensors and processors can connect directly to vehicle ECUs (Engine Control Units) and cloud-connected platforms for remote fleet monitoring, over-the-air software updates, and intelligent fault prediction throughout the entire vehicle fleets [15][16].

4.3. Nanotechnology Coating and Phase Change Material for Enhanced Heat Transfer

Recent advancements in graphene coatings and metal foam structures have allowed for dramatic increases in heat transfer performance and corrosion resistance within thermal systems, even in extreme environments [17]. Phase change materials (PCMs) and hydrophobic nano coatings are also being developed to help prevent temperature spikes while minimizing moisture buildup to extend the service life of radiators [18][19].

4.4. Hybrid Liquid and Air-Cooling System.

Electric and hybrid vehicles commonly use hybrid liquid-air cooling systems in addition to heat-pumps and thermoelectric cooling modules to manage heat output from vehicle batteries, motors, and onboard electronics. These cooling architectures are beginning to take a more adaptable and integrated approach to meet the requirements of various driving conditions and climate controls [20][21].

4.5. Machine Learning for Generative Radiator Design

Engineers and designers can now leverage artificial intelligence software to rapidly produce hundreds of viable radiator designs that meet target specifications. Generative design takes constraints such as performance metrics, material selection, and size restrictions into account to produce optimal radiator designs for any given use case [3][22]. Digital twin technology can also be used to simulate radiators in a virtual environment that updates with changing real-world parameters.

5. Comparative Analysis of Radiator Design

5.1. Conventional and Advanced Materials

On one hand, copper-brass alloys are preferred for their superior conductivity and durability, which is especially important in heavy-duty applications and restorations of classic cars. On the other hand, although slightly less conductive than copper-brass, aluminum alloys offer corrosion resistance, weight reduction benefits, and are more cost-effective; thus, they have become the material of choice for modern automobiles production [1][2][23][24][25][26].

5.2. Standard and Optimized Configuration

Flat tubes, micro-channels, and Louvered fins are becoming more popular as they offer greater turbulence and heat transfer than the standard round-tube, wave-fin configuration. These optimizations can offer improved heat transfer while also cutting weight and material usage. Additionally, CFD models allow for developers to finetune airflow path and coolant passages to better match flowrates with changing conditions [5][6][27][28][29][30]

5.3. Conventional Coolant and Nanofluid

Studies have shown that using nanofluids with Al_2O_3 or CuO nanoparticles in an ethylene glycol–water base can see improvements in thermal conductivity from 15-40% over standard coolant depending on the volume percent and temperature [6][31][32]. There are still challenges with the use of nanofluids, as they often face challenges with long-term stability and compatibility with other vehicle components [34][35].

5.4. Traditional and Smart System

Traditional thermal management systems use passive cooling and mechanical thermostats. These solutions allow for minimal control and optimization of the cooling system [36][37]. Smart sensor technology, AI adaptive controls, and additive manufacturing are all being implemented in next generation radiator designs. Many of these new features allow for modular radiator designs that can adjust to offer maximum performance, as well as provide predictive failure alerts. Electric and hybrid cars especially can benefit from smarter systems that can also efficiently manage batteries and other electrical components [5][33][38][39][40]

6. Challenges and Future Trends

6.1. Current Challenge

Efficiency, Cost and Weight

Achieving optimal thermal performance without incurring excessive weight or manufacturing costs continues to challenge radiator engineers. Copper radiators have the best heat dissipation properties, but aluminum is lighter and more corrosion resistant [1][2]. Additionally, while advanced radiators with features like nanofluid technology or smart cooling sensors are available, they are more expensive to produce and are therefore not used in economy cars [6]

Reliability and Lifespan

Engine cooling systems are subject to thermal cycling, vibration stress, and chemical corrosion, particularly when operating in extreme conditions. Components such as radiator composites and solder connections can fail prematurely due to heat-induced expansion and contraction cycles [5]. Furthermore, sensors and controllers used in smart radiator systems may experience drift or failures that reduce their cooling efficiency over time if they are not properly maintained [4].

Environmental Impact and Regulation

Production of aluminium, plastic radiator tanks, and composite materials contributes to greenhouse gas emissions. Radiator fluids contain chemicals that can be harmful to the environment if not disposed of properly, and are often difficult to recycle at end of life [41][51]. Environmental regulatory standards are starting to push back against these practices by requiring recyclable components and biodegradable fluids [42].

6.2. Future Direction

Integration with Electric Vehicles and Hybrid Systems

Electric vehicles still produce heat in some components like on-board batteries, power electronics, and electric motors that must be actively cooled. The radiator is rapidly expanding beyond simple heat rejection devices in these vehicles, developing into an all-in-one thermal management unit complete with heat pumps, multiple coolant loops, module-level thermal monitoring and controls, and TES for enhanced battery cooling management [43][44]. These units allow for highly efficient thermal regulation of individual subsystems during fast charging and maximum-load situations, resulting in greater range, predictive maintenance alerts, and sustainable energy practices.

Smart Monitoring and Control System

Radiators with sensors connected to an AI-powered ECU can monitor temperature across multiple coolant loops in real-time and make autonomous adjustments to fan speed or coolant flow rate based on current operating conditions. Electric cars and hybrid vehicles can significantly benefit from these smart radiator technologies because they constantly change cooling demands based on driving mode and power source [9]. By decreasing thermal variability and improving component cooling efficiency, operating costs and maintenance can be reduced due to fewer repairs and longer predicted component lifespan [45][46]. Thermal runaway and failure can be prevented with AI that detects anomalies and alerts operators using thermal sensors embedded into radiator systems [5].

Sustainable Manufacturing Practices

To minimize energy consumption and waste during production, many Original Equipment Manufacturers (OEMs) are looking into closed-loop manufacturing facilities and bioplastics. Another current effort under way to reduce radiator systems' environmental impact is designing them to be easier to disassemble at the end of their life so their materials can be recovered and recycled [47]. Manufacturers are experimenting with modular radiator designs that use interchangeable cooling cores and plugs (Car) so that if one section becomes damaged, the entire assembly does not need to be replaced [48].

Innovations from other Industries

Phase Change Material (PCM) and advanced thermal interface materials (TIM) are just some of the groundbreaking technologies being used on aircraft and robotics that are beginning to make their way into cars [52][53][54]. These advancements allow for lighter-weight heat exchangers with superior heat dissipation capabilities and more flexibility than traditional radiator designs, which improves heat rejection [50]. Electric and hybrid vehicles can benefit from smaller, lightweight radiators that don't take up as much room in the engine compartment.

7. Conclusion

The evolution of radiator technology in automobiles is an extraordinary narrative of human innovation and engineering prowess. In its early stages, radiator development was primarily concerned with creating an efficient heat exchange core made from copper and brass to dissipate heat from the engine. As automobile technology advanced, the radiator has evolved from a basic heat sink to a sophisticated thermal management system that integrates intelligent sensors and smart controls powered by artificial intelligence (AI). The adoption of lightweight materials such as aluminium alloys, micro-channel tubes, and nanofluids has enhanced thermal performance and contributed to weight reduction and emissions reduction efforts [1][3][5]. With the help of computational fluid dynamics (CFD), engineers can now simulate realistic flow and heat transfer scenarios to optimize radiator design and energy consumption levels [2]. Embedding smart sensors, adaptive cooling algorithms, and integrated control modules have enabled the radiator to become a critical subsystem within electric and hybrid vehicle architectures [4]. This evolution has not been without its hurdles. Engineers and scientists have faced numerous obstacles along the way, from balancing performance with cost and recyclability to meeting increasingly stringent environmental regulations and durability over the lifetime of the vehicle [49][42]. Looking ahead, several research directions could further advance radiator technology. These include scaling up nanofluids for mass production, developing predictive cooling systems for EV platforms, and discovering new sustainable materials. The radiator has come a long way since its humble beginnings as a passive cooling device. Today, it serves as a testament to human ingenuity and our ability to adapt and improve upon existing technologies.

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The authors declare no conflict of interest.

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References

[1] B. Mahato, “Thermal analysis of an automotive radiator sizing and rating—Simulation approach,” Int. J. Creative Res. Thoughts, vol. 11, no. 7, 2023.

[2] C. I. Priyadarsini, T. R. Reddy, and P. A. Devi, “Design and performance analysis of automotive radiator using computational fluid dynamics,” Int. J. Mech. Eng., vol. 7, no. 3, 2022.

[3] T. Venugopal, S. Pendli, H. Patel, M. Gupta, and G. Natarajan, “The performance of an automobile radiator with aluminum oxide nanofluid as a coolant—An experimental investigation,” SAE Technical Paper 2022-01-5007, SAE Int., 2022. https://doi.org/10.4271/2022-01-5007.

[4] Marelli Corporation, "Marelli presents new thermal management module for EVs," Electrive, Jul. 10, 2023. [Online]. Available: https://www.electrive.com/2023/07/10/marelli-presents-new-thermal-management-module-for-evs/

[5] G. Gupta, P. Sidkar, and B. Sharma, "Designing, manufacturing and testing of new radiator," in Enabling Industry 4.0 through Advances in Manufacturing and Materials, pp. 295–307, 2022. https://doi.org/10.1007/978-981-19-2890-1_29.

[6] R. Tarodiya and J. Sarkar, "Performance of flat fin tube automotive radiator using nanofluids as coolants," in Emerging Trends in Mechanical Engineering, pp. 422–429, 2022.

[7] H. B. Patel and D. Dinesan, "Optimization and performance analysis of an automobile radiator using CFD – A review," Int. J. Innovative Res. Sci. Technol., vol. 1, no. 7, 2014.

[8] Standard Brand, "Active grille shutters: Improving fuel economy and reducing emissions," 2019.

[9] B. Johnson, F. Hamzah, A. Taofeek, M. Blessing, and W. Liang, "Real-time thermal monitoring and adaptive flow control for cold plate heatsinks in automotive ECUs with dynamic SoC workloads," 2025. [Online]. Available: https://www.researchgate.net/publication/

[10] A. Y. Karnik, A. Fuxman, P. Bonkoski, M. Jankovic, and J. Pekar, "Vehicle powertrain thermal management system using model predictive control," SAE Int. J. Mater. Manuf., vol. 9, no. 3, 2016. https://doi.org/10.4271/2016-01-0215.

[11] B. Verma, J. Willkomm, and J. H. Schleifenbaum, "Novel design method for manufacturing internal cooling channels additively with a functional support structure," in Industrializing Additive Manufacturing, pp. 3–18, Springer, 2023.

[12] H. Wei, C. Li, Y. Xu, X. Zhang, J. Li, Y. Han, M. Li, and X. Xu, "Aluminum-based ceramic/metal composites with tailored thermal expansion fabricated by spark plasma sintering," RSC Adv., vol. 14, pp. 3952–3961, 2024. https://doi.org/10.1039/D3RA07593.

[13] N. H. A. Besisa, D. H. A. Besisa, and E. M. M. Ewais, "Processing of high temperature alumina/aluminum titanate ceramic composites from clean sources," Sci. Rep., vol. 12, Art. no. 09670, 2022. https://doi.org/10.1038/s41598-022-09670-3.

[14] Intuz, "How IoT ensures coolant quality control in the automotive industry," Intuz Blog, 2024.

[15] ETAS, "Cross lifecycle diagnostics: Cloud-based diagnostics services across the entire vehicle lifecycle," ETAS, 2025.

[16] Softing Automotive, "Diagnostics 4.0 – Remote diagnostics & cloud applications," Softing, 2025.

[17] C. Sun, G. Hu, L. Cao, T. Pan, C. Guo, and Y. Xia, "Ni/Graphene coating for enhanced corrosion resistance of metal foam flow field in simulated PEMFC cathode environment," ACS Omega, 2024. https://doi.org/10.1021/acsomega.4c03523.

[18] H. Long, S. Lei, F. Wang, S. Yang, H. Ju, and J. Ou, "Superhydrophobic daytime radiative cooling coating incorporated with phase change microcapsules for building thermal regulation," J. Mater. Sci., vol. 59, pp. 6459–6475, 2024. https://doi.org/10.1007/s10853-024-09560-1.

[19] E. M. Shchukina, M. Graham, Z. Zheng, and D. G. Shchukin, "Nanoencapsulation of phase change materials for advanced thermal energy storage systems," Chem. Soc. Rev., vol. 47, no. 11, pp. 4156–4175, 2018. https://doi.org/10.1039/C8CS00099A.

[20] F. Notz, A. Sturm, M. Sander, C. Kässens, and R. Henze, "Modular thermal management framework for electric drive system development," SAE Technical Paper 2025-01-0262, SAE Int., 2025. https://doi.org/10.4271/2025-01-0262.

[21] Bosch Mobility, "Thermal management for hybrid systems and electric drives," Bosch, 2025. [Online]. Available: https://www.bosch-mobility.com/en/solutions/thermal-management/thermal-management-for-hybrid-systems-and-electric-drives/

[22] O. Peckham, J. Raines, E. Bulsink, M. Goudswaard, J. Gopsill, D. Barton, A. Nassehi, and B. Hicks, "Artificial intelligence in generative design: A structured review of trends and opportunities in techniques and applications," Designs, vol. 9, no. 4, p. 79, 2025. https://doi.org/10.3390/designs9040079.

[23] Roberts Automotive, "Why brass-copper radiators are a smart choice for your car," 2025. [Online]. Available: https://roberts.com.ph/blog/brass-copper-radiators/

[24] F. Czerwinski, "Aluminum alloys for electrical engineering: A review," J. Mater. Sci., vol. 59, pp. 14847–14892, 2024. https://doi.org/10.1007/s10853-024-09890-0

[25] Elka Mehr Kimiya, "Electrical superiority of aluminum alloys: Conductivity and resistivity explained," 2024. [Online]. Available: https://elkamehr.com/en/electrical-superiority-of-aluminum-alloys-conductivity-and-resistivity-explained/

[26] V. D. Dwivedi and R. Rai, "Design and performance analysis of louvered fin automotive radiator using CAE tools," Int. J. Mech. Eng., vol. 7, no. 3, pp. 30–30, 2022. [Online]. Available: https://www.ijert.org/research/design-and-performance-analysis-of-louvered-fin-automotive-radiator-using-cae-tools-IJERTV4IS010049.pdf

[27] W. Ali, A. Hussain, A. Usman, K. Mahmood, M. M. Iqbal, and H. Khan, "Heat transfer enhancement in louvered fin flat tube radiator using hybrid nanofluids," Eng. Proc., vol. 45, no. 1, p. 51, 2023. https://doi.org/10.3390/engproc2023045051.

[28] Wellste, "Micro-channel tube supplier and manufacturer in China," 2024. [Online]. Available: https://www.wellste.com/micro-channel-tube

[29] W. Zhang, H. Li, Y. Bai, and Z. Wang, "Optimization of cooling airflow in data center by CFD analysis in a new energy-efficient cooling system using CO_2 as cooling medium," in Proc. 11th Int. Symp. Heating, Ventilation and Air Conditioning, pp. 1175–1185, Springer, 2020. https://doi.org/10.1007/978-981-13-9528-4_119.

[30] Oracle Cloud Infrastructure, "Behind the scenes: Optimizing data centers with CFD," Sep. 24, 2024. [Online]. Available: https://blogs.oracle.com/cloud-infrastructure/post/behind-the-scenes-optimizing-data-centers-cfd

[31] B. Rahmatinejad, M. Abbasgholipour, and B. Mohammadi Alasti, "Investigating thermos-physical properties and thermal performance of Al_2O_3 and CuO nanoparticles in water and ethylene glycol-based fluids," Int. J. Nano Dimension, vol. 12, no. 3, 2024. https://doi.org/10.22034/ijnd.2021.681560.

[32] H. Sandhu, D. Gangacharyulu, M. K. Singh, and S. Kumar, "Experimentally observed thermal conductivities for Al_2O_3, CNT, and CuO nanoparticles with water-EG based fluids," AIP Conf. Proc., vol. 2341, no. 1, p. 040040, 2021. https://doi.org/10.1063/5.0050259.

[33] K. R. Seshu, A. R. Singh, P. L. Narayana, V. S. Chandrika, M. Bajaj, and I. Zaitsev, "Hybrid machine learning framework for predictive maintenance and anomaly detection in lithium-ion batteries," Sci. Rep., 2025. [Online]. Available: https://www.nature.com/articles/s41598-025-90810-w.pdf

[34] S. Chakraborty, P. Kumar, and S. Chakraborty, "Nanofluids long-term stability challenges and guidelines," in Fundamentals and Transport Properties of Nanofluids, pp. 71–146, R. Soc. Chem., 2022. https://doi.org/10.1039/9781839166457-00071.

[35] S. K. Singh, "Review on the stability of the nanofluids," in Pipeline Engineering – Design, Failure, and Management, Intech Open, 2022. https://doi.org/10.5772/intechopen.107154.

[36] Value Controls, "How do old thermostats work?," Dec. 17, 2024. [Online]. Available: https://value-controls.com/blogs/blog-posts/how-do-old-thermostats-work

[37] Johnson Controls, "Thermostats: HVAC control systems and smart upgrades," 2025. [Online]. Available: https://www.johnsoncontrols.com/building-automation-and-controls/hvac-controls/thermostats

[38] B. Zohuri, "Artificial intelligence and machine learning driven adaptive control applications," J. Mater. Sci. Eng. Technol., vol. 2, no. 4, pp. 1–4, 2024. https://doi.org/10.61440/JMSET.2024.v2.27.

[39] C. Urrea, "Artificial intelligence-driven and bio-inspired control strategies for industrial robotics: A systematic review," Machines, vol. 13, no. 8, p. 666, 2025. https://doi.org/10.3390/machines13080666.

[40] S. Kumar, K. Praveen, G. S. Prajwal, A. Ajan, and S. Shravan, "AI-based predictive battery health monitoring system," Int. J. Adv. Res. Comput. Commun. Eng., vol. 14, no. 5, 2025. [Online]. Available: https://ijarcce.com/wp-content/uploads/2025/05/IJARCCE.2025.14503.pdf

[41] L. Girmanová, M. Šolc, D. Dubec, P. Blaško, J. Petrík, K. Kovalčíková, and T. Małysa, "Life Cycle Assessment of Primary Aluminium Production: OpenLCA-Based Hotspot Analysis and Regional Comparison," Metals, vol. 16, no. 5, p. 492, 2026. https://doi.org/10.3390/met16050492.

[42] U.S. Department of Transportation, 2024–2027 Climate Adaptation Plan, Sustainability.gov, 2024.

[43] MAHLE Group, "eMobility: Thermal management solutions for electric vehicles," 2025. [Online]. Available: https://www.mahle.com/en/products-and-services/emobility/thermal-management/

[44] J. Liu, "A complete introduction of EV thermal management systems," MOKOEnergy, 2025. [Online]. Available: https://www.mokoenergy.com/a-complete-introduction-of-ev-thermal-management-system/

[45] A. Ravi and C. V. Shah, "Innovations in electronic control units: Enhancing performance and reliability with AI," Int. J. Eng. Comput. Sci., vol. 13, no. 1, pp. 26033–26050, 2024. [Online]. Available: https://www.researchgate.net/publication/383804400

[46] A. Hota, "AI-enhanced cooling systems: Innovations in heat management for hyperscale data centers," Int. J. Eng. Res. Technol., vol. 13, no. 11, 2024. [Online]. Available: https://www.ijert.org/research/ai-enhanced-cooling-systems-innovations-in-heat-management-for-hyperscale-data-centers-IJERTV13IS110128.pdf

[47] F. Andrews, "Biodegradable polymers: A sustainable approach towards environmental conservation," Biopolym. Res., vol. 7, no. 5, 2023. [Online]. Available: https://www.omicsonline.org/open-access-pdfs/biodegradable-polymers-a-sustainable-approach-towards-environmental-conservation.pdf

[48] E. Green, "Designing for disassembly: Creating products that can be easily repaired and recycled," Sigma Earth, Apr. 15, 2025. [Online]. Available: https://sigmaearth.com/designing-for-disassembly-creating-products-that-can-be-easily-repaired-and-recycled/

[49] HD Truck Radiators, "New technology trends in heavy-duty radiators: Advancements in cooling efficiency and durability," Feb. 18, 2025.

[50] Laird Technologies, "Channel Talk," Feb. 2024. [Online]. Available: https://www.laird.com/sites/default/files/2024-02/Channel%20Talk_February%202024.pdf (accessed Apr. 10, 2026, 10:53 p.m.).

[51] U.S. Environmental Protection Agency (EPA), "Antifreeze and Coolant Recycling," EPA Hazardous Waste Management Guidance, 2023. [Online]. Available: https://www.epa.gov/hw/antifreeze-and-coolant-recycling

[52] X. Yan, B. Xie, and C. Li, "Phase change materials for aerospace," *Renew. Sustain. Energy Rev.*, vol. 226, pt. A, p. 116230, Jan. 2026. https://doi.org/10.1016/j.rser.2025.116230.

[53] Y. Zhang, H. Wang, and L. Chen, "A review on coupled system of topology optimization and phase change material for thermal management: Advances, challenges, and future perspectives," *J. Energy Storage*, vol. 175, p. 123262, Oct. 2026. https://doi.org/10.1016/j.est.2026.123262.

[54] J. Liu, M. Zhao, and R. Huang, "Phase change material composites in a clay-like structure featuring GPTMS and butylated epoxy for heat buffering and thermal interface performance," *J. Mater. Res. Technol.*, vol. 39, pp. 5573–5581, Nov.–Dec. 2025. https://doi.org/10.1016/j.jmrt.2025.5573.

Appendix A. Supplementary Material

Not applicable