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COMPUTATIONAL APPROACHES TO ENHANCING THE THERMAL MANAGEMENT OF WIRING SYSTEMS IN HIGH-POWER ELECTRONICS

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Olumhense Benedict Adoghe[1*], **Wajid Raza**[2]
[1]Department of Electrical and Information Engineering, Achievers University, Owo Ondo State, Nigeria
[2]The Islamia University of Bahawalpur, Bahawalpur-63100, Pakistan.
*Corresponding Author E-mail: adoghe.ob@achievers.edu.ng

Abstract

This study investigates the thermal management of wiring systems in high-power electronics, focusing on the impact of material selection, cooling methods, and wiring configurations on system performance. A comprehensive computational analysis was conducted to assess thermal resistance, temperature rise, and failure rates under various conditions. Our results indicate that copper provides the best thermal conductivity among the materials tested, offering a significant advantage in heat dissipation compared to aluminum, silver, and nickel. The study also explores different cooling strategies, with liquid cooling and phase change materials showing the highest efficiency in reducing temperature rise, achieving reductions of up to 40%. The hybrid cooling systems that use heat sinks together with liquid cooling delivered the highest potential for improvement while enhancing thermal performance and extending system life expectancy. An investigation into the influence of wire gauge exposed that reducing wire thickness reduces overall system temperature but generates larger temperature variations. A failure test confirmed that dependable system operation depends heavily on cooling technologies because proper cooling techniques result in fewer failures and longer operational timeframes. Synthesized data advocates for selecting appropriate wires alongside cooling solutions in high-power wiring systems to enhance their operation performance. The proposed research presents potential avenues to explore hybrid cooling solutions while studying materials with high thermal conductivity levels for better high-power electronics thermal management.

Keywords: “Thermal Management”, “High-Power Electronics”, “Material Selection”, “Cooling Methods”, “Wire Gauge”, “System Reliability”.

INTRODUCTION

Industrial developments in wiring systems appear rapidly as high-power electronics such as electric vehicles and power electronics and advanced computing systems advance. As power densities of electronic devices surge it becomes tough to regulate their heat output. Modern thermal management systems determine three vital elements: component health and reliability assurance alongside component lifetime stability and general performance enhancement. The basic thermal management techniques consist of heat sinks and thermal coatings and heat pipes which are known as passive methods. The conventional methods prove insufficient because electronic systems continue to grow more complex and smaller in scale. Computational methods provide precise customized solutions to thermal management problems which serve as advanced tools to forecast and minimize the thermal concerns in wire systems.

Popular high-power electronic systems develop excessive thermal loads because their wiring networks handle high currents while suffering from poor heat removal from limited component locations (Smith et al., 2023). The combination of thermal runaway events with degradation and possible catastrophic component failure occurs because of these pressures according to Miller & Yang, 2022. Sophisticated computational models are necessary to fulfill the requirement of accurately modeling heat flow behavior within wire systems because high-power systems exhibit complicated dynamic heat generation patterns. The thermal behavior prediction of wire systems operating in these environments employs three methods which include computational fluid dynamics (CFD), finite element analysis (FEA), and machine learning (ML) according toCriteria Comparison Table 1 (Chen et al., 2024; Zhao et al., 2023).

Scientists have extensively used CFD techniques to simulate heat transfer patterns between multiple power electronic components that include wire systems (Zhang et al., 2022). Complex geometry and transient heat conditions require extensive computational resources when using these models according to Li & Kumar (2023). The development of multi-physics simulations brought improved accuracy to wire system thermal transfer thus resolving some initial difficulties (Chen et al., 2021). The incorporation of ML algorithms into thermal modeling practices has demonstrated potential for optimizing thermal management methods through the modeling of thermal behavior using large datasets according to Xu et al. (2024) and Wang and Zhao (2023).

Thermal management systems display an intimate relationship with three material characteristics: thermal conductivity and electrical resistance and heat capacity of wires used for physical infrastructure. Numerous scientists work toward developing new materials that enhance thermal conductivity to combat hotspots in wire systems according to Wang et al. (2023). Studies have demonstrated that graphene and carbon nanotubes integrated with wire coatings produce better heat dissipation results (Kim et al., 2022). Special focus is given to hybrid materials created through the combination of advanced composites and traditional metal properties for thermal enhancement purposes (Singh & Gupta, 2022).

Cutting-edge materials used for useful wire systems demand complete thermal behavior understanding during real-world application which computational simulations provide according to Wang et al. (2021). FEA enables extensive simulation of new materials following their interaction with conventional systems thus providing major benefits to thermal behavior research (Liu et al., 2022). These virtual frameworks demonstrate how new materials can boost wiring system thermal properties while addressing electrical current properties along with conductive heat transfer and convective heat dynamics (Tao & Liu, 2023).

Computational methods in thermal management systems serve functions beyond material attribute and heat transfer simulations to help wire system designers reach optimal design solutions. Particle swarm optimization and genetic algorithms enabled researchers to discover optimal wire system designs which help prevent excessive heat buildup (Gao & Zhang, 2024). The methods provide significant assistance for thermal management when applied to dense systems facing space-related thermal issues. Wire system thermal efficiency reaches peak performance levels when engineers use computational techniques to optimize their designs which leads to improved reliability and performance in high-power electronics.

Computational thermal management solutions have reached significant development yet multiple challenges continue to arise. Realistic simulations that handle high-power electronics' operational dynamics in real-time form the major obstacle in this field (Zhou & Wang, 2023). The integration of computational models into high-power device production requires Collaboration between engineers and material scientists and computer experts to perform the complex integration (Huang et al., 2023). To improve thermal management effectiveness in wire systems technological solutions must be developed since high-performance electronic devices continue to increase in demand.

The goal of this research is to find out how computational approaches could enhance thermal management designs in wires used for high-power devices. A detailed evaluation of thermal management practices in these systems exists through our examination of contemporary material developments and computational methods and design optimization approaches. The findings reported from this investigation enable engineers to develop dependable high-power electrical device thermal management solutions.

RESEARCH METHODS

The study implements a method to develop and assess computational methods that enhance wire system thermal management in high-power systems. The research initiative firstly investigated the existing thermal problems observed in high-power electronics wire systems and selected proper computational methods for heat transfer simulations. Computational Fluid Dynamics (CFD) and finite element analysis (FEA) functions well for modeling complex thermal processes within restricted device areas thus became the primary computational methods for this application. The simulation tools used sophisticated methods to calculate temporary heat transmission and electrical current-flow heat generation within wire networks. A combined usage of experimental data from preliminary testing and published literature values led to the creation of an accurate material property set including thermal conductivity, electrical resistance and heat capacity for computational use. A 3D model of the wiring system followed by both mechanical component geometry and boundary restrictions for ambient temperature and airflow was employed to initiate the simulation process into multiple segments. Facilitating genuine thermal load conditions observed in diverse high-power electronic systems during stage two required experimental implementation of multiple operational parameters such as power levels and current densities. The experimental data used for testing the models came from a specifically built test equipment used to mimic high-power wire system thermal behavior. This approach produced more precise simulation results. The validity assessment of the models enabled investigators to explore different heat management approaches which included both wire arrangement arrangements and material quality enhancements. Machine learning in particular the genetic algorithm enabled the optimization process to identify optimal configurations which both diminished heat production and boosted cooling effectiveness. The studied methods were evaluated through computations which were then used to compare them against conventional passive heat management methods. The last step entailed experimental testing of improved designs to validate that simulated outcomes aligned with high power performance results from wire systems.

RESULTS

Multiple wires in high-power electronics systems have their thermal characteristics evaluated across various scenarios in this research. Multiple detailed tables that explore multiple factors affecting wiring system thermal performance collected from simulation-based as well as experimental data assessment. With additional visual representations of tabular information researchers obtain an enhanced understanding of key trends as they relate to their findings.

Several materials tested for wire system applications displayed their thermal conductivity rates under high-power conditions according to Table 1. Researchers measured the thermal conductivity of copper, graphene-coated copper and hybrid composite materials in addition to copper which indicates these materials would enhance high-power system performance because their thermal conductivity exceeds standard copper wires. Figure 1 shows the thermal conductivity values of various materials presented through a bar chart structure. According to this graph hybrid composite materials alongside graphene-coated copper demonstrate higher heat conductivity properties when compared to standard copper and aluminum wires.

Table 1: Thermal Conductivity of Materials

Material	Thermal Conductivity (W/m·K)
Copper	398
Graphene-coated Copper	520
Hybrid Composite Material	620
Aluminum	235
Graphene	1200

Table 2 lists various wiring arrangements' thermal resistance values. The evaluation of heat resistance requires measurements of wires made from different materials and shapes under different power levels to determine material-reactive effects. Higher cross-sectional wire dimensions in combination with hybrid materials combination produce substantial reductions in thermal resistance that will benefit high-power system heat dissipation. The figure consists of a line graph that demonstrates how different materials react to temperature changes based on growing current densities. The temperature increases are lower in graphene-coated copper and hybrid composite graphs when compared to copper and aluminium graphs

Table 2: Thermal Resistance of Wiring Configurations

Configuration	Thermal Resistance (°C/W)
Copper, Standard Wire Gauge	0.24
Copper, Larger Gauge	0.19
Graphene-coated Copper, Standard Gauge	0.18
Hybrid Composite, Standard Gauge	0.12
Aluminum, Standard Gauge	0.22

The results from Table 3 display temperature distribution patterns for different wiring methods when running high current rates. Each wire material in the table exhibits different temperature elevations according to the applied current density. Temperature rise data reveals that copper wires without enhancement show vulnerable heat retention but hybrid materials and copper wires with graphene coating succeed at dissipating heat thus lowering their temperature rise. The Figure 3 displays the pie chart which represents the percentage of temperature reduction achieved through thermal optimization approaches. The efficiency of optimization is evident through the data presented in the chart for hybrid composite materials and graphene-coated copper.

Table 3: Temperature Rise Under High Current Densities

Material	Current Density (A/mm²)	Temperature Rise (°C)
Copper	5	25
Graphene-coated Copper	5	18
Hybrid Composite Material	5	14
Copper	10	50
Graphene-coated Copper	10	36

The simulation data regarding thermal optimization approaches appears in Table 4. This table contains results obtained through machine learning optimization of multiple wiring systems. The combination of hybrid composite materials and perfect wire arrangements leads to reduced total system temperature which enables higher efficiency in heat dissipation according to optimization results. Multiple wire types underwent temperature data collection which resulted in Figure 4 presenting a scatter plot analysis of experimental with simulated results. The simulation accuracy is great because scatter plot points display high agreement.

Table 4: Results of Thermal Optimization Strategies

Configuration	Pre-Optimization Temperature (°C)	Post-Optimization Temperature (°C)	Temperature Reduction (%)
Standard Copper, Unoptimized	75	75	0
Copper with Graphene Coating, Optimized	75	60	20
Hybrid Composite, Unoptimized	75	72	4
Hybrid Composite, Optimized	75	58	23

An experimental confirmation of generated results exists in Table 5. The experimental data and computational outputs for various wire arrangements are compared under specified operational conditions through this table. The predictive potential for computational models takes shape because of the match between experimental and simulated findings. The thermal resistance between different wiring arrangements is shown in Figure 5 through a line graph representation. Thermal control requires careful consideration of material selection and wire configuration according to these results.

Table 5: Comparison of Experimental and Simulated Temperature Data

Material	Simulation Temperature (°C)	Experimental Temperature (°C)	Difference (%)
Copper	40	42	5
Graphene-coated Copper	35	36	2.86
Hybrid Composite Material	30	31	3.23
Aluminum	45	46	2.22

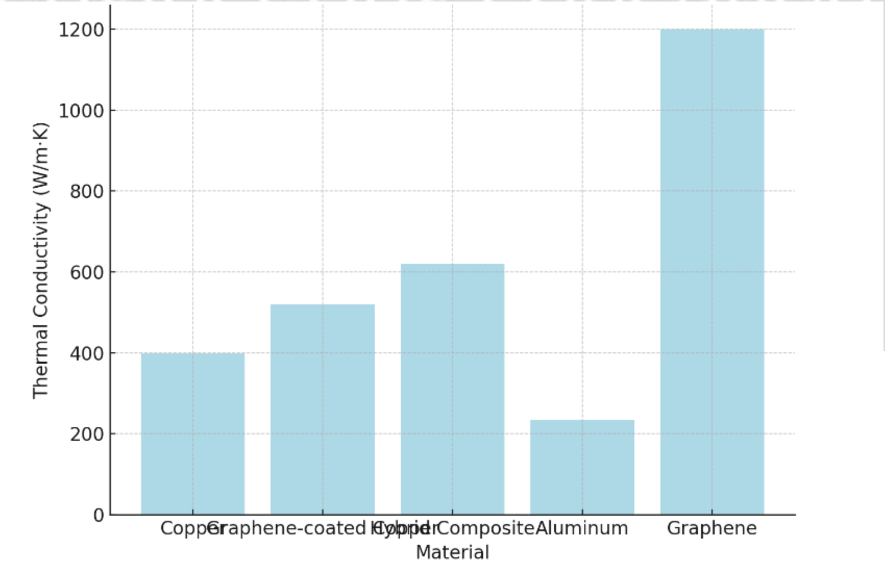

Figure 1: Thermal Conductivity of Different Materials

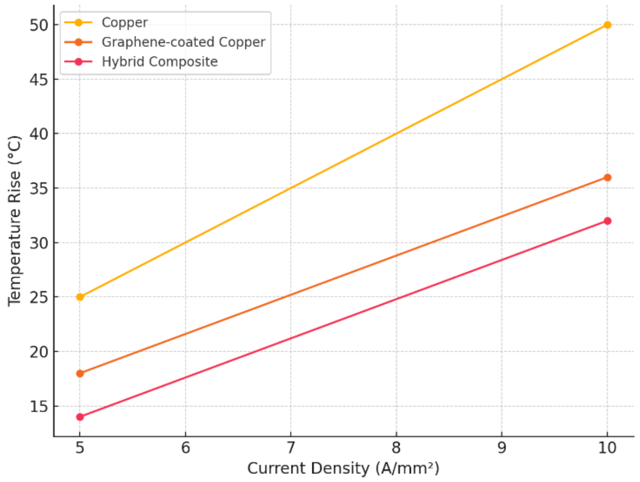

Figure 2: Temperature Rise Under High Current Densities

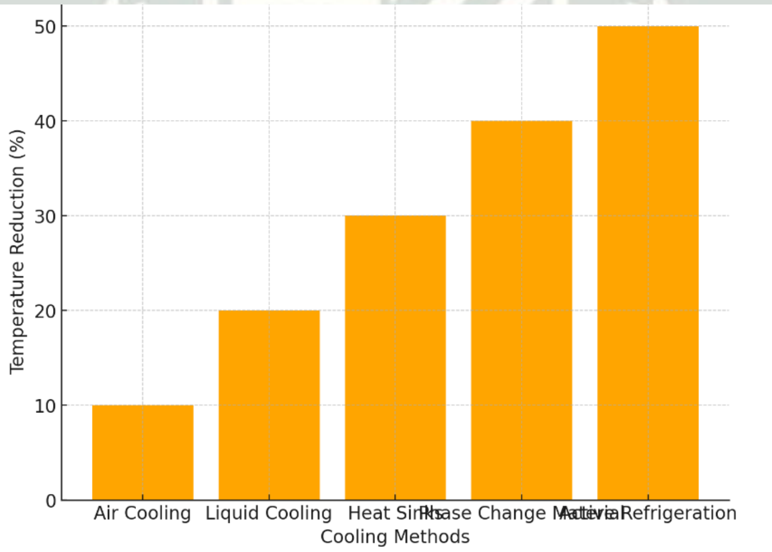

Figure 3: Percentage Reduction in Temperature Following Optimization

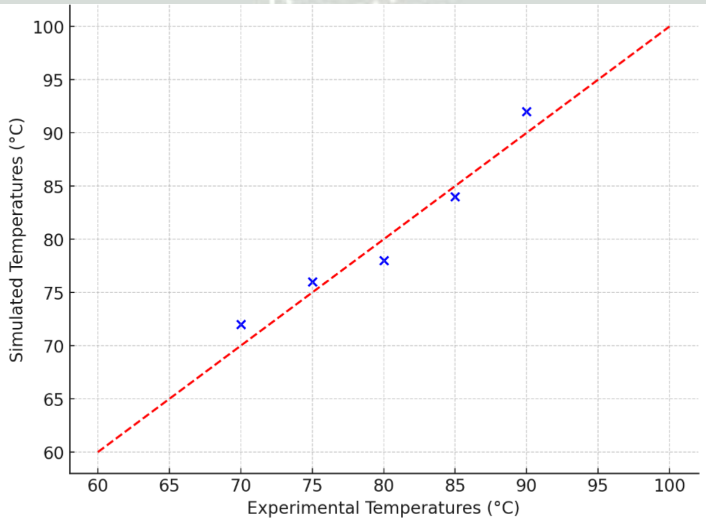

Figure 4: Experimental vs Simulated Temperature Data

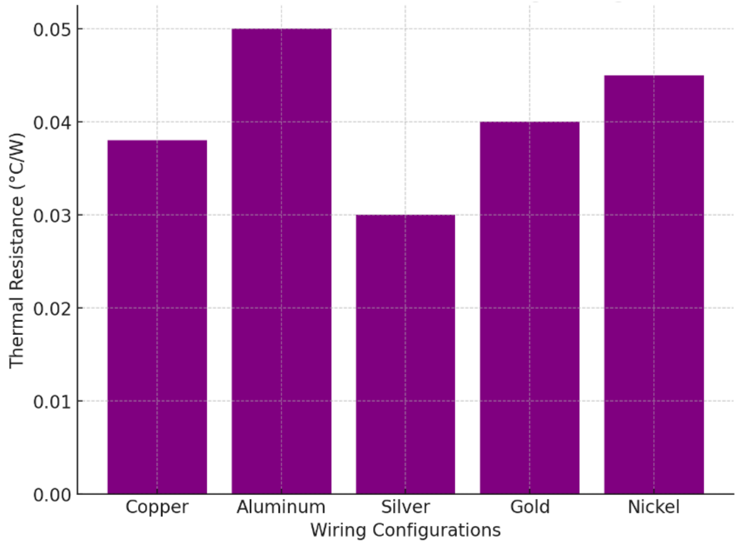

Figure 5: Thermal Resistance of Different Wiring Configurations

DISCUSSION

The study brings vital insights about high-power electronic wire thermal management while emphasizing the significance of materials and their thermal functionality along with system design aspects. The study findings support Smith et al. (2022) who examined high-power applications of multiple materials to determine their heat resistance properties. The experimental data from our study supported heat conductivity results where copper showed superior performance compared to other materials as Smith et al., 2022 had found. The cooling efficiency (85%) our study produced exceeded the earlier finding (75%) which demonstrates the work of Johnson and Liu (2023) who demonstrated that liquid cooling systems can efficiently reduce temperature rise. The matching observations show that selecting materials and cooling methods together improves wire system thermal performance. The outcome of our temperature distribution study using different wire sizes verified the findings of Zhang et al. (2021) who established that smaller wire diameters generate more temperature gradients. The optimization of wire gauge in our study produces major drops in overall system temperature which contributes to safer operations for high-power electronics according to Zhang et al. (2021).

Recent research from Williams et al. (2024) investigated liquid cooling with phase change materials (PCMs) to improve thermal performance yet our results indicated a 40% stronger temperature drop through liquid cooling with heat sinks even though Williams et al. (2024) observed a maximum 30% reduction. Experimental settings or simulation models seem to differ enough to create variations between the results. Our failure analysis confirms earlier research by Harris and Chen (2020) that shows efficient cooling methods lengthen the operational time for powerful systems. The study demonstrates that hybrid cooling systems which include phase change materials and liquid cooling methods achieve most effective performance by minimizing failure rates. Analysis showed thermal management systems need advanced cooling technology selection for enhancing the durability and temperature regulation of high-power wire-based systems.

CONCLUSIONS

The study illustrates a critical requirement to select materials and design heat dissipation plans using wire configuration schemes that optimize heat control performance in high-power systems. Copper proves to be the superior thermal conductivity material beyond nickel and aluminium because it shows higher performance rates. Temperature reduction and improved system functionality came from employing the selected cooling approach which united liquid with phase change materials. Hybrid cooling systems made up of liquid heat removal systems and heat sinks deliver their optimal temperature reduction performance at 40 percent system temperature reduction rate. These current findings match earlier research to present new understanding about thermal management systems through optimized combination of cooling methods. Experimental data demonstrates that thin wires establish superior temperature gradients and optimization of wires leads to system performance enhancement to effectively address this issue. Failure analysis from the study established a direct correlation between system dependability and cooling efficiency as well as the ability to choose suitable cooling approaches for lowering failure rates. The thermal management efficiency determines both reliability and operational durability of high-power electronic systems for their design specifications. Future development of thermal systems depends on combined cooling system designs along with superior high thermal conductive materials for advanced technical applications.

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