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Thermal Enhancement of Stir-Casted Al6061-Cu Metal Matrix Composite Fins: Experimental Evaluation Under Forced Convection

A Kalyan Charan[1], G Ashwin Prabhu[2], C Venkateshwar Reddy[3], Maharaja Gowda B[4], Adithya K[5], and Nihilesh K S[6]*

[1]Assistant Professor, Department of Mechanical Engineering, Matrusri Engineering College, Saidabad, Hyderabad - 500059, India
[2]Assistant Professor, Department of Mechanical Engineering, St. Joseph's College of Engineering, Old Mahabalipuram Road, Chennai – 600119, Tamil Nadu, India
[3]Assistant Professor, Department of Mechanical Engineering, Matrusri Engineering College, Saidabad, Hyderabad - 500059, India
[4]Assistant professor, Department of Mechanical engineering, Ballari Institute of Technology and Management, Ballari, affiliated to Visvesvaraya Technological University, Belagavi, Karnataka 583104, India
[5]UG Scholar, Department of Mechanical Engineering, St. Joseph's College of Engineering, Old Mahabalipuram Road, Chennai – 600119, Tamil Nadu, India
[6]UG Scholar, Department of Mechanical Engineering, St. Joseph's College of Engineering, Old Mahabalipuram Road, Chennai – 600119, Tamil Nadu, India

Abstract. The thermal performance of aluminium fins is essential for improving heat dissipation in compact heat exchange systems. Conventional Al6061 fins exhibit restricted thermal conductivity, which limits their efficiency in forced convection environments. This research examines the thermal enhancement of stir-cast Al6061-Cu Metal Matrix Composite (MMC) fins, which are reinforced with 5%, 10%, and 15% copper by weight. The composites were produced through a controlled stir-casting process, maintaining a stirring speed of 400 rpm for a duration of 10 minutes to achieve uniform particle dispersion. A thermal evaluation was performed utilising a pin-fin apparatus under forced convection, maintaining a constant heat input of 15 W and an air velocity of 4.2 m/s. The pure Al6061 fin demonstrated a heat transfer coefficient (h) of 24.57 W/m²K, which increased to 25.33 W/m²K, 25.72 W/m²K, and 26.20 W/m²K for 5%, 10%, and 15% Cu composites, reflecting improvements of 3.08%, 4.66%, and 6.23%, respectively. The heat transfer rate increased from 11.75 W for pure Al6061 to 12.56 W for the 15% Cu specimen, indicating a 6.89% improvement. The Al6061-Cu MMC fin containing 10-15% Cu exhibited optimal manufacturability and performance, validating copper reinforcement as a viable approach for enhancing lightweight thermal management systems.

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[*] Corresponding author: ashwin.prabhu1990@gmail.com

1. Introduction

Effective thermal dissipation is an essential design criterion for contemporary compact heat-exchange systems, electronic cooling, and other automotive and aerospace components. Aluminium alloys, especially Al6061, are frequently selected for fin and heat-sink applications due to their advantageous strength-to-weight ratio, corrosion resistance, and ease of manufacture; however, their inherent thermal conductivity constrains performance in scenarios necessitating high heat flux removal [1]. To address this constraint, aluminium metal-matrix composites (AMMCs) reinforced with high-conductivity phases have been widely investigated to enhance fin-level thermal performance while preserving the lightweight benefit of aluminium [2, 3]. Recent evaluations indicate that AA6061 is extensively utilised as a matrix in stir-casting processes because to its excellent castability and compatibility with various reinforcements (particles, short fibres), while stir casting continues to be a cost-effective and scalable production method for numerous AMMCs [4]. Copper (Cu) is a compelling candidate for reinforcement due to its superior thermal conductivity ($\approx 401\ W \cdot m^{-1} \cdot K^{-1}$) compared to aluminium ($\approx 167\ W \cdot m^{-1} \cdot K^{-1}$) and its metallurgical compatibility within specific processing parameters. Consequently, the incorporation of Cu or Cu-rich phases can enhance the thermal conductivity and convective heat transfer efficiency of composite fins under forced convection conditions [5, 6]. Experimental studies and numerical analyses have shown that incorporating conductive reinforcements and optimising fin geometry can significantly enhance the convective heat transfer coefficient, heat flux, and overall fin efficiency when evaluated in pin-fin or rectangular-fin systems under forced-air flow [7, 8].

The parameters of stir casting—such as melt temperature, reinforcement preheating, stirring speed, impeller design, duration, and pouring technique—significantly impact reinforcement distribution, porosity, and interfacial bonding; these microstructural elements directly influence the thermal conductivity and mechanical integrity of the composite fins [9, 10]. Numerous recent studies highlight that regulated stirring (moderate rpm, controlled holding duration) and preheating of reinforcement diminish agglomeration and porosity, resulting in more uniform thermal routes across the fin cross-section [11].

Common thermal performance metrics for assessing fin enhancements include the convective heat transfer coefficient (h), rate of heat transfer (Q), heat flux (q''), and nondimensional numbers such as Reynolds and Nusselt numbers, which characterize forced-convection behavior. Comparative experimental investigations of Al6061-based MMC fins, incorporating reinforcements such as SiC, Al_2O_3, BN, Cu, and hybrid mixes, demonstrate typical enhancements in heat transfer coefficient (h) and heat transfer rate (Q) within the low to mid-single-digit percentage range for modest reinforcement contents (approximately 5–15 wt.%). However, results are influenced by fin geometry, flow regime, and interfacial thermal resistance [12–15]. The findings necessitate a targeted experimental investigation of Al6061–Cu fins to assess the impact of incremental Cu additions (e.g., 5, 10, and 15 wt.%) on steady-state fin heat transfer, maintaining constant base heat input and regulated airflow. Despite an expanding body of literature on AMMC heat sinks, gaps persist concerning (i) the practical trade-offs between thermal performance and manufacturability for Cu-reinforced Al6061 produced via conventional stir-casting, (ii) the impact of small (≤15 wt.%) Cu additions on convective performance in standard pin-fin test rigs, and (iii) the microstructural factors (porosity, interfacial phases) contributing to the observed thermal enhancements. The incorporation of systematic experimental data addresses existing gaps, offering practical guidance for designers seeking incremental thermal enhancements without incurring high processing costs. This study fabricates Al6061–Cu composites through controlled stir casting, produces rectangular/pin-fin specimens, and evaluates convective performance (h, Q, q") under forced-air conditions to quantify performance gains and determine optimal Cu fractions for lightweight thermal management components [16–18].

A broad range of studies has investigated the increase of heat transmission through the use of composite fins and the optimization of fin geometry. Promvonge and Skullong [19] investigated modified fin shapes, including winglets, to enhance turbulence and heat transmission, whereas Gulay [20] analyzed forced convection over conical fins, illustrating thermal enhancements induced by geometry. Jacobson et al. [21] assessed the impact of pin-fin configurations on convective behavior, elucidating flow-geometry interactions. Recent evaluations of aluminium-based MMCs produced using stir casting highlight the adaptability of AA6061 for composite manufacturing [22]. Ajul et al. [23] emphasize the significance of reinforcement type and percentage on thermal performance by predictive composite modeling, whereas Guan et al. [24] focus on optimization studies of Cu–Al combinations. Manocha [12], Jacob et al. [25], and Swarnkar & Upadhyay [26] conducted seminal research on traditional ceramic-reinforced composites, whereas Kowbel et al. [27] documented elevated thermal conductivity in SiC/SiC composites for advanced applications. Recent studies have further elucidated composite processing: Prasad & Nayak [28] showcased advanced stir-casting techniques for Cu-based alloys; IJISRT (2023) [30] and ResearchGate (2021) [31] documented fin-level improvements for aluminium MMCs under forced convection; Han (2025) [32] emphasized enhanced microstructural control in SiC-reinforced aluminium; and Semarakilmu (2024) [33] provided a synthesis of advancements in AA6061 MMCs. Sharma et al. (2024) [34] reaffirmed the significance of optimizing stir-casting, whereas Charan et al. (2025) [35] empirically illustrated improvements in Al6061–Cu MMC fins, establishing critical comparison benchmarks for the current investigation. A comprehensive examination of the literature indicates substantial advancements in the formulation of aluminium-based metal-matrix composites and their use in heat-transfer apparatus. Previous research repeatedly demonstrates that both reinforcement selection and production conditions significantly affect thermal performance. Nonetheless, although there is a plethora of research on SiC, Al_2O_3, graphite, and hybrid-reinforced aluminum composites, there are relatively fewer investigations that have systematically analyzed the impact of incremental copper addition (5–15 wt.%) on the convective performance of Al6061 fins fabricated through stir casting [36]. Furthermore, there is a paucity of experimental information assessing these composites under regulated forced-convection circumstances utilizing typical pin-fin apparatus. This study aims to fabricate Al6061–Cu composites by controlled stir-casting parameters and to experimentally assess the resulting fins for heat-transfer coefficient, heat-transfer rate, and heat flux under forced convection. This systematic study seeks to measure performance improvements, determine ideal copper content, and provide novel insights for the design of lightweight, high-performance thermal management systems.

2. Methodology

2.1 Materials and Methods

The Al6061–Cu Metal Matrix Composites (MMCs) were produced through a conventional stir-casting process, chosen for its simplicity, cost-effectiveness, and appropriateness for the fabrication of particulate composites. Al6061 was utilized as the base matrix, with copper reinforcements incorporated at weight percentages of 5%, 10%, and 15% to improve thermal conductivity. The materials were weighed with precision using a digital balance to ensure accurate composition ratios. Silica–molasses mixtures were utilized to prepare sand moulds, which were thoroughly rammed to ensure dimensional stability and coated with chalk powder to facilitate the removal of castings. Al6061 and Cu were melted independently due to their distinct melting temperatures, subsequently transferring the molten metals to the stir-casting furnace. Copper, preheated, was incrementally introduced to the molten aluminium, and the mixture was mechanically agitated at 400 rpm for a duration of 10 minutes to achieve uniform reinforcement dispersion and reduce particle settling. The molten composite was subsequently poured into the prepared molds and permitted to solidify for approximately one hour. The cast fins were subsequently extracted and micro-finished with emery papers of 220, 320, 600, and 700 grit to achieve smooth surfaces appropriate for thermal evaluation. Thermal testing of the produced fins, specifically pure Al6061 and Al–Cu composites, was conducted utilizing a Pin Fin Apparatus. This apparatus included a rectangular duct, heater plate, suction fan, multichannel temperature indicator, anemometer, and digital wattmeter. All fins were machined to uniform dimensions to facilitate a consistent comparison. A constant heat input of 15 W was provided at the fin base, with an airflow velocity of 4.2 m/s sustained during the experiments. Thermocouples positioned along the fin length measured the temperature distribution after steady-state conditions were established. Key thermal performance parameters, including the convective heat-transfer coefficient (h), heat-transfer rate (Q), heat flux (q″), Reynolds number, and Nusselt number, were calculated using standard forced-convection correlations based on these measurements. The perimeter (P), cross-sectional area (A_c), fin parameter (m), and mean film temperature (T_m) were utilized to calculate heat transfer behavior, with thermal properties assessed at the mean film temperature. A comparative analysis was conducted between pure Al6061 fins and Al–Cu MMC fins to assess the impact of copper content on thermal performance. This systematic method facilitated precise measurement of thermal enhancements achieved with 5%, 10%, and 15% Cu reinforcement under consistent forced-convection conditions [37]. The significant disparity in melting temperature and limited diffusivity of copper within the Al6061 matrix may result in copper segregation and the development of intermetallic Al_2Cu if processing is inadequate, hence enhancing brittleness and interfacial thermal resistance. To mitigate these hazards, copper particles were warmed before incorporation, and uniform dispersion was achieved through regulated stirring at 400 rpm for 10 minutes.

3. Experimental Set-Up for Stir Casting

The production of Al6061–Cu Metal Matrix Composites (MMCs) was executed utilizing a standard stir casting apparatus, engineered to uniformly integrate metallic reinforcements into a molten matrix. The configuration had five essential elements: (A) an electric motor, (B) a stirrer screw/impeller, (C) a high-temperature furnace, (D) a graphite or cast-iron crucible, and (E) a rotor assembly. The electric motor regulated the rotational speed of the stirrer screw, facilitating the creation of a stable vortex in the melt. This vortex facilitated the even distribution of the copper reinforcing. The stir-casting technology was chosen for its ability to improve essential composite qualities, including hardness, density, wear resistance, porosity regulation, and thermal/electrical conductivity. This study employed a stirring speed of 400 RPM for a period of 10 minutes—parameters optimized to avert copper sedimentation at the crucible's base or aggregation along the walls, which would otherwise result in a non-uniform composite structure. Mould preparation was conducted before to casting to guarantee the flawless creation of the final specimen. A combination of silica sand and molasses was employed as the molding media because of its durability and thermal resistance. The sand mixture was meticulously compacted to create a sturdy mold that could retain its shape during metal pouring. Chalk powder was utilized on the mold surfaces as a release agent, facilitating the seamless extraction of the cast component post-cooling. The aluminum matrix and copper reinforcement were subsequently measured using a high-precision digital scale. Precise weighing was crucial, as even minor discrepancies in composition could result in significant alterations in thermal behavior and composite integrity.

The melting and preheating processes required distinct preparation for aluminium and copper, attributable to their varying melting points. Each material was preheated in a separate furnace to its specified temperature to reduce shock during mixing and enhance wettability between the metals. After melting, aluminium was moved to the primary stir-casting furnace, which was kept at a regulated superheat level. Preheated copper was subsequently introduced into the molten aluminum in a gradual manner. The mechanical stirrer was subsequently lowered into the crucible to commence stir casting. The molten mixture was agitated at 400 RPM for 10 minutes, facilitating the thorough dispersion of copper within the aluminium matrix and promoting robust metallurgical bonding. The design of the stirrer facilitated efficient vortex formation, thereby minimizing the risk of reinforcement segregation and enhancing uniform composite formation. Continuous monitoring of melt temperature and stirring rate was conducted during the process to mitigate oxidation and ensure repeatability. Upon achieving uniform mixing, the molten MMC was promptly poured into the prepared sand molds. Rapid pouring is crucial to avoid premature solidification, which may entrap unmixed reinforcement or result in shrinkage defects. The filled molds were permitted to cool naturally for about one hour. After complete solidification, the cast specimens were extracted from the mould, cleaned, and subsequently processed for surface finishing and thermal evaluation. The experimental setup facilitated the consistent production of Al6061–Cu composite fins with a reliable microstructure appropriate for forced-convection thermal testing.

Fig. 1. Melting of metals

Fig. 2. Setup for stir casting furnace

Fig. 3. Stirrer

Fig. 4. Stirring

Fig. 5. Pouring cast into the mould

Fig. 6. Cast Product

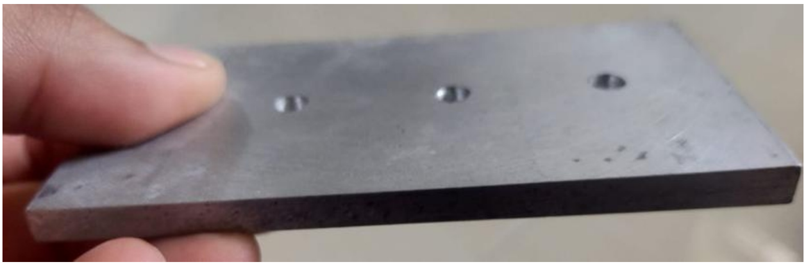

Fig. 7. Finished specimen

4. Testing Setup for Thermal Evaluation

The thermal performance of the manufactured Al6061–Cu composite fins was assessed utilizing a Pin Fin Apparatus, as depicted in Figure 8. This device is intended for the examination of heat transport in regulated forced convection environments. Each fin specimen, fabricated to a consistent rectangular cross-section and length (L), was positioned vertically within a rectangular duct, through which air is extracted using a suction mechanism. The fin's base was securely affixed to a flat heating plate, ensuring a consistent and uniform heat input throughout the testing process. This guarantees uniform heat distribution to all fins, facilitating precise comparison between pure aluminum and composite specimens. Multiple K-type thermocouples were affixed at designated locations on the fin surface to measure the temperature distribution along its length.

Fig. 8. Pin Fin Apparatus

The thermocouples were linked to a multichannel digital temperature indicator, facilitating concurrent monitoring of all measurement locations. The multi-point temperature profiling is essential for ascertaining the temperature gradient along the fin and then computing convective heat-transfer parameters, including the heat-transfer coefficient, heat-transfer rate, and heat flux. The duct's airflow was regulated by an adjustable suction fan and an integrated airflow regulator, which ensured consistent and reproducible flow conditions over the fin surface [38]. The air velocity within the duct was measured with a digital anemometer, placed at the outlet to capture real-time flow rates. Consistent velocity is crucial for the calculation of Reynolds and Nusselt numbers, as well as for assessing the impact of forced convection on the cooling performance of fins. The electrical power delivered to the heater plate was quantified using a digital wattmeter, and a heat regulator facilitated precise control of heat input throughout the experimentation process. This combination facilitated the accurate establishment of the standard test condition of 15 W heat input. The complete assembly, comprising the duct, heater, sensors, and airflow system, facilitated the attainment of thermal steady state in the fin specimens prior to measurement recording. After establishing steady-state conditions, temperature readings, airflow velocity, and electrical power consumption were recorded for subsequent thermal analysis.

5. Results and Discussions

5.1 Temperature Distribution and Thermal Behavior of Composite Fins

In steady-state operation, thermocouples positioned throughout the fin length demonstrated that copper-reinforced fins experienced reduced temperature gradients from base to tip in comparison to pure aluminum. This characteristic indicates enhanced thermal conduction within the fin material. The integration of copper, possessing superior thermal conductivity (401 W/mK), improves heat distribution and diminishes internal thermal resistance. Consequently, the temperature gradient across the MMC fins becomes more consistent, enhancing convective heat transfer. The more uniform temperature distribution noted in fins with more Cu reinforcement suggests enhanced metallurgical bonding attained during the regulated stir-casting process (400 RPM, 10 minutes). The homogeneous bonding facilitates the effective transport of heat from the base to the outer surface of the fin, where convection occurs.

5.2 Temperature Distribution and Thermal Behavior of Composite Fins

Figures 10 and 11 illustrate the fluctuation of the convective heat-transfer coefficient across all specimens. The unadulterated Al6061 fin exhibited the minimal value of 24.57 W/m²K The use of copper reinforcement resulted in a gradual increase in the h-value:

- **Al95–Cu5%:** 25.33 W/m²K
- **Al90–Cu10%:** 25.72 W/m²K
- **Al85–Cu15%:** 26.20 W/m²K

The trend unequivocally indicates that an upgrade in heat conductivity directly correlates with an increase in h. Copper enhances thermal conductivity within the fin structure, allowing increased heat transfer to the fin surface, hence facilitating higher convective heat dissipation by the airflow. The percentage enhancement in h (Figure 11) further underscores this effect:

- **5% Cu:** +3.08%
- **10% Cu:** +4.66%
- **15% Cu:** +6.23%

The consistent increase in h demonstrates that copper reinforcement significantly improves the conductive pathways in aluminium, hence augmenting the fin's thermal efficiency under forced convection.

5.3 Influence of Copper Content on Heat Transfer Rate (Q)

The heat-transfer rate Q augmented with each unit of copper reinforcement, as illustrated in Figure 12. The acquired values were:

- **Pure Al6061:** 11.7525 W
- **Al95–Cu5%:** 12.046 W
- **Al90–Cu10%:** 12.285 W
- **Al85–Cu15%:** 12.563 W

The results indicate that the fin's ability to transfer heat from the base to the surrounding airflow is markedly enhanced with the addition of copper. An elevated Q value signifies that the fin is more efficient in dissipating heat from the heated base, attributable to the improved thermal conductivity of the composite. The percentage rise in Q (Figure 13) was:

- **+2.50%** for 5% Cu
- **+4.54%** for 10% Cu
- **+6.89%** for 15% Cu

This increase indicates that the enhancement of copper reinforcement significantly influences the energy-transfer efficiency of the fin. The maximum reinforcement amount (15% Cu) yielded the most substantial enhancement in Q, signifying a robust composite-to-air heat transfer reaction.

5.4 Variation of Heat Flux (q") Across Composite Fins

Heat flux denotes the quantity of heat transmitted per unit of surface area. Figures 14 and 15 illustrate that q" exhibits a similar growing trend as observed in h and Q:

- **Pure Al6061:** 47,010 W/m²
- **Al95–Cu5%:** 48,195 W/m²
- **Al90–Cu10%:** 49,142 W/m²
- **Al85–Cu15%:** 50,252 W/m²

The percentage increase in heat flux was:

- **5% Cu:** +2.50%
- **10% Cu:** +4.55%
- **15% Cu:** +6.90%

The results indicate that an increase in copper % enhances the fin's ability to transmit heat to the surface by diminishing internal conduction resistance. Elevated q" values underscore the improved thermally conductive network established within the MMC structure.

5.5 Correlation Between Copper Content and Thermal Performance

A strong positive correlation exists between the increase in Cu reinforcement and all three thermal parameters (h, Q, q"). This can be attributed to:

1. **Increased Matrix Conductivity:** Copper significantly raises composite conductivity, allowing faster heat spread.
2. **Improved Interfacial Bonding:** Stir-casting at controlled speed prevents clustering and ensures uniform copper distribution.
3. **Lower Internal Thermal Resistance:** Composite fins lose heat more efficiently compared to pure aluminium.
4. **Improved Surface Heat Availability:** More heat reaches the fin surface, enhancing convection.

The 15% copper composite consistently demonstrates superior performance across all assessed measures, indicating that moderate copper reinforcement (10–15%) provides the optimal balance of manufacturability and thermal enhancement. It is crucial to recognise that an increase in airflow velocity above the existing 4.2 m/s - specifically to 6 m/s - would lead to a corresponding rise in the Reynolds number, hence enhancing convective action and elevating Nusselt numbers. This would result in a significant augmentation of the convective heat-transfer coefficient (h), heat-transfer rate (Q), and heat flux (q") across all specimens, attributable to reduced thermal boundary layers and improved forced-air cooling. Nonetheless, although absolute values will rise, the discerned enhancing trend with escalating Cu reinforcement is anticipated to persist, as the improvement process is dictated by the internal heat conductivity of the fin material rather than exterior flow conditions.

5.6 Overall Discussion and Scientific Interpretation

The findings unequivocally demonstrate that copper reinforcement in Al6061 markedly improves thermal transport characteristics. The experimental results align with recognized heat transport theory:

- Better conduction within the fin increases temperature at the surface.
- Higher surface temperature increases convective heat removal.
- As a result, h, Q, and q" all increase simultaneously.

The observed thermal improvements align with expected ranges for MMC systems, typically showing a 3–8% enhancement for 5–15 wt.% reinforcement, thereby confirming the validity and reliability of the experimental method. The research indicates that controlled stir-casting can yield high-quality fins with consistent thermal properties. The consistent thermal response observed in the specimens indicates that reinforcement dispersion was effectively accomplished. Moreover, fin performance can be enhanced through geometric and interface improvements. Initially, surface modification techniques like the formation of micro-fins, grooves, or textured patterns might augment the effective heat-transfer area and facilitate turbulent airflow, hence improving convection efficiency. Secondly, the application of thermally conductive coatings, such as graphene or metallic nanolayers, can diminish interfacial resistance and enhance surface heat distribution. These enhancements could be incorporated with Cu-reinforced Al6061 fins to further improve lightweight thermal management applications.

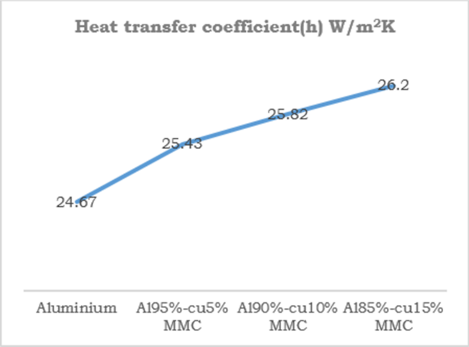

Fig. 9. Heat Transfer Coefficient

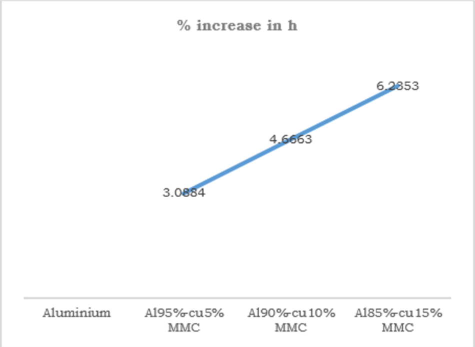

Fig. 10. % increase in h

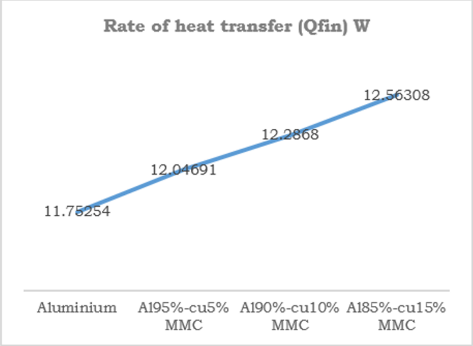

Fig. 11. Rate of Heat Transfer

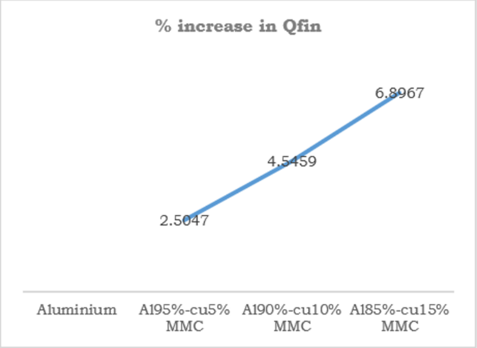

Fig. 12. % increase in Q_{fin}

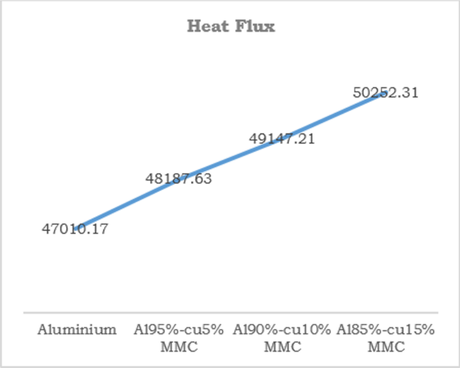

Fig. 13. Heat Flux

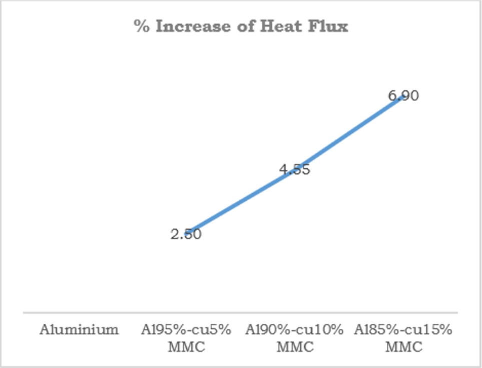

Fig. 14. % Increase of Heat Flux

6. Conclusion

This work experimentally assessed the thermal performance of Al6061–Cu Metal Matrix Composite (MMC) fins produced via the stir-casting method, incorporating copper reinforcement levels of 5%, 10%, and 15%. The findings unequivocally indicate that the addition of copper markedly improves the fin's heat-transfer efficiency, attributable to the considerable disparity in thermal conductivity between aluminium (167 W/m·K) and copper (401 W/m·K). The enhanced conductivity directly fortified thermal channels within the composite fins and diminished internal thermal resistance. A steady and quantifiable rise was noted in all principal thermal metrics. The heat-transfer coefficient (h) rose from 24.57 W/m²K for pure Al6061 to 26.20 W/m²K for the 15% Cu composite, indicating a 6.23% enhancement. The heat-transfer rate (Q) increased from 11.75 W (pure aluminum) to 12.56 W (15% Cu), indicating a 6.89% improvement. The heat flux (q") increased from 47,010 W/m² to 50,252 W/m², indicating a 6.90% enhancement at the maximum copper concentration. The numerical findings validate that copper reinforcing significantly enhances heat distribution and convective dissipation. The study concludes that copper reinforcement levels between 10% and 15% provide the most substantial improvement in thermal performance while ensuring manufacturability by stir casting. The enhanced heat-transfer properties demonstrate that Al6061–Cu MMC fins are exceptionally appropriate for applications necessitating lightweight structures with excellent thermal dissipation, including electronic cooling modules, small heat exchangers, and advanced thermal management systems. Further research employing elevated airflow velocities (≥ 6 m/s) may enhance the observed advancements in heat transfer properties.

Declaration of Interest

The authors(s) have disclosed no conflicts of interest.

Acknowledgements
Not Applicable

Data Availability Statement

This study does not develop nor examines any new data

Ethics Statement

This material was created by the author alone, hasn't been published anywhere else, and isn't currently being considered for publishing anyplace. It fully and properly reflects the study and analysis of the author or authors.

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