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Heat Transfer

Abstract

Heat transfer is the transfer of heat from one region to another, and it plays a critical role in day-to-day life and various engineering applications. Heat transfer comes in three forms known as conduction, convection, and radiation. Conduction is direct heat flow through physical materials, convection is heat flow through a fluid, and lastly radiation is heat flow through electromagnetic waves. This report presents an experimental analysis of the cooling performance of aluminum and acrylic plates under natural and forced convection. The experiment involved monitoring the cooling of the plates using thermistor-based temperature measurements and evaluating the heat transfer performance through dimensionless parameters. Relationships between $\ln(\theta)$ and τ were derived, leading to calculations of the Biot number (Bi) and convective heat transfer coefficient (h) for each scenario. The findings emphasize the critical influence of material properties and convection modes on thermal management, offering insights into designing efficient heat sinks for energy systems.

Introduction

Efficient heat transfer is a cornerstone of energy system performance, particularly for energy generation systems' heat sink components, specialized heat exchangers designed to cool down high-temperature systems or devices [1]. This study investigates the cooling performance of aluminum and acrylic plates under free and forced convection conditions to evaluate their suitability for thermal management applications. The experiment employs thermistor-based temperature sensors integrated with Arduino and MATLAB scripts to ensure accurate and automated data collection. Each experiment was repeated three times to account for variability, and results were averaged to enhance precision. Doing this gave results that validated aluminum's superior cooling performance, ultimately showcasing its effectiveness for high-efficiency heat sinks under forced convection. The thermal behavior of the plates was analyzed using the lumped capacitance model, which allows us to neglect thermal gradients in the plate and easily solve heat transfer differential equations, therefore leaving us with an assumption of uniform temperature distribution across the plate, which is a valid assumption when $Bi<0.1$ [2]. The following equations govern the experiment:

- **Dimensionless Temperature (θ)**:

$$\theta = (T - T_{\infty}) / (T_o - T_{\infty}) \qquad (1)$$

where T is the plate temperature, T_{∞} is the ambient temperature, and T_o is the initial plate temperature.

- **Dimensionless Time (τ)**:

$$\tau = kAt/\rho cdV \qquad (2)$$

where k is the thermal conductivity, ρ is density, c is specific heat capacity, and t is time.

- **Biot Number (Bi)**:

$$Bi = hL_c/k \qquad (3)$$

Where L_c is the characteristic length. The characteristic length L_c for two-sided convection is:

$$L_c = d/2$$

with d as the plate thickness.

The slope of ln(θ) vs. τ provides Bi, and the convective heat transfer coefficient (h) is calculated as:

$$h = slope\,.\,k\,/L_c \qquad (4)$$

The report aims to provide actionable insights for designing efficient thermal systems by evaluating material performance and the effect of convection modes on cooling rates. This will allow for a deeper understanding on the relationships between various parameters and their respective heat transfer rates.

Results

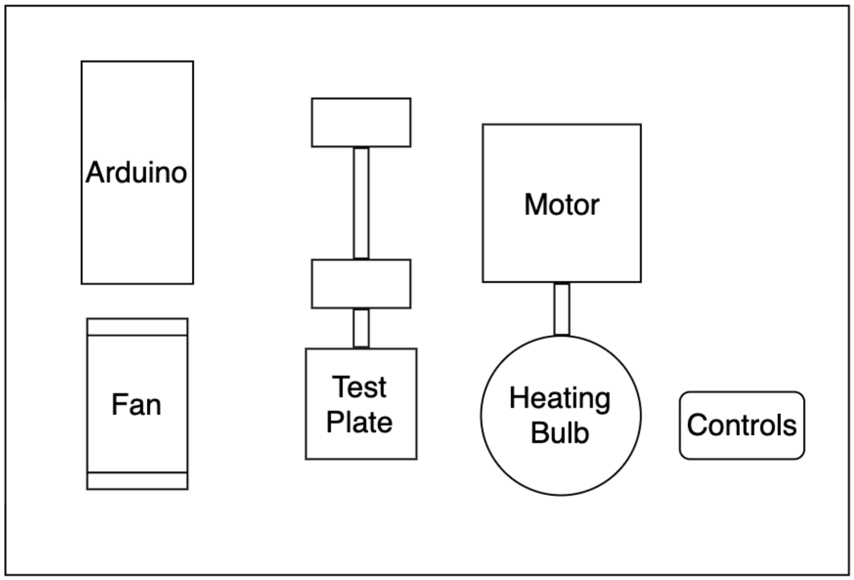

Figure 1*: Schematic diagram of the experimental setup for the heat sink cooling performance evaluation. A heating bulb is controlled by the motor and its respective controls, the bulb lands on the plate to heat it up and the fan is used for cooling. This is powered by the Arduino.*

In this experiment, cooling performances of aluminum and acrylic plates were analyzed under free and forced convection conditions in order to quantify how material properties and modes of convection influence cooling rates. This experiment was conducted with a simple experimental setup that consisted of an Arduino and Custom PCB that were used for controlling the system, an up/down controlled stepper motor and arm that held the heating bulb for heating, a test plate (aluminum or acrylic) that was to be heated or cooled, and a fan for cooling. In order to use this experimental setup to collect adequate data, four different cooling scenarios were considered, these scenarios had samples of either acrylic or aluminum with the convection mode set to either free or forced. Once the plates were heated and cooled, MATLAB was used to collect data regarding temperature and time. Each experiment was repeated three times to account for experimental variability, and the results were averaged to improve accuracy. The data collected included ambient temperature ($T\infty$), plate temperature (T), and time (t). Using the dimensionless parameters defined in Equations (1) and (2) in the introduction, the relationships between $\ln(\theta)$ and τ were plotted to evaluate cooling trends.

The $\ln(\theta)$ vs. τ plots for each experimental condition provide clear insights into the cooling behavior of the materials. For example, the plot for aluminum under free convection, shown in figure 1, demonstrates a smooth and consistent decay, indicative of efficient heat dissipation. In comparison, acrylic under free convection, shown in figure 2, displays a slower cooling rate with a less steep slope, reflecting its lower thermal conductivity.

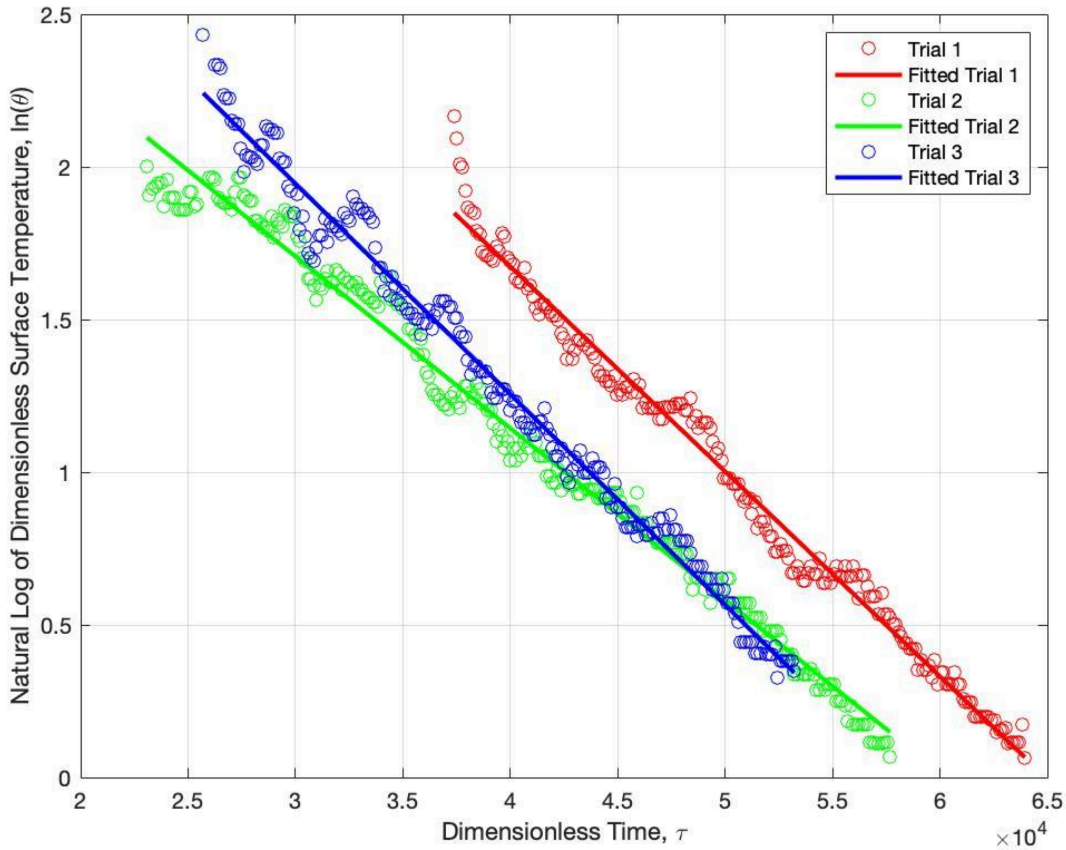

Figure 2*: Plot of ln(θ) vs. τ for aluminum under free convection. The smooth decay curve reflects efficient heat dissipation due to aluminum's high thermal conductivity.*

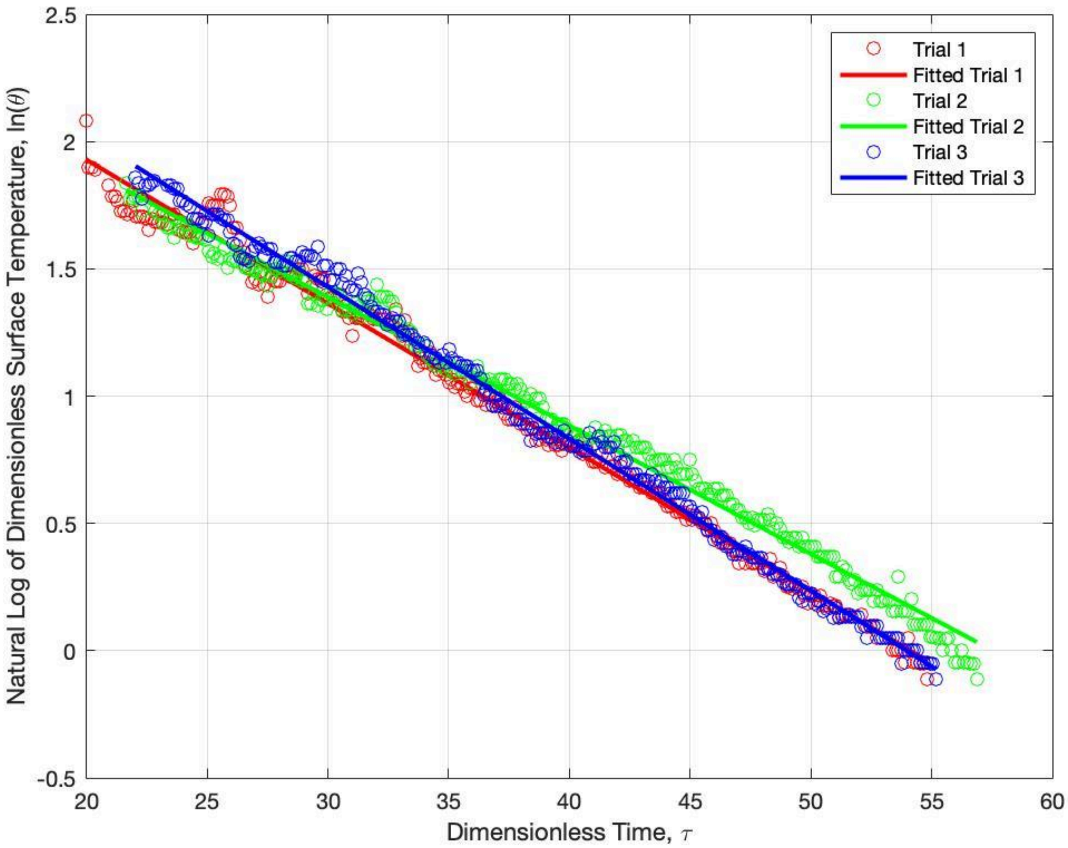

***Figure 3**: Plot of ln(θ) vs. τ for acrylic under free convection. The less steep decay indicates slower cooling rates, consistent with acrylic's lower thermal conductivity.*

When forced convection is introduced, the cooling rates increase significantly for both materials. The plot for aluminum under forced convection, shown in **figure 3**, exhibits a steeper slope compared to the free convection scenario, highlighting the enhanced heat transfer due to active air movement. Similarly, the plot for acrylic under forced convection, shown in **figure 4**, demonstrates the highest cooling rate among all scenarios, driven by a combination of forced convection and its higher surface temperature gradient.

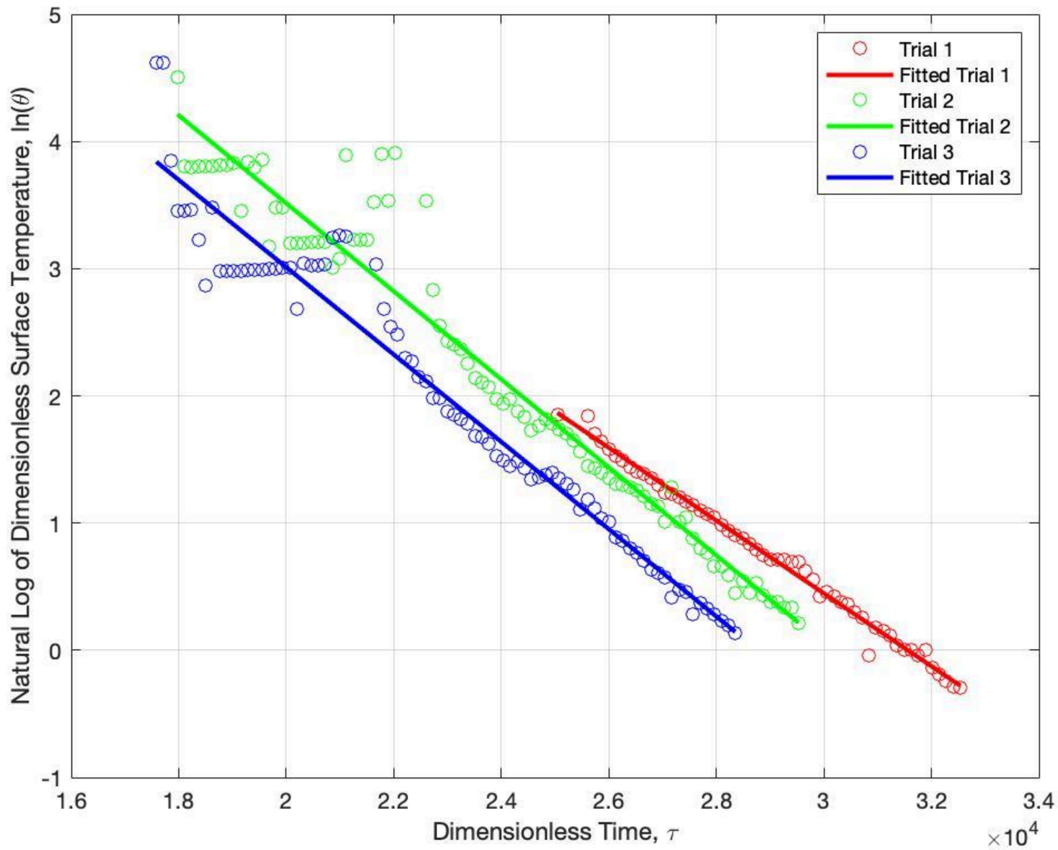

***Figure 4**: Plot of ln(θ)vs. τ for aluminum under forced convection. The steeper slope highlights the enhanced heat transfer resulting from active air movement.*

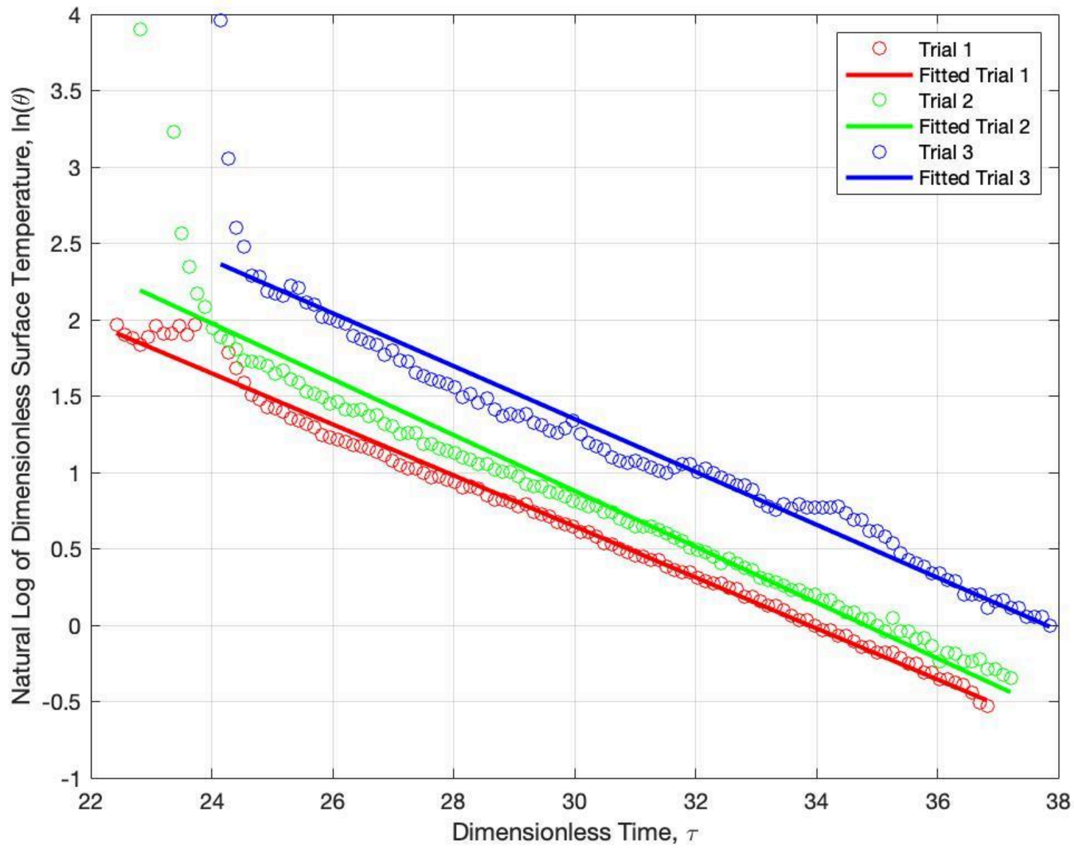

***Figure 5**: Plot of ln(θ) vs. τ for acrylic under forced convection. The rapid decay showcases the combined effects of forced convection and the surface temperature gradient.*

The calculated Biot numbers and convective heat transfer coefficients (h) varied significantly across the different experimental scenarios, reflecting the influence of material properties and convection modes. For aluminum under free convection, the Biot number was 6.4137e-5, corresponding to a heat transfer coefficient of 16.1528 W/m^2K. When forced convection was applied, the Biot number increased slightly to 3.2507e-4, with h rising to 81.8687 W/m^2K. Similarly, for acrylic under free convection, the Biot number was 0.0555, with a comparatively low h value of 13.7070 W/m^2K. Under forced convection, acrylic exhibited a Biot number of 0.1731 and a significantly higher h value of 43.0380 W/m^2K. These results indicate that aluminum's superior thermal conductivity contributes to its lower Biot numbers, while forced convection enhances the overall heat transfer rate for both materials, as evidenced by the increased h values.

Table 1: *Biot Number (Bi) Across Trials for Different Experimental Scenarios*

(Bi = Biot Number)	Trial 1	Trial 2	Trial 3	Average Value
Bi Free Acrylic	0.0565	0.0504	0.0596	0.0555
Bi Forced Acrylic	0.1670	0.1828	0.1731	0.1743
Bi Free Aluminum	0.00006712	0.000056296	0.000068995	6.4137e-5
Bi Forced Aluminum	0.00028618	0.00034589	0.00034313	3.2507e-4

Table 2: *Heat Transfer Coefficient (h) Across Trials for Different Experimental Scenarios*

(h = Heat Transfer Coefficient)	Trial 1	Trial 2	Trial 3	Average Value
h Free Acrylic $[W/m^2K]$	13.9568	12.4439	14.7202	13.7070
h Forced Acrylic $[W/m^2K]$	41.2371	45.1358	42.7410	43.0380
h Free Aluminum	16.9034	14.1784	17.3766	16.1528

$[W/m^2K]$				
h Forced Aluminum $[W/m^2K]$	72.0743	87.1138	86.4179	81.8687

These tables present the results of Biot numbers and heat transfer coefficients across the four discussed experimental cases: free acrylic, forced acrylic, forced aluminum, and free aluminum. As previously stated, the experiment was repeated three times and final results were averaged to strengthen the data and make it more reliable. Our findings display that the values for forced convection end up being higher than those for free convection, alongside this, the values for aluminum are consistently higher than those for acrylic. This further demonstrates aluminum's superior thermal performance over acrylic.

Discussion

The experimental results demonstrate significant differences in the thermal performance of aluminum and acrylic plates under free and forced convection conditions. These differences arise from the inherent thermal properties of the materials, the impact of convective cooling, and the validity of the lumped capacitance model.

Aluminum's high thermal conductivity (k = 204 W/mK) allows for rapid heat dissipation throughout the material, resulting in consistently faster cooling rates compared to acrylic (k = 0.2 W/mK). This is evident from the steeper slopes observed in the $\ln(\theta)$ vs. τ plots for aluminum, reflecting efficient thermal energy transfer to the surrounding environment.

Conversely, acrylic, with its lower thermal conductivity, exhibits slower heat transfer, as indicated by the more gradual decay of $\ln(\theta)$. These differences highlight the importance of material selection in designing thermal management systems.

The mode of convection significantly affects the cooling performance of both materials. Forced convection, achieved through active air movement, provides a larger heat transfer coefficient (h) due to the increased rate of energy exchange between the plate surface and the surrounding air. For instance, the forced convection scenarios for both aluminum and acrylic showed significantly higher h values compared to their free convection counterparts. This observation underscores the role of convective airflows in enhancing the cooling efficiency of systems where rapid heat dissipation is critical.

The consistently low Biot numbers ($Bi < 0.1$) calculated for all experimental scenarios confirm the validity of the lumped capacitance model. This validates the assumption of negligible internal thermal resistance and uniform temperature distribution within the plates. The model's applicability simplifies the analysis of thermal behavior, as it eliminates the need to account for internal temperature gradients. The agreement between experimental and theoretical values for Biot numbers and h further supports the reliability of the experimental approach and calculations.

Free convection scenarios demonstrated slower cooling due to the reliance on natural buoyancy forces to remove heat. The corresponding h values were significantly lower, reflecting the reduced heat transfer rates. For example, aluminum under free convection exhibited $h =$ 16.1528 W/m^2K, while under forced convection, this value increased to 81.8687 $\mathrm{W/m^2}K$. Acrylic followed a similar trend, with $h = 13.7070$ W/m^2K in free convection and $h = 43.0380$ $W/m^2\mathrm{K}$ in forced convection. These findings highlight the substantial impact of airflow conditions on thermal management, particularly for materials with lower thermal conductivities.

The insights gained from this experiment have important implications for the design and optimization of energy systems. Aluminum's superior cooling performance makes it the preferred choice for applications requiring efficient heat dissipation, such as electronic heat sinks or energy storage systems. Forced convection should be prioritized in scenarios where rapid thermal management is crucial, as it significantly improves cooling rates across all materials.

While the experiment demonstrated consistent trends, some sources of error could have influenced the accuracy of the results. Variations in thermistor calibration, Arduino latency in temperature readings, and environmental factors such as ambient airflow could have introduced minor deviations. Additionally, the assumption of constant ambient temperature may not hold perfectly in forced convection scenarios due to localized air movement. Future experiments could address these limitations by improving measurement precision and implementing real-time environmental controls.

References

[1] Moradikazerouni, Alireza. "Heat Transfer Characteristics of Thermal Energy Storage System Using Single and Multi-Phase Cooled Heat Sinks: A Review." *Journal of Energy Storage*, Elsevier, 15 Feb. 2022, www.sciencedirect.com/science/article/abs/pii/S2352152X22001347. Accessed 26 Nov. 2024.

[2] Mendez, Patricio F. *The Lumped Capacitance Method*, University of Alberta, sites.ualberta.ca/~ccwj/Assets/Teaching/CHE314/3_Lumped_capacitance/Handout/LaTeX/lumped_capacitance.pdf. Accessed 26 Nov. 2024.

Peer Review 1

Aikhoje Alakhume

The report effectively addresses the key elements of the experiment, including the comparison of cooling performance between aluminum and acrylic plates under free and forced convection. The abstract provides a concise summary of the work but could be improved by including a broader motivation and a clearer articulation of the study's significance. The introduction does a good job of explaining the context and objectives, but it would benefit from more explicit references to support claims and a clearer statement of the knowledge gap. The results section describes key trends and interpretations, such as the faster cooling rate of aluminum due to its higher thermal conductivity, but lacks quantitative data and detailed discussion of uncertainties or limitations. You can include in your plots the average for all three trials for each mode and material for the cooling and then include a best-fit line to better visualize it. The methods section is adequately detailed but could better outline assumptions and data processing techniques. The discussion provides logical interpretations of the results but needs stronger connections to broader applications and a deeper exploration of uncertainties. Overall, while the report aligns with the WLOs, it would benefit significantly from the inclusion of properly formatted figures, quantitative analysis, and references to enhance clarity and scientific rigor.

Peer Review 2

Kaitlyn Srihavong

Introduction:

Strengths:

- The introduction follows an inverted pyramid structure effectively, starting with a broad overview of heat transfer before narrowing down to the specifics of the study.

● The motivation for investigating aluminum and acrylic plates under different convection modes is clear and relevant to thermal management applications.

● The inclusion of the lumped capacitance model and associated assumptions is a good approach to frame the study's methodology.

Suggestions:

1. Knowledge Gap/Motivation:

● The knowledge gap is implied but not explicitly stated. Consider explicitly identifying what specific gap in the literature or practical applications this study addresses (e.g., "Limited comparative studies on material-specific cooling efficiency under free vs. forced convection").

2. Background Information:

● While sufficient for understanding the experiment, the background could benefit from references to previous experimental work or reviews on forced and free convection.

3. Single Statement of "In this work":

● The statement "This study investigates..." does address the motivation but could be refined to directly link the experiment to the stated gap (e.g., "In this work, we aim to quantify how material thermal properties and convection modes influence cooling rates to inform heat sink design").

Flow and Accessibility:

Strengths:

● The report's flow is logical, transitioning smoothly from introduction to methods, results, and discussion.

● The use of equations early on provides a solid theoretical foundation for interpreting the results.

Suggestions:

1. Grouping of Ideas:

● Some ideas in the introduction might be better placed in the methods or results sections. For example, the detailed description of experimental equations and parameters might interrupt the broader narrative in the introduction.

Results and Methods:

Strengths:

● The repeated trials and averaging to address variability are well-noted.

● The inclusion of $\ln(\theta)$ vs. τ plots is excellent for visualizing trends.

Suggestions:

1. Level of Detail:

● The results section focuses on trends, but more quantitative comparisons (e.g., rate differences between materials) could add depth.

● Provide more details about the fan speed or airflow rates in forced convection conditions to ensure reproducibility.

2. Major Observations:

● Consider explicitly stating unexpected findings, if any, or emphasizing the consistency of results with theoretical expectations.

3. Supporting Interpretations:

● While the calculated h values support your conclusions, adding error analysis or confidence intervals could strengthen the findings.

Discussion and Conclusions:

Strengths:

● The discussion appropriately links results to material properties and convection modes.

● Practical implications for heat sink design are well-highlighted.

Suggestions:

1. Addressing the Knowledge Gap:

● Summarize how the results address the stated gap (e.g., "The findings confirm aluminum's superior cooling performance, highlighting its suitability for high-efficiency heat sinks, especially under forced convection").

2. Future Work:

● Briefly propose follow-up experiments to address limitations (e.g., testing additional materials, varying ambient conditions).

3. Quantitative Support:

● Include a direct comparison (e.g., percentage improvement in cooling rate under forced convection) to underscore the advantages.

Abstract:

● Tighten the abstract to focus on key findings (e.g., mention specific improvements in cooling rates for aluminum under forced convection).

1. Figures and Tables:

● Ensure all figures are labeled consistently and include relevant units (e.g., W/m2K for h values).