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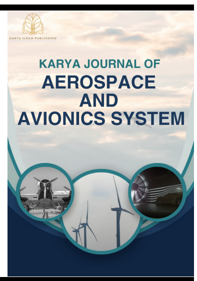

Numerical Study of Heat Distribution of Triangular Cooling Ducts on Solar-Powered UAV Wing

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ABSTRACT

The performance of solar cells is significantly impacted by environmental factors, particularly temperature, which directly influences their voltage output. Higher temperatures lead to reduced voltage, thereby diminishing the efficiency of solar cells. This study investigates the thermal behavior of solar cells integrated into the wings of solar-powered unmanned aerial vehicles (UAVs) and proposes innovative cooling duct designs to enhance their efficiency. Using Clark Y airfoils, cooling duct models were designed and modeled in CATIA, followed by computational fluid dynamics (CFD) simulations conducted in ANSYS Fluent. The results indicate that the proposed cooling ducts reduce the average temperature of solar cells by 16.33% compared to a baseline design lacking cooling mechanisms. These findings provide a framework for optimizing solar-powered UAVs for both military and civilian applications by improving energy efficiency and operational reliability. This study also serves as a reference for advancing the design and thermal management strategies of solar-powered UAV systems.

1. Introduction

The rapid escalation of global energy demands, coupled with the depletion of fossil fuel reserves, has necessitated the exploration of alternative and sustainable energy sources. Among the various renewable energy options hydropower, wind, geothermal, and bioenergy solar energy has emerged as one of the most promising due to its abundance, sustainability, and adaptability across diverse applications, including in the aviation sector [1,2]. The development of solar-powered unmanned aerial vehicles (UAVs) represents a convergence of renewable energy technology and aerospace engineering, offering substantial advantages in terms of endurance, operational cost, and environmental impact for both civilian and military missions [3].

Solar-powered UAVs operate by harnessing sunlight through photovoltaic (PV) cells, converting solar radiation into electrical energy for propulsion. During daytime operations, excess energy is stored in onboard energy storage systems (typically lithium based batteries) to enable night time

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flight, ensuring continuous operation over extended periods [4]. However, the efficiency of PV cells is inherently sensitive to environmental conditions temperature, irradiance, and shading with temperature emerging as a critical factor. As operating temperatures increase, the open-circuit voltage (Voc) of solar cells decreases due to the narrowing of the semiconductor band gap, resulting in lower power output and system efficiency [5,6].

According to Saidur et al., only 5–20% of the incident solar radiation is effectively converted into electrical energy, with the remaining energy contributing to thermal accumulation in the solar cells [7]. This thermal load not only reduces efficiency but also accelerates material degradation, thereby compromising the lifespan and reliability of the PV system. To counteract these negative thermal effects, researchers have proposed various thermal management techniques, including passive and active cooling systems [8]. Passive cooling, which utilizes natural airflow or radiative heat dissipation, offers the advantages of low energy consumption, minimal added weight, and mechanical simplicity, making it highly suitable for lightweight UAV platforms [9].

A notable passive cooling solution involves the integration of cooling ducts beneath PV cells mounted on UAV wings. These ducts utilize forced convection from ambient airflow during flight to dissipate heat and maintain lower cell temperatures. Murzello et al. conducted CFD simulations to examine this concept and reported a temperature reduction of up to 4°C, which corresponded to a 0.5% increase in power output per unit wingspan under cruising conditions [10]. Similarly, Colozza proposed the use of air-cooled passages below PV arrays, leveraging low-temperature air at high altitudes to enhance convective heat transfer, further demonstrating 9% lift enhancement and 13% drag penalty associated with duct implementation [11].

Additional studies by Chu *et al*., [12} and Safyanu *et al*., [13] have highlighted the importance of energy system optimization in solar UAV design, emphasizing the synergy between aerodynamic efficiency, solar energy harvesting, and thermal management for achieving prolonged flight durations. Despite these advancements, the literature reveals a research gap in the geometric optimization of cooling ducts particularly in terms of shape, size, and placement to maximize heat dissipation while minimizing aerodynamic penalties.

This study aims to address this gap by designing and evaluating three cooling duct geometries rectangular, semicircular, and triangular integrated into Clark Y airfoil-based UAV wings. The models are developed using CATIA V5 and analyzed via Computational Fluid Dynamics (CFD) simulations in ANSYS Fluent. By assessing the temperature distribution, airflow patterns, and thermal gradients around each duct configuration, this study seeks to identify the optimal design for improving solar cell performance and overall UAV efficiency.

2. Methodology

This study adopts a computational approach to analyze and optimize the thermal management performance of cooling ducts integrated into the wings of solar-powered UAVs. The methodology involves three main phases: the design and modeling of UAV wings with various cooling duct configurations, computational fluid dynamics (CFD) simulation for thermal analysis, and a comparative evaluation of the temperature distribution and aerodynamic performance of each model. The software used includes CATIA V5 for detailed 3D modeling and ANSYS Fluent for CFD simulations.

2.1 Wing and Cooling Duct Design

The wing design is based on the Clark Y airfoil, which is widely recognized for its favorable lift-to-drag ratio and aerodynamic stability [13], making it suitable for small aircraft and UAV applications. The UAV wing model used in this study has a chord length of 350 mm and a wingspan of 700 mm as shown in Figure 1. This baseline model was modified to incorporate three different cooling duct geometries - rectangular, semicircular, and triangular as in Figure 2-4. These variations were selected to explore the impact of duct shape on heat dissipation performance. All duct designs maintained a consistent length and depth to ensure a fair and controlled comparison.

Design and modeling were performed using CATIA V5, an industry-standard computer-aided design (CAD) and engineering (CAE) software suite known for its precise parametric modeling capabilities. CATIA enabled the construction of high-fidelity three-dimensional models of the UAV wing, facilitating the integration and refinement of each cooling duct design with high accuracy. The software's interactive interface and advanced modeling tools allowed for efficient iteration and optimization of the cooling duct structures in alignment with the aerodynamic constraints of the UAV wing profile [14].

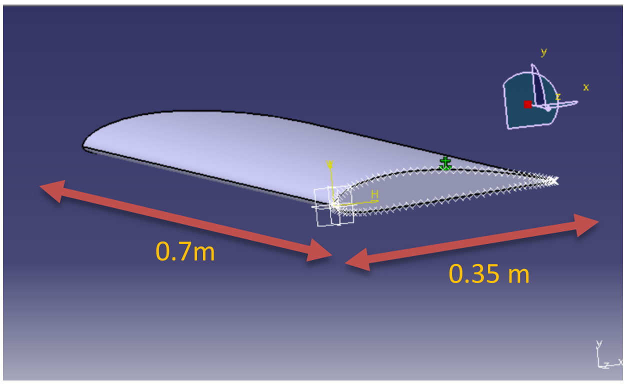

Fig. 1. Clark-Y plain airfoil

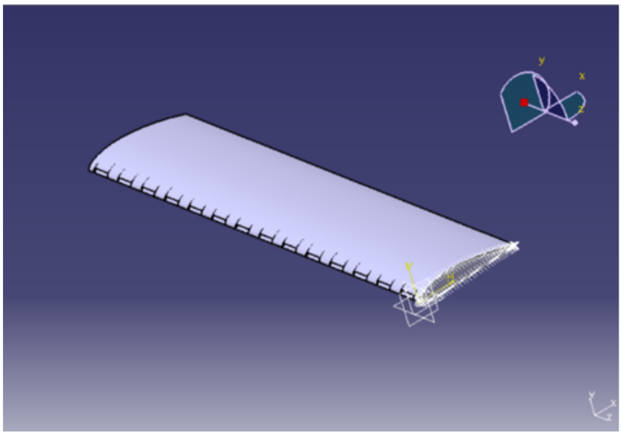
Fig. 2. Clark-Y airfoil with cylindrical trailing edge

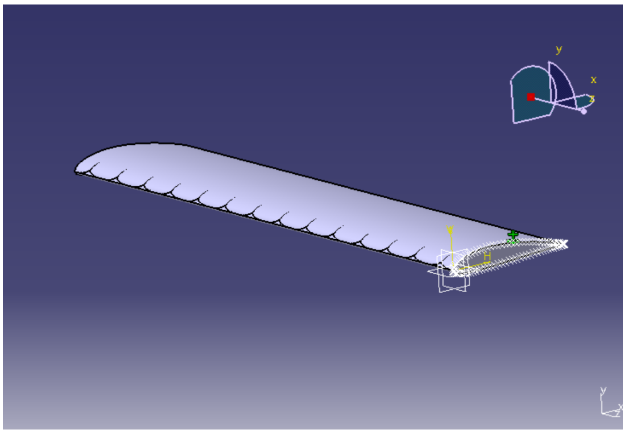

Fig. 3. NACA 2410 plain airfoil

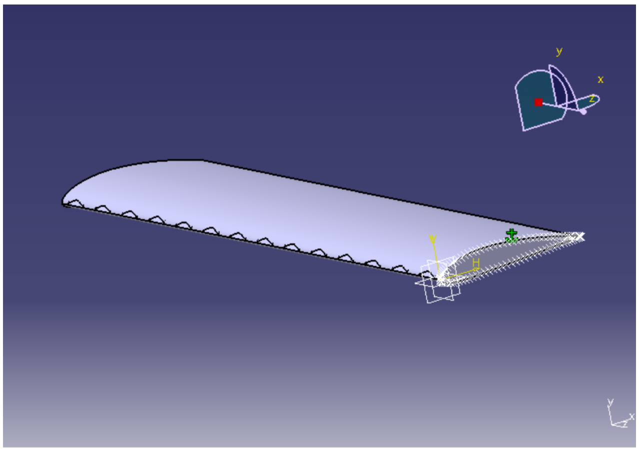

Fig. 4. NACA 2410 with cylindrical trailing edge

2.2 CFD Simulation

CFD simulations were conducted using ANSYS Fluent 2024, a robust computational tool for simulating fluid flow, heat transfer, and turbulence in complex geometries. A flow domain was defined around the UAV wing, with dimensions set to twice the wing chord length and a depth of 0.7 meters, to accurately capture airflow and thermal behavior. Meshing of the domain was carried out using ICEM CFD, with finer mesh settings around critical regions such as the duct surfaces, leading edges, and trailing edges of the wing. Mesh quality was validated by achieving a minimum orthogonal quality of 0.15 and ensuring skewness remained within acceptable limits to enhance the reliability of the simulation results.

The simulations were configured under conditions replicating typical flight environments. Ambient air temperature was set to 360.15 K (33°C), and simulations were conducted at inlet airspeeds of 5, 10, 15, and 20 meters per second to observe the impact of airflow on cooling performance. A solar heat flux of 950 W/m^2 was applied to simulate peak solar irradiance, and a heat generation rate of 3.705×10^6 W/m^3 was specified for the solar cells based on standard photovoltaic performance metrics [7,9]. The pressure at the outlet boundary was set to atmospheric pressure, and the energy equation was activated to enable heat transfer analysis. The k-ε turbulence model was selected for its robustness and efficiency in handling external aerodynamic flows, especially around bluff bodies like airfoils [15]. Coupled thermal boundary conditions were applied to simulate the interaction of conduction and convection across the UAV wing surfaces and ducts.

Post-processing of the simulation results was performed within ANSYS Fluent to extract critical data on temperature distribution, airflow velocity, and pressure gradients across the wing surface and within the cooling ducts. Key metrics included the maximum and average temperatures observed over the solar cell region, the percentage reduction in temperature relative to the baseline model without ducts, and the visual assessment of airflow patterns to evaluate the efficiency of heat dissipation. Initial results indicated that the triangular duct configuration provided enhanced airflow mixing and turbulence, which led to improved convective heat transfer and reduced thermal accumulation.

Comparative analysis of the three duct designs was carried out under identical boundary and environmental conditions to ensure objectivity and consistency. Simulation reliability was reinforced through mesh independence studies and validation against findings from previous literature [10], [11]. Additionally, statistical methods were employed to quantify performance differences among the models. These analyses were aimed at identifying the most effective cooling duct geometry for maintaining optimal solar cell temperatures and improving the energy efficiency of solar-powered UAVs during extended flight operations.

3. Result and Discussion

3.1 Quantitative Data

3.1.1 Temperature distribution analysis

The simulation results revealed that all three cooling duct configurations successfully reduced the operating temperature of the solar cells compared to the baseline model, which lacked any form of cooling mechanism. Among the modified designs, the triangular duct demonstrated the greatest temperature reduction, followed by the rectangular and semicircular ducts.

Figure 5 represents flight velocity of 15 m/s and an ambient temperature of 360.15 K (33°C), the baseline model recorded an average solar cell surface temperature of 44°C. In comparison, the triangular duct model achieved a reduced temperature of 33°C, representing a 25% reduction in temperature. The rectangular duct reduced the temperature to 36°C, an 18.18% reduction, while the semicircular duct achieved a temperature of 38°C, corresponding to a 13.64% reduction. These findings are consistent across other tested velocities, with temperature reductions increasing with airflow velocity due to enhanced convective heat transfer, as predicted by Nusselt number correlations [16].

The superior performance of the triangular duct can be attributed to its sharp-edged geometry, which induced increased airflow turbulence and mixing within the duct, thereby enhancing convective heat dissipation. This result is consistent with findings by Colozza [11], who noted that airflow-induced convection plays a critical role in reducing solar cell temperatures during flight.

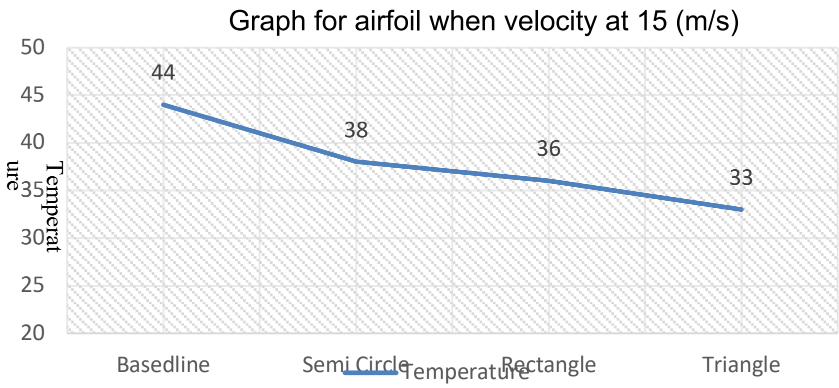

Fig. 5. Temperature distribution at 15 m/s and zero Angle of Attack (AoA)

Duct Shape

3.1.2 Temperature - velocity relationship

A key outcome of this study is the relationship between airflow velocity and the average surface temperature of the solar cells for each airfoil configuration. The data, presented in Figure 6 shows that temperature decreases with increasing velocity for all models due to enhanced convective heat transfer. However, the magnitude of temperature reduction varies across different duct geometries. The graph reveals that temperature reduction is most significant between 5 m/s and 15 m/s, beyond which the temperature decrease plateaus, particularly for the triangular duct. This suggests a diminishing return effect, where increased airflow yields smaller incremental cooling benefits at higher speeds.

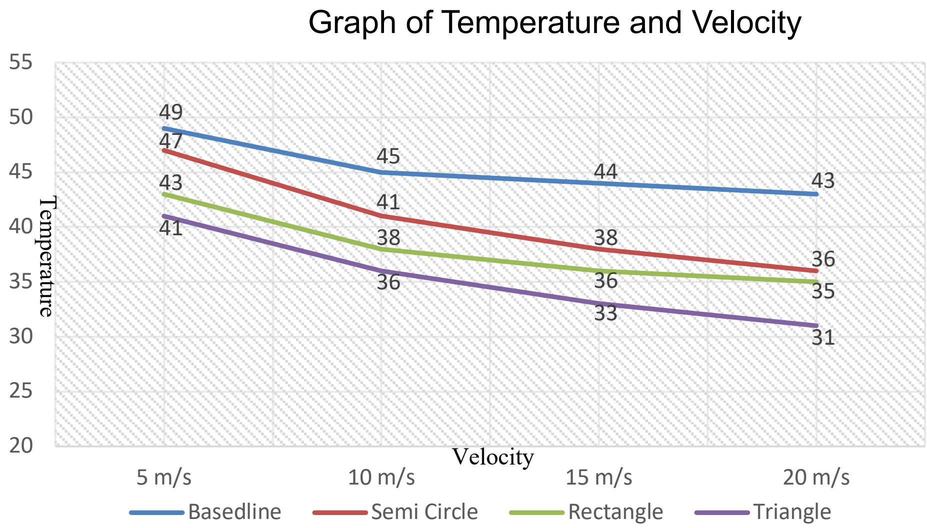

Fig. 6. Temperature – velocity relationship at zero Angle of Attack (AoA)

3.2 Qualitative Data
3.2.1 Temperature contours visualization

Flow visualization through temperature and pressure contours further substantiated the quantitative temperature data. The baseline model exhibited thermal accumulation along the leading edge and upper wing surface, with minimal heat dispersion. In contrast, all three modified models displayed improved airflow penetration and more uniform temperature gradients, particularly in the triangular duct model, where hotspots were effectively minimized.

Figure 7 shows the temperature contour for the baseline airfoil, indicating higher localized heating, especially near the central wing section. Figures 8–10 illustrate the contours for the semicircular, rectangular, and triangular duct models, respectively. The triangular duct configuration displayed wider regions of lower temperature across the wing surface, confirming its enhanced thermal dissipation capability.

From an aerodynamic standpoint, while all duct configurations introduced some drag penalty, the triangular duct achieved an optimal balance between heat dissipation and aerodynamic efficiency. This finding aligns with Murzello *et al*., [10], who reported that carefully designed duct geometries can enhance thermal performance without significantly compromising aerodynamic lift.

The observed temperature reductions directly translate into improved solar cell efficiency, as solar cells typically exhibit a negative temperature coefficient, with power output decreasing by 0.258% per 1°C increase above 25°C [7]. Based on this coefficient, the triangular duct model's 11°C reduction in temperature from the baseline would correspond to a 2.84% improvement in power

Karya Journal of Aerospace and Avionics System
Volume 1, Issue 1 (2025) 22-30

output, which is substantial in UAV applications where energy efficiency directly affects flight endurance and mission effectiveness.

A comparative evaluation of the three duct designs confirms that duct geometry significantly influences thermal performance. The triang ular duct, by promoting airflow mixing and enhanced convection, emerges as the most effective design for thermal management in solar-powered UAVs. The findings underscore the importance of geometric optimization in UAV wing design, particularly for integrating passive cooling systems that enhance solar cell performance without adding significant weight or energy consumption.

These results provide a validated framework for future solar UAV design improvements, particularly in aerospace platforms requiring long-duration flight capabilities. Furthermore, they demonstrate that CFD simulations are effective tools for predicting thermal behavior and guiding design optimization in aerospace applications [16].

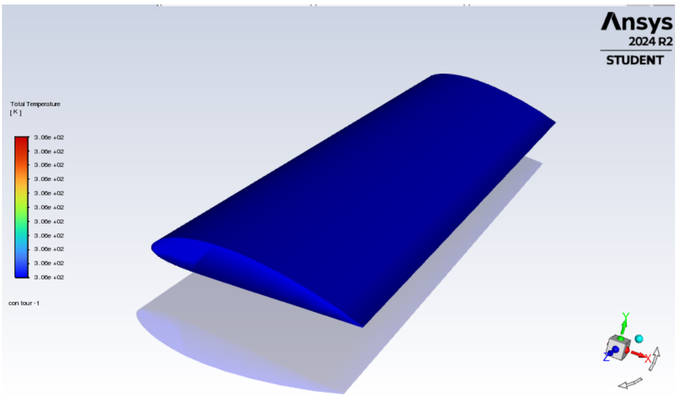

Fig. 7. Temperature contours for baseline duct airfoil

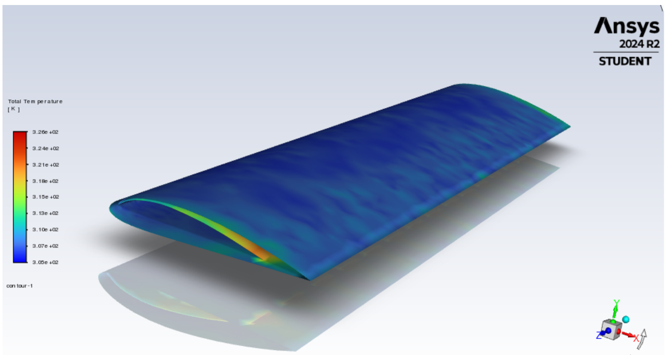

Fig. 8. Temperature contours for semi-circle airfoil

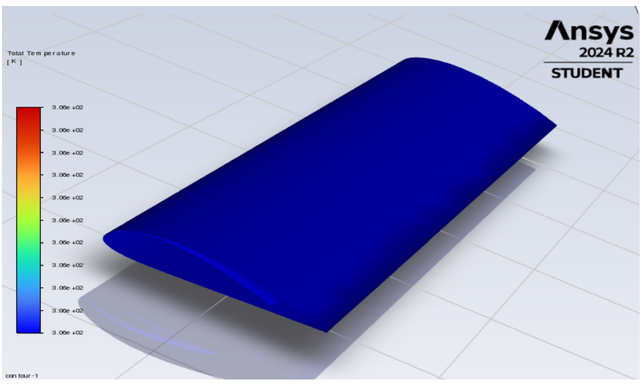

Fig. 9. Temperature contours for triangle duct airfoil

Karya Journal of Aerospace and Avionics System
Volume 1, Issue 1 (2025) 22-30

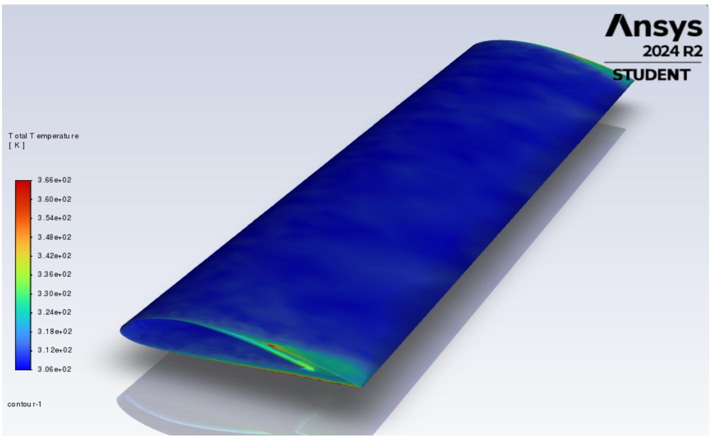

Fig. 10. Temperature contours for rectangle duct airfoil

4. Conclusions

The simulation results demonstrated that all cooling duct configurations contributed to a significant reduction in solar cell temperature compared to the baseline model lacking any cooling mechanism. Among the designs, the triangular duct geometry consistently achieved the greatest reduction in operating temperature, lowering it by 25% at 15 m/s flight velocity. This temperature decrease corresponds to an estimated 2.84% improvement in solar cell efficiency, based on standard temperature coefficients for PV performance. The triangular duct's superior performance is attributed to its enhanced airflow mixing and increased turbulence, which promotes effective convective heat transfer.

Additionally, the flow visualization indicated that the triangular duct design minimized thermal hotspots and ensured a more uniform temperature distribution across the wing surface, improving not only thermal but also aerodynamic performance. These findings support the feasibility and effectiveness of passive cooling strategies in solar-powered UAV applications, particularly where energy efficiency and flight endurance are critical.

In conclusion, this research validates the triangular cooling duct as the optimal design for thermal management in solar UAV systems, offering a practical and efficient solution for enhancing PV cell performance without compromising aerodynamic integrity. The methodology and results of this study provide a valuable reference for future UAV design optimization, contributing to the broader advancement of sustainable aviation technologies.

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