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Performance Analysis of a Bioinspired Albatross Airfoil with Heated Top Wing Surface: Experimental Study

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Applications of unmanned aerial vehicles are becoming more attainable through the increase in system efficiency. As seen in nature, birds like the albatross utilize the temperature effects resulting from their wings' color to increase their flight efficiency. In this paper, the effects that differences in surface temperatures of birds' black/white wings, colored flat plates, and albatross airfoil (GOE 174) with heating films is investigated. Such effects are applicable to the efficiency of fixed-wing drones. Experimentally, it is observed that the surface temperature of black birds' wings is over 50% higher than white wings under solar radiation. The application of a novel heated top surface on an airfoil (GOE 174) results in the drag coefficient decreasing up to 60% and the lift coefficient increasing up to 70% in specified angles of attack compared to a non-heated top surface. This method of utilizing thermal effects can be considered as a new applicable way to increase the flight efficiency in fixed wing unmanned aerial vehicles.

I. Introduction

In recent decades, there has been a tremendous effort in the design of drones. As technologies advance, the need for high performance drones with a magnitude of capabilities including unmanned, micro, and nano air vehicles has increased for both civilian and military applications[1]. This introduces a new era in which autonomous unmanned aerial vehicles are capable of perceiving and generating solutions in complex environments[2, 3]. Drones' benefits include the potential to carry out a variety of operations including: reconnaissance, patrolling, protection, transportation of loads, and aerology[4]. Due to their several potential applications and functions, the popularity of these devices has greatly risen, leading to a variety of unique drones with different sizes, shapes, and weights[1, 4]. Moreover, the development in micro-electro-mechanical systems (MEMS), sensors, fabrication and navigation methods, and power systems have made the design and manufacturing of a wide range of drones possible[1]. In other words, drones often vary widely in their configurations depending on the platform and mission. Therefore, there are various classifications for them based on different parameters[1].

Considerable advantages of drones have led to the conduction of a myriad of studies aiming to optimize and enhance the ability of this group of planes[5]. To this end, several research studies from distinct disciplines (mechanical, aerospace, material, electrical, computer science, etc.) have focused on the design, optimization, and performance enhancement of drones which resulted in the development and fabrication

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of various types of these unmanned systems. Most relevantly, in the past decade, there has been a push to design and fabricate drones which can accomplish high endurance missions at optimal performance[1, 6].

With the present energy crisis, there is an ever-increasing need for research in performance enhancement techniques. Since nature has developed objects, processes, materials, and the functions to increase efficiency, it has the best answers when we seek to improve or optimize a system. Thus, the fields of biomimetics and bioinspiration allow us to mimic avian to develop methods for reducing drag in all types of transportations in air and water[7, 8]. Avian flight can be considered as very efficient flying machines; thus, bio-inspired designs offer potential benefits for drones[3]. Inspired from natural flyers, the evolution of unmanned aerial vehicles has advanced drastically over the past few years, and due to the birds' flight capabilities, they are an ideal study subject to base the design of drones upon. Based upon the research witnessed in migrating birds, engineers have worked on developing similar capabilities in drones in order to improve their endurance, altitude, velocity, maneuverability, compressibility, stealth, and/or payload[3]. To this end, several bio-inspired designs have helped to improve upon drones' speed, endurance, efficiency, and maneuverability.

It was investigated by Hassanalian et al.[9, 10] that the black and white colors of migrating birds' wings, such as albatrosses, shearwaters, sooty terns, and black skimmers have an effect on their skin drag reduction[9-11]. In this study, the migration routes of birds with black and white colors, including the latitudes and longitudes, the time of migration, and the corresponding marine and atmospheric characteristics such as wind speed, ambient temperature, ocean temperature, and sky temperature of their flight routes were extracted[9]. The thermal effects of top and bottom sides of the wing with two different colors (white and black) were studied. Using Blasius boundary condition, it was shown that the boundary layer around the wings of the birds with black color on top have less density and more viscosity than white color[9]. In other words, for the dark colors there is an increase in the wing surface temperature and therefore a corresponding decrease in the density and an increase in the viscosity, but the total skin drag decreases.

Generally, the effects of temperature have been studied experimentally and numerically on both laminar and turbulent boundary layers for a long time[12-17]. Various tests have been performed on low-speed and long-chord airfoils for de-icing of the airplanes' wings[18]. It has been shown that there are considerable effects on lift and drag performance of the wings with a heated leading edge[19]. The Reynolds number changes inversely with the temperature of the flow and decreases as the temperature increases. Generally, for laminar flow, with increasing the temperature the local Reynolds number and the corresponding wall shear stress and skin friction drag decrease. Dragan investigated the thermal effects on performance of a NACA 2510 airfoil[19]. In this study, the NACA 2510 airfoil with adiabatic walls and the same airfoil with heated patches were compared and it was indicated that surface temperature distribution influences the aerodynamics of an airfoil[19].

It should be noted that mechanisms of drag reduction in ocean-migrating birds are opening a new bioinspired performance enhancement technique called the heated boundary layer. In this paper, a novel mechanism for fixed wing drones that provides a heated boundary layer of air over the top part of its wing is proposed. This is accomplished through applying a heated blanket and temperature controller on the top part of the drone's wing. This concept will be able to increase the performance of fixed wing drones by increasing the lift and decreasing the drag forces.

II. Flight characteristics and geometries of albatrosses

Generally, birds have different flight modes which can be divided into two modes, namely, powered fight (hovering and flapping flights) and unpowered flight (soaring and gliding Fights). Some types of migrating birds like albatrosses can fly long distance trips of 15200 km over the ocean without any flapping motion during 46 days[20, 21]. These large migrating birds fly most of their lives over the oceans and return to small oceanic islands only for breeding[22]. Albatrosses which have a wingspan of 3.5m and weight of 8.5 kg are able to fly with maximum ground speeds of over 35 m/s[23]. These birds can also maintain these speeds for more than 8 hours without any flapping motion[24]. Assuming a maximum lift to drag ratio of 20, an albatross need a power of 81 W for flying at 19.5m/s[25].

Different theories have been proposed by researchers to explain how these migrating birds can fly without flapping and just extending their wings. These birds due to their anatomical adaptations have an elbow-lock system and without any muscle activity can keep their wing open[25]. The main theory behind their long and low cost flight is their special flight mode, which is called dynamic soaring. Albatrosses are able to take advantage of wind shear to gain required energy for flying. These migrating birds increase their height above the ocean surface and apply the wind speed to gain energy. Also they can use updrafts caused by wind blowing over waves to gain energy which is called wave-slope soaring. It should be noted that wind blowing over the ocean waves has both wind shear and vertical motions that influence on each other[10]. Albatrosses generally have two types of movement in different scales; one is large-scale movement that appears as a steady-state cruise of long-distance flight and next is small scale movement which is flight maneuvers of highly dynamic nature. The large scale movements are of the order of hundreds to thousands of kilometers and the small-scale movements are of the order of tens to hundreds of meters constituting dynamic soaring[26].

Albatrosses as ocean migrating birds have black and white colors. The concentration of melanin in top feathers of these migrating birds causing the wings to appear black on top. As discussed before, these birds have drag reduction due to heated boundary layer on the top of their wings. In Fig. 1, views of colors of the wings of albatrosses are shown, respectively.

Figure 1: Views of albatross's wings colors.

III. Energy balance and governing equations for albatrosses

It is obvious that the heat absorption of dark colored objects is greater than lighter colored objects. Considering this heat transfer principle, it was indicated computationally by Hassanalian et al., that the top surface of the albatross's wings has a higher temperature once they are exposed to the sun radiation due to their black color[10]. To this end, they conducted a research on thermal effects of the color of the albatross's wings in their flight performance. In their research, they assumed that when heat reaches the surface of these migrating birds, a portion is absorbed, another is reflected, and the rest is transmitted. Since the wings are considered as opaque surfaces, the transmitted portion was neglected. Considering the wing as a flat plate, an energy balance equation was written for the top part of the albatross wing as follows[9, 10]:

$$\alpha_s G_s + \alpha_{sky} G_{atm} = h(T_S - T_\infty) + \varepsilon\sigma T_S^4 \quad (1)$$

where α_s, α_{sky}, ε, σ, G_s, G_{atm}, h, T_s, and T_∞ are solar absorptivity of surface and sky, emissivity of surface, Stefan–Boltzmann constant, solar irradiation, irradiation at the earth's surface due to atmospheric emission, convective heat transfer coefficient, and surface and environment temperatures, respectively[9]. It has been assumed that the absorptivity of the sky is almost equal to the emissivity of the surface ($\alpha_{sky} \approx \varepsilon$) and the irradiation at the earth's surface due to atmospheric emission is $G_{atm} = \sigma T_{sky}^4$, where T_{sky} is the effective sky temperature, the energy balance finally has been written as[9, 10]:

$$\alpha_s G_s = h(T_S - T_\infty) + \varepsilon\sigma\left(T_S^4 - T_{sky}^4\right) \quad (2)$$

Solving the above energy balance, it has been shown that the temperature difference between the bright and dark colored top wing surface is around 10 °C for a flat plate[9]. Finally, considering the effects of the temperature on the viscosity and the density of the air, the skin drag force was calculated in different seasons. It follows from the primary results performed by Hassanalian et al.[9, 10], that a dark colored wing generates less drag than a white colored one for different seasons. This means that for the albatross, its black top wings are helping it to improve its flight performance by reducing the drag force. Since the previous study by Hassanalian et al. [9, 10] is lack of experiment, in this study with inspiration from albatross wing color, some experimental tests in a wind tunnel are carried-out by heating the top surface of the albatross airfoil, GOE-174.

IV. Study on effects of birds' wings colors on their surface temperature

To investigate the surface temperatures of different wing colors two wings, one black and one white, of similar size and shape are placed under a heat lamp. The heat lamp is located 40 cm above the Styrofoam surface that the wings are placed on, simulating sun irradiation. The two wings are exposed to the heat lamp for 12 minutes, and their surface temperatures are measured by a thermal camera every 30 seconds. To measure the radiation of the heat lamp, a SM206 Digital Solar Power Meter Sun Light Radiation Measuring Testing Instrument is used. In Figure 2, the experimental setup and the black and white wings are shown.

Figure 2. View of experimental setup with black and white wings.

In Figure 3, the measured radiation of the heat lamp with the Solar Power Meter over a 12 minute period is shown. The results shows that with increasing the time, the radiation of the heat lamp increases.

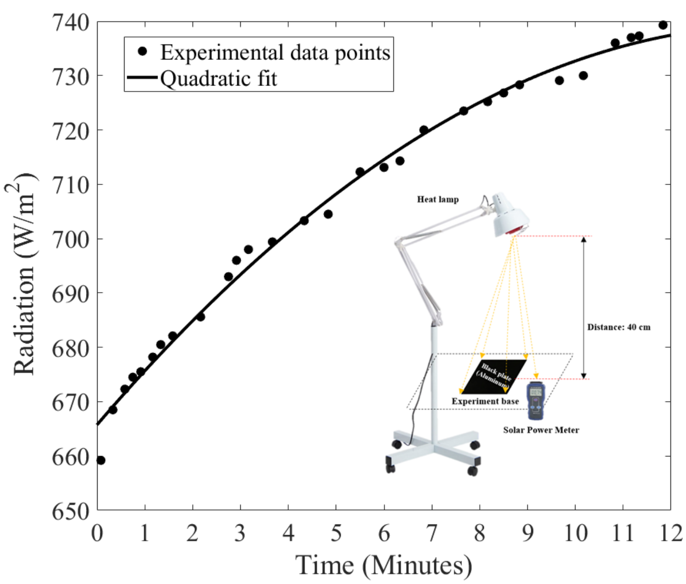


Figure 3. Radiation versus time for heat lamp with 40 cm distance from the plate.

Various tests are performed on the black and white color wings. The thermal images of a black and white wings at 30 second intervals that show the temperature distribution of the black and white wing together are shown in Figure 4. The extreme contrast of the black and white surface temperatures is present in these images.

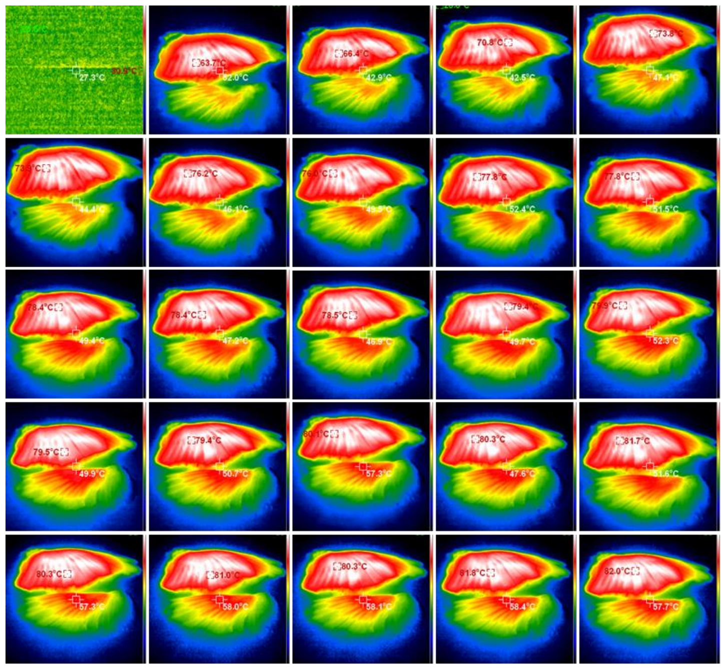
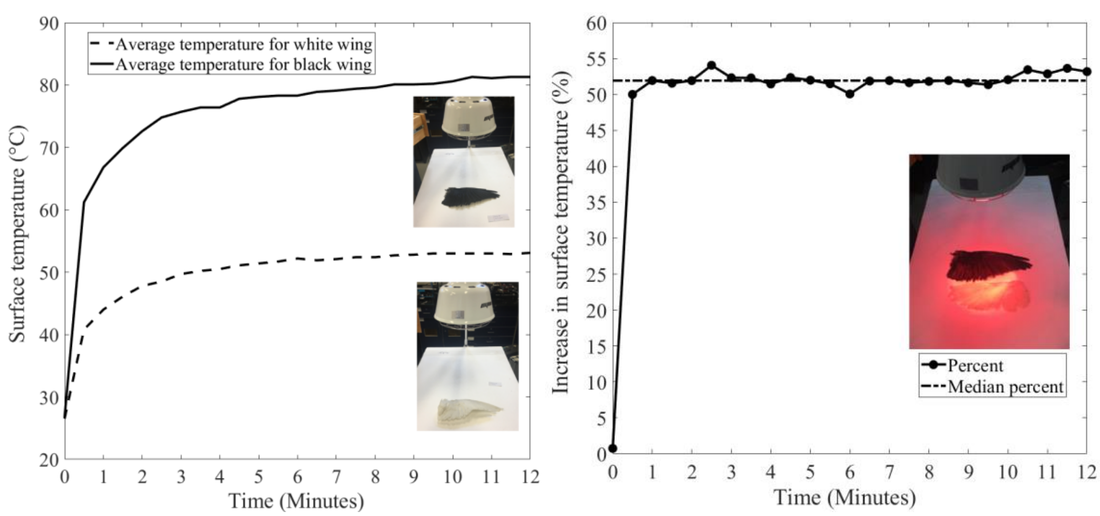


Figure 4. Thermal images of black (top) and white (bottom) wings in 30-second intervals.

The maximum temperatures over time for three tests of the black and white wings were recorded with the thermal camera. The averages of the black and white wings are compared in Figure 5(a). The maximum average surface temperature reached for the black and white wings are 81.3 °C and 53.1 °C, respectively. The median percent increase in surface temperature from the white wing to the black wing is 52%, as noted in Figure 5(b). The results show that birds' wings with black and white colors can have different surface temperature once they are exposes to the sun radiation.



(a) **(b)**

Figure 5: View of (a) comparison of average surface temperatures of black and white color wings and (b) percent increase in surface temperature for black wing compared to white wing.

V. Experimental study on effects of color on surface temperature of aluminum plates

To study the effects of the colors on surface temperature of flat plates with black and white colors, a static experiment is setup in the laboratory. In this experiment, the surface temperature of two black and white aluminum flat plates is measured under a heat lamp. The heat lamp has the same distance of 40 cm from the plates, similar to previous experiment carried-out on birds' wings. The two aluminum plates are exposed to the heat lamp for 12 minutes and their surface temperatures are measured by a thermal camera and laser thermometer. It should be noted that the experiments are conducted in a wood-base material to decrease the conductivity effects. The surface temperature distribution for the aluminum flat plates with white and black colors is shown in Figure 6. It is indicated by a thermal imaging camera that for a similar value of the radiation in this experiment, different surface temperatures can be recorded for white and black color plates. As can be seen in Figure 6, the results demonstrate higher values of surface temperature for the black colored flat plate compared to the white colored due to the its higher value of solar absorptivity. The dark and white colors have a solar absorptivity of 0.97 and 0.21, respectively. The same trend was seen in section 4 for the feathers of the black and white color wings.

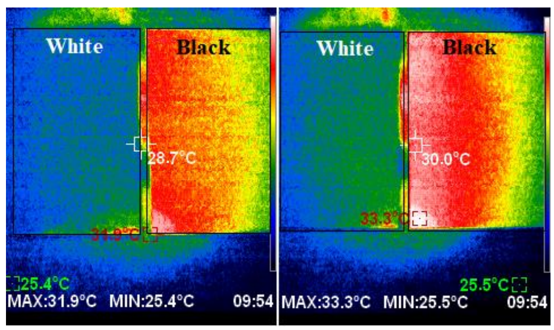


Figure 6. Surface temperature distribution for black and white aluminum plates.

Figure 7 demonstrates the comparison of surface temperature for the wood-base white and black aluminum plates. It is apparent that a maximum temperature difference of almost 22 °C can be found between white and black colored aluminum plates. As can be seen in Figures 5(a) and 7, the surface temperature for both black and white color wings are higher than the surface temperature of the aluminum flat plate with black and white colors, respectively. The main reason of this difference in surface temperature is the value of the conductivity coefficient for the aluminum flat plate and the feathers. The results indicate that feathers can have higher values of the surface temperatures.

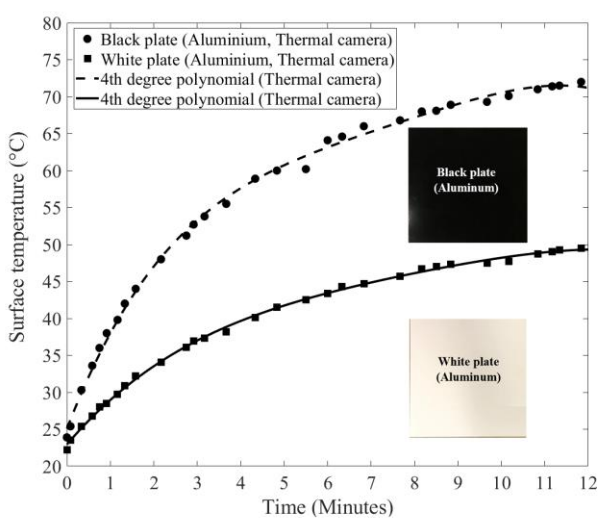


Figure 7. Surface temperature versus time for black and white aluminum plates.

VI. Experimental study on albatross airfoil with heated top surface

In this experimental study, the airfoil of the Wandering albatross (Diomedea exulans), as one of the largest migrating seabirds, is analyzed. The well-defined geometric airfoil for the albatross, GOE 174, is presented in Figure 8.

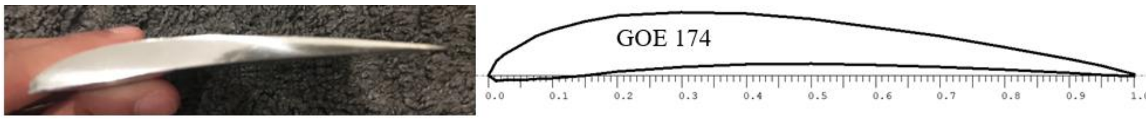


Figure 8. View of the GOE 174 airfoil used for analysis.

For this study, a wingspan of 100 mm and chord length of 100 mm is produced using aluminum cast (see Figure 8). A heating blanket with thickness of 0.5 mm with input power of 75 W is designed using silicone heating film and attached with a digital temperature controller to the wings (see Figure 9). For the working temperature of 20 °C in the wind tunnel, the top surface of the wing is covered with heating blanket and is tested at different angles of attack at a speed of 15 m/s.

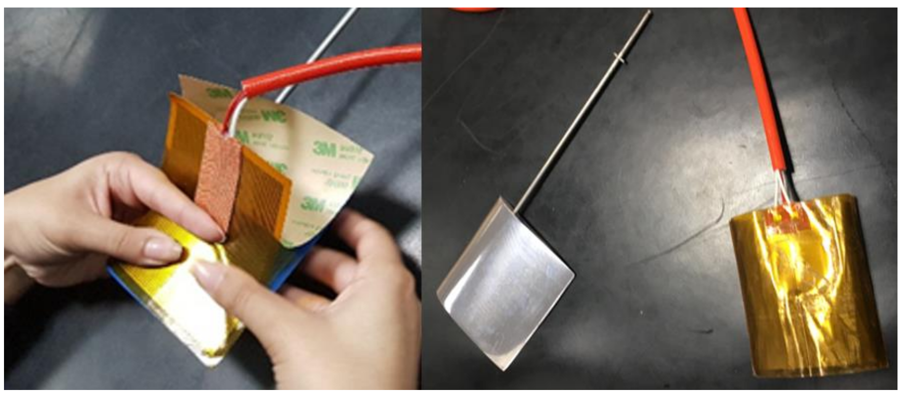
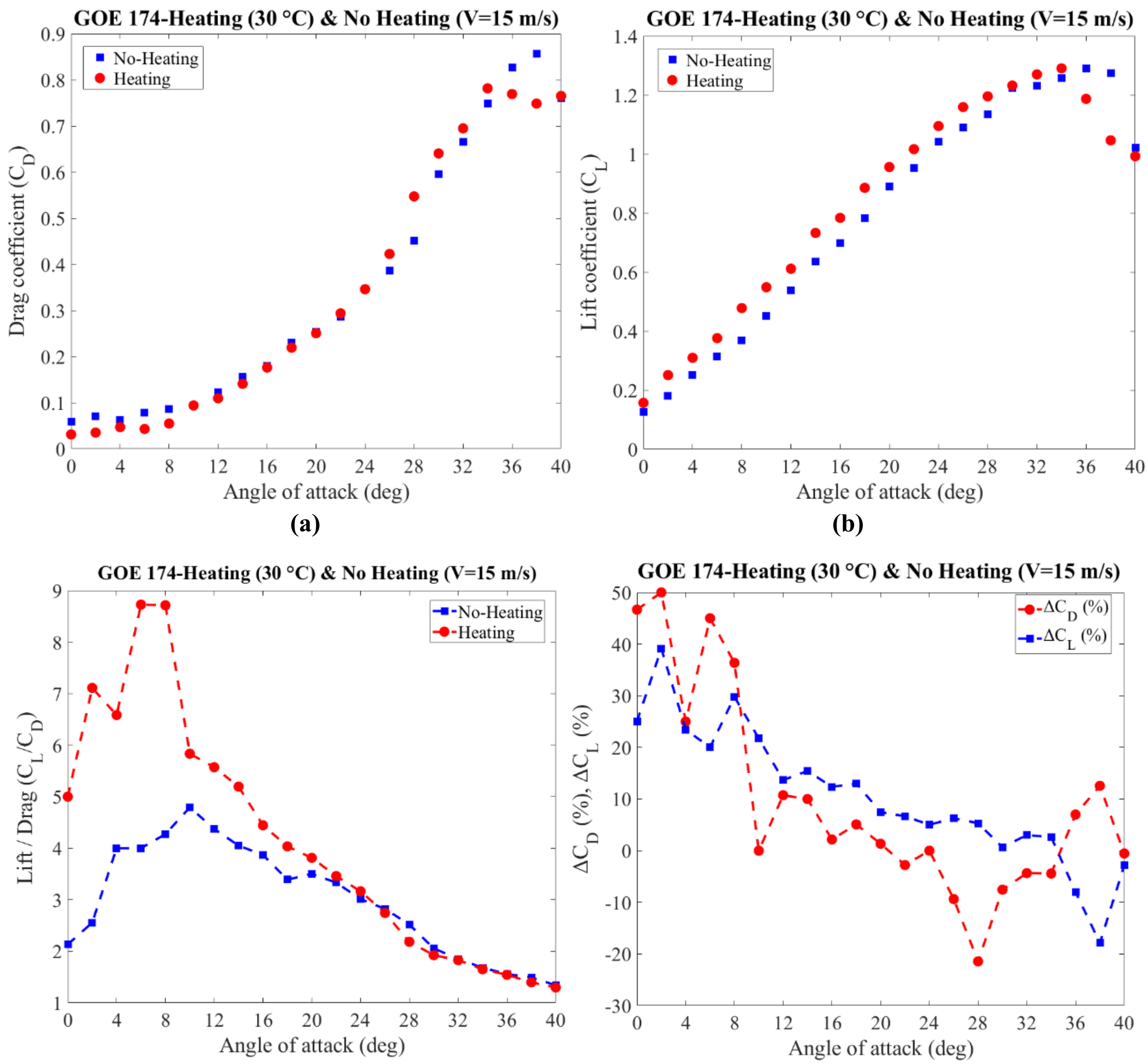


Figure 9. Views of aluminum wing and heating film on top surface of the wing.

The aluminum case airfoil is testing in the Educational Wind Tunnel HM 170. In Figure 10, a view of the designed experiment for wind tunnel testing is shown. In this experiment, the aerodynamic forces of drag and lift are with top surface heated and not heated.

Figure 10: View of Educational Wind Tunnel HM 170 and designed experiment for wind tunnel testing.

In this experiment, the ambient temperature of the wind tunnel is 20 °C and the temperature of top wing surface is set to 30 °C in the case of the heating. The experiment is carried-out for the wings with top heating and no heating conditions. In other words, a temperature difference of 10 °C is created for the top part of the wing, which is similar to the difference between the white and dark colored top wing surface of albatross calculated by Hassanalian et al.[9-11]. Experimental results for the lift and drag coefficients, lift to drag ratio, and the relative changes (percentages) of the lift and drag coefficients versus angle of attack for heating and no heating conditions at a wind speed of 15 m/s are obtained. The results are shown in Figures. 11(a)-11(d) in different angles of attack. It should be noted that in Figure 11(d) ΔC_D and ΔC_L indicate the drag reduction and lift enhancement percentages.



(c) (d)

Figure 11: View of (a) drag coefficient, (b) lift coefficient, (c) lift to drag, and (d) relative changes (percentages) of the lift and drag coefficients versus angle of attack of GOE 174 for heating and no heating conditions in the wind speed of 15 m/s.

Figure 11(a) shows that for bioinspired albatross airfoil (GOE 174), the drag coefficient is decreasing with increasing the top surface temperature for angles of attack that are less than 20 degrees. Figure 11(b) demonstrates that the lift coefficient for the top-heated wing increases until an angle of attack of 34 degrees. The experimental results in Figure 11(c) show that the lift to drag ratio increases for angles of attack up to 24 degrees and the maximum value of the lift to drag ratio can be achieved in angles of attack of 6 to 8 degrees. Figure 11(d) indicates that relative changes of drag and lift coefficients decrease with increasing the angle of attack and the maximum values can be seen in angles of attack of 0 to 2 degrees. It is apparent from Figure 11(d) that a drag reduction of 50% and lift enhancement of 40% can be obtained for a top-heated wing at an angle of attack of 2 degrees.

VII. Conclusions

Thermal analysis of temperature differences identified in natural flyers has been carried out to better understand the impact it can have on flight efficiency. Experimental studies were performed on black and white wings as well as aluminum plates to study the effects of their emissivity on their surface temperature. It was shown that black colors can get over 50% hotter than white, and due to the different conductivity coefficients, the bird wings reach higher temperatures than the same colored aluminum plates. These effects seem to play a major role in birds' efficiency. Through the application of such concept, a study was performed on heated top surfaces the GOE 174 airfoil. It has been found that at low angles of attack the overall efficiency can be substantially increased through the application of a thin, heated layer on the top surface of the airfoil.

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