A Comparison Study on AC-DBD Plasma and Electrical Heating for Aircraft Icing Mitigation

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A comparison study of utilizing thermal effects of a Dielectric-Barrier-Discharge (DBD) plasma actuator and a conventional electrical film heater for aircraft icing mitigation was performed in an Icing Research Tunnel available at Iowa State University (i.e., ISU-IRT). A NACA0012 airfoil/wing model embedded with an AC-DBD plasma actuator and a conventional electrical film heater over the airfoil surface was tested under a typical aircraft icing condition. While a high-speed imaging system was used to record the dynamic ice accretion and transient surface water transport processes over the airfoil surface, an infrared (IR) thermal imaging system was also utilized to map the corresponding surface temperature distributions over the airfoil surface simultaneously to quantify the unsteady heat transfer and phase changing process over the ice accreting airfoil surface. It was found that, for the same input power, the AC-DBD plasma actuator and the electrical film heater showed almost the equivalent effectiveness in preventing ice accretion over the airfoil surface. With the same total power input, further optimization of the AC-DBD plasma actuator with a duty-cycle modulation was found to have a better anti-/de-icing performance, in comparison to the conventional electrical film heater. The findings derived from the present study demonstrated the potential of a new class of anti-/de-icing strategy by leveraging the thermal effects of DBD plasma actuators for aircraft in-flight icing mitigation.

I. Introduction

Ice accretion on aircraft surfaces has been widely recognized as a significant safety hazard in cold weather, especially when aircraft travel through clouds with supercooled water droplets suspended. Many aviation accidents have been reported attributing to ice accretion on aircraft. Petty and Floyd¹, who summarized accidents that were caused by aircraft icing, found that there were more than 800 fatalities resulting from ice accumulations in the past 20 years. Depending on the flight conditions and environmental parameters, the in-flight ice accretion can be either rime or glaze². When the ambient temperature is relatively cold (i.e., typically below -10 °C) and the airflow is dry with a lower liquid water content (LWC), supercooled water droplets would freeze immediately upon impact on the aircraft surfaces, forming rime ice. At warmer temperatures, i.e., just below the water freezing temperature, if the LWC level in the airflow is relatively high, the impinged supercooled water droplets would freeze partially, with the remaining water mass transporting along the surface prior to freezing downstream, forming much complex ice shapes, which is called glaze ice. Because of its wet nature, glaze ice tends to extend further and substantially deform the ice accreting surface with the formation of “horns” growing outward in the airflow, causing large scale flow separations. Glaze icing is considered to be more dangerous since it usually leads to much more dramatic increases in drag and decreases in lift³. Although many efforts have been made in recent years⁴-¹¹, aircraft icing remains an important unsolved problem that is threatening the aviation safety.

While a number of anti-/de-icing systems have already been developed and implemented for aircraft icing mitigation, i.e., freezing-point depressants, thermal melting, and surface deformation¹², current anti-/de-icing strategies suffer from various drawbacks. For example, aqueous solutions of propylene and ethylene glycol (minimum of 50% concentration) along with other chemical additives are widely used for aircraft anti-/de-icing at airports¹³. Propylene and ethylene glycol, although readily biodegradable, exert an extremely high biochemical oxygen demand on aquatic systems that result in killing fish and other aquatic creatures due to the depletion of dissolved oxygen¹⁴.

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There has been an increasing concern of the environmental impacts from the aircraft anti-/de-icing fluid swept away with storm and melt water runoff at airports to ground water and nearby waterways. Pneumatic de-icing systems with rubber boots have been used to break off ice chunks accreted at airfoil leading edge for aircraft in-flight icing mitigation, but they are usually very heavy and sometimes unreliable. Ultrasonic and mechanical de-icing solutions are not easily integrated into existing aircraft and pose foreign object damage (FOD) hazards to engines. While electro-thermal de-icing systems have also been used to melt out ice by heating aircraft wing surfaces, they are usually very inefficient and have demanding power requirements, and can also cause damage to composite materials from overheating. Furthermore, the melted water may simply run back and re-freeze at a downstream location to cause uncontrolled ice accretion. In looking to improve the operational performance of aircraft in cold weather, methods and techniques for more efficient anti/de-icing performance but with less complexity and adverse environmental impacts are highly desirable.

Dielectric barrier discharge (DBD) plasma actuation is a form of ionized gas discharge generated by the application of high amplitude and high frequency AC voltage (AC-DBD) or nanosecond-scale pulsed voltage (ns-DBD) between two electrodes separated by a dielectric layer. The use of DBD plasma actuators as active flow control mechanisms has gained significant interest in the aerodynamic community, with its unique advantages including absence of moving components, fast response time, easy implementation and stable operation. Figure 1 shows a general configuration of a DBD plasma actuator, which has two electrodes (i.e., exposed electrode vs. encapsulated electrode) attached to the opposing surfaces of a dielectric barrier material. For AC-DBD, powered by an alternating current, ionized air molecules are formed in the discharge region above the encapsulated electrode, inducing a small fluid velocity adding momentum to the boundary layer. For ns-DBD plasma actuators, they usually induce an ultrafast gas heating mechanism eventually leading to the generation of a shockwave and suppression of boundary layer transition. Therefore, for the application of DBD plasma actuators on aircraft, they are usually designed to be located at the regions where the aerodynamic characteristics alter greatly as incoming flow changes, e.g., airfoil leading edge, duct lip of aero-engines, etc. It should be noted that, such aerodynamically delicate regions are always the preferential sites of in-flight ice accretion in cold weathers. Inspirationly, DBD plasma actuators have also been revealed to have significant thermal effects along with the ionic wind generation, which can be utilized for icing control as an alternative function of plasma actuators.

As revealed by Stanfield et al. and Dong et al., during a DBD plasma discharge, the rotational temperature of the gas above the grounded electrode of the DBD actuator can be up to 200 °C, while the vibrational temperatures were observed to be an order of magnitude higher than the rotational temperature. They also found that the primary mechanism for the heating of the dielectric layer is through heat transfer from the plasma, i.e., through direct injection, convection and radiation. The previous study also revealed that the maximum temperatures are always located near the edge of the exposed high-voltage electrode. To further characterize the thermal effects of DBD plasma discharge, Tirumala et al. conducted an infrared thermography measurement on the surface of a thick dielectric DBD plasma actuator. It was found that the predominant mechanism of dielectric heating is due to the heat transfer from the plasma to the gas which then heats up the dielectric surface through forced convection. The increase in temperature was found to have linear relationship with both the applied voltage and the input frequency. Adopting the significant thermal effects of DBD plasma actuation, Cai et al. conducted a feasibility study of the anti-/de-icing performance of an AC-DBD plasma actuator on an ice accreting cylinder model. It was found that the AC-DBD plasma actuator was very effective in both anti-icing and de-icing operations. Recently, a ns-DBD plasma actuator was also examined in the de-icing operations on an iced plate. With the ultrafast heating process of the ns-plasma actuator, the ice layer formed on the test plate was effectively removed. In spite of the noticeable advances made in the development of DBD plasma actuation, there have been some unresolved challenges.
actuators for icing control, the thermal physics of DBD plasma discharge and their applicability for aircraft in-flight icing mitigation remains unexplored, especially the operational performance of DBD plasma for icing control in comparison with the conventional electrical heating methods. There is no comparative data available in literatures to evaluate the effectiveness of DBD plasma and conventional electrical heating methods in term of icing mitigation on airfoil/wing models with equivalent power input. With this in mind, a comparison study between DBD plasma actuation and conventional electrical heating pertinent to icing mitigation on an airfoil model was performed systematically in this study to provide essential operational concepts for the development of a potential new class of anti-/de-icing strategy leveraging DBD plasma actuators tailored specifically for aircraft in-flight icing mitigation.

In the present study, an AC-DBD plasma actuator was fabricated and implemented to achieve anti-icing operations on an NACA 0012 airfoil in a typical glaze icing condition. In the meantime, a conventional electrical film heater was also attached on the airfoil model, side-by-side with the plasma actuator. The comparison study was conducted in the unique Icing Research Tunnel available at Iowa State University (i.e., ISU-IRT). While a high-speed camera was used to capture the transient details of the dynamic ice accretion and water transport processes over the airfoil model, an infrared thermal imaging system was utilized to map the surface temperature evolutions during the dynamic icing processes (with the AC-DBD plasma and the electrical film heater turned on). The temporally-synchronized-and-resolved measurements enabled the correlation between the icing-morphology and surface temperature distributions, which highlighted the underlying physics of thermal energy transfer in AC-DBD plasma actuation and electrical heating, and revealed their operational performance for icing mitigation.

II. Test Model and Experimental Setup

The comparison study of AC-DBD plasma actuation and electrical film heater for icing mitigation was performed in the unique Icing Research Tunnel available at Aerospace Engineering Department of Iowa State University (i.e., ISU-IRT). As schematically shown in Fig. 2, the ISU-IRT is a multifunctional icing research tunnel with a test section of 2.0 m in length × 0.4 m in width × 0.4 m in height with four side walls being optically transparent. It has a capacity of generating a maximum wind speed of 60m/s and an airflow temperature down to −25 °C. An array of 8 pneumatic atomizer/spray nozzles are installed at the entrance of the contraction section of the icing tunnel to inject micro-sized water droplets (10 ~ 100 μm in size) into the airflow. By manipulating the water flow rate through the spray nozzles, the liquid water content (LWC) in ISU-IRT could be adjusted (i.e., LWC ranging from 0.1 g/m³ to 5.0 g/m³). In summary, ISU-IRT can be used to simulate atmospheric icing phenomena over a range of icing conditions (i.e., from dry rime to extremely wet glaze ice conditions). A NACA 0012 airfoil model was used in this study, which was made of a hard-plastic material and manufactured by using a rapid prototyping machine (i.e., 3-D printing) that builds 3-D models layer-by-layer with a resolution of about 25 microns. The wing model has a chord length of \( c = 150 \) mm, which spanned the width of the test section. Supported by a stainless-steel rod, the wing was mounted at its quarter-chord and oriented horizontally across the middle of the test section.

Figure 2: A schematic of the icing research tunnel and experimental setup used in the present study.
The high-speed video was recorded using a metal-oxide semiconductor camera (PCO Tech, Dimax) which was installed 500 mm above the airfoil by using a 60 mm lens (Nikon, 60 mm Nikkor 2.8D). The camera was positioned approximately normal to the wing chord, with a measurement interest of 210 × 210 mm² and a pixel resolution of 9.5 pixels/mm. An in-situ calibration procedure as suggested by Soloff et al. was performed to dewarp the captured images before extracting physical features. Each test trial consisted of 3000 images acquired at a frame rate of 10 Hz. As for the infrared camera (FLIR A615), it was mounted 300 mm above and normal to the airfoil. The area of interest in infrared measurement is of 110 × 90 mm², with a corresponding pixel resolution of 5.3 pixels/mm. Radiation from the ice accretion airfoil model will firstly pass through an infrared window (FLIR IR Window-IRW-4C) before reaching the IR camera. Each test trial consisted of 15000 images acquired at a frame rate of 50 Hz. An in-situ calibration was performed to validate the infrared measurement results through establishing a relationship between measured count number from IR camera and temperature acquired by thermocouples. The measurement uncertainty for the IR camera was found to be less than 0.5°C. The high-speed camera and the IR camera were connected to a digital delay generator (Berkeley Nucleonics, model 575) that synchronized the timing between them.

![Figure 3: Schematic of a NACA 0012 airfoil/wing model with the AC-DBD plasma actuators and electrical film heater attached side-by-side on the surface.](image)

Figure 3 shows the configuration of the AC-DBD plasma actuator and the electrical film heater fabricated over the NACA 0012 airfoil model. The plasma actuator consisted of four encapsulated electrodes and five exposed electrodes, with the same thickness of about 70 µm as shown in Fig. 3. In the present study, three layers of Kapton film (i.e., 130 µm for each layer) were integrated to serve as the dielectric barrier to separate the encapsulated electrodes from the exposed electrodes. Ranging from the leading-edge position to about 0.27 chord length of the airfoil, four encapsulated electrodes were distributed evenly along the test model with separation distance of 3 mm. The length of the buried electrodes was about 350 mm, and the width was 10.0 mm (except the one at the leading edge which was 5.0 mm). As reported by Waldman and Hu, most of the ice would be formed around the leading edge of the airfoil. Therefore, it will be of great benefit to ensure a successful anti-icing on the front part of wing. In order to achieve leading edge anti-icing, the width of the first encapsulated electrode was reduced to 5.0 mm to generate more plasma at the leading-edge region, while the encapsulated electrodes were attached symmetrically around the leading edge of airfoil. As for the exposed electrodes (i.e., 96 mm in length and 3.0 mm in width), they were placed right above the covered electrodes with zero overlap between them. As clearly shown in Fig. 3, an electrical film heater (i.e., Kapton® Polyimide Film insulated heater) was attached on the other half side of the airfoil model, with a coverage area of 50.8
mm ×101.6 mm, which consists of an etched foil element of 0.013 mm thickness that is encapsulated between two layers of 0.05 mm Polyimide Film and 0.025 mm FEP adhesive tape. As shown in Fig. 3, a DC source was used to provide power supply for the electrical film heater.

Table 1. Experimental parameters used in the present study.

<table>
<thead>
<tr>
<th>$U_\infty$</th>
<th>$T_\infty$</th>
<th>LWC</th>
<th>$V_{p-p}$</th>
<th>$f$</th>
<th>$P_{input}$</th>
<th>$P_d$</th>
</tr>
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<tbody>
<tr>
<td>40 m/s</td>
<td>-5 °C</td>
<td>1.0 g/m$^3$</td>
<td>5 ~ 20 kV</td>
<td>10 kHz</td>
<td>40 W ~ 80 W</td>
<td>7.8 ~ 15.6 kW/m$^2$</td>
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In the present study, a typical glaze ice accretion was produced at the freestream air velocity of $U_\infty = 40$m/s, LWC = 1.0 g/m$^3$, and airflow temperature of $T_\infty = -5$ °C. The angle of attack ($\alpha$) of the airfoil model was set at $\alpha = 0^\circ$ throughout the experiments. The plasma actuator was wired to a high-voltage AC power supply (Nanjing Suman Co., CTP-2000K), which can provide maximum 30kV peak-to-peak sinusoidal voltage with a center frequency of 10 kHz. While the AC current was measured by using a high response current probe (Pearson Electronics, Inc., Pearson 2877), the high-amplitude voltage was measured by using a high voltage probe (i.e., P6015A from Tektronix®), and monitored and recorded by an oscilloscope (Tektronix DPO3054). The voltage of the sinusoidal excitation to the electrodes in the present study was manipulated with a variable voltage transformer at a constant frequency of 10 kHz.

During the experiments, to quantitatively compare the operational performance of the AC-DBD plasma actuator and the electrical film heater under different icing conditions, the applied power (or power density, $P_d$) to the plasma actuators was adjusted to be equivalent with that of the electrical film heater. Detailed experimental parameters were listed in Table 1.

III. Results and Discussions

A. Thermal Effects of AC-DBD Plasma Actuation

Recent studies$^{26,29-32}$ have demonstrated that DBD plasma actuators have significant thermal effects along with the generation of ionic airflow. With the high-voltage signal applied to the exposed electrode, a high-intensity electric field is generated between the exposed electrode and the grounded electrode separated by a dielectric layer. Driven by the electric field, the free electrons and ions in the air are responsible for energy transmission from the external power source to gas$^{32,35}$. The free electrons get energy from the electric field through acceleration, and then collide with neutrals and ions in the air. If an elastic collision occurs, there is an immediate but only a small portion of total energy release, while in inelastic collisions, ionized particles and excited molecules can be produced, which are the main sources of energy heating the gas. Collision between ions and neutrals/electrons is another source that contributes to the thermal energy generation in DBD plasma actuation$^{30}$. Therefore, the thermal energy generated during plasma discharge can be expressed using Eq. (1):

$$E_{\text{heat}} = E_{\text{ele}} + E_{\text{ion}}$$

where $E_{\text{heat}}$ denotes the thermal energy generated in plasma discharge, $E_{\text{ele}}$ is the energy released through collision between electrons (i.e., accelerated in electric field) and neutrals or ions, and $E_{\text{ion}}$ is the energy released through collision/quenching between ions and neutrals or free electrons.

In a recent study by Rodrigues et al.$^{37}$, it was also found that for lower voltage supplies at which there is no plasma formation, the input energy is almost equal to the thermal energy dissipated into the dielectric layer. It was suggested that at such low voltage levels, the energy applied to the plasma actuator can be completely converted into dielectric heating since there is no plasma formation and momentum transfer to the surrounding air.
Figure 4: Time evolution of the surface temperature distribution over the airfoil model with the AC-DBD plasma actuator operated at $V_{pp}=12.5\text{kV}, f=10\text{ kHz}$, at the test condition of $U_\infty=40\text{m/s}, \text{and } T_\infty=-5^\circ\text{C}$.

Figure 4 shows the time evolution of the surface temperature distribution over the airfoil model with the AC-DBD plasma actuator operated at $V_{pp}=12.5\text{kV}, f=10\text{ kHz}$, under the test condition of $U_\infty=40\text{m/s}, \text{and } T_\infty=-5^\circ\text{C}$. It is clearly seen that after the plasma actuator was enabled, the surface temperatures over the dielectric layer and the exposed electrodes were increased rapidly, with the local surface temperatures at the edges of the exposed electrodes increased from -5 °C to more than 25 °C in less than five seconds. The temperature distribution pattern was found to be rather uniform along the span-wise. It has been reported in the previous studies\textsuperscript{38} that the response time of momentum transfer in plasma discharge is in the order of 10–100 ms. As suggested by Rodrigues et al.\textsuperscript{37}, the dielectric layer heating would be initiated even before the generation of ionic airflow driven by the momentum transfer. Therefore, the response time for thermal energy generation was suggested to be shorter than that of the momentum transfer in plasma discharge. Figure 4(a) shows the surface temperature distribution over the airfoil model with the plasma actuators being turned on for $t=0.4\text{ s}$. It was found that the surface heating was first initiated at the edges of the exposed electrodes with an evident local temperature increase, (i.e., as indicated by the white strips in the temperature map over the airfoil shown in Fig. 4(a)). As the time goes on, more and more thermal energy was generated during the plasma discharge as shown in Fig. 4(b) to Fig. 4(d). It is clearly seen that the maximum temperatures were always located at the edges of the exposed high-voltage electrodes, which was also observed in the previous studies\textsuperscript{31}. It was also found that, during the plasma discharge, the temperature over the exposed electrodes (i.e., made of Copper tape) appeared to be much higher than that over the dielectric layer (i.e., fabricated with Kapton film). It is suggested that the temperature difference between the electrode surfaces and the dielectric layer surfaces is essentially caused by the significantly different thermal conductivities of the Copper tape and Kapton film (i.e., Copper tape of 385.0 W/m·K vs. Kapton film of 1.57 W/m·K). When comparing the surface temperatures at the different discharge locations on the dielectric layer (i.e., spacings between the exposed electrodes) as shown in Fig. 4(b) to Fig. 4(d), it was found that the surface temperature was the minimum at the leading edge, and increased accordingly at further downstream locations, which was due to the chordwise development of convective heat transfer intensity, i.e., with the maximum heat convection being at the leading edge and decreasing gradually in downstream\textsuperscript{39}.  

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Figure 5: The span-averaged temperature profiles along the airfoil chord at the different instances with the plasma actuator being operated at $V_{p-p}=12.5\,\text{kV}$, $f=10\,\text{kHz}$, under the test condition of $U_\infty=40\,\text{m/s}$, and $T_\infty=-5^\circ\text{C}$.

In order to further evaluate the thermal effects of the AC-DBD plasma actuation over the airfoil surface, the span-averaged temperature profiles along the airfoil chord were extracted at the different instances after the plasma actuator was enabled at $V_{p-p}=12.5\,\text{kV}$, $f=10\,\text{kHz}$, under the test condition of $U_\infty=40\,\text{m/s}$, and $T_\infty=-5^\circ\text{C}$ as shown in Fig. 5. The chordwise locations of the exposed electrodes were also illustrated in Fig. 5. It is clearly seen that the temperature profiles at the different time instances have a similar distribution pattern, with the temperature peaks being located at the edges of the exposed electrodes. For example, at the time instance of $t=0.4\,\text{s}$, while the surface temperatures over the dielectric layer were almost not changed and still below zero, the local temperature peaks at the electrode edges were found to be increased above zero and even higher than $5^\circ\text{C}$ as shown in Fig. 5. Along with the rapid temperature rise at the edges of the exposed electrodes, the temperatures over the electrode surfaces were also found to increase significantly in comparison to that over the dielectric layer. It is well known that the predominant heating mechanism in plasma discharge is due to the heat transfer from the plasma to the gas which then heats up the dielectric surface through forced convection \textsuperscript{32}. When the airfoil model with the plasma actuator was exposed in a cold airflow, the hot air generated in plasma discharge was not only concentrated above the dielectric layer, but also convected over the exposed electrodes. Thus, the temperature increase was also observed over the surfaces of the exposed electrodes. The magnitude of temperature increase over the electrodes/dielectric layer surfaces was essentially determined by the Biot number \textsuperscript{39}, which is defined as a simple index of the ratio of the heat transfer resistances inside of and at the surface of a body, and usually expressed as:

$$Bi = \frac{L \cdot h}{k}$$

where $L$ is the characteristic length of the body exposed in a fluid, $h$ is the convective heat transfer coefficient of the fluid, and $k$ is the thermal conductivity of the body. A smaller value of the Biot number implies a faster thermal response of the bode. Assume the heat convection coefficients at the adjacent electrode and dielectric layer are the same, the thermal response, i.e., surface temperature increase, of the exposed electrode and dielectric layer, can be quantitatively compared using Eq. (3):

$$\frac{Bi_{ele}}{Bi_{die}} = \frac{k_{die}}{k_{ele}}$$

where $Bi_{ele}$ is the Biot number for the exposed electrode, $Bi_{die}$ is the Biot number for the dielectric layer, and $k_{die}$ and $k_{ele}$ are the thermal conductivities of the dielectric layer and the exposed electrode, respectively. Based on the thermal conductivity values given above (i.e., Copper tape of $385.0\,\text{W/m} \cdot \text{K}$ vs. Kapton film of $1.57\,\text{W/m} \cdot \text{K}$), the ratio of the Biot number between the exposed electrode and dielectric layer was calculated to be $Bi_{ele}/Bi_{die} \approx 0.004$, which indicates that a much faster thermal response (i.e., temperature increase) is expected on the electrode surfaces exposed in the hot air. This is validated by the temperature profiles as shown in Fig. 5.
As the time goes on, the surface temperature appeared to increase rapidly, with the maximum temperature increased to more than 35 °C after 6.4 seconds operation of the plasma actuator. As can be seen clearly in Fig. 5, the temperature around the third exposed electrode was always higher than those over the other locations, which is suggested to be a result of the development of the thermal boundary layer over the airfoil surface. Since only one-side plasma discharge was actuated at the last electrode (the fourth electrode) as shown in Fig. 5, the surface temperature at the fourth electrode appeared to be lower than that at the third electrode, with only one temperature peak at the upper edge of the electrode. Further details on the time evolution of the surface temperatures will be discussed in the following sections.

B. Heat Transfer Mechanisms during Droplet Impingement on Plasma Region and Electrical Film Heater

In looking to compare the AC-DBD plasma actuation and electrical heating method for icing mitigation on the airfoil/wing model, a fundamental understanding of the heat transfer mechanisms during the droplet impingement on the plasma region (i.e., dielectric surface) and the electrical film heater is highly desirable to elucidate the underlying physics of the complex multiphase interaction before and during the droplet impingement.

![Figure 6: Heating mechanisms of an impinging droplet on two different surfaces: (a) electrical film heater, (b) Kapton dielectric layer with plasma discharge actuated above.](image)

Figure 6 shows the schematics of the heating mechanisms of the impinging droplets on two different surfaces, i.e., electrical film heater vs. Kapton dielectric layer with plasma discharge actuated above. For the electrical film heater, the thermal energy is generated at the film surface through resistive heating converted from the external electrical power source. Although some of the thermal energy is dissipated to the airflow within the thermal boundary layer through convective heat transfer, which may warm up the impinging droplet before contact with the hot surface, the dominating heating mechanism of the droplet is through heat conduction during the dynamic impinging process (i.e., impacting, splashing, and receding) as shown in Fig. 6(a). Due to the large temperature difference between the impinging droplet and the hot surface, the thermal energy is transferred from the surface into the droplet, which can keep the droplet warm (i.e., above the freezing point) or even evaporate the small-sized droplet during the impingement.

For the AC-DBD plasma actuation, however, the primary heating mechanism is through heat transfer from the plasma to the gas, which then heats up the dielectric surface through direct injection, convection and radiation, which is a reverse thermal path in comparison with that in the conventional electrical heating. Therefore, during the droplet impingement onto the surface with plasma discharge, the droplet is not only heated up through heat conduction in contact with the hot dielectric surface, but also effectively heated through forced convective heat transfer when it travels through the hot air in the plasma region as shown in Fig. 6(b). As revealed by Li et al. [40], the transient temperature of an in-flight droplet can be calculated using Eq. (4)

\[
T = T_c - T_e + T_e \exp \left[ \frac{(6\alpha h)}{(\rho c_p D)} \right] \exp \left[ \frac{(6\alpha h)}{(\rho c_p D)} \right]
\] (4)
where $T$ is the transient temperature of the in-flight droplet, $h$ is the convection coefficient of air around the surface of the in-flight droplet, $T_e$ is the temperature of surrounding air of the droplet, $\rho$ is the density of the droplet, $c_p$ is the specific heat of the droplet; $t_r$ is the time of flight of the droplet in the convective airflow, and $D$ is the diameter of the flying droplet. It is obvious that, for the same time of flight, a higher temperature of the surrounding air would imply a higher transient temperature of the in-flight droplet. Therefore, the temperature of the droplet before impacting on the surface with plasma discharge is expected to be much higher than that impinging onto the electrical film heater.

For the implementations of AC-DBD plasma actuator and electrical film heater for icing mitigation on aircraft, although the heating mechanisms of the two methods are different, they both utilize thermal energy to prevent the impinging supercooled water droplets from being frozen on the airfoil/wing surfaces. It should be noted that the conventional electrical film heaters usually have almost 100% energy efficiency in the sense that all the input electric energy is converted to thermal energy, while for AC-DBD plasma actuators, the heating efficiency varies from 50% to 90% in different operating conditions. In order to quantitatively evaluate the overall anti-icing performances of the two methods, the total power inputs were always kept identical in the comparison study of the plasma actuation and electro-heating during the icing experiments.

C. Anti-icing Performance of AC-DBD Plasma Actuation and Electrical Heating

In performing the ice accretion experiments, the ISU-IRT was operated at a prescribed frozen-cold temperature level (e.g., $T_e = -5$ °C for the present study) for at least 60 minutes in order to ensure ISU-IRT reaching a thermal steady state. Then, the DBD plasma actuator and the electrical film heater embedded over the airfoil/wing surface were switched on for about 60 seconds to achieve a thermal equilibrium state before turning on the water spray system of ISU-IRT. After the water spray system was switched on at $t = t_0$, the super-cooled water droplets carried by the incoming airflow would impinge onto the surface of the airfoil/wing model to start the ice accretion process. During the experiments, the high-speed imaging system and the IR thermal imaging system were synchronized to reveal the dynamic ice accretion process and the surface temperature evolution over the airfoil model simultaneously.

Figure 7 shows four typical snapshots of the instantaneous ice accretion with the power density of the plasma actuator and the electrical film heater being the same at $P_d = 7.8$ kW/m². The box in red dashed lines indicates the measurement window of the IR thermal imaging system. Since similar features were also observed for other test cases, only the measurement results obtained under the icing condition of $U_x = 40$ m/s, $T_e = -5$ °C and $LWC = 1.0$ g/m³ were shown and analyzed here for conciseness. As shown clearly in Fig. 7(a), at the beginning stage of the ice accretion experiment (i.e., at the time instance of $t = 10.0$ s), when the supercooled water droplets impinged onto the airfoil surface, since both the plasma actuator and the electrical film heater were enabled with the surface temperatures being well above the freezing point of water, the impinged water droplets were kept warm, and no longer in the supercooled state, by absorbing the thermal energy generated in plasma actuation and electrical heating. Therefore, the coverage regions of the plasma actuator and the electrical film heater on the airfoil model (i.e., from the leading edge to ~27% chord length) were free of ice, but with evident water film/rivulets runback being observed as shown in Fig. 7(a).

Driven by the boundary layer airflow over the airfoil surface, the unfrozen water film/rivulets flow was found to run back to the further downstream regions. It can be seen clearly that, the runback water started to refreeze in the downstream region after about 60% chord length on the electrical film heater side, while the water runback over the plasma side appeared to be less and very few ice formation was observed. It is suggested that at the beginning stage of water impingement, the air over the plasma region was sufficiently heated which can effectively melt and evaporate the small-sized water droplets (i.e., with diameters less than 100 µm) that traveled through it. For the droplets impinged onto the electrical film heater, since the thermal energy was mainly transferred from the bottom substrate, and the input power was not sufficiently high to instantly evaporate the water droplets, they were quickly formed into rivulets/film and transported downstream, and refroze due to the intense convective heat transfer. As the time goes on, more and more water droplets impinged onto the plasma region and the electrical film heater over the airfoil. Since the deposited water film over the dielectric layer/exposed electrodes of the plasma actuator would have a complex interaction with the plasma $^{41}$, which may result in a degradation of the thermal effects during plasma discharge, more and more water were found to be collected and transported downstream over the surface, and started to refreeze as can be seen in Fig. 7(b). In the meantime, more rivulets-shaped ice formation was observed in the downstream region of the electro-heater side. The water/ice rivulets formed in the early stage of ice accretion (on both plasma and electro-heater sides) became the transport channels for the further collected water on the airfoil surface. As the time goes on, more and more water was collected and frozen downstream as shown in Fig. 7(c) and Fig. 7(d).

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In order to achieve a better anti-icing performance of both the AC-DBD plasma actuator and the electrical film heater under the same icing condition, the power inputs to the plasma actuator and the electrical film heater were increased by a factor of two (i.e., $P_d = 15.6 \text{ kW/m}^2$) to generate more thermal energy in the sense of preventing ice formation on the airfoil surface. The typical snapshots of the instantaneous water runback/ice accretion under this operational condition are shown in Fig. 8. It can be clearly seen that, with the higher power input, the airfoil surface was completely free of ice on both sides of the airfoil in the early stage of water collection (i.e., $t \leq 50 \text{ s}$) as shown in Fig. 8(a) to Fig. 8(c). Similar to that observed in the case with lower power input, the plasma side of the airfoil surface appeared to have less water runback in comparison to that on the electro-heater side. It was also found that the runback velocity of the surface water rivulets on the plasma side was slower than that on the electro-heater side, which is suggested to be caused by the different roughness distributions on the two sides of the airfoil leading edge. Since the slower runback velocity of the surface water would allow a longer and more sufficient heat convection to take away the heat in the water, as more and more water droplets impinged on the airfoil surface, ice started to form at a nearer location on the plasma side after about $t = 200 \text{ s}$ of water spray as shown in Fig. 8(d).
Figure 8: Typical snapshots of the dynamic ice accretion process with the power density of the plasma actuators and the film heater being $P_d = 15.6 \text{ kW/m}^2$ under the icing condition of $U_\infty = 40 \text{ m/s}$, $T_\infty = -5 ^\circ \text{C}$ and $LWC = 1.0 \text{ g/m}^3$.

Figure 9 shows the time evolution of the temperature distributions over the airfoil surface with the power density being kept constant at $P_d = 15.6 \text{ kW/m}^2$ on both sides of the airfoil before and during the ice accretion process at $U_\infty = 40 \text{ m/s}$, $T_\infty = -5 ^\circ \text{C}$ and $LWC = 1.0 \text{ g/m}^3$. The corresponding surface temperature variations at the different chordwise locations (i.e., location A at 2% chord, B at 10% chord, C at 18% chord, D at 45% chord, as indicated in Fig. 9(a)) on the two sides (i.e., plasma side vs. electro-heater side) of the airfoil model are also shown in Fig. 10. As can be seen clearly in Fig. 9(a), after the plasma actuator was enabled for $t = 10 \text{ s}$, the temperatures over the surfaces of the exposed electrodes were found to increase to about $10 ^\circ \text{C}$, while the temperatures over the dielectric surface (i.e., the spacings between the electrodes) were still kept below zero (i.e., the freezing point), which has been discussed in the previous section. The electrical film heater was enabled simultaneously with the plasma actuator during the test. It was found that there was a strip-patterned temperature distribution over the electro-heater after 10 seconds of operation as shown in Fig. 9(a). Such strip-like temperature distribution was essentially due to the configuration of the etched foil resistance element encapsulated between the Polymide films in the electro-heater. As the time goes on, more and more thermal energies were generated on both the plasma side and the electro-heater side of the airfoil. After running the plasma actuator and the electro-heater for about 60 seconds, a thermal equilibrium state was achieved on both sides of the airfoil model as indicated by the flattening temperature variation curves at $t = 60 \text{ s}$ shown in Fig. 10 (a) and Fig. 10(b). At this thermal equilibrium state, it was found that the temperature distribution on the electrical film heater was much higher than that over the plasma region as clearly shown in Fig. 9(b). The temperatures at location C (i.e., 18% chord) were found to be the maximum on both sides with values of $20 ^\circ \text{C}$ and $90 ^\circ \text{C}$ on the plasma side and the electro-heater side, respectively. As mentioned above, while the thermal energy generated by the electrical film heater is mainly at the film surface through resistive heating, the primary heating mechanism in AC-DBD plasma...
Actuation is through heat transfer from the plasma to the gas, which then heats up the dielectric/electrodes surfaces through direct injection, convection and radiation. Therefore, with the same power input, the measured surface temperature on the electro-heater surface appeared to be much higher than that over the plasma region. It was also found that, after the thermal equilibrium state was achieved, the temperature appeared to be higher at locations further away from the leading edge (until location C at 18% chord length) as clearly shown in Fig. 9 and Fig. 10. It is suggested that such temperature gradient was due to the development of the thermal boundary layer over the airfoil surface, with the maximum heat convection at the leading edge and decreasing gradually in downstream region.

Figure 9: Time evolution of the surface temperature distributions over the plasma and electro-heater sides of the airfoil surface with the input power density being $P_d = 15.6 \text{ kW/m}^2$ before (i.e., (a) and (b)) and during (i.e., (c) and (d)) the ice accretion process at $U_x = 40\text{m/s}$, $T_x = -5^\circ \text{C}$ and $LWC = 1.0 \text{ g/m}^3$.

As indicated in Fig. 10, the ice accretion process was started at $t = 60 \text{s}$ after the plasma actuator and the electrical film heater were enabled. This time instant was also defined as $t_0$, as given in Fig. 9(c) and Fig. 9(d). It was found that after the supercooled water droplets impinged onto the airfoil surface, for instance at $t = t_0 + 25 \text{s}$, while the temperature on the electro-heater surface decreased significantly, the temperature on the plasma region only dropped slightly as shown in Fig. 9 (c). As the time goes on, although more and more water was collected on the airfoil surface, since the power input to the plasma actuator and the electro-heater were sufficiently high to prevent ice accretion over the surfaces, the mass transport and energy transfer on the two sides of the airfoil were found to reach an equilibrium state, as indicated by the almost unchanged temperature distributions after $t = t_0 + 200 \text{s}$ as shown in Fig. 9(d). More quantitatively speaking, after the water droplets impinged on the airfoil surface, while the temperature drop on the plasma region was about 33% (i.e., the temperature dropped from 12 °C to 8 °C at location A and B, and dropped from 18 °C to 12 °C at location C) as shown in Fig. 10(a), the temperature decrease on the electrical film heater was around 70% (i.e., the temperature decreased from 25 °C to 6 °C at location A, from 60 °C to 20 °C at location B, and from 90 °C to 25 °C at location C) as shown in Fig. 10(b). Such temperature variations before and after the water impingement can be explained by the different heating mechanisms discussed in the previous section. For the electrical film heater, since the thermal energy was mainly generated at the heater surface, and then transferred into the impinged supercooled water droplets instantly upon impact, the measured surface temperature, therefore, appeared to drop...
significant when the temperature different was large between the surface and the water droplets. For the droplets impingement on the plasma region, however, the droplets had been effectively heated through forced heat convection when they traveled through the hot air in the plasma region before impacting on the warm dielectric/electrodes surface.

Figure 10: Surface temperature variations at the different chordwise locations on (a) the plasma side and (b) the electro-heater side over the airfoil model before and during ice accretion process at \( U_{\infty} = 40 \text{ m/s}, T_{\infty} = -5 \text{ °C} \) and \( LWC = 1.0 \text{ g/m}^3 \), with the input power density being kept at \( P_d = 15.6 \text{ kW/m}^2 \).

D. Further optimization of AC-DBD Plasma Actuation for Icing Mitigation

Based on the above comparison study of the anti-icing performances of AC-DBD plasma actuation and electrical heating, it can be concluded that, for the same power input, the two methods showed almost equivalent effectiveness in the sense of icing prevention over the airfoil surface. However, since DBD plasma actuators have a unique advantage of fast response time (in the order of 10–100 ms) in terms of momentum transfer \(^{38}\) and thermal effects \(^{37}\) in plasma discharge, the implementation of the AC-DBD plasma actuator for icing mitigation can be further optimized by adopting a duty-cycle control. Thus, with the same instantaneous power input to the plasma actuator, the total power consumption can be reduced, for example, half of the energy can be saved when using a duty cycle of \( \tau = 50\% \). In the present study, an explorative study of the anti-icing performance of duty-cycled plasma actuation was also performed in comparison to that of the electrical heating method with the same total power input under the same icing condition (i.e., \( U_{\infty} = 40 \text{ m/s}, T_{\infty} = -5 \text{ °C} \) and \( LWC = 1.0 \text{ g/m}^3 \)).

Figure 11 shows four typical snapshots of the ice accretion process with the instantaneous input power density of the duty-cycled plasma actuation (with a duty cycle of \( \tau = 50\% \) at frequency of \( f_{\text{duty-cycle}} = 250 \text{ Hz} \)) being \( P_d = 15.6 \text{ kW/m}^2 \), while the power density of the electro-film heater was kept at \( P_d = 7.8 \text{ kW/m}^2 \). In this comparison, although the instantaneous power inputs were different for the plasma actuator and the electrical film heater, the total power consumptions over time remained the same. It can be seen clearly in Fig. 11(a) that, when the supercooled water droplets impinged onto the airfoil surface, since both the plasma side and the electro-heater side were heated up, the impinged supercooled water droplets would instantly absorb the thermal energy upon impact, with the temperature increased above zero (i.e., the freezing point of water) and being no longer in supercooled state. As a consequence, the impinged water quickly merged into film or rivulets, which were transported downstream driven by the boundary layer airflow over the airfoil surface as shown in Fig. 11(a). It was found that the surface water runback on the plasma side was much lesser than that on the electro-heater side, which is suggested to be caused by the more significant evaporation of the impinging droplets over the plasma region. As the time goes on, more and more water droplets impinged on the airfoil with more water runback appeared in the downstream region (i.e., after 50% chord length) as shown in Fig. 11(b). Since the temperature of the surface water was not sufficiently high, the heat stored in the water was rapidly removed by the intense heat convection during the runback process, therefore, the rivulets-shaped ice was formed as clearly seen in Fig. 11(c) to Fig. 11(d). It should be noted that, although both sides of the airfoil had ice formations in the downstream region, the plasma side obviously had much lesser ice accretion in comparison to that on the electro-heater side. It is suggested that, with the duty-cycle modulation of the AC-DBD plasma actuator, the plasma actuation would have a better anti-icing performance in comparison to the conventional electrical film heater.
Figure 11: Typical snapshots of the ice accretion process with the instantaneous input power density of the duty-cycled plasma actuation (with a duty cycle of $\tau = 50\%$ at frequency of $f_{\text{duty-cycle}} = 250$ Hz) being $P_d = 15.6$ kW/m$^2$, while the power density of electro-film heater was $P_d = 7.8$ kW/m$^2$ under the icing condition of $U_\infty = 40$ m/s, $T_\infty = -5$ ºC and $LWC = 1.0$ g/m$^3$.

**IV. Conclusions**

In the present study, a comparison study between AC-DBD plasma actuation and conventional electrical heating method for icing mitigation on an airfoil model was performed to demonstrated the potential of utilizing DBD plasma actuators for aircraft in-flight icing mitigation. The experimental study was performed in the Icing Research Tunnel available at Aerospace Engineering Department of Iowa State University (i.e., ISU-IRT). A NACA0012 airfoil/wing model embedded with an AC-DBD plasma actuator and a conventional electrical film heater over the airfoil surface was tested in the ISU-IRT under a typical glaze icing condition. During the experiments, while a high-speed imaging system was used to record the dynamic ice accretion and transient surface water transport processes over the airfoil surface, an infrared (IR) thermal imaging system was also utilized to map the corresponding surface temperature distributions over the airfoil surface simultaneously. Based on the side-by-side comparisons of the measurement results (i.e., snapshots of the visualization images and quantitative surface temperature distributions) for the plasma side against those of the electro-heater side under the same icing condition, the effectiveness of using the thermal effects induced by DBD plasma actuation and conventional electrical heating for aircraft icing mitigation was compared and evaluated in details.
It was found that, for the same input power density, the temperature distribution on the electro-film heater was much higher than that over the plasma region before the water droplets impingement, which was essentially due to the different heating mechanisms of the two methods (i.e., for the electrical film heater, the thermal energy was mainly generated at the heater surface, while in AC-DBD plasma actuation, the heating path is through heat transfer from the plasma to the gas, which then heats up the dielectric/electrodes surface through direct injection, convection and radiation). After the water droplets impinged onto the airfoil surface, while the surface temperature over the electrical film heater dropped significantly due to the instant heat transfer from the electro-heater surface to the impinged water, the measured surface temperature over the plasma side appeared to decrease slightly, since the impinged water droplets were not only heated up through heat conduction in contact with the hot dielectric/electrodes surfaces, but also effectively heated through forced heat convection when they traveled through the hot air in the plasma region. As a result, the AC-DBD plasma actuator and the electrical film heater showed almost the equivalent effectiveness in the sense of icing prevention over the airfoil surface.

Further optimization of the AC-DBD plasma actuator was also achieved by adopting a duty-cycle modulation, based on its unique advantage of fast response time in terms of momentum transfer and thermal effects in plasma discharge. The implementation of the duty-cycled plasma actuation can reduce the total power consumption over time, while the same instantaneous power input was applied to the plasma actuator, for example, half of the energy can be saved when using a duty cycle of \( \tau = 50\% \). By comparing the anti-icing performances of the duty-cycled plasma actuation and the electrical heating method with the same total power input under the same icing condition, it was found that, the duty-cycled plasma actuation have a better anti-icing performance in comparison to the conventional electrical film heater.

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