An experimental study of icing physics and anti-/de-icing techniques for structural cables

by

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The student author, whose presentation of the scholarship herein was approved by the program of study committee, is solely responsible for the content of this dissertation. The Graduate College will ensure this dissertation is globally accessible and will not permit alterations after a degree is conferred.

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ABSTRACT

Atmospheric icing is one of the major problems faced in cold regions. The problems caused by the icing mainly has adverse effect on several engineering structures and machines. For instance, the electric power transmission cables, aircrafts wings and other critical components exposed to atmosphere, wind turbines, suspension bridge cables etc. are some of the engineering structures which are severely affected by atmospheric icing. Some of the icing events can have very critical after-effects. In recent years the damaging effect of atmospheric icing on transmission lines has become an increasingly important. As we become more dependent on reliable energy and communications, even in remote areas, transmission line failure is a costly inconvenience at the very least, and it can threaten human life. At the same time, it is desirable to minimize construction and maintenance costs. These circumstances have called for more research into the causes of atmospheric icing and its effects on transmission lines. Significant progress must be made in our understanding of the problem. One of the most important factors that need attention is the understanding of the combined effect of the wind and the shape of accreted ice on the loads exerted on a conductor.

In this study, experimental investigations were conducted to examine the dynamic ice accretion process over the surface of a high-voltage power transmission cable model and characterize the effects of the ice accretion on the aerodynamic forces acting on the test model. The experimental study was carried out by leveraging the unique Icing Research Tunnel of Iowa State University (i.e., ISU-IRT) to generate typical wet glaze and dry rime icing conditions experienced by power transmission cables. In the first phase of the study, a cylindrical power cable model, which has the same diameter as that of typical power transmission cables, was mounted in ISU-IRT for the ice accretion experiments. In addition to using a high-speed digital imaging system to record the dynamic ice accretion process, a novel digital image projection (DIP) based
technique was utilized to quantify the 3D shapes of the ice structures accreted on the surface of the power cable model as a function of the ice accretion time. The time variations of the aerodynamic drag force acting on the test model during the dynamic ice accretion process were also measured quantitatively by using high-sensitive force/moment transducers mounted at the two ends of the test model.

In the second phase, an aluminum conductor steel reinforced (ACSR) model, which is the most commonly used type of transmission cable model was investigated in the same manner. In the third phase, a series of two ACSR conductors (bundled conductors) were used to understand the effects of the presence of the windward conductor on the ice accretion of the leeward conductor. The ice structures accreted over the surface of the power cable model were found to change significantly under different icing conditions (i.e., rime icing vs. glaze icing). The characteristics of the aerodynamic drag acting on the test model was found to vary significantly during the dynamic ice accretion process, highly dependent on the type of ice structure which accreted on the test model. The acquired snapshots of the ice accretion images and the measured 3D shapes of the accreted ice structures on the test model are correlated with the aerodynamic force measurement results to elucidate the underlying physics. The icing characteristics of smooth cylinder was different from the ACSR conductor indicating that the effects of icing is dependent on the outer profile of the conductor. The ACSR conductor accreted much more ice and was subjected to more severe drag forces. The study using bundled conductors revealed that the effects of icing on the leeward conductor are significantly modified by the presence of a windward conductor.

In the next phase, several anti-icing techniques have been investigated. Very recently, dielectric barrier discharge (DBD) plasma actuation has been suggested as a promising, alternative anti-/de-icing method, by leveraging the thermal effects induced by DBD plasma generation.
Several anti-icing hydrophobic and super hydrophobic coatings and hybridization with DBD plasma were also investigated and was found to be effective in mitigating the effects of icing.

The final phase of the study was conducted in the black wind tunnel at IOWA state university. This study aimed to establish a metamodeling-based technique to optimize the parameters of a dielectric barrier discharge (DBD) plasma used for flow separation over the surface of a wind turbine model in deep stall. The applied voltage and frequency for the NS-DBD plasma actuation were used as the design variables to demonstrate the optimization procedure. The highest possible lift coefficient of the turbine airfoil model at deep stalled angles of attack (i.e., $\alpha = 22^\circ$ and $24^\circ$) were selected as the objective function for the optimization. It was found that, while the metamodeling-based procedure could accurately predict the objective function within the bounds of the design variables with an uncertainty $\sim 2\%$, a global accuracy level of $\sim 97\%$ was achieved within the whole design space.
CHAPTER 1. GENERAL INTRODUCTION

Background and Motivation

Atmospheric icing is one of the major problems faced in cold regions. The problems caused by the icing has adverse effect on several engineering structures and machines. For instance, the electric power transmission cables, aircrafts wings and other critical components exposed to atmosphere, wind turbines, suspension bridge cables etc. are some of the engineering structures which are severely affected by atmospheric icing. Some of the icing after-effects could be very critical. The adverse effects caused by the ice accretion on power transmission lines has always been a serious problem and it is the major focus of this paper. Ice accretion on transmission line cables due to freezing rain and also due to in-cloud icing reduces the reliability of electrical power distribution networks during the most critical cold periods, and may lead to major damages to power lines [1]–[3]. It had led to several incidents and accidents in the past. For instance, a major icing event which occurred in Quebec and Ontario in winter 1998 had led to loss of power for about one million customers for about 3-30 days. Material damage was also substantial with hundreds of miles of transmission, sub-transmission and distribution lines being destroyed leading to an estimated cost of one billion Canadian dollars for reconstruction. Social cost involved in the incident exceeded three times that amount [4]. In extreme cases, the atmospheric icing can cause severe damages to transmission cables and associated towers resulting in extensive electric power breakdown.

The shape and the density of the ice accreted on the cable are of major interest in investigating the potential risks involved. The wide variations in size, density, and shape of the ice formations cause an equally wide variety of loads to be imposed on the structural system of the transmission line. The weight of the accreted ice increases the vertical load on the conductors as
well as the support structures. Combined effect of ice and wind can cause the transverse load on a transmission line to be increased significantly. It can cause vibrational loads due to wind if the ice deposition is asymmetric [5]. Natural winds can cause wind induced vibrations (oscillations caused by the vortex shedding) on transmission line conductors. These vibrations may adversely affect the reliability and durability of conductors and associated components. Damping devices may be used to attenuate this. However, when ice precipitations accrete on the conductors, the situation can change dramatically. The vibrations of conductors coated with ice may then occur in frequency ranges outside the design range of the dampers. Galloping, another wind-induced instability, also occurs on ice-accreted conductors and may result in large amplitude low frequency conductor displacements similar to ice coated suspension bridge cables mentioned earlier [6]. In addition, ice accumulation may also lead to flashover, where two conductors in wind induced motion would come in contact resulting in electrical discharge across them. Flashover may also happen when ice coated conductor sheds ice which results in sudden vertical displacement of the conductor [7]–[9].

Direct observation of the effects of icing on overhead power lines is absolutely necessary preliminary to any understanding of the many phenomena that can occur. Without such observations, unrealistic assumptions about the mechanisms could be made and it may lead to incorrect or incomplete solutions based on analysis. Since the number of variables such as the overhead line designs, the thickness and density of the ice or snow deposits, and the wind loadings to name a few, is large, detailed experiments needs to conducted in order to understand the effect of these parameters. Measurements conducted on transmission lines or test lines with natural or artificial ice are included to better understand and quantify those phenomena. Many of these effects have partial or approximate models supported by field data, to assist in reducing the damage.
However, there is a need for more work for complete understanding, including cooperative ventures employing the different resources available to universities and utilities [6]. Many high voltage transmission lines used bundled conductors rather than single conductors. The ice accretion characteristics of the windward conductor could be very different from leeward conductors. This phenomenon also needs investigation.

While a number of studies has been conducted recently on transmission cable icing phenomena [10]–[15], very little can be found in literature to quantify the 3D shapes of the ice structures accreted dynamically on the surfaces of transmission cables and characterize the time-evolution of aerodynamic forces acting on power transmission cables during the dynamic ice accretion process under different icing conditions. A digital form of accreted ice could be very much useful for conducting dry wind tunnel tests as well as numerical studies.

The harmful effects of ice accretion could be mitigated using proper anti-icing techniques. Several hydrophobic/super hydrophobic coatings could be used for this purpose. Use of dielectric barrier discharge plasma may seem to be a good option as the required electrical power for the plasma could be taken from the power line itself.

In the present study, a comprehensive experimental investigation was conducted to examine the dynamic ice accretion process over the surface of a typical power transmission cable and characterize the effects of the ice accretion on the aerodynamic forces acting on the cable. Studies are also conducted on bundled conductors to assess the effects of windward conductor on the leeward conductor. Suitable anti icing techniques are also proposed.

**Literature Review**

**Types of Ice Accretion**

It is well known that ice accretion on cold surfaces can be of several types depending on the icing conditions. Rime and glaze ice are two very common icing conditions—the specific type
is dependent on the ambient air temperature, wind velocity, liquid water content (LWC) of the oncoming air, and median volumetric diameters (MVD) of the impinging water droplets. Relatively low temperatures less than -10 °C and lower LWC favors a dry regime of icing where all the water impinging on the surfaces immediately freezes to form rime ice. Warmer temperatures around -5 °C and relatively higher LWC level favors a wet icing regime where only a portion of the impinging water freezes in the impingement area and the remaining unfrozen water runs back over the surface of the material and can freeze in the downstream locations causing glaze ice formation [16], [17]. Rime ice accretion usually tends to follow the original contour of the model, since the water droplets freeze almost immediately upon impingement on to the surface. This is often associated with less aerodynamic penalties as compared to glaze ice which follows an irregular ice profile. Glaze ice is the most dangerous type of ice. As glaze ice is caused by wet icing conditions, it forms much more complicated shapes and hence have larger aerodynamic penalties.

Man-made structures at elevated regions like top of mountains are often exposed to rime icing. In other areas, wet snow or freezing rain (glaze ice) likewise affect infrastructure at lower altitudes. Therefore, power lines, wind turbines, telecommunication towers or high masts, ski lifts and other buildings are designed to withstand the loads and other adverse effects due to icing, as well as ice loads affecting their mechanical strength or operational reliability in many ways [6].

Figure 1-1 shows the largest ice ever accreted on power transmission lines. This accretion was observed in Norway in April 1961, and the greatest elliptic cross-section diameter was measured at 1.4 m and the smallest at 0.95 m. A one-metre length of the accretion was collected and weighed 305 kg.
Figure 1-2 shows a wet snow incidence in Iceland. The cross-section accretion is in this case quite uniform in physical appearance, without a pronounced pattern showing the elliptic build-up.

**Figure 1-1:** Rime icing on a 22 kV electric power line in Norway April 1961, 1 400 m above sea level. The ice load was measured to 305 kg/m

**Figure 1-2:** Wet snow accretion on a collapsed power line in Iceland
Atmospheric Icing Process

Atmospheric icing is a generic term for all types of accretion of frozen water substance, generally belonging to two main categories: (1) precipitation icing, and (2) in-cloud icing. Both may cause severe damage to the types of infrastructures mentioned above.

Precipitation icing

Precipitation icing may result in glaze, wet snow or dry snow, depending on how the precipitation is influenced by variations in temperature near the ground and up to a few hundred meters above ground. Such icing is experienced any place where precipitation, in combination with freezing temperatures, occurs. Freezing rain requires a specific temperature distribution with elevation. Generally it is the result of temperature inversion where the temperature near the ground surface is colder than the air above it which is opposite of the general observation. In such cases, falling snow can melt as it passes through a warmer region to become wet water droplets. As this falls down to cooler regions below, it enters a super cooled state and freezes on the cable surfaces [18]. Dry snow may accrete when wind speeds are sufficiently low, typically less than 2 m/s. Although this sometimes causes heavy snowfall, density never exceeds 100 kg/m³. Hence the accreted masses are, in most cases, much lower than the loads the power lines are designed for. Wet snow is generally formed during a very narrow surface air temperature interval, slightly above 0°C. Snowflakes falling through air with increasing temperatures near the ground may eventually meet temperatures above the freezing point. As soon as snowflakes meet above-freezing temperatures, they start to melt. And when liquid water appears between the branches of a snowflake, it becomes sticky and can adhere to other objects. However, once a snowflake becomes very wet, like slush, the adhesion force is diminished, and most of its mass will drop off the object. It is not fully known at which liquid-to-frozen water mixing ratio the adhesive forces are strongest,
but in general flakes adhere readily to objects when their liquid water content (LWC) lies between 15 to 40% of the total mass of the snowflake [6].

**In-cloud icing**

In-cloud icing occurs only within clouds consisting of supercooled droplets, which are droplets that remain liquid at a temperature below 0°C. Depending on the cloud LWC, the size distribution of the cloud droplets, temperature and wind speed (perpendicular to the object), soft or hard rime may occur. It therefore occurs most often near the top of exposed mountains. The intensity and duration of in-cloud icing depends on the flux of liquid water in the cloud, which again depends on many parameters such as temperature, wind speed, stability, depth of cloud, height above cloud base and distance from coastline [6].

**Icing Models**

To describe precipitation icing (wet snow and freezing rain) the most important parameters are:

- Precipitation rate
- Surface air temperature
- Liquid water content of snow flakes
- Wind speed and wind direction
- Air temperature
- Relative humidity and visibility

For in-cloud icing the parameters are:

- Liquid water content in the cloud
- Droplet size distribution
- Air temperature
• Wind speed wind direction

• Relative humidity

It is also important to include parameters of the cable model, such as surface properties, shape, linear dimensions, torsional stiffness, etc.

The fundamental physics of ice accretion are demonstrated by equation (1.1) from the ISO Standard ISO 12494 (2000), also called the Makkonen model

\[
\frac{dM}{dt} = \alpha_1 \alpha_2 \alpha_3 (LWC) U A
\]

where \( \alpha_1 \) = collision efficiency (for in-cloud icing and freezing rain, \( \alpha_1 = \alpha_1(V,D,d) \))

\( \alpha_2 \) = sticking efficiency (mainly for wet snow)

\( \alpha_3 \) = freezing efficiency (determines “dry” and “wet” growth for rime ice and freezing rain)

\( M \) = accreted ice mass (per unit length)

\( LWC \) = liquid water mass/unit volume

\( U \) = wind speed (perpendicular to accreting object)

\( A \) = cross-sectional area of object.

Over the years, numerous studies, including both laboratory and field studies, have been performed to quantify the coefficients \( \alpha_1, \alpha_2 \) and \( \alpha_3 \). There has been however, by far, much less effort expended to determine the meteorological input elements like air temperature, LWC, wind (speed and direction). One of the objectives of this study is to investigate the effects of these parameters.

**Previous Studies on Transmission Cable Icing**

Koss et.al. [19] studied the ice accretion on a circular cylinder at moderate temperatures in the Altitude Icing Wind Tunnel at the National Research Council of Canada (NRC) in Ottawa with the purpose of establishing detailed knowledge on the shape characteristics of ice accretion
on circular cylinders under the specific conditions where large amplitude vibration of iced bridge have been observed in nature. With respect to temperature, three main ranges could be isolated. The low temperature range (-5 °C to -4 °C) with dry ice growth, the high temperature range (-2 °C to -1 °C) characterized by wet ice growth and a transition range at around -3 °C.

Qing et. al. [20] studied the ice accretion on bundled conductors by both simulation and experiments. They found that ice accretion on a windward conductor is the same as that on a single conductor. It was also observed that for 2-bundled conductors, when two conductors are not in the same horizontal line, the windward conductor does not have an impact on the leeward conductor. When the angle between two conductors is close to 0°, the windward conductor has an impact on the leeward conductor. Icing experiments on bundled conductor were carried out in this study to verify the simulation results.

Krzysztof Szilder [21] developed a morphogenetic numerical model that can simulate ice accretions on arbitrarily oriented cylinders exposed to freezing rain precipitation. This predictive model was validated experimentally for a limited number of conditions in an aeronautical icing wind tunnel under horizontal droplet impingement. He also developed a zero-order analytical model that identifies the location and size of freezing rain ice formation on a cylinder in a fully 3D geometrical space. The validated morphogenetic model can be used to predict complex three-dimensional ice accretion shapes on overhead transmission lines, bridge cables, telecommunication masts or any other cylindrical objects exposed to freezing rain.

Artificial intelligence has been used to predict the ice accretion on transmission line models. Zamani et. al. [15] applied the learning algorithm of Support Vector Machines to the outputs of a Numerical Weather Prediction model. The first forecasting system relies on an icing model. The second system learns an effective forecasting model directly from meteorological
features. Using a data set of eight different icing events, empirical comparison of the performance of the various ice accretion forecasting systems was conducted. Several experiments were also conducted to investigate the effectiveness of the forecasting algorithms. Results of their study indicated that the proposed forecasting system is significantly more accurate than many existing others.

Makkonen and Wichura [22] applied a simple wet snow accretion model to reconstruct the snow accretion process that happened in Germany in November 2005 which caused extensive damage to electric power lines. The maximum wet snow loads estimated by the model were found to be in good agreement with the observations.

Xinmin et. al. [23] studied ice accretion on dry wind tunnel using D-shaped and crescent shaped ice blocks attached to a transmission cable model. It was observed that aerodynamic coefficients were less affected by the wind speed. But they were influenced more by the type and thickness of ice, type of conductor and angle of attack. With increase in ice thickness, the aerodynamic coefficients increased significantly.

**Ice Profile Estimation**

Ice shape data from icing wind tunnel tests are often used by other groups for follow-on computational or experimental aerodynamic studies; development of design criteria or requirements; engineering tool development, improvement or validation. Therefore, it would be very useful if the ice shapes accreted on the conductor could be documented for future use.

It should be noted that, a number of intrusive techniques have been developed for quantitative measurements of ice shapes accreted over test models, e.g., hand tracing method [24], and mold-and-casting method [25]. However, they are usually very time consuming and expensive in implementation (i.e., mold-and-casting method). Furthermore, some of the fragile ice features might even be damaged during the ice shape measurements. More recently, non-intrusive laser
light sheet scanning technique has also been developed for 3-D ice shape measurements [26], [27]. However, the laser scanning method can only measure 2-D profiles of accreted ice structures directly, and relies on a line-by-line scanning operation to reconstruct 3D ice shapes, which could be very time consuming and much involved in instrumentation for high-resolution measurements of complex 3D ice structures. NASA used 3D scanner in their icing wind tunnel facility to record the ice profiles accreted on the airfoils exposed to icing conditions. They were able to accurately document the ice profile using this technique in a digital form [24]. Ice profiles documented in digital form are much more useful as they could be directly used for numerical simulations as well as rapid prototyped to be used in dry wind tunnel tests.

References


CHAPTER 2. DYNAMIC ICE ACCRETION PROCESS AND ITS EFFECTS ON THE AERODYNAMIC DRAG CHARACTERISTICS OF A POWER TRANSMISSION CABLE MODEL

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Abstract

An experimental study was conducted to examine the dynamic ice accretion process over the surface of a high-voltage power transmission cable model and characterize the effects of the ice accretion on the aerodynamic forces acting on the test model. The experimental study was carried out by leveraging the unique Icing Research Tunnel of Iowa State University (i.e., ISU-IRT) to generate typical wet glaze and dry rime icing conditions experienced by power transmission cables. A cylindrical power cable model, which has the same diameter as that of typical power transmission cables, was mounted in ISU-IRT for the ice accretion experiments. In addition to using a high-speed digital imaging system to record the dynamic ice accretion process, a novel digital image projection (DIP) based technique was utilized to quantify the 3D shapes of the ice structures accreted on the surface of the power cable model as a function of the ice accretion time. The time variations of the aerodynamic drag force acting on the test model during the dynamic ice accretion process were also measured quantitatively by using high-sensitive force/moment traducers mounted at two ends of the test model. The ice structures accreted over the surface of the power cable model were found to change significantly under different icing conditions (i.e., rime icing vs. glaze icing). The characteristics of the aerodynamic drag acting on the test model was found to vary significantly during the dynamic ice accretion process, highly depending on what types of ice structures were accreted on the test model. The acquired snapshots
of the ice accretion images and the measured 3D shapes of the accreted ice structures on the test model are correlated with the aerodynamic force measurement results to elucidate the underlying physics.

**Introduction**

Atmospheric icing on electric power transmission lines/cables has been known to be a serious problem in cold regions. Power cable icing due to freezing rain and/or caused by in cloud icing has been found to reduce the reliability of electrical power distribution networks, leading to major damages to power lines [1–3]. In extreme cases, ice accretion on power transmission cables/lines has been found to cause severe damages to transmission power cables and associated towers, resulting in extensive electric power breakdown. For instance, a major icing event which occurred in Quebec and Ontario in winter 1998 led to loss of power for about one million customers in the region for about 3 ~ 30 days [4]. Material damages were also substantial with hundreds of miles of transmission, sub-transmission and distribution lines being destroyed, leading to an estimated cost of one billion of Canadian dollars for reconstruction. Social cost involved in the incident was found to exceed three times that amount [5].

The shape and the density of the ice accreted on power cables are of major interest in investigating the potential risks involved. The wide variations of the accreted ice structures in size, density, and shape cause an equally wide variety of loads to be imposed on the structural system of the power transmission lines/cables. The weight of the accreted ice increases the vertical load on the conductors as well as the support structures. Combined effects of ice and wind can cause the transverse loads on a transmission line/cable to increase greatly. It can also cause vibrational loads due to wind if the ice deposition is asymmetric [6]. Natural winds can cause wind-induced vibrations (oscillations caused by the vortex shedding) on transmission line conductors. These vibrations may adversely affect the reliability and durability of conductors and associated
components [7]. While damping devices may be used to attenuate this, however, when ice precipitations accrete on the conductors, the situation can change dramatically. The vibrations of conductors coated with ice may occur in frequency ranges outside the design range of the dampers. Galloping, another wind-induced instability, would also occur on ice-accreted conductors and may result in large amplitude low frequency conductor displacements [5] similar to ice coated suspension bridge cables [8,9]. In addition, ice accumulation on power cables may also lead to flashover, where two conductors in wind-induced motion would come in contact and result in electrical discharge across them. Flashover may also happen when ice coated conductor sheds ice which results in sudden vertical displacement of the conductor [10–12].

It is well known that, ice accretion on cold surfaces can be of different ice types, depending on the icing conditions. Rime and glaze icing are the two most commonly seen icing conditions – the specific type is dependent on the ambient air temperature, wind velocity, liquid water content (LWC) of the incoming airflow and median volumetric diameters (MVD) of the impinging water droplets. Usually, relatively low temperatures colder than \(-10 \, ^\circ\text{C}\) and lower \(LWC\) level favors a dry regime of icing where all the water impinging on the surfaces immediately freeze to form rime ice. Warmer temperatures around \(-5 \, ^\circ\text{C}\) and relatively higher \(LWC\) level would favor a wet icing regime, where only a portion of the impinging water would freeze in the impingement area and the remaining frozen water runs back and then freezes subsequently in the downstream, causing the formation of glaze ice [13,14]. Rime ice accretion usually tends to follow the original contour of the object as the water droplets freeze almost immediately upon impingement on the surface. This is often associated with less aerodynamic penalties. Glaze ice is known as the most dangerous type of ice. As glaze ice is caused by wet icing conditions, it forms much more complicated ice shapes, hence, have much larger negative effects on the aerodynamic performance [14,15].
A better understanding about the dynamic ice accretion process on power transmission cables/lines is highly desirable for the development of counter measures for power cable icing mitigation. While a number of studies has been conducted recently on power cable icing phenomena [16–21], very little can be found in literature to quantify the 3D shapes of the ice structures accreted dynamically on the surfaces of power cables and characterize the time-evolution of aerodynamic forces acting on power cables during the dynamic ice accretion process under different icing conditions. In the present study, a comprehensive experimental investigation was conducted to examine the dynamic ice accretion process over the surfaces of typical power transmission cables and characterize the effects of the ice accretion on the aerodynamic forces acting on the power cables. The experimental study was conducted in an Icing Research Tunnel available at Iowa State University (i.e., ISU-IRT). A cylindrical power cable model with the same diameter of typical power transmission cables/lines (i.e., $D = 29\text{mm}$) was mounted in ISU-IRT and subjected to both wet glaze and dry rime icing conditions. During the experiments, in addition to using a high-speed imaging system to record the dynamic ice accretion process, a novel digital image projection (DIP) based 3D shape scanning system was also utilized to quantify the 3D shapes of the ice structures accreted on the surface of the power cable model as a function of the ice accretion time. The aerodynamic drag forces acting on the power cable model during the dynamic icing process were also measured by using a pair of high-sensitive force/moment load cell mounted at two ends of the test model. The acquired snapshots of the ice accretion images and the measured 3D shapes of the accreted ice structures on the test model were correlated with the aerodynamic force measurements in order to elucidate the underlying physics for a better understanding of the dynamic ice accretion process and its effects on the aerodynamic characteristics of the power transmission cables/lines.
Experimental Setup and Test Model

Icing Research Tunnel and Test Model used in the Present Study.

The experiment study was conducted in the Icing Research Tunnel of Iowa State University (i.e., ISU-IRT). ISU-IRT, which was originally donated by Collins Aerospace System (i.e., formerly Goodrich Corporation), is a newly refurbished research-grade multifunctional icing research tunnel. As shown schematically in Fig.2-1, ISU-IRT has a test section of 2.0 m in length × 0.4 m in width × 0.4 m in height with all of the side walls being optically transparent. It has a capacity of generating a maximum wind speed up to 60 m/s and airflow temperature down to −25°C. The turbulence level of the oncoming airflow at the entrance of the test section was found to be about 3.0%, as measured by using a hot wire anemometer. A water spray system, which consists of arrays of 8 pneumatic atomizing spray nozzles (Spraying Systems Co., 1/8NPT-SU11), was installed at the entrance of the contraction section of ISU-IRT to inject micro-sized water droplets (10~100 µm in size) into the test section. The desired liquid water content (LWC) level and the medium volumetric diameter (MVD) of the airborne water droplets can be achieved by regulating the water flow rate and air/water pressures supplied to the spray nozzles. In summary, ISU-IRT can be used to simulate atmospheric icing phenomena over a range of icing conditions (i.e., from very dry rime icing to extremely wet glaze icing conditions). By leveraging ISU-IRT, extensive researches have been conducted to study various atmospheric icing phenomena, including aircraft icing, aero-engine icing, wind turbine icing and cable-stayed bridge icing [8,13,15,22].

As shown schematically in Fig. 2-1, a cylindrical test model was mounted horizontally in the test section of ISU-IRT for the present study. The test model was designed to have the same outer diameter as commonly used high-voltage power transmission cables/lines (i.e., \(D=29\) mm), and has the spanwise length of \(L=400\) mm (i.e., the same as the spanwise length of the ISU-IRT.
test section). The surface of the power cable model used in the present study was found to be hydrophilic with the contact angle of sessile water droplets over the surface of the power cable model being about 65°, which is in the range of the surface wettability of typical power cables as reported in Li et al. (2018).

During the experiments, the velocity of the incoming airflow in ISU-IRT was kept at \( V_\infty = 20 \text{m/s} \) (i.e., a typical wind speed of power cable icing events in cold winters). The corresponding Reynolds number based on the diameter of the test model is about 50,000 (i.e., \( Re = 50,000 \)). Both typical rime and glaze icing conditions that power transmission cables usually experience in cold winters were simulated in the present study. While ambient temperature and the liquid water content (LWC) level of the incoming airflow in ISU-IRT was set at \( T_\infty = -5.0^\circ \text{C} \) and

**Figure 2-2:** Schematics of ISU-IRT and the power cable model used in the present study
LWC=2.0 g/m³ for the glaze icing experiments, the corresponding testing parameters were set at $T_\infty = -15.0^\circ C$ and $LWC=1.0 $ g/m³ for experiments under the rime icing condition.

**Quantification of the Dynamic Ice Accretion Process on the Surface of the Power Cable Model**

In the present study, a high-speed imaging system (PCO-Dimax-S1, acquisition rate up to 25,000 frames per second with 1008 pixels by 1008 pixels in spatial resolution) along with a 60-mm Macro Lens (Nikon, 60 mm Nikkor 2.8D) was used to record the dynamic ice accretion process (i.e., transient water film runback, rivulet formation, and accumulated ice growth) over the ice accreting surfaces of the test model. The camera was positioned vertically above the test model. Low-flicker illumination was provided by a pair of 150 W fiber-coupled halogen lamps (AmScope, HL250-AS). The key features of the dynamic ice accreting process would be revealed qualitatively based on the time sequences of the acquired snapshots of the ice accretion images.

In addition to acquiring snapshot images to visualize the dynamic ice accretion process, a novel digital image projection (DIP) based 3D scanning system was also used to achieve “in-situ” measurements of the 3D shapes of the ice structures with the test model still being mounted inside ISU-IRT. The DIP system is based on the principle of structured light triangulation in a fashion similar to stereo vision technique, but replacing one of the cameras in the stereo pair with a digital projector[24]. A digital image with known pattern characteristics was projected onto the test object of interest (i.e., ice structures accreted over the surface of the power cable model for the present study). Due to the complex three-dimensional (3D) geometrical profiles of the test objects (i.e., the surface of the accreted ice structures), the projected digital patterns are deformed when observed from a perspective different from the projection axis. By comparing the distorted digital patterns (i.e., acquired images with ice structures accreted over the surface of the transmission cable model) with a reference digital pattern without the test objects on the reference surface, the
3D profile of the iced test model can be retrieved quantitatively. Further information about the technical basis and implementation of the DIP system is available in Zhang et al. (2015).

After conducting a careful calibration operation to register the correlation relationship between the digital projector and high-resolution camera, the iced test model was rotated at every 30 degrees around its center for the DIP image acquisitions. The DIP images were processed to retrieve 3D profiles of the ice structures acquired at different phase angles and then combined automatically to reconstruct the 3D shapes of the ice structures accreted over the surfaces of the test mode.

The DIP-based 3D scanning system used in the present study is capable of quantitatively measuring fully 3D shapes of complex ice structures accreted over the power cable model. In comparison with those conventional methods (i.e., hand-tracing method, mold-and-casting method, or laser light sheet scanning technique), the DIP-based 3D scanning system used in the present study is much faster (i.e., ~ 10s for each test case) to achieve full 3D shape measurements of ice structures over the entire span of the test model and also much easier to implement for “in-situ” measurements of 3D ice shapes with the test model still being mounted inside the icing tunnel. For the DIP-based 3D scanning operation, while the airflow was paused, the ambient temperature was kept at the same level as the ice accretion testing. The changes in the morphologies of the ice structures are believed to be very small due to the scanning operation. This technique was used to successfully record the 3D profile of the ice accreted over a wind turbine airfoil at the ISU-IRT as part of an earlier study [25]. Preliminary results of this campaign on transmission cable icing studies could also be seen in (Veerakumar et al., 2019).

In order to estimate the measurement uncertainty of the DIP-based 3D scanning system, a test plate with a series of roughness elements in the form of hemispheres of different sizes was
custom designed and 3D printed with a high-accuracy rapid prototyping machine (i.e., the accuracy level of 10 micrometers), as shown in Figure 2-2. Then, the DIP-based 3D scanning system was used to measure the roughness elements 3D printed on the test plate. Since the nominal height distributions of the hemispheres are known, the measurement accuracy of the DIP-based 3D scanning system can be evaluated by quantitatively comparing the measured results against the nominal heights of the hemispheres. Figure 2-2 also gives the quantitative comparison of the measured profiles against the nominal data of both the concave and convex hemispheres of 8.0 mm in diameter along two arbitrarily selected traces passing through the centers of the hemispheres. It can be seen clearly that the measured results agree with the nominal height profiles very well for both the concave and convex hemispheres. Based on the measurement data at about 500 points around the hemispheres, the mean and root-mean-squared (i.e., RMS) values of the differences between the measurement results and the nominal values were calculated. The averaged difference between the measurement results and the nominal height values (i.e., the measurement uncertainty of the DIP-based 3D scanning system) was found to be ~150 micrometers, which is about 2.0 % of the nominal diameters of the 8.0mm hemispheres. Similar measurement uncertainty level was also found for the other hemispheres with different diameters.

(a) Test plate with hemispheres at different sizes   (b) Measured data vs. the nominal data

Figure 2-3: The test plate and the measured profiles using the DIP-based 3-D scanning system
Aerodynamic Force Measurement with High-Sensitive, Multi-Axis Force-Moment Transducers

In the present study, a pair of high-sensitive, multi-axis force-moment transducers (ATI-Mini 45) were mounted at two ends of the power cable model to measure the unsteady aerodynamic forces acting on the test model during the dynamic ice accreting process. The force/moment transducers are composed of foil strain gage bridges, which can measure the aerodynamic forces along three orthogonal axes, and the moment (torque) about each axis. The precision of the force-moment transducer for the force measurements is ± 0.25% of the full range (10N). During the experiments, the two sets of the force/torque transducers were synchronized via a 16-bit data acquisition system (NI USB-6218) at the data acquisition of 1,000 Hz. More details of the force transducer and the force measuring technique could be found in the recent work of Gao et al. (2019c).

Experimental Results and Discussion

Before performing the ice accretion experiments, ISU-IRT was operated at a prescribed frozen-cold temperature level (i.e., -15.0 °C for the rime icing experiments and – 5.0 °C for the glaze icing experiment for the present study) for at least 20 min to ensure ISU-IRT reaching a thermal steady state. Since the temperature inside the ISU-IRT was set to be well below the water frozen temperature (i.e. at 0.0 °C), after switching on the water spray system of the ISU-IRT, the water droplets exhausted from the water spray nozzles would be in a super-cooled state. Dynamic ice accretion process was found to start immediately, upon the impacting of the super-cooled water droplets onto the power cable model.

The Experimental Results Under the Rime Icing Condition

As described above, the ice accretion process over a solid surface can be either glaze icing and rime icing process, depending on the combined effects of ambient temperature, wind speed,
size of the super-cooled water droplets, and Liquid Water Content (LWC) level in the incoming airflow [14,27]. Figure 2-3 shows typical snapshot images of the ice accretion process to reveal the dynamic ice accretion process over the surface of the test model under a typical rime icing condition of $V_\infty = 20$ m/s, $T_\infty = -15^\circ$C, and $LWC = 1.0 \text{ g/m}^3$. The snapshot images were acquired at six representative instants (i.e., of 0 s, 200 s, 400 s, 600s, 800s and 1,000s) after switching on the water spray system. It can be seen clearly that, since the icing experiment was conducted under a very cold condition (i.e., $T_\infty = -15^\circ$C), the super-cooled water droplets were found to be frozen into ice almost instantly upon impacting onto the surface of the power cable model. As described in Liu and Hu, (2018b), since the latent heat of fusion released during the phase changing process of the impinged super-cooled water droplets would be removed/dissipated very rapidly under the rime icing condition, all the impacted water droplets were found to be frozen into solid ice immediately. The ice structures were found to accumulate mainly around the leading edges of the power cable model (i.e., mainly within the direct impinging zone of the super-cooled water droplets) without any noticeable surface water runback on the surface of the test model. The accreted ice structures were found to be rather rough and have milk-white and opaque appearances. Such experimental observations are found to be of the typical characteristics of a rime icing process, as described in Liu & Hu (2018). As the ice accretion time increases, while the ice layer accreted on the front surface of the power cable model were found to become thicker and thicker, the outer profile of the iced test model was found to become rougher and rougher.

Figure 2-4 gives the typical measurement results of the DIP-based 3D scanning system at the six representative instants after starting the ice accretion experiment. The characteristics of the dynamic ice accreting process as well as time evolution of the complex ice structures accreted over the surface of the power cable model were revealed much more clearly and quantitatively. Based
on the measured 3D shapes of the ice structures accreted over the surface of the test model, the outer profiles of the ice layer accreted on the power cable model can be extracted. Figure 2-5(a) gives of the outer profiles of the ice layer accreted on the test model as a function of the ice accretion time by extracting the 3D shapes of the ice structures accreted at the midsection of the test model. Figure 2-5(b) shows the extracted profiles of the ice layer accreted on the test model at five selected sections at different spanwise locations after performing 1,000s of the ice accretion experiment.

Figure 2-3: Typical snapshots of the ice structures accreted over the surface of the test model under a typical rime icing condition of $V_\infty = 20 \text{ m/s}$, $T_\infty = -15 \text{ °C}$, and $\text{LWC} = 1.0 \text{ g/ m}^3$.

Figure 2-4: Measured 3D shapes of the ice structures accreted on the surface of the test model under the rime icing condition.
Based on the quantitative measurements of the ice structures accreted over the surface of the power cable model as those shown in Fig.2-4 and Fig.2-5, the characteristics of the dynamic ice accretion process were shown more clearly and quantitatively. As described above, upon the impact of the super-cooled water droplets onto the surface of the test model, a layer of ice was found to form immediately over the surface of the power cable model, mainly on the front surface of the power cable model. As shown quantitatively in Fig.2-5(a), the rime ice accretion was found to be restricted within the direct impinging zone of the super-cooled water droplets with the upper and lower limits of the rime ice layer accreted on the test model at $\theta_{\text{upper-limit}} \approx 75^\circ$ and $\theta_{\text{lower-limit}} \approx -75^\circ$, respectively. Since the impacted super-cooled water droplets would be frozen into solid ice instantly under the rime icing condition, no runback water and/or formation of runback ice on the backside of the test model was observed. It can also be seen that, corresponding to the continuous impact of more and more super-cooled water droplets onto the test model, while the thickness of the ice layer accreted on front surface of the test model increases monotonically, the surface of the iced power cable model was found to become rougher and rougher, as the ice accretion time increases.

As described in Anderson & Tsao (2005), the rime ice accretion process would be affected mainly by the distribution characteristics of the collection efficiency of the super-cooled water droplets carried by the incoming airflow. Corresponding to the higher water collection efficiency in the region near the leading edge of the test model [28], the thickness of the ice layer accreted near the leading edge of the power cable model was found to increase much faster than those at further downstream regions, as shown clearly in Fig.2-5(a). As a result, the shape of the iced test model was found to be elongated more significantly along the airflow direction, which makes the outer profile of the iced test model to become more and more “streamlined” in shape, instead of
Figure 2-5: Extracted profiles of the ice layer accreted on the test model under the rime icing condition.
(a) Time variations of the ice layer profiles   (b) Spanwise variations of the ice layer profiles.
staying in circular shape (i.e., a bluff body), as the ice accretion time increases. The obvious shape change of the test model due to the ice accretion would cause significant changes on the aerodynamic forces acting on the test model, which was shown quantitatively from the aerodynamic force measurements to be described later.

As indicated schematically in Fig.2-5, while the ice accretion experiment of the present study was conducted with the direction of the gravity force being normal to the incoming airflow direction, the ice structures accreted over the surface of the test model were found to be almost symmetric in relation to the incoming airflow direction under the rime icing condition. It indicates that the gravity force would not affect the rime ice accretion process over the test model, since the impacted super-cooled water droplets would be frozen into solid ice instantly upon impacting onto the test model. As also shown quantitatively in Fig.2-5(b), the outer profiles of the ice layer extracted at different spanwise sections were found to agree with each other well, indicating that the ice structures accreted on the power cable model would be rather uniform along the spanwise direction of the test model under the rime icing condition.

As described above, the aerodynamic forces acting on the power cable model during the dynamic ice accreting process were also measured by using a pair of high-sensitive force-moment transducers (ATI-IA Mini 45) mounted at two ends of the test model. Figure 2-6 gives the measured aerodynamic drag data as a function of ice accretion time under the rime icing condition. While the total duration of the force measurements was 1,100 seconds, the water spray system of ISU-IRT was switched on at 100 seconds after turning on the force-moment transducers (i.e., to start the ice accretion process at \( t = 100 \)s). By averaging the measured measurement data within the first 100 seconds (i.e., before starting the ice accretion process), the mean value of the aerodynamic drag acting on the test model, \( D_0 \), was calculated. In the present study, the value of
$D_0$ is used as the baseline to evaluate the effects of the dynamic ice accretion process on the aerodynamic drag forces acting on the power cable model. It should be noted that, the corresponding drag coefficient of the power cable model for the test case without any ice accretion was found to be 1.16 (i.e., $C_D = 1.16$). The measurement result of the present study was found to be in good agreement with the standard drag coefficient value (i.e., $C_D = 1.20$) of a circular cylinder reported in the previous studies at the same Reynolds number level [29].

It should be noted that, the projected area of the iced test model along the airflow direction would change dynamically due to the ice accumulation over the test model during the ice accretion experiment. Instead of using drag coefficient, the aerodynamic drag data measured during the dynamic ice accretion process were presented in term of normalized drag force, i.e., the measured instantaneous drag data were normalized by the baseline drag $D_0$. Hence, the label of Y-axis in Fig.2-6 is set as $D/D_0$. As described above, while the instantaneous drag acting on the test model were acquired with a data acquisition frequency of 1,000Hz, the moving averaged values of the instantaneously measured drag data (i.e., averaging over every 5 seconds of the instantaneous measurements) were also calculated and plotted in Fig.2-6 for comparison.

It can be seen clearly that, induced by the periodic shedding of the unsteady vortices from two sides of the cylindrical test model similar as those described in Chen et al., (2014), the instantaneous aerodynamic forces acting on the power cable model were found to fluctuate significantly. After the water spray system was switched on at $t = 100$ s, the super-cooled water droplets would impinge onto the surface of the test model to start the ice accretion process immediately, mainly on the front surface of the test model (i.e., within the direct impinging zone of the super-cooled droplets) as shown clearly in Fig.2-5. The formation of the rime ice structures at the initial stage of the icing process (i.e., $t = 100s \sim 150s$) would result in a much roughened
surface of the test model. This would affect the development of the boundary layer airflow (i.e., laminar boundary layer growth, transition and separation) over the front surface of the test model greatly. The much roughed surface near the leading edge of the power cable model due to the rime ice accretion would result in a greater friction force, thereby, causing the slight increase of the drag force (i.e., ~4% greater) at the initial stage of the rime icing process (i.e., $t = 100s \sim 150s$), as shown clearly in Fig.2-6.

![Figure 2-6: The measured aerodynamic drag on the test model under the rime icing condition](image)

As the time increases, with more and more super-cooled water droplets impinging onto the test model, the ice layer accreted over the front surface of the power cable model would become thicker and thicker, which would change the outer profile of the iced test model substantially. As shown clearly in Fig.2-5(a), the rime ice accumulation on the front surface of the test model tends to make the outer profile of the iced power cable model to change gradually from a cylindrical-shaped bluff body to a “streamlined” body. As a result, the aerodynamic drag force acting on the ice accreting test model was found to decrease gradually as the ice accretion time increases. More
specifically, due to the substantial rime ice accretion on power cable model, the averaged aerodynamic drag force acting on the test model at \( t = 1,100 \text{s} \) (i.e., after 1,000 seconds of the ice accretion experiment) was found to become only about 65% of the baseline value (i.e., the value without any ice accretion on the test model).

**The Experimental Results Under a Typical Glaze Icing Condition**

In the present study, the dynamic ice accretion process and its effects on the wind loads acting on the power cable model were also investigated under a typical glaze icing condition. For the glaze icing experiments, while the velocity of the incoming airflow in ISU-IRT was still kept at \( V_\infty = 20 \text{m/s} \), the ambient temperature was increased to a much warmer level (i.e., \( T_\infty = -5 \degree \text{C} \)) and the \( LWC \) level in the incoming airflow was also much higher (i.e., \( LWC = 2.0 \text{ g/ m}^3 \)). Figure 2-7 shows the typical snapshot images to reveal the dynamic ice accretion process over the surface of the power cable model under the glaze icing condition. It can be seen clearly that, the glassy ice structures accreted over the surface of the test model was found to be transparent, and have a smooth-looking appearance with obvious water runback under the glaze icing condition, which are the typical features of a glaze icing process as described by Liu [31]. The experimental observation can be explained by the fact that, corresponding to the much higher LWC level in the incoming airflow under the glaze icing condition, much more super-cooled water droplets would impact onto the surface of the test model and undergo phase changing (i.e., solidification) process within the same time duration. Thus, a much more significant amount of latent heat of fusion would be released over the surface of the test model within the same duration of the ice accretion experiment. Due to the relatively higher ambient temperature (i.e., \( T_\infty = -5 \degree \text{C} \)) under the glaze icing condition, the significant amount of the latent heat of fusion released during the solidification process could not be removed/dissipated fast enough by convective and/or conductive heat transfer process. This would result in the local accumulation of the released latent heat of fusion over the icing accreting
surface of the test model. Therefore, only a portion of the super-cooled water droplets were found to be frozen into solid ice upon impacting, while rest of the impinged water mass would still stay in liquid state. As driven by the airflow around the test model, the unfrozen water mass was found to run back over the ice accreting surface of the test model to form rivulet flows, similar as those described by Zhang et al., (2015). The runback surface water was found to be frozen into solid ice subsequently to form rivulet-shaped ice structures at further downstream locations (i.e., in the downstream region beyond the direct impinging zone of the super-cooled droplets). As the time increases, with more and more super-cooled water droplets impacting onto the test model, the ice layer accreted on the power cable model was found to become thicker and thicker, as shown clearly in Fig.2-7.

**Figure 2-7:** Typical snapshots of the ice structures accreted over the surface of the test model under a typical glaze icing condition of $V_\infty = 20$ m/s, $T_\infty = -5$ °C, and LWC = 2.0 g/ m$^3$. 
Figure 2-8: 3D shapes of the ice structures accreted on the test model under the glaze icing condition.

The characteristics of the dynamic ice accretion process under the glaze icing condition were shown much more clearly and quantitatively from the measured 3D shapes of the ice structures accreted over the surface of the power cable model. While Fig. 2-8 shows the time evolution of the 3D-shapes of the glaze ice structures accreted over the surface of the test model measured by using the DIP-based 3D scanning system, Fig. 2-9 gives the outer profiles of the accreted glaze ice layer extracted from the measurement results of the 3D scanning system. As described above, under the glaze icing condition, since not all of the super-cooled water droplets would be frozen into solid ice instantly after impinging onto the test model, a portion of the impacted water mass would stay in liquid over the surface of the test model. Driven by the airflow around the test model, the unfrozen water would run back, and re-distribute the impacted water mass over the ice accreting surface of the test model. Therefore, as shown clearly in Fig. 2-9(a), the glaze ice layer accreted over the surface of the test model was found to be much more uniformly distributed along the azimuthal direction. In comparison, the accreted ice layer would grow much faster in the region near the leading edge of the test model under the rime icing condition. As a result, the outer profile of the iced test model was found to remain a cylindrical-shaped bluff-body under the glaze icing condition, instead of becoming “streamlined-shape” due to the ice accretion as under the rime icing condition.
condition. It can also be seen that, as the time increases, while the accreted ice layer over the surface of the test model was found to become thicker and thicker, the iced test model was found to stay as a bluff body in general with the diameter of the cylindrical-shaped ice layer becoming bigger and bigger.

It can be seen that, as driven by the frozen-cold airflow around the test model, the unfrozen surface water was found to run back rapidly to form rivulet flows over the ice accreting surface, causing the formation of complex rivulet-shaped ice structures over the surface of the model. As shown clearly in Fig.2-9(b), due to the formation of the isolated, rivulet-shaped ice structures over the surface of the test model, the thickness of the ice layer accreted over the test model was found to vary significantly along the spanwise direction of the test model.

As described and shown clearly in Fig.2-5, since the rime icing process would be restricted within the direct impinging zone of the super-cooled water droplets, the upper and lower limits of the rime ice layer accreted on the front surface of the test model were found to be at $\theta_{\text{upper-limit}} \approx 75^\circ$ and $\theta_{\text{lower-limit}} \approx -75^\circ$, respectively. However, under the glaze icing condition, since the water runback would transport the unfrozen water mass to much further downstream regions (i.e., beyond the direct impinging zone of the super-cooled water droplets), the glaze ice layer accreted on the surface of the test model was found to have a much wider coverage. The upper and lower limits of the glaze ice layer accreted over the test model were found to reach to $\theta_{\text{upper-limit}} \approx 120^\circ$ and $\theta_{\text{lower-limit}} \approx -120^\circ$, respectively.

It can also be seen that, due to the gravity effect, the runback water over the lower surface of the test model was found to easy to break into rivulet flows, and then form more complicated runback ice structures subsequently near the bottom of the test model, in comparison to those over the upper surface of the test model. Since the irregular-shaped runback ice structures accreted over
the surface of the test model would intrude further into the incoming airflow to cause large-scale flow separation, it would induce much greater aerodynamic drag force acting on the iced test model, which was revealed more quantitatively from the force measurements given in Fig. 2-10.

(a) Time variations of the ice layer profiles  
(b) Spanwise variations of the ice layer profiles.

**Figure 2-9:** Extracted profiles of the ice layer accreted on the test model under the glaze icing condition.
As shown clearly Fig.2-10, the characteristics of the dynamic aerodynamic drag force acting on the power cable model under the glaze icing condition were found to be quite different from those under the rime icing condition.

![Figure 2-10: Measured aerodynamic drag force acting on the test model under the glaze icing condition.](image)

As described above, since the impacted super-cooled water droplets could not be frozen into solid ice completely under the glaze icing condition, the unfrozen water mass would run back over the surface of the test model, driven by the airflow around the test model. At the initial stage of the glaze icing process (i.e., within the first 20 seconds of the ice accretion process), while the ice layer accreted on the test model is still very thin, the existence of the runback water film would affect the development of the boundary layer airflow over the front surface of the test model greatly. More specifically, in comparison to the “dry” surface case (i.e., without runback water on the test model), the runback water film over the front surface of the test model could act as a “lubricant” to make the airflow moving more smoothly around the “wet” surface of the test model. It would make the “wet” surface of the test model becoming a “slip” surface for the boundary layer
airflow over the test model. This would delay the separation of the boundary layer air stream flowing over the surface of the test model. As a result, the aerodynamic drag force acting on the power cable model was found to decrease greatly at the initial stage of the glaze ice accretion process (i.e., up to 25% drag reduction within ~ 20 seconds after turning on the water spray system of ISU-IRT) as shown clearly in Fig.2-10.

As the ice accretion time increases, with more and more super-cooled water droplets impinging onto the test model, the glaze ice layer accreted over the surface of the test model would become thicker and thicker. Due to the continuously increasing diameter of the iced test model as shown quantitatively in Fig.2-9(a), the projected area of the iced power cable model along the incoming airflow direction would become bigger and bigger. As a result, the aerodynamic drag force acting on the test model was found to increase monotonically as the ice accretion time increases. Furthermore, as shown clearly in Fig.2-8 and Fig.2-9, more and more irregular-shaped runback ice structures were found to form over the surface of the test model due to the subsequent freezing of the runback water at the later stage of the glaze icing process (i.e., after 200 seconds of the ice accretion experiment). The formation of the irregular-shaped runback ice structures would induce large-scale flow separation, which would also contribute to the continuous increase of the aerodynamic drag force acting on the iced power cable model under the glaze icing condition.

**Growth of The Ice Mass Accumulated on the Test Model Under the Rime And Glaze Icing**

Based on the measurement results of the DIP-based 3D scanning system as those shown in Fig.2-4 and Fig.2-8, the total volume of the ice structures accreted on the power cable model under both the rime and glaze icing conditions can also be determined. As reported in the recent study of Liu et al. (2017), while the density of typical glaze ice is about 900 kg/m$^3$, the density of typical rime ice would be about 880 kg/m$^3$. Therefore, the total mass of the ice structures accreted
over the surface of the power cable model as a function of the ice accretion time under both the rime and glaze icing conditions can also be determined quantitatively.

Figure 2-11 gives the measured ice mass accumulation on the power cable model within a unit span as a function of the ice accretion time. It can be seen clearly that, the ice mass accumulated on the power cable model was found to increase monotonically with the ice accretion time under both the rime and glaze icing conditions, as expected. However, the growth characteristics of the ice mass accumulated on the test model were found to be quite different under different icing conditions. While the mass of the ice layer accumulated on the test model would increase linearly with the ice accretion time under the rime icing condition, the ice mass accumulated on the test model was found to grow much faster under the glaze icing condition with its relationship to the ice accretion time being fitted well by using a parabolic function. More specifically, while the LWC level of the incoming airflow for the rime icing experiments was set at $LWC = 1.0 \text{ g/m}^3$ in the present study, the LWC level for the glaze icing case was at $LWC = 2.0 \text{ g/m}^3$, (i.e., 2 times of that of the rime icing case). However, after the same ice accretion duration of 1000 seconds, while the mass of the ice layer accumulated on the power cable model under the rime icing condition was found to be about 0.209 kg/m, the corresponding value under the glaze icing condition was found to become 0.598 kg/m (i.e., about 3 times as that of the rime icing case). The significant difference in the growth of the ice mass accumulated on the test model is believed to be closely related to the different characteristics of the dynamic ice accretion process under the rime and glaze icing conditions.
Figure 2-11: Measured ice mass accumulated on the test model as a function of the time.

As described above, the ice structures would accrete only on the front surface of the power cable model (i.e., only within the direct impinging zone of the super-cooled water droplets) under the rime icing condition. As the ice accretion time increases, while the rime ice layer accreted over the front surface of the test model would become thicker and thicker, the outer profile of the iced test model was found to become more and more in “streamlined” shape. As shown quantitatively in Fig.2-5, the projected area of the iced test model along the incoming airflow direction (i.e., the area to intercept the super-cooled water droplets carried by the incoming airflow) was found to be almost unchanged during the entire duration of the ice accretion experiment. Therefore, the mass of the ice layer accumulated on the power cable model was found to increase linearly with the ice accretion time under the rime icing condition, as shown clearly in Fig.2-11.

In comparison to the scenario of the rime ice accretion process, the dynamic icing process under glaze icing condition was found to become much more complicated, due to the existence of
the unfrozen water mass that can run back readily over the ice accreting surface of the test model. As described above, under the glaze icing condition, since the runback of the unfrozen water would re-distribute the impacted water mass over the surface of the test model, the glaze ice layer accumulated on the test model was found to have a much wider coverage and become more uniformly distributed azimuthally. The outer profile of the iced test model was found to be still in cylindrical-shape, as shown clearly in Fig.2-9. As the ice accretion time increases, with the glaze ice layer accreted over the surface of the test model becoming thicker and thicker, the outer diameter of the iced test model was found to become bigger and bigger. As a result, the projected area of the iced test model along the incoming airflow direction was found to increase continuously with the ice accretion time. Correspondingly, the airborne super-cooled water droplets over a much wider range would impact onto the iced test model and turn into solid ice, resulting in the much rapid, nonlinear growth of the ice mass accumulated on the test model. Furthermore, as shown clearly in Fig.2-8 and Fig.2-9, more and more irregular-shaped ice structures would be formed on the test model at the later stage of the glaze icing process, due to the frozen of the runback water to form rivulet-shaped ice structures. The irregular-shaped runback ice structures would protrude further into the incoming airflow, thereby, catch more airborne super-cooled water droplets to further promote the rapid growth of the ice mass accumulated on the power cable model at the later stage of the glaze icing process.

Conclusions

In the present study, an experimental investigation was conducted to examine the dynamic ice accretion process over the surfaces of typical high-voltage power transmission cables and characterize the effects of the ice accretion on the aerodynamic forces acting on the power cables. The experimental study was performed by leveraging an Icing Research Tunnel available at Iowa State University (i.e., ISU-IRT) to generate typical atmospheric icing conditions (i.e., both wet
glaze and dry rime icing conditions) experienced by power transmission cables. A cylindrical test model, which has the same diameter as that of typical power transmission cables (i.e., $D = 29\text{mm}$), was mounted in ISU-IRT for the ice accretion experiments. In the present study, the velocity of the incoming airflow in ISU-IRT was kept at a constant value of $V_\infty=20\text{m/s}$ during the ice accretion experiments. While the temperature and the liquid water content (LWC) level of the incoming airflow was set to be at $T_\infty= -5.0^\circ\text{C}$ and $LWC=2.0\ \text{g/m}^3$ for the glaze icing experiments, the corresponding values were set to be $T_\infty= -15.0^\circ\text{C}$ and $LWC=1.0\ \text{g/m}^3$ for the experiments under the rime icing condition. In addition to using a high-speed digital imaging system to record the dynamic ice accretion process, a novel digital image projection (DIP) based 3D scanning system was also used to quantify the 3D shapes of the ice structures accreted on the surface of the power cable model as a function of the ice accretion time. The time variations of the aerodynamic drag forces acting on the test model during the dynamic ice accretion process were also measured quantitatively by using a pair of high-sensitive force/moment traducers mounted at two ends of the test model.

It was found that, after impacting onto the surface of the power cable model, the super-cooled water droplets carried by the incoming airflow would be frozen into solid ice instantly under the rime icing condition. While the ice structures were found to accrete mainly within a relatively narrow region on the front surface of the test model (i.e., within the direct impinging zone of the super-cooled water droplets), the outer profile of the iced power cable model was found to become more and more streamlined in shape. While the rime ice structures accreted on the surface of the test model were found to be opaque and have a rough, milk-white appearance, the total mass of the ice accumulated on the test model was found to increase linearly with the ice accretion time.
The dynamic ice accretion process over the surface of the test model was found to become much more complicated under the glaze icing condition. Upon impacting onto the surface of the test model, only a portion of the super-cooled water droplets would be frozen into solid ice instantly, and the rest of the impacted water mass would stay in liquid state. The unfrozen surface water was found to run back freely, as driven by the airflow around the test model. Since the water runback would re-distribute the impacted water mass, the glaze ice layer accumulated on surface of the power cable model was found to have a much wider coverage and become more uniformly distributed azimuthally. As the ice accretion time increases, while the glaze ice layer accreted over the surface of the test model was found to become thicker and thicker, the outer profile of the iced test model was found to be still in cylindrical shape. With the continuous increase of the outer diameter of the iced test model, the airborne super-cooled water droplets over a much greater region would be able to impinge onto the iced test model and turned into solid ice subsequently. As a result, the total mass of the glaze ice accumulated on the test model was found to grow much faster with a nonlinear relationship to the ice accretion time.

The characteristics of the aerodynamic drag force acting on the power cable model was found to highly dependent on the type of ice structures that accreted on the test model. Under the rime icing condition, while the aerodynamic drag force acting on the power cable model was found to increase slightly (i.e., ~ 4% increase) at the initial stage of the rime icing process, then decrease gradually as the ice accretion time increases. Since the rime ice accretion would make the iced test model to be more and more streamlined in shape, the aerodynamic drag force acting on the iced test model was found to reduce to only ~ 70% of the baseline case (i.e., the case without any ice accretion on the test model) after 1,000 seconds of the ice accretion experiment. On the contrary, the aerodynamic drag acting on the test model was found to decrease substantially (i.e., up to 30%
in drag reduction) at the early stage of the glaze icing process, then increase monotonically with the ice accretion time under the glaze icing condition. After the same ice accretion time of 1000 seconds, the aerodynamic drag force acting on the iced test model after 1,000 seconds of the glaze ice accretion experiment was found to increase to ~ 140% of the baseline case.

References


CHAPTER 3. AN EXPERIMENTAL STUDY OF ATMOSPHERIC ICING PROCESS ON POWER TRANSMISSION LINE

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Abstract

Atmospheric icing poses a major threat to power transmission lines in cold regions. In the present study, an experimental investigation was conducted to examine the atmospheric icing process on high-voltage power transmission lines and characterize the effects of the ice accretion on the aerodynamic forces acting on the transmission lines. The experimental study was conducted in the Icing Research Tunnel located at the Iowa State University (ISU-IRT). An Aluminum Conductor Steel Reinforced (ACSR) test model with the same diameter of a commonly used high-voltage power transmission line cable (D = 29 mm) is subjected to typical glaze and rime icing conditions. An incoming wind speed of 20 m/s, a liquid water content (LWC) of 2.0 g/m$^3$ and an ambient temperature of -5 $^\circ$C was used to study glaze ice accumulation. The LWC and ambient temperature for rime ice was 1.0 g/m$^3$ and -15 $^\circ$C at the same wind speed. A high-resolution 3D scanner was used to extract the 3D shapes of the ice structures accreted over surface of the cylindrical test model as a function of the ice accretion time. A high-speed imaging camera was also used to record the dynamic icing process. While the aerodynamic drag force acting on the test model was measured using a force transducer during the dynamic ice accreting process, a high-resolution Particle Image Velocimetry (PIV) system was also used to quantify the characteristics of the wake flow behind the test model. It was found that, the effect of icing on the drag force of the test model was different for glaze and rime ice. Drag force increased continuously throughout
the icing event in the case of glaze ice whereas for the case of rime ice it reduced to a slightly lower value by the end of icing event. The aerodynamic force measurement results were correlated with the PIV flow field measurements to elucidate the underlying physics.

**Keywords:** Transmission cable icing, Particle Image Velocimetry, 3D Scan, Ice profile, Icing research tunnel.

**Introduction**

Atmospheric icing is one of the major problems faced in cold regions. The problems caused by the icing has adverse effect on several engineering structures and machines. For instance, the electric power transmission cables, aircrafts wings and other critical components exposed to atmosphere, wind turbines, suspension bridge cables etc. are some of the engineering structures which are severely affected by atmospheric icing. Some of the icing after-effects could be very critical. The adverse effects caused by the ice accretion on power transmission lines has always been a serious problem and it is the major focus of this paper. Ice accretions on transmission line cables due to freezing rain and also due to in-cloud icing reduces the reliability of electrical power distribution networks during the most critical cold periods, and may lead to major damages to power lines [1–3]. It had led to several incidents and accidents in the past. For instance, a major icing event which occurred in Quebec and Ontario in winter 1998 had led to loss of power for about one million customers for about 3-30 days. Material damage was also substantial with hundreds of miles of transmission, sub-transmission and distribution lines being destroyed leading to an estimated cost of one billion Canadian dollars for reconstruction. Social cost involved in the incident exceeded three times that amount [4]. In extreme cases, the atmospheric icing can cause severe damages to transmission cables and associated towers resulting in extensive electric power breakdown.
The shape and the density of the ice accreted on the cable are of major interest in investigating the potential risks involved. The wide variations in size, density, and shape of the ice formations cause an equally wide variety of loads to be imposed on the structural system of the transmission line. The weight of the accreted ice increases the vertical load on the conductors as well as the support structures. Combined effect of ice and wind can cause the transverse load on a transmission line to be increased significantly. It can cause vibrational loads due to wind if the ice deposition is asymmetric [5]. Natural winds can cause wind induced vibrations (oscillations caused by the vortex shedding) on transmission line conductors. These vibrations may adversely affect the reliability and durability of conductors and associated components. Damping devices may be used to attenuate this. However, when ice precipitations accrete on the conductors, the situation can change dramatically. The vibrations of conductors coated with ice may then occur in frequency ranges outside the design range of the dampers. Galloping, another wind-induced instability, also occurs on ice-accreted conductors and may result in large amplitude low frequency conductor displacements similar to ice coated suspension bridge cables mentioned earlier [6]. In addition, ice accumulation may also lead to flashover, where two conductors in wind induced motion would come in contact resulting in electrical discharge across them. Flashover may also happen when ice coated conductor sheds ice which results in sudden vertical displacement of the conductor [7–9].

It is well known that ice accretion on cold surfaces can be of several types depending on the icing conditions. Rime and glaze ice are two very common icing conditions—the specific type is dependent on the ambient air temperature, wind velocity, liquid water content (LWC) of the oncoming air, and median volumetric diameters (MVD) of the impinging water droplets. Relatively low temperatures less than -10 °C and lower LWC favors a dry regime of icing where
all the water impinging on the surfaces immediately freezes to form rime ice. Warmer temperatures around -5 °C and relatively higher LWC level favors a wet icing regime where only a portion of the impinging water freezes in the impingement area and the remaining unfrozen water runs back over the surface of the material and can freeze in the downstream locations causing glaze ice formation [10,11]. Rime ice accretion usually tends to follow the original contour of the model, since the water droplets freeze almost immediately upon impingement on to the surface. This is often associated with less aerodynamic penalties as compared to glaze ice which follows an irregular ice profile. Glaze ice is the most dangerous type of ice. As glaze ice is caused by wet icing conditions, it forms much more complicated shapes and hence have larger aerodynamic penalties.

A better understanding of the dynamic ice accretion process on power transmission cables is highly desirable for the development of counter measures for icing mitigation. While a number of studies has been conducted recently on transmission cable icing phenomena [12–17], very little can be found in literature to quantify the 3D shapes of the ice structures accreted dynamically on the surfaces of transmission cables and characterize the time-evolution of aerodynamic forces acting on power transmission cables during the dynamic ice accretion process under different icing conditions. In the present study, a comprehensive experimental investigation was conducted to examine the dynamic ice accretion process over the surface of a typical power transmission cable and characterize the effects of the ice accretion on the aerodynamic forces acting on the cable. The experimental study was conducted in the Icing Research Tunnel located at Iowa State University (i.e., ISU-IRT). Aluminum conductor steel-reinforced (ACSR) conductor is a type of high-capacity, high-strength stranded conductor typically used in overhead power lines. The outer strands are made of high-purity aluminum, chosen for its good conductivity, low weight and low
cost. The central strand is made of steel for additional strength to help support the weight of the conductor. The test model used in this study was an actual ACSR power transmission cable of diameter \( D = 29 \text{ mm} \) which is a typical diameter used for high voltage power transmission of the order of 220 kV. The model was mounted in ISU-IRT and subjected to both wet glaze and dry rime icing conditions. It was observed in previous icing studies by Laforte et al. [18] by subjecting a relatively smoother shaped conductor to icing environment, that the shape of the conductor affects the ice accumulation and shedding. As part of this campaign, another cylindrical model made of aluminum and of same dimension was also used to compare the effect of the outer profile of the conductor on ice accretion as well as aerodynamic forces acting on the conductor. While the detailed analysis on the cylindrical model is discussed in [19], the relevant details for comparison of results with the ACSR model are only presented here. During the experiments, in addition to using a high-speed imaging system to record the dynamic ice accretion process, a digital image projection (DIP) based 3D scanning system was utilized to quantify the 3D shapes of the ice structures accreted on the surface of the power transmission cable model as a function of ice accretion time. The aerodynamic drag forces acting on the transmission cable model during the dynamic icing process were also measured by using a pair of high-sensitive force/moment load cell mounted at two ends of the test model. A high-resolution Particle Image Velocimetry (PIV) system was also used to characterize the behaviors of the turbulent airflows over the ice accreting model. The detailed PIV flow field measurements were correlated with the dynamic aerodynamic force data and the measured 3D shapes of the accreted ice structures to gain further insight into the underlying physics for better understanding of the effects of ice accretion process and its effects on the aerodynamic characteristics of the power transmission cables/lines.
Experimental Set Up and Test Model

Icing Research Tunnel and Test Model

The experiments were conducted at Iowa State University –Icing Research Tunnel, (ISU-IRT) originally donated by Collins Aerospace System (i.e., formerly Goodrich Corporation). It is a newly refurbished research-grade multifunctional icing research tunnel. As shown schematically in Fig. 3-1, ISU-IRT has a test section of 2.0 m in length × 0.4 m in width × 0.4 m in height with all of the side walls being optically transparent. ISU-IRT allows wind speeds to be accelerated to 60 m/s and airflow temperature to be cooled down to −25 °C. The turbulence level of the oncoming airflow at the entrance of the test section was estimated to be about 3.0 %, as measured by a hot wire anemometer. A water spray system, which consists of arrays of 8 pneumatic atomizing spray nozzles (Spraying Systems Co., 1/8NPT-SU11), was installed at the entrance of the contraction section of ISU-IRT to inject micro-sized water droplets (10–100 μm in size) into the test section. The desired liquid water content (LWC) level and the medium volumetric diameter (MVD) of the airborne water droplets can be achieved by regulating the water flow rate and air/water pressures supplied to the spray nozzles. In summary, ISU-IRT can be used to simulate atmospheric icing phenomena over a range of icing conditions (i.e., from very dry rime icing to extremely wet glaze icing conditions). By leveraging ISU-IRT, extensive research work has been previously conducted to investigate various atmospheric icing phenomena, including aircraft icing, aero-engine icing, wind turbine icing and cable stayed bridge icing [19–23].

As mentioned earlier, the present study is performed on a transmission cable model (ACSR model) 29 mm in overall diameter as shown in Fig. 3-1. The cylindrical test model used for the previous study is also shown. The model spanned the whole width of the IRT (i.e., L = 0.4 m). The surface of the transmission cable model used in the present study was found to be hydrophilic with the contact angle of sessile water droplets over the surface of the transmission cable model being
about 65°, which is in the range of the surface wettability of typical transmission cables as reported by Li et al. [24].

**Figure 3-4:** Icing Research Tunnel and test models

During the experiments, the velocity of the incoming airflow in ISU-IRT was kept at $V_\infty = 20$ m/s which is a typical wind speed during transmission cable icing events in cold winters. The corresponding Reynolds number based on the diameter of the test model is $Re = 50,000$. Typical rime and glaze icing conditions that power transmission cables usually experience in cold winters were simulated in the present study. While ambient temperature and the liquid water content (LWC) level of the incoming airflow in ISU-IRT was set at $T_\infty = -5.0$ °C and LWC
for the glaze icing experiments, the corresponding testing parameters were set at $T_\infty = -15.0 \, ^\circ C$ and $LWC = 1.0 \, g/m^3$ for experiments under the rime icing condition. Icing duration of the experiments was 1000 s.

**Quantification of the Dynamic Ice Accretion Process on the Surface of the Test Model**

In the present study, a high-speed imaging system (PCO-Dimax-S1, acquisition rate up to 25,000 frames per second with 1008 pixels by 1008 pixels in spatial resolution) along with a 60-mm Macro Lens (Nikon, 60 mm Nikkor 2.8D) was used to record the dynamic images of the ice accretion process (i.e., transient water film runback, rivulet formation, and accumulated ice growth) over the ice accreting surfaces of the test model. The camera was positioned vertically above the test model. Low-flicker illumination was provided by a pair of 150 W fiber-coupled halogen lamps (AmScope, HL250-AS). The key features of the dynamic ice accreting process would be revealed qualitatively based on the sequentially snapshots of the ice accretion process.

In addition to acquiring snapshot images to visualize the dynamic ice accretion process, a novel digital image projection (DIP) based 3D scanning system was also used to achieve “in-situ” measurements of the 3D shapes of the ice structures with the test model still being mounted inside ISU-IRT. The DIP system is based on the principle of structured light triangulation which is similar in principle to stereo vision technique, but replacing one of the cameras in the stereo vision technique with a digital projector [25]. A digital image with known pattern characteristics was projected onto the test object of interest (i.e., ice structures accreted over the surface of the transmission cable model for the present study). Due to the complex three-dimensional (3D) geometrical profiles of the test objects (i.e., the surface of the accreted ice structures), the projected digital patterns are deformed when observed from a perspective different from the projection axis. By comparing the distorted digital patterns (i.e., acquired images with ice structures accreted over the surface of the transmission cable model) with a reference digital pattern without the test objects
on the reference surface, the 3D profile of the iced test model can be retrieved quantitatively. Further information about the technical basis and implementation of the DIP system is available in [25].

After conducting a careful calibration operation to register the correlation relationship between the digital projector and high-resolution camera, the iced test model was rotated at every 20° around its center for the DIP image acquisitions. The DIP images were processed to retrieve 3D profiles of the ice structures acquired at different phase angles and then combined automatically to reconstruct the 3D shapes of the ice structures accreted over the surfaces of the test model.

It should be noted that, while a number of intrusive techniques have been developed for quantitative measurements of ice shapes accreted over test models, e.g., hand tracing method [26], and mold-and-casting method [27], they are usually very time consuming and expensive in implementation (i.e., mold-and-casting method). Furthermore, some of the fragile ice features might even be damaged during the ice shape measurements. More recently, non-intrusive laser light sheet scanning technique has also been developed for 3-D ice shape measurements [28,29]. However, the laser scanning method can only measure 2-D profiles of accreted ice structures directly, and relies on a line-by-line scanning operation to reconstruct 3D ice shapes, which could be very time consuming and much involved in instrumentation for high-resolution measurements of complex 3D ice structures. The DIP-based 3D scanning system used in the present study is capable of quantitatively measuring complex 3D shapes of ice structures accreted over the transmission cable model. In comparison with those conventional methods (i.e., hand-tracing method, mold-and-casting method, or laser light sheet scanning technique), the DIP-based 3D scanning system used in the present study is much faster (i.e., ~ 10s per scan) to achieve full 3D shape measurements of ice structures over the entire span of the test model and also much easier
to implement for “in-situ” measurements of 3D ice shapes with the test model still being mounted inside the icing tunnel. For the DIP-based 3D scanning operation, while the airflow was paused, the ambient temperature was maintained at the same level as that used for ice accretion experiment. The changes in the morphologies of the ice structures are believed to be very small due to the scanning operation.

In order to estimate the measurement uncertainty of the DIP-based 3D scanning system, a test plate with a series of roughness elements in the form of hemispheres of different sizes was custom designed. This plate was 3D printed with a high-accuracy rapid prototyping machine with an accuracy level of 10 µm, as shown in Fig. 3-2(a). Then, the DIP-based 3D scanning system was used to measure the roughness elements 3D printed on the test plate. Since the actual height distributions of the hemispheres are known, the measurement accuracy of the DIP-based 3D scanning system can be evaluated by quantitatively comparing the measured results against the actual heights of the hemispheres. Figure 3-3-2(b) gives the quantitative comparison of the measured profiles against the actual data of both the concave and convex hemispheres of 8.0 mm in diameter along two arbitrarily selected traces passing through the centers of the hemispheres. It can be seen clearly that the measured results agree with the real height profiles quite well for both the concave and convex hemispheres. Based on the measurement data at about 500 points around the hemispheres, the mean and root-mean-squared (i.e., RMS) values of the differences between the measurement results and the actual values were calculated. The averaged difference between the measurement results and the actual height values (i.e., the measurement uncertainty of the DIP-based 3D scanning system) was found to be ~150 micrometers, which is about 3.0% of the diameters of the 8.0mm hemispheres. Similar measurement uncertainty level was also found for the other hemispheres with different diameters.
Aerodynamic Force Measurements with Multi-Axis Force-Moment Transducers

In the present study, a pair of high-sensitive, multi-axis force-moment transducers (ATI-IA Mini 45) were mounted at two ends of the transmission cable model to measure the unsteady aerodynamic forces acting on the test model during the dynamic ice accreting process. The force/moment transducers are composed of foil strain gage bridges, which can measure the aerodynamic forces along three orthogonal axes, and the moment (torque) about each axis. The precision of the force-moment transducer for the force measurements is ± 0.25% of the full range. During the experiments, the two sets of the force/torque transducers were synchronized via a 16-bit data acquisition system (NI USB-6218) at the data acquisition rate of 2,000 Hz.

Wake Measurements with a Digital Particle Image Velocimetry (PIV) System

A digital Particle Image Velocimetry (PIV) was used to map the velocity fields over the cylinder. Acquired images were processed using DaVis 7.2 software. For the PIV measurements...
before the ice accretion process, the incoming airflow was seeded with ∼ 1 μm oil droplets using a smoke generator, while the airborne super-cooled water droplets were used as the tracer particles for the PIV measurements during the ice accretion process. It should be noted that, since the super-cooled water droplets suspended in the incoming airflow were estimated to have a mean volume diameter (MVD) of approximately 20 μm, the corresponding Stokes number of the water droplets was estimated to be about 1.0 (i.e., St ≈ 1.0), indicating a reasonable dynamic response of the droplets in terms of following the airflow. Illumination was provided by a double-pulsed Nd:YAG laser (Evergreen, Big Sky Laser) adjusted on the second harmonic and emitting two pulses of 200 mJ at the wavelength of 532 nm with a repetition rate of 15 Hz. The laser beam was shaped to a thin sheet by a set of mirrors, spherical, and cylindrical lenses. The thickness of the laser sheet in the measurement region was about 1.0 mm. A high-resolution 12-bit digital camera (2048 pixel by 2048 pixel resolution, PCO-Tech) with a Nikon Nikkor 60 mm 1:2.8 D lens was used to acquire images of tracer particles for the PIV measurements. The digital camera and the double-pulsed Nd:YAG lasers were connected to a workstation (host computer) via a Digital Delay Generator (Berkeley Nucleonics, Model 565), which controlled the timing of the laser illumination and the image acquisition for the PIV measurements. After acquiring the PIV images, instantaneous velocity vectors were obtained by frame to frame cross-correlation of the patterns of particle images, using an interrogation window of 32 pixels × 32 pixels. An effective overlap of 50 % of the interrogation windows was employed in PIV image processing. In the present study, a cinema sequence of about 300 instantaneous PIV measurements were used to calculate the ensemble-averaged flow field around the transmission line model. The measurement uncertainty level for the instantaneous PIV measurements is estimated to be within 5.0 %, while the uncertainty level for the measurements of the ensemble-averaged flow field being about 3.0 %.
Experimental results and discussion

Before performing the ice accretion experiments, ISU-IRT was operated at a prescribed cold temperature level (i.e., -15.0 °C for the rime icing experiments and – 5.0 °C for the glaze icing experiment) for at least 20 minutes to ensure that the tunnel reaches a thermal steady state. Since the temperature inside the ISU-IRT was set to be well below the freezing temperature of water temperature (i.e. at 0.0 °C), after switching on the water spray system, the water droplets exhausted from the water spray nozzles would be in a super-cooled state. Dynamic ice accretion process was found to start immediately, upon the impingement of the super-cooled water droplets onto the test model.

Rime Ice Accumulation

The ice accretion process over a solid surface could be of several types depending on the combined effects of ambient temperature, wind speed, size of the super-cooled water droplets, and Liquid Water Content (LWC) level in the incoming airflow [11,30]. Figure 3-3 shows typical snapshot images of the ice accretion process to reveal the dynamic icing process over the surface of the test model (ACSR model) under a typical rime icing condition of $V_\infty = 20$ m/s, $T_\infty = -15$ °C, and LWC = 1.0 g/ m$^3$. The snapshot images corresponding to six representative instants (i.e., of 0 s, 200 s, 400 s, 600 s, 800 s and 1,000 s) after switching on the water spray system are shown in Fig. 3-3. It can be seen clearly that, since the ambient temperature was very low (i.e., $T_\infty = -15$ °C), the super-cooled water droplets were found to freeze into ice almost instantly upon impinging onto the surface of the transmission cable model. As described in [11], since the latent heat of fusion released during the phase changing process of the impinging super-cooled water droplets would be removed/dissipated very rapidly under the rime icing condition, all the impacted water droplets were found to be frozen into solid ice immediately. The ice structures were found to accumulate mainly around the leading edges of the test model (i.e., mainly within the direct
impinging zone of the super-cooled water droplets) without any noticeable surface water runback over the surface. The accreted ice structures were found to be rather rough, and had milky-white and opaque appearance. Such experimental observations are found in typical a rime icing process, as described in [11]. As ice accretion progressed, the ice layer on the front surface of the test model was found to increase in thickness while the outer profile was found to become rougher and rougher.

**Figure 3- 3:** Representative snapshots of the ice structures accreted over the surface of the test model under a typical rime icing condition of $V_\infty = 20$ m/s, $T_\infty = -15$ °C, and LWC = 1.0 g/ m$^3$.

**Figure 3- 4:** Measured 3D shapes of the ice structures accreted on the surface of the test model under the rime icing condition.
Figure 3-5: Extracted profiles of the ice layer on the test model under the rime icing condition.
Figure 3-4 gives the typical measurement results of the DIP-based 3D scanning system at six representative instants after starting the ice accretion experiment. The characteristics of the dynamic ice accreting process as well as time evolution of the complex ice structures accreted over the surface of the test model were revealed much more clearly and quantitatively. Based on the measured 3D shapes of the ice structures accreted over the surface of the test model, the outer profiles of the ice layer accreted on the test model can be extracted. Figure 3-5(a) shows the outer profiles of the ice layer accreted on the test model as a function of the ice accretion time by extracting the 2D shapes of the ice structures accreted at the mid-section of the test model. Figure 3-5(b) shows the extracted profiles of the ice layer accreted on the test model at five selected sections at different spanwise locations after being subjected to 1,000 s of ice accretion.

Based on the quantitative measurements of the ice structures accreted over the surface of the transmission cable model as in Fig. 3-4 and Fig. 3-5, the characteristics of the dynamic ice accretion process were shown more clearly and quantitatively. As described above, upon the impact of the super-cooled water droplets onto the surface of the test model, a layer of ice was found to form immediately over the surface of the test model, mainly on the forward side facing the oncoming airflow. As shown quantitatively in Fig. 3-5, the rime ice accretion was found to be restricted within the direct impinging zone of the super-cooled water droplets with the upper and lower limits of the rime ice layer accreted on the test model at $\theta_{\text{upper-limit}} \approx 80^\circ$ and $\theta_{\text{lower-limit}} \approx -80^\circ$, respectively. Since the impacted super-cooled water droplets would be frozen into solid ice instantly under the rime icing condition, no runback water and subsequent formation of runback ice was observed on the rear side of the model. As described by Anderson & Tsao [30], the rime ice accretion process would be affected mainly by the distribution characteristics of the collection efficiency of the super-cooled water droplets carried by the incoming airflow around the outer
surface of the model. Corresponding to the higher water collection efficiency in the region near the leading edge of the test model [31], the thickness of the ice layer accreted near the leading edge of the test model was found to increase at a much faster rate than that at further downstream locations of the model, as shown clearly in Fig. 3-5(a).

As indicated schematically in Fig. 3-5, while the ice accretion experiment of the present study was conducted with the direction of the gravity force being normal to the incoming airflow direction, the ice structures accreted over the surface of the test model were found to be almost symmetric in relation to the oncoming airflow direction under the rime icing condition. It indicates that the gravity force would not affect the rime ice accretion process over the test model, since the super-cooled water droplets freeze into solid ice instantly upon impingement onto the test model. As shown quantitatively in Fig. 3-5(b), the outer profiles of the ice layer extracted at different spanwise sections were found to be almost similar, indicating that the ice structures accreted on the transmission cable model would be rather uniform along the spanwise direction under the rime icing condition. This is clearly in contrast with glaze icing condition in which case there is considerable spanwise variation of the ice profiles as would be described later.

As described above, the aerodynamic forces acting on the test model during the dynamic ice accreting process were also measured by using a pair of high-sensitive force-moment transducers (ATI-IA Mini 45) mounted at two ends of the test model. Figure 3-6 gives the measured aerodynamic drag data as a function of ice accretion time under the rime icing condition. The total duration of the force measurements was 1,100 seconds. The water spray system of ISU-IRT was switched on at 100 seconds after turning on the force-moment transducers (i.e., to start the ice accretion process at \( t = 100 \)s). By averaging the measured measurement data within the first 100 seconds (i.e., before starting the ice accretion process), the mean value of the aerodynamic
drag acting on the test model, $D_0$, was calculated. In the present study, the value of $D_0$ is used as the baseline to evaluate the effects of the dynamic ice accretion on the aerodynamic drag force acting on the model. During the initial phase of experiments with the smooth cylindrical model, it was found that drag coefficient of the model for the test case without any ice accretion was found to be 1.16 (i.e., $C_D = 1.16$). The measurement result of this study was found to be in good agreement with the standard drag coefficient value (i.e., $C_D = 1.20$) of a circular cylinder reported in the previous studies at the same Reynolds number [32].

It should be noted that, the projected area of the iced test model along the airflow direction would change dynamically due to the ice accumulation over the test model during the ice accretion experiment, though this is more evident in case of glaze ice than rime ice. Instead of using drag coefficient, the aerodynamic drag data measured during the dynamic ice accretion process is presented in terms of normalized drag force, i.e., the measured instantaneous drag force data were normalized by the baseline drag force $D_0$. Hence, the label of Y-axis in Fig. 3-6 is set as $D/D_0$. As described above, while the instantaneous drag acting on the test model were acquired with a data acquisition frequency of 2,000Hz, the moving averaged values of the instantaneously measured drag data (i.e., averaging over every 5 seconds of the instantaneous measurements) was also calculated and plotted in Fig. 3-6 for comparison.

Since the time averaged wake velocity field data at discrete time steps is available from PIV measurements, the drag coefficient could be calculated by calculating the wake momentum deficit in the flow direction. By estimating the stream wise wake momentum deficit on a rectangular control volume defined at sufficiently upstream and downstream locations, the drag coefficient could be estimated. Following the work of Hu and Koochesfahani [33], the drag coefficient was found from the following equation.
\[ C_D = \frac{2}{D} \int_{-H}^{H} \left( \frac{U(y)}{U_\infty} \left( 1 - \frac{u(y)}{U_\infty} \right) - \frac{u_{rms}(y)^2 - v_{rms}(y)^2}{u_\infty^2} + \frac{1}{2} \frac{(U_{free\text{-}stream})^2}{u_\infty^2} - 1 \right) dy \]

In this expression, \( U_\infty \) is the upstream flow velocity, \( U(y) \) is the mean stream wise velocity profile in the wake, \( U_{rms} \) and \( V_{rms} \) are the r.m.s. profiles of the stream wise and transverse velocity fluctuations, and \( U_{free\text{-}stream} \) is the free-stream velocity outside the wake region and is higher than \( U_\infty \) due to the finite width of the test section. The drag coefficient values so obtained are normalized with the baseline value without any ice accumulation as mentioned earlier. The moving averaged values obtained in the case of smooth cylinder test model could also be seen in Fig. 3- 6.

It can be seen clearly that, induced by the periodic shedding of the unsteady vortices from two sides of the test model similar to the description in [34], the instantaneous aerodynamic forces acting on the test model were found to fluctuate significantly. After the water spray system was switched on at \( t = 100 \) s, the super-cooled water droplets impinged onto the surface of the test model to start the ice accretion process immediately, mainly on the front surface of the model (i.e., within the direct impinging zone of the super-cooled droplets) as shown clearly in Fig. 3- 5.

**Figure 3- 6:** Aerodynamic drag force acting on the test model under the rime icing condition.
As time progresses, with more and more super-cooled water droplets impinging onto the test model, the ice layer accreted over the front surface of the transmission cable model would become thicker and thicker, which would change the outer profile of the iced test model substantially. As described earlier, rime ice tends to conform to the original shape of the test model. As shown clearly in Fig. 3-5, the rime ice accumulation on the front surface of the test model tends to maintain the shape of model throughout the icing process. It was observed in the case of cylindrical model that the outer profile of the iced model changes gradually from a cylindrical-shaped bluff body to a streamlined body. As a result, the aerodynamic drag force acting on this model was found to decrease gradually and then tend to stabilize with the ice accretion time as could be seen in Fig. 3-6. More specifically, due to the substantial rime ice accretion on cylindrical test model, the averaged aerodynamic drag force acting on the test model at \( t = 1,100 \) s (i.e., after 1,000 seconds of the ice accretion experiment) was found to be about 65% of the baseline value (i.e., the value without any ice accretion on the test model). At the same time, in the case of the ACSR test model, the drag force was found to reduce to 90% of the original value at the end of icing event. This difference between the models is attributed to two factors. First, as the outer profile was originally non-cylindrical for the ACSR conductor, the effect of streamlining was less prominent as compared to the case of smooth cylindrical model. Fig. 3-7 shows a comparison between the outer profile of the ACSR test model and cylindrical test model at \( t = 400 \) s of icing. It may be noticed that while the ice structures accreted on the cylindrical test model uniformly streamlined the original cylindrical shape, the process was not same for the ACSR test model. Though ice structures followed the original contour at large, there were “extended ice structures”, as highlighted in Fig. 3-7, distributed throughout the iced model. These structures would interfere with the smooth flow over the iced model to the downstream direction by acting as “air traps”
thereby by increasing the drag force acting on the test model. This is also believed to nullify some of the drag reduction obtained from streamlining. This is proposed as another reason why the drag force on the ACSR model shows a lower drag reduction as compared to the smooth cylinder model. So the net effect is to have a 10% reduction in the drag force as opposed to 35% reduction in the case of smooth cylinder.

![Figure 3- 7: Comparison of ice profiles between ACSR and cylindrical test model at t = 400 s.](image)

In the present study, PIV measurements were also used to investigate the changes of the ensemble-averaged airflow characteristics induced by the ice accretion over the test model at different instances of time. The image acquisition was done at 15 Hz frequency. Fig. 3- 8 shows the ensemble averaged flow field at six representative instants during the ice accretion experiment. As mentioned earlier, before the start of icing process, the incoming airflow was seeded with ~1 μm oil droplets by using a smoke generator, while the airborne super-cooled water droplets were used as the tracer particles for the PIV measurements during the ice accretion process. The ensemble average image was created using 300 image pairs recorded over a 20 second window
around the representative time steps. For instance, to reveal the ensemble averaged velocity field corresponding to $t = 200$ s, the images acquired between $t = 190$ s to $t = 210$ s were used. Representative ice shapes are also shown in the Figure 3-. As time progresses, the width of the wake region does not exhibit any significant change. This due to the typical characteristic of super-cooled water droplets under rime icing condition to immediately freeze into ice solid ice and leave no traces of runback water. As collection efficiency of the super-cooled water droplets impinging on the model reduces away from the leading edge of the model, the extent of the ice layer in the vertical direction essentially does not exceed the diameter of the test model. In other words, the projected area in the flow direction essentially remains the same. This result is also in clear contrast to the case of glaze ice accretion where the wake region undergoes a substantial increase in width due to the presence of runback water as to be described later.
Figure 3-8: Time averaged PIV flow field visualization for the rime ice accumulation over the model every 200 seconds of icing

Glaze Ice Accumulation

For the glaze icing experiments, while the velocity of the incoming airflow in ISU-IRT was still kept at $V_\infty = 20\text{m/s}$, the ambient temperature was increased to a much warmer temperature (i.e., $T_\infty = -5 \text{ °C}$) and the LWC level in the incoming airflow was also higher (i.e., LWC = 2.0 g/m$^3$). Figure 3-9 shows the typical snapshot images to reveal the dynamic ice accretion process over the surface of the test model under the glaze icing condition. It can be seen clearly that, the ice structures with a glassy appearance that accreted over the surface of the test model was found to be transparent, and have a smooth appearance with water runback which are typical features of a glaze icing process as described in [35]. This experimental observation can be explained by the fact that, corresponding to the much higher LWC level in the incoming airflow under the glaze icing condition, more super-cooled water droplets would impact onto the surface of the test model and undergo phase changing (i.e., solidification) process within the same time duration. Thus, a significantly larger amount of latent heat of fusion would be released over the surface of the test model within the same duration of the ice accretion experiment. Due to the relatively higher ambient temperature (i.e., $T_\infty = -5 \text{ °C}$) under the glaze icing condition, this larger amount of the
latent heat could not be removed/dissipated fast enough by convective and/or conductive heat transfer process. This would result in the local accumulation of the released latent heat of fusion over the surface of the test model. Therefore, only a portion of the super-cooled water droplets were found to be frozen into solid ice upon impingement, while rest of the impinged water mass still remains in the liquid state. Driven by the airflow around the test model, the unfrozen water mass was found to run back over the ice accreting surface of the test model to form rivulet flows, similar to that described by [25]. The runback surface water was found to be frozen into solid ice subsequently to form rivulet-shaped ice structures at downstream locations (i.e., in the downstream region beyond the direct impinging zone of the super-cooled droplets). As time progresses, with more and more super-cooled water droplets impinging onto the test model, the ice layer accreted on the transmission cable model was found to become thicker and thicker, as shown clearly in Fig. 3-9.

**Figure 3-9:** Typical snapshots of the ice structures accreted over the surface of the test model under a typical glaze icing condition of $V_\infty = 20$ m/s, $T_\infty = -5$ °C, and LWC = 2.0 g/ m$^3$. 
Figure 3-10: 3D shapes of the ice structures accreted on the test model under the glaze icing condition.

Figure 3-11: Extracted profiles of the ice layer accreted on the test model under the glaze icing condition.

The characteristics of the dynamic ice accretion process under the glaze icing condition could be observed quantitatively and with more clarity from the measured 3D shapes of the ice structures accreted over the surface of the test model. While Fig. 3-10 shows the time evolution
of the 3D-shapes of the glaze ice structures accreted over the surface of the test model measured, Fig. 3-11 gives the outer profile of the accreted glaze ice layer extracted from the measurement results of the 3D scanning system at five different sections. It can be seen that, as driven by the frozen-cold airflow around the test model, the unfrozen surface water was found to run back rapidly to form rivulet flows over the ice accreting surface, causing the formation of complex rivulet-shaped ice structures over the surface of the model. As shown clearly in Fig. 3-11, due to the formation of the isolated, rivulet-shaped ice structures over the surface of the test model, the thickness of the ice layer accreted over the test model was found to exhibit a significant variation along the spanwise direction of the test model.

As shown in Fig. 3-5, since the rime icing process would be restricted within the direct impinging zone of the super-cooled water droplets, the upper and lower limits of the rime ice layer accreted on the front surface of the test model were found to be at $\theta_{\text{upper-limit}} = 80^\circ$ and $\theta_{\text{lower-limit}} = -80^\circ$, respectively. However, under the glaze icing condition, since the water runback would transport the unfrozen water mass to much further downstream regions (i.e., beyond the direct impinging zone of the super-cooled water droplets), the glaze ice layer accreted on the surface of the test model was found to have a much wider coverage. As shown in Fig. 3-11, the upper and lower limits of the glaze ice layer accreted over the test model were found to reach approximately, $\theta_{\text{upper-limit}} = 125^\circ$ and $\theta_{\text{lower-limit}} = -135^\circ$. However, there are spanwise variations in the sectional ice profiles unlike the rime ice accretion. At occasional spanwise locations, for instance section 2 in Fig. 3-11, it could be seen that the ice accreted over the entire $360^\circ$ of the model.

It can also be seen that, due to the gravity effects, the runback water over the lower surface of the test model readily broke into rivulet flows, and then form more complicated runback ice structures subsequently near the bottom of the model, in comparison to those over the upper surface
of the test model. Since the irregular-shaped runback ice structures accreted over the surface of the test model would intrude further into the incoming airflow to cause large-scale flow separation, it would result in much greater aerodynamic drag force acting on the iced test model, which was revealed more quantitatively from the force measurements given in Fig. 3-12.

**Figure 3-12:** Measured aerodynamic drag force acting on the test model under the glaze icing condition.

The characteristics of the dynamic aerodynamic drag force acting on the transmission cable model under the glaze icing condition were found to be quite different from those under the rime icing condition. As described above, since the impinging super-cooled water droplets were not frozen into solid ice completely under the glaze icing condition, the unfrozen water mass would run back over the surface of the test model, driven by the airflow around the test model. It was observed that while the outer profile of the test model did not have any significant impact on the fraction of water that turned into ice in the case of rime ice, it played an important role for glaze ice and thereby had a significant impact on the drag force experienced by the model. The difference in outer profile between the models also played an important role in changing the boundary layer
airflow around the model in the initial phase of icing. However, after the surfaces accreted a small quantity of ice, the governing mechanism of ice accretion was not different. In the case of the cylindrical model, during the initial stage of the glaze icing process (i.e., within the first 20 seconds of the ice accretion process), the ice layer accreted on the test model was still very thin. However, the existence of the runback water film would affect the development of the boundary layer airflow over the front surface of the test model significantly. More specifically, in comparison to the “dry” surface case (i.e., without runback water on the test model), the runback water film over the front surface of the test model could act as a “lubricant” to make the airflow moving more smoothly around the “wet” surface of the test model. It would make the “wet” surface of the test model to act as a “slip” surface for the boundary layer airflow over the test model. This would delay the separation of the boundary layer air streams flowing over the surface of the test model. As a result, the aerodynamic drag force acting on the cylindrical test model was found to decrease by about 25% within ~ 20 seconds after turning on the water spray system of ISU-IRT as shown clearly in Fig. 3-12. This was not the case for the ACSR model as the outer profile being made up of thin strands of aluminum would act as hindrance to the smooth flow of runback water over the surface to reach the point of separation. It was observed during the dynamic imaging that a portion of the water that reaches the top and bottom surfaces of the test model will eventually be carried away by the airflow without freezing into ice in glaze icing condition. As more water droplets were retained at the forward part due to the cross sectional shape of the ACSR model, less water was carried away with the airflow and subsequently a larger proportion of the impinging water was frozen into ice. This frozen ice layer acts as nucleation points for the forthcoming water droplets, eventually leading to larger mass of ice being accreted in the case of ACSR model.
As the ice accretion time increased, with more and more super-cooled water droplets impinging onto the test model (both in the case of cylindrical model as well as ACSR model), the glaze ice layer accreted over the surface of the test model became thicker and thicker. Due to the continuous increase of diameter of the iced test model the projected area of the iced transmission cable model along the incoming airflow direction would become bigger and bigger. As a result, the aerodynamic drag force acting on the test model was found to increase monotonically as the ice accretion time increases. Furthermore, the formation of the irregular-shaped runback ice structures would induce large-scale flow separation, which would also contribute to the continuous increase of the aerodynamic drag force acting on the iced transmission cable model under the glaze icing condition.

The corresponding PIV images are shown in Fig. 3-13. A comparison with the wake profile of the rime ice accretion in Fig 8 would indicate that, as time progresses, the wake region seems to undergo a considerable increase in width. Representative ice profiles are also shown in the Figure 3-. A comparison between the no ice condition and icing condition after 1000 seconds indicates that the width of the wake region has undergone and appreciable enlargement from about 2 D to 4.5 D, where D is the diameter of the cylinder with a corresponding increase in drag force. This is partly due to the higher LWC (2 g/m³ as opposed to 1 g/m³ for rime ice) and also due to the runback water which freezes outside the region of impingement in random shapes.

Figure 3-14 compares the non-dimensionalized drag force acting on the ACSR model and cylindrical model for both rime and glaze icing condition. It could be seen that while rime icing on the smooth cylinder has the least drag penalty, the ACSR model under the glaze icing condition undergoes the most severe effects of aerodynamic drag force.
Figure 3-13: Time averaged PIV flow field visualization for the glaze ice accumulation over the model every 200 seconds of icing.
Growth of the Ice Mass on the Test Model

Based on the measurement results of the DIP-based 3D scanning system as those shown in Fig. 3-4 and Fig. 3-10, the total volume of the ice structures accreted on the transmission cable model under both the rime and glaze icing conditions can also be determined. As reported in the recent study of [36], the density of typical glaze ice is about 900 kg/m$^3$ while the density of typical rime ice would be about 880 kg/m$^3$. Therefore, the total mass of the ice structures accreted over the surface of the both test models as a function of the ice accretion time under both the rime and glaze icing conditions can also be determined quantitatively.
Figure 3-15: Measured ice mass accumulated on the test model as a function of the time.

Figure 3-15 gives the measured mass of ice accumulated on the both test models within a unit span as a function of the ice accretion time. It can be seen clearly that, the ice mass accumulated on the models in all cases was found to increase monotonically with the increasing ice accretion time under both the rime and glaze icing conditions, as expected. However, the growth characteristics of the ice mass accumulated on the test model were found to be quite different under different icing conditions. While the mass of the ice layer accumulated on the test model would increase linearly with the ice accretion time under the rime icing condition, the ice mass accumulated on the test model was found to grow much faster under the glaze icing condition with its relationship to the ice accretion time following a parabolic function. For the case of rime
ice, the rate of growth of ice mass was found to be exactly same for both models as could be seen in Fig. 3-15. But the models under glaze icing condition exhibited different trends. More specifically, while the LWC level of the incoming airflow for the rime icing experiments was set at LWC = 1.0 g/m³ in the present study, the LWC level for the glaze icing case was at LWC = 2.0 g/m³, (i.e., 2 times of that of the rime icing case). However, after the same ice accretion duration of 1000 seconds, while the mass of the ice layer accumulated under the rime icing condition was found to be about 0.209 kg/m for both test models, the corresponding value under the glaze icing condition was found to be 0.598 kg/m for the smooth cylindrical model (i.e., about 3 times as that of the corresponding rime icing case) and 1.060 kg/m for the ACSR test model (i.e., about 5 times as that of the corresponding rime icing case). The significant difference in the growth of the ice mass accumulated on the test models is believed to be closely related to the different characteristics of the dynamic ice accretion process under the rime and glaze icing conditions as well as to the outer profile of the models.

As described earlier, the ice structures would accrete only on the front surface of the transmission cable model (i.e., only within the direct impinging zone of the super-cooled water droplets) under the rime icing condition. As the ice accretion time increases, while the rime ice layer accreted over the front surface of the test model would become thicker and thicker, the outer profile of the iced test model was found to become more and more “streamlined” in shape. As shown quantitatively in Fig. 3-5, the projected area of the iced test model along the incoming airflow direction (i.e., the area to intercept the super-cooled water droplets carried by the incoming airflow) was found to be almost unchanged during the entire duration of the ice accretion experiment. Therefore, the mass of the ice layer accumulated on both test models was found to increase linearly with the icing time under the rime icing condition, as shown clearly in Fig. 3-14.
In comparison to the scenario of the rime ice accretion process, the dynamic icing process under glaze icing condition was found to become much more complicated, due to the existence of the unfrozen water mass that can run back readily over the surface of the test model. Since the runback of the unfrozen water would re-distribute the impinging water mass over the surface of the test model, the glaze ice layer accumulated on the test model was found to have a much wider coverage and become more uniformly distributed in azimuthal direction. The irregular-shaped runback ice structures would intrude further into the incoming airflow, thereby intercepting more airborne super-cooled water droplets to further promote the rapid growth of the ice mass accumulated on the test models at the subsequent stages of the glaze icing process.

The outer profile of the conductor did not impact the mass of accreted ice under rime icing condition. However, it played a significant role in case of glaze ice accretion. It could be noticed from Fig 15 that at the end of icing process (i.e., $t = 1000$ s of icing) the mass of glaze ice that accreted on the ACSR model was about 75% more than that of smooth cylindrical model under similar conditions. This demonstrates that outer profile of the model influences the runback water characteristics and thereby the total mass of ice accumulation in case of glaze ice. The side view of the test models could be seen in Fig. 3-1. The outer profile being made up of thin strands of aluminum would act as hindrance to the smooth flow of runback water over the surface which would entrap more water in the space between adjacent strands. This would lead to more water retention over the surface of the conductor which further acts as nucleation points for the forthcoming water droplets eventually leading to larger mass of ice being accreted in the case of ACSR model as explained earlier.

**Conclusion**

In the present study, experimental investigations were conducted to examine the dynamic ice accretion process over the surfaces of typical high-voltage power transmission cables and
characterize the effects of the ice accretion on the aerodynamic forces acting on the transmission cables. The experimental study was performed at the Icing Research Tunnel at Iowa State University (i.e., ISU-IRT) to generate typical atmospheric icing conditions (i.e., both wet glaze and dry rime icing conditions) experienced by power transmission cables. An ACSR conductor, having the same diameter as that of typical high voltage power transmission cables (i.e., $D = 29$ mm), was mounted in ISU-IRT for the ice accretion experiments. In the present study, the velocity of the incoming airflow in ISU-IRT was kept at a constant value of $V_\infty = 20$ m/s during the ice accretion experiments. While the temperature and the liquid water content (LWC) level of the incoming airflow was set to be $T_\infty = -5.0$ °C and $LWC = 2.0$ g/m$^3$ for the glaze icing experiments, the corresponding values were set to be $T_\infty = -15.0$ °C and $LWC = 1.0$ g/m$^3$ for the experiments under the rime icing condition. In addition to using a high-speed digital imaging system to record the dynamic ice accretion process, a novel digital image projection (DIP) based 3D scanning system was also used to quantify the 3D shapes of the ice structures accreted on the surface of the transmission cable model as a function of the ice accretion time. The time variations of the aerodynamic drag forces acting on the test models during the dynamic ice accretion process were also measured quantitatively by using a pair of high-sensitive force/moment transducers mounted at two ends of the test model.

It was found that, under the rime icing condition, the super-cooled water droplets carried by the incoming airflow would be frozen into solid ice instantly upon impingement onto the surface of the transmission cable model. The ice structures were found to accrete mainly within a relatively narrow region on the front surface of the test model (i.e., within the direct impinging zone of the super cooled water droplets) and the projected area in the airflow direction remained essentially the same. While the rime ice structures accreted on the surface of the test model were
found to be opaque and have a rough, milk-white appearance, the total mass of the ice layer accumulated on the test model was found to increase linearly with the ice accretion time. By comparing results of a previous campaign using smooth cylinder as test model of same dimension subjected to similar icing condition, it was seen that the outer profile did not change the mass of ice accumulated in case of rime ice.

The dynamic ice accretion process over the surface of the test model was found to be more complicated under the glaze icing condition. Upon impinging onto the surface of the test model, only a portion of the super-cooled water droplets would freeze into solid ice instantly, and the rest would stay in liquid state. The unfrozen surface water was found to run back freely, driven by the airflow around the test model. Since the water runback would re-distribute the impinged water mass, the glaze ice layer accumulated on surface of the test model was found to have a much wider coverage and become more uniformly distributed azimuthally. As the ice accretion time increases the glaze ice layer accreted over the surface of the test model was found to become thicker and thicker. With the continuous increase of the outer diameter of the iced test model, the airborne super-cooled water droplets over a much greater region would be able to impinge onto the iced test model and turn into solid ice subsequently. As a result, the total mass of the glaze ice accumulated on the test model was found to grow much faster with a nonlinear relationship to the ice accretion time. In the case of glaze ice it was found that outer profile strongly influences the amount of ice that accretes over the surface. The smooth cylinder model accreted much less ice under similar conditions of icing.

The characteristics of the aerodynamic drag force acting on the transmission cable model was found to be highly dependent on the types of ice structures that accreted on the test model. Under the rime icing condition, the aerodynamic drag force acting on the ACSR model was found
to reduce to about 90% of the original value at the end of the rime icing process. On the contrary, the aerodynamic drag acting on the ACSR model was found to increase monotonically with the ice accretion time under the glaze icing condition. The aerodynamic drag force acting on the iced test model after 1,000 seconds of glaze ice accretion was found to increase to ~180% of the baseline case.

Particle image velocimetry (PIV) results substantiate the findings from the load cell where it was found that the width of the wake was more or less constant throughout the icing process in case of rime ice. The wake width was found to increase monotonically with time under glaze icing condition, with a corresponding increase of the drag force. The mass of ice accumulated on the test model was also estimated from the DIP based 3D scanning system. It was found that mass of ice under glaze icing condition followed a parabolic trend while the rime ice accretion followed a linear trend with ice accretion time.

References


CHAPTER 4. AN EXPERIMENTAL STUDY OF ATMOSPHERIC ICING PROCESS ON BUNDLED CONDUCTORS

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Abstract

Atmospheric icing poses a major threat to power transmission lines in cold regions. In the present study, experimental investigations were conducted to examine the dynamic ice accretion process over the surfaces of a two-bundle high-voltage power transmission cables and characterize the effects of the ice accretion on the aerodynamic forces acting on the transmission cables. The experimental study was performed at the Icing Research Tunnel at Iowa State University (i.e., ISU-IRT) to generate typical atmospheric icing conditions (i.e., both wet glaze and dry rime icing conditions) experienced by power transmission cables. An incoming wind speed of 20 m/s, a liquid water content (LWC) of 2.0 g/m³ and an ambient temperature of -5 °C was used to study glaze ice accumulation. The LWC and ambient temperature for rime ice was 1.0 g/m³ and -15 °C at the same wind speed. A high-resolution 3D scanner was used to extract the 3D shapes of the ice structures accreted over surface of the cylindrical test model as a function of the ice accretion time. A high speed imaging camera was also used to record the dynamic icing process. While the aerodynamic drag force acting on the test model was measured using a force transducer during the dynamic ice accreting process, a high-resolution Particle Image Velocimetry (PIV) system was also used to quantify the characteristics of the wake flow behind the test model. The two-conductors were placed at different horizontal spacings as well as different angular orientations. It was found that the effect of icing on the leeward conductor was significantly different when the windward
conductor was placed in positions which interfered with the leeward conductor. In both cases of icing, it was found that at the lowest horizontal spacing between conductors (6D), the effect of windward conductor was felt severely by the leeward conductor and the effect diminished with increased spacing. When the angular spacing was changed from 0° to 15° similar observations were made with all parameters becoming independent of the windward conductor at an angle of 15°. The aerodynamic force measurement results were correlated with the PIV flow field measurements to elucidate the underlying physics.

**Keywords:** Transmission cable icing, Bundled conductors. Particle Image Velocimetry, 3D Scan, Ice profile, Icing research tunnel.

**Introduction**

The aftereffects of atmospheric icing on structures is a major problem in cold countries. Engineering structures severely affected by atmospheric icing includes electric power transmission cables, aircrafts wings and other critical components exposed to atmosphere, wind turbines, suspension bridge cables etc. The adverse effects caused by the ice accretion on power transmission lines has always been a serious problem and it is the major focus of this paper. Ice accretions on transmission line cables due to freezing rain and also due to in-cloud icing reduces the reliability of electrical power distribution networks during the most critical cold periods and may lead to major damages to power lines [1–3]. Icing on conductors have led to several incidents and accidents in the past. For instance, a major icing event which occurred in Quebec and Ontario in winter 1998 had led to loss of power for about one million customers for about 3-30 days. Material damage was also substantial with hundreds of miles of transmission, sub-transmission and distribution lines being destroyed leading to an estimated cost of one billion Canadian dollars for reconstruction. Social cost involved in the incident exceeded three times that amount [4]. In
extreme cases, the atmospheric icing can cause severe damages to transmission cables and associated towers resulting in extensive electric power breakdown.

The shape and the density of the ice accreted on the cable are of major interest in investigating the potential risks involved. The wide variations in size, density, and shape of the ice formations cause an equally wide variety of loads to be imposed on the structural system of the transmission line. The weight of the accreted ice increases the vertical load on the conductors as well as the support structures. Combined effect of ice and wind can cause the transverse load on a transmission line to be increased significantly. It can cause vibrational loads due to wind if the ice deposition is asymmetric [5]. Natural winds can cause wind induced vibrations (oscillations caused by the vortex shedding) on transmission line conductors. These vibrations may adversely affect the reliability and durability of conductors and associated components. Damping devices may be used to attenuate this. However, when ice precipitations accrete on the conductors, the situation can change dramatically. The vibrations of conductors coated with ice may then occur in frequency ranges outside the design range of the dampers. Galloping, another wind-induced instability, also occurs on ice-accreted conductors and may result in large amplitude low frequency conductor displacements similar to ice coated suspension bridge cables mentioned earlier [6]. In addition, ice accumulation may also lead to flashover, where two conductors in wind induced motion would come in contact resulting in electrical discharge across them. Flashover may also happen when ice coated conductor sheds ice which results in sudden vertical displacement of the conductor [7–9].

It is well known that ice accretion on cold surfaces can be of several types depending on the icing conditions. Rime and glaze ice are two very common icing conditions—the specific type is dependent on the ambient air temperature, wind velocity, liquid water content (LWC) of the
oncoming air, and median volumetric diameters (MVD) of the impinging water droplets. Relatively low temperatures less than -10 °C and lower LWC favors a dry regime of icing where all the water impinging on the surfaces immediately freezes to form rime ice. Warmer temperatures around -5 °C and relatively higher LWC level favors a wet icing regime where only a portion of the impinging water freezes in the impingement area and the remaining unfrozen water runs back over the surface of the material and can freeze in the downstream locations causing glaze ice formation [10,11]. Rime ice accretion usually tends to follow the original contour of the model, since the water droplets freeze almost immediately upon impingement on to the surface. This is often associated with less aerodynamic penalties as compared to glaze ice which follows an irregular ice profile. Glaze ice is the most dangerous type of ice. As glaze ice is caused by wet icing conditions, it forms much more complicated shapes and hence have larger aerodynamic penalties.

A better understanding of the dynamic ice accretion process on power transmission cables is highly desirable for the development of counter measures for icing mitigation. While a number of studies has been conducted recently on transmission cable icing phenomena [12–17], very little can be found in literature to quantify the 3D shapes of the ice structures accreted dynamically on the surfaces of transmission cables and characterize the time-evolution of aerodynamic forces acting on power transmission cables during the dynamic ice accretion process under different icing conditions.

A bundle conductor is a conductor made up of two or more sub-conductors and is used as one phase conductor. For voltages greater than 220 kV it is preferable to use more than one conductor per phase which is known as Bundle conductor [18]. They are used in high voltage transmission for electrical advantages. With increasing power requirement, bundled conductor has
been a main style of erection in order to restrain corona development and reduce the line impedance, especially in the extra high voltage and ultra-high voltage transmission system [19]. Icing on bundled conductors is significantly different from that of single conductor as the presence of windward conductor affects the leeward conductor.

Wind tunnel studies have been conducted in the past to investigate the aerodynamic coefficients of these conductors. For instance, Xin-Min et. al. [20] conducted studies on the a 4-conductor bundle in a wind tunnel with artificial crescent shaped ice of various thickness attached on the bare conductor. The spacing between the conductors varied from ~ 15 D to 18 D where, D is the diameter of the conductor. It was found that the drag coefficient of the leeward conductor was affected by the presence of the wind ward conductor until the angle of attack between them was about 10°. When the angle between the conductor with reference to the wind flow was more than this, the wind ward conductor did not influence the leeward conductor. A similar study was conducted with crescent shaped ice as well as sector shaped ice (sector of a cylinder) by Xu et. al. [21]. It was found that, unsteady aerodynamic characteristics of crescent-shape and sector-shape iced 4-bundle conductors are totally different indicating that the actual shape of ice could influence the aerodynamic characteristics of the ice accreted conductor. Qing et. al. [18] studied the bundled conductor icing using simulations and experiments and found that ice accretion on a windward conductor is the same as that on a single conductor and both single and the wind ward conductor of the bundle have the same local collision efficiency and ice mass. It was also found that the spacing between the conductors in the bundled affects the ice accretion characteristics of the leeward conductor. It was also concluded that as the windward conductors have an influence on leeward conductors, accurate results of ice mass on the leeward only be obtained by separately investigating the leeward conductor.
In the present study, a comprehensive experimental investigation was conducted to examine the dynamic ice accretion process over the surface of a two-conductor bundle where each conductor is a typical power transmission cable. It was found from Particle Image Velocity (PIV) measurements during previous studies during an earlier campaign on a single conductor studies that the height of the wake region caused by the ice accretion is does not extend much outside the layer of ice accreted on the conductor [22]. This indicates that the results of a study on two bundled conductors could be very well extrapolated to three or more bundled conductors. The study aims to characterize the effects of the ice accretion on the aerodynamic forces acting on the leeward conductor. The experimental study was conducted in the Icing Research Tunnel located at Iowa State University (i.e., ISU-IRT). Aluminum conductor steel-reinforced (ACSR) conductor is a type of high-capacity, high-strength stranded conductor typically used in overhead power lines. The outer strands are made of high-purity aluminum, chosen for its good conductivity, low weight and low cost [8]. The central strand is made of steel for additional strength to help support the weight of the conductor. The test model used in this study was an actual ACSR power transmission cable of diameter (D = 29 mm) which is a typical diameter used for high voltage power transmission of the order of 220 kV. The spacing between conductors varied between 6D to 14 D in steps of 2D where D is the diameter of the cable model. The influence of the angle of attack between the windward and leeward conductor with respect to the airflow direction was also studied by subjecting the conductors at 0°, 2.5°, 5°, 7.5°, 10° and 15°. The layout of the conductor set up shown in Fig. 4-1.

The models were mounted in ISU-IRT as per the spacing and angles mentioned earlier and subjected to both wet glaze and dry rime icing conditions. As indicated earlier and proven by other studies the ice accretion characteristics of the windward conductor is not influenced by the
presence of leeward conductor. Therefore, all measurements were done on the leeward conductor. During the experiments, in addition to using a high-speed imaging system to record the dynamic ice accretion process, a digital image projection (DIP) based 3D scanning system was utilized to quantify the 3D shapes of the ice structures accreted on the surface of the leeward cable model at the end of icing. The aerodynamic drag forces acting on the leeward cable model during the dynamic icing process were also measured by using a pair of high-sensitive force/moment load cell mounted at two ends of the test model. A high-resolution Particle Image Velocimetry (PIV) system was also used to characterize the behaviors of the turbulent airflows over the same model. The detailed PIV flow field measurements were correlated with the dynamic aerodynamic force data and the measured 3D shapes of the accreted ice structures to gain further insight into the underlying physics for better understanding of the effects of ice accretion process and its effects on the aerodynamic characteristics of the bundled power transmission cables/lines.

![Diagram of bundled conductors](image)

**Figure 4-1.** The layout of the bundled conductors used for the study.

**Experimental Set Up and Test Model**

**Icing Research Tunnel and Test Model**

The experiments were conducted at Iowa State University –Icing Research Tunnel, (ISU-IRT) originally donated by Collins Aerospace System (i.e., formerly Goodrich Corporation). It is a newly refurbished research-grade multifunctional icing research tunnel. ISU-IRT has a test section of 2.0 m in length × 0.4 m in width × 0.4 m in height with all of the side walls being optically transparent. ISU-IRT allows wind speeds to be accelerated to 60 m/s and airflow
temperature to be cooled down to −25 °C. The turbulence level of the oncoming airflow at the entrance of the test section was estimated to be about 3.0 %, as measured by a hot wire anemometer. A water spray system, which consists of arrays of 8 pneumatic atomizing spray nozzles (Spraying Systems Co., 1/8NPT-SU11), was installed at the entrance of the contraction section of ISU-IRT to inject micro-sized water droplets (10–100 μm in size) into the test section. The desired liquid water content (LWC) level and the medium volumetric diameter (MVD) of the airborne water droplets can be achieved by regulating the water flow rate and air/water pressures supplied to the spray nozzles. In summary, ISU-IRT can be used to simulate atmospheric icing phenomena over a range of icing conditions (i.e., from very dry rime icing to extremely wet glaze icing conditions). By leveraging ISU-IRT, extensive research work has been previously conducted to investigate various atmospheric icing phenomena, including aircraft icing, aero-engine icing, wind turbine icing and cable stayed bridge icing [22–26].

**Figure 4-2** Experimental set up
The experimental set up is shown in Fig. 4-2. As mentioned earlier, the present study is performed on a two-bundle transmission cable model. Each of the conductor is an ACSR conductor 29 mm in overall diameter as shown in Fig. 1. The models spanned the whole width of the IRT (i.e., L = 0.4 m). The surface of the transmission cable model used in the present study was found to be hydrophilic with the contact angle of sessile water droplets over the surface of the transmission cable model being about 65°, which is in the range of the surface wettability of typical transmission cables as reported by Li et al. [27].

During the experiments, the velocity of the incoming airflow in ISU-IRT was kept at $V_\infty = 20 \text{ m/s}$ which is a typical wind speed during transmission cable icing events in cold winters. The corresponding Reynolds number based on the diameter of the test model is $Re = 50,000$. Typical rime and glaze icing conditions that power transmission cables usually experience in cold winters were simulated in the present study. While ambient temperature and the liquid water content (LWC) level of the incoming airflow in ISU-IRT was set at $T_\infty = -5.0 \degree \text{C}$ and LWC = 2.0 g/m$^3$ for the glaze icing experiments, the corresponding testing parameters were set at $T_\infty = -15.0 \degree \text{C}$ and LWC = 1.0 g/m$^3$ for experiments under the rime icing condition. Icing duration of the experiments was 1000 s.

**Quantification of the Dynamic Ice Accretion Process on the Surface of the Test Model**

In the present study, a high-speed imaging system (PCO-Dimax-S1, acquisition rate up to 25,000 frames per second with 1008 pixels by 1008 pixels in spatial resolution) along with a 60-mm Macro Lens (Nikon, 60 mm Nikkor 2.8D) was used to record the dynamic images of the ice accretion process (i.e., transient water film runback, rivulet formation, and accumulated ice growth) over the ice accreting surfaces of the leeward conductor model. The camera was positioned vertically above the test model. Low-flicker illumination was provided by a pair of 150 W fiber-coupled halogen lamps (AmScope, HL250-AS). The key features of the dynamic ice
accreting process would be revealed qualitatively based on the sequentially snapshots of the ice accretion process.

In addition to acquiring snapshot images to visualize the dynamic ice accretion process, a novel digital image projection (DIP) based 3D scanning system was also used to achieve “in-situ” measurements of the 3D shapes of the ice structures with the test model (leeward conductor) still being mounted inside ISU-IRT. The DIP system is based on the principle of structured light triangulation which is similar in principle to stereo vision technique, but replacing one of the cameras in the stereo vision technique with a digital projector [28]. A digital image with known pattern characteristics was projected onto the test object of interest (i.e., ice structures accreted over the surface of the transmission cable model for the present study). Due to the complex three-dimensional (3D) geometrical profiles of the test objects (i.e., the surface of the accreted ice structures), the projected digital patterns are deformed when observed from a perspective different from the projection axis. By comparing the distorted digital patterns (i.e., acquired images with ice structures accreted over the surface of the transmission cable model) with a reference digital pattern without the test objects on the reference surface, the 3D profile of the iced test model can be retrieved quantitatively. Further information about the technical basis and implementation of the DIP system is available in [28].

After conducting a careful calibration operation to register the correlation relationship between the digital projector and high-resolution camera, the iced test model was rotated at every 20° around its center for the DIP image acquisitions. The DIP images were processed to retrieve 3D profiles of the ice structures acquired at different phase angles and then combined automatically to reconstruct the 3D shapes of the ice structures accreted over the surfaces of the test model.
It should be noted that, while a number of intrusive techniques have been developed for quantitative measurements of ice shapes accreted over test models, e.g., hand tracing method [29], and mold-and-casting method [30], they are usually very time consuming and expensive in implementation (i.e., mold-and-casting method). Furthermore, some of the fragile ice features might even be damaged during the ice shape measurements. More recently, non-intrusive laser light sheet scanning technique has also been developed for 3-D ice shape measurements [31,32]. However, the laser scanning method can only measure 2-D profiles of accreted ice structures directly, and relies on a line-by-line scanning operation to reconstruct 3D ice shapes, which could be very time consuming and much involved in instrumentation for high-resolution measurements of complex 3D ice structures. The DIP-based 3D scanning system used in the present study is capable of quantitatively measuring complex 3D shapes of ice structures accreted over the transmission cable model. In comparison with those conventional methods (i.e., hand-tracing method, mold-and-casting method, or laser light sheet scanning technique), the DIP-based 3D scanning system used in the present study is much faster (i.e., ~10s per scan) to achieve full 3D shape measurements of ice structures over the entire span of the test model and also much easier to implement for “in-situ” measurements of 3D ice shapes with the test model still being mounted inside the icing tunnel. For the DIP-based 3D scanning operation, while the airflow was paused, the ambient temperature was maintained at the same level as that used for ice accretion experiment. The changes in the morphologies of the ice structures are believed to be very small due to the scanning operation.

In order to estimate the measurement uncertainty of the DIP-based 3D scanning system, a test plate with a series of roughness elements in the form of hemispheres of different sizes was custom designed. This plate was 3D printed with a high-accuracy rapid prototyping machine with
an accuracy level of 10 µm, as shown in Fig. 4-3(a). Then, the DIP-based 3D scanning system was used to measure the roughness elements 3D printed on the test plate. Since the actual height distributions of the hemispheres are known, the measurement accuracy of the DIP-based 3D scanning system can be evaluated by quantitatively comparing the measured results against the actual heights of the hemispheres. Figure 4-3(b) gives the quantitative comparison of the measured profiles against the actual data of both the concave and convex hemispheres of 8.0 mm in diameter along two arbitrarily selected traces passing through the centers of the hemispheres. It can be seen clearly that the measured results agree with the real height profiles quite well for both the concave and convex hemispheres. Based on the measurement data at about 500 points around the hemispheres, the mean and root-mean-squared (i.e., RMS) values of the differences between the measurement results and the actual values were calculated. The averaged difference between the measurement results and the actual height values (i.e., the measurement uncertainty of the DIP-based 3D scanning system) was found to be ~150 micrometers, which is about 3.0 % of the diameters of the 8.0mm hemispheres. Similar measurement uncertainty level was also found for the other hemispheres with different diameters.

**Figure 4-3:** Test plate and estimated profiles by using the DIP-based 3-D scanning system
Aerodynamic Force Measurements with Multi-Axis Force-Moment Transducers

In the present study, a pair of high-sensitive, multi-axis force-moment transducers (ATI-IA Mini 45) were mounted at two ends of the leeward cable model to measure the unsteady aerodynamic forces acting on the test model during the dynamic ice accreting process. The force/moment transducers are composed of foil strain gage bridges, which can measure the aerodynamic forces along three orthogonal axes, and the moment (torque) about each axis. The precision of the force-moment transducer for the force measurements is ± 0.25% of the full range. During the experiments, the two sets of the force/torque transducers were synchronized via a 16-bit data acquisition system (NI USB-6218) at the data acquisition of rate of 2,000 Hz.

Wake Measurements with a Digital Particle Image Velocimetry (PIV) System

A digital Particle Image Velocimetry (PIV) was used to map the velocity fields over the leeward conductor model. Acquired images were processed using DaVis 7.2 software. For the PIV measurements before the ice accretion process, the incoming airflow was seeded with ∼ 1 μm oil droplets using a smoke generator, while the airborne super-cooled water droplets were used as the tracer particles for the PIV measurements during the ice accretion process. It should be noted that, since the super-cooled water droplets suspended in the incoming airflow were estimated to have a mean volume diameter (MVD) of approximately 20 μm, the corresponding Stokes number of the water droplets was estimated to be about 1.0 (i.e., St ≈ 1.0), indicating a reasonable dynamic response of the droplets in terms of following the airflow. Illumination was provided by a double-pulsed Nd:YAG laser (Evergreen, Big Sky Laser) adjusted on the second harmonic and emitting two pulses of 200 mJ at the wavelength of 532 nm with a repetition rate of 15 Hz. The laser beam was shaped to a thin sheet by a set of mirrors, spherical, and cylindrical lenses. The thickness of the laser sheet in the measurement region was about 1.0 mm. A high-resolution 12-bit digital camera (2048 pixel by 2048 pixel resolution, PCO-Tech) with a Nikon Nikkor 60 mm 1:2.8 D lens
was used to acquire images of tracer particles for the PIV measurements. The digital camera and the double-pulsed Nd:YAG lasers were connected to a workstation (host computer) via a Digital Delay Generator (Berkeley Nucleonics, Model 565), which controlled the timing of the laser illumination and the image acquisition for the PIV measurements. After acquiring the PIV images, instantaneous velocity vectors were obtained by frame to frame cross-correlation of the patterns of particle images, using an interrogation window of 32 pixels × 32 pixels. An effective overlap of 50% of the interrogation windows was employed in PIV image processing. In the present study, a cinema sequence of about 300 instantaneous PIV measurements were used to calculate the ensemble-averaged flow field around the transmission line model. The measurement uncertainty level for the instantaneous PIV measurements is estimated to be within 5.0%, while the uncertainty level for the measurements of the ensemble-averaged flow field being about 3.0%.

**Experimental Results and Discussion**

Before performing the ice accretion experiments, ISU-IRT was operated at a prescribed cold temperature level (i.e., -15.0 °C for the rime icing experiments and – 5.0 °C for the glaze icing experiment) for at least 20 minutes to ensure that the tunnel reaches a thermal steady state. Since the temperature inside the ISU-IRT was set to be well below the freezing temperature of water temperature (i.e. at 0.0 °C), after switching on the water spray system, the water droplets exhausted from the water spray nozzles would be in a super-cooled state. Dynamic ice accretion process was found to start immediately, upon the impingement of the super-cooled water droplets onto the test model.

**Rime Ice Accumulation (Effect of Spacing Between Conductors)**

The ice accretion process over a solid surface could be of several types depending on the combined effects of ambient temperature, wind speed, size of the super-cooled water droplets, and Liquid Water Content (LWC) level in the incoming airflow [11,33]. Figure 4-4 shows typical
snapshot images of the ice accretion process to reveal the dynamic icing process over the surface of the test model (leeward conductor model) under a typical rime icing condition of $V_\infty = 20$ m/s, $T_\infty = -15$ °C, and $LWC = 1.0$ g/ m$^3$. For comparison, the ice accretion on a single conductor (i.e., only the windward conductor is present) is also provided. The snapshot images at the end of icing process ($t = 600$ s) are shown in Fig. 4-4 for single conductor as well as for different spacing between the windward and leeward conductor. It can be seen clearly that, since the ambient temperature was very low (i.e., $T_\infty = -15$ °C), the super-cooled water droplets were found to freeze into ice almost instantly upon impinging onto the surface of the transmission cable model. As described in [11], since the latent heat of fusion released during the phase changing process of the impinging super-cooled water droplets would be removed/dissipated very rapidly under the rime icing condition, all the impacted water droplets were found to be frozen into solid ice immediately. The ice structures were found to accumulate mainly around the leading edges of the test model (i.e., mainly within the direct impinging zone of the super-cooled water droplets) without any noticeable surface water runback over the surface. The accreted ice structures were found to be rather rough and had milky-white and opaque appearance. Such experimental observations are found in typical a rime icing process, as described in [11].

It could be clearly seen from Fig. 4-4 that as the spacing between the conductors increases from 6D to 14D, the ice thickness at the end of the process also increases. At the smallest spacing between conductors (i.e., 6D), the windward conductor acts as a strong interference to the leeward conductor and the less supercooled water droplets impinge on the leeward conductor. When the spacing between the conductors increase, the wake flow pattern provide less interference to the leeward conductor and hence more supercooled water droplets impinge on the leeward conductor increasing the ice layer thickness.
Figure 4-5 gives the typical measurement results of the DIP-based 3D scanning system for selected cases (single conductor, 6D and 12D cases) of the rime ice accretion experiment. The characteristics of the dynamic ice accreting process over the surface of the test model were revealed much more clearly and quantitatively. The cross-sectional view of the ice accretion is also provided in the figure. It could be clearly seen from the cross section that as the single conductor accretes the maximum ice as there is no inference for the supercooled water droplets to impinge on the model. At the minimum spacing tested (i.e., 6D) the supercooled water droplets have maximum interference from the windward conductor and therefore minimum ice accretes on the surface. When the spacing is increased to 12D, it could be clearly seen that more ice accretes on the conductor than the 6D case, but still it is much lesser than the single conductor. This indicates that even at a spacing of 12D the wake flow has not fully recovered from the effect of windward conductor.

![Figure 4-4: Representative snapshots of the ice structures accreted over the surface of the test model at the end of icing at different spacing under a typical rime icing condition of \( V_\infty = 20 \, \text{m/s}, T_\infty = -15 \, ^\circ\text{C}, \) and \( \text{LWC} = 1.0 \, \text{g/m}^3. \)](image)
Figure 4-5: Measured 3D shapes of the ice structures accreted on the surface of the test model at selected cases at the end of icing under the rime icing condition.

As described above, the aerodynamic forces acting on the test model during the dynamic ice accreting process were also measured by using a pair of high-sensitive force-moment transducers (ATI-IA Mini 45) mounted at two ends of the test model. Figure 4-6 gives the mean aerodynamic drag data as a function of ice accretion time under the rime icing condition. The total duration of the force measurements was 700 seconds. The water spray system of ISU-IRT was switched on at 100 seconds after turning on the force-moment transducers (i.e., to start the ice accretion process at \( t = 100s \)). By averaging the measurement data within the first 100 seconds for a single conductor (i.e., before starting the ice accretion process), the mean value of the aerodynamic drag acting on the test model, \( D_0 \), was calculated. In the present study, the value of \( D_0 \) is used as the baseline to evaluate the effects of the dynamic ice accretion on the aerodynamic drag force acting on the model. During the initial phase of experiments with the smooth cylindrical model, it was found that drag coefficient of the model for the test case without any ice accretion was found to be 1.16 (i.e., \( C_D =1.16 \)). The measurement result of this study was found to be in good agreement with the standard drag coefficient value (i.e., \( C_D =1.20 \)) of a circular cylinder reported in the previous studies at the same Reynolds number [34].
It should be noted that, the projected area of the iced test model along the airflow direction would change dynamically due to the ice accumulation over the test model during the ice accretion experiment, though this is more evident in case of glaze ice than rime ice. Instead of using drag coefficient, the aerodynamic drag data measured during the dynamic ice accretion process is presented in terms of normalized drag force, i.e., the measured instantaneous drag force data were normalized by the baseline drag force for a single conductor before the icing process $D_0$. For comparison of data, the drag forces acting on the leeward conductor at different spacings are also normalized with the same value $D_0$. Hence, the label of Y-axis in Fig. 4-6 is set as $D/D_0$. As described above, while the instantaneous drag acting on the test model were acquired with a data acquisition frequency of 2,000Hz, the moving averaged values of the instantaneously measured drag data (i.e., averaging over every 5 seconds of the instantaneous measurements) is plotted in Fig. 4-6 for comparison.

It could be seen that the single conductor had a distinct drag characteristic compared to the other cases with spacing. In general, after the water spray system was switched on at $t = 100$ s, the super-cooled water droplets impinges onto the surface of the test model to start the ice accretion process immediately, mainly on the front surface of the model (i.e., within the direct impinging zone of the super-cooled droplets) as shown clearly in Fig. 4-4 and Fig. 4-5. As time progresses, with more and more super-cooled water droplets impinging onto the test model, the ice layer accreted over the front surface of the transmission cable model would become thicker and thicker which would change the outer profile of the iced test model substantially. As described earlier, rime ice tends to conform to the original shape of the test model. As shown clearly in Fig. 4-5, the rime ice accumulation on the front surface of the test model tends to maintain the shape of model throughout the icing process. The drag force was found to reduce to 95% of the original value at
the end of icing event. This is due to more collection efficiency at the leading edge which tends to slightly streamline the shape of the conductor. For the cases with spacing, it could be seen that as the spacing increases from 6D to 14D, the normalized drag force also increases, from about 65% of the single conductor value for the case of 6D to about 75% for the case of 14D. The amount of ice accreted on the leeward conductor is much lesser due to the interference from the forward conductor. Therefore, there was not enough ice accretion to cause the streamline effect especially at smaller spacings. But as the spacing approaches 12D, slight effects of streamlining could be seen.

**Figure 4-6:** Aerodynamic drag force acting on the test model under the rime icing condition.

In the present study, PIV measurements were also used to investigate the changes of the ensemble-averaged airflow characteristics induced by the ice accretion over the test model for selected cases (single conductor, 6D and 12D cases). The image acquisition was done at 15 Hz frequency. Fig. 4-7 shows the ensemble averaged flow field for these cases during the ice accretion experiment. The airborne super-cooled water droplets were used as the tracer particles for the PIV measurements during the ice accretion process. The ensemble average image corresponding to the
end of icing event was created using 300 image pairs recorded over the last 20 seconds of the process. Clearly a velocity deficit could be observed ahead of the leeward conductor causing a significant drop in the amount of super cooled water droplets carried by the airflow and subsequent drop in the mass of accreted ice. The trailing part of the vortex left by the windward conductor could also be seen in the case of 6D spacing between the two conductors. Representative ice shapes are also shown in the figure.

![Figure 4-7: Time averaged PIV flow field visualization for the rime ice accumulation at the end of icing process (t = 600 s) for selected cases](image)

**a) Single Conductor  

b) 6D  

c) 12D**

**Figure 4-7:** Time averaged PIV flow field visualization for the rime ice accumulation at the end of icing process (t = 600 s) for selected cases

**Rime Ice Accumulation (Effect of Angle Between Conductors)**

In this section, the effect of angle between the conductors with respect to the wind direction is discussed. The windward conductor was placed at a spacing of 12D from the leeward conductor. At this spacing, the leeward conductor was places at different angles based on the wind flow direction as shown in Fig. 4-1. The angles of attack used were 0°, 2.5°, 5°, 7.5°, 10° and 15°. The dynamic images record by the high-speed camera at the end of icing event (t = 600 s) are shown in Fig. 4-8. It may be noticed that with increasing angle of the leeward conductor, the amount of ice accreted on the conductor increases. At an angle of 15°, the ice accretion on the leeward conductor is practically same as the windward conductor. This was also verified later from the drag force measurements. Therefore, the upper limit of angular spacing was limited to 15°.
Figure 4-9 gives the typical measurement results of the DIP-based 3D scanning system for selected cases of angular positions (single conductor, 0° and 7.5°) of the leeward conductor. The characteristics of the dynamic ice accreting process of the complex ice structures accreted over the surface of the test model were revealed much more clearly and quantitatively. The cross-sectional view of the ice accretion is also provided in the figure. Ice accretion on a single conductor is also provided for reference. When the spacing is increased, it could be clearly seen that more ice accretes on the conductor than, but still it is much lesser than the single conductor.

Figure 4-8: Representative snapshots of the ice structures accreted over the surface of the leeward conductor model at the end of icing at different angles between the conductor under a typical rime icing condition of $V_\infty = 20$ m/s, $T_\infty = -15$ °C, and LWC = 1.0 g/ m$^3$. 
**Figure 4-9:** Measured 3D shapes of the ice structures accreted on the surface of the test model at selected cases at the end of icing under the rime icing condition.

**Figure 4-10:** Aerodynamic drag force acting on the test model under the rime icing condition.

The mean dynamic drag force measurements are shown in Fig. 4-10. It may be seen that at an angle of 0° (i.e., the leeward conductor is directly in the wake of windward conductor), the normalized drag force acting on the leeward conductor even before the icing process is about 75% of the windward conductor. With increasing angular spacing, it could be seen that, the drag force
slowly increases and at angle of 15°, the drag coefficient profile of both conductors are almost overlapping indicating that the leeward conductor is out of the wake effects of the windward conductor.

The time averaged PIV results at the end of icing process for selected cases (single conductor, 0° and 7.5°) are also shown in Fig. 4-11. A velocity deficit could be observed ahead of the leeward conductor at an angle of 0° causing a significant drop in the amount of super cooled water droplets carried by the airflow and subsequent drop in the mass of accreted ice. But as the angular position is increased to 7.5°, it may be observed that the velocity deficit is more prominent at the bottom part of the leeward conductor as compared to the top part. This is because, at this angular position, the leeward conductor was placed towards the downward direction.

Figure 4-11: Time averaged PIV flow field visualization for the rime ice accumulation at the end of icing process (t = 600 s) for selected angle of attack cases.

Glaze Ice Accretion (Effect of Spacing Between Conductors)

For the glaze icing experiments, while the velocity of the incoming airflow in ISU-IRT was still kept at \( V_\infty = 20 \text{ m/s} \), the ambient temperature was increased to a much warmer temperature (i.e., \( T_\infty = 5 \text{ °C} \)) and the LWC level in the incoming airflow was also higher (i.e., LWC = 2.0 g/m\(^3\)). Figure 4-12 shows the typical snapshot images to reveal the dynamic ice accretion process over the surface of the test model under the glaze icing condition. It can be seen clearly from the
case of a single conductor under glaze icing condition that, the ice structures with a glassy appearance that accreted over the surface of the test model was found to be transparent and have a smooth appearance with water runback which are typical features of a glaze icing process as described in [35]. This experimental observation can be explained by the fact that, corresponding to the much higher LWC level in the incoming airflow under the glaze icing condition, more super-cooled water droplets would impact onto the surface of the test model and undergo phase changing (i.e., solidification) process within the same time duration. Thus, a significantly larger amount of latent heat of fusion would be released over the surface of the test model within the same duration of the ice accretion experiment. Due to the relatively higher ambient temperature (i.e., $T_\infty = -5 \, ^\circ C$) under the glaze icing condition, this larger amount of the latent heat could not be removed/dissipated fast enough by convective and/or conductive heat transfer process. This would result in the local accumulation of the released latent heat of fusion over the surface of the test model. Therefore, only a portion of the super-cooled water droplets were found to be frozen into solid ice upon impingement, while rest of the impinged water mass still remains in the liquid state. Driven by the airflow around the test model, the unfrozen water mass was found to run back over the ice accreting surface of the test model to from rivulet flows, similar to that described by [28]. The runback surface water was found to be frozen into solid ice subsequently to form rivulet-shaped ice structures at downstream locations (i.e., in the downstream region beyond the direct impinging zone of the super-cooled droplets). But glaze ice accumulation showed a considerable variation on the accreted ice characteristics with different spacing between conductors as compared to rime ice. In the case of 6D, the ice accretion mostly resembles rime icing with more minute roughness elements which are generally not characteristics of glaze ice accumulation. This is because the wake behind the windward conductor influences the ice accretion characteristics of
the leeward conductor. This was later verified with PIV measurements. The larger supercooled water droplets are not able to follow the wake vortices and impinge in the leeward conductor placed at the rear while only the smaller droplets are able to do so. This creates the smaller roughness elements on the surface as shown. Even though, this effect was seen to diminish with increased spacing, it was observed that at higher spacings smaller liquid water droplets where seemed to coalesce into larger droplets and convert into ice. This was because the oncoming liquid water droplets did not directly impinge on the leeward conductor to the interference by the leeward conductor. The accumulated droplets on the leeward conductor moved around over the surface due to relatively warmer temperatures as compared to rime ice and coalesced to form larger drops and subsequently froze into larger ice structures.

**Figure 4-12:** Representative snapshots of the ice structures accreted over the surface of the test model at the end of icing at different spacing under a typical glaze icing condition of $V_\infty = 20$ m/s, $T_\infty = -5$ °C, and LWC = 2.0 g/ m$^3$. 
The characteristics of the dynamic ice accretion process under the glaze icing condition could be observed quantitatively and with more clarity from the measured 3D shapes of the ice structures accreted over the surface of the test model for selected cases (Single conductor, 6D and 12D). It can be seen in the case of a single conductor that, due to the gravity effects, the runback water over the lower surface of the test model readily broke into rivulet flows, and then form more complicated runback ice structures subsequently near the bottom of the model, in comparison to those over the upper surface of the test model. Since the irregular-shaped runback ice structures accreted over the surface of the test model would intrude further into the incoming airflow to cause large-scale flow separation, it would result in much greater aerodynamic drag force acting on the iced test model, which was revealed more quantitatively from the force measurements as described later. But for the case of leeward conductor at different spacing the ice accretion was seen to be significantly lower with no rivulets on the downward direction. This is due to the lower apparent LWC experienced by the leeward conductor due to the interception by the windward conductor.
Lower LWC would cause the latent heat transfer process to be faster thereby avoiding the larger rivulet formation observed in the case of single conductor.

**Figure 4-14:** Measured aerodynamic drag force acting on the test model under the glaze icing condition.

The characteristics of the dynamic aerodynamic drag force acting on the single conductor under the glaze icing condition were found to be quite different from those under the rime icing condition as shown in Fig. 4-14. As described above, since the impinging super-cooled water droplets were not frozen into solid ice completely under the glaze icing condition, the unfrozen water mass would run back over the surface of the test model, driven by the airflow around it. It was observed during the dynamic imaging that a portion of the water that reaches the top and bottom surfaces of the test model will eventually be carried away by the airflow without freezing into ice in glaze icing condition. The remaining droplets would freeze into ice. This frozen ice layer acts as nucleation points for the forthcoming water droplets, eventually leading to larger mass of ice being accreted. As the ice accretion time increased, with more and more super-cooled water droplets impinging onto the test model, the glaze ice layer accreted over the surface of the test
model became thicker and thicker. Due to the continuous increase of diameter of the iced test model the projected area of the iced transmission cable model along the incoming airflow direction would become bigger and bigger. As a result, the aerodynamic drag force acting on the test model was found to increase monotonically as the ice accretion time increases to about 1.65 times the initial value. Furthermore, the formation of the irregular-shaped runback ice structures would induce large-scale flow separation, which would also contribute to the continuous increase of the aerodynamic drag force acting on the iced single conductor under the glaze icing condition. However, the situation was different for the leeward conductor at various spacing ratios. It was seen that, for the case of 6D, the ice accretion streamlined the conductor to a large extend (which are typical characteristics of rime ice accretions as mentioned earlier). This resulted in a continuous decrease in the drag force with time as could be seen in Fig. 4-14. This effect was less prominent for the case of 8D. For spacing ratios from 10D to 14D, the drag force was mostly invariant. This is because due to the absence of rivulet formation, the projected area in the flow direction was essentially constant and this could not intercept more water droplets as in the case of single conductor.

The corresponding PIV images are shown in Fig. 4-15. A comparison with the wake profile of the rime ice accretion in Fig. 4-7 would indicate that, as time progresses, the wake region seems to undergo an increase in width. Representative ice profiles are also shown in the figure. A comparison between rime and glaze ice accretion on a single conductor at the end of icing, indicates that the width of the wake region has undergone and appreciable enlargement from about 2.75D in case of rime ice to 3.5 D in the case of glaze ice, where D is the diameter of the cylinder with a corresponding increase in drag force. This is partly due to the higher LWC (2 g/m³ as opposed to 1 g/m³ for rime ice) and also due to the run back water which freezes outside the region
of impingement in random shapes. However, for the case of 6D, a major portion of the wake of the windward conductor could be seen in Fig. 4-15 indicating a contrast with rime ice. This indicates that there is a larger interception of the supercooled water droplets caused by the presence of windward conductor in case of glaze ice which explains the rougher ice elements accreted in this case. Even though the velocity deficit ahead of the leeward conductor is reduced at 12D, the wake width in this case is very small as compared to the single conductor.

![Figure 4-15](image)

**Figure 4-15:** Time averaged PIV flow field visualization for the glaze ice accumulation at the end of icing process (t = 600 s) for selected cases

**Glaze Ice Accumulation (Effect of Angle Between Conductors)**

As in the case of rime ice, the windward conductor was placed at a spacing of 12D from the leeward conductor. At this spacing, the leeward conductor was placed at different angles based on the wind flow direction as shown in Fig. 4-1. The angles of attack used were similar to the case of time ice (0°, 2.5°, 5°, 7.5°, 10° and 15°). The dynamic images recorded by the high-speed camera at the end of icing event (t = 600 s) are shown in Fig. 4-16. It may be noticed that with increasing angle of the leeward conductor, the amount of ice accreted on the conductor increases. At an angle of 7.5°, the ice structures look similar to a single conductor which might lead to a conclusion that the windward conductor no more affects the leeward conductor beyond this angle. However, this is not true as could be seen from the 3D scanned ice profiles as well as drag force measurements.
as to be discussed later.

**Figure 4-16:** Representative snapshots of the ice structures accreted over the surface of the leeward conductor model at the end of icing at different angles between the conductor under a typical glaze icing condition of $V_\infty = 20$ m/s, $T_\infty = -5 \degree C$, and $LWC = 2.0 \text{ g/ m}^3$.

Due to very close angular spacings and restrictions on providing holes on the acrylic panel of the ISU-IRT, the hole corresponding to $7.5^\circ$ was made at the bottom. Therefore, the interference at this angle ($7.5^\circ$) was felt more severely at the bottom portion of the leeward conductor. As could be seen in the experimental setup in Fig. 4-2, the high-speed camera was placed vertically above the test model. Therefore, the dynamic icing images obtained from this view at an angle of $7.5^\circ$ looks similar to a single conductor. From the drag force measurement, it was clear that, it was at an angle of $15^\circ$, that the ice accretion on the leeward conductor becomes practically same as the windward conductor.
Figure 4-17 gives the typical measurement results of the DIP-based 3D scanning system for selected cases of angular positions (single conductor, 0° and 7.5°) of the leeward conductor. As in the previous cases, the characteristics of the dynamic ice accreting process of the complex ice structures accreted over the surface of the test model were revealed much more clearly and quantitatively. When the spacing is increased, it could be clearly seen that more ice accretes on the conductor than, but still it is much lesser than the single conductor. As pointed out in the previous section, it could be seen from the scanned ice profiles at an angle of 7.5°, that the large rivulet structures at the bottom of the single conductor is absent. This is due to the relative position of the windward conductor which was located at the bottom portion of the side panel. This intercepted more super cooled water droplets which was bound to impact the bottom portion of the leeward conductor.
Figure 4-18: Measured aerodynamic drag force acting on the test model under the glaze icing condition.

Figure 4-18 shows the dynamic drag force measurements under the glaze icing conditions at various angular spacing $s$ between the conductors. As could be seen, the normalized drag force increased from $\sim 75\%$ of that of the single conductor to $\sim 100\%$ while the angular position was increased from $0^\circ$ to $15^\circ$. At $15^\circ$, the drag force is practically same as that of a single conductor indicating that the effect of the windward conductor is not felt by the leeward conductor beyond this angle.

Figure 4-19: Time averaged PIV flow field visualization for the glaze ice accumulation at the end of icing process ($t = 600$ s) for selected cases
The time averaged PIV results at the end of icing process for selected cases (single conductor, 0° and 7.5°) are also shown in Fig. 4-19. A velocity deficit could be observed ahead of the leeward conductor at an angle of 0° causing a significant drop in the amount of super cooled water droplets carried by the airflow and subsequent drop in the mass of accreted ice. But as the angular position is increased to 7.5°, it may be observed that the velocity deficit is more prominent at the bottom part of the leeward conductor as compared to the top part. This is due to the reason explained earlier. A drastic change in the size of the vortices could be seen at both cases as compared to the single conductor.

Conclusion

In the present study, experimental investigations were conducted to examine the dynamic ice accretion process over the surfaces of a two-bundle high-voltage power transmission cables and characterize the effects of the ice accretion on the aerodynamic forces acting on the transmission cables. The experimental study was performed at the Icing Research Tunnel at Iowa State University (i.e., ISU-IRT) to generate typical atmospheric icing conditions (i.e., both wet glaze and dry rime icing conditions) experienced by power transmission cables. An ACSR conductor, having the same diameter as that of typical high voltage power transmission cables (i.e., $D = 29$ mm), was mounted in ISU-IRT for the ice accretion experiments. In the present study, the velocity of the incoming airflow in ISU-IRT was kept at a constant value of $V_\infty = 20$ m/s during the ice accretion experiments. While the temperature and the liquid water content (LWC) level of the incoming airflow was set to be at $T_\infty = -5.0$ °C and $LWC = 2.0$ g/m$^3$ for the glaze icing experiments, the corresponding values were set to be $T_\infty = -15.0$ °C and $LWC = 1.0$ g/m$^3$ for the experiments under the rime icing condition. In addition to using a high-speed digital imaging system to record the dynamic ice accretion process, a novel digital image projection (DIP) based
3D scanning system was also used to quantify the 3D shapes of the ice structures accreted on the surface of the transmission cable model as a function of the ice accretion time. The time variations of the aerodynamic drag forces acting on the test models during the dynamic ice accretion process were also measured quantitatively by using a pair of high-sensitive force/moment transducers mounted at two ends of the test model. The two bundle conductors were placed at various spacing ratios (6D, 8D, 10D, 12D, 14D), where D is the diameter of the conductor and also at various angular positions with respect to the incoming flow direction (0°, 2.5°, 5°, 7.5°, 10° and 15°). All measurements were made on the leeward conductor. As the ice accretion characteristics of the windward conductor will not be altered by the presence of the leeward conductor, the windward conductor is practically same as a single conductor subjected to icing conditions. Therefore, a single conductor measurement was also made for both rime and glaze ice and is used as the reference of comparison of parameters.

It was found that, under the rime icing condition, the super-cooled water droplets carried by the incoming airflow would be frozen into solid ice instantly upon impingement onto the surface of the transmission cable model. The ice structures were found to accrete mainly within a relatively narrow region on the front surface of the test model (i.e., within the direct impinging zone of the super cooled water droplets) and the projected area in the airflow direction remained essentially the same. While the rime ice structures accreted on the surface of the test model were found to be opaque and have a rough, milk-white appearance, the total mass of the ice layer accumulated on the test model was found to increase linearly with the ice accretion time. It was found that when the spacing between the conductors was increased from 6D to 14D, the ice accretion characteristics of the leeward conductor like amount of ice accreted and drag force acting on the model increased proportionately. While the angular spacing was increased from 0° to 15°,
similar observations were made. It was found that the ice accretion characteristics of the windward conductor becomes independent of the leeward conductor at angle of 15°. PIV results indicate that the vortex structures had a significant reduction in width when the windward conductor was placed ahead of the leeward conductor.

The dynamic ice accretion process over the surface of the test model was found to be more complicated under the glaze icing condition. This was more prominent in case of a single conductor. Upon impinging onto the surface of the test model, only a portion of the super-cooled water droplets would freeze into solid ice instantly, and the rest would stay in liquid state. The unfrozen surface water was found to run back freely, driven by the airflow around the test model. Since the water runback would re-distribute the impinged water mass, the glaze ice layer accumulated on surface of the test model was found to have a much wider coverage and become more uniformly distributed azimuthally. As the ice accretion time increases the glaze ice layer accreted over the surface of the test model was found to become thicker and thicker. With the continuous increase of the outer diameter of the iced test model, the airborne super-cooled water droplets over a much greater region would be able to impinge onto the iced test model and turn into solid ice subsequently. As a result, the total mass of the glaze ice accumulated on the test model was found to grow much faster with a nonlinear relationship to the ice accretion time.

The characteristics of the aerodynamic drag force acting on the transmission cable model was found to be highly dependent on the types of ice structures that accreted on the test model. Under the rime icing condition, the aerodynamic drag force acting on the singe conductor model was found to reduce to about 95 % of the original value at the end of the rime icing process. On the contrary, the aerodynamic drag acting on the same model was found to increase monotonically with the ice accretion time under the glaze icing condition. The aerodynamic drag force acting on
the iced test model after 600 seconds of glaze ice accretion was found to increase to \( \sim 165\% \) of the baseline case. However, when the windward conductor was placed, the drag force measurements showed considerable difference for both rime and glaze ice. For the case of rime ice, when the spacing between the conductor was changed from 6D to 12D, the normalized drag force increased from \( \sim 65\% \) to \( \sim 75\% \) of the single conductor. When the windward conductor was placed at various angular positions (0° to 15°), the normalized drag force increased from \( \sim 75\% \) to 100% of that of the single conductor indicating that at 15°, the windward conductor no more influences the leeward conductor. The dynamic drag force in general did not exhibit major changes with time. The horizontal spacing between the conductors was fixed at 12D, which is a typical value for transmission cable bundles, for the angular measurements. However, for the case of glaze ice the drag force measurements changed significantly with time and also with different positions of the windward conductor.

Particle image velocimetry (PIV) results substantiate the findings from the load cell where it was found that the width of the wake was significantly impacted when the windward conductor was placed at positions where it influenced the leeward conductor. In the case of glaze ice when the leeward conductor was placed at 6D from the windward conductor, the wake structures of the latter strongly interfered with the ice accretion characteristics of the former almost changing the ice structures to rime ice even under glaze icing conditions.

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References


CHAPTER 5. AN EXPERIMENTAL STUDY OF ANTI-ICING PROCESS ON POWER TRANSMISSION LINE

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Abstract

In the present study, an experimental investigation was conducted to examine the anti-icing techniques over a high-voltage power transmission line. The experimental study was conducted in the Icing Research Tunnel located at the Iowa State University (ISU-IRT). The test model was a cylindrical rod of PVC with diameter of a commonly used high-voltage power transmission line cable (D = 29 mm). The model was subjected to typical glaze and rime icing conditions. An incoming wind speed of 20 m/s, a liquid water content (LWC) of 1.0 g/m³ and an ambient temperature of -5 °C was used to study glaze ice accumulation. LWC of 0.5 g/m³ at a temperature of -10 °C was used to study rime ice accretion at same wind speed. DBD plasma and superhydrophobic coated surfaces (SHS) were the anti-icing techniques tested. It was found that the plasma actuator located at the leading edge was able to prevent the freezing of water droplets near the leading edge. But these droplets froze at downstream locations. While SHS was used without plasma, it was found that ice was frozen only at the leading edge and downstream regions were ice free. While both techniques were used simultaneously, the entire transmission line cable model was ice free. Multiple plasma actuators without SHS was also tested. Six plasma actuators located at uniform angular spacings were able to keep the surface ice free without the SHS coating.

Keywords: Transmission cable icing, Particle Image Velocimetry, 3D Scan, Ice profile, Icing research tunnel.
Introduction

The problems caused by the atmospheric icing has severe effect on several engineering structures and machines. Electric power transmission cables, aircrafts wings and other critical components, wind turbines, suspension bridge cables etc. are some of the engineering structures which are severely affected by atmospheric icing. The adverse effects caused by the ice accretion on power transmission lines and methods to mitigate this problem by anti-icing techniques is a widely researched problem. Ice accretions on transmission line cables due to freezing rain and also due to in-cloud icing reduces the reliability of electrical power distribution networks during the most critical cold periods and may lead to major damages to power lines [1–3]. Though this research area has been pursued for a long time, the research in this field has been intensified after the 1998 winter storm in Canada. A major icing event which occurred in Quebec and Ontario in winter 1998 had led to loss of power for about one million customers for about 3-30 days. Material damage was also substantial with hundreds of miles of transmission, sub-transmission and distribution lines being destroyed leading to an estimated cost of one billion Canadian dollars for reconstruction. Social cost involved in the incident exceeded three times that amount [4] . In extreme cases, the atmospheric icing can cause severe damages to transmission cables and associated towers resulting in extensive electric power breakdown.

The shape and the density of the ice that accrete on the cable are of major interest in investigating the potential risks involved. The wide variations in size, density, and shape of the ice formations cause an equally wide variety of loads to be imposed on the structural system of the transmission line. The weight of the accreted ice increases the vertical load on the conductors as well as the support structures. Combined effect of ice and wind can cause the transverse load on a transmission line to be increased significantly. It can cause vibrational loads due to wind if the ice deposition is asymmetric [5]. Natural winds can cause wind induced vibrations (oscillations
caused by the vortex shedding) on transmission line conductors. These vibrations may adversely affect the reliability and durability of conductors and associated components. Damping devices may be used to attenuate this. However, when ice precipitations accrete on the conductors, the situation can change dramatically. The vibrations of conductors coated with ice may then occur in frequency ranges outside the design range of the dampers. Galloping, another wind-induced instability, also occurs on ice-accreted conductors and may result in large amplitude low frequency conductor displacements similar to ice coated suspension bridge cables mentioned earlier [6]. In addition, ice accumulation may also lead to flashover, where two conductors in wind induced motion would come in contact resulting in electrical discharge across them. Flashover may also happen when ice coated conductor sheds ice which results in sudden vertical displacement of the conductor [7–9].

Operations carried out after ice storms, while conductors are covered with significant layers of ice are called as de-icing operations. Anti-icing systems are activated before the storm to prevent any significant deposit throughout the precipitation. This will also ensure that lines will not undergo any static or dynamic overloads and problems of fatigue and galloping minimized. Any de-icing attempt carried out in initial phases are also categorized as anti-icing. There are several techniques of anti/de-icing transmission cable lines. A classification of de-icing and anti-icing methods into four categories, passive, thermal, mechanical, and miscellaneous, based on the physical principle used in the method of ice removal, was proposed by Laforte et. al. [10]. While thermal methods are based on the melting of the ice, mechanical methods are based on the breaking down of the ice. Passive methods are based on natural forces without using an input energy source. Thermal methods mainly involve Joule heating by increasing the current intensity above the normal level to reduce the ice accretion. This is done by briefly raising the current intensity as in
Polhman and Landers (1982) [5] or by short-circuiting the conductor as attempted in Manitoba Hydro et. al. [5]. Live load current technique and short current melting technique have been experimented in China [11]. Rolling method in which the ice is broken using a mobile pulley system pulled by an operator on the ground, is the only mechanical technique which has become operational for the de-icing of conductors [12]. The passive methods are those which do not require any external energy supply other than from natural forces: wind, gravity, incident radiation and temperature variations [10]. One of passive techniques involves hydrophobic superhydrophobic coatings. These coatings introduce low surface adhesion and prevent water droplet sticking onto surfaces [13].

Surface wettability has a substantial effect on ice accretion process over surfaces. In case of bare aluminum conductor, the surface is hydrophilic with a contact angle ~ 65°. On the other hand, the surface coated with superhydrophobic coatings have contact angle >150°.

It is crucial to remove the water from the surface before it freezes on the surface. During the icing conditions, the temperature of liquid water droplets is below freezing point. Therefore, this removal process needs to be much faster. Droplets can be moved away if any external force is able to overcome capillary forces acting on the water. It is well described in Waldman et al. [13] that, capillary forces can be estimated with equation 5.1.

$$F_{cap} = \pi R \gamma_{LG} \left[ \sin \left( \frac{\Delta \theta}{2} \right) \sin \left( \frac{\theta_{adv} + \theta_{rec}}{2} \right) \right]$$  \hspace{0.5cm} (5.1)

Here R is the radius of the water droplet, and $\gamma_{LG}$ is the surface tension of the liquid-gas interface. Liu et al. estimated the ratio of capillary forces acting on the droplets between two surfaces and showed that capillary forces acting on hydrophilic surfaces is 25 times larger than SHS (Eq. 5.2).

$$\frac{F_{cap, Enamel}}{F_{cap, Hydrobead}} \approx 25$$  \hspace{0.5cm} (5.2)
In the case of SHS, capillary force acting on the droplet is very low. Therefore droplet on SHS is highly mobile, compared to the one on the hydrophilic surface. It is much easier to overcome the capillary forces; especially if aerodynamic or gravitational forces are present, which suggests that under same conditions, elimination of water droplets over the surface is much easier with the application of super hydrophobic coating on the surface.

One attractive application of SHS, in addition to the extraordinary water-repellency, is their potential to reduce snow/ice accumulation on solid surfaces. Cao et al. [14] studied the anti-icing properties of SHS coatings over an aluminum plate under both laboratorial and natural icing conditions. Their results indicate that that SHS could alleviate ice formation/accretion to some extent. Mangini et al. [15] investigated the mechanism of runback ice formation on a SHS and reported that surface wetting property could dramatically change the ice formation process. Other passive anti-icing approaches, such as using slippery liquid-infused porous surfaces (SLIPS) [16–18] and soft PDMS materials [19], have also been explored under various icing conditions in recent years. Most of the previous research in use of water repellent surfaces in aerodynamics was for airfoil applications. As demonstrated by Liu et al. [19] and Waldman et al. [13], for airfoil/wing models coated with hydro-/ice-phobic coatings, ice formation/accretion would significantly be mitigated since the aerodynamic forces exerted from the boundary layer airflows would sweep away the water/ice from most of the SHS coated airfoil/wing surfaces. However, ice was still found to form in the vicinity of the stagnation line near the airfoil/wing leading edge. This highlights one of the major challenges facing hydro-/ice-phobic coating strategies. The hydro-/ice-phobic coatings could produce low adhesion forces between the surface and water/ice and rely on aerodynamic shear forces acting tangentially to the surface to remove the water/ice accretion. Such passive approaches would break down near the stagnation line because the shear forces near the
stagnation line are very small or completely vanishes. Further exacerbating the problem is that the water collection efficiency is a maximum at the airfoil stagnation line. Use of dielectric barrier discharge (DBD) based plasma could be a solution to this.

DBD plasma has been used for flow control for the last two decades. Roth et al. [20] are among the first to report that dielectric-barrier-discharge (DBD) plasma actuation would have favorable effects on flow control about two decades ago. Since then, numerous studies have been conducted to employ DBD plasma actuation for various flow control applications [21–27]. Plasma based flow control technique has several advantages in comparison to other traditional techniques used for active flow control. It does not involve any moving parts which significantly reduces the mechanical wear and tear. The response time of DBD plasma activation is very short which happens also instantaneously when triggered with the high voltage pulses [25]. DBD plasma actuators can be surface mounted and require lower electrical power for the flow control operations [28]. Due to relatively simply system setup for DBD plasma generation, DBD plasma actuators can also be incorporated into existing structures easily. Numerical Optimization studies using DBD plasma actuators has also been performed in the past to find the most effective combination of triggering variables for optimized performance [29].

Figure 5-1: shows the schematic of a typical DBD plasma actuator.

As shown in the figure, a dielectric layer is sandwiched between two metal electrodes and the whole system can then be flush mounted to the surface over which the flow control is desired. The material used as the dielectric layer is typically an electrical insulator, such as Teflon, Kapton,
Poly-Vinyl Chloride (PVC), glass, ceramic or Plexiglas. The air close to the electrode would get ionized and creates the surface plasma when high voltages are applied to the exposed electrode with the other (encapsulated) electrode electrically grounded. DBD plasma actuation has been found to modify the flow fields over airfoil surfaces favorably under controlled conditions when operated within a range of Reynolds number and angles of attack [21–27].

Alternating current based dielectric barrier discharge (i.e., AC-DBD) plasma and nano-second based dielectric barrier discharge (i.e., NS-DBD) plasma are two most used DBD plasma configurations used for flow control studies. AC-DBD plasma, activated by an alternating current at relatively high voltages (typically ~ 10 ~ 30 kV) has been found to be able to induce an ionic wind in quiescent conditions with flow velocities typically of the order of 4 ~ 7 m/s [26,30]. This induced velocity is primarily responsible for the flow separation control. In the case of NS-DBD plasma, intermittent high voltage pulses at some predefined frequency are applied with pulse rise times lasting for only a few nanoseconds as opposed to the continuous sinusoidally varying alternating currents in AC-DBD plasma generation.

However, at high free stream velocities, AC-DBD plasma actuators were found to be ineffective due to the velocity of induced flow is limited to 8m/s [25]. Besides induced airflow, thermal energy is also generated by plasma actuation. In case of AC-DBD plasma while being used for flow control, the part of the input electrical energy which get released in thermal form was considered as “inefficient” [25]; however, this feature of DBD plasma has been leveraged for aircraft icing mitigation [31–35].

Because of the thermal energy generation, surface temperature of DBD plasma actuator dielectric layer increase significantly during plasma actuation [36]. The heating of the surface is caused by heat transfer from the plasma [37,38]. During the discharge, temperature of the gas at
plasma region can be significantly high as rotational temperature of the gas can be 400K at the edge of exposed electrode [39]. Recent study of Rodrigues et al. [40] provided thermodynamic analysis for dielectric layer of plasma actuators.

In the present study, an experimental investigation is conducted to study various anti-icing studies on a transmission line cable model. The experiments were conducted at Iowa State University Icing Research Tunnel (ISU-IRT). AC-DBD plasma was used in combination with passive coating (SHS) to reduce the severe effects of ice accretion on these conductors. AC-DBD plasma is particularly appealing for transmission cable as no separate plasma generator needs to be used in this case like in the case of DBD plasma for flow control applications. The high voltage pulses required for plasma generation is available on the transmission line conductor itself. To the best of authors knowledge, this is the first attempt made to anti ice transmission lines using DBD plasma.

**Experimental Set Up and Test Model**

**Icing Research Tunnel and Test Model**

The experiments were conducted at Iowa State University –Icing Research Tunnel, (ISU-IRT) originally donated by Collins Aerospace System (i.e., formerly Goodrich Corporation). It is a newly refurbished research-grade multifunctional icing research tunnel. ISU-IRT has a test section of 2.0 m in length × 0.4 m in width × 0.4 m in height with all of the side walls being optically transparent. ISU-IRT allows wind speeds to be accelerated to 100 m/s and airflow temperature to be cooled down to −25 °C. The turbulence level of the oncoming airflow at the entrance of the test section was estimated to be about 3.0 %, as measured by a hot wire anemometer. A water spray system, which consists of arrays of 8 pneumatic atomizing spray nozzles (Spraying Systems Co., 1/8NPT-SU11), was installed at the entrance of the contraction section of ISU-IRT to inject micro-sized water droplets (10–100 μm in size) into the test section.
The desired liquid water content (LWC) level and the medium volumetric diameter (MVD) of the airborne water droplets can be achieved by regulating the water flow rate and air/water pressures supplied to the spray nozzles. In summary, ISU-IRT can be used to simulate atmospheric icing phenomena over a range of icing conditions (i.e., from very dry rime icing to extremely wet glaze icing conditions). By leveraging ISU-IRT, extensive research work has been previously conducted to investigate various atmospheric icing phenomena, including aircraft icing, aero-engine icing, wind turbine icing and cable stayed bridge icing [41–45].

Figure 5-2: Icing Research Tunnel and test model

As mentioned earlier, the present study is performed on a transmission cable model (ACSR model) 29 mm in overall diameter as shown in Fig. 5-2. The test model used in the study is shown
in Fig. 5-3. As explained earlier and shown in in Fig. 5-1, the surface of the model on which the DBD actuators are mounted needs to be covered with several layers of dielectric barrier material. This would render the outer profile to be circular as opposed to the usual twisted cable strands. Also, since the AC-DBD plasma requires voltages over ~10kV, to avoid the risk of electrical shock, a cylindrical model made of PVC was used as the conductor model. The diameter of the conductor was ~29 mm which is a typical diameter for transmission line cables. While this technique is applied to real world transmission lines, the high voltage available in the conductors could be used to generate the plasma pulses. The exposed electrode was connected to high voltage pulses and the encapsulated electrode was grounded electrically. The surface of the transmission cable model used in the present study was found to be hydrophilic with the contact angle of sessile water droplets over the surface of the transmission cable model being about 65°, which is in the range of the surface wettability of typical transmission cables as reported by Li et al. [46].

**Plasma Generator**

During the experiments, the DBD plasma actuators were powered by a high-voltage alternating current power source (Nanjing Suman Company, model CTP-2000 K). Voltage and current measurements were obtained from a high-voltage probe (Textronix P6015) and a current probe (Pearson model 2877). The voltage and current pulses were obtained using a National Instruments data acquisition card NI-6221 and the LabVIEW program.

**High Speed Imaging**

In the present study, a high-speed imaging system (PCO-Dimax-S1, acquisition rate up to 25,000 frames per second with 1008 pixels by 1008 pixels in spatial resolution) along with a 60-mm Macro Lens (Nikon, 60 mm Nikkor 2.8D) was used to record the dynamic ice accretion process (i.e., transient water film runback, rivulet formation, and accumulated ice growth) over the ice accreting surfaces of the test model. The camera was positioned vertically above the test model.
Low-flicker illumination was provided by a pair of 150 W fiber-coupled halogen lamps (AmScope, HL250-AS). The key features of the dynamic ice accreting process would be revealed qualitatively based on the time sequences of the acquired snapshots of the ice accretion images.

**Thermal Imaging**

Temperature maps during the plasma actuation over the surface of the model was achieved with an infrared thermal imaging system (FLIR-A615). IR thermal imaging system was mounted above the cylinder at a distance of 0.3 m. IR thermal imaging was started simultaneously with plasma actuation and recorded with a frequency of 50 Hz. IR camera calibration that takes different material emissivity into account was performed.

First, the entire surface of the conductor model was covered with a copper film 100 microns thick. About 6 layers of dielectric material (PVC) film was then wrapped around the model. Finally, the ground electrode was also mounted on the surface, which was a copper tape, 3mm wide as shown in Fig. 5-3.

During the experiments, the velocity of the incoming airflow in ISU-IRT was kept at $V_\infty = 20$ m/s which is a typical wind speed during transmission cable icing events in cold winters. The corresponding Reynolds number based on the diameter of the test model is $Re = 50,000$. Typical glaze icing conditions that power transmission cables usually experience in cold winters were simulated in the present study. The ambient temperature and the liquid water content (LWC) level of the incoming airflow in ISU-IRT was set at $T_\infty = -5.0$ °C and $LWC = 1.0$ g/m$^3$ for the glaze icing experiments. The ambient temperature and the liquid water content (LWC) level was set at $T_\infty = -10.0$ °C and $LWC = 0.5$ g/m$^3$ for the rime icing experiments. To investigate the effect of anti-icing technique, the model was subjected to an icing conditions for 300 s with the anti-icing techniques activated.
Experimental results and discussion

Glaze Icing Conditions

Before performing the ice accretion experiments, ISU-IRT was operated at a prescribed cold temperature level (i.e.– 5.0 °C) for at least 20 minutes to ensure that the tunnel reaches a thermal steady state. Since the temperature inside the ISU-IRT was set to be well below the freezing temperature of water temperature (i.e. at 0.0 °C), after switching on the water spray system, the water droplets exiting from the water spray nozzles would be in a super-cooled state. The Liquid Water Content (LWC) for the glaze icing experiments was 1 gm/m³. Dynamic ice accretion process was found to start immediately, upon the impingement of the super-cooled water droplets onto the test model.

![Diagram of DBD plasma actuators mounted on a test model](image)

**Figure 5-3:** Tests model with DBD plasma actuators mounted.

Figure 5-4 shows the typical snapshot images to reveal the ice structures before the ice accretion as well as after the accreting event at the end of 300 seconds. It can be seen clearly that, the ice structures with a glassy appearance that accreted over the surface of the test model was found to be transparent and have a smooth appearance with water runback which are typical features of a glaze icing process as described in [46]. This experimental observation can be
explained by the fact that super-cooled water droplets would impact onto the surface of the test model and undergo phase changing (i.e., solidification) process. Glaze ice accretion has a relatively larger LWC as compared to rime ice accretion. Thus, a significantly larger amount of latent heat of fusion would be released over the surface of the test model within the same duration of the ice accretion experiment. Due to the relatively higher ambient temperature (i.e., $T_\infty = -5 \, ^{\circ}C$) under the glaze icing condition, this larger amount of the latent heat could not be removed/dissipated fast enough by convective and/or conductive heat transfer process. This would result in the local accumulation of the released latent heat of fusion over the surface of the test model. Therefore, only a portion of the super-cooled water droplets were found to be frozen into solid ice upon impingement, while rest of the impinged water mass still remains in the liquid state. Driven by the airflow around the test model, the unfrozen water mass was found to run back over the ice accreting surface of the test model to from rivulet flows, similar to that described by [13]. The runback surface water was found to be frozen into solid ice subsequently to form rivulet-shaped ice structures at downstream locations (i.e., in the downstream region beyond the direct impinging zone of the super-cooled droplets).

![Figure 5-4: Typical snapshots of the ice structures accreted over the surface of the test model at the end of icing (t = 300 s) under a typical glaze icing condition of $V_\infty = 20 \, m/s$, $T_\infty = -5 \, ^{\circ}C$ (a) no ice condition (b) LWC = 1.0 g/ m$^3$.](image)

Experiments were then conducted to see the effect of plasma actuators on ice mitigation.
A plasma actuator system was made as shown in Fig 5-3. The first set of experiments were performed with six plasma actuators placed at equal angular positions i.e., 60° apart as shown in Fig. 5-5 (a). The encapsulated electrode was connected to the ground of the power source and exposed electrodes were connected to the high voltage port. When triggered this creates plasma on both sides of the exposed electrodes as could be seen in Fig. 5-3. As mentioned earlier, the thermal effect of this generated plasma could be used for ice mitigation. A typical plot of voltage and current on the plasma actuator while in operation is acquired using an oscilloscope and shown in Fig. 5-5 (b).

Figure 5-5: (a) Schematic diagram of the plasma actuators. 6 exposed electrodes equally spaced can be seen. (b) Typical voltage current characteristics of the plasma actuator while in operation.
Figure 5-6 shows the results of this experiment. The first experiment was conducted with the exposed electrode triggered with a high voltage pulse of 10 kV peak-to-peak. It may be noted that the actuator was placed in such a way that one of the actuators was exactly at the leading edge with reference to the flow direction. The snapshot at the end of the icing process is shown in Fig. 5-6 (a). By comparing Fig. 5-4 (b) with 5-6 (a) it could be seen that the region close to the copper tapes has less ice as compared to the region in between them. This is because the thermal energy concentrated close to the copper tape prevented the supercooled water droplets from freezing and ice was formed in the region away from the copper tape where the thermal effect was not felt. While this improved the situation as compared to the case with no plasma actuator, it did not render the surface ice free. In order to increase the thermal energy deposit to keep the surface ice free, the applied voltage was increased to 12 kV peak-to-peak from 10 kV. The result could be seen in Fig. 5-6 (b). It could be seen that there were no traces of ice. The entire surface was rendered ice free from the increased thermal energy deposit. The unfrozen water droplets were carried away from the surface by the airflow eventually.

The power required for this process is plotted as a function of time in Fig. 5-7. The instantaneous power is obtained as the product of instantaneous voltage and current as shown in Fig. 5-5- (b). The total experimental duration was 360 seconds where the plasma actuator was turned on at the beginning and maintained at same condition for 60 seconds before turning on the water spray system to start the icing process. It could be seen from Fig. 5-7 that the electrical power consumption was about 300 Watts per meter length of the model at the beginning before the icing process began. But with water droplet impingement, it dropped continuously till a steady state was reached at about a power of 200 W. This could be attributed to addition of water droplets at the tip of the actuator, which increases the resistance to the current pulses. A drop in applied voltage was
also observed with the ice accretion. Similar effect have been previously reported by [47]. So, the effective power consumption during the process is about 200 W on a long duration basis.

![Figure 5-6: Snapshot of the icing process over the surface of the test model at the end of icing (t = 300 s) under a typical glaze icing condition (a) V = 10 kV, (b) V = 12 kV.]

![Figure 5-7: Power consumption pattern during the icing process.]

The instantaneous temperature profile over the surface of the model was acquired using infra-red imaging system. Figure 5-8 (a) shows a typical instant during the de-icing process. The copper actuators are also highlighted in the figure. The flow direction is also shown in the figure. Figure 5-8 (b) shows the model of the cylinder with the actuator locations. Streaks of water droplet flow also could be seen in the infra-red image. It may be seen that the highest temperature over
the surface is close to the edge of water droplets. The temperature contour depicts $\Delta T$, which represents the difference in temperature with respect to the freezing point of water ($0 \, ^\circ C$). The plasma was kept on for 60 seconds before the impingement of super-cooled water droplets started. The water droplet impingement continued for 300 seconds after that with a total plasma on time of 360 seconds.

The temperature profile at a typical location over course of the icing process is shown in Fig. 5-9. The mean temperature (spatially averaged) over the actuator surface at a location (highlighted by the red dashed line) as a function of time is shown in Fig. 5-9. Temperature was found to rise with more plasma on time. The highest temperature observed was around 8.5 $^\circ C$ above the reference ($0 \, ^\circ C$). It may be noted that the infra-red image is shown for the case corresponding to a peak-to-peak voltage of 12 kV which resulted in successful anti-icing. It was observed that if the applied voltage was below this level, it resulted in ice formation over the surface and eventually covering the actuator with ice. This resulted in the embedding the plasma with ice and substantial drop in the plasma power. The temperature over the surface was found to decrease with time upon covering with ice in this context.

**Figure 5-8:** (a) Instantaneous Infra-red image during the anti-icing process. (b) model of the cylinder with the actuator locations.
Attempts were also made with lesser number of actuators. Three actuators were symmetrical placed around the model at 120° apart. It was observed that with lesser number of actuators, higher voltage needs to be supplied for the same plasma power consumption. Attempts were also conducted to investigate if anti-icing could be obtained with lower power consumption. It was observed that even with the same starting plasma power as in the case of six actuators, anti-icing could not be obtained with three actuators. This is due to the fact that the region of influence of each plasma actuator strip was limited and there were larger regions in between the actuators where the heating effect was not felt. Attempts were also made to place the leading edge of water impingement midway between two actuators. It was observed that ice was formed on the leading edge though other parts of the surface was rendered ice free. Attempts were also made with wider actuators with twice and thrice the width of the actuators used in this experiment which did not result in successful anti-icing.
Rime Icing Conditions

Experiments were also conducted under rime icing conditions. The Liquid Water Content (LWC) for the rime icing experiments was 0.5 gm/m³ and the ambient temperature in the tunnel was maintained at -10 °C. Other parameters remained same as the glaze icing conditions. The plasma was activated 60 seconds before the start of the water spray process.

![t = 0 s](image) ![t = 300 s](image)

(a) (b)

**Figure 5-10:** Typical snapshots of the ice structures accreted over the surface of the test model at the end of icing (t = 300 s) under a typical rime icing condition of $V_\infty = 20$ m/s, $T_\infty = -10$ °C (a) no ice condition (b) LWC = 0.5 g/ m³

Figure 5- 10 shows typical snapshot images of the ice accretion process over the test model to reveal the ice structure at the beginning (Fig. 5-10 (a)) and end (Fig. 5-10 (b)) of the ice accretion process under conditions of $V_\infty = 20$ m/s, $T_\infty = -10$ °C, and LWC = 0.5 g/ m³. It can be seen clearly that, since the icing experiment was conducted under a very cold condition (i.e., $T_\infty = -10$ °C), the super-cooled water droplets were found to be frozen into ice almost instantly upon impacting onto the surface of the power cable model. As described in [48], since the latent heat of fusion released during the phase changing process of the impinged super-cooled water droplets would be removed/dissipated very rapidly under the rime icing condition, all the impacted water droplets were found to be frozen into solid ice immediately. The ice structures were found to accumulate mainly around the leading edges of the power cable model (i.e., mainly within the direct impinging
zone of the super-cooled water droplets) without any noticeable surface water runback on the surface of the test model. The accreted ice structures were found to be rather rough and have milky-white and opaque appearances. Such experimental observations are found to be typical characteristics of a rime icing process, as described in [49]. As the ice accretion time increases, the ice layer accreted on the front surface of the power cable model were found to become thicker and thicker while the outer profile of the iced test model was found to become rougher and rougher. It may be noted that no plasma actuator was mounted at this stage.

![Snapshot of the icing process](image)

**Figure 5-11:** Snapshot of the icing process over the surface of the test model at the end of icing (t = 300 s) under a typical rime icing condition (a) V = 10 kV, (b) V = 12 kV, (c) = 14 kV

After the baseline case without plasma was tested, the plasma actuators were mounted as explained in the previous section. Six actuators were mounted around the cylinder at equal intervals as in the case of glaze ice. Figure 5-11 shows the results of this experiment. The first experiment was conducted with the exposed electrode triggered with a high voltage pulse of 10 kV peak-to-peak. The actuator was placed with one of the actuators exactly at the leading edge with reference to the flow direction. The snapshot at the end of the icing process is shown in Fig. 5-11 (a). It could be seen that there is no significant improvement from the baseline case. In order to prevent the ice accretion, the thermal energy deposit has to be increased. The applied voltage
was increased to 12 kV peak-to-peak from 10 kV. The result could be seen in Fig. 5-11 (b). It
could be seen that though there was a significant improvement, the surface was not completely ice
free. The region in between the two actuators on the forward side still had ice accretion. The
experiment was repeated with the applied voltage increased to 14 kV peak-to-peak. The result
could be seen in Fig. 5-11 (c). The entire surface was rendered ice free from the increased thermal
energy deposit. The unfrozen water droplets were carried away from the surface by the airflow
eventually.

![Graph showing power consumption as a function of time during rime icing process.](image)

**Figure 5-12:** Power consumption as a function of time during the rime icing process.

The power required for this process is plotted as a function of time in Fig. 5-12. It could be
seen that the electrical power consumption was about 450 Watts per meter length of the model at
the beginning before the icing process began. But with water droplet impingement, it dropped
continuously till a steady state was reached at about a power of 400 W. This could be because of
the addition of water droplets at the tip of the actuator, which increases the resistance to the current
pulses. A drop in applied voltage was also observed with the ice accretion as in the case of glaze
ice.
The instantaneous temperature profile over the surface of the model acquired using infra-red imaging system is shown in Fig. 5-13 (a). Figure 5-13 (b) shows the model of the cylinder with the actuator locations. Streaks of water droplet flow also could be seen in the infra-red image. It may be seen that the highest temperature over the surface is close to the edge of water droplets as in the case of glaze ice. The plasma was kept on for 60 seconds before the impingement of super-cooled water droplets started. The water droplet impingement continued for 300 seconds after that with a total plasma on time of 360 seconds.

**Figure 5-13:** (a) Instantaneous Infra-red image during the anti-icing process. (b) model of the cylinder with the actuator locations.

The temperature profile at a typical location over the icing duration is shown in Fig. 5-14. The mean temperature (spatially averaged) over the actuator surface along the dashed line shown in Fig. 5-13 (a) as a function of time is shown in Fig. 5-14. Temperature was found to rise with more plasma on time similar to the case of glaze ice accretion. The highest temperature observed
was around 14 °C above the reference (0 °C). It may be noted that the infra-red image is shown for the case corresponding to a peak-to-peak voltage of 14 kV which resulted in successful anti-icing.

![Graph](image.png)

**Figure 5-14:** Evolution of temperature with time over the surface. Spatially averaged temperature at the location highlighted with the dashed line Fig. 5-13 (a) is shown here.

**Experiments with Super Hydrophobic Coating**

Experiments were conducted under glaze icing conditions to test the effect of SHS coating. The testing conditions were same as before. The Liquid Water Content (LWC) for experiments was 1 gm/m³ with an airflow velocity of 20 m/s and an ambient temperature of -5°C. The icing duration was 300s. The entire surface of the model was first coated with SHS material. Commercially purchased coating material ‘Hydrobead’ was used in this case. In the case of SHS, capillary force acting on the droplet is very low. Therefore droplet on SHS is highly mobile, compared to the one on the hydrophilic surface. It is much easier to overcome the capillary forces; especially if aerodynamic or gravitational forces are present, which suggest under same conditions,
elimination of water droplets over the surface is much easier with the application of SHS on the model.

Results could be seen in Fig. 5-15. Figure 5-15 (a) shows the baseline case with no anti-icing technique applied. The surface accreted a significant amount of ice as could be seen in the figure. The experiment was then repeated with the whole surface of the model coated with superhydrophobic material. Fig. 5-15 (b) shows the result of this experiment. It could be seen that at the end of icing process (i.e., $t = 300$ s), the region near the leading edge was covered with ice whereas the downstream region is completely ice free. This is because of the reason explained earlier where the region near leading edge is directly impacted by the droplets and the SHS surfaces cannot prevent the ice formation in this region. The water droplets undergo a transition from Cassie-Baxter state to Wenzel state as shown in Fig.5-16. When droplets are gently rested on a SHS surface, it maintains super hydrophobicity. But if it is impacted with a force, the air cushion beneath is lost and droplets gets interlocked on the surface protrusions. However, the ice structures in this region are quite different. The water droplets impinging on the SHS, due to its inherent slippery nature, moves around over the surface and in the process coalesce to form larger globular droplets which subsequently freeze resulting in the ice structures seen.

Experiments were then repeated with a single plasma actuator mounted on the model surface. The exposed electrode of the plasma actuator was mounted at the leading edge of the model facing the oncoming airflow. The experiment was repeated under similar conditions with only this plasma actuator triggered. The applied voltage was 12 kV in this case. The frequency of applied plasma remained at 6 kHz. It may be noted that at this stage no surface coating was applied to mitigate the ice accretion. The result could be seen in Fig. 5-15(c). As explained earlier the DBD plasma has a thermal effect near the location of plasma where a part of the input energy is
converted to heat. This heat would prevent the impinging water droplets at the leading edge from freezing on the surface. But this effect is restricted only to the region near the plasma. Outside this region, where the thermal effect is not felt, the ice accretion process in not hindered. In addition, the unfrozen water droplets from the region close to leading edge also travels over the surface of the model driven by the airflow. This results in severe ice deposition at the downstream regions away from the leading edge as seen in the Fig. 5-15(c).

Figure 5-15: Snapshots of the icing process over the surface of the test model at the end of icing (t = 300 s) under a typical glaze icing condition with different anti-icing techniques. (a) Baseline case with no anti icing. (b) Only SHS coating applied. (c) Only Plasma triggered ON at leading edge (d) Both SHS coating and Plasma applied.
Ice accreted regions in Fig. 5-15(b) and Fig. 5-15(c) are complementary in nature indicating that if these techniques are combined to form a hybrid one, it may keep the surface completely ice free. This is shown in Fig. 5-15 (d) where the plasma is triggered on over the SHS coated surface. The hybrid technique can render the surface almost ice free. The water droplets impinging on the leading edge are prevented from freezing by the plasma. The water then runs back over the surface. SHS coated surface prevent the freezing in region downstream of the leading edge. The small amount of water droplets present on the surface are dynamically carried by the airflow and gets replaced by new droplets, but the ice layer does not grow over the surface.

**Figure 5-16:** Transition from Cassie Baxter State to Wenzel State

**Figure 5-17:** Power consumption as a function of time.
It was observed that the power consumed for this process is far less than that with multiple actuators. While in all previous experiments it was observed that the power consumption drops with the impingement of water droplets, in the hybrid case, the power first spiked to about 360 W/m length before dropping to about 100 W/m as shown in Fig. 5-17. This could be attributed to the chemical reaction between the SHS and DBD plasma. The DBD plasma was found to react with the coating material and the coating material eventually destroyed in the area of influence of plasma. When impacted with water droplets, a medium of low resistance could be created which causes the power to spike until all the chemical mixture is washed away by the impinging droplets. However, after the initial spike which lasted for a few seconds, the power consumption remained stable at 100 W/m length of actuator.

The most widely adopted technique for anti-deicing of long power networks is the thermal method which relies on Joule heating. Short circuit method is commonly adopted where all the current is sent through once cable at a time until the ice melts off. It requires that electric power should be disconnected from consumer lines during the operation. The effectiveness is also limited by resistance of wire material which is typically lower. Typical power consumption is of the order of 1 -10 kW/m² of surface area of the cable [50]. While this technique requires expensive infrastructure, the anti-deicing by plasma requires less equipment as the power for the operation is extracted from the lines. Also, the consumer lines need not be disconnected. For a comparison, the power consumption during this experiment was converted to Watts per unit area of model surface and it ranges from 1 kW/m² to 4 kW/m² which is lower than that of Joule heating. The former (1 kW/m² )corresponds to power in case of the hybrid technique and the latter (4 kW/m²) for the case of rime ice. In short, anti-deicing by DBD plasma could be a very promising technique for structural cables. This technique could also be effectively used for suspension bridge cables.
Conclusion

In the present study, experimental investigations were conducted to examine the anti-icing techniques to mitigate the effects of dynamic ice accretion process over the surfaces of typical high-voltage power transmission cables. The experimental study was performed at the Icing Research Tunnel at Iowa State University (i.e., ISU-IRT) to generate typical glaze and rime icing conditions experienced by power transmission cables. A cylindrical model of diameter 29 mm made of PVC was used as test model. In the present study, the velocity of the incoming airflow in ISU-IRT was kept at a constant value of $V_\infty = 20$ m/s during the ice accretion experiments. While the temperature and the liquid water content (LWC) level of the incoming airflow was set to be at $T_\infty = -5.0 \, ^\circ C$, LWC was set at 1.0 g/m$^3$ for the glaze icing experiments. The conditions were $T_\infty = -10.0 \, ^\circ C$, LWC was set at 0.5 g/m$^3$ for the rime icing experiments. Active, passive and hybrid techniques were tested. DBD plasma was used as the active technique and superhydrophobic coating was used as the passive technique and a combination of them were used as hybrid technique.

The dynamic ice accretion process over the surface of the test model was found to be complicated under the glaze icing condition. Upon impinging onto the surface of the test model, only a portion of the super-cooled water droplets would freeze into solid ice instantly, and the rest would stay in liquid state. The unfrozen surface water was found to run back freely, driven by the airflow around the test model. Since the water runback would re-distribute the impinged water mass, the glaze ice layer accumulated on surface of the test model was found to have a much wider coverage and become more uniformly distributed azimuthally. As the ice accretion time increases the glaze ice layer accreted over the surface of the test model was found to become thicker and thicker.
Under the rime icing condition, it was seen clearly that the super-cooled water droplets were found to be frozen into ice almost instantly upon impacting onto the surface of the power cable model. The ice structures were found to accumulate mainly around the leading edges of the power cable model (i.e., mainly within the direct impinging zone of the super-cooled water droplets) without any noticeable surface water runback on the surface of the test model.

In both cases, using six plasma actuators located around the test model at equal angular spacing were able to successfully prevent the ice accretion. Anti-icing under Glaze icing conditions required about 200 W/m length of cable and under rime icing conditions, about 400 W/m length.

It was found that the plasma actuator located at the leading edge was able to prevent the freezing of water droplets near the leading edge under glaze icing conditions. But these droplets froze at downstream locations. While SHS was used without plasma, it was found that ice was frozen only at the leading edge and downstream regions were ice free. While both techniques were used simultaneously, the entire transmission line cable model was ice free.

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**References**


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CHAPTER 6. METAMODELING-BASED PARAMETRIC OPTIMIZATION OF DBD PLASMA ACTUATION TO SUPPRESS FLOW SEPARATION OVER A WIND TURBINE AIRFOIL MODEL

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Abstract

While dielectric-barrier-discharge (DBD) based plasma actuators have been successfully demonstrated to suppress massive flow separation over wind turbine blades to reduce the transient aerodynamic loadings acting on the turbine blades, it is still a non-trivial task to establish a best combination of various operating parameters for a DBD plasma actuation system to achieve the optimized flow control effectiveness. In the present study, a regression Kriging based metamodeling technique is developed to optimize the operating parameters of a DBD plasma actuation system for the deep stall suppression over the surface of a wind turbine blade section/airfoil model. The data points were experimentally obtained by embedding a nanosecond-pulsed DBD (NS-DBD) plasma actuator at the leading edge of the airfoil model. The applied voltage and frequency for the NS-DBD plasma actuation were used as the design variables to demonstrate the optimization procedure. The highest possible lift coefficient of the turbine airfoil model at deep stalled angles of attack (i.e., \( \alpha = 22^\circ \) and \( 24^\circ \)) were selected as the objective function for the optimization. It was found that, while the metamodeling-based procedure could accurately predict the objective function within the bounds of the design variables with an uncertainty \( \sim 2\% \), a global accuracy level of \( \sim 97\% \) was achieved within the whole design space.
Keywords: Wind turbine aerodynamics; Dielectric-Barrier-Discharge (DBD) plasma actuation; Active flow control; Wind turbine airfoil stall suppression.

Introduction

Wind energy industry is currently undergoing a period of rapid growth on a global scale fueled by increasingly stringent norms on the utilization of conventional fossil fuels for power production. For instance, the U.S. Department of Energy (DOE) initiated the Wind Vision study where the costs and benefits of continued investments on wind energy was quantified. The study evaluates an ambitious, yet credible scenario in which wind energy will serve 20 percent of the nation’s total electric power demand by 2030, and 35 percent by 2050 [1]. Other countries have increased their wind power capacity as well in recent years. For example, wind power installation in China has been growing recently by an annual rate of ~10% until 2020 [2].

Attempts to extract more energy from the wind has led to bigger and bigger rotor diameters of wind turbine blades. While turbine rotor diameters of ~120 meters is quite common today, one of the major challenges faced by large-scale wind turbines is the constant variations in the direction and speed of the turbulent atmospheric boundary layer (ABL) winds which the turbines are exposed to. The ability of a wind turbine to respond to the rapid fluctuations of ABL winds in both speed and direction is hindered by the massive rotational inertia of the large-scale turbine assembly as a whole. Thus, wind turbine blades often operate under less than optimal conditions in relation to the instantaneous ABL wind speeds and directions [3]. The highly turbulent nature of the ABL winds would induce unsteady wind loadings acting on the turbine blades, which has become a severe problem with larger rotor diameters. If the unsteady wind loads can be reduced to a lower level, it will lead to a lighter structure and longer fatigue lifetime of the turbine blades, thereby, better economics of power production [4]. Mitigating the unsteady wind loads acting on a turbine blade, could be realized by using various flow control methods, including mechanically operated
flaps or adding momentum to the flow at specific locations on the turbine blades [5]. For example, van Dam et al. [6] suggested to utilize trailing edge flaps to control flow separation over turbine blades. While the use of trailing edge flaps has been revealed to be effective in providing unsteady wind load mitigation, the major disadvantage of such a method is the mechanical complexity, added mass, and additional maintenance requirements. Such drawbacks could be avoided if the flow control devices can devoid of moving parts. Plasma-based flow control approach has been suggested to be a potential solution for flow separation control to mitigate the unsteady wind loadings acting on wind turbine blades [7].

Roth et al. [8] are among the first to report that dielectric-barrier-discharge (DBD) plasma actuation would have favorable effects on flow control about two decades ago. Since then, numerous studies have been conducted to employ DBD plasma actuation for various flow control applications [9–15]. Plasma based flow control technique has several advantages in comparison to other traditional techniques used for active flow control. It does not involve any moving parts which significantly reduces the mechanical wear and tear. The response time of DBD plasma activation is very short which happens also instantaneously when triggered with the high voltage pulses [13]. DBD plasma actuators can be surface mounted and require lower electrical power for the flow control operations [16]. Due to relatively simply system setup for DBD plasma generation, DBD plasma actuators can also be incorporated into existing structures easily.

![Figure 6-1: Schematic diagram of a DBD plasma actuator](image-url)
Figure 6-1 shows the schematic of a typical DBD plasma actuator used for flow control. As shown in Fig. 6-1, a dielectric layer is sandwiched between two metal electrodes and the whole system can then be flush mounted to the surface over which the flow control is desired. The material used as the dielectric layer is typically an electrical insulator, such as Teflon, Kapton, Poly-Vinyl Chloride (PVC), glass, ceramic or Plexiglas. The air close to the electrode would get ionized and creates the surface plasma when high voltages are applied to the exposed electrode with the other (encapsulated) electrode electrically grounded. DBD plasma actuation has been found to modify the flow fields over airfoil surfaces favorably under controlled conditions when operated within a range of Reynolds number and angles of attack [9–15].

Alternating current based dielectric barrier discharge (i.e., AC-DBD) plasma and nanosecond based dielectric barrier discharge (i.e., NS-DBD) plasma are two most commonly used DBD plasma configurations used for flow control studies. AC-DBD plasma, activated by an alternating current at relatively high voltages (typically ~ 10 ~ 30 kV) has been found to be able to induce an ionic wind in quiescent conditions with flow velocities typically of the order of 4 ~ 7 m/s [14,17]. This induced velocity is primarily responsible for the flow separation control. In the case of NS-DBD plasma, intermittent high voltage pulses at some predefined frequency are applied with pulse rise times lasting for only a few nanoseconds as opposed to the continuous sinusoidally varying alternating currents in AC-DBD plasma generation. While NS-DBD plasma actuation induces lower momentum effects in comparison to AC-DBD plasma [18], it was found to exhibit a superior flow control performance due to the rapid deposition of energy by the short plasma pulses to cause steep thermal gradients in the localized area. The fast thermalization of NS-DBD plasma has also be found to induce a shock wave and associated secondary vortex which will
interact with the main flow by exciting the inherent flow instabilities to augment the flow control effects [11,18,19].

While majority of the previous studies of plasma-based flow control focused on suppression flow separations over the surfaces of airfoil/wing models designed for aeronautical applications, only a few efforts can be found in literature to apply plasma-based technique to control flow separation or/and airfoil stall for wind turbine applications. Nelson et al. [7] proposed a novel smart wind turbine blade concept, where the effectiveness of plasma-based flow control was exploited. The regions over the wind turbine blades requiring individual control could be identified and mounted with DBD plasma actuators and separate control strategies could be devised to meet multiple control objectives. More recently, active flow control using plasma actuators on wind turbine airfoil has been investigated numerically by Hikaru et al. [20] on an NREL S825 airfoil at the Reynolds number of 750k and an angle of attack ($\alpha$) = 22.1°. The turbine airfoil profile corresponding to 75% of blade radius was used for the simulations at a wind speed of 10 m/s. A DBD plasma actuator was located at the leading edge of the wind turbine airfoil section. The uncontrolled flow, characterized by massive separation near the leading edge, was controlled by turning on the DBD plasma actuator. Due to the relatively high angle of attack of the thick wind turbine airfoil, while it was not able to completely suppress the flow separation over the airfoil surface with the DBD plasma actuation, a partial reattachment was realized. The lift-to-drag ratio, which was used as a performance indicator, was found to increase from 2.24 to 6.53 by turning on the DBD plasma actuator.

It should be noted that, there are a number of operating parameters (design variables) involved in a well-designed DBD plasma actuator, including the applied voltage and frequency of the activation, the width of the exposed and encapsulated electrodes, the material and thickness of
the dielectric layer. Forte et al. [14] conducted a comprehensive investigation on the effects of all the important design variables mentioned above for an AC-DBD plasma actuator by varying one parameter at a time, while the others remained constant. Then the effects of each parameter on effectiveness of flow control was investigated. Dawson et al. [12] also conducted a similar study for NS-DBD plasma actuation. While these previous studies have contributed immensely to a better understanding about plasma-based flow control techniques, only a small fraction of the entire parametric design space was explored due to the inherent nature of varying only parameter at a time. Characterizing the whole design space using experiments would require a large number of expensive evaluations. The cost of the experiments can severely limit the optimization and design space exploration.

Use of a metamodel model-based optimization technique could be a solution to this problem. Metamodelling techniques are generally used to for parametric optimization when conducting simulations or experiments to explore the entire design space is very expensive [21,22]. Metamodels are the mathematical models developed based on experiments or simulations conducted at selected locations within the whole parametric design space, instead of exploring the entire design space. Various mathematical schemes would then be employed to predict the objective function of the optimization problem throughout the design space using the metamodel, i.e., a metamodel uses the value of the objective function at selected sample points to create a mathematical model which could then predict the objective function anywhere within the parametric design space with reasonable accuracy. Metamodeling-based optimization techniques allow multiple design variables to be simultaneously varied and have been applied to several expensive parametric optimization studies in recent years, including rotor blade design and optimization [23], high speed civil transport [24], airfoil shape optimization [25], diffuser shape
optimization [26] and supersonic turbine [27,28]. It should be noted that as the number of variables increases, the number of samples needed increases considerably and also the cost of tuning the model increases as well. Indeed, it is well accepted that studies involving more than ten variables becomes increasingly hard and those with more than a few thousand variables could be completely intractable. However the important design variables as mentioned earlier for plasma-based flow control are about six, and therefore metamodel-based optimization technique could be utilized for optimizing those variables without significantly increasing the complexity.

Kriging is one of the most popularly used metamodeling techniques. The use of Kriging is attractive in many optimization problems because it can give good predictions of complex objective functions in the parametric space and also provide a credible estimate of the possible error in these predictions [29]. While applying this technique to experimental data, care should be taken because two identical experiments conducted under similar conditions may not yield the exact same response due to random and human errors. Kriging metamodels could be based on an interpolating scheme or a regression scheme. Interpolation Kriging metamodels would ensure that the model passes through all the sample data points. A noisy data resulting from an experimental error could affect the prediction accuracy of the interpolation Kriging metamodel. The random error in physical experiments lends itself to the use of a regression model as a noise filter which would not restrict the model to go through all the points [29].

In the present study, we report the progress made in our recent efforts to conduct a parametric optimization of design variables of DBD plasma actuation using a metamodeling-based technique in order to suppress the massive flow separation over the surface of a wind turbine airfoil in deep stall. A turbine blade model with DU-96-W-180 airfoil shape in the cross-section was designed and manufactured for the present study. A DBD plasma actuator working in nano-second
mode (i.e., NS-DBD) was embedded at the leading edge of the turbine airfoil model for flow separation control. The parameters of interest (design variables) used in the present study are the applied voltage and frequency of the NS-DBD plasma pulses. The turbine airfoil model was mounted in a low-speed wind tunnel at the angle of attack of $\alpha = 24^\circ$ with a chord-based Reynolds number of $Re = 200K$. The objective of the present study is to find the optimum combination of these design variables of the NS-DBD plasma actuation for maximizing the lift coefficient ($C_l$) of the turbine airfoil model at the given angle of attack. The design variables are simultaneously varied in the design space as per a sampling scheme obtained using the Latin hyper cube (LHS) sampling technique. In order to verify the effects of Reynolds number and $\alpha$ in the magnitude of optimum parameters, the turbine airfoil model was also subjected to a different Reynold number and $\alpha$ (i.e., with Reynolds number of $Re = 300k$ and $\alpha = 22^\circ$). The data points used for the optimization procedure were obtained experimentally by integrating the measured surface pressure distributions over the wind turbine airfoil model to obtain the lift coefficients ($C_l$) of the turbine airfoil model. These $C_l$ values obtained served as evaluated objective function values at the initial sample locations for the metamodel. A digital Particle Image Velocimetry (PIV) system was also used in the present study to quantify the airflow field over the airfoil surface for the selected cases.

It should be noted that, while a wide variety of previous studies have been conducted on DBD plasma-based flow control, parametric optimization of DBD plasma actuation using the metamodeling-based technique has never been attempted. To the best of authors’ knowledge, this is the first attempt to combine experimental measurements with metamodeling-based techniques in order to establish the best combination of various operating parameters (design variables) of a DBD plasma actuation system. The present study aims to demonstrate that parametric optimization of the whole design space could be accomplished with lesser number of sample data points and
yet maintain reasonable accuracy of prediction of the objective function within the bounds of design variables. Such metamodeling based techniques could drastically reduce the number of experiments required for characterizing the whole design space.

**Problem Definition for the Optimization**

The present study utilizes a metamodel-based optimization technique to estimate the optimum values of the applied voltage and frequency of a NS-DBD plasma system for obtaining the maximum lift coefficient ($C_l$) of a turbine airfoil operating in deep stall condition. An increase in the $C_l$ of the turbine airfoil model is an indicator of improvement in partial reattachment of the separated flow over the airfoil surface. Since surface pressure measurements are acquired during the experiments, the objective function of the present study is seeking the maximum possible $C_l$ ($C_{l_{max}}$) and the combination of design variables which could achieve that value. The bounds on the design variables were decided based on previous experiments using a similar configuration. It was observed that applied voltages to the DBD plasma actuator in excess of 17 kV tends to burn through the dielectric layer (i.e., for the given dielectric layer used in the present study). The frequency of the applied voltage pulses exceeding 500 Hz and lower than 10 Hz did not seem to have any effects on the flow separation over the airfoil surface. Accordingly, the applied voltage was varied between 5.0kV to 14.0 kV, and the range of frequency of the applied voltage pulses was set to be within 10 Hz to 500 Hz which are the bounds of the design variables used here.

Thus, the optimization problem is formulated as:

$$\min_x F(x) = -C_l$$

$$s.t. \ x_{lb} \leq x \leq x_{ub}$$

Here, $F(x)$ represent objective or cost function with $x = [V \ f]^T$ is a column vector with voltage and frequency as the design variables. The negative sign is used for maximizing objective
function with minimization optimizer. The objective function is subjected to design variable bounds $x_{lb} \leq x \leq x_{ub}$, where $x_{lb} = [5 \ 10]^T$ and $x_{ub} = [14 \ 500]^T$ are the lower and upper bounds for design variable vector, respectively.

For comparing the effectiveness of DBD plasma actuation on improving the lift coefficient of the turbine airfoil model, the baseline lift coefficient for the test case with a passive actuator was used. The test case with the passive actuator refers to the scenario with the DBD plasma actuator being mounted at the airfoil leading edge but without turning the plasma actuators on.

**Experimental Setup and Test Model**

**Wind Tunnel used for the Present Study.**

The experimental study was performed at a low-speed, closed-circuit wind tunnel located at Aerospace Engineering Department of Iowa State University. The tunnel has a test section with a dimension of 0.45 m in width × 0.6 m in height × 1.45 m in length and four optically transparent walls. It has a relatively large contraction section (i.e., 10:1 in area ratio) upstream of the test section along with series of honeycomb, screen structures, and cooling system installed ahead of the contraction section to provide uniform, low turbulent incoming flow to enter the test section. The maximum airflow speed in the test section can go up to 40 m/s with the turbulence intensity level being 0.2 %, as measured using a hotwire anemometer.

**Wind Turbine Airfoil Model used for the Present Study.**

As shown schematically in Fig. 6-2, a wind turbine blade section model with DU-96-W-180 airfoil shape in the cross section was designed and manufactured for the present experimental study. The DU-96-W-180 airfoil, which is a cambered airfoil with a blunt trailing edge and a maximum thickness of 18% chord length, is a widely-used airfoil designed specifically for wind turbine applications [31]. The airfoil shape is known for its favorable aerodynamic performance and strong structural strength, which are very important for wind turbine blades. The turbine airfoil
model has a chord length of $C = 150$ mm and spanwise length of 600m (i.e., the same as the width of the wind tunnel test section). It was manufactured by using a rapid prototyping machine (i.e., 3D printer) with a polymer-composite-based material. The surface of the turbine airfoil model was coated with several layers of spray-on primer, and wet-sanded by using fine sandpapers (up to 2000 grit) to achieve a very smooth, glossy surface finish with ~20 µm in characteristic roughness. As shown in Fig. 6-2(b), 42 pressure taps were incorporated in the design of the airfoil model.

![Isometric view and Side view of the turbine airfoil model](image)

(a) Schematic of the turbine airfoil model embedded with the DBD plasma actuator

(b) Distribution of surface pressure taps around the turbine airfoil model.

**Figure 6-2:** The schematics of the turbine airfoil model with a NS-DBD plasma actuator embedded at the airfoil leading edge and distribution of surface pressure taps around the turbine airfoil model.
NS-DBD Plasma Actuator

A DBD plasma actuator was embedded around the leading edge of the airfoil model, as shown schematically in Fig. 6- 2(a). Both the encapsulated and exposed electrode had a width of 3.0mm and was made of ~100 microns thick copper film. The electrodes cover the entire span of the turbine airfoil model to ensure a spanwise uniform plasma formation to prevent any 3-dimensional effects. A layer of PVC film with a thickness of ~300 microns was used as the dielectric layer in the present study.

The DBD plasma actuator was powered by using high voltage pulses with a FID nanosecond pulse generator (FPG 20-10NM15), which has the capability to generate pulsed up to 20kV voltage (i.e., ~20ns in pulse width) and pulse repetition frequency (PRF) up to 10 kHz. The applied voltage and current pluses were monitored by using a Tektronix MDO3102 Mixed Domain Oscilloscope with 5 GSa/s sampling rate. It should be noted that, NS-DBD plasma actuation could create electromagnetic interference (EMI) effects to nearby electronic components. The EMI effects were mitigated by proper grounding of all equipment and covering the test section and all the electronic components and cables with a curtain of conductive metallic fabric.

Surface Pressure Measurements

As shown in Fig. 6- 2(b), 42 pressure taps were arranged in the mid-section of the turbine airfoil model to measure the surface pressure distribution around the airfoil surface. The pressure taps were connected to two units of miniature digital pressure scanners (Measurement Specialties Inc, Model number 32HD-0411021120, 32 channels per unit) with Tygon tubing of 1.5 mm diameter and 0.5 m length. The miniature digital pressure scanners incorporate temperature-compensated piezo-resistive pressure sensors with a pneumatic calibration valve, RAM, 16bit A/D converter, and a microprocessor in a compact self-contained module. The precision of the pressure acquisition system is ±0.03 % of the ±10 inch H2O full scale range. During the experiments, the
instantaneous surface pressure measurement data were acquired for 10 seconds at a data acquisition rate of 1,000 Hz. It should also be noted that, since the exposed electrode of the DBD plasma actuator (~100µm in thickness) was placed at the leading edge of the airfoil model, it would cover a few pressure taps near the airfoil leading edge on the suction side. The surface pressure values at these locations will be obtained by extrapolating the surface pressure values measured at the neighbors taps. Similar extrapolation schemes were widely used in similar studies with plasma flow control[16].

**Particle Image Velocimetry (PIV) Measurements**

In addition to the surface pressure measurements, a digital Particle Image Velocimetry (PIV) system was also used to conduct airflow field measurements to quantify the changes of the flow characteristics around the airfoil model with and without the NS-DBD plasma actuation. As shown schematically in Fig. 6-3, the PIV measurements were conducted in the vertical planes near the mid-section of the airfoil model (i.e., slightly away from the middle plane with the pressure taps). For the PIV measurements, the oncoming airflow was seeded with 1 ~ 5 µm oil droplets by using a seeding generator. Illumination was provided by a double-pulsed Nd:YAG laser (Evergreen, Big Sky Laser) adjusted on the second harmonic and emitting two pulses of 200 mJ at the wavelength of 532 nm with a repetition rate of 10 Hz. The laser beam was shaped to a thin sheet by a set of mirrors, spherical, and cylindrical lenses. The thickness of the laser sheet in the measurement region was about 1.0 mm. A high-resolution 12-bit digital camera (2048 pixel by 2048 pixel resolution, PCO-Tech) with a Nikon Nikkor 60 mm 1:2.8 D lens was used to acquire images of tracer particles for the PIV measurements. The digital camera and the double-pulsed Nd:YAG lasers were connected to a workstation (host computer) via a Digital Delay Generator (Berkeley Nucleonics, Model 565), which controlled the timing of the laser illumination and the image acquisition for the PIV measurements.
After acquiring the PIV images, instantaneous velocity vectors were obtained by frame to frame cross-correlation of the patterns of particle images, using an interrogation window size of 32 pixels × 32 pixels. An effective overlap of 50 % of the interrogation windows was employed in PIV image processing. In the present study, a cinema sequence of about 300 instantaneous PIV measurements were used to calculate the ensemble-averaged flow field around the airfoil model for the test cases with and without the NS-DBD actuation. The measurement uncertainty level for the instantaneous PIV measurements is estimated to be within 5.0 %, while the uncertainty level for the measurements of the ensemble-averaged flow field being about 3.0 %.

**Metamodeling-based Optimization**

**Optimization Algorithm**

Figure 6-4 shows the flowchart of the optimization algorithm which subsequently improves metamodel with infill criteria. The details of the optimization algorithm are explained below.
The optimization algorithm starts with generation of initial samples in design domain. Latin
Hypercube sampling (LHS) technique is used for generating initial design samples \( (x_1, x_2, \ldots, x_n) \),
where \( x_i \) represents \( i^{th} \) sample in total \( n_s \) design samples. For this study, voltage and frequency are
considered as design variables as mentioned earlier. LHS method ensures the good distribution of
sampling points over the entire design space such that entire range of each design variable is
covered. This is done by dividing considered cumulative probability distribution \([0 \text{ to } 1]\) of points
in equal parts and randomly sampling each interval to recreate input probability distribution [32].
Additionally, to ensure space fillingness property of the design space, the Morris-Mitchell criterion
is used. More details on this scheme is given by Morris & Mitchell [33].
One of the challenges of surrogate based optimization study is to decide required number of initial samples for accurate construction of metamodel. Having higher number of samples are always preferred for ensuring metamodel accuracy. However, in the present study, 12 samples per design variable are selected as initial sampling plan considering high cost of experimental evaluation of objective function (i.e., for two design variables, applied voltage and frequency, 24 sample points were used).

**Regression Kriging**

The surrogate based optimization techniques are widely used in field of optimization especially when objective function evaluation is expensive. In this technique an approximate cost function of expensive experiments are constructed which then is used in conjunction with a global optimizer to find optimum result. Kriging is a popular geostatistical technique which has been extensively used for multidisciplinary design and optimization studies [26]. Kriging method is named after the pioneering work of D.G. Krige [34], which was formally developed by Matheron [35]. Kriging method (interpolation kriging) generally assumes that the objective function value evaluated at sample points, which is used for generating the metamodel, does not have an error and represents true value. This method is capable of capturing complex multimodal landscape of the objective function. However, when the method is presented with noisy data, as that obtained from experiments, it could produce incorrect global optimum. In such cases regression Kriging method which extracts a smooth trend from the data and filters noise is preferred [29].

Regression Kriging method is primarily an extension of the interpolation Kriging method. The interpolation Kriging method is hereafter called as Kriging method. Therefore, first the Kriging method is presented. Later the modifications to handle noisy data is addressed through regression Kriging method. Kriging model start with set of sample data $n_s$ observed at initial
sampling plan obtained by LHS method. Kriging metamodel is built as a combination of a global approximation function plus a localized departure as

\[ y(x) = g(x) + Z(x), \]  

(2)

where \( y(x) \) is the unknown function sought and \( Z(x) \) is realization of a normally distributed Gaussian random process with zero mean, variance \( \sigma^2 \) and nonzero covariance [36]. Function \( g(x) \) is a global approximation of the design space and \( Z(x) \) represents the localized deviations from global function over design domain with \( n_s \) sampled data points \((x^1, x^2, \ldots, x^{n_s})\) where \( x^i = [x_1, x_2, \ldots, x_K]^T \subset \mathbb{R}^K \). Function \( Z(x) \) has a covariance matrix given by

\[ \text{Cov}[Z(x^i), Z(x^j)] = \sigma^2 R([R(x^i, x^j)]), \]  

(3)

where \( R \) represents the correlation matrix and \( R(x^i, x^j) \) is a correlation function between any two sampled data points \( x^i \) and \( x^j \). This makes \( R \) a \((n_s, n_s)\) symmetric matrix with ones along the diagonal. The correlation function \( R \) is a user defined function and for this study we have used Gaussian correlation function of the form

\[ R(x^i, x^j) = \exp \left[ -\sum_{k=1}^{K} \theta_k |x^i_k - x^j_k|^2 \right], \]  

(4)

where \( \theta_k \) represents the unknown correlation parameters which determines shape of gaussian correlation function and \( x^i_k \) and \( x^j_k \) represents \( k^{th} \) component of any two sample points \( x^i \) and \( x^j \).

Predicted estimates of the function sought at the unsampled points are given by

\[ \hat{y}(x_u) = \hat{\beta} + r^T(x_u) R^{-1}(y - g\hat{\beta}), \]  

(5)

where \( y \) is a column vector of length \( n_s \) which holds the sample values of the response. Function \( g \) is a column vector of similar length filled with ones when \( g(x) \) is considered constant. The function \( r^T(x_u) \) is the correlation vector of length \( n_s \) between an untried \( x_u \) and the sampled data points \((x^1, x^2, \ldots, x^{n_s})\) given by
\[ r^T(x_u) = [ R(x_u, x^1), R(x_u, x^2), \ldots, R(x_u, x^{n_y}) ]^T, \]  
and \( \hat{\beta} \) is estimated as
\[ \hat{\beta} = (g^T R^{-1} g)^{-1} g^T R^{-1} y. \]  
Variance between the underlying global model with \( \hat{\beta} \) and \( y \) is evaluated as
\[ \hat{\sigma}^2 = \frac{\left[ (y - g\hat{\beta})^T R^{-1} (y - g\hat{\beta}) \right]}{n_s}. \]  
Finally, Kriging model is trained over sampled data by maximizing ln-likelihood function given by
\[ l(\theta_k) = -\left[ n_s \ln(\hat{\sigma}^2) + \ln|R| \right]/2, \]
with parameters \( \theta_k > 0 \), where \( \hat{\sigma}^2 \) and \(|R|\) are both functions of \( \theta_k \). The best estimate of \( \theta_k \) is obtained by solving the unconstrained optimization problem with global optimizer for maximizing the likelihood function. In this work we have used genetic algorithm, a global search method for maximizing likelihood function.

As mentioned above, Kriging method could result in error when presented with noisy data when more points are included in close proximity to each other. This problem of approximating a noisy data is solved by adopting a regression Kriging technique which allows Kriging model to regress over data [29]. This is accomplished by adding regularization parameter \( \lambda \) to the diagonal elements of Kriging correlation matrix \( R \), making it \( R + \lambda I \) for regression Kriging method where \( I \) is an identity matrix. This addition of regularization parameter does not force predictor to pass through sample points and it is evaluated by optimizing maximum likelihood function along with \( \theta_k \) parameter. The regression Kriging predictor is given by
\[ \hat{y}_r(x_u) = \hat{\beta}_r + r^T(x_u) (R + \lambda I)^{-1} (y - g\hat{\beta}_r), \]  
where
\[ \hat{\beta}_r = (g^T (R + \lambda I)^{-1} g)^{-1} g^T (R + \lambda I)^{-1} y. \]
and variance $\sigma_r^2$ of regression Kriging model is computed by

$$
\hat{\sigma}_r^2 = \frac{[ (y - g\hat{\beta}_r)^T (R + \lambda I)^{-1} (y - g \hat{\beta}_r) ]}{n_s} .
$$

(12)

The subscript $r$ in above equations denotes regression. The regression Kriging model is described in detail in Forrester et al. [29].

**Infill Criteria**

The training of a regression Kriging model with initial sample data provide an approximation of objective function over the whole parametric design space. This metamodel can be further refined by providing more sample data points to the metamodel in design domain based on infill criteria. Each infill point is an additional objective function evaluation supplied to the optimizer to create a refined metamodel. The addition of infill points improves global and local accuracy of the metamodel offering better estimate of global optimum. In every optimization iteration regression Kriging metamodel is constructed based on existing points. The new point then suggested based on infill criteria. Later that point is added to the initial sample and metamodel is rebuilt with augmented data set. This process is followed till metamodel satisfy termination criteria. In this study we will use expected improvement (EI) as an infill criterion for balance exploration and exploitation of objective function [29]. The EI for regression Kriging is an extension to the EI method for Kriging which uses reinterpolation technique [29] for finding new infill point. The infill point is obtained by maximizing EI improvement function given by

$$
E[I(x)] = \begin{cases} 
(y_{min} - \hat{y}) \Phi\left(\frac{(y_{min}-\hat{y})}{\hat{s}}\right) + \hat{s} \phi\left(\frac{(y_{min}-\hat{y})}{\hat{s}}\right), & \hat{s} > 0 \\
0, & \hat{s} = 0
\end{cases}
$$

(13)

where $\Phi()$ and $\phi()$ are normal cumulative distribution function and probability density function. The mean square error of metamodel $\hat{s}^2$ is given by

$$
\hat{s}^2 = \hat{\sigma}_{ri}^2 \left[ 1 - r^T R^{-1} r \right].
$$

(14)
The $\hat{\sigma}_{rl}^2$ is variance of regression Kriging metamodel with reinterpolation technique and it is given by

$$\hat{\sigma}_{rl}^2 = \frac{\left[ (y - g\hat{\beta}_r)^T (R + \lambda I)^{-1} R (R + \lambda I)^{-1} (y - g\hat{\beta}_r) \right]}{n_s}. \quad (15)$$

It should be noted that $\hat{s}$ goes to zero at already sampled points [29] which produces zero EI value. This technique makes sure that existing data point does not resample with infill criteria which makes this infill procedure eventually find the global optimum [37]. The EI method for regression Kriging with reinterpolation technique is described in Forrester et al. [29].

**Termination Criteria**

It is common to use a preset number of infill points (fixed budget infill process) or overall global accuracy of the metamodel as the termination criteria. Global accuracy of the metamodel refers to how accurately the model can predict the objective function throughout the whole design space and local accuracy refers to how accurately the objective function can be predicted at the optimum point. In this study, a fixed budget of 10 infill points were used. The optimization was terminated when this fixed budget was exceeded or the global error reduced to 2%, whichever happened first. The global accuracy of regression Kriging metamodel is estimated by generating test data sample and evaluating normalized root mean squared error (NRMSE) at test data points. A separate set of 20 data points as per the LHS sampling technique distributed throughout the design space was measured. The metamodel was used to predict the objective function values at these 20 locations. Later the objective function values at test data are experimentally measured as discussed earlier. Then the NRMSE of the metamodel is estimated by

$$NRMSE = \sqrt{\frac{\sum_{i=1}^{n_{Test}} (F_{Test}^i - F_{Metamodel}^i)^2}{n_{Test} \cdot F_{max (IS)}}}, \quad (16)$$
where $F_{\text{Test}}$ and $F_{\text{Metamodel}}$ represents objective function value of test data sample with experimental evaluation and metamodel prediction respectively. The $n_{\text{Test}}$ represents the number of test data samples (20 in this study). The root mean squared error is then normalized with maximum objective function value $F_{\text{max}}(IS)$ of the initial sampling (IS) plan of 24 data points.

**Results and Discussions**

**Baseline Verification**

In the present study, a baseline test case with no plasma actuator mounted around the airfoil leading edge was performed to characterize the aerodynamic performance of the airfoil model at the Reynolds numbers of $Re = 0.2 \times 10^6$ and $0.4 \times 10^6$ for the angles of attack between $-2^\circ$ to $30^\circ$ (i.e., $\alpha = -2^\circ \sim 30^\circ$). During the experiments, all the pressure taps were available for surface pressure measurement as no plasma actuator was mounted at the airfoil leading edge. The blockage of the test model at $\alpha =10^\circ$ was only about 4%. The airfoil model spanned the entire test section to avoid any three-dimensional effects at the ends of the test model.

The pressure distribution over the surface of the turbine airfoil model were measured every $2^\circ$ intervals. The measured pressure distributions were integrated to obtain the $C_l$ at the given $\alpha$’s, as depicted in Fig. 6-5. The $C_l$ values were compared with the measurement results reported previously by other researchers with the test model of same DU-96-W-180 airfoil shape at the Reynolds number of $Re \approx 1.0 \times 10^6$ [20]. It can be seen clearly that, the measured lift coefficients of the present study agree well with those reported in the published work of Timmer and van Rooij [31] until close to the stall point (i.e., $\alpha \approx 10^\circ$). The measured $C_l$ values of the present study were found to be lower than those reported by Timmer and van Rooij [31] at the higher angles of attack beyond the stall point (i.e., $\alpha > 10^\circ$) due to the much higher Reynolds number used in their experiments.
Figure 6-5. Measured lift coefficient of DU-96-W-180 airfoil model without plasma actuator

Sampling Points

The sampling points distribution in terms of the design variables used here (i.e., the voltage and frequency) are shown in Fig. 6-6. As mentioned earlier, 24 LHS sample data points were used in the present study.

Figure 6-6. The distribution of the design variables used in the present study.
Pressure Measurements with Plasma Actuator Turning ON

Rethmel et al. [38] used NS-DBD plasma for flow separation control over a NACA-0015 airfoil surface. They found that the frequency of NS-DBD plasma activation is very critical to the effectiveness of the flow control. Similar as the setup used in the present study, since the plasma actuator was mounted at the leading edge of the airfoil model, some of the pressure taps close to airfoil leading edge were unavailable for the surface pressure measurements. Therefore, the magnitude of pressure coefficient at the nearest measurable point closest to the airfoil leading edge, at different non-dimensional plasma activation frequencies, $f^+$ were compared. As described in Rethmel et al. [38], the frequency of plasma activation in non-dimensional terms, $f^+$. Non-dimensional frequency is defined as $f^+ = \frac{fx}{U_\infty}$. In this equation, $f$ is the frequency of applied plasma pulses, $x$ is the distance over the suction surface from the leading edge to the point of separation of the flow and $U_\infty$ is the free stream velocity.

It was revealed that for relatively lower $\alpha$’s close to stall, the pressure coefficient was not sensitive to activation frequency. This refers to a condition where the plasma actuator merely acts an active trip and no natural flow instabilities are excited. At higher $\alpha$, it was found that there was a clear frequency preference where the optimum non-dimensional frequency was reported to be 1.9 ($f^+ = 1.9$) indicating excitation of natural flow instabilities. Zheng et al. [11] reports a similar finding where they categorized the flow control regime into two based on $\alpha$. The first regime extended from the start of leading-edge separation to about $2^\circ$ past this angle (i.e., $\alpha_{stall} < \alpha > \alpha_{stall} + 2^\circ$). It was observed that within this regime, the plasma actuator merely acts like an active trip where there is no frequency preference. However, for the second regime which is corresponding to higher $\alpha$’s (i.e., $\alpha > \alpha_{stall} + 2^\circ$), the NS-DBD actuator continues providing perturbations and generating spanwise vortices, resulting in a partially reattached flow. i.e., the effect on plasma on
flow control could be observed only beyond $2^\circ$ past leading edge separation. Similar observations were also made in the present study, as shown clearly in Fig. 6-7.

![Figure 6-7](image_url)

**Figure 6-7:** The measured surface pressure distributions over the turbine airfoil model for some selected frequencies of applied plasma at the Reynolds number 200k and $\alpha = 20^\circ$.

In the present study, the surface pressure distribution over the surface of the turbine airfoil model were first obtained without switching on the NS-DBD plasma actuator (i.e., passive actuator case) to obtain the baseline for comparison. Then, the NS-DBD plasma actuator was switched on as per the applied voltages and frequencies obtained from the sampling scheme given in Fig. 6-6. It was found that the airflow would separate almost completely from the entire upper surface starting at the angle of attack of $\alpha = 20^\circ$ without the plasma activation (i.e., the airfoil enters a deep stall state at $\alpha = 20^\circ$ without plasma actuation). As reveals from the measurement results given in Fig. 6-7, the surface pressure distribution shows a partial reattachment at $\alpha = 20^\circ$ when the plasma actuator is turned on. But the extent of reattachment does not vary with the frequency of the applied voltage pulses irrespective of voltage. It indicates that no flow instabilities are excited by the
plasma actuation, and the plasma actuator would merely act as an active trip. Therefore, at \( \alpha \)’s less than 20\(^\circ\), the plasma actuator was found to be not effective with the setup used in the present study.

![Graph](image_url)  

**Figure 6-8** The measured surface pressure distribution over the airfoil surface for selected sample data points at the Reynolds number of Re=300K and \( \alpha = 22^\circ \).

For the cases with higher \( \alpha \)’s, the effectiveness of the plasma actuation for flow separation suppression could be clearly observed. Figure 6-8 shows a representative plot of five different cases of plasma activation under the experimental conditions of Reynolds number of Re=300k and \( \alpha = 22^\circ \). The no plasma case shows that airfoil is under deep stall. When the NS-DBD plasma actuator was switched on, some combination of the applied voltages and frequencies were found to have less impact on the flow separation control, while some other combinations were found to be have more favorable effects.

**Initial Regression Kriging Metamodel**

The measurement results at \( \alpha = 24^\circ \) and Reynolds number of Re=200k are presented first. As described earlier, the measured surface pressure distribution for each test case was integrated to obtain the total lift forces acting on the airfoil model under the given test conditions (i.e., for the
24 combinations of applied voltage and frequency as in the sampling scheme). The \( C_l \) was thereby obtained for each of the sample points. Then, a regression kriging metamodel was created based on the values of the design variables at the initial 24 samples data points and the corresponding \( C_l \) values. A regression Kriging predictor function was then used to predict the \( C_l \) throughout the parametric design space. The contour plot of the predicted \( C_l \) values is shown in Fig. 6-9. The initial samples used for creating the metamodel can also be seen on the contour plot. It may be noted the frequency has been expressed in non-dimensional terms \( f^+ \).

![Contour plot showing predicted lift coefficient values](image)

**Figure 6-9.** Predicted lift coefficient contour with initial sample points (\( Re = 200K \) and \( \alpha = 24^\circ \))

### Adding Infill Points

A set of infill points are used to improve the global and local accuracy of the metamodel. Each infill point is an additional value of \( C_l \) evaluated at a new sample point at a different combination of input variables (voltage and frequency in this study) suggested by the infill criteria explained earlier. Each infill point was separately added to the metamodel sequentially and a new refined metamodel was created each time with the latest infill point added to the set of sample points.
points already available. i.e., each new metamodel has one additional sample data point compared to the previous one. In order to estimate the global accuracy of the model, a separate set of 20 test data points uniformly distributed across the design space were measured experimentally. The sampling scheme was once again designed based on the Latin Hypercube sampling (LHS) technique mentioned earlier. The distribution of the test data points is shown in Fig. 6-10. The corresponding $C_i$ values obtained from the experiments were compared with the predicted values from the refined metamodel. The NRMSE of the all the sampling points were calculated as explained earlier, and the process of adding infill points was terminated when the fixed budget of 10 infill points was reached. The fixed budget of 10 infill points were used up before the global error reduced to 2%. It was found that the NRMSE was about 2.5% at the end of infill process. But it could be seen that even before the infill process was conducted the NRMSE was reasonably low (about 2.75%) which indicates that regression Kriging technique is well suited for this optimization and the initial number of samples chosen (i.e., 24 samples) is reasonable. The resulting contour plot and NRMSE distribution are shown in Figs. 6-11 and 6-12, respectively.

Figure 6-10: The 20 test data points used to estimate the global accuracy of the model
As described above, a high-resolution digital PIV system was used in the present study to quantify the flow field around the airfoil model in order to reveal the effectiveness of flow separation suppression by using the NS-DBD plasma actuation. Figure 6-13 gives the ensemble-averaged PIV measurement results for the test cases before and after turning on the NS-DBD plasma actuator. It can be seen clearly that, before turning on the plasma actuator, the airfoil was in deep stall at AOA ≈ 24° with massive flow separation over almost the entire airfoil upper
surface. As a result, the lift coefficient of the airfoil model would be significantly reduced. However, after the plasma actuator was turned on, the flow separation point over the upper surface of the airfoil model was found to push much further downstream, and the flow separation over the front portion of the airfoil model was found to be suppressed effectively. Here, the optimum combination of the design variables corresponding to $\alpha = 24^\circ$ and $Re=200k$ have been used to activate the plasma. The applied voltage was 13.8 kV and the $f^+$ was 0.4.

![Figure 6-13](image) PIV measurement results to reveal the dramatic changes of the flow characteristics around the airfoil model at AOA $\approx 24^\circ$ before and after turning on the NS-DBD plasma actuator

The final metamodel was used to predict the $C_{l_{max}}$ (objective function). The $C_{l_{max}}$ was predicted at a voltage of 13.8 kV and non-dimensional frequency, $f^+$, of 0.4 as shown in Table 6-1. The $C_{l_{max}}$ thus obtained was verified with experiments. It was found that the error in the predicted $C_{l_{max}}$ was about 2% of the experimentally verified value. The results of the study conducted to verify the dependence of optimum parameters on Reynolds number and $\alpha$ are shown in Fig. 6-14 and 6-15. This case corresponds to a different Reynolds number ($Re = 300 k$) and $\alpha = 22^\circ$. The same sampling scheme and test parameters were used here as in the previous case. Figure
6-14 shows the contour plot of the lift coefficients predicted by the regression kriging metamodel created with only the initial 24 samples. Figure 6-15 shows the same predicted by the refined metamodel after the infill process. Again, the fixed budget infill points criterion was reached before the NRMSE dropped below 2%. The error in $C_{l_{max}}$ predicted by this new model was also experimentally verified to be about 2%. The results of both cases are shown in Table 6-1. Case I corresponds to $\alpha = 24^\circ$ at Reynolds number of 200k while Case II corresponds to $\alpha = 22^\circ$ at Reynolds number of 300k.

**Figure 6-14:** Predicted lift coefficient contour plot with initial sample points (Re= 300k & $\alpha = 22^\circ$)

**Figure 6-15.** Predicted lift coefficient contour with metamodel after infill (Re=300k and $\alpha = 22^\circ$)
It should be noted that, by comparing the predicted maximum lift coefficient from Fig. 6-9 and 11 that the optimum parameters before the infill process were \( V = 13.5 \text{ kV} \) and \( f^+ = 0.25 \), and after adding the infill points, it was 13.8 kV and 0.4. The difference is more prominent in the case II corresponding to Reynolds number 300k and \( \alpha = 22^\circ \) which indicates that the infill points helps to improve the local accuracy as well as the global accuracy of the model.

It should be pointed out that, there is no common consensus on the optimum \( f^+ \) as it is found to be different for different studies. For instance, Zheng et al. [19] conducted experiments on the use of NS-DBD plasma on a NACA 0015 airfoil model at Reynolds number of 468k and \( \alpha \) ranging from 16.5° to 21°. It was found that the optimum forcing frequency (\( f^+ \)), using the maximum lift coefficient as a performance indicator was around 0.4-0.5. This range was maintained even at a different Reynolds number of 268k over a similar range of \( \alpha \)’s indicating that the optimum non-dimensional forcing frequency using a given performance indicator may not vary with \( \alpha \) and Reynolds number. However, the study by Rethmel et al. [38] on flow separation control over same airfoil using NS-DBD plasma reported the optimum \( f^+ \) to be 1.9. This could be due to different performance indicators used in studies. The former study used \( C_l \) and the latter study used the pressure coefficient at the nearest measurable point as the performance indicator.

Such parametric evaluations of the objective function using metamodeling techniques over the whole design space could be used for optimizing economics of power production. The average electrical power consumed by the plasma actuator operating in nano-second mode may be estimated from the instantaneous voltage and current measurements as

\[
P_{avg} = \frac{1}{t_2-t_1} \int_{t_1}^{t_2} V(t)I(t)dt, \tag{17}
\]

where \( V \) is the instantaneous applied voltage in Volts, \( I \) is the instantaneous current generated in amperes and \( t \) is the time in seconds.
Table 6-1. Summary of the final results

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Case I Re 200k, $\alpha = 24^\circ$</th>
<th>Case II Re 300k, $\alpha = 22^\circ$</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_l$</td>
<td>0.830</td>
<td>0.869</td>
<td>Measured $C_l$ value without NS-DBD Plasma actuation</td>
</tr>
<tr>
<td>Predicted $C_{l_{max}}$</td>
<td>1.169</td>
<td>1.132</td>
<td>Predicted $C_{l_{max}}$ value (with plasma)</td>
</tr>
<tr>
<td>V</td>
<td>13.8</td>
<td>13.8</td>
<td>Predicted voltage (kV)</td>
</tr>
<tr>
<td>$f^+$</td>
<td>0.4</td>
<td>0.4</td>
<td>Predicted actuation Frequency, $f^+$</td>
</tr>
<tr>
<td>Experimental $C_{l_{max}}$</td>
<td>1.145</td>
<td>1.109</td>
<td>Experimentally measured $C_{l_{max}}$ value</td>
</tr>
<tr>
<td>Error</td>
<td>2.10 %</td>
<td>2.07 %</td>
<td>Relative prediction error</td>
</tr>
</tbody>
</table>

The instantaneous voltage and current were measured using a voltage probe and current probe connected to the oscilloscope. The energy consumed in a single pulse is first estimated from the oscilloscope data and it can be converted to electrical power based on number of pulses per second (frequency of plasma). The optimum forcing frequency for Case I in dimensional terms is $\sim 50$ Hz. Figure 6-16 shows the electrical power consumed by the plasma actuator as a function of applied voltage for a fixed frequency of 50 Hz. NS-DBD plasma power consumption is a linear function of frequency. The power consumed is expressed in W/m length of the actuator. It may be observed from Fig. 6-11 that a reduction in voltage from about 14 kV to 12 kV would reduce the $C_{l_{max}}$ negligibly $(-1.5\%)$ whereas from Fig. 6-14 it could be seen that this would reduce the power consumption from 3.5 W/m to 2.75 W/m which is $\sim 20\%$ less electrical power being consumed. Since active flow control continuously consumes energy for operation, having a metamodel which could accurately predict the whole parametric design space could help to achieve a tradeoff between power consumption and economics of power production in large wind farms.
Conclusion

While Dielectric-Barrier-Discharge (DBD) plasma-based approach has been demonstrated recently to be effective to suppress flow separation/airfoil stall to improve turbine power production performance and mitigate the unsteady wind loadings acting on turbine blades, it is still a non-trivial task to optimize the design variables of a DBD plasma actuation system to maximum its effectiveness for flow control. In the present study, a regression kriging-based metamodeling technique is employed to optimize the operation parameters of a DBD plasma system to suppress the massive flow separation/airfoil stall over the surface of a wind turbine airfoil model. While most of previous studies on DBD plasma-based flow control varied only one parameter at a time, the present study used a regression Kriging based metamodel approach to explore the whole design space by varying multiple design variables, which could drastically reduce the number of experiments required for the operation parameter optimization.

Figure 6-16. Power consumed by the plasma actuator as a function of the applied voltage
In the present study, a wind turbine blade section model with DU-96-W-180 airfoil profile in the cross section was designed/manufactured and mounted in a low-speed wind tunnel for an experimental investigation. A DBD plasma actuation system was embedded around the leading edge of the turbine airfoil model in order to demonstrate the use of regression kriging metamodeling technique for parametric optimization of input parameters. During the experiments, the DBD plasma system was operated in a nanosecond-pulsed plasma actuation mode (i.e., NS-DBD plasma). Two operation parameters (i.e., applied voltage and frequency) for the NS-DBD Plasma actuation were varied simultaneously as per a predefined sampling scheme to create a metamodel. The lift coefficient of the turbine airfoil model at a typical deep stall $\alpha = 24^\circ$ at the Reynolds number level of $\text{Re}=200k$ was chosen as the objective function to be optimized. The surface pressure distribution over the airfoil model was measured and integrated to obtain the lift coefficient of the airfoil model at the selected sample points. The data set served as the evaluations of the objective function at the sample points to be fed to the metamodel. An initial regression kriging metamodel was created which was further improved by adding infill points to create the final refined model. A metamodel trained prediction function was then established to predict the lift coefficient of the airfoil model throughout the whole 2D design space. The final value of the lift coefficient of the airfoil model predicted via the metamodeling was experimentally verified, and the error was found to be about 2.0%. The global error of the metamodel within the entire design space were found to be about 3.0%. The procedure was also repeated at $\alpha = 22^\circ$ at the Reynolds number of $\text{Re}=300k$ to verify the sensitivity of the optimum parameters to the Reynolds number and $\alpha$. It was demonstrated successfully that the Metamodeling-based optimization technique would save the cost of extensive experimentation required to explore the whole design space by performing experiments only at sample locations, yet without much loss in accuracy.
Acknowledgements

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References


CHAPTER 7. GENERAL CONCLUSION

This research includes five different topics. The major findings are summarized here. The experimental study on cable icing was carried out by leveraging the unique Icing Research Tunnel of Iowa State University (i.e., ISU-IRT) to generate typical wet glaze and dry rime icing conditions experienced by power transmission cables. In addition to using a high-speed digital imaging system to record the dynamic ice accretion process, a novel digital image projection (DIP) based technique was utilized to quantify the 3D shapes of the ice structures accreted on the surface of the power cable model as a function of the ice accretion time. The time variations of the aerodynamic drag force acting on the test model during the dynamic ice accretion process were also measured quantitatively by using high-sensitive force/moment traducers mounted at two ends of the test model. The acquired snapshots of the ice accretion images and the measured 3D shapes of the accreted ice structures on the test model are correlated with the aerodynamic force measurement results to elucidate the underlying physics.

The first part of the research was done to quantitatively understand the dynamic ice accretion process on cylindrical transmission cable models. A cylindrical power cable model, which has the same diameter as that of typical power transmission cables, was mounted in ISU-IRT for the ice accretion experiments. An incoming wind speed of 20 m/s, a liquid water content (LWC) of 2.0 g/m$^3$ and an ambient temperature of -5 $^\circ$C was used to study glaze ice accumulation. The LWC and ambient temperature for rime ice was 1.0 g/m$^3$ and -15 $^\circ$C at the same wind speed. The ice structures accreted over the surface of the power cable model were found to change significantly under different icing conditions (i.e., rime icing vs. glaze icing). The characteristics of the aerodynamic drag acting on the test model was found to vary significantly during the
dynamic ice accretion process, highly depending on what types of ice structures were accreted on the test model. 3D scan technique was able to quantitatively measure the ice profiles accurately.

In the second phase of the research, an Aluminum Conductor Steel Reinforced (ACSR) test model with the same diameter of a commonly-used high-voltage power transmission line cable ($D = 29$ mm) was subjected to typical glaze and rime icing conditions. The ambient conditions were same as the previous case. It was found by comparing both the studies that, aerodynamic drag force at the end of the ice accretion ($t = 1000$ s) is dependent of the outer profile of the conductor. In case of rime ice, the drag force drops by about 65% of the baseline case for a cylinder while it decreased only to 90% in case of ACSR conductor. For the case of glaze ice, both types of cables showed an increase in drag. While smooth cylinder showed an increase to 140% of baseline case, the ACSR case showed an increase up to 180%. The mass of accreted ice was significantly affected by the outer profile of the conductor in case of glaze ice accretion whereas it was independent of the outer profile in case of rime ice.

In the third phase of the research, experimental investigations were conducted to examine the dynamic ice accretion process over the surfaces of a two-bundle high-voltage power transmission cables and characterize the effects of the ice accretion on the aerodynamic forces acting on the leeward conductor in the wake of a windward conductor for rime and glaze ice accretion. The two-conductors were placed at different horizontal spacings as well as different angular spacings. It was found that the effect of icing on the leeward conductor was significantly different when the windward conductor was placed in positions which interfered with the leeward conductor. In both cases of icing it was found that at the lowest horizontal spacing between conductors (6D), the effect of windward conductor was felt severely by the leeward conductor and the effect diminished with increased spacing. When the angular spacing was changed from $0^\circ$ to
15° similar observations were made with all measurements of the leeward conductor becoming independent of presence of the windward conductor at an angle of 15°.

In the next phase, potential anti-icing techniques were investigated. The test model was a cylindrical rod of PVC with the same diameter of a commonly used high-voltage power transmission line cable (D = 29 mm). The model was subjected to typical glaze conditions. An incoming wind speed of 20 m/s, a liquid water content (LWC) of 1.0 g/m³ and 2.0 g/m³ and an ambient temperature of -5 °C was used to study glaze ice accumulation. Icing duration was set to be 300 seconds to investigate whether the anti-icing techniques can keep the surface ice free. DBD plasma and superhydrophobic coated surfaces (SHS) were the anti-icing techniques tested. It was found that the plasma actuator located at the leading edge was able to prevent the freezing of water droplets near the leading edge. But these droplets froze at downstream locations. While SHS was used without plasma, it was found that ice was frozen only at the leading edge and downstream regions were ice free. While both techniques were used simultaneously (hybridized), the entire transmission line cable model was ice free. Multiple plasma actuators without SHS were also tested successfully. Six plasma actuators located at uniform angular spacings were able to keep the surface ice free even in the case of rime ice.

The final phase of the study was conducted in the black wind tunnel at IOWA state university. This study aimed to establish a metamodeling-based technique to optimize the parameters of a dielectric barrier discharge (DBD) plasma used for flow separation over the surface of a wind turbine model in deep stall. As there are several variables involved in the study, it is a non-trivial task to establish a best combination of various operating parameters for a DBD plasma actuation system to achieve the optimized flow control effectiveness. In the present study, a regression Kriging based metamodeling technique is developed to optimize the operating
parameters of a DBD plasma actuation system for the deep stall suppression over the surface of a wind turbine blade section. The data points were experimentally obtained by embedding a nanosecond-pulsed DBD (NS-DBD) plasma actuator at the leading edge of the airfoil model. The applied voltage and frequency for the NS-DBD plasma actuation were used as the design variables to demonstrate the optimization procedure. The highest possible lift coefficient of the turbine airfoil model at deep stalled angles of attack (i.e., $\alpha = 22^\circ$ and $24^\circ$) were selected as the objective function for the optimization. It was found that, while the metamodeling-based procedure could accurately predict the objective function within the bounds of the design variables with an uncertainty $\sim 2\%$, a global accuracy level of $\sim 97\%$ was achieved within the whole design space.