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Experimental investigation on the icing physics and anti-/de-Icing technology of an aircraft pitot probe

by

Faisal Omar Al-Masri

A thesis submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Aerospace Engineering

Program of Study Committee:
Hui Hu, Major Professor
Ashraf Bastawros
Liming Xiong

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 thesis. The Graduate College will ensure this thesis is globally accessible and will not permit alterations after a degree is conferred.

Iowa State University
Ames, Iowa
2020

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I would like to dedicate this work to my parents
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Pitot probes are one of the most important components of an airplane, directly responsible for the flight safety and secure decisions of pilots by providing crucial airspeed and altitude data. They are constantly at risk of performance deterioration due to ice accretion that can block the stagnation port, thereby, providing incorrect readings to the pilot that can lead to fatal accidents if not treated immediately. By leveraging the unique Icing Research Tunnel at Iowa State University (i.e., ISU-IRT) a series of experimental studies are conducted to investigate the dynamic ice accretion process over the surface of a commonly-used aircraft pitot probe and to evaluate the effectiveness of various anti-/de-icing methods for Pitot probe icing mitigation. During the experiments, in addition to using a high-resolution imaging system to record the dynamic ice accretion and anti-/de-icing processes over the surface of the Pitot probe under different icing test conditions, a high-speed Infrared (IR) thermal imaging system is also used to map the corresponding surface temperature distributions on the Pitot probe in order to characterize the unsteady heat transfer process associated with the ice accretion and anti-/de-icing process. In addition to performing a parametric study to evaluate the performance of a conventional thermal-based icing protection system embedded inside the Pitot-probe as a function of the electric power input for the anti-/de-icing operation, a novel hybrid icing protection strategy is proposed that combines the electric heating with a bio-inspired superhydrophobic (SHS) coating to coat the Pitot probe in order to minimize the power consumption for the anti-/de-icing operation. In comparison to that required by the conventional thermal-based system to heat up the Pitot probe brutally for icing protection, the proposed hybrid strategy is found to be able to achieve completely ice free conditions over the entire surface of the Pitot probe with only about 35% of the required power input (i.e., up to 65% power consumption) for the anti-/de-icing operation.
CHAPTER 1. INTRODUCTION

1.1 Aircraft Icing

Aircraft Icing is widely recognized as a significant hazard to the overall performance and safety of aircraft in cold weather[1]. Ice accretion on the wings results in the loss of lift and a gain in weight and drag [2], ice shedding from the aircraft surface can damage the airframe and engine components [3] and ice accretion on sensitive components like pitot probes can affect the velocity and altitude readings obtained by the pilot, often disconnecting the autopilot functionality and causing numerous fatal crashes during extreme weather events[4]. Icing can affect radio communications, control surfaces, brakes, and landing gear as well as UAVs and wind turbine blades[3]. While research progress has been made in recent years to provide a better understanding about aircraft icing phenomena, aircraft icing remains an important unsolved problem at the top of the National Transportation Safety Board’s most wanted list of aviation safety improvements.

There have been many occurrences of the devastating effects of aircraft icing on the safety of aircraft. Continental Flight 3407 crashed in Buffalo, New York due to ice buildup on its wings, killing all 49 people aboard and 1 person on the ground as the plane hit a residential home. The weather consisted of light snow and fog, the pilots discussed significant ice buildup on the aircraft’s wings and windshield, the crash was eventually blamed on the pilot’s inappropriate response to the stall warnings that happened due to the ice buildup on the wings [5]. Another fatal accident attributed to aircraft icing, specifically pitot probe icing was the Air France Flight 447 that crashed in the Atlantic Ocean and killed all 228 people on board. The final report concluded that the aircraft crashed after temporary inconsistencies between the airspeed measurements – likely due to the aircraft’s pitot probes being obstructed by ice crystals – caused the autopilot to disconnect, after which the crew reacted incorrectly causing the aircraft to enter an aerodynamic
2

stall from which it could not recover[6]. These examples are some of many that show the dangers of aircraft icing[1].

Ice accretion is governed by two distinct aspects. The rate at which the water droplets impinge on the body, and that usually depends on the shape of the body, the Liquid Water Content (LWC) in the atmosphere, and the speed of the body. The second aspect is the rate at which the impinging water will freeze to form ice, that is governed by the heat transfer from the surface of the body. If the droplets freeze on impact, the ice tends to be a white opaque accretion known as rime ice[7], this usually forms at lower temperatures, below -10°C, and at lower LWCs, usually below 1 g/m³. At higher temperatures closer to freezing, coupled with higher LWCs, not all the impinging water freezes on impact and a considerable amount runs back along the surface and then freezes. This type of icing leads to complex shapes characterized by horns on the upper and lower surface of the wing and is generally translucent in appearance. This is known as glaze icing. Glaze icing is known to pose a bigger threat to flight performance than rime icing due to the runback process that covers more area [7]. An example of glaze and rime ice formation is shown in figure 1.1.

![Formation of glaze and rime ice on propeller blades](image)

**Figure 1.1 Formation of glaze and rime ice on propeller blades [8]**

### 1.2 Ice Protection Systems

To combat the negative effects of aircraft icing, ice protection systems are put in place that utilize what is known about the accretion process and the properties of the surface. There are currently several ice protection systems that are used based on the type of aircraft that either
prevent the ice formation (Anti-Icing) or remove ice that has already accreted (De-Icing). The following section gives a brief overview on some of the most commonly used ice protection systems based on the FAA Advisory Circular 91-74B

1.2.1 De-Icing Systems

**Electro-thermal:** Uses joule heating to De-Ice surfaces by heating them to a temperature above the freezing point to break the bond of the accreted ice. The ice is then carried away by the airflow. If the heater is allowed to operate continuously, it will also act as an anti-icing system as it prevents the freezing of the impinging water droplets. This is generally used for smaller surfaces as it is very power consuming.

![Figure 1. 2 IR thermography image of a pitot probe equipped with an electro-thermal system](image)

**Pneumatic boots:** Consist of rubber tubes attached to critical aircraft surfaces in either the spanwise or chordwise direction. They are collapsed during normal operation to avoid disrupting the airflow over the wings. The tubes are then inflated intermittently to crack the ice and allow the airflow to carry it away. Due to its intermittent nature, ice free conditions are rarely achieved and so this is used to minimize the effects of icing instead.

![Figure 1. 3 Pneumatic boots](image)
**Electro-Impact or Electro-Mechanical:** Uses pulses of energy to de-ice a surface by producing rapid flexing movements of the airplanes surface. This can be achieved through ultrasonic or piezoelectric mechanisms.

### 1.2.2 Anti-Icing Systems

**Bleed air IPS:** Utilizes the hot air from the compressor section of the engine to eliminate ice formation on critical surfaces.

**Evaporative/Running Wet Systems:** Utilize a chemical agent that lowers the freezing point of water and decreases the friction coefficient to prevent the ice adhesion to the surface.

### 1.3 Passive Ice Protection Systems

Unlike the conventional active ice protection techniques, these methods do not have active control and energy requirements, nor do they need complex systems and moving parts to remove or prevent ice accretion. Instead, they utilize functionalized surfaces that tend to repel the liquid water upon contact. Experiments have demonstrated the some superhydrophobic coatings can also have icephobic properties, that droplets can bounce off of them without phase change, and that they can alter the adhesion strength of ice on an otherwise hydrophilic surface, with the commercial Hydrobead coating reducing it by up to a factor of 3.5 [9].

#### 1.3.1 Superhydrophobic Coatings

The superhydrophobicity of a surface depends on a combination of surface energy and surface texture. A common example of this in nature is the lotus leaf that exhibits superhydrophobic properties due to its unique protruding features called papillae that vary in height [10]. The presence of these papillae on the leaf reduces the contact area of water by supporting the droplet weight. The increased contact angle reduces the contact area of the droplet with the surface leading to a weaker adhesion of water to the surface, this allows the water to easily roll off the surface [11].
The papillae are also covered with a waxy material that reduces the surface free energy of the lotus leaf and further enhances its superhydrophobic properties[10].

Taking inspiration from the lotus leaf, researchers started developing superhydrophobic coatings for multiple applications. The effectiveness of different coatings as passive ice protection systems has been studied extensively, this includes studies on aero-engine, airfoil and even wind turbine anti-icing. The superhydrophobicity of these coatings aims to reduce the surface adhesion strength of the ice as well as the ice volume by repelling the water droplets and it has proven effectiveness in reducing the ice formation in static cases [11].

Dynamic cases on the other hand prove to be trickier, and dynamic impingement of supercooled water droplets at high velocities challenged the effectiveness of these methods. Figure 1.5 shows how a superhydrophobic wing surface reduces the area of the wing covered in ice. Here, the aerodynamic stresses from the airflow over the wing surface sweep away super-cooled water droplets from most of the wing’s surface, thus eliminating water runback and the ice rivulets characteristic of glaze icing. However, ice still forms at the leading edge in the vicinity of the stagnation line. This highlights one of the major challenges facing water- and ice-phobic coating strategies. These coatings produce low adhesion forces between the water and/or ice and rely on aerodynamic stresses acting tangentially to the surface to remove the accretion. This approach fails at the stagnation line because the required shear stress near the stagnation line is very small or completely vanishes. Furthermore, the collection efficiency is a maximum at the stagnation line. This example illustrates how coatings that are effectively ice-phobic at nominal conditions may not perform well under in-flight impact icing conditions and necessitates exploring a hybrid option that can take advantage of the passive SHS while also eliminating the problem at the leading edge through an active ice protection system. [9]
Figure 1. 4 SEM image of upper side of lotus leaf illustrating the water repelling properties and the papillae responsible for them

Figure 1. 5 Photo illustrating the water repelling effects of a surface treated with a Super Hydrophobic Coating and how that affects the ice accretion process

1.4 Pitot probes

A pitot probe is a crucial flow measurement device that is used to measure fluid flow velocity, it can be found on aircraft, boats and has other industrial applications. It uses a stagnation port and a static pressure port to measure the airspeed of an aircraft through Bernoulli’s equation[12]. A drain hole is also present to force out any water present in the tube from rain or due to the de-icing process. The moving fluid is brought to rest by the stagnation port as there is no outlet to allow the
flow to continue, this measured pressure is the stagnation pressure of the fluid, it is also known as the total pressure or – in aviation – pitot pressure. This pressure cannot itself be used to determine airspeed. However, Bernoulli’s equation states that the stagnation pressure is equal to the sum of both the static and dynamic pressure. This can be written as equation 1 below.

\[ p_{total} = p_{static} + \left( \frac{\rho u^2}{2} \right) \]

\[ u = \sqrt{\frac{2(p_{total} - p_{static})}{\rho}} \]

*Equation 1.1 Bernoulli’s equation to find airspeed*

![Diagram of pitot-static system illustrating all relevant ports, instrumentation, and ice protection systems](image)

*Figure 1.6 Diagram of pitot-static system illustrating all relevant ports, instrumentation, and ice protection systems*

Most modern aircraft employ a pitot-static system that separates the stagnation port and the static port by having a separate port on the fuselage instead of on the tube. The two pressure sources are then connected to measurement instruments that determine the airspeed, vertical speed, and the altitude of the aircraft. This data is crucial to the safety and performance of flight and any blocking of the ports can be very detrimental to the flight safety[13].
1.5 Pitot Probe Icing

Due to the method of operation of pitot probes, the stagnation port is an easy target for icing and that is a cause for many complications. As ice accretes around the surface of the pitot probe it eventually completely blocks the stagnation port causing the total pressure measurement to be stuck on the value it had before blocking. Static ports and drain holes are also susceptible to blockages and these can cause further complications[13].

If the stagnation port and drain hole are blocked but the static port is not, the airspeed indicator will be the only thing that is affected. It will register an increase in speed when the aircraft climbs even though the actual airspeed is constant. This is due to the total pressure in the system remaining constant when in fact, the atmospheric pressure and static pressure are decreasing. The airspeed indicator will also show a decrease in airspeed when the aircraft descends for the same reason. If the drain hole is not blocked, the pitot probe becomes a relatively inaccurate static port and so the airspeed indicator will be comparing two inaccurate pressure readings leading to further discrepancies in the speed measurements[13].

A blocked static port is more dangerous as it affects all the pitot-static instruments. If a static port is blocked due to airframe or pitot probe icing, the altimeter is frozen at a constant value, the altitude at which the blockage occurred. The vertical speed indicator will read zero and will not change at all regardless of the real vertical speed. The airspeed indicator will reverse the error that occurs with a clogged stagnation port and the airspeed reading will be less than the real speed of the aircraft as the aircraft ascends. When the aircraft is descending the airspeed will be higher than the real speed of the aircraft [13].
1.6 Pitot probe De-Icing

The current most common ice protection method used with pitot probes is equipping them with a heating element. In fact, a heated pitot probe is required in all aircraft certificated for instrument flight except aircraft certificated as Experimental Amateur-Built.

The heating element utilizes conduction with the inner walls of the tube to raise the temperature of the surface to that above the freezing point, the ice is then broken off and carried away with the airflow while any liquid water inside the probe is drained through the drain hole. Heated pitot
probes have a majority of their power concentrated near the stagnation port while the remainder of the probe receives less heat. This ensures that the stagnation port can be effectively de-iced whenever ice is detected so inconsistencies in airspeed measurements are minimized.

The issue with the current de-icing method is the high power needed by the pitot probe to ensure ice free conditions. This high power consumption is not an efficient way to protect the pitot probe from icing as it relies on a limited power source, the high temperatures experienced by the surface of the pitot probe can be damaging and can cause surface oxidation and the heat source has also been known to fail and malfunction which leaves the pitot probe vulnerable to the dangers of icing.

![Figure 1. 9 Oxidation damage visible on a Boeing B787 pitot probe](image)

*Figure 1. 9 Oxidation damage visible on a Boeing B787 pitot probe*

![Figure 1. 10 IR image of failed pitot probe heater shows a much cooler pitot probe that is susceptible to icing](image)

*Figure 1. 10 IR image of failed pitot probe heater shows a much cooler pitot probe that is susceptible to icing*
1.7 Motivation Objective

Aircraft icing is a complex issue that is detrimental to the safety and performance of flight, and though multiple ice protection systems currently exist to reduce the damage of icing, the problem still persists, and further research is required to further improve the performance and cost efficiency of this problem. The existing method of de-icing pitot probes is very power consuming and damaging to the components and so a more efficient method is needed to combat this problem, it also neglects the rest of the pitot probe allowing ice to accrete more freely on parts like the holder, extended icing on that part can also be detrimental to the performance of the pitot probe. The lack of research available on the icing physics of a pitot probe makes it more difficult to come up with an improved ice protection system, and the lack of information on the current de-icing method make it more difficult to gauge its effectiveness and shortcomings.

An experimental investigation that fills in the gaps of this knowledge and studies the icing of a pitot probe at different conditions, then tests the effectiveness of the current de-icing method will enable progress in finding a more effective ice protection system by figuring out exactly where the problems lie and how to improve on them.

The Aircraft icing physics and anti-deicing technology laboratory in the department of Aerospace Engineering at Iowa State University is associated with working on the experimental studies of icing physics on models of various surfaces susceptible to damage due to icing, experimental heat transfer, and ice accretion processes over different surfaces. The core objective of this group is to give researchers the information needed to improve current icing models by providing the empirical data necessary for more accurate prediction of ice formation and accretion processes. It also develops more robust anti-/de-icing strategies to ensure safer and more efficient operation of various functional devices such as aircraft and aircraft components, wind turbines and
even power cables in cold weather. The work done for this thesis lines up with this objective of
the research group.

1.8 Thesis Organization

This thesis consists of four chapters. The first chapter gives an introduction and background to
the current study. The research and further possible work are summarized with a conclusion in the
fourth chapter.

Chapter 2 presents a qualitative study of the icing physics on a pitot probe at different flow
conditions. It explores the rime and glaze icing processes, providing qualitative and quantitative
data to better understand them. An unsteady heat transfer analysis of the icing process is also
discussed in this chapter.

Chapter 3 provides the results of a parametric study that tested the heating element of the pitot
probe for anti-icing and de-icing at multiple flow conditions and power settings to gauge the
effectiveness and power consumption of the heating element. The results of this study show the
minimum power setting required to maintain ice free conditions as well as a comprehensive heat
transfer study through the results of IR thermography and thermocouple measurements. It also
introduces a hybrid approach to de-icing by incorporating a superhydrophobic coating on the
surface of the pitot probe, the coating is tested with the heating element to minimize the power
consumption needed to attain ice free conditions. Both the de-icing time for the leading edge and
of the pitot probe holder are investigated.

Chapter 4 provides an overall conclusion to the work conducted over the course of this thesis
and introduces what future work may be conducted beyond the scope of this thesis.

References

AIAA Aerospace Sciences Meeting and Exhibit, 2006, p. 82.


CHAPTER 2. AN EXPERIMENTAL INVESTIGATION OF DYNAMIC ICE ACCRETION PROCESS ON A PITOT PROBE MODEL UNDER VARIOUS ICING CONDITIONS

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Abstract

In the present study, the dynamic ice accretion process over a typical pitot probe model (PH 500 series from Aero Instruments Co.) was experimentally investigated under a variety of icing conditions typically experienced by a pitot probe during flight. The experiments were conducted in the Icing Research Tunnel of Iowa State University (ISU-IRT). Rime and Glaze ice conditions were reproduced by varying the airflow temperature and liquid water content (LWC) in the ISU-IRT. The dynamic ice accretion process was recorded with a high-speed imaging system, and the time varying temperature distribution over the ice accreting pitot probe surface was recorded with an infrared thermal imaging system. Time variations of the ice thickness accreted along the pitot probe stagnation point (leading edge) and pitot probe holder were extracted from the acquired high resolution images of the ice accreting process. Due to the runback of the impacted water in the glaze icing case, the growth rate of the ice layer accreted along the stagnation port and pitot probe holder was much slower when compared to that of the rime icing case. Nevertheless, this surface water transport behavior expanded the ice influencing region making glaze icing the more dangerous icing condition. The transient process of droplet impingement, water film/rivulets formation, and ice roughness growth were temporally resolved from the temperature evolutions during the dynamic icing process, a ‘plateau’ region was also observed in
the glaze icing case due to the complex multiphase mass/heat transfer associated with the surface water transport behaviors.

2.1 Introduction:

Pitot probes are crucial aircraft instrumentation that use pressure data from the incoming airflow to calculate the airspeed, altitude and altitude trend using a series of pressure ports designed to gather the stagnation and static pressures of the airflow[1]. When operating in cold humid conditions, icing events are expected and when left long enough can block the pressure ports causing performance degradations that alter the pressure data input into the measurement system, leading to false speed and altitude measurements that can affect the decisions made by the pilot and can end with a fatal crash [2], [3].

Ice accretion occurs when super-cooled water droplets impinge onto the surface of the pitot probe and release the tremendous amounts of latent heat of fusion associated with the solidification process of the impacted super-cooled droplets. The freezing of the impinged water mass can be complete or partial depending on how rapidly the latent heat of fusion can be released into the ambient air; this gives the two main types of icing studied in these investigations, rime, and glaze. Rime ice usually formed at very cold temperatures when the impinged water droplets freeze immediately upon impact. Glaze ice on the other hand, forms at warmer temperatures closer to the freezing point of water in which case the impacted water would freeze partially, and the remaining water would coalesce into films/rivulets and run back over the surface. The wet nature of the glaze ice contributes to the formation of very irregular ice shapes, making the ice accreting process much more complicated [4].

Pitot probe icing is different from other aircraft icing phenomena because it deals with the blockage of the ports instead of the aerodynamic degradation caused by the icing[2]. This means that the focal point of the research will be on the stagnation port since that is the most crucial
component of the pitot probe. The icing accretion of the pitot probe holder is also studied because it houses the pressure tubes, heating element electrodes and the drain hole and so must be properly preserved as well, the unchecked icing on the holder can also eventually grow large enough to affect the pressure readings by altering the flow around the stagnation port.

In the present study, a comprehensive investigation was conducted to examine the dynamic ice accretion process over the surface of a typical aircraft pitot probe under various icing conditions. The experimental study was conducted in the Icing Research Tunnel available at Iowa State University (i.e., ISU-IRT). In the sections that follow, the fundamental mechanisms of pitot probe icing are illustrated at first, after that the experimental setup and test model used are described. Then, the results of the dynamic ice accretion processes, ice impact regions and surface temperature distributions under the different icing conditions are discussed to provide more insight to the underlying physics in the complex ice accretion process.

2.2 Experimental setup and tested pitot probe airfoil model

2.2.1 ISU-IRT

The experimental investigation was performed in the Icing Research Tunnel available at the Aerospace Engineering Department of Iowa State University (ISU-IRT). The IRT shown in figure 2.1 has a test section of 2.0 m in length x 0.4 m in width x 0.4 m in height with four optically transparent panels. The ISU-IRT is capable of generating speeds up to 60 m/s and can reach temperatures as low as -25°C. Eight pneumatic atomizer/spray nozzles were installed at the entrance of the contraction section to inject micro-sized water droplets (10~100 μm) into the airflow. A range of liquid water contents (LWC) from 0.1 g/m³ to 10.0 g/m³ can be achieved by manipulating the flow rate through the spray nozzles. Therefore, the ISU-IRT is capable of simulating a wide range of atmospheric icing phenomena.
2.2.2 High Speed Cameras and Thermal Data Acquisition

As seen in Figure 2.1, two high speed cameras were used to capture the dynamic icing process over the pitot probe’s surface, an IR thermal imaging system was also used to quantitatively measure the corresponding surface temperature distributions over the pitot probe’s surface. The two systems were synchronized and triggered by using a digital delay/pulse generator (BNC, Model 577). One high speed camera (PCO Tech, Dimax) was installed right above the test model with a 24 mm lens (Nikon, 24 mm Nikor 2.8D), providing a top view of the pitot probe with a resolution of 1600 x 888 pixels at 5.08 pixels/mm, another high speed camera was placed adjacent to the pitot probe, this setup provided a clear view of the icing occurring at the stagnation point and at the pitot probe holder which allows for a better understanding of the ice accretion. The IR system was composed of an IR camera (FLIR, A615) and an IR inspection window (FLIR, IR Window-IRW-4c), it can detect waves within a range of 7.5-14 μm and was placed above the test model, providing a field view of 640 x 480 pixels with a resolution of 4.77 pixels/mm. Since the measured surface temperature is proportional to the emissivity, and the original Nickel plating was damaged and has an emissivity of around 0.03, the pitot probe was plated in white protective enamel to ensure a homogenous icing process as well as, the option of using an IR camera to capture temperature data. The protective enamel has an emissivity value of 0.96, while water and ice have an emissivity of 0.95~0.96 and 0.96~0.98, respectively. Since the emissivity values of these materials have a difference of only 3%, the uncertainty of the measured surface caused by emissivity can be considered negligible. A high accuracy thermocouple was used on the surface of the pitot probe to provide in-situ calibration of the surface temperature measurements by the IR camera[5].
2.2.3 Pressure Measurements

To confirm the functionality of the pitot probe, and to witness the effect of icing on the pressure readings provided by it. A DAS with a 10” H$_2$O range was used for the pressure data acquisition. Since the metal pitot probe did not contain a static port, a 3D printed pitot-static probe based on the current pitot probe’s configuration was used to study the effects of the icing on the pressure measurements. Both total and static pressure measurements were then acquired by the DAS pressure transducer.

2.2.4 Pitot probe Model

An Aero Instruments Co. model PH 500 series pitot probe was used for the investigation. It has the typical “L” configuration that is common for aircraft pitot probes. It has got electrodes to connect the heating element to a power source and a tube for total pressure measurements. The original surface is Nickel plated and is rather shiny but damaged due to it being a used pitot probe. The Nickel surface has a contact angle of around 50° making it a rather hydrophilic surface and has an emissivity of 0.03. To ensure a homogenous ice accretion process and to improve the quality of the high-speed photographs, the pitot probe was coated by a white enamel layer. The enamel layer has an emissivity of 0.96, this ensures accurate IR temperature readings[6], it also has a contact angle of 65° which is also considered hydrophilic, providing an accurate representation of the ice accretion process.

![Figure 2.1 Schematic of the ISU-IRT including test section and instrumentation](image-url)
2.3 Case Study

2.3.1 Case Design

In the present study, the dynamic ice accretion process was comprehensively investigated under different icing conditions through a series of icing experiments that covered a wide range of icing parameters, including the ambient air temperature, incoming airflow velocity, liquid water content and median volumetric diameter. The incoming airflow velocity and MVD were controlled at 40 m/s and 20-30 $\mu m$ to simulate the impinging water droplets in real flight environments, albeit at a much slower velocity. The LWC and ambient air temperature were varied depending on the icing scenario being studied, table 1 shows all the cases studied in this investigation with the rime ice cases being conducted at lower temperatures and LWCs and the glaze icing conditions studied at high temperatures and larger LWCs.

2.3.2 Identification of Ice Types

Snapshots of the ice accretion on the pitot probe model obtained from the high-speed imaging results are used to further identify the ice types formed in the different test cases. The formation of runback rivulets is the most distinguishing feature between rime and glaze icing. The isolated rivulets are an indication of typical glaze icing while an absence of rivulet formation is characteristic of rime ice formation. The different appearances of the ice structures provide further
evidence in identifying the different ice formations, rime ice has a milky ice layer with crystalline structures while a clear ice layer is seen in the glaze ice conditions.

2.4 Results and discussion

2.4.1 Effects of icing on the pitot probe’s pressure measurements

A 3D printed pitot-static probe modeled after the pitot probe used in this investigation was studied under various icing conditions to block different ports to study the effect of that blockage on the pressure measurements derived from the pitot probe, the experiments were conducted in an open-circuit tunnel to make sure the total pressure changes when the flow velocity is reduced from 40 m/s to 20 m/s.

![Figure 2](image1.png)

Figure 2. 3 CAD drawings of the pitot probe showing all 3 holes of interest

The first case studied was at a LWC of 1 g/m³ and a temperature of -10 °C, this was capable of achieving icing conditions that only blocked the stagnation port. When that happens, the drain hole acts as a relatively inaccurate static port, the plot in figure 2.4 shows how the total pressure changes after the blockage occurred as it now follows a trend similar to that of the static port, the values are not identical due to the complete flow separation that occurs near the drain hole that alters the pressure measurements slightly. The pitot probe is now comparing two inaccurate pressure readings that will give the pilot an erroneous velocity measurement.

The second case studied at a LWC of 2 g/m³ and a temperature of -10 °C, this was capable of achieving a totally blocked pitot probe and as is seen in figure 2.5 this causes the pressure
measurements to remain stagnant even after the velocity was reduced from 40 m/s to 20 m/s. When this happens, the altimeter would be frozen at a constant value. The airspeed indicator will reverse the error that occurs and the airspeed reading will be less than the real speed of the aircraft as the aircraft ascends.

2.4.2 Full life cycle of the dynamic icing process on the pitot probe

Figure 2.6 shows the dynamic ice accretion process on the pitot probe surface under rime and glaze ice conditions for the different liquid water contents at different icing moments. Fig 2.6a. shows the dynamic icing process under the glaze icing condition. Due to the unique shape of the pitot probe, ice accretion is concentrated on two surfaces, the leading edge of the pitot probe which contains the stagnation port, and the leading edge of the holder which is reminiscent of an airfoil. These two stagnation points experience the most icing and are the focal points of this investigation.
Three stages of the glaze icing process, water droplets impingement, rivulet formation and ice accretion along the leading edge, are illustrated in figure 2.6. In the first stage, the super-cooled water droplets carried by the oncoming airflow impinge onto the region near the stagnation port and the pitot probe holder; and the wind-driven surface water quickly forms into a thin water film that advances further downstream. During this process, the thickness of the water film decreases as it transports downstream. When the thickness of water film achieves the minimum limitation (i.e., defined as a function of surface tension and shear stress) at the water/air interface[7], the film front would split into isolated water rivulets, indicating the start of the second stage. While the water rivulets move downstream, the convective heat transfer would take away the remaining latent heat of fusion in the runback water[8][9], generating the rivulets-shaped ice formation as can be observed in the snapshot at t = 90 s. Then, the icing process comes into the third stage, the icicles start to build up towards the leading edges with most of the impinged water droplets collected and frozen along the leading edges. Compared to the glaze ice accretion, the ice layer formed in the rime icing case has a milky appearance with crystalline structures as shown in figure 2.6b. It should be noted that, while the ice accretion features revealed above would be representative of most typical icing scenarios over the surfaces of a pitot probe, the actual morphologies of ice structures accreted over the pitot probe surface would be affected by many contributing factors, including ambient temperature, LWC level, wind speed and the ice accretion duration, in this investigation, the effects of LWC level, ambient temperature and ice accretion duration have been studied.
2.4.3 Quantification of the icing impacted regions

Two icing impacted regions are highlighted according to the full life-cycle icing accretion process. The quantification of these regions can give not only a more explicit understanding of the
icing process, but also a constructive reference for the optimization of resistant heater installation for pitot probe icing mitigation.

The two icing impacted regions are the leading-edge icing on the stagnation port and pitot probe holder. Due to their insignificance to the pitot probe performance, the ice film and ice rivulet length are not calculated. The main region studied here is the ice accretion concentrated along the leading edges of the pitot probe. \( L_{LE} \) is the span-wise-averaged thickness of ice accretion along the leading edge. The boundary line of ice in front of the test model is extracted by using the method given in Waldman et al [5]. The difference in snapshot intensity caused by the existence of water/ice are calculated by comparing the changes between the time sequences of snapshots with the initial reference. \( L_{LE} \) is then determined by the span-wise-averaged distance between the boundary line and leading edge.

### 2.4.4 Dynamic ice accretion at the pitot probe leading edges

Figure 2.8 shows the leading edge ice thickness growth variations over time for the various ice accretion conditions studied at the pitot probe holder and stagnation port, respectively. As the time goes on, the normalized ice thickness increases. Early on in the ice accretion process, nonlinear phenomena are observed in the glaze ice conditions at the warmer temperatures, this is due to the water runback over the pitot probe surfaces. After that, the ice growth shows linear behavior and the straight lines in figure 2.8 are the linear fitting results with their slopes representing the growth rate of leading edge ice thickness. The accumulated mass is defined by Eq 2.1.

\[
m = LWC \cdot v \cdot A \cdot t
\]

And the rate of mass accumulation is given by Eq 2.2.

\[
\dot{m} = \frac{dm}{dt} = LWC \cdot v \cdot A
\]
Where \( v \) is the airflow velocity, \( A \) is the unit area, and \( t \) is the accretion time.

The volumetric rate is found by dividing the mass flow rate with the ice density, this leads to the ice thickness in Eq 2.3.

\[
L_{\text{Ice thickness}} = \frac{LWC \cdot v}{\rho}
\]

Since the variation of ice density is relatively small under the different icing conditions\[10\], as the incoming airflow velocity is kept the same, the growth rate of ice accretion would be proportional to the LWC level. In the present study, LWC values of 0.5 g/m\(^3\) and 1 g/m\(^3\) were studied for both the rime and glaze icing conditions. The ratio of total ice growth rate between the different LWCs can be estimated at 2.0. It has been demonstrated that the growth of leading edge ice thickness is a good indication of the growth of ice accretion over the surface if all of the impinged water droplets are frozen and accumulated around the LE region\[11\]. In the present study, the ratio of the total ice growth rate for the two rime icing conditions is 1.58 and for the glaze icing conditions was 1.67. This does not compare well to the estimated ratio of 2.0, due to the presence of icing in locations other than the leading edges owing to the unique shape of the pitot probe that experiences icing on its conical leading edge, tube, and holder part. On the other hand, for the same LWC, the ratio of rime icing growth rate to that of the glaze icing is 2.0, illustrating the effects of water runback over the surface caused by the boundary layer airflow that results in a much thinner layer of ice.

*Figure 2.8 Showing the time varied ice thickness for the stagnation port and pitot probe holder, respectively.*
2.4.5 Time evolution of the surface temperature during the icing process.

Unsteady heat transfer takes place during the dynamic icing process. The surface temperature contours give an index to the unsteady heat transfers and provide a more elaborate view of the icing process. The area of the high-temperature region undergoes the process of expanding for both the rime and glaze icing cases. In the glaze icing case, the much larger amount of water collected over the airfoil surface leads to a faster expansion of the high temperature region. The heat transfer is studied on three main regions of the pitot probe, the stagnation port, the tube, and the holder. The stagnation port has the largest increase in temperature due to the larger amount of ice accretion observed on it while the tube shows almost a negligible temperature change, this is due to the stagnation port dominating most of the icing. The holder part shows leading edge icing as well as the growth of an ice film and it has a slightly lower temperature increase than the stagnation port. It should be noted that, the temperature distribution over the ice accreting pitot probe surface is not monotonous under the glaze icing condition and regions with relatively low surface temperatures are observed inside the icing impacted area. In the case of a larger LWC of 2.0, the temperature variations are similar to the previous case but the rise in temperature due to the formation of ice rivulets is clearly illustrated in the holder part [8].

![Figure 2.9](image)

**Figure 2.9** Showing the time varied temperature at the stagnation point (T1), the tube (T2) and the holder (T3) and the surface temperature distribution of the pitot probe halfway through the icing process
2.5 Conclusions

An experimental study of the dynamic ice accretion process on a pitot probe under various conditions was conducted in the ISU-IRT. The test cases in the present study compare the rime and glaze icing conditions at the typical temperatures of -15°C and -5°C for a range of LWCs the pitot probe may experience, 0.5-1 g/m³ for rime ice and 0.5-2.0 g/m³ for glaze ice. The full life cycle of dynamic ice accretion could be divided into two or three stages depending on the different icing morphologies. Under a glaze icing condition three stages were observed, water droplet impingement and water film expansion, the rivulet formation, and the further ice accretion along the leading edge of the airfoil model. Under a rime icing condition, there are mainly two stages: droplet impingement and continuous ice accretion. To further quantify the icing process, two icing impacted regions were identified and studied, the stagnation port and the pitot probe holder, these were leading edge icing dominant and so the ice thickness along the leading edge was calculated. The stagnation port experienced thicker ice growth than the pitot probe holder, while the holder showed a larger area of icing; and an ice film and rivulets were clearly present at the higher LWC cases. Ice thicknesses along the airfoil LE would increase in a general linear trend during the dynamic ice accretion process. The ice thickness and corresponding ice growth rate were found to be smaller than the expected value under the glaze icing condition, which is mainly due to the surface water runback phenomena. Moreover, time evolutions of the surface temperature distributions during the icing process were provided.

References


CHAPTER 3. A HYBRID STRATEGY COMBINING MINIMIZED RESISTIVE HEATING AND A SUPERHYDROPHOBIC COATING FOR PITOT PROBE ICING MITIGATION

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Abstract

The anti-/de-icing performance of the pitot probe heating element; and a hybrid strategy that utilizes a superhydrophobic coating that covers the entire pitot probe surface alongside the heater were explored for pitot probe icing mitigation. The study was conducted in the Icing Research Tunnel at Iowa State University (ISU-IRT) with a PH 500 series pitot probe model from Aero Instruments Co. exposed under glaze icing conditions at a high Liquid Water Content (LWC) of 2.0 g/m$^3$, the heaviest of the icing conditions studied previously. While the superhydrophobic surface (SHS) covered the entirety of the pitot probe, the heater was placed much closer to the pitot probe stagnation point (leading edge) and was still able to keep the entire blade surface ice free in the anti-icing tests; and to achieve fully ice free conditions in the de-icing tests. In comparison to the current strategy of solely using the pitot heater to achieve ice free conditions that consumes a lot of power, the hybrid strategy was found to achieve the same anti-/de-icing performance with up to a 50% power decrease that make this a very promising strategy for pitot probe icing mitigation.

3.1 Introduction:

The pitot probe is a very crucial instrument vital for the safe operation of an aircraft, virtually all aircraft are equipped with one, and most commercial aircraft introduce redundancies by having multiple pitot probes in case one malfunctions. The pitot probe is part of a larger system
known as the pitot-static system, a system of pressure-sensitive instruments that determine the aircraft’s airspeed, altitude, and altitude trend. The pitot probe and static port use pressure data and utilize the principle of air pressure gradient to assess the speed and altitude. The pitot probe measures the stagnation pressure and is often located on the front section of an aircraft, facing forward where its stagnation port is exposed to the relative wind. Due to the importance of the pitot probe measurements, any errors in the pitot-static system readings can be extremely dangerous and potentially safety critical[1]. A common problem facing pitot probes is the issue of ice accretion that can block the stagnation port and lead to erroneous velocity measurements[2]. This was evident in the fatal Air France Flight 447 when ice crystals accreted in or around the pitot probe, this led to a false reading of total air pressure data and caused the aircraft’s flight control system to automatically misconfigure for a lower speed. This caused the autopilot to disconnect, the crew reacted incorrectly, and the aircraft ultimately entered an aerodynamic stall from which it did not recover. This accident is the deadliest in the history of Air France, as well as the deadliest aviation accident involving the Airbus A330 [3]. Knowing these dangers, it is necessary to develop effective strategies for pitot probe icing mitigation.

While a number of anti-/de-icing methods have been developed in recent years, they were developed for aircraft anti-/de-icing applications and can hardly translate to pitot probe de-icing due to its unique shape, small size, and specific application. The anti-/de-icing methods can usually be divided into two categories, active and passive methods. The active methods usually rely on an external energy input and include surface heating methods, usually with hot air or resistive heating, and mechanical actuation methods that utilize inflated rubber boots to break off the accreted ice so it can be blown away with the airflow. Passive methods on the other hand, rely on ice-phobic
and hydrophobic coatings that rely on the surface properties to repel the impinging water droplets allowing them to be blown away by the airflow before they get the chance to freeze[4].

Among the various active anti-/de-icing methods, surface heating methods are considered to be the most efficient approaches to prevent the accretion of ice on the aircraft surface. The most common of these heating methods is resistive heating that utilizes electric heaters installed on the outer surfaces of aircraft components, they have a relatively low energy consumption and high flexibility of installation [5]. In the case of a pitot probe, the heater is installed inside the tube and can be toggled by the pilot whenever needed. However, due to the presence of multiple pitot probes, the long duration of some flights and the limited energy on board, the pitot heat can be power consuming and a more efficient de-icing method that can minimize the power consumption is desired[6].

Due to their low installation cost and negligible energy consumption, a passive anti-icing approach utilizing hydro-/ice-phobic surface coatings has seen more attention recently as a viable strategy for aircraft icing mitigation. Inspired by the self-cleaning capability of the lotus leaf and duck feathers, many efforts have been made to emulate that behavior by developing bioinspired Super-Hydrophobic Surfaces (SHS) on which water droplets bead up with a very large contact angle and drip off rapidly when the surface is slightly inclined[7][8][9][10][11]. On top of their water repelling properties, these SHS have potential to reduce snow/ice accumulation on surfaces[12][13]. Under a frost free environment, SHS was found to show promising behaviors in delaying ice formation[12], even at temperatures as low as -30°C. A study conducted by Gao et al. investigated the icing properties of SHS coatings over an aluminum plate under both laboratorial and natural icing conditions and confirmed the anti-icing properties of the SHS [12]. Mangini et al. investigated the mechanism of runback ice formation on a superhydrophobic surface and found
that its surface wetting properties could dramatically change the ice formation process[14]. More recently, Khedir et al. conducted a comprehensive review to summarize the recent research progress on the development of various superhydrophobic surfaces and their applications for icing mitigation [15]. Other passive anti-icing approaches, such as using slippery liquid-infused porous surfaces (SLIPS) [16][17][18] and soft PDMS materials[19] have also been explored under various icing conditions in recent years. As demonstrated by Liu et al. [19] and Waldman et al. [20] for airfoil/wing models coated with hydro-/ ice-phobic coatings, ice formation/accretion would be mitigated greatly since the aerodynamic forces exerted from the boundary layer airflows would sweep away the water/ice away from most of the SHS coated airfoil/wing surfaces. Despite the promising results, SHS were unable to achieve completely ice free conditions as ice was still found to form in the stagnation line near the airfoil leading edge; indicating that no passive anti-icing method can completely prevent ice accretion over the entire solid surface. This is due to the biggest weakness in the way hydro-/ice-phobic coatings operate, they rely on the aerodynamic shear forces acting tangentially to the surface to remove the water/ice accretion, this is possible because of the low adhesion forces between the surface and the water/ice. Unfortunately, at the stagnation line, these shear forces are almost negligible, and the water retention is at a maximum at the stagnation line [20].

In order to ensure safe flight and efficient ice free operation of the pitot probe, a novel and effective anti-/de-icing strategy must be developed. In this study, a hybrid anti-/de-icing strategy is explored by adding a SHS to the already existing resistive heating method currently used in pitot probes in order to minimize the resistive heating and therefore, the power required to achieve ice free conditions. The hybrid strategy was experimentally evaluated and compared with other conventional passive and active anti-/de-icing strategies in terms of effectiveness and required
power consumption. This study was conducted in the Icing Research Tunnel available at Iowa State University (ISU-IRT) to generate the glaze and rime icing conditions typically experienced by a pitot probe during flight. A used pitot probe model PH 500 series from Aero Instrument Co. was chosen as the model for this test due to its simple configuration and widespread use. During the experiments, while a highspeed imaging system was used to record the dynamic ice accretion processes on the pitot probe model, an infrared (IR) thermal imaging system was utilized to map the surface temperature distributions during the dynamic anti-/de-icing operation. A parametric study was also performed in order to optimize the design parameters of the hybrid anti-/de-icing strategy in order to minimize the power consumption needed for the anti-/de-icing operation.

3.2 A brief description of the hybrid anti-/de-icing strategy

The current most commonly used anti-/de-icing method for pitot probes utilizes a powerful resistive heater placed in the center of the tube near the stagnation port and is off or at low power for most of the flight time. When the pilot detects ice accretion, the heater is powered up until the pitot probe reaches ice free conditions and the process is repeated. Due to the hydrophilic nature of the surface of the pitot probe, the ice strongly adheres to it and so a very high power is needed to achieve ice free conditions. On top of the stagnation port, the pitot probe holder is another region of interest that experiences heavy ice accretion, and due to its distance from the resistive heater it takes longer for it to achieve ice free conditions and requires a higher power input to be get hot enough to achieve a water runback regime, not unlike the heaters used for wind turbine de-icing[21]. Having the pitot heater consume this much power and reach such high temperatures can be inefficient and dangerous to the electrical components, it can also cause oxidation at the pitot probe surface which is damaging to its performance and integrity. On top of that, it is susceptible to electrical failure that could mean no heat is provided at all leaving the pitot probe vulnerable to the dangers of icing.
While runback icing is not a grave issue for the stagnation port, the same cannot be said about the airfoil shaped pitot probe holder. It already receives very little heating and when operating in the wet water runback regime the impacting water would accumulate over the holder’s surface as it is driven by the boundary layer flow. Since the recently warmed surface water is cooled down rapidly as it runs back over the frozen surface, it can refreeze, and the ice accretion starts again further downstream. One way to prevent this from happening would be to heat up the entire holder’s surface but that would require a much larger heater and beats the point of finding a more efficient anti-/de-icing method.

Knowing this, a study was conducted to explore and evaluate a hybrid approach to the anti-/de-icing method that combines the current pitot heater, an active method, with the passive SHS coating method for pitot probe icing mitigation. In this study, the previous icing results that were conducted without any surface treatments were used as the comparison baseline. The anti-/de-icing performance of the pitot heater without any surface modifications is investigated next. A SHS is then applied on the pitot probe to bounce off the impinging water droplets and to reduce the capillary force/ice adhesion strength of the runback water/ice mixtures over the surface, and the anti-icing properties of that are studied without the use of any heat in order to compare the icing phenomena with and without surface modifications. Finally, the spray-on SHS was studied alongside the pitot heater for the hybrid approach and the power consumption is compared with that of the purely heating case.

3.3 Experimental setup and test model

3.3.1 ISU-IRT used in the present study

The experimental study was conducted in the ISU-IRT, a unique multifunctional icing research tunnel shown schematically in Fig 3.1, the ISU-IRT has a test section with four optically transparent side walls to allow for a multitude of views for visual data capture and has dimensions...
of 2.0 m in length, 0.4 m in width and 0.4 m in height. It can generate wind speeds up to 100 m/s and can reach temperatures as low as -25°C. An array of pneumatic spray nozzles (Spraying Systems Co., 1/8NPT-SU11) were installed at the entrance of the contraction section and can generate micro-sized water droplets with a Mean Volumetric Diameter (MVD) ranging from 10πm to 100 μm depending on the air/water pressure and the flowrate supplied to the spray nozzles. The ISU-IRT is thus capable of generating a multitude of atmospheric icing conditions that are typically experienced by a pitot probe during flight.

3.3.2 The pitot probe model used in the present study

A used pitot probe model PH 500 series from Aero Instrument Co. was chosen as the model for this test due to its simple configuration and widespread use. The metal coating on the surface of the pitot probe was unfortunately damaged and the surface was not homogenous, to bypass this issue, the surface was sanded with up to 2000 grid fine sandpaper to achieve a very smooth finish. Then, a thin layer of all-weather protective spray-on white enamel coating (Rustoleum™, Flat Protective Enamel, white in color) was applied to the surface to give it a nice white finish that can clearly show the ice accretion process as well as provide accurate results with the IR camera. A 24 V heating system was already equipped on the pitot probe and acted as the resistive heating anti-/de-icing method, the heater was installed near the center of the tube section of the pitot probe, this provides sufficient leading edge heating to the stagnation port but not enough to the pitot probe holder. To ensure the enamel coating does not interfere with the icing properties of the surface, the contact angle of it was found to be 65° while the contact angle of the original Nickel coating was 50°, both these values are hydrophilic and so the icing properties were not altered by this modification and provided results representative of conventional pitot probe icing. For the
superhydrophobic cases, a SHS was achieved by spraying a commercially available superhydrophobic coating (Hydrobead™) to cover the entire pitot probe surface.

The pitot heat was powered by a Direct Current (DC) power supply. The output voltage was set by the investigators and the current was provided by the power supply, and those values were used to determine the power consumption for the anti-/de-icing operation. In order to determine the minimum value of power required to achieve ice free conditions, a series of experiments were conducted starting at the highest voltage value the pitot heat was rated for, 24 V, and was slightly reduced until the pitot heat cannot provide ice free conditions anymore. This was repeated for anti-icing experiments by heating up the pitot probe before starting the spray and for de-icing experiments that allowed enough ice to accrete before the heater was activated. The smallest power input required for successful anti-/de-icing operation was recorded as the required minimum power consumption.

3.3.3 Experimental parameters used in the present study

A comprehensive parametric study was conducted to assess the effectiveness of the various icing mitigation techniques investigated, as shown in earlier studies, despite the rime ice having a larger thickness, the glaze icing is still the more dangerous form of icing due to the presence of runback icing and ice rivulets in the downstream, and so the anti-/de-icing performance was studied for glaze icing conditions which was achieved at a freestream temperature of -5°C and a LWC value of 2.0 g/m³. It is assumed that if the anti-/de-icing system can achieve ice free conditions at these parameters then it can do that for lower LWCs and for rime icing situations. For these test cases the ISU-IRT was operated at the prescribed temperature level of -5°C until the ISU-IRT reaches a thermal steady state, the water spray system is then turned on and the LWC level was adjusted. The anti-icing performance of the heater is then studied by activating the heater and allowing the pitot probe to reach a thermal steady state before turning on the spray and
observing the icing process. The de-icing performance of the heater was studied by activating the heater after 30 seconds of ice accretion. The anti-icing performance of the SHS was investigated without any heating and was compared to the icing of a hydrophilic pitot probe. Finally, the anti-/de-icing performance of the hybrid system was studied, and the results were evaluated.

3.3.4 High-Speed imaging system and Infrared (IR) thermal imaging systems used in the present study

As seen in Figure 3.1, two high speed cameras were used to capture the dynamic icing process over the pitot probe’s surface, an IR thermal imaging system was also used to quantitatively measure the corresponding surface temperature distributions over the pitot probe’s surface. The two systems were synchronized and triggered by using a digital delay/pulse generator (BNC, Model 577). One high speed camera (PCO Tech, Dimax) was installed right above the test model with a 24 mm lens (Nikon, 24 mm Nikor 2.8 D), providing a top view of the pitot probe with a resolution of 1600 x 888 pixels at 5.08 pixels/mm, another high speed camera was placed adjacent to the pitot probe, this setup provided a clear view of the icing occurring at the stagnation point and at the probe holder which allows for a better understanding of the ice accretion. The IR system was composed of an IR camera (FLIR, A615) and an IR inspection window (FLIR, IR Window-IRW-4c), it can detect waves within a range of 7.5-14 μm and was placed above the test model, providing a field view of 640 x 480 pixels with a resolution of 4.77 pixels/mm. Since the measured surface temperature is proportional to the emissivity, and the original Nickel plating was damaged and has an emissivity of around 0.03, the pitot probe was plated in white protective enamel to ensure a homogenous icing process as well as, the option of using an IR camera to capture temperature data. The protective enamel has an emissivity value of 0.96, while water and ice have an emissivity of 0.95~0.96 and 0.96~0.98, respectively. Since the emissivity values of these materials have a difference of only 3%, the uncertainty of the measured surface caused by
emissivity can be considered negligible. A high accuracy thermocouple was used on the surface of the pitot probe to provide in-situ calibration of the surface temperature measurements by the IR camera.

![Figure 3.1 Schematic of the ISU-IRT including test section and instrumentation.](image)

![Figure 3.2 IR image showing the heated pitot probe and the most heated locations](image)

3.4 Measurement results and discussions

3.4.1 Comparison of the anti-/de-icing performance of the various strategies

An anti-/de-icing strategy is considered successful when the pitot probe reaches ice free conditions, either with no ice accreting whatsoever in anti-icing techniques or by totally removing all the ice in anti-icing techniques. The power required to achieve that without any surface modifications will be the reference point to which the performance of the hybrid system is judged. That is, 48 W for anti-icing to achieve completely ice free conditions and 95.8 W for de-icing to achieve ice free conditions.
The first test conducted was the anti-icing test which had the heater on before the water impingement process. The test was conducted at a freestream velocity of 40 m/s and a freestream temperature of -5°C and a LWC level of 2 g/m³. At a power level of 24 W, the pitot probe had no problem achieving ice free conditions at the stagnation port, though a clear water film was observed on the probe due to operating in the runback regime, this does not cause any concerns as the water does not get the chance to freeze. On the other hand, the holder cannot achieve ice free conditions at this power level as not enough heat reaches it to be able to enter the water runback regime, ice rivulets can be clearly seen as well and most of the holder surface is covered in ice by now. Doubling the power level to 48 W at the same icing conditions yields much better results, the pitot probe experiences slight ice accretion at the holder part early on but that is quickly melted and removed, no runback icing is visible either meaning the entire holder is at a temperature hot enough to enter the water runback regime, a thin water film is still visible on the pitot probe but no icing occurs.

Figure 3.3 The anti-icing performance of the pitot heater at 24 W

Figure 3.4 The ice free pitot probe when the heater was set at 48 W

Figure 3.5 shows the baseline hydrophilic surface icing without any icing mitigation techniques under the glaze icing conditions mentioned above. It is clearly visible that after the
impingement of the supercooled water droplets at the stagnation point and the pitot probe holder that only some of them froze into ice. The remaining water droplets formed a thin water film flow at first and then run back as they are driven by the boundary later flow over the surface. A thick conical ice layer formed around the stagnation port and kept growing while the water runback froze into icicle like structures that can be seen protruding from the tube’s surface, these structures only formed at one side of the tube due to slightly angled shape of the pitot probe. The pitot probe holder experienced more extreme icing as the water film at the leading edge split onto multiple rivulets running back and eventually froze into ice at the downstream locations. As the experiment progressed, the ice structures formed on the pitot probe surfaces kept growing larger and larger with a transparent appearance typical of glaze icing, until most of the surface was covered with complicated glaze ice structures.

Figure 3. 5 The ice accretion on the hydrophilic surface

Figure 3.6 now shows what the icing process looks like when using a SHS, much less ice accretion is observed on the surfaces, especially beyond the stagnation port and the leading edge of the holder where most of the ice accretion was concentrated. The icicle like structures can still be seen on the surface of the tube but they were less pronounced than the ones seen on the hydrophilic surface. This is because the unfrozen surface water was able to run back much faster over the SHS coated pitot probe surface and was shed off before getting the chance to freeze. As a result, the once messy and almost fully covered pitot probe holder now only experienced leading
edge icing and no rivulets were observed. This phenomena can be explained by the much larger contact angle of the water and smaller wet area over the SHS-coated surface, allowing the same velocity of 40 m/s to now be able to exert much larger aerodynamic shear forces that can blow away these droplets. The weaker capillary force and ice adhesion strength also enable a much faster moving speed of the runback water/ice mixtures over the SHS-coated surface. Unfortunately, the aerodynamic shear forces near the leading edges are much smaller and even vanish at the stagnation line. As a result, once ice accretes over these surfaces it becomes much easier for the subsequent super-cooled water droplets impinging on the surface to freeze, thus accelerating the ice accretion process near the leading edges. Therefore, as shown clearly in Fig. 3.6, while the passive strategy with SHS coating was found to be able to reduce ice accretion over the SHS-coated pitot probe surface significantly, it is still far from sufficient to successfully prevent ice formation/accretion over the entire surface of the pitot probe model. Furthermore, despite the improved anti-icing performance, it can be seen quantitatively in figure 3.7 that after enough time, the ice thickness at the leading edges is almost identical to the hydrophilic surface, this means that the stagnation port is still prone to blocking and the holder can still allow much more ice accretion. This is because the aerodynamic shear forces at the leading edge are much weaker and the water collection efficiency is at its highest. This reinforces the fact that active heating method is necessary to achieve ice free conditions at the leading edges.

![Image](image.png)

*Figure 3.6* Showing the anti-icing performance of the SHS
Knowing this, the hybrid system is finally tested for its anti-icing performance. The surface is coated with the SHS and the same procedure is repeated from earlier. While 24 W was not enough to achieve a completely ice free condition on the hydrophilic surface, and a clear water film was observed on the tube, the hybrid system was able to achieve totally ice free conditions. The stagnation port experiences no icing and this time no water film is observed on the tube either. The pitot probe holder initially experiences some slight icing, but after 120 seconds, the ice is completely shed, and the pitot probe achieves ice free conditions. The presence of the hydrophilic surface greatly reduced the adhesion strength of the ice on the pitot probe holder allowing the connection between it and the ice to be easily severed by the heat and then it was a matter of the boundary layer flow eventually driving the ice off. As expected, no ice rivulets or any runback icing was observed with the SHS. The hybrid system thus achieved a 50% decrease in power consumption while maintaining an outstanding anti-icing performance that kept the pitot probe safe for the duration of the experiment.
While the hybrid anti-icing technique proved successful in reducing the power necessary to achieve ice free conditions when compared to solely using the heater, having the heater constantly on is still very power consuming and dangerous for the longevity of the electrical components of the heater as well. Fortunately, pitot probe icing only becomes unsafe when the ports get blocked and so a different more power efficient technique is to activate the pitot heat when dangerous amounts of ice have already accreted. The performance of the pitot heater was thus studied in a de-icing scenario for the same glaze icing conditions mentioned earlier. The pitot probe was placed in the tunnel and the surface temperature was allowed to reach the freestream temperature. After that the spray was initiated and the ice was left to accrete for 30 seconds before the heater was activated. The ice accreted in the familiar clear glaze ice formation, with most of the icing present on the pitot probe holder due to its airfoil like shape. Once the heat was activated it did not take long for the stagnation point to become ice free due to its proximity to the heater and small area, the holder required more time due to the large icing area and the extensive presence of runback icing. The lowest power setting to achieve ice free conditions on the hydrophilic was 96 W and that needed 47 and 193 seconds to achieve ice free conditions for the stagnation port and the holder to be completely free of ice. It should be noted that despite the time it took to de-ice the stagnation port, it was not blocked the entire time.
The hybrid approach was then tested for its de-icing capabilities. The SHS was already known to accrete less ice due to the lower capillary force required to blow away the supercooled water droplets as well as for its lower ice adhesion strength, and these properties benefited the de-icing performance greatly. The same experiment was conducted and once the heater was activated, it took much less time for the stagnation port and holder to reach ice free conditions. (WHY). On top of that, the minimum power required to achieve completely ice free conditions was reduced from 96 W to 62 W, a nearly 35 % decrease in power consumption.

Figure 3. 9 De-icing performance of the hybrid system at 62 W

3.4.2 Measured surface temperature distributions during the anti-/de-icing operation

Figure 3.10 shows the temperature measurements over time for the pitot probe during the anti-icing process at 48 W. After the electric heating element was switched on, the surface temperature in the region near the leading edge was found to increase monotonically at first, then reached a surface temperature greater than the water frozen temperature (i.e., $T > 0 \, ^\circ C$). The surface temperature at the stagnation port was found to be much higher than that in the holder due to the much stronger heater presence. The water spray system of ISU-IRT was switched to start the anti-/de-icing experiment. As revealed clearly from the temperature results, upon the impacting of the super-cooled water droplets onto the pitot probe model, the surface temperature of the heated surface near the pitot probe leading edge was found to drop dramatically at first, and then reached a stable state eventually. For this case, the temperature of the heated surface near the leading edge
was found to stay slightly above the water frozen temperature. It indicates that, after the super-cooled water droplets impinged onto the heated tube surface, they (i.e., with their original temperature being $T_\infty = -5 \, ^\circ C$) heated up rapidly and stayed in the liquid phase. The impacted surface water would run back, as driven by the boundary layer airflow over the surface of the model. Since the ambient temperature was kept at a frozen-cold temperature of $T_\infty = -5.0 \, ^\circ C$ during the anti-/de-icing experiment, the runback water was found to be re-frozen into ice at further downstream locations of the hydrophilic surface. The temperature plots show that the stagnation port and the tube achieved a great temperature rise once the heater was activated while the holder surface temperature barely rose in comparison. Based on these observations, the most obvious action to improve the heater’s performance would be to either change its location or use an even stronger heater, but in order to fully heat the holder a much more power consuming heater would have to be used, which go against the goals of this research.

![Figure 3](image1.png)

**Figure 3.** Temperature measurements over time for the three regions of interest

### 3.4.3 Parametric study to determine most optimum power setting.

As seen in tables 3.1 and 3.2, ice free conditions were achieved at a variety of power settings, the fastest being at 132 W. At this setting, the impacted water droplets over the pitot probe surface would be heated up to a temperature much higher than the water-freezing temperature to prevent ice accretion. While this has kept the entire pitot probe surface ice-free, a portion of this
power is wasted on overheating the impacted water droplets. Therefore, a parametric study was also performed to minimize the required power input for the hybrid anti-/de-icing operation. In this study, the input voltage was gradually reduced by 2 V, starting with a maximum setting of 24 V until the lowest voltage input can be found while still maintaining ice free conditions when tested for the typical glaze icing condition used for all the other tests in this study.

Figure 3.11 shows snapshots of the hybrid anti-icing strategy with the heating element operating at 24 W, the heat was enough to prevent the ice from accreting on the leading edge of the pitot probe but for the holder that received less heat, the impacted super-cooled water droplets were frozen into ice. Once the ice accreted onto the holder leading edge, subsequent water would accumulate rapidly over the surface of the accreted ice to promote much faster ice growth. As the size of the accreted structures increases, the aerodynamic shear force acting on them would increase, eventually becoming strong enough to overcome the ice adhesion strength over the SHS-coated surfaces causing the large ice chunk to shed off the surface. This procedure is also typical for the de-icing strategy that consumes less power as it only uses heat after ice has accreted instead of keeping the heater on indefinitely.

Figure 3.11 The anti-icing performance of the SHS and 24 W of power

Figure 3.12 shows what happens at a slightly higher power setting of 48 W is used. The super-cooled water droplets here are heated up rapidly to a temperature much higher than the water freezing temperature after impact onto the heated surface. This warmer water would run back very
rapidly over the SHS-coated surface and would rapidly shed from the trailing edge before getting the chance to freeze again. As a result, the SHS-coated surface was found to be completely ice free. Looking at the tables below shows an expected trend of shorter de-icing times as the power increases and when a hybrid approach is used, the de-icing time for the holder also decreases while it barely changes for the stagnation port leading edge, this is because the heater is so close to the stagnation part that it remains the primary de-icing method even after a SHS was introduced. However for the holder part, only a fraction of the thermal energy is transferred from the leading edge and so by using a hybrid system and eliminating runback icing and the complex ice shapes that also reduces the ice adhesion, the relatively low heat that reaches the holder is enough now to achieve ice free conditions faster.

![Image]

**Figure 3.12 The anti-icing performance of the SHS and 48 W of power**

**Table 3.1 Parametric study of the anti-icing process**

<table>
<thead>
<tr>
<th>Power (W)</th>
<th>Leading edge ice removal (within 200 s)</th>
<th>Holder ice removal (within 200 s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Heating</td>
<td>Hybrid</td>
</tr>
<tr>
<td>6.4</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>9.5</td>
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<td>v</td>
<td>v</td>
</tr>
<tr>
<td>24</td>
<td>v</td>
<td>v</td>
</tr>
<tr>
<td>35</td>
<td>v</td>
<td>v</td>
</tr>
<tr>
<td>40</td>
<td>v</td>
<td>v</td>
</tr>
<tr>
<td>48</td>
<td>v</td>
<td>v</td>
</tr>
</tbody>
</table>
Table 3. 2 Parametric study results of the de-icing process

<table>
<thead>
<tr>
<th>Power (W)</th>
<th>Leading edge ice removal time (s)</th>
<th>Holder ice removal time (s)</th>
</tr>
</thead>
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<td>Heating</td>
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<tr>
<td>48</td>
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<td>30</td>
</tr>
</tbody>
</table>

3.5 Conclusion

In the present study, a hybrid anti-/de-icing strategy that combines minimized surface heating and a SHS coating to cover the entire probe's surface was explored for pitot probe icing mitigation. The experimental study was conducted at the ISU-IRT, which was used to generate the wet glaze icing condition used in this study. A model PH 500 pitot probe from Aero Instruments Co. was used and mounted in the test section of the ISU-IRT to evaluate the effectiveness of the factory provided pitot heater as well as the hybrid strategy explored in this study. The test cases investigated included: 1) The pitot probe model with the original hydrophilic surface as the comparison baseline to represent conventional pitot probe icing. 2) A passive anti-icing strategy that had the pitot probe surface coated with a SHS. 3) An active anti-/de-icing strategy that tests the effectiveness and shortcomings of the pitot probe heater. 4) A hybrid anti-de-icing strategy that combines the SHS with the pitot heat in order to reduce the power necessary to achieve ice free conditions. During the experiment, while a high-speed imaging system was utilized to reveal the dynamic ice accretion process over the surface of the pitot probe model under different icing conditions, a high-speed infrared (IR) thermal imaging system was also used to quantify the time evolutions of the temperature distributions over the surface of the pitot probe model during the anti-/de-icing operations with different anti-/de-icing strategies.
It was found that, in comparison to the baseline case, the ice accretion area over the SHS coated pitot probe surface was much smaller due to the much faster runback speed of the impacted surface water and the weaker ice accretion strength over the SHS coated surface. However, ice was still found to build up in the region near the pitot probe stagnation point and the pitot probe holder due to the much weaker aerodynamic shear forces in the region near the stagnation line. It indicates that, it is impossible to keep the entire pitot probe surface ice-free by using only the passive anti-icing strategy with SHS coatings. While the pitot probe heater was found to be effective in heating up the impacted water droplets to mitigate ice accretion, the water runback was found to still accrete over the hydrophilic surface in the downstream region beyond the capacity of the heater.

In order to counteract the defects of both icing mitigation strategies, a hybrid strategy combining both the SHS coating and the pitot probe heating was employed. The hybrid strategy was found to be capable of keeping the entire pitot probe surface completely ice free under the test glaze conditions. A parametric study was then conducted to minimize the power consumed by the pitot heater and was found to achieve power reductions of up to 50%, making the hybrid strategy a very promising anti-/de-icing method that can ensure safe and more efficient operation of a pitot probe in cold environments.

References


CHAPTER 4. CONCLUSIONS AND FUTURE WORK

4.1 Conclusions

Pitot probe icing has been a constant threat to the safe flight of aircraft by providing false pressure readings that can be a source of confusion for the pilots. In the present study, by utilizing the ISU-IRT, a series of experimental investigations were conducted to investigate the dynamic ice accretion process over the surface of a typical aircraft pitot probe and to explore current anti-/de-icing methods as well as a novel hybrid icing mitigation strategy.

A comprehensive experimental study was conducted to investigate the dynamic ice accretion process over a pitot probe surface under various icing conditions ranging from wet glaze to dry rime ice. High speed cameras were used to characterize the time variant ice accretion process while an IR camera was used to capture the surface temperature distributions. The ice thicknesses at two areas of interest were computed and the extent of the icing was discovered to help device a more optimum icing mitigation technique.

The anti-/de-icing performance of the factory provided pitot probe heater was then investigated and the power requirements of ice free conditions were recorded. The pitot probe heating was then minimized by introducing a bio-inspired superhydrophobic coating on the pitot probe surface to reduce the capillary force required to blow away the impinging water as well as the ice adhesion strength of the accreted ice. The hybrid approach was shown to achieve power reductions of up to 50%.

The findings derived from the studies conducted can lead to a better understanding of the underlying physics pertinent to the pitot probe icing phenomena, which could be used to improve ice accretion models as well as to develop even more effective ice mitigation techniques to provide safe flight in cold weather.
4.2 Future work

The studies conducted only investigated the icing process of rime and glaze ice, the Air France crash was caused due to the accretion ice crystal icing, the Advanced Flow Diagnostics and Experimental Aerodynamics lab running the ISU-IRT has been developing a crystal icing facility that is capable of studying the icing physics of ice crystals as well as the anti-/de-icing performance of various icing mitigation technology against this unique problem.