AN EXPERIMENTAL STUDY OF THE ICING PROCESS WITHIN SMALL WATER DROPLETS IMPINGING ONTO A FROZEN COLD PLATE

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Abstract—T **An experimental investigation was conducted to quantify the unsteady heat transfer and phase changing process within small icing water droplets in order to elucidate underlying physics to improve our understanding of the important microphysical process of icing phenomena. A novel, lifetime-based molecular tagging thermometry (MTT) technique was developed and implemented to achieve temporally-and-spatially resolved temperature distribution measurements to reveal the time evolution of the unsteady heat transfer and dynamic phase changing process within micro-sized water droplets in the course of icing process. It was found that, after a water droplet impinged onto a frozen cold surface, the liquid water at the bottom of the droplet would be frozen and turned to solid ice rapidly, while the upper portion of the droplet was still in liquid state. As the time goes by, the interface between the liquid phase water and solid phase ice was found to move upward continuously with more and more liquid water within the droplet turned to solid ice. Interestingly, the averaged temperature of the remaining liquid water within the small icing droplet was found to increase, rather than decrease, continuously in the course of icing process. The volume expansion of the water droplet during the icing process was found to be mainly upward to cause droplet height growth rather than radial to enlarge the contact area of the droplet on the test plate. As a result, the spherical-cap-shaped water droplet was found to turn to a prolate-spheroid-shaped ice crystal with cusp-like top at the end of the icing process**.

Keywords- Icing Physics of Water Droplets; Solidification Process; Micro Scale Heat Transfercomponent; Molecular Tagging Thermometry .

I. INTRODUCTION

Ice accretion on cold surfaces is a topic of great concern for a number of engineering applications. Ice formation an accretion on power cable and radio masts have been found to cause significant damaged or destroyed completely the electric equipment on numerous occasions [1]. Aircraft icing is widely recognized as one of the most serious weather hazards to aircraft operations [2]. The importance of proper ice control for aircraft operation in cold climate was highlighted by many aircraft crashes in recent years like the Continental Connection Flight 3407 crashed in Buffalo, New York due to ice buildup on its wing killing all 49 people aboard and 1 person on the ground as the plane hit a residential home on February 14, 2009. Wind turbine icing represents the most significant threat to the integrity of wind turbines in cold weather. It has been found that ice accretion on turbine blades would decrease power production of the wind turbines significantly [3]. Ice accretion and irregular shedding during wind turbine operation would lead to load imbalances as well as excessive turbine vibration, often causing the wind turbine to shut off [4]. Icing was also found to affect the reliability of anemometers, thereby, leading to inaccurate wind speed measurements and resulting in resource estimation errors[5].

Advancing the technology for safe and efficient operation of numerous functional devices in atmospheric icing conditions requires a better understanding of the icing physics. While a number of theoretic and numerical studies have been conducted in recent years to develop ice prediction tools for improved ice protection system designs [6-9], many details of important micro-physical processes that are responsible for the ice formation and accretion on frozen cold surfaces are still unclear. Fundamental icing physics studies capable of providing accurate measurements to quantify important microphysical processes associated with icing phenomena are highly desirable in order to elucidate the underlying physics.

In this study, we report an experimental icing physics study to quantify the transient behavior of the phase changing and heat transfer process within small water droplets impinging onto a frozen cold plate. It should be noted that this is a fundamental icing physics study. Instead of reproducing every detail of the icing phenomena for a specific engineering application, the present study was aimed to elucidate underlying fundamental physics to improve our understanding about the important microphysical processes pertinent to various icing phenomena found in nature, which include power cable icing, wind turbine icing and aircraft icing. To the best knowledge of the authors, this is the first effort of its nature. The new findings derived from the icing physics studies as the one reported here will lead to a better understanding of the important microphysical processes, which could be used to improve current icing accretion models for more accurate prediction of ice formation and accretion on frozen cold surface as well as the development of effective icing

mitigation and protection systems for various engineering applications.

II. EXPERIMENTAL SETUP

A novel, lifetime-based molecular tagging thermometry (MTT) technique [10, 11] was used in the present study to achieve simultaneous measurements of droplet size and water temperature distribution within small icing droplets to quantify the unsteady heat transfer and transient phase changing process. Unlike commonly-used Laser Induced Fluorescence (LIF) based thermometry techniques that rely on information obtained from the intensity axis of the photoluminescence emission process [12], the lifetime-based MTT technique relies on the information contained in the time axis of the phosphorescence emission process, as temperature change would cause significant variations in the phosphorescence lifetime of some phosphorescent dyes [13- 16]. Phosphorescent 1-BrNp·Mβ-CD·ROH molecules were used as the molecular tracers in the present study, whose phosphorescence lifetime was found to decrease from 7.20 ms to 1.10 ms as the temperature changes from $1.0°C$ to 40.0 $°C$ [13]. For the lifetime-based MTT measurements, a pulsed laser was used to tag phosphorescent 1-BrNp·Mβ-CD·ROH molecules premixed within small water droplets. Long-lived laser-induced phosphorescence is imaged at two successive times after the same laser excitation pulse. While the size of the icing water droplet (in terms of shape profile, height, contact area and volume of the droplet) was determined instantaneously from the acquired phosphorescence images, the transient temperature measurement of the liquid water inside the icing droplet was achieved by taking advantage of the temperature dependence of phosphorescence lifetime, which was estimated from the intensity ratio of the acquired phosphorescence image pair. Further information about the technical basis of lifetime-based MTT technique and photoluminescence properties of phosphorescent tracer molecules of 1-BrNp·Mβ-CD·ROH is available at Ref.16.
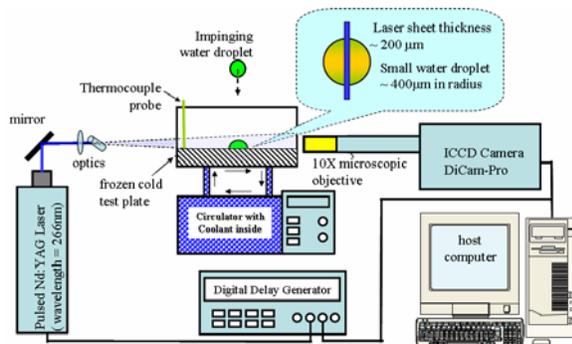

Fig. 1: Experimental setup for icing droplet study

Fig. 1 shows the schematic of the experimental setup used in the present study. A droplet generator was used to generate micro-sized water droplets (~ 400 μm in radius, 0.062μL in volume, and initial temperature of $20.5°C$) to impinge onto a frozen cold test plate. The temperature of the test plate, which was monitored by using a thermocouple, was kept constant at a pre-selected low temperature level by using a Constant Temperature Bath Circulator (Neslab RTE-211). A laser sheet (~200μm in thickness) from a pulsed Nd:Yag laser at a quadrupled wavelength of 266nm was used to tag the premixed tracer molecules along the middle plane of the small water droplets. A 12-bit gated intensified CCD camera (PCO DiCam-Pro, Cooke Corp.) with a 10X microscopic objective (Mitsutoyo infinity-corrected, NA= 0.28, depth of field = 3.5μm) was used to capture the phosphorescence emission. The camera and the pulsed Nd:Yag laser were connected to a workstation via a digital delay generator (BNC 555 DDG), which controlled the timing of the laser illumination and the image acquisition. For the lifetime-based MTT measurements, the first phosphorescence image was acquired at 0.5 ms after the laser excitation pulse and the second image at 3.5 ms after the same laser pulse with the same exposure time of 1.5 ms for the two image acquisitions. It is noted that, due to the low concentration of the tracer molecules used for the MTT measurements, the effects of the molecular tracers on the physical properties of water and icing process are believed to be very small. Since the low energy level and repetition rate of the pulse laser excitations are used for the MTT measurements, the effects of the energy deposition due to the pulsed laser excitation on the icing process is expected to be negligible. The uncertainty of the MTT measurements was estimated to be within $0.5°C$. Further information about the experimental setup, procedures to implement the lifetime-based MTT technique to quantify the phase changing process within small icing water droplets, and measurement uncertainty estimation is available at Ref. 17.

III. RESULTS AND DISCUSSIONS

Fig. 2 shows the time sequence of the acquired phosphorescence images of a water droplet after it impinged onto a frozen cold test plate (TW = -2.0°C). The corresponding instantaneous temperature distributions of the remaining liquid water within the icing droplet measured by using the lifetime-based MTT technique are also given in the figure. In the phosphorescence images, the "brighter" region in the upper portion of the droplet represents liquid phase – water; while the "darker" region at the bottom indicates solid phase – ice. It can be seen clearly that the liquid water at the bottom of the droplet was frozen and turned to solid ice rapidly, while the upper portion of the droplet was still in liquid state. As the time goes by, the interface between the liquid water and solid ice was found to move upward gradually. At about 35s after it impinged onto the test plate, the droplet was found to turn into a solid ice crystal completely.
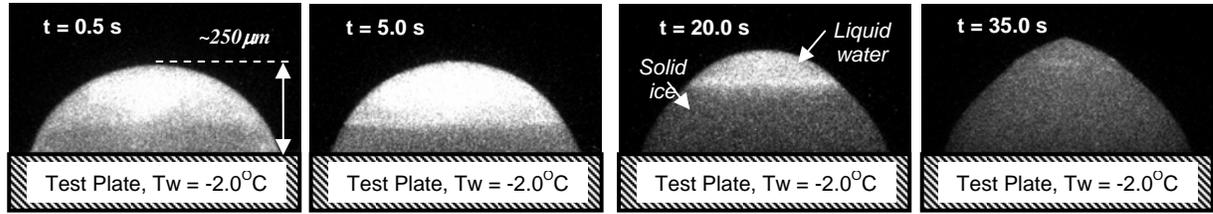
(a). Phosphorescence images
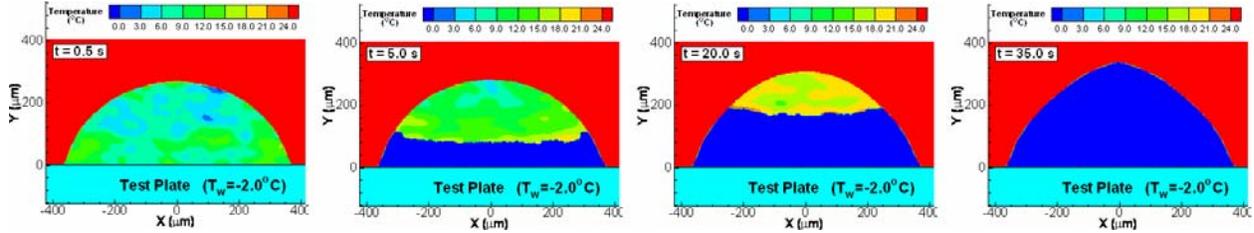
(b). Lifetime-based MTT measurement results

Fig. 2: Time evolution of the phase changing process within a small icing water droplet

Based on the time sequences of the instantaneous MTT measurements as those shown in Fig. 2, the time evolution of the averaged temperature of the remaining liquid water within the icing droplet in the course of icing process can be determined, which is shown in Fig. 3. It should be noted that, the initial temperature of the liquid water droplet was 20.5 °C before impinging onto the frozen cold test plate, the rapid temperature drop of the water droplet at the moment as it impinged onto the frozen cold test plate (i.e., the event happened within the first 0.5s) were not able to be resolved due to the low temporal resolution (i.e., $f = 2.0$Hz) of the MTT measurements. Interestingly, as shown in Fig. 3, the averaged temperature of the remaining liquid water within the icing droplet was found to increase, instead of decrease, monotonically with time in the course of icing process. The temperature increase is believed to be closely related to the heat release of the latent heat of solidification in the course of the icing process. As visualized clearly from the MTT measurement results given in Fig. 2, the liquid water at the bottom of the icing droplet would turn to solid ice rapidly as the droplet impinged onto the frozen cold test plate. It is well known that a significant amount of latent heat of solidification would be released as liquid water turned to solid ice. While some of the released latent heat of solidification would be conducted through the cold test plate and dissipated by the thermal bath circulator, a portion of the released latent heat of solidification would be conducted through the interface between the solid ice and the liquid water within the icing droplet to heat the remaining liquid water with the icing droplet. In the course of icing process, more and more liquid water was found to turn to ice with the latent heat of solidification releasing continuously, while the total amount of the remaining liquid water within the icing droplet would become less and less. As a result, the averaged temperature of the remaining liquid water within the icing droplet would increase

monotonically with time until the droplet turned to ice crystal completely. The temperature increase of the remaining liquid water during icing process was also predicted in the numerical: simulations of Myers et al. [7-8] and Brakel et al. [9]. It should also be noted that, the rapid temperature rise during the freezing of liquid metals caused by the release of latent heat is well known in material science and engineering, and is called "*recalescence*" phenomenon [18].
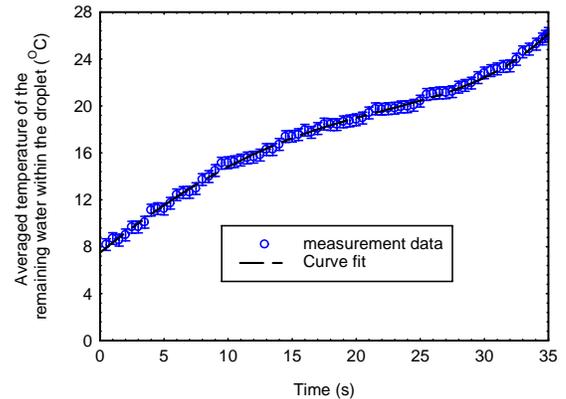

Fig. 3: The averaged temperature of the remaining liquid water in the icing droplet versus time (TW = -2.0 °C)

Fig. 4 shows the variations of the droplet shape profiles in the course of the icing process. It can be seen clearly that the water droplet was round, as a cap of a sphere, at the beginning, as expected. The spherical-cap-shaped profile was found to be sharpened substantially and become prolate-spheroid-shaped in the course of the icing process. It should be noted that a distinctive cusp-like tip instead of a round top was found to form at the top of the droplet when the water droplet was frozen completely to become an ice crystal at $t = 35$s. A similar cusp-like sharp tip was

also reported by Anderson *et al.* [19] when they studied droplet solidification process for ultrapure material production. They suggested that a theory involving dynamics growth angles at the tri-junction between solid ice, liquid water, and surrounding air can be used to explain the formation of the cusp-like sharp top in droplet solidification process.
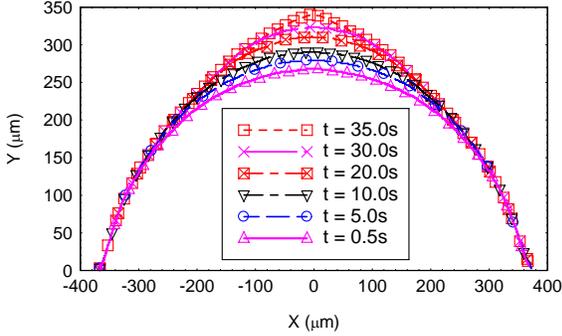

Fig. 4: The variations of the shape profile the icing droplet versus time ($T_W = -2.0\ ^O C$)

It is well known that a liquid water droplet will experience volume expansion as turning into solid ice. The time evolution of the droplet volume expansion in the course of the icing process was also revealed clearly from the variation of the droplet shape profiles given in Fig. 4. While the contact radius of the droplet on the test plate was almost constant, the height of the droplet was found to increase continuously during the icing process. It indicates that, the volume expansion of the water droplet would be mainly upward to cause droplet growth in height rather than in radius in the course of icing process. The volume of the droplet can be determined based on the measured droplet shape profiles with a reasonable axisymmetric assumption. Fig. 5 shows the time histogram of the volume expansion of the droplet, V/VO, in the course of the icing process, where $VO \approx 0.062\ \mu L$ is the initial volume of the water droplet. The volume of the droplet was found to increase rapidly at the beginning of the icing process more liquid water was frozen and turned into ice. The volume expansion rate was found to decrease with time since less and less liquid water was found to remain within the droplet. The volume expansion profile was found to become a flat line at about $t = 35s$, which indicates that the volume of the droplet would not change with time anymore after the water droplet turned to solid ice crystal completely. The averaged specific weight of the icing droplet,γ, in the course of the icing process can also be determined based on the measured droplet volume expansion profile, which is also given in Fig. 5. For comparison, the standard value of the specific weight of pure ice (i.e., $\gamma_{ice} = 0.9167$) was also plot in the figure as the dashed straight line. It can be seen clearly that the specific weight of the icing droplet would become smaller and smaller as more and more remaining water turned to solid ice. When the water droplet turned to solid ice crystal completely at $t = 35s$, the specific weight of the

ice crystal was found to become $\gamma = 0.9165$, which agree with the standard value of pure ice $\gamma_{ice} = 0.9167$ very well.
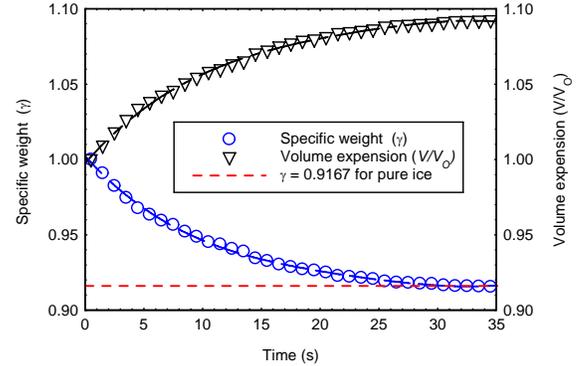

Fig. 5: The volume (V/V_O) and the specific weight (γ) of the icing droplet versus time $T_W = -2.0\ ^O C$

IV. SUMMARY REMARKS

In summary, we reported an icing physics study to quantify the transient phase changing process within small icing water droplets impinging onto a frozen cold plate to elucidate underlying physics of the importance microphysical processes pertinent to wind turbine icing phenomena. A lifetime-based molecular tagging thermometry (MTT) technique was used to achieve simultaneous measurements of droplet size and water temperature within the small icing droplets. It was found that, after a water droplet impinged onto a frozen cold surface, the liquid water at the bottom of the droplet would be frozen and turned to solid ice rapidly, while the upper portion of the droplet was still in liquid state. As the time goes by, the interface between the liquid phase water and solid phase ice was found to move upward continuously with more and more liquid water within the droplet turned to solid ice. Interestingly, the averaged temperature of the remaining liquid water within the small icing droplet was found to increase, rather than decrease, continuously in the course of icing process. The temperature of the remaining liquid water is believed to be due to the heat release of the latent heat during solidification process. The volume expansion of the water droplet during the icing process was found to be mainly upward to cause droplet height growth. As a result, the spherical-cap-shaped water droplet was found to turn to a prolate-spheroid-shaped ice crystal with cusp-like top at the end of the icing process.

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