FREEZING OF WATER IN AN OPEN CHANNEL FLOW UNDER SUPERCOOLED AMBIENT CONDITIONS: PRELIMINARY RESULTS

Anatolij R. Karev[1], Masoud Farzaneh[1], Laszlo Kollar[1] and Sandy Vaslon[1]

ABSTRACT

The thermal structure of an experimentally modeled ice accretion with a water film in an icing wind tunnel is investigated here at both inner and outer interfaces using non-destructive remote sensing techniques and traditional thermometry. The water film developing into rivulets was produced by spraying of an aerosol flow from a single water-dispersing nozzle cloud onto the iced bottom of a thermally insulated channel. The water film was then driven by a concurrent air flow at negative temperatures. The shear-driven water film thus created was thereby forced to freeze from below due to convection and evaporation from its surface. Heat conduction lengthwise along the bottom of the channel and perpendicular to it was controlled by measuring the outer surface of the bottom of the channel at several sites. The surface temperature of the flowing water film developing into rivulets, as measured by infrared camera, was found to be negative throughout all the experiments.

INTRODUCTION

A number of atmospheric icing models incorporate, in different ways, the concept of a

[1] NSERC/Hydro-Québec/UQAC Industrial Chair on Atmospheric Icing of Power Network Equipment (CIGELE) and Canada Research Chair on Atmospheric Icing Engineering of Power Networks (INGIVRE), Université du Québec à Chicoutimi, Département des Sciences Appliquées, 555 blvd de l'Université, Chicoutimi, Québec, Canada G7H 2B1

thin water film which appears and starts flowing when there is an excess of incoming supercooled water onto an icing surface. The precise dynamics of this film, however, and its thermodynamic properties, are still not known clearly. From the time of the first introduction of the concept of a water film on the surface of growing atmospheric ice (Schumann, 1938) and the subsequent introduction of the freezing fraction concept (Messinger, 1953) up to and including late eighties, it was thought that the temperature of this water film should be equal to the equilibrium temperature between the water and ice, or water fusion temperature T_m=273.15 K. Thus, all atmospheric icing models originating from forties onward were based entirely on the heat balance calculation of an icing surface, where the temperature of water fusion was taken as the reference point, distinguishing the solid from the liquid states of water. A series of experiments with artificial hailstones grown in laboratory simulations of natural conditions (List et al., 1989; Greenan and List, 1995) confirmed that the temperature of the water film on an icing surface in the wet mode is always below 0 ^{o}C. Yet over 30 years earlier, there was only one theoretical model, proposed by Kachurin (1962), which predicted supercooling of icing surfaces in both icing modes: with and without a water film. This icing model, initially developed for aircraft icing and then applied to the problem of icing of non-rotating cylinders (Kachurin et al., 1974), was based on the dynamics of a supercooled water film flowing over an icing surface and incorporating a Couette shear layer as well as the concept of eddy diffusivity in a flowing water film. Because Kachurin's work was largely unknown in the West, classical run-back icing models, such as the one proposed by Lozowski et al. (1979), continued to adopt the heat balance calculation of an icing surface, and parallel attempts were made to understand and explain theoretically the recorded water supercooling by introducing concept of non-isotropic heat transfer (List, 1990). Simultaneously, Kachurin's idea was successfully applied for computing hailstone growth processes and for explaining experimentally observed supercooling (Gvelisiani, 1968; Karev, 1993). Recently, the experimental data freshly obtained from the parallel fields of thin water film flow gave new birth to the initial idea and made it possible to specify its applicability to the icing processes (Karev et al., 2003a and 2003b). Moreover, a parallel was drawn between the hailstone growth and atmospheric icing processes by recording experimentally the supercooling at the surface of a water-film flowing on icing cylinder (Karev and Farzaneh, 2003). This investigation is an attempt to record water film supercooling by experimentally modeling a Couette shear water layer in plane, which flows on an ice surface at the bottom of a channel and freezes from below. Such an experimental configuration is of scientific interest primarily because of its similarity to all natural icing processes involving the appearance and flow of an aerosol-created water film on an ice surface. The simplifications carried out in relation to the natural icing problem consist in: (i) altering the collection efficiency by applying the corresponding coefficient of the settling of supercooled aerosol particles; (ii) making the shear stress constant lengthwise along the ice-covered bottom of a channel; and, (iii) eliminating the streamwise air pressure gradient. To avoid any inadvertent influence on the ice accretion process, a non-destructive remote sensing technique was applied using an infrared (IR) camera.

THEORETICAL BACKGROUND FOR IR MEASUREMENTS

In our previous studies on atmospheric ice formation on horizontal cylinders (Karev and Farzaneh, 2003), industrial IR pyrometers were used as detectors of electromagnetic waves emitted from the surface under investigation. Such instrumentation, as shown by the results of these studies, is hypersensitive to a number of ambient and geometrical parameters, and mainly to ambient temperature changes. Moreover, calibration adjustment must be made *prior* to taking the measurements by comparing real temperatures, as measured by a reliable instrument such as a thermocouple, with the readout from the IR instrument. The uncertainties in measuring resulted even with 2 ^{o}C errors obtained by using IR pyrometers do not exist for FLIR IR camera SC-2000, for which all ambient conditions, including local emissivity of investigated surfaces, may be adjusted after the IR pictures were taken. The camera covers a 7 to 13 μm spectral range in the long wavelength infrared (LWIR) band which corresponds approximately to an 8 to 14 μm atmospheric window, thus the influence of air humidity, having also been selected between adjustable ambient parameters, is minimal. The seeming problem of angular variation of the IR emissivity of ice and water surfaces in the LWIR band (Rees and James, 1992) may be solved in a simple manner by the adjustment of local emissivity according to the angle of observation using tabulated values of emissivity for different angles. We refer readers to our previous investigation (Karev and Farzaneh, 2003) for an in-depth discussion of all problems arising during the IR measurement of the ice surface temperatures. A greater part of these problems were solved for this particular IR camera.

EXPERIMENTAL SET-UP

The experiments were carried out at the CIGELE atmospheric icing research wind tunnel which is a horizontal closed-loop low-speed wind tunnel with a total length of about 30m, including a 3-m long test section with a rectangular cross-section 0.46m high and 91.5m wide. Ice was prepared in long narrow open channels prior to each run of experiments. Two different channels were used for this purpose. One was longer than the other with a length of 1.22 m, a width of $6.7 \cdot 10^{-2}$ m, and a wall height of $2.5 \cdot 10^{-2}$ m. The length of the second one was 0.91 m, its width was $7.8 \cdot 10^{-2}$ m and its wall height was 7.6 cm, making it possible to deposit thicker ice in it. The channel was placed in the middle of the test section of the wind tunnel 0.12 m downstream of the water supply. This distance was chosen so that the aerosol cloud might reach the edge of the channel and cover it by half of the cross-section. Water was provided by a single water-dispersing nozzle mounted on an aluminum rake that was fixed to the top of the wind tunnel. The temperature of the ice was measured by six T Type thermocouples that were installed right below the surface of the ice and at the bottom of the channel at three different stations, 0.5 cm, 15 cm and 30 cm behind the leading edge of the channel. During the experiments, additional ice accumulated on the surface of the prepared ice, thus the thermocouples no longer provided the exact temperature of the ice surface, which is why a FLIR SC-2000 IR camera was applied in order to measure the temperature of the water layer flowing on the surface of the ice. The infrared camera was placed 60 cm downstream the leading edge of the channel in a box installed on the top of the wind tunnel. This box might be turned such that the angle of camera to the horizontal direction was 45 degrees, and thus, the entire channel became visible in the camera. Three experiments were performed involving different air velocities, V_{a1}=10 ms^{-1}, V_{a2}=20 ms^{-1} and V_{a3}=30 ms^{-1}, while the following parameters were kept constant: temperature of ambient air, $T_a = -15\ {}^\circ C$, temperature of supplied water, $T_w = 2\ {}^\circ C$, and water flow rate, $Q_w = 1.83 \cdot 10^{-5}\ m^3 s^{-1}$. The longer channel was used for the experiments where the air velocity was 10 m/s and 20 m/s, while the shorter one was applied for the case of 30 ms^{-1} speed. The duration of each run was 15 minutes, while the thermocouples provided data at every second, and images were taken by the infrared camera initially every 15 seconds by the end of the experiment increasing to 30 seconds.

RESULTS AND DISCUSSION

Figures 1 and *2* present the temperatures measured at different designated sites in the bulk ice and on the surface of the water film which flowed on the ice surface. It may be seen in the figures that the start of the ice accretion process influences the temperature measured at all six points. The initial surge of heat flux throughout the ice to the bottom of the channel is recognizable by sudden changes in the temperature at any given site. The first two experiments were performed for the ice thickness h=$2 \cdot 10^{-2}$ m, while the experiment with V_{a3}=30 m/s was performed for thicker ice, h=$5.1 \cdot 10^{-2}$ m, so that the heat surge was greater, but the final temperature at the bottom of the channel at the end of the experiment was lower. Such an anomaly in temperature behavior was always observed at the interface between the prepared ice accretion and the bottom of the channel. At this interface, the oscillations of temperature occur at the beginning of the icing process. These oscillations are related to fluctuations in the main direction of latent heat transfer and go from the one occurring throughout the accreting ice layer to the one released into the ambient medium. As the ice accretion develops, the oscillations die down and the entire heat flux is directed towards the ambient medium solely as a result of the low value

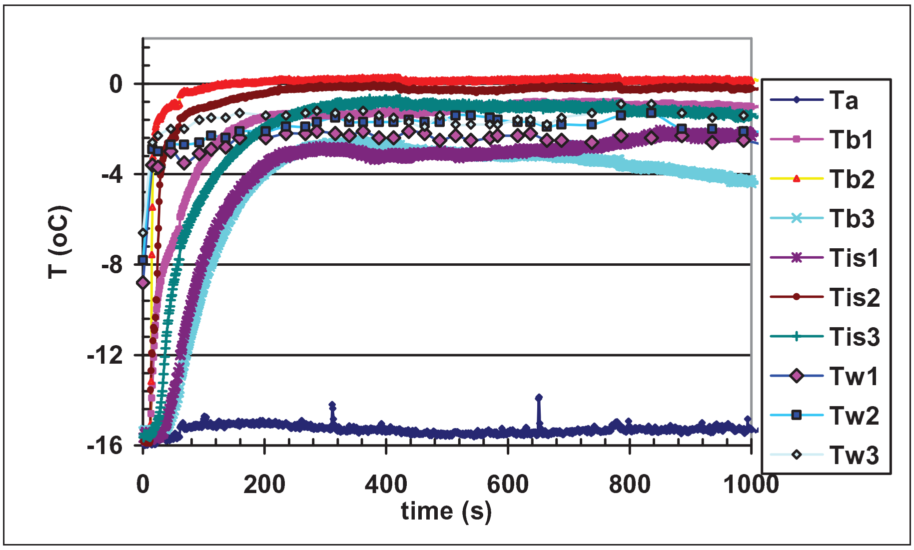

Figure 1. *Typical plot of the temperatures measured by thermocouples and IR camera during the experiment with a small channel and* V_a*=20* $m \cdot s^{-1}$*:* T_a*- air temperature;* T_b*- temperature of bottom of the channel;* T_{is} *-ice surface temperature;* T_w*- temperature of the surface of flowing water measured by IR camera. 1.,2. and 3. designate chosen sites.*

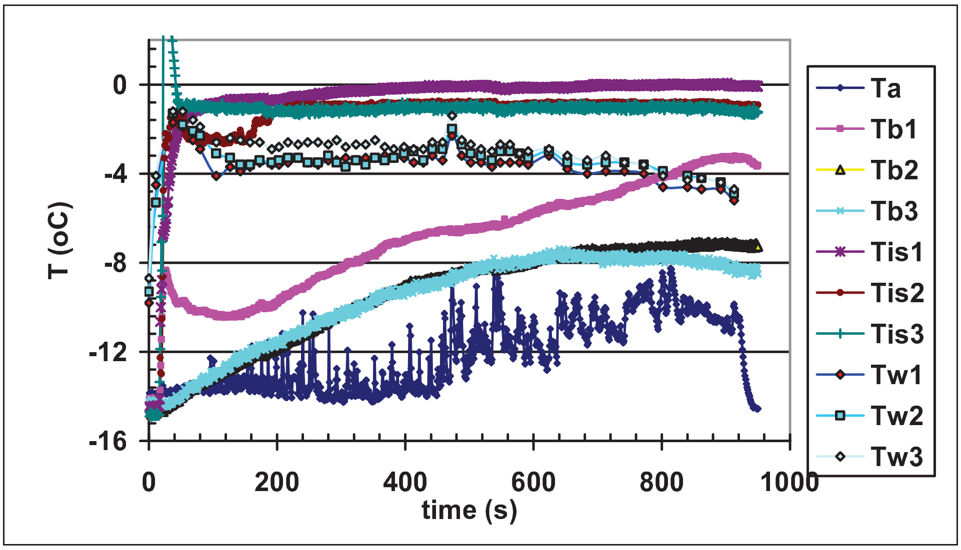

Figure 2. *Typical plot of the temperatures measured by thermocouples and IR camera during the experiment with a large channel and V_a=30 m·s^{-1}: T_a- air temperature; T_b- temperature of the bottom of channel; T_{is} -ice surface temperature; T_w- temperature of the surface of flowing water measured by IR camera. 1.,2. and 3. designate chosen sites.*

of the coefficient of the heat conduction of ice. Consequently, the icing surface, after initial temperature surge, chills gradually to the ambient temperature. The temperature of the ice surface, even under conditions for water film appearance, remains negative at all times throughout the entire ice accretion process. This temperature displays some weak lengthwise distribution from the leading edge of the channel, where the supercooled aerosol is supplied, to its trailing edge, where the water rivulets form and freeze. From the comparison of the two figures, it may be concluded that the supercooling of flowing water film on the surface of ice depends on the air speed: for V_a=30 m·s^{-1} it is about -4 ^{o}C, as compared to the lower supercooling of -2^{o}C obtained whith the air speed of 20 m.s^{-1}. The investigation should be, however, made in the future concerning the role of initial ice thickness.

During the process of ice formation, the local temperature of a supercooled water film changes slightly over time, displaying a final stabilization depending on the given ambient conditions. It was found that heat transfer throughout the water film to the concurrent air flow is a pivotal factor in maintaining a water film on the ice accretion being formed at the bottom of the channel.

CONCLUSIONS

The results of spatio-temporal remote IR and traditional thermometry measurements were presented and discussed in this investigation into the surface temperatures of an ice-covered channel during the process of ice accretion in an icing wind tunnel. It was demonstrated that the surface temperature of accreting ice, i.e. the surface temperature of flowing water film, remains supercooled at all times during the experiment. The lengthwise temperature distribution in bulk ice accreted at the bottom of the channel and in flowing water film was observed and recorded. In spite of the theory (Messinger, 1955) which proposes the assumption, that the surface temperature is 0^{o}C for the icing regime with a water film on the ice surface, the temperatures of water flowing on the surface of prepared ice were negative even when frozen rivulets were observed at the trailing edge of the channel providing evidence of flowing water. It should be noted that the terminology "wet" and "dry" which since the time of Schumann's theoretical work (1938) is usually applied in various models in order to distinguish between the ice accretion icing regimes with and without a water film on the icing surface, has now become obsolete and misleading in the light of further research. Finding an alternative to the contemporary distinction between the two icing regimes mentioned should be the main objective of subsequent research in the physics of atmosphere and atmospheric icing. To date, only one theory (Kachurin, 1962), mentioned in the Introduction, satisfies the requirements, and with certain modifications (Karev et al., 2003a and b), should be tested in future experimental work.

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