# NEW DYNAMIC ASPECTS OF CONTEMPORANEOUS CONCEPTS IN ATMOSPHERIC ICING MODELLING

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## ABSTRACT

This article addresses several heretofore unexplored aspects of modern concepts in the theory of atmospheric ice accretion on the surface of a test body placed within a supercooled aerosol cloud. The air velocity of a flowing aerosol cloud in experiments carried out in an icing wind tunnel is considered as a vector which forms angles with the cylinder axis in the vertical plane passing in both streamwise and lateral directions. This complicates both momentum- and heat-transfer from the icing surface, introducing different types of water film instabilities and modifying the accreting ice mass. Under conditions modeling freezing rain (ZR) and in-cloud icing (CI), the ice mass accreted on the experimental cylinder oriented streamwise was always found to be smaller than the mass accreted on the cylinder oriented perpendicular to air flow.

## INTRODUCTION

All contemporaneous icing theories make use of a cylindrical body set horizontally with its axis perpendicular to a supercooled aerosol flow. Such a spatial disposition leads to a frequently used tendency of simplifying natural icing processes by presenting them in a two-dimensional (2-D), mostly circular form. Under extremely cold ambient conditions, when aerosol droplets freeze upon contact with the icing surface without spreading over it, a simplified 2-D representation of the icing process for theoretical and experimental

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investigation is recommended. Such a step would save computation time and would not forego any significant feature of the process, provided the spatial uniformity of the LWC of the aerosol cloud in the experiment is preserved. The 2-D consideration fails, however, under ambient conditions favorable to the appearance of a supercooled water film on the surface of a growing ice accretion, since the dynamics of this film, which is pivotal to heat- and mass-exchanges, is not adequately addressed. If the cylinder axis forms some angle streamwise of the aerosol flow in the horizontal or vertical planes, thereby setting the water film in motion under the influence of air flow or gravity, then additional aspects will appear of the ice accretion process occurring underneath the flowing film. This type of complex flow does not resemble accepted notions of water film flow in icing models. Examples of simplified concepts of water film flow in icing models include: (i) circular flow around the cylinder concurrent with strong air flow, as in water run-back models of icing of a non-rotating horizontal cylinder (Kachurin, 1974; Lozowski et al., 1979); (ii) circular flow counter-current to a weak air stream on the upper half of the cylinder towards the lower half, as in models for pendant ice formation (Szilder and Lozowski, 2000); (iii) lengthwise on a vertical cylinder, as in current models for ice sponginess (Blackmore et al., 2002). In the second instance, by excluding airflow influence and considering gravity only by reformulating the 2-D problem of water flow in the vertical plane passing through the cylinder axis, it is possible to define icicle spacing (de Bruin, 1999; Farzaneh et al., 2003) as a feature affected by the *Rayleigh-Taylor instability* between the layers of two fluids of different densities (Taylor, 1950). In this experimental sequence, the icing body is a non-rotating cylinder tilted with the horizontal plane either streamwise or lateral to the air flow. The corresponding water film flow is, thus, a combination of the three simple types presented earlier. Based on theoretical considerations, the introduction of an additional flow of one of the two superposed fluids, at a relative horizontal velocity, would create a different type of oscillation, the *Kelvin-Helmholtz instability* at the boundary between the fluids (Chandrasekhar, 1961). By introducing the thermal factor as a uniform transverse temperature gradient, *thermocapillary instability* (Chandrasekhar, 1961) would arise. Furthermore, in a flowing transitional water film, the introduction of heat transfer from below would result in stabilizing laminar flow due to an increase in the *indifference Reynolds number* (Strazisar et al., 1977). The issue of water flow on icing surfaces is, thus, more complex than it seemed initially. The main goal of this investigation is to evaluate the potential significance of water flow direction in the final mass and shape of ice accretions for different inclined angles of a cylinder.

A subsidiary goal is imposed by the different droplet size distributions (DSD), and by different manners of water supply to the icing surface in three atmospheric icing phenomena: in-cloud icing (CI), freezing drizzle (ZL) and freezing rain (ZR). In the cloud droplet range, which is set at droplet diameters of 10 μm to 50 μm (Jeck, 1996), the droplets are not generally affected by gravitational forces and may float or be wafted by in-cloud main drafts in any direction. Since horizontal movements in stratified winter clouds predominate, the CI may be successfully modeled in a wind tunnel by the horizontal flow of a supercooled aerosol cloud streaming over an experimental cylindrical body set in any position. In the ZR droplet range, which covers diameters from several tens of microns to several millimeters, the droplets are already noticeably affected by gravitational settling. Thus, the vertical component of rain droplet velocity may be considered a major factor during the impinging and spreading of droplets on an icing surface, to be taken into account throughout experimental modeling. The factors promoting drizzle production should exist during formation and development of the ZL droplet range which forms a part of the ZR range (Jeck, 1996) and which conventionally covers diameters from 50 μm to 500 μm. Since the presence of air turbulence or wind shear is one of those drizzle-promoting factors, either of two the manners of supercooled water supply to an icing surface mentioned earlier may be considered in ZL. This simplified division of droplet cloud ranges and the categorization of types of water supply to an icing surface cannot be other than conventional, since air turbulence or wind shear may exist in all three ice-producing phenomena, depending on prevailing thermodynamic conditions. The preceding categorization contributes, however, to defining a second goal of this research: to investigate how the obvious differences in (i) DSD within a droplet cloud of various ice-producing phenomena, and, (ii) the application of corresponding manners of water supply, influence the results of experimental modeling of icing on an inclined cylinder.

## EXPERIMENTAL SET-UP

### Facilities and Designing of Experiments

The experiments were carried out at the CIGELE atmospheric icing research wind tunnel, a horizontal closed-loop low-speed wind tunnel 30 m total length, including a 3 m test section with a rectangular cross-section 0.46 m high and 0.915 m wide. For this series of experiments, special devices were designed to fix the experimental cylinder rigidly in various inclined positions either perpendicular or streamwise to aerosol flow direction. Cylinder dimensions were 0.915 m in length and $3.81 \cdot 10^{-2}$ m in diameter.

Two means of water supply were applied in this investigation. The first was a standard single spray-bar system with three air-assisted nozzles mounted at the tunnel center-line, and 0.2 m left and right of this line. The system modeled CI by producing an aerosol cloud with a DSD characterized by a median volume droplet diameter (MVD) of approximately 30 μm. Regular tap water at room temperature was used for atomization 4.4 m upstream from the icing cylinder, which is sufficient for droplets several tens of microns in diameter of to cool down to ambient air temperature and even slightly lower due to the relative humidity factor. The liquid water content (LWC), $w$ ($g \cdot m^{-3}$), of the modeled aerosol cloud was kept constant throughout all experiments. The second means of water supply, for modeling ZR, was a single water-dispersing nozzle mounted on an aluminum rake attached to the ceiling of the test section and movable horizontally. The nozzle produced a droplet cloud with an ellipsoidal cross-section and a wide spectrum of droplet sizes as shown by a MVD of approximately 400 μm. Under corresponding ambient conditions, for the larger droplets in the DSD the distance from the ceiling to the icing object is not sufficient for any significant cooling if the water at room temperature is used. This fact involves working with a commercially designed machine manufactured by CIMCO and capable of cooling flowing water down to 1-2 $^{o}$C. The water flow rate in the entire series was kept constant at 0.9 l/min. The temperature of the water used in this dispersing system was, thus, deemed a significant parameter and measured by an Omega T Type thermocouple at a distance of $2.54 \cdot 10^{-2}$ m from the nozzle edge inside the water line. The same type of thermocouple was used for measuring the air temperature.

**Selecting Experimental Conditions**

In order to maintain constant the influence of the thermal or dynamic factors mentioned in the introduction, it was decided to keep air temperature, $T_a$ ($^{o}$C), and air speed, $V_a$($m \cdot s^{-1}$), constant at $T_a$=-10 $^{o}$C and $V_a$=20 $m \cdot s^{-1}$ throughout the experimental series. This choice was dictated mainly by the potential for adequately modeling ZR in this icing wind tunnel configuration, which the frequently used value of air temperature for ZR $T_a$=-5 $^{o}$C did not originally allow. Jeck (1996), however, reported that the value $T_a$=-10 $^{o}$C is also fairly frequent in ZR, especially when it occurs aloft. The LWC of a flowing aerosol cloud should be in a range which covers the water supply rate characteristic of natural CI conditions (up to 1.3 g·m$^{-3}$), but one of the goals of this research involves the application of the same thermodynamic conditions ($T_a$ and $V_a$) for both the icing phenomena modeled: CI and ZR. With a pre-chosen $T_a$=-10 $^{o}$C for modeling ZR, the LWC should be at least doubled to obtain flowing water effects similar to those for $T_a$> -5 $^{o}$C. The chosen value for LWC of 3.2 g·m$^{-3}$ for experimental modeling of CI may seem unrealistic since it approaches the range of the LWC for convective clouds. It may be simply shown, however, that the pair of variables chosen for these experiments ($w$=3.2 g·m$^{-3}$; $T_a$= -10 $^{o}$C) will have the same effects on the formation of excess water on an icing surface as the pair representing natural conditions ($w$<1.3 g·m$^{-3}$; $T_a$> -5 $^{o}$C). The duration of each experimental trial was set at a constant 15 minutes.

## RESULTS AND DISCUSSION

### Experimental Output

The following data were collected as the output of the experimental series: (i) ice mass per unit of cylinder length, d$M$/d$l$ (g·cm$^{-1}$); (ii) ice shape; (iii) state of ice surface and size of surface roughness elements; (iv) ice accretion profiles along the cylinder length. A thin preheated aluminum cutter was used to cut the ice specimens for weighing. The selected length and position at which all data were collected were 10.2 cm left and right of the cylinder centre. Ice shape and the size of surface roughness elements were examined through digital photography of ice specimens extracted from various locations. Ice accretion profiles were collected in two ways: by drawing the profiles manually on cardboard and by processing the data gathered from photographs of the profiled specimens. Only the ice mass data will be presented due to a shortage of space.

### Mass of Modeled In-cloud Ice Accretion

The data presented in *Figure 1a* were obtained through experimental modeling of CI of a horizontal cylinder set at different orientations relative to a flowing supercooled aerosol cloud. The results of two different series of experiments with an inclined cylinder are presented: (i) a variable inclined angle, $\alpha$, formed between the horizontal plane and the axis of the cylinder set perpendicular to the air flow; and, (ii) a variable inclined angle, $\beta$, formed between the horizontal plane and the axis of the cylinder set parallel to the air flow. In the first series, the experiments were carried out for an inclination to the right hand side only, assuming that symmetry exists around the centerline of the test section. In the second series, the inclination of the icing cylinder was examined on both sides. Conventionally, the positive inclined angle $\beta$ corresponds to the exposure of the lower half of the experimental cylinder to the air flow, while the negative inclined angle $\beta$ corresponds to the exposure of the upper half to the air flow. An interesting finding emerges from the series with the inclined cylinder set perpendicular to the aerosol flow: a maximum of ice growth mass appears for a small inclined angle formed between the axis of the cylinder and the horizontal plane. This effect may be ascribed to the increased mass transfer of supercooled water on the surface of the cylinder from the raised edge to the center due to gravity. For the combination of thermodynamic parameters used in the entire series of experiments, this inclined angle, which is optimal for the redistribution of water on an icing surface, was found to be around $\alpha \approx 8^o$. As compared to the standard experimental configuration of a horizontal cylinder, *i.e.* for $\alpha = 0^o$, this positioning brings about an 11%-increase in ice mass. If the inclined angle is greater than this, the effects of gravity dominate over the effects of air shear stress, and the mass of the local ice accretion decreases, since the excess water flows faster along the cylinder. It may be assumed that for other combinations of thermodynamic parameters, the maximum of ice mass may be obtained for various inclined angles. The shapes of ice pendants in the experiments with inclined cylinders are also considerably different compared to standard configuration, while the variety of their shapes increase, when $\alpha \approx 8^o$. The same may be said about roughness elements since their shape and volume seem to reach maximal development for this configuration. With a further increase in the inclined angle, the variety of roughness elements and ice pendants decreases considerably, and a certain amount of uniformity in their distribution may be observed. The shape of ice accretions, however, will never be similar to the ones obtained for standard cylinder orientation. The closer the orientation of the cylinder is to standard orientation, the more uniform the shapes of ice accretions along the cylinder are. A further conclusion, which may be drawn from the study of *Fig. 1a*, concerns the potential minimum of ice mass for the cylinder parallel to the aerosol flow. In this series, experiments with $\beta = 0^o$ were not carried out due to the possible influence of cylinder support on the results of experimental modeling. The low minimum may be assumed for this position, however, as regards the gravitational droplet settling process even for the air speeds accepted in this series. All ice accretions for the grazing angles investigated here have the shape of white feathers as observed on cylinders with a standard orientation at some angle from the stagnation line, since effective LWC in such a position is relatively low. The series of experiments for

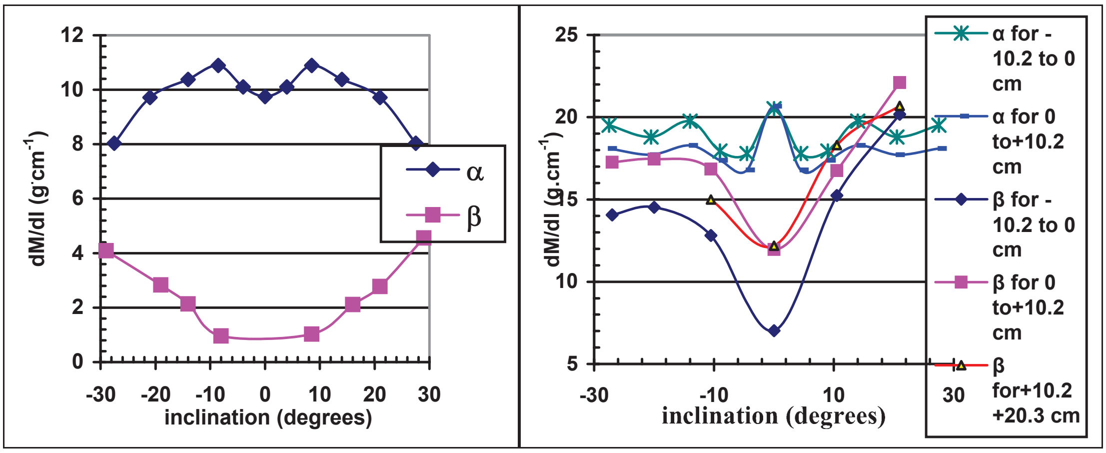


**Figure 1.** *Ice mass obtained with the inclined cylinder for a) CI (left); and b) ZR (right)*

$\beta$=29$^{o}$ was repeated for doubled LWC and a higher air temperature, $T_a$=-5$^{o}$, to attain conditions with water flowing on the cylinder surface. The results, however, were always negative. From *Fig. 1a* it is clear that the ice mass increases with the increase of angle $\beta$ in the whole range of measurements for positive and negative angles starting from $\beta$=0$^{o}$, i.e. there is no maximum. A further difference between the two sets of results presented in *Fig. 1a* is that there is no symmetry around $\beta$=0$^{o}$, the mass increase with the increase of $\beta$ occurs more rapidly if the lower half of the cylinder is exposed to the flow.

**Mass of Ice Accretion during Freezing Rain Modeling**

*Fig. 1b* presents the results obtained for the second type of water supply to the cylindrical icing surface for modeling ZR conditions with a single water-dispersing nozzle mounted on an aluminum rake. The same two sets of cylinder orientation were used in the experiments, as shown in *Fig. 1a*. The temperature of cooled water in the nozzle kept constant between 1.2 and 1.8 $^{o}$C. For the perpendicular cylinder orientation with a variable $\alpha$ angle, results are very similar to those obtained for modeling CI and presented in *Fig. 1a*, except for $\alpha$=0$^{o}$, which will be the subject of additional investigation at a later date. One surprising result of the research is the dependence of ice mass on the inclined angle $\beta$ as found for the streamwise orientation of a cylinder. In spite of a significantly different type of water supply, as compared to the double series modeling CI (*Fig.1a)*, and the different type of ice deposit observed in both cases, the dependence of ice mass on the inclined angle is remarkably similar for both the icing phenomena modeled. There is a minimum of ice mass at 0$^{o}$ inclined angle with two increasingly divergent branches for positive and negative $\beta$. Furthermore, as in CI modeling, the increase of the mass for positive $\beta$ angles is steeper than that for the negative $\beta$. This difference is even more striking than in the case of CI.

## CONCLUDING REMARKS

The dependence of ice mass accreted on an inclined cylinder on the inclination angle to the air flow was investigated by modeling CI and ZR conditions. In spite the different types of water supply and the different DSD used to model both icing phenomena, as well as different ice accretion shapes obtained for a streamwise oriented cylinder, a distinct resemblance exists between both sets of results as regards the dependence of ice mass on the inclined angle. Furthermore, ice mass accreted on the inclined cylinder oriented perpendicular to the air flow is mostly greater than the mass accreted on the inclined cylinder oriented streamwise, at least for the range of inclination angles used in this investigation. The dynamics of water film flow should be scrutinized in depth (3-D) to explain theoretically the results obtained. A further dynamic aspect to be investigated at a later date may be related to the varying directions and absolute values of the air velocity.

## ACKNOWLEDGMENTS

This study was carried out within the framework of the NSERC/Hydro-Quebec Industrial Chair on Atmospheric Icing of Power Network Equipment (CIGELE) at the University of Quebec in Chicoutimi. The authors would like to thank all the sponsors of the CIGELE for their financial support. Valuable help provided by CIGELE technician P.Camirand in designing and manufacturing devices for this experimental series is also gratefully acknowledged. We are also most grateful to M. L. Sinclair for editorial assistance.

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