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**AN EXPERIMENTAL ASSESSMENT OF SCALING
PARAMETERS FOR SELECTING VELOCITY IN ICING
WIND TUNNEL TESTS**

by

**Telamon McCullough
B.A.Sc.**

**A thesis submitted to
The Faculty of Graduate Studies and Research
in partial fulfillment of the requirements for the degree of
Master of Applied Science**

**Ottawa-Carleton Institute for
Mechanical and Aerospace Engineering**

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Chair,
Department of Mechanical and Aerospace Engineering

Thesis Supervisor

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June 5, 2001

ABSTRACT

This thesis documents icing wind tunnel tests carried out to assess scaling laws required to correctly simulate in-flight ice accretion on aircraft. In-flight icing occurs when supercooled water droplets impinge and freeze on an aircraft surface, seriously affecting flight safety and performance. Two differently sized NACA 0012 airfoils were tested in the National Research Council of Canada's Altitude Icing Wind Tunnel (AIWT), to investigate the validity of scaling parameters based on the behaviour of surface water present in glaze ice accretion. The ice shapes produced in the AIWT were also compared to ice shapes produced on a similarly sized airfoil under nominally the same conditions in the NASA Icing Research Tunnel. This inter-tunnel comparison resulted in noticeably different ice shapes. The scaling parameter investigation was inconclusive and indicated that a more accurate ice-shape tracing method is required. The errors in the tracing technique were comparable to the ice shape variations produced by the different scaling parameters, obscuring the effects of the scaling parameters on the ice shape.

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NOMENCLATURE

A	Sensible to latent heat ratio
A_c	Accumulation parameter
B	Convective to latent heat ratio
b	Relative heat parameter
c	Chord length
c, λ	Trajectory parameter constants.
Ca	Capillary number
C_D	Drag coefficient
C_f	Skin friction coefficient
C_p	Pressure coefficient
C_{pu}	Specific heat capacity of air at constant pressure
C_w	Specific heat capacity of water
D	Diameter of body nose region
d	Droplet diameter
dy_o, ds	Spacing between droplets at point of release and on the surface
$\bar{D}$	Drag vector
$\bar{D}_{stokes}$	Drag vector due to Stokes' law
h_c	Convective heat transfer coefficient
h_{fg}	Latent heat of vaporisation
h_{fs}	Latent heat of fusion
h_{sg}	Latent heat of sublimation
K	Inertia parameter
$\bar{K}$	Droplet trajectory parameter
L	Characteristic length
LWC	Liquid water content
M	Mach number
m	Droplet mass
$\dot{m}_{imp}$	Mass flow rate of impinging water droplets
$\dot{m}_r$	Mass flow rate of runback surface water
MVD	Droplet mean volume diameter
n	Freezing fraction
n_o	Freezing fraction at the stagnation point
p_∞	Ambient air pressure
$p_{vap,s}$	Vapour pressure at the ice surface
$p_{vap,\infty}$	Vapour pressure in the freestream
q_c	Heat loss through convection
q_e	Heat loss through evaporation
q_k	Heat gain through kinetic energy of incoming droplets
q_f	Heat gain through the release of latent heat of fusion

q_w	Heat absorbed by incoming water droplets
r	Recovery factor
R	Ideal gas constant
Re	Reynolds number
Re_{rel}	Reynolds number based on relative velocity
Re_U	Reynolds number based on freestream velocity
t	Time
T_o	Stagnation temperature
T_r	Recovery temperature
T_s	Surface temperature
t_w	Surface water film thickness
T_∞	Ambient static air temperature
t'	Non-dimensional time
U_a	Air speed
U_d	Droplet Speed
u_w	Mean velocity in surface water film
U_∞	Freestream air speed
$\bar{U}_a$	Air velocity
$\bar{U}_d$	Droplet velocity
$\bar{U}_a'$	Non-dimensional air velocity
$\bar{U}_d'$	Non-dimensional droplet velocity
V	Impingement volume
We	Weber number
We_d	Weber number based on droplet diameter
We_L	Weber number based on chordlength
We_t	Weber number based on surface film thickness
$\bar{x}$	Position vector
$\bar{x}'$	Non-dimensional position vector
α	Angle of attack
β	Collection efficiency
γ	C_p/C_v for air
θ	Position angle on the body
ρ_a	Density of air
ρ_i	Density of ice
ρ_w	Density of water
μ_w	Absolute viscosity of water
μ_a	Absolute viscosity of air
σ	Surface tension at air and water interface

1 INTRODUCTION

This thesis documents an experimental investigation into scaling laws for icing wind tunnel tests, which are intended to simulate in-flight ice accretion on aircraft, at a reduced scale.

Ice accretion is the accumulation of cold water droplets freezing onto a cold surface. The ice steadily builds on itself creating complex structures with time, even when they begin as very simple shapes or if they accrete on simple structures. The structures, on which ice forms, can be any objects located in a humid and cold environment, such as power lines, ships, exterior structures and aircraft components (see Figures 1.1 to 1.4).

In-flight icing is a manifestation of the aforementioned ice accretion, while aircraft are in flight. The water source is supercooled liquid water droplets suspended in clouds, which remain supercooled as long as there are no particles available to act as freezing nuclei (Wagner et al., 1997). As aircraft pass through these clouds, the water droplets impact the surface. Typically the surface temperature is below freezing, causing the droplets to nucleate and freeze on the aircraft. These droplets generate ice structures

on the leading edges of wings, engine inlets, propellers, tail sections and fuselage. This has serious implications for flight safety.

The accumulation of ice affects aircraft aerodynamics, stability and control, can cause engine damage and adds weight. The ice structures alter the aerodynamics by altering the size, shape and roughness of the lifting surfaces. This causes a decrease in available lift and an increase in drag (increasing fuel consumption and lowering airspeed), seriously affecting safety and performance. More importantly, ice accretions substantially increase the stall speed. This seriously degrades flight safety, especially if the pilot is unaware of the problem or of its severity, because the minimum speed at which the aircraft can remain airborne is substantially increased.

Furthermore, ice accretion on control surfaces affects the stability and control of the aircraft, creating a significant hazard. Especially susceptible to icing are helicopters, which operate at more icing-prone altitudes than other aircraft and whose rotor blades sweep through relatively large distances. Finally, accumulation near the engines is a twofold hazard. Not only does the ice affect the streamlines near the inlets, which may cause inefficiencies, stall, surge or even flame-out, but any ice that releases from the nacelles may be drawn into the engine and cause serious damage to the compressor or fan blades.

Due to the hazards associated with in-flight icing, aircraft designs must pass through stringent tests before being approved. One method of accumulating icing data is through flight-testing. This is dangerous, costly and time consuming, but is also unreliable as it depends on correct weather conditions. The alternatives are icing wind tunnel testing and computer modelling. Insufficient knowledge of ice accretion physics contributes to limited success in computer modelling. This leaves icing wind tunnel testing. Since, however, large-scale icing wind tunnels would be very difficult and costly to cool, full-scale tests are often impractical; reduced scale modelling is thus attractive. Unfortunately, not all the relevant scaling parameters are known, which undermines the reliability of reduced scale experiments in icing wind tunnels. This thesis work continues

investigations into relevant scaling parameters and also compares icing test results from two different icing wind tunnels on similar sized NACA 0012 airfoils.

The method used to examine various scaling parameters was to test two NACA 0012 airfoils of different chord lengths, the larger one serving as a reference model and the smaller one as a subscale model. The subscale model was exposed to a number of different conditions selected by matching the established scaling parameters plus one of a number of candidate scaling parameters to select airspeed. The best match between the reference and subscale ice shapes would indicate the best of the candidate parameters for selecting airspeed. Also created in the testing process were profiles of the reference runs that could be compared to runs under supposedly identical conditions on a similar airfoil in the NASA Icing Research Tunnel (IRT). All experiments were performed at the Altitude Icing Wind Tunnel (AIWT) facility at the National Research Council of Canada (NRC).

Chapter 2 of this thesis presents a background to ice accretion and a literature review of the subject, focusing on in-flight icing. Chapter 3 provides a review of similarity requirements and non-dimensional parameters relevant to icing. Chapter 4 presents the experimental method, the design of the models used and the experimental procedures used in the present work. Chapter 5 presents the experimental results and a discussion. Chapter 6 presents the conclusions drawn from the test results and Chapter 7 puts forward recommendations for future experiments in this area.

2 BACKGROUND AND LITERATURE REVIEW

This chapter provides background information on in-flight ice accretion, covering the icing process, ice types and recent developments in the field.

2.1 THE IN-FLIGHT ICING PROCESS

Water droplets are often suspended in cloud formations in a supercooled state. Liquid water may easily exist at ambient temperatures below freezing provided there is an absence of a freezing nucleus (Wagner et al., 1997), hence, water may exist at a supercooled liquid state for extended periods of time. When an aircraft passes through a cloud, the droplets deviate from the airflow streamlines if the inertial forces are large enough (Wagner et al., 1997). The drops will then impact the aircraft surface, which acts as a freezing nucleus. The droplets immediately lose their supercooled state and freeze partially or completely onto the surface (Kind et al., 1998 a). Latent heat of fusion is released from the droplets, tending to heat the ice and the surface, or substrate, beneath it. As steady state is reached, however, virtually all the heat is transferred to the ambient air. Heat is simultaneously removed by convective and evaporative heat transfer (Messinger, 1953).

The temperature of the impact area is affected by the rate of latent heat released by freezing and by the rate of heat lost by convection and evaporation to the air. The liquid water content (*LWC*), which is the mass of water per unit volume of air, determines the quantity of latent heat that can be released. Consequently, it partly determines the accumulation of ice and the fraction of the impinging droplets that will freeze completely. The ratio of droplet mass that freezes upon impact to total droplet mass that impinges on the surface was termed by Messinger in 1953 as the freezing fraction. A high *LWC*, which supplies more latent heat than can be removed, coupled with an ambient temperature only slightly below freezing, makes for a low freezing fraction (Wagner et al., 1997). That is, only a fraction of the impinging liquid water freezes and there is liquid water present on the ice-accretion surface. With a high airspeed and a low static air temperature, the convective heat transfer increases. Combining this with a low *LWC*, forces the freezing fraction to unity (Wagner et al., 1997). In other words, all the droplets freeze immediately on impact.

Finally, any ice particles that are suspended in the air do not appear to affect the accretion. They seem to bounce off any solid surface they encounter (Wagner et al., 1997).

2.2 ICE ACCRETION TYPES

Ice accretion may be divided into three main categories, based on appearance and the necessary conditions to create them. They are rime, glaze and mixed ice. Using Ruff's classification (1986), they can also be separated according to freezing fraction. For freezing fraction equal to 1.0, where both ambient air temperature and *LWC* are low, rime ice occurs. Glaze ice on the other hand, occurs for freezing fraction less than about 0.3, with a high *LWC* and near freezing temperatures. Finally, for freezing fractions between 0.3 and 1.0, mixed icing occurs, which incorporates characteristics of both glaze and rime icing. The following three sections will describe the three icing conditions in more detail.

2.2.1 Rime Icing

Rime ice occurs when the freezing fraction equals unity, that is all droplets freeze completely when and where they impinge upon the surface. The required conditions are a low temperature and a low *LWC*. This allows the rate of convective heat transfer away from the impact region to equal the rate of heat released by the latent heat of fusion (Hansman, 1992). As all the water droplets freeze completely at the impact point, computer simulation of rime icing is relatively easy (Kind et al., 1998 a). Characteristics of rime ice (Figure 2.1) are a white, opaque appearance, with an aerodynamically shaped profile (Ruff, 1986). Originally, this white opaque colour was attributed to air pockets being trapped between rapidly freezing water droplets; however, investigations by Macklin (1962) suggest that air bubbles dissolved within the liquid droplets are trapped upon freezing.

Feather formation is common in rime icing and can also occur in glaze icing. Feathers are an example of localised rime icing, where crystalline structures grow normal to the surface or into the flow as more droplets impinge on them. With time, these feathers merge to form larger, brittle structures. Feathers appear to grow when protrusions penetrate into the turbulent boundary layer. The tops of these protrusions see higher local velocity and a higher local collection efficiency, β , than the surrounding surface. This higher velocity results in a higher convective heat transfer coefficient at the top of the protrusion; combined with higher β , this results in rapidly growing localised ice formation called feathers.

2.2.2 Glaze Icing

Glaze ice occurs when the freezing fraction is substantially less than unity; hence, there is a substantial quantity of water that remains unfrozen on the surface after impacting the substrate. In this case, the rate of convective heat transfer is lower than the rate of latent heat that would be released if all of the impinging water froze immediately

upon impact. Much of the liquid water on the surface runs back in rivulets and freezes further downstream, where the convective heat transfer is greater and impingement is less (Wagner et al., 1997). This is known as runback ice and is responsible for the formation of horns (Hansman et al., 1993). Horns are an accumulation of runback ice in the off-stagnation zones where there is increased roughness and thus increased convective heat loss. The lower freezing fraction in glaze icing strongly influences the ice appearance, as any dissolved air can be released more readily from the droplets through a slower freezing process (Macklin, 1962). Hence, the appearance of glaze ice is clear and rough (Figure 2.2).

Computer simulations of glaze icing have met with many obstacles. Computer simulations of rime icing rely on tracking the particle trajectories to the point of impingement and freezing, and then accreting new particles on top of frozen ones to predict the ice shape (Wagner et al., 1997). In the case of glaze icing, where there is incomplete freezing and possible runback, the aforementioned accretion and shape prediction methods are insufficient. There is no guarantee that the droplets will remain where they impinge; hence the computer codes must be modified to incorporate water motion on the surface, rivulet flow and surface film dynamics (Bilanin, 1991). To date, computational simulations have not been successful in dealing with this behaviour and experiments are the most reliable method of predicting and recreating ice shapes (Kind et al., 1998 a). Furthermore, it is still unclear as to whether all the impinging water freezes on the wing, or whether some splashes or separates from the surface and is carried downstream (Bilanin, 1991).

Although not as prevalent as in rime icing, feathers do occur in glaze icing. As the feathers merge to form larger structures, voids are left near the roots of adjacent feathers causing the bulk density of the feather accretion to be lower than that of glaze ice. These gaps are subsequently filled by runback water, which increases the bulk density of the ice.

2.2.3 Mixed Icing

Mixed ice accretion occurs for stagnation-point freezing fraction between approximately 0.3 and 1.0 and displays characteristics of both glaze and rime icing (Ruff, 1986). The glaze ice occurs in regions of relatively high β and/or low convection, whereas rime ice occurs elsewhere on the surface (Hansman et al., 1993). In mixed icing neither LWC nor ambient air temperatures are in one extreme or the other. Initial characteristics of mixed icing are clear glaze ice in the stagnation region and opaque rime ice in off-stagnation regions; however, as the accretion progresses, the general appearance near the boundary layer transition becomes one of clear and opaque ice streaks (Hansman et al., 1993). The course of accretion begins with unfrozen water running back in rivulets to regions of higher heat transfer. In the transition region, the convection is high enough to freeze the water, creating nucleation points, that promote feather growth. Unlike rime ice, where the feathers are brittle and often closely spaced, the nucleation density is low, meaning that the feathers are widely spaced. The gaps at the roots are filled by runback water (Hansman et al., 1993). As feathers are a form of rime ice and runback is glaze ice, the result is a streaked appearance (Olsen and Walker, 1986).

2.3 RECENT DEVELOPMENTS

2.3.1 Surface Water Effects

Recent investigations indicate that the runback water in glaze icing strongly affects the ice shape. Close-up video experiments by Olsen and Walker (1986) and Hansman et al. (1993) have observed a liquid water film in the stagnation region, which separates into individual beads that are carried downstream and freeze. These beads act as roughness elements that increase the heat transfer coefficient and cause formation of horns and feathers. Hansman et al. (1989) have speculated that these roughness elements have a direct influence on the location of boundary layer transition. Hansman et al. (1993) have further observed the presence of rivulets from the runback water, which may

affect transition in a similar manner as the roughness elements are assumed to do. Furthermore, both Bilanin (1991) and Bilanin and Anderson (1995) present splashing of droplets on the surface as an important consideration. These three observations all suggest that both surface tension and water viscosity are important. Bilanin and Anderson (1995) confirmed the influence of surface tension by adding a surfactant to the spray, while Kind et al. (1998 b) investigated the importance of water viscosity to glaze and mixed ice accretion on the basis of experiments using a water-propanol solution in the spray.

2.3.2 Effects of the Substrate Material

Hansman and Turnock (1989) found that the ice accretion shape differs very little between aluminum cylinders of different surface roughnesses. Of the cylinders tested, one had a knurled surface, while the other had a highly polished surface. A further investigation by Hansman and Turnock revealed that thermal properties of the substrate material also plays only a very small role, by testing a thin-walled aluminum cylinder and a solid Plexiglas cylinder, which produced very little difference in the ice accretions. The explanation offered by Hansman (1992) is that for most icing conditions there are initial brief transient rime ice growths on the surface, caused by heat conduction into the substrate. This rime ice layer then acts as a thermal insulator, causing insensitivity to substrate properties and any further accretion builds on the ice surface, independent of the surface roughness or thermal properties of the substrate.

Anderson and Shin (1997) also tested the effect of the initial ice layer on subsequent accretion, by testing one set of conditions for 30 seconds and subsequently changing the tunnel conditions for the remainder of the test. The 30-second accretion had very little effect on the ultimate ice shape. Anderson and Shin's observations are similar to Hansman's observations. After the 30-second ice accretion, the surface is insulated by a short period ice layer, which is not large enough to affect subsequent accretion, but is large enough to insulate against substrate properties.

Additional evidence that substrate properties do not affect the final ice accretion is presented by Kind and Oleskiw (2001), who ran tests using solid aluminum and Plexiglas cylinders. The resulting ice accretions did not differ significantly.

3 ICING SCALING LAWS AND NON-DIMENSIONAL PARAMETERS

The following sections outline various scaling practices used in icing tests. The focus is on glaze icing, where the impinging water does not freeze immediately upon impact. The Messinger heat transfer equations are described to explain some aspects of the ice accretion process in detail. An attempt at deriving a scaling method through the Buckingham- π theorem is described, which illustrates some important scaling parameters. Finally, more recent and successful methods are explained to identify the logic behind the experiments conducted in the research leading to this thesis.

3.1 MESSINGER THERMODYNAMIC MODEL

The Messinger model (1953) is the backbone of ice accretion analysis. The model is not a scaling method, but it deals specifically with the thermal energy balance in ice accretion, and is therefore a very useful tool to discuss the physical process. The model is based on an energy balance between the heat added to and removed from a control volume on the accreting ice surface. The underlying surface is assumed to behave adiabatically and radiation heat transfer is neglected since it is small compared with other contributions to the energy balance. Figure 3.1 illustrates the process and indicates the heat transfer mechanisms. The mechanisms for heat addition are:

- 1) kinetic energy of the incoming droplets

$$q_k = \dot{m}_{imp} \frac{U_{\infty}^2}{2} \quad (3.1)$$

where $\dot{m}_{imp}$ is the impingement mass flow rate per unit surface area covered by the control volume and U_{∞} is the freestream airspeed.

- 2) release of latent heat of fusion, h_{fs} , upon freezing of the incoming droplets and runback water

$$q_f = (\dot{m}_{imp} + \dot{m}_r) n h_{fs} \quad (3.2)$$

where n is the local freezing fraction and $\dot{m}_r$ is the runback mass flow rate per unit area.

The mechanisms for heat removal are:

- 1) convective heat transfer from the surface to the air

$$q_c = h_c (T_s - T_r) \quad (3.3)$$

where h_c is the convective heat transfer coefficient, T_r is the recovery temperature and T_s is the surface temperature ($T_s = 0^\circ\text{C}$ in the case of glaze icing). The recovery temperature is the air temperature that would be produced on an adiabatic surface, due to viscous effects.

$$T_r = T_{\infty} + \frac{r U_{\infty}^2}{2 C_{pa}} \quad (3.4)$$

Here r is the recovery factor. The recovery factor accounts for the irreversibilities and heat transfer in the boundary layer when the air is decelerated by viscous shear stresses near the surface. By definition,

$$r = \frac{T_r - T_\infty}{T_o - T_\infty} \quad (3.5)$$

where T_o is the stagnation temperature of the air. Note that in the low-speed case, T_r reduces to T_∞ . In the high-speed case, however, if T_∞ is close to T_s , T_r may be higher than T_s reversing the direction of heat transfer. If $T_r > 0^\circ\text{C}$, however, icing does not normally occur.

2) evaporative heat loss

$$q_e = 2.90 h_c \frac{h_{fg}}{\rho_\infty} (p_{\text{vap},s} - p_{\text{vap},\infty}) \quad (3.6)$$

where the constant 2.90 is an empirical factor relating mass transfer to heat transfer (Messinger, 1953) and h_{fg} is the latent heat of vaporisation. Equation 3.6 is valid for $n < 1$, where n is the local freezing fraction. If $n = 1$, then h_{fg} must be replaced by the latent heat of sublimation, h_{sg} .

3) heat required to heat incoming droplets up to the surface temperature

$$q_w = \dot{m}_{\text{imp}} C_w (T_s - T_\infty) \quad (3.7)$$

Hence the overall heat balance at the adiabatic surface becomes:

$$q_c + q_e + q_w = q_k + q_f \quad (3.8)$$

The above equation determines the portion of liquid water droplets that hit the surface that will freeze. This is known as the freezing fraction, and is derived later in this chapter.

3.2 APPLICATION OF THE BUCKINGHAM- Π THEOREM

Bilanin (1991) attempts to uncover a reliable scaling method for ice accretion through the application of the Buckingham- π theorem. Upon encountering an icing cloud, the air is nearly saturated, which leads Bilanin to neglect additional evaporation and condensation. He further assumes that the heat capacity of the aerodynamic surface is very small, so that the thermal response of the substrate is negligible. He also recognises, but ignores, the liquid water film on the surface.

Starting from a list of parameters assumed to affect ice accretion (see Table 3.1) dimensional analysis was applied, resulting in 18 dimensionless groups (see Table 3.2). The first two groups, π_1 and π_2 , are independent of the fluid properties and depend solely on geometry. Parameters π_3 and π_4 , require that if the characteristic length is varied, so do the droplet size and the mean spacing between droplets. Parameters π_5 - π_{13} are property ratios for air and water, which can be easily matched when the same fluids are used for reference and subscale tests. Parameter π_{14} imposes a constant ratio between the freezing and ambient air temperatures. Since, however, the freezing temperature of water is constant, all subscale tests must be done at the same ambient air static temperature as the reference case. If this is done, the ratio of latent heat of fusion to enthalpy of the air is held constant and parameter π_{15} is satisfied.

Unfortunately, the last three parameters in Table 3.2, Mach number squared, Reynolds number and Weber number, are not so easily matched. These parameters are:

$$M^2 = \frac{U^2}{\gamma R T_\infty}$$

$$Re = \frac{\rho_a U_\infty L}{\mu_a}$$

$$We = \frac{\rho_a U_\infty^2 L}{\sigma}$$

As the temperature range for glaze icing is very narrow, T_∞ , μ_a and σ are virtually constant (Anderson 1994). These parameters require that free stream velocity be varied according to:

$$U_\infty = \text{const}$$

$$U_\infty \propto \frac{1}{L}$$

$$U_\infty \propto \frac{1}{\sqrt{L}}$$

Hence, it is impossible to match all three parameters at once, in reduced scaling tests and the Buckingham- π theorem fails to produce a workable scaling method. A further conclusion is that ice accretion is not a phenomenon that can be scaled exactly, though this does not rule out the possibility of approximate scaling solutions. These will be investigated in the following sections.

3.3 CURRENT SCALING PRACTICES AND NON-DIMENSIONAL PARAMETERS

As ice accretion is based on supercooled droplets impinging and perhaps freezing on the substrate, the shape, quantity and type of ice built up on a surface depends on certain physical phenomena. These phenomena can be expressed in non-dimensional terms in order to discover scaling laws. These phenomena include the flow field around the ice accretion and the solid body, the droplet trajectories, which dictate where the droplets will impinge, the impingement-freezing process, and the liquid water flow on the glaze ice surface.

In the following subsections, scaling requirements are discussed in terms of the physical mechanisms that are involved. The discussion is mainly based on that of Kind et al. (1998 a).

3.3.1 Flow Field Scaling Requirements

Dynamic similarity of the flow field requires identical streamline shape as well as identical pressure, force and moment coefficients. These can be obtained through

geometrically similar reference and subscale models and by matching the Reynolds number and the Mach number. As mentioned before, matching both M and Re is impossible at reduced scale, however, the majority of icing encounters occur at low speeds, where compressibility effects are negligible. Hence, M can be ignored. Furthermore, Anderson (1994) argued that, since icing occurs at the leading edge, where the boundary layer is still thin, the ice roughness fixes the transition point and the bluff body shape of the ice will regulate the separation point of the boundary layer. Since the ice accretion would trip the boundary layer, the flow would tend to be independent of Re , which could then be neglected provided the differences between Re_S and Re_R are not too great. Bilanin (1991), however, defended the use of Re based on its influence on heat transfer and recently, Anderson and Ruff (1999) used it as an optional scaling parameter.

3.3.2 Droplet Trajectory Scaling Requirements

Matching the droplet trajectory is important in order to ensure that the droplets follow the same trajectory in the reference and subscale cases. This produces similar impingement patterns, which are necessary in producing similar ice shapes.

This discussion is based on work by Ruff (1986), Bragg (1982) and Kind et al. (1998 a). Droplet trajectories can be evaluated by applying Newton's Second Law to a droplet approximated as a sphere, while assuming that the droplet concentration is low (less than 700 droplets of about 20 μm diameter per cc) allowing the effects of two-phase flow and droplet collision and breakup to be neglected (Ruff, 1986). Furthermore, in typical icing conditions, the average size of natural water droplets encountered in-flight is about 20 μm (Wagner et al., 1997), with a normal range of about 10 to 50 μm (Bragg, 1982). This implies that the gravitational forces are negligible compared to the drag forces. Hence, only the viscous drag force, $\bar{D}$, due to the relative velocity between the particle and the freestream, is considered. The equation of motion for the water droplet is therefore:

$$m \frac{d^2 \bar{x}}{dt^2} = \bar{D} \quad (3.9)$$

As mentioned above, the droplet is approximated as a rigid sphere of diameter d , meaning that Stokes' equation for the drag of spheres:

$$\bar{D}_{Stokes} = 3\pi \mu_a d (\bar{U}_a - \bar{U}_d) \quad (3.10)$$

can be applied, when Re_{rel} is less than 1.0 (see Figure 3.2).

$$Re_{rel} = \frac{\rho_a (U_a - U_d) d}{\mu_a} \quad (3.11)$$

U_a is the local air speed and U_d is the droplet speed. Most icing conditions, however, occur in conditions where $Re_{rel} > 1.0$. Hence, the following correction factor must be applied:

$$\frac{C_D Re_{rel}}{24} = f[Re] \quad (3.12)$$

which reduces to unity, when $Re_{rel} < 1.0$. Applying the correction factor to Stokes' equation, results in a general expression for viscous drag.

$$\bar{D} = 3\pi \mu_a d \left(\frac{C_D Re_{rel}}{24} \right) (\bar{U}_a - \bar{U}_d) \quad (3.13)$$

Non-dimensionalising the droplet equation of motion (Equation 3.9)

$$K \left(\frac{d^2 \bar{x}'}{dt'^2} \right) = \left(\frac{C_D Re_{rel}}{24} \right) (\bar{U}_a' - \bar{U}_d') \quad (3.14)$$

produces two non-dimensional parameters. These are the Reynolds number based on relative velocity, Re_{rel} , and the inertia parameter, K .

$$K = \frac{\rho_w d^2 U_\infty}{18 L \mu_d} \quad (3.15)$$

In order for the droplet trajectory to be matched, the parameters, K and Re_{rel} , require that the freestream velocity, U_∞ , must be related to droplet diameter, d , by both:

$$U_\infty \propto \frac{1}{d^2} \qquad U_\infty \propto \frac{1}{d}$$

To resolve this constraint, Bragg assumes that the correction factor can be expressed as:

$$C_D Re_{rel}/24 = c Re_{rel}^\lambda \quad (3.16)$$

which appears as a straight line with a slope of λ and the y-intercept c , when plotted on a log-log plot over the range of Re_U covered by the droplets. Recalling that Re_{rel} can be expressed as:

$$Re_{rel} = \frac{\rho_a U_\infty d}{\mu_a} |\bar{U}'_a - \bar{U}'_d| = Re_U |\bar{U}'_a - \bar{U}'_d| \quad (3.17)$$

the trajectory equation can now be rewritten as:

$$\left(\frac{d^2 \bar{x}'}{dt'^2} \right) = c \left(\frac{Re_U^\lambda}{K} \right) |\bar{U}'_a - \bar{U}'_d|^\lambda (\bar{U}'_a - \bar{U}'_d) \quad (3.18)$$

where both c and λ are constants. On the basis of this result, Bragg defines the trajectory parameter as:

$$\bar{K} = \frac{K}{Re_c^\lambda} \quad (3.19)$$

Bragg advocates values of $c = 0.845$ and $\lambda = 0.35$, as illustrated from Figure 3.3. A single parameter, $\bar{K}$, now exists that relates inertial forces to drag forces, allowing more flexibility than the parameters resulting from the dimensional analysis. Although Bragg's results require an approximation to the drag law (Equation 3.16), Figure 3.4 shows that the approximation, and hence the trajectory parameter, holds well over the normal range of Re_v . It should be mentioned that icing conditions with droplets much larger than those considered above can sometimes be encountered. In such supercooled large droplet (SLD) conditions a substantial portion of the liquid water content consists of droplets ranging from 50 to 500 μm in diameter. All of the above scaling considerations still apply, but in addition, gravitational forces become important above about 200 μm .

3.3.3 Impingement and Freezing Scaling Requirements

The impingement-freezing process mainly deals with the accumulation of ice on the surface and the thermodynamics involved in the Messinger heat balance.

3.3.3.1 Water Accumulation Scaling Requirements

Another necessary scaling requirement is based on the quantity of ice accumulated on the substrate. In order to ensure that the reference and subscale specimens will exhibit similar ice growth, the two basic requirements of ice similarity must be met: similar quantity and similar shape. The first is addressed here, whereas the second is a function of a combination of parameters and is currently unresolved.

To correctly scale the total impingement volume, V , the following relation for V and L must be met:

$$\left(\frac{V}{L^3}\right)_S = \left(\frac{V}{L^3}\right)_R \quad (3.20)$$

where subscripts S and R denote subscale and reference models respectively. L is the characteristic length, and the impingement volume, V , for time t , is:

$$V = \frac{LWC U_{\infty} L^2 \beta t}{\rho_i} \quad (3.21)$$

where β is the local collection efficiency defined below. This leads to a relation for impingement volume over a time interval, t , for both reference and subscale:

$$\left(\frac{LWC U_{\infty} \beta t}{\rho_i L}\right)_S = \left(\frac{LWC U_{\infty} \beta t}{\rho_i L}\right)_R \quad (3.22)$$

The local collection efficiency is defined as the ratio of the area through which the water passes upstream of the surface to the impingement area (Figure 3.5), that is:

$$\beta = \frac{dy_o}{ds} \quad (3.23)$$

Here dy_o is the cross-stream spacing between droplets far upstream of the body and ds is the spacing between droplets on the surface, after impingement. Since, however, the flow fields and droplet trajectories are matched by virtue of dynamic similarity, β must also have the same value at all corresponding points on the subscale and reference bodies. Furthermore, the density of ice on the body, ρ_i , is assumed to be the same for both scales. Therefore, Equation 3.22 may be simplified to:

$$\left(\frac{LWC U_{\infty} t}{L} \right)_S = \left(\frac{LWC U_{\infty} t}{L} \right)_R \quad (3.24)$$

This non-dimensional group is known as the accumulation parameter, A_c . Through the presence of the time variable, flexibility has been introduced into the expression as to the choice of both LWC and freestream velocity, U_{∞} .

3.3.3.2 Surface Thermodynamic Scaling Requirements

As indicated in the Messinger heat equations in section 3.1, rime ice is formed when the rate of heat removed from the control volume is equal to the rate of heat added, meaning that the freezing fraction reaches unity and all water droplets freeze immediately upon impingement. With glaze icing, the rate of heat removal is less than the possible rate of latent heat release, hence the freezing fraction is less than unity and liquid water exists on the surface.

As freezing fraction denotes the portion of frozen water to total water that has impinged on the local surface, it seems logical that this parameter is fairly important to scaling success and should, therefore, be matched in reduced-scale tests.

Returning to the Messinger equations, it is observed that in icing conditions the ambient air is usually saturated, causing the rate of evaporative heat transfer, q_e , to be approximately equal to that of convective heat transfer, q_c (Kind et al., 1997). Therefore:

$$\frac{q_e}{q_c} \approx 1$$

It is further observed that the kinetic energy term, q_k , can usually be neglected. Equation 3.8 can thus be rewritten as:

$$q_c + \frac{q_e}{q_c} q_c + q_w = q_f \quad (3.25)$$

Substituting equations 3.1 through 3.7 the above expression becomes:

$$\left(1 + \frac{q_e}{q_c}\right) h_c (T_s - T_r) + \dot{m}_{imp} C_w (T_s - T_\infty) = (\dot{m}_{imp} + \dot{m}_r) n h_{fs} \quad (3.26)$$

Noting that $T_s = 0^\circ\text{C}$ for glaze icing and that:

$$\dot{m}_{imp} = LWC \beta U_\infty$$

Equation 3.26 can be rearranged to solve for the freezing fraction:

$$n = \frac{\left(1 + \frac{q_e}{q_c}\right) h_c (T_s - T_r)}{LWC U_\infty \beta \left(1 + \frac{\dot{m}_r}{\dot{m}_{imp}}\right) h_{fs}} + \frac{C_w (T_s - T_\infty)}{\left(1 + \frac{\dot{m}_r}{\dot{m}_{imp}}\right) h_{fs}} \quad (3.27)$$

Since correct scaling of the flow field, droplet trajectories, ice accumulation, and freezing fraction imply that all mass flows will be correctly scaled, scaling of n requires the matching of A and B , where B is the convective to latent heat ratio:

$$B = \frac{\left(1 + \frac{q_e}{q_c}\right) h_c (T_s - T_r)}{LWC U_\infty h_{fs}} \quad (3.28)$$

and A is the sensible to latent heat ratio:

$$A = \frac{C_w (T_s - T_\infty)}{h_{fs}} \quad (3.29)$$

Another parameter is the relative heat factor, presented by Messinger (1953):

$$b = 2 \beta A/B \quad (3.30)$$

Most workers have focused on matching only the freezing fraction at the stagnation point, that is, from Equation 3.27, the sum $(A+B/\beta)$, rather than matching A and B individually. However, Kind and Oleskiw (2001) suggest that it is important to match A and B individually. As A is strictly temperature dependent (it is independent of position), it can be matched through matching the static temperature in reference and subscale cases. B , however, is a function of both h_c and q_c/q_c and thus varies with position on the ice surface. Thus, if A is not matched and B is chosen to match n at the stagnation point, then it is unlikely that the distribution of B and n over the remainder of the ice surface will match. Essentially, if the reference and subscale ambient air temperatures are equal, then both A and B are matched.

Calculating the actual heat transfer coefficient, h_c , is very difficult as h_c depends on many factors including the freestream Reynolds number, the overall body and ice shape, the surface roughness and the location on the body. Expressions for h_c are usually taken from correlations for simple bodies and smooth surfaces, which are very well studied. This may not create serious problems for experimental studies, as the scaling requirement is simply to match n . Therefore, if both reference and subscale correlations for h_c are erroneous, but the error factor is the same, matching is still achieved, at least approximately (Kind, 2001). The error factor must simply be the same.

3.3.4 Surface Water Scaling Requirements

A recent consideration in the glaze ice accretion process is the scaling of surface water effects. Numerous surface water mechanisms have been proposed and experiments indicate that real surface water behaviour is a combination of liquid film flow, droplet splashing, and runback water forming rivulets and individual beads.

In fact, Al-Khalil et al. (1994) observed, through close-up photography, that in addition to a thin film of liquid water at the stagnation point, rivulets and droplets form on the surface. Current glaze icing mass balance models assume that there is surface flow continuity. This implies that liquid water upstream of the control volume will flow into the control volume, while all the liquid water present in the control volume will flow downstream and out of the control volume (Hansman and Turnock, 1989). This assumption is valid for conditions in which the liquid film completely covers the surface. Olsen and Walker (1986) conducted high-speed photography tests at NASA that suggested that other modes of runback exist. Namely, the studies observed uniform liquid films near the stagnation point, but observed the coalescence of the surface film into stationary beads, surrounded by dry areas, further back.

The NASA studies implied two possible scenarios for surface water flow acknowledging the presence of surface beads, both of which are possible depending on conditions (Hansman and Turnock, 1989). The first scenario involves the water beads growing until the heat transfer from the roughened surface (due to the beading) increases sufficiently to raise the freezing fraction to unity. In this case, no water would flow out of the control volume. The second scenario involves the beads growing due to coalescence and impingement until external shear and pressure forces force the beads along the surface or tear them from the surface. Here, also, it is improbable that the water flows into the next control volume, meaning that surface flow continuity is invalid. As flow continuity is implicit in the Messinger and other icing equations, the aforementioned scenarios may explain why experimental ice accretion is less than theoretical quantities at

conditions near freezing (Hansman and Turnock, 1989), and thus have different overall shapes.

The aforementioned discoveries are important because the liquid surface water affects ice accretion by directly influencing ice shape and by influencing the heat transfer to the freestream. As surface tension is expected to influence splashing, as well as rivulet and bead formation on the surface (Bilanin and Anderson, 1995), the Weber number, We , which is a ratio of inertia forces to surface tension forces, should be matched. Which should be the characteristic length in the Weber number is still unclear, though both the droplet diameter and the film thickness yield approximately the same results. Kind et al. (1998 b) also suggest that viscosity in the liquid water film is important, introducing the film Capillary number, Ca , which is a ratio of the water-viscosity forces to surface-tension forces.

$$Ca_w = \frac{\mu_w u_w}{\sigma} \quad (3.31)$$

Kind (2001) derives an approximate expression for film thickness, t_w , using a superposition of Couette and Poiseuille flow for surface water flow velocity, u_w , to obtain a Weber number, We_t , based on film thickness, that is

$$We_t = \frac{\rho_a U_\infty^2 t_w}{\sigma} \quad (3.32)$$

where:

$$t_w^2 = \frac{\mu_w LWC U_\infty \beta (1-n) (D/2) \sin \theta}{\rho_w (0.5 \rho_a U_\infty^2) (C_f / 2 + 0.42 \Delta C_p t_w / D)} \quad (3.33)$$

Based on this method, the expressions for We_r and Ca_w are identical, meaning that if one is matched, the other is automatically matched, thereby reducing the number of scaling parameters.

4 EXPERIMENTS

In all tests $\bar{K}$, A_c , and the freezing fraction at the stagnation point, n_o , were matched, thereby determining MVD , LWC and the runtime. This left T_∞ and U_∞ to be determined. In most subscale runs T_∞ was chosen to be equal to the reference and U_∞ was chosen by matching an additional scaling parameter, referred to as the velocity scaling parameter. Various velocity scaling parameters were used to select U_∞ and the main objective of the experiments was to identify the velocity scaling parameter that produced the best match between reference and subscale ice accretions. The parameters tested were We_L , We_t and Ca , which were introduced in Chapter 3 (Equations 3.32 and 3.33). In order to conduct the tests, two NACA 0012 airfoils were used: one had a chord length of 500 mm and the other a chord length of 222 mm. These served as the reference and subscale models, respectively. Both had a span of 570 mm, which was the AIWT test section width.

The following sections cover important aspects of the experimental facilities, models, and methods. They also cover the experimental process, including any encountered problems and their solutions, along with a detailed explanation of the experimental conditions.

4.1 NRC ALTITUDE ICING WIND TUNNEL FACILITY

All icing tests were conducted at the National Research Council's (NRC) Altitude Icing Wind Tunnel (AIWT) in Ottawa, Canada. The AIWT is a closed circuit tunnel, with a square test-section, 57 cm high x 57 cm wide (see Figure 4.1). Heat is removed from the air at every pass around the circuit by a heat exchanger, allowing the static air temperature to be controlled at values from -35°C to $+40^{\circ}\text{C}$. The unblocked test-section airspeed can reach over 100 m/s. A spray system is used to inject water droplets into the air to create icing conditions. The spray system uses distilled water and 3 spray bars using a 3-4-3 nozzle pattern. It is capable of producing a uniform spray core of about 30 cm x 30 cm, a *LWC* range between 0.1 g/m^3 and 2 g/m^3 , and a droplet mean volume diameter, *MVD*, range between $8 \mu\text{m}$ to $35 \mu\text{m}$. The tunnel also has an altitude control, which can simulate altitudes up to 6000 m above sea level; this was not operational at the time of the experiments.

The tunnel conditions are computer controlled. The data are collected by a computer data acquisition system, which samples the data at 25 Hz and then averages the data to 1 Hz for display and writing to an archived data file. Video images are captured by an image capture card in a PC and the video is recorded on an S-VHS recorder. More detailed information on AIWT characteristics and operation can be found in Oleskiw et al. (2001). In particular, tunnel flow and spray calibration results are available in that paper.

4.2 DESIGN OF MODELS

The in-house FORTRAN potential flow solvers INVAIRF, CASCANAL and MULTAIRF, were used to calculate wall interference effects for the 500 mm reference airfoil as installed in the AIWT. For present purposes, peak interference is defined as the increase in peak velocity on an airfoil due to blockage, as a percentage of the peak velocity on an isolated airfoil. Calculations were done for 0° and 2° angle of attack. The

largest chord length possible with interference of 5% or less was found to be 500 mm. In fact, the interference at $\alpha = 0^\circ$ was 2.7%, while at $\alpha = 2^\circ$ it was 5.1%. 500 mm was thus set as the reference-airfoil size and the blockage effects were judged to be insignificant for the purposes of ice accretion.

The subscale airfoil was sized in order to be substantially smaller than the reference airfoil, while still being large enough to allow an easily measured ice accretion to develop. The chord ratio between reference and subscale was somewhat arbitrarily selected as Kind and Oleskiw's (2001) cylinder diameter ratio of 45:20, giving the subscale a chord length of 222 mm. Although the aspect ratio of the reference airfoil was 1.14, causing some concern as to pressure distributions and wall-effects, the airfoil created little or no lift and thus little or no vorticity at the tunnel sidewalls. Additionally, the ice profile was measured at midspan, where spanwise non-uniformity effects would be at a minimum. This was deemed to be acceptable in view of the advantages of keeping the subscale airfoil reasonably large.

The airfoils were manufactured by the Science Technology Centre (STC) at Carleton University. Based on discussions with STC machinists and AIWT staff, a solid airfoil design fabricated with Ren Shape 450 was chosen. Ren Shape is a grain-free polyurethane board, and was selected based on its very good machining properties and reasonable cost. Further advantages are that Ren Shape maintains dimensional stability in extreme temperature and humidity and has also proved to have very good thermal insulating properties making it a very good approximation to the adiabatic wall condition assumed in the Messinger theory. The airfoil was a sandwich of Ren Shape slices cut to the NACA-0012 profiles on a CNC machine, assembled on two steel tension rods and epoxied together under compression (Figure 4.2). The rods not only aligned the slices, but also provided the load bearing supports for the airfoils in the icing wind tunnel. They were designed to withstand aerodynamic loads produced by a 5° angle of attack. Two type-T thermocouples were embedded 2 mm below the surface of the leading edge of each airfoil at midspan. Table 4.1 contains more detailed information about Ren Shape.

4.3 SELECTION OF TEST CONDITIONS

As previously mentioned, the objective of the experiments was to identify the velocity scaling parameter that produced the best match between reference and subscale ice accretion shapes. The reference run conditions were chosen to be the same as conditions used by Anderson (1996) and Anderson and Ruff (1999) in their experiments on a 533 mm chord NACA 0012 airfoil in the NASA Icing Research Tunnel (IRT), allowing for a comparison between facilities. The run conditions are presented in Table 4.2.

There were five reference runs, Ref 1, Ref 2, Ref 3, Ref 4 and Ref 1 tested at 2° angle of attack. There were five associated subscale runs for each reference run, though Ref 1 at 2° angle of attack only had three subscale runs. The test conditions are available in Table 4.3. The profiles produced by these runs are analysed in detail in Chapter 5.

4.4 OUTLINE OF EXPERIMENTAL PROCEDURE

Prior to each test run, the air speed and static temperature were allowed to stabilise along with the readings of the thermocouples under the airfoil surface. Unfortunately, as the Ren Shape proved to be an excellent insulator, the model temperature had difficulty reaching the ambient tunnel air temperature in a reasonable length of time. Consequently, most of the runs were done with airfoil temperature between 2 and 4 degrees warmer than the static air temperature, but still below 0°C.

Between test runs, the ice was removed from the airfoils by means of a heat gun. The thermal conductivity of the Ren Shape, however, was so low that the ice, which usually released quite easily from a heated aluminum or Plexiglas substrate, held on for a very long time. This prolonged each test considerably creating unforeseen time constraints, in an already short experimental period. Consequently, only the first reference case, Ref 1, was tested for repeatability.

The desired spray conditions, such as liquid water content (*LWC*) and droplet mean volume diameter (*MVD*), were set by selecting the appropriate air pressure and water flow rate to the spray bars, as indicated by AIWT calibration data. The AIWT had recently been calibrated and calibration information is found in Oleskiw et al. (2001).

Three methods of recording ice profiles were used. An S-VHS video recorder ran for the entire length of each run from an analog video camera feed, thus recording ice accretion over time. The images were then saved using a digital frame-grabber board in the PC. The video camera was positioned outside the Plexiglas wall of the test section looking in along the span (see Figure 4.3). The camera was repositioned depending on the ice and airfoil size. At the end of each run, a thin slit was melted in the ice accretion at midspan and a cold aluminum plate was inserted. At this point, a digital photographic image was taken and the ice profile was manually traced onto the plate. The wind tunnel was kept running to prevent the ice from melting. The tracings were compared to the digital images and the IRT tracings, making up the main experimental results.

4.5 PRELIMINARY TEST RUNS AND OBSERVATIONS

With the performance of the first reference case, it quickly became apparent that the ice profile was very different from that of corresponding NASA-IRT results. These inconsistencies created concern about the Ren Shape, which had never been used before in icing tests. As mentioned in Chapter 2, tests by Anderson and Shin (1997) and Hansman and Turnock (1989) indicated that the substrate material was unimportant in the formation of ice; nevertheless, questions as to porosity, surface roughness and conductance of the material were once again raised. A simple test was conducted to determine whether the Ren Shape needed some sort of covering (such as aluminum or a sealant paint) to adjust the surface properties. A strip of aluminum tape 0.13 mm thick was placed on the airfoil in the mid-span region. The spray was applied for 15 seconds and the accretion was studied at this point. Ice crystallised up to 3 cm further back on the aluminum strip than on the bare Ren Shape. There was, however, no further growth in this 3 cm region for the remainder of the run. The spray was restarted and the test run

was continued to completion. A visual inspection was done, but there was no difference seen between the ice accumulated on the bare Ren Shape and that on the aluminum-covered region. As there was some variability across the span, due to a certain inherent randomness in the ice shape, any effect of the aluminum tape on the profile was well within the experimental error.

5 RESULTS AND DISCUSSION

The following sections cover the experimental results and discuss the findings. Comparisons are made between the AIWT ice-shape tracings and the digital images, between the AIWT reference tracings and the subscale tracings and between the AIWT reference tracings with the IRT tracings.

5.1 COMPARISON OF NRC TRACINGS AND DIGITAL IMAGES

The following paragraphs outline an assessment of how representative the mid-span ice-shape tracings are of the actual overall ice shape across the span. The assessment is done by comparing the reference and subscale tracings with the digital images. The tracings and the reference case images are presented as examples in Figures 5.1-5.5 and 5.6-5.9, respectively. The remainder of the images are in Appendix A.

The digital video camera was used to take the images that were used to confirm the quality of the ice-accretion profile tracings at mid-span. The camera commanded a clear view of the front and top of the accretions (see Figures 5.6-5.9), though due to the camera angle, the bottom of the accretions are a little difficult to see. In an overall sense, the mid-span tracings (Figures 5.1-5.5) reflected the cutting plane profiles (Figures

5.6-5.9) reasonably well. There were some variations between the tracings and the ice shape, however, that should be addressed.

The majority of the tracings were a little smaller than the ice profiles seen in the digital image (compare, for example, Figures 5.4 and 5.9). One major cause was that the angle of the pencil varied throughout the tracing process. If the pencil were kept completely horizontal, then the tracing would be more or less accurate (though there would be an inherent offset equal to the pencil diameter). However, if the pencil were angled towards the ice shape, the tracing would be noticeably smaller, while if the pencil were angled away from the ice, the tracing would be larger in that area. Another problem was that some of the ice accumulation was melted away by the hot metal cutter at the edge of the cutting plane. This also shrank the ice profile noticeably, reducing any details of the ice. The aforementioned problems apply to both reference and subscale tracings. Although the absolute magnitude of error in the tracings is essentially equal for both reference and subscale cases, the relative magnitude of error in the subscale tracings was larger.

A further difference between the tracings and the images was the inability to capture feathers in the tracings. Feathers were located downstream of the horns in the images. Many of these feathers fell off the substrate during the tracing process. Others appear to be at the cutting line in the images, but in reality were slightly further along the span. Not much force was required to remove these, and any feather that was touched by the pencil fell off almost immediately.

A final observation is that the tracings at mid-span are not necessarily reflective of the overall ice shape because of irregular variation of the shape across the span. Not only can there be errors due to the tracing method, but there may also be local shape irregularities at the cutting plane. Hence, the tracing reflects the local ice shape, which can be noticeably different from that at other spanwise stations. The mid-span tracings are, consequently, not entirely reflective of the overall spanwise ice shape. The overall ice shape varied substantially from run to run with shapes ranging from barbell shapes,

with larger ends, to shapes with tapering ends. Typically, the overall ice shapes were uniform over, approximately, the central 15 cm of the airfoil span, though this value fluctuated between 20 cm and 10 cm in certain cases.

In summary, the tracings were lacking the feathers present in the images; the feathers either broke off during the tracing process or were not directly at the cutting plane. Moreover, some melting occurs at the edge of the cutting plane, slightly reducing the apparent ice-accretion size and detail. Although the uncertainties in the tracing technique are problematic, some observations can still be made in comparing the reference and subscale tracings.

5.2 COMPARISON OF REFERENCE AND SUBSCALE TRACINGS

Recall that the reference conditions for the $\alpha = 0^\circ$ cases were selected based on conditions used by Anderson (1996) and Anderson and Ruff (1999). These reference runs are tabulated in Table 4.2 and are labelled Ref 1, Ref 2, Ref 3, and Ref 4. As mentioned earlier, the subscale conditions were chosen by matching A_c , $\bar{K}$ and n_o , while U_∞ was selected by matching one of the velocity scaling parameters, We_L , We_t , Ca or We_d . The subscale ice accretion which most closely matches the reference ice accretion shape would indicate the best velocity scaling parameter. The following paragraphs compare the reference and subscale tracings in an attempt to identify the best velocity scaling parameter. The tracings are presented in Figures 5.1-5.5 and some complementary digital images appear in Figure 5.6 to 5.13. As seen from the $(B+A)$ values in Table 4.3, the freezing fractions for runs Ref 1 and Ref 4 placed these runs in the glaze ice regime. Conversely, runs Ref 2 and Ref 3 are closer to the mixed ice regime, which Ruff (1986) defines as $n > 0.3$. The values of B in Table 4.3 were computed using the assumption that:

$$h_i \propto Re_L^{0.805}$$

5.2.1 Repeatability of Ice Accretions (Figure 5.1a)

The first tracings that should be addressed are the repeatability runs of Ref 1. These were the first and last run conditions of the experiments in the AIWT and were conducted to test the repeatability of the experiments. By inspection of Figure 5.1a, the ice accumulations are approximately equal, though the first accretion had slightly more accumulation volume than the last. In addition, the upstream face of the first ice accretion was angled more upstream than that of the last accretion, which was angled downstream. Finally, the last accretion has somewhat more definition, which may be due both to melting of the ice in the first run and an improvement in tracing technique for the last run. Overall, the repeatability of the tests was good and the variability was within the tracing error envelope.

5.2.2 Ref 1 and Subsl 1.1 to 1.5 (Figure 5.1)

When matching We_L (5.1c) between the subscale and reference cases, the local irregularities (Figure 5.10) distorted the tracing too much to create a good match. The tracing has a distorted appearance that bears little resemblance to the reference shape. Matching We_t (5.1b) and Ca (5.1d) yielded somewhat better results. The runs matching Ca gave a better overall ice shape, but matching We_t gave a better upstream face. The two runs (5.1e) and (5.1f) performed at different freestream static temperature, T_∞ , were expected to yield very different profiles, but they did not. In fact, matching We_d (5.1f) with different T_∞ produced a very similar accretion shape to the reference shape.

5.2.3 Ref 2 and Subsl 2.1 to 2.5 (Figure 5.2)

All of the subscale runs for this reference case displayed reasonably good results. The ice shapes for the runs with matching We_t (5.2b) and We_L (5.2c) resembled the reference ice shape quite well, though the tops of the accretions were flattened, possibly due to melting at the cutting plane. Results with matching of Ca (5.2d) were not quite as

good as there was more ice accumulation than in the reference case (5.2a). The shape of the subscale resembled the reference fairly well, though. Again, the T_∞ variations did not produce drastically different results. The run with We_d (5.2f) matched produced a very similar profile to the reference, possibly the best of all.

5.2.4 Ref 3 and Subsl 3.1 to 3.5 (Figure 5.3)

All of the subscale runs for this reference case displayed a comparable ice accumulation amount to the reference. The profile shapes were somewhat different, but there were feathers on the reference that were not included in the reference tracing. The feathers in subscale runs (5.3b) and (5.3f) appeared to fill with glaze ice and become part of the main structure, which may account for some of the tracing differences. Furthermore, a number of the subscale tracings included localised irregularities at the tracing plane (Figures 5.11-5.13), which produced somewhat different profiles from the reference.

5.2.5 Ref 4 and Subsl 4.1 to 4.5 (Figure 5.4)

The match between subscale and reference ice-shape tracings was poorest for this set of runs. The freezing fraction was the lowest of all the test runs, creating the most susceptibility to horn formation. The reference tracing (5.4a) had a flat windward face shape, with two large horns behind the main accumulation. These horns were absent from the majority of the subscale tracings, though matching We_r (5.4b) and Ca (5.4d) displayed some evidence of similar horns. The only tracing to exhibit a reasonably flat front face was tracing (5.4f) which is for matched We_d at a T_∞ different from the reference value. All the other tracings exhibited either strongly concave or convex frontal profiles.

5.2.6 Ref land Subsl 1.1 to 1.3 at $\alpha = 2^\circ$ (Figure 5.5)

The subscale runs for this case displayed some degree of similarity to the reference case, though the similarity was not terribly strong. The angle of the upstream face was somewhat similar, but the volume of accumulations was too little. Matching We_L (5.5c) and Ca (5.5d) seemed to yield better results than We_t (5.5b).

5.3 COMPARISON OF NRC AND NASA TRACINGS

The icing conditions for the reference runs conducted at NRC were chosen to be essentially the same as those used by Anderson (1996) and Anderson and Ruff (1999) for tests on a NACA 0012 airfoil of 533 mm chord, in the IRT. Recall that the present reference runs also used a NACA 0012 airfoil, 500 mm in chord length. Comparisons of the AIWT and IRT results were thus expected to be of interest. The conditions for the AIWT and IRT test runs can be found in Tables 4.2 and 4.3. This section compares the tracings of the AIWT reference runs with the tracings of the IRT runs. The comparison plots appear in Figure 5.14.

The amount of accumulated ice was mostly similar for corresponding runs in the two facilities, but other than this, there is little resemblance between the AIWT and IRT tracings. As mentioned previously, the AIWT tracings did not depict the feathers contained in the digital images. The IRT tracings, however, depicted feathers, though the feathers were much larger than those in the AIWT digital images. Although the IRT and the AIWT tracing techniques are believed to be essentially the same, the IRT tracing technique may be less intrusive to the ice shape, allowing the feathers to remain intact. The IRT tracings also had horns, but the horns were very different from those in the AIWT tracings. In some occurrences the IRT horns were angled forward while the AIWT horns were angled back or normal to the surface (Figures 5.14a and 5.14b). In other cases, the AIWT tracings contained horns and the IRT tracings did not (Figure 5.14c). Even the amount of accumulation varied in Figures 5.14a and 5.14d. Either way, the AIWT horns were always angled opposite to the IRT horns. As the horns play a

dominant role in the overall ice shape, especially in the concavity of the front of the profile, the variations in horn angles caused the AIWT profiles to have opposite concavity to the IRT profiles. In essence, the AIWT profiles and corresponding IRT profiles had little in common.

It is highly improbable that the airfoil size difference (500 vs 533 mm) was responsible for the large differences in the ice shapes. Although there is a large difference in tunnel size (the AIWT is 0.57 m high by 0.57 m wide, while the IRT is 1.83 m high by 2.74 m wide) blockage calculations mentioned in section 4.2 predicted no more than 2.7% interference in the AIWT at zero angle of attack for a clean airfoil. The interference increases with time as ice accumulates. Perhaps the different substrate materials affected the ice shape. The AIWT airfoils used Ren Shape while the IRT airfoils used aluminum. This possibility is discussed in the following section. What is clear is that the differences were not a function of tracing errors; the differences were too great to be explained by this. A further possibility, which, due to its complexity is not investigated in this thesis, is that facility design characteristics such as spray system design, droplet residence time, and heat exchanger design were responsible for the difference in ice shapes under nominally the same test conditions. Whatever the reason, the fact that the AIWT tracings did not match the IRT tracings is very significant and warrants further study.

5.4 DISCUSSION OF MODEL MATERIAL

Due to the large difference between the AIWT and the corresponding IRT ice profiles, there was a serious concern regarding possible effects of Ren Shape 450 on the ice formation. As mentioned earlier, a strip of aluminum tape was applied to the reference airfoil surface and the effect of the tape on the ice shape was investigated. No ice shape difference was noticeable between the bare Ren Shape surface and that covered by aluminum tape. Consequently, it seems as though the surface roughness and thermal properties of the Ren Shape had no bearing on the ice shape, reflecting results of Hansman and Turnock (1989), Anderson and Shin (1997) and Kind and Oleskiw (2001).

Another important effect of the Ren Shape on the icing conditions was the ability to simulate the Messinger adiabatic wall condition. As will be illustrated in section 5.6, the thermocouples measured an increase in temperature of 3°C throughout the runs, but then stabilised near the end of the runs. The effect of this increase is probably negligible in view of the low thermal conductivity and the ability of the material to retain the heat at the surface. In fact, the Ren Shape probably emulates the Messinger wall condition far better than more commonly used aluminum models. Therefore, it seems that unless the ice accretion is highly sensitive to substrates, at temperatures very near freezing, the Ren Shape did not influence the results.

5.5 FURTHER DISCUSSION OF THE TRACING TECHNIQUE

The results of the experiments were inconclusive regarding scaling. This may mean that a suitable velocity scaling parameter for determining freestream velocity has yet to be found. It may also be that tracing errors and effects of stochastic spanwise ice-shape variations on the representativeness of mid-span tracings obscured any clear experimental results regarding scaling parameters. It is clear that inherent errors in the ice tracing technique are of equal magnitude to effects of differing scaling parameters on the experimental results. This implies that the tracing technique is unsuitable when testing for small variations in ice shape.

The tracing technique is subject to loss of detail due to melting of the ice, loss of feathers and inherent variability in the ice accretion. The technique must be improved upon before more meaningful results, especially quantitative ones, can be obtained.

The improved technique must be non-intrusive and must somehow average results at multiple stations across the span. This would reduce sensitivity to irregular spanwise variability. An intermediate, though somewhat costly and time consuming, method (until the necessary tracing technology becomes available) would be to average the mid-span tracings over a number of identical runs. The technique should also produce better accuracy of tracings at each spanwise station. Furthermore, if a mechanised system were

used human error could be eliminated. Finally, it would also be desirable to have the ability to capture meaningful spanwise average ice shapes at intermediate times as well as at the end of test runs.

5.6 STABILITY OF TUNNEL CONDITIONS

In light of the results, the stability of the AIWT tunnel conditions during test runs should be evaluated. Two sets of evaluations are presented here. The stability of the conditions during the two repeatability runs for reference case Ref 1 are verified; namely the wind speed, the ambient air static temperature, T_∞ , the droplet MVD , the LWC and the temperature read by the two T-type thermocouples 2 mm below the surface at the airfoil's leading edge. Furthermore, the stability of the conditions during the reference and three sub-scale cases of Ref 1 are verified by examining the behaviour of the same parameters as listed above.

The plots of the run conditions over time for the repeatability runs Ref 1 are presented in Figures 5.15 through 5.19. The run condition data were retrieved from the archived data files.

The AIWT wind speed is very stable throughout both runs. The LWC varies by 0.05 g/m^3 and T_∞ varies by 0.1°C . The MVD for the first run is very stable varying only by $1 \text{ }\mu\text{m}$, but the MVD for the second repeatability run fluctuates between $25 \text{ }\mu\text{m}$ and $35 \text{ }\mu\text{m}$. Figure 5.20 indicates that for a 533 mm airfoil, varying the MVD from $25 \text{ }\mu\text{m}$ to $35 \text{ }\mu\text{m}$ changes the collection efficiency at the stagnation line, β_n , by 5%, if the nominal MVD is $30 \text{ }\mu\text{m}$. These values will be about the same for the 500 mm airfoil used in the present AIWT tests. The airfoil thermocouples indicated an increase of 3°C from an initial -6°C and seemed to stabilise towards the end of the runs. These temperature variations are not critical as the Ren Shape is such a good thermal insulator. As the glaze icing begins, the temperature below the model surface rises slowly towards 0°C , as

indicated by the thermocouple readings. Note also that as soon as some ice forms on the surface, it insulates the exposed ice-accretion surface from the model surface.

The plots of run conditions over time for the reference run Ref 1 and the subscale runs Subsc1 1.1-1.3 are presented in Figures 5.21 through 5.25.

In these runs, the AIWT wind speed is again quite stable over the entire run, while the air static temperature varies by less than 0.2°C . Both *MVD* and *LWC* exhibit noticeable fluctuations at the beginning of the runs; these are due to stabilisation of the spray water flow rate at the beginning of each test. *LWC* and *MVD* had initial spikes of 0.2 g/m^3 and $1 \text{ }\mu\text{m}$ variability respectively, but both settled quickly as the run progressed. As illustrated in Figure 5.20, $1 \text{ }\mu\text{m}$ variation in *MVD* varies β_0 by less than 5% on a 267 mm airfoil. Anderson (2001) states that an increase in *LWC* of 0.2 g/m^3 results in noticeable but probably negligible effects on the ice shape. Lastly, the readings of the thermocouples in the models increase by about 2.5°C for the large model and about 0.5°C for the small one. As the temperature variations were no larger than those in the repeatability runs, the same argument applies in ignoring these variations.

The turbulence intensity has been measured in both the AIWT and the IRT. As increased freestream turbulence trips the boundary layer earlier and makes the laminar sublayer thinner (Sugawara et al., 1988), significant differences between the two facilities may cause transition in different locations, producing different magnitudes of heat transfer from the surface and altering the freezing fraction and the ice shape. However, Poinatte (1990) measured the IRT turbulence intensity with spray off as 0.7% at 94 m/s, while Oleskiw et al. (2001) measured the AIWT turbulence intensity with spray off as 1.4% at 132 m/s. This does not seem to be a large enough difference to explain the mismatch between icing facility profiles. Furthermore, since the ice accretion will trip the boundary layer, almost immediately, the freestream turbulence intensity should not affect icing to any noticeable degree. On the other hand, as will be elaborated on in the following section, there is reason to believe that surface roughness noticeably affects heat transfer as it trips the boundary layer and causes the transition point to creep forward. If

this creeping behaviour plays a large role in the freezing fraction characteristics, then perhaps even small amounts of turbulence intensity could affect results (Sugawara et al., 1988). This is a topic for further investigation.

5.7 HEAT TRANSFER

One of the main influences on ice shape is the convective heat transfer. This regulates the removal of heat from the ice surface, which governs the freezing fraction, and hence the ice type and shape. The convective heat transfer depends on the boundary layer and on surface roughness (Achenbach, 1977).

Roughness is caused by water rivulets, water beads and ice-surface irregularities, though the initial point of ice-surface roughness appears to be related to the boundary layer transition from laminar to turbulent flow. As time progresses, however, the smooth/rough transition point migrates forward towards the stagnation point (Hansman et al., 1989). A laminar boundary layer causes less heat transfer, which results in a relatively low freezing fraction and in runback. This water tends to form into beads and to freeze at the boundary layer transition location where the convective heat transfer coefficient, h_c , becomes higher. This tends to move the roughness onset forward, which trips the boundary layer earlier (Hansman, 1992). Roughness enhances heat transfer by locally disturbing the boundary layer (Poinsatte, 1990).

As heat transfer is also proportional to Re^x , more strength is given to Bilanin's (1991) argument that Re should be matched along with We , to match surface water behaviour. For laminar boundary layers, $x = 0.5$; however, for turbulent boundary layers, x is not so well known. The exponent $x = 0.805$ was used for all heat transfer calculations in this thesis, however, it is still unclear whether this is the correct value and how to incorporate roughness into the h_c when roughness varies with time.

Reynolds number was not matched in the AIWT runs. Although matching Re adds further constraints to already constrained test conditions, Anderson (2000), Bilanin

(1991) and others suggest that matching Re is important, not particularly in terms of the flow field, but in terms of heat transfer and surface water behaviour.

Finally, Myers' modification (2001) to the Messinger model (1953) takes into account more of the details of the freezing process. This is modelled as a Stefan problem for phase change at a phase boundary. However, for very thin water films, such as the present experiments where calculated water film thicknesses were between 5 and 15 μm , Myers' model reduces to the Messinger model.

5.8 SUMMARY OF RESULTS

The results presented above are inconclusive as to which is the best velocity scaling parameter. Though there were a few subscale tracings that matched their reference cases to a reasonable degree, the majority did not match very well. It is possible that none of the parameters tested is a suitable parameter, but it is equally possible that the errors in the tracing technique are of equal magnitude to the ice shape variations, obscuring any trends in the results.

6 CONCLUSIONS

The results in Chapter 5 are inconclusive as to the best velocity scaling parameter to use when selecting the freestream velocity for reduced-scale glaze-icing tests.

Errors in the ice tracing technique are comparable in magnitude to ice-shape differences in the experimental results, preventing an accurate comparison of scaling parameters. The present tracing technique deforms the ice at the tracing plane, allows for pieces of ice to be lost or broken, and is susceptible to the pencil angle and ice shape irregularities. A better tracing method is required.

Large differences were observed between ice shapes for AIWT reference runs and IRT runs for nominally the same conditions. The differences were too great to be a function of tracing errors, which suggests that different icing facilities create noticeably different ice shapes under the nominally same run conditions. A proper inter-facility comparison is required to confirm this and investigate the reasons for it.

In addition to experimental measurement problems, interpretation of icing test results is made more difficult by gross approximations that are still being used in the

theory. Roughness and convective heat transfer play an important role in ice accretion, yet their magnitudes and effects are not accurately known.

7 RECOMMENDATIONS

An improved technique should be used to acquire the ice shape profiles. The technique should be non-intrusive and should somehow average results at several stations along the span. This would reduce sensitivity to the local and spanwise variability. A mechanised system would be advantageous as human error could be eliminated. Lastly, it would be desirable to capture meaningful spanwise average ice shapes at intermediate times as well as at end of test runs.

An inter-facility comparison should be conducted between the AIWT, the IRT and other icing test facilities. A comparison could be made between the tunnel characteristics and either the differences or the similarities of the ice shapes. Trends in these similarities or differences may suggest a cause for these differences and may indicate a relation between ice shapes and tunnel characteristics. Tunnel construction, layout, size or components, or a combination of these may drastically affect the ice shape. This comparison could lead to interesting revelations about icing physics and testing requirements.

More tests should also be conducted to ensure repeatability of results. Due to a lack of time and the slow rates of removing ice from the Ren Shape surface, only one repeatability run was performed in the present test series.

In addition, more investigations of the convective heat transfer coefficient, h_c , should be conducted, as this plays such a strong role in ice accretion, especially glaze icing. Furthermore, this coefficient changes as a result of ice profile changes, roughness effects and changes in local velocity. One way to approximate h_c would be to replicate some of the shapes captured on video in a computer simulation. Thus, h_c could be computed at different time intervals and a relationship with time could be formulated. Another way of matching h_c may be to try matching Re . If Re plays such a dominant role in surface viscous shear and in heat transfer, then matching We or other velocity parameters may be of secondary importance.

Moreover, the question of droplets splashing on the surface has still not been resolved. As all analyses assume that impacting droplets adhere and remain on the surface upon impact, it seems reasonable to investigate this assumption.

Finally, since the substrate on which ice is formed seems to play such an insignificant role in the profiles, incorporation of the ability to melt ice rapidly (that is, a high thermal conductivity) off the material into the design of future models is strongly suggested. This would cut down on experimental time significantly, allowing for more repeatability tests or further investigations. If the present Ren Shape airfoils are to be reused in the future, adjustments should somehow be made to the surface to reduce the time taken to remove the ice.

Table 3.1 List of variables used in dimensional analysis.
(Bilanin, 1991)

Symbol	Description	Units
δ	Ice thickness	L
d	Drop diameter	L
ℓ	Mean distance between drops	L
L	Characteristic length	L
ρ_a	Density of air	M / L ³
ρ_w	Density of water	M / L ³
ρ_i	Density of ice	M / L ³
ν_a	Kinematic viscosity of air	L ² / T
ν_w	Kinematic viscosity of water	L ² / T
k_a	Thermal conductivity air	ML / T ³ °
k_w	Thermal conductivity water	ML / T ³ °
k_i	Thermal conductivity ice	ML / T ³ °
c_{pa}	Specific heat capacity of air	L ² / T ² °
c_{pw}	Specific heat capacity of water	L ² / T ² °
c_{pi}	Specific heat capacity of ice	L ² / T ² °
h_{fs}	Latent heat of fusion	L ² / T ²
T_a	Air temperature	°
T_f	Freezing temperature	°
$\sigma_{w/a}$	Surface tension of water/air interface	M / T ²
γ	Droplet contact angle	M / T ²
U_∞	Free stream air speed	L / T
s	Distance along surface	L
t	Time	T

Table 3.2 Non-dimensional parameters from dimensional analysis.
(Bilanin, 1991)

$\pi_1 = \frac{t U_\infty}{L}$	$\pi_2 = \frac{s}{L}$	$\pi_3 = \frac{d}{L}$
$\pi_4 = \frac{d}{\ell}$	$\pi_5 = \frac{\rho_a}{\rho_w}$	$\pi_6 = \frac{\rho_i}{\rho_w}$
$\pi_7 = \frac{c_{pa}}{c_{pw}}$	$\pi_8 = \frac{c_{pw}}{c_{pi}}$	$\pi_9 = \frac{k_a}{k_w}$
$\pi_{10} = \frac{k_w}{k_i}$	$\pi_{11} = \frac{\nu_a}{\nu_w}$	$\pi_{12} = \gamma$
$\pi_{13} = \frac{c_{pa} \nu_a \rho_a}{k_a}$	$\pi_{14} = \frac{T_f}{T_a}$	$\pi_{15} = \frac{h_{fs}}{c_{pa} T_a}$
$\pi_{16} = \frac{U_\infty^2}{c_{pa} T_a}$	$\pi_{17} = \frac{U_\infty L}{\nu_a}$	$\pi_{18} = \frac{\rho_a U_\infty^2 L}{\sigma_{w/a}}$

Table 4.1 Ren Shape material properties.
(MF Composites Inc., Ciba-Geigy Distributor for Canada.
<http://www.mfcomposites.com/renshap2.htm>. 3/20/01)

Properties	450 Modeling
Board size, inches (size in approximate)	60×16×2
Colour, visual	Lt. Brown
Density, ASTM D-792, g/cc (lb/ft ³)	0.66 (41)
Hardness, ASTM D-2240, Shore D	65
Flexural strength, ASTM D-790, psi	4,000
Flexural modulus, ASTM D-790, psi	144,000
Tensile strength, ASTM D-638, psi	2,300
Comprehensive strength, ASTM D-695 (0.2% offset), psi	2,800
Comprehensive Modulus of Elasticity, ASTM D- 695, psi	135,000
Glass Transition Temperature (tg), DMA, ASTM D-4065, °F(°C)	205 (96)
Coefficient of Thermal Expansion per TMA, ASTM D-3386, in/in/°F (−22°F to +86°F)	36×10 ^{−6}
in/in/°C (−30°C to +30°C)	65×10 ^{−6}
<i>Data at room temperature</i>	

Table 4.2 NASA IRT icing conditions.
Anderson (1996) and Anderson and Ruff (1999)

Source	Figure	L (mm)	V_{∞} (m/s)	P_{∞} (Pa)	T_{∞} (K)	LWC (g/m ³)	MVD (μ m)	run time (sec)	t/c
Anderson (1996) AIAA-96-0633	19-0012R	533	67.0	100000	263	1.00	30	438	0.12
Anderson and Ruff (1999) AIAA-99-0244	9-111R	533	67.1	100000	261.9	0.61	40	672	0.12
	11-113R	533	67.1	100000	267.5	0.61	40	672	0.12
	8-110R	533	67.3	100000	259.1	0.61	40	672	0.12
IRT Figures	AIWT Run								
19-0012R	Ref 1								
9-111R	Ref 2								
8-110R	Ref 3								
11-113R	Ref 4								
None	Ref 1 <i>at $\alpha = 2^{\circ}$ uses the same conditions as Ref 1</i>								

Table 4.3 NRC AIWT reference and subscale icing conditions.

(implemented Januray 22, 2001; T. McCullough)

Run No.	L (mm)	V _∞ (m/s)	P _∞ (Pa)	T _∞ (K)	LWC (g/m ³)	MVD (μm)	run time (sec)	t/c
Ref 1	500	67.00	100000	263.0	1.00	30.0	438	0.12
Subscl 1.1	222	89.70	100000	263.0	0.98	16.3	148	0.12
Subscl 1.2	222	100.55	100000	263.0	0.89	15.6	146	0.12
Subscl 1.3	222	67.00	100000	263.0	1.17	18.3	167	0.12
Subscl 1.4	222	74.89	100000	261.0	1.79	17.6	98	0.12
Subscl 1.5	222	90.63	100000	261.0	1.61	16.3	90	0.12
Ref 2	500	67.10	100000	261.9	0.61	40.0	672	0.12
Subscl 2.1	222	88.64	100000	261.9	0.62	21.9	224	0.12
Subscl 2.2	222	100.70	100000	261.9	0.56	20.8	217	0.12
Subscl 2.3	222	67.10	100000	261.9	0.72	24.5	254	0.12
Subscl 2.4	222	74.11	100000	259.0	1.10	23.6	150	0.12
Subscl 2.5	222	90.41	100000	259.0	0.99	21.8	136	0.12
Ref 3	500	67.30	100000	259.1	0.61	40.0	672	0.12
Subscl 3.1	222	88.45	100000	259.1	0.63	22.0	219	0.12
Subscl 3.2	222	101.00	100000	259.1	0.58	20.9	208	0.12
Subscl 3.3	222	67.30	100000	259.1	0.72	24.5	253	0.12
Subscl 3.4	222	105.09	100000	262.0	0.36	20.5	323	0.12
Subscl 3.5	222	92.05	100000	262.0	0.40	21.6	330	0.12
Ref 4	500	67.10	100000	267.5	0.61	40.0	672	0.12
Subscl 4.1	222	97.65	100000	267.5	0.45	21.1	276	0.12
Subscl 4.2	222	100.70	100000	267.5	0.42	20.9	285	0.12
Subscl 4.3	222	67.10	100000	267.5	0.72	24.5	254	0.12
Subscl 4.4	222	73.34	100000	266.0	1.18	23.7	141	0.12
Subscl 4.5	222	90.72	100000	266.0	0.97	21.8	138	0.12

(continued on p. 52)

Table 4.3 (cont.)

(implemented January 22, 2001; T. McCullough)

K_{bar}	A_c	Re_L	Ca	We_L	We_d	B	A	$B + A$ ($\sim \beta n_o$)	T_{film} (μm)	We_t
0.067	0.059	2610708	1.675	41300	2.48	0.1080	0.1257	0.2338	19.23	1.589
0.067	0.059	1551858	2.242	32867	2.42	0.1083	0.1257	0.2340	10.73	<u>1.589</u>
0.067	0.059	1739602	2.514	41300	2.90	0.1083	0.1257	0.2340	9.74	1.812
0.067	0.059	1159155	<u>1.675</u>	18337	1.51	0.1083	0.1257	0.2340	13.32	1.100
0.067	0.059	1305640	1.872	23088	1.83	0.0831	0.1509	0.2340	15.28	1.589
0.067	0.059	1579976	2.266	33809	<u>2.48</u>	0.0831	0.1509	0.2340	13.38	2.038
0.108	0.055	2625586	1.678	41597	3.33	0.1998	0.1396	0.3394	14.19	1.181
0.108	0.055	1539929	2.216	32228	3.18	0.1994	0.1396	0.3390	8.14	<u>1.181</u>
0.108	0.055	1749509	2.517	41597	3.91	0.1994	0.1396	0.3390	7.34	1.375
0.108	0.055	1165760	<u>1.678</u>	18469	2.04	0.1994	0.1396	0.3390	9.91	0.824
0.108	0.055	1301949	1.853	22781	2.42	0.1630	0.1760	0.3390	11.51	1.181
0.108	0.055	1588277	2.260	33904	<u>3.33</u>	0.1630	0.1760	0.3390	10.00	1.528
0.108	0.055	2661870	1.683	42298	3.38	0.2584	0.1748	0.4332	13.11	1.109
0.108	0.055	1553231	2.211	32436	3.21	0.2582	0.1748	0.4330	7.59	<u>1.109</u>
0.108	0.055	1773696	2.525	42298	3.98	0.2582	0.1748	0.4330	6.88	1.311
0.108	0.055	1181871	<u>1.683</u>	18780	2.07	0.2582	0.1748	0.4330	9.19	0.777
0.108	0.055	1825152	2.627	45289	4.18	0.2947	0.1383	0.4330	5.44	1.109
0.108	0.055	1598561	2.301	34742	<u>3.38</u>	0.2947	0.1383	0.4330	6.08	0.951
0.109	0.055	2570620	1.678	40726	3.26	0.0851	0.0692	0.1542	16.10	1.311
0.109	0.055	1660949	2.441	38294	3.64	0.0848	0.0692	0.1540	7.60	<u>1.311</u>
0.109	0.055	1712880	2.517	40726	3.83	0.0848	0.0692	0.1540	7.31	1.342
0.109	0.055	1141355	<u>1.678</u>	18083	1.99	0.0848	0.0692	0.1540	11.24	0.915
0.109	0.055	1254589	1.834	21726	2.32	0.0660	0.0880	0.1540	13.40	1.311
0.109	0.055	1551780	2.268	33238	<u>3.26</u>	0.0660	0.0880	0.1540	11.22	1.679

Note: underlining denotes values matched to reference case

Figure 1.1 Rime ice accretion at 1220 m on Cairgorm, Scotland.
(Lozowski and Gates, 1991)

Figure 1.2 The *Piarnu* on her return to Tallin from the cold
Baltic Sea in 1969.
(Aksyutin, 1979)

Figure 1.3 Ice on a transmission line near Grenoble, France.
(Lozowski and Gates, 1991)

Figure 1.4 Ice formation on an Airbus aircraft wing.
(van Hengst et al., 1997)

Figure 2.1 Typical rime ice accretion.
(van Hengst et al., 1997)

Figure 2.2 Typical glaze ice accretion.
(van Hengst et al., 1997)

Figure 3.1 Heat transfer mechanisms in Messinger model.
(Hansman and Turnock, 1989)

Figure 3.2 Drag coefficients for spheres and disks.
(Streeter and Wylie, 1985)

Figure 3.3 Standard sphere drag curve and approximation.
(Bragg, 1982)

Figure 3.4 Collection efficiency of an NACA 65A004 airfoil as a
function of $\bar{K}$.
(Bragg, 1982)

Figure 3.5 Local collection efficiency for a 2D airfoil.
(Kind et al., 1998 a)

Figure 4.1 Altitude Icing Wind Tunnel at the National Research Council of Canada.
(Oleskiw et al., 2001)

Figure 4.2 Schematic for reference and subscale NACA 0012 models.

Figure 4.3 Position of the digital video camera with respect to the airfoil.

(a) Ref 1
Reference
 $c = 500 \text{ mm}$

(b) Subsl 1.1
Match We_t
 $c = 222 \text{ mm}$

(c) Subsl 1.2
Match We_L
 $c = 222 \text{ mm}$

(d) Subsl 1.3
Match Ca
 $c = 222 \text{ mm}$

(e) Subsl 1.4
Match We_t , new T_∞
 $c = 222 \text{ mm}$

(f) Subsl 1.5
Match We_d , new T_∞
 $c = 222 \text{ mm}$

Figure 5.1 A_c , n_o , $\bar{K}$ matched along with one velocity scaling parameter.

(a) Ref 2
Reference
 $c = 500$ mm

(b) Subsl 2.1
Match We_t
 $c = 222$ mm

(c) Subsl 2.2
Match We_L
 $c = 222$ mm

(d) Subsl 2.3
Match Ca
 $c = 222$ mm

(e) Subsl 2.4
Match We_t , new T_∞
 $c = 222$ mm

(f) Subsl 2.5
Match We_d , new T_∞
 $c = 222$ mm

Figure 5.2 A_c , n_o , $\bar{K}$ matched along with one velocity scaling parameter.

(a) Ref 3
Reference
 $c = 500$ mm

(b) Subsc 3.1
Match We_t
 $c = 222$ mm

(c) Subsc 3.2
Match We_L
 $c = 222$ mm

(d) Subsc 3.3
Match Ca
 $c = 222$ mm

(e) Subsc 3.4
Match We_t , new T_∞
 $c = 222$ mm

(f) Subsc 3.5
Match We_d , new T_∞
 $c = 222$ mm

Figure 5.3 A_c , n_o , $\bar{K}$ matched along with one velocity scaling parameter.

(a) Ref 4
Reference
 $c = 500 \text{ mm}$

(b) Subsl 4.1
Match We_t
 $c = 222 \text{ mm}$

(c) Subsl 4.2
Match We_L
 $c = 222 \text{ mm}$

(d) Subsl 4.3
Match Ca
 $c = 222 \text{ mm}$

(e) Subsl 4.4
Match We_t , new T_∞
 $c = 222 \text{ mm}$

(f) Subsl 4.5
Match We_t , new T_∞
 $c = 222 \text{ mm}$

Figure 5.4 A_c , n_o , $\bar{K}$ matched along with one velocity scaling parameter.

(a) Ref 1
Reference
 $\alpha = 2^\circ$
 $c = 500 \text{ mm}$

(b) Subsc 1.1
Match We_t
 $\alpha = 2^\circ$
 $c = 222 \text{ mm}$

(c) Subsc 1.2
Match We_L
 $\alpha = 2^\circ$
 $c = 222 \text{ mm}$

(d) Subsc 2.3
Match Ca
 $\alpha = 2^\circ$
 $c = 222 \text{ mm}$

Figure 5.5 A_c , n_p , $\bar{K}$ matched along with one velocity scaling parameter.

Figure 5.6 Digital image for Ref 1 ice accretion.

Figure 5.7 Digital image for Ref 2 ice accretions.

Figure 5.8 Digital image for Ref 3 ice accretion.

Figure 5.9 Digital image for Ref 4 ice accretion.

Figure 5.10 Digital image for Subsc1 1.2 ice accretion.

Figure 5.11 Digital image for Subsc1 3.1 ice accretion.

Figure 5.12 Digital image for Subsl 3.2 ice accretion.

Figure 5.13 Digital image for Subsl 3.3 ice accretion.

(a) Case Ref 1 and 19-0012R

(b) Case Ref 2 and 9-111R

(c) Case Ref 3 and 8-110R

(d) Case Ref 4 and 11-113R

Figure 5.14 Comparison between AIWT reference ice-shape tracings ($c = 500 \text{ mm}$) and IRT tracings ($c = 533 \text{ mm}$).

Figure 5.15 Freestream velocity variation with time for the first and second repeatability runs of Ref 1.

Figure 5.16 Ambient air temperature, T_{∞} , variation with time for the first and second repeatability runs of Ref 1.

Figure 5.17 Droplet *MVD* variation with time for the first and second repeatability runs of Ref 1.

Figure 5.18 *LWC* variation with time for the first and second repeatability runs of Ref 1.

Figure 5.19 Thermocouples *A* and *B* variation with time for the first and second repeatability runs of Ref 1.

Figure 5.20 Collection efficiency at the stagnation point for 533 and 267 mm NACA 0012 airfoils at 0° angle of attack.
(Anderson, 2001)

Figure 5.21 Freestream velocity variation with time for Ref 1 and Subsc1 1.1-1.3.

Figure 5.22 Ambient air temperature, T_{∞} , variation with time for Ref 1 and Subsc1 1.1-1.3.

Figure 5.23 Droplet *MVD* variation with time for Ref 1 and Subsc1 1.1-1.3.

Figure 5.24 *LWC* variation with time for Ref 1 and Subsc1 1.1-1.3.

Figure 5.25 Thermocouples *A* and *B* variation with time for Ref 1 and Subscl 1.1-1.3.

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APPENDIX A

Appendix A is located on the accompanying compact disk. The CD contains:

- Digital images of all reference and subscale runs
- AIWT run conditions for all reference and subscale runs
- Full design drawings of the two airfoils
- Spreadsheets used in the experiments with built-in equations