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**AN INVESTIGATION INTO THE EFFECTS
OF MODIFYING THE SURFACE TENSION OF THE SPRAY
WATER IN ICING TUNNEL TESTS**

by

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B. Eng., B. Sc.

A Thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfilment of the requirements for the degree of
Masters of Engineering

Ottawa-Carleton Institute for
Mechanical and Aerospace Engineering

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Thomas William Dillon

in partial fulfilment of the requirements for
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21 September 1998

ABSTRACT

This thesis documents an experimental investigation into the feasibility of modifying the surface tension of the spray water used for ice accretion tests carried out in icing wind tunnels. In-flight ice accretion occurs when water droplets impinge and freeze on an aircraft which can cause serious degradation of the performance and handling qualities of the aircraft. The approach used in this thesis was to test circular cylinders of two different diameters with sprays of pure water and solutions of pure water and 1-propanol. The 1-propanol reduced the surface tension of the spray water. The tests were carried out in the National Research Council's (NRC) icing wind tunnel. The results indicate that a non-dimensional parameter involving surface tension and viscosity of the liquid water is important to the glaze ice accretion process. The results also suggest that there may be no need to manipulate the surface tension of the spray water.

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NOMENCLATURE

A	scaling parameter (Equation (22))
A_c	accumulation parameter ($LWC U_\infty/\rho_i L$)
A_r	area
b	relative heat parameter (Equation (24))
B	convective/latent heat parameter (Equation (23))
c	proportionality constant in approximate drag law (Equation (6))
c	speed of sound
C	constant in heat transfer coefficient (Equation (29))
Ca	Capillary number ($\mu_l U_\infty/\sigma^g$)
c_p	specific heat at constant pressure
C_D	drag coefficient
d	droplet diameter
$\bar{D}$	drag force vector
Fr	Froude number ($U_\infty/(Lg)^{1/2}$)
g	acceleration due to gravity
$\bar{g}$	gravity vector
h	convection heat transfer coefficient
h_{fg}	latent heat of evaporation
h_{fs}	latent heat of fusion
h_{sg}	latent heat of sublimation
k	thermal conductivity
K	inertia parameter ($\rho_d^2 U_\infty/18L\mu_d$)
$\bar{K}$	trajectory scaling parameter (Equation (8))
K_o	modified inertia parameter
l	mean distance between droplets
L	characteristic length
LWC	liquid water content
m	droplet mass
$\dot{m}''$	unit rate of water catch
M	Mach number (U_∞/c)
MVD	median volume diameter
n	freezing fraction
p	pressure
p_{vap}	vapour pressure

Pr	Prandtl number ($c_{p,a}\mu_d/k_a$)
q_c	heat loss due to convection
q_e	heat loss due to sublimation or evaporation of water
q_f	heat gain due to the release of the latent heat of fusion
q_K	heat gain due to the kinetic energy of the water droplets
q_v	heat gain due to the viscous or frictional heating in the boundary layer
q_w	sensible heat gain by the impinging water droplets due to the temperature rise from T_∞ to T_s
r	recovery factor
R_1, R_2	radii of curvature
Re_d	free stream Reynolds number based on droplet diameter ($\rho_a U_\infty d/\mu_a$)
Re_L	free stream Reynolds number based on characteristic length ($\rho_a U_\infty L/\mu_a$)
Re_{rel}	relative Reynolds number based on droplet diameter ($\rho_a U_\infty d / \bar{U}_a - \bar{U}_d /\mu_a$)
s, ds	distance along aerofoil surface
s_l	lower-surface impingement limit
s_u	upper-surface impingement limit
S	model scale factor (Equation (10))
Sc	Schmidt number ($\mu_d/\rho_d L$)
t	time
t'	dimensionless time ($U_\infty t/L$)
T	temperature
U	velocity
$\bar{U}$	velocity vector
$\bar{U}'$	dimensionless velocity vector ($\bar{U}/U_\infty$)
V''	volume of liquid water and/or ice per unit surface area
We	Weber number ($\rho_a U_\infty^2 L/\sigma$)
x	exponent in heat transfer coefficient (Equation (25))
$\bar{x}$	droplet position vector
y_o, dy_o	vertical distance between s_l and s_u and vertical distance between adjacent droplet trajectories far upstream of the aerofoil
z	vertical height from a reference plane

β	local collection efficiency
γ	contact angle of liquid water with aerofoil or ice surface
δ	ice thickness
ε	ratio of molecular weights of water vapour and dry air
λ	exponent in approximate drag law (Equation (6))
μ	absolute viscosity
ν	kinematic viscosity
ρ	density
σ	surface tension

SUBSCRIPTS

a	air
d	droplet
f	full scale
fr	freezing
l	liquid
m	model scale
s	solid
surf	surface
w	water
∞	free stream

SUPERSCRIPTS

lg	liquid / gas interface
sg	solid / gas interface
sl	solid / liquid interface

1 INTRODUCTION

This thesis documents an experimental investigation into the feasibility of modifying the surface tension of the spray water used for ice accretion tests carried out in icing wind tunnels. Such modification may allow more flexibility in satisfying scaling requirements that apply to icing wind tunnel tests.

Ice accretion is a process that occurs when water droplets impinge and freeze on an object. The shape of the resulting ice accretion is usually very complex. Even for an accretion that starts on a simple shape, as the accretion process progresses over time, the shape of the accretion becomes increasingly complex. Lozowski and Gates (1991) state that for lengthy accretions the shapes are often very convoluted with large roughness elements and icicles complicating the geometry. Some ice accretion shapes occur with such frequency that terms such as "horned" and "spearhead" are common descriptions. Ice accretion can occur on any type of object. Examples include transmission lines, ships, hailstones, and aircraft engine intakes (Figures 1 through 6). In-flight ice accretion is a particular form of this process.

In-flight ice accretion usually occurs when an aircraft enters a region of air containing clouds of supercooled water droplets. The supercooled water droplets then impinge on the surface of the aircraft. When the surface temperature of the aircraft is at the

freezing temperature or below, the impinging water droplets lose their supercooled condition and freeze, resulting in an accretion of ice. The accretion tends to degrade the aerodynamic performance of the aircraft's lifting surfaces, including the wings, the horizontal tail, and any rotary wings including propellers. The change in the aerodynamic characteristics caused by the ice accretion is a function of the ice's size and shape, which is in turn a complex function of the type of ice, the lifting surface geometry, the angle of attack, and the ice accretion time. The accretion not only degrades the aerodynamic performance of the aircraft's lifting surfaces, but it also affects the handling of the aircraft. The longitudinal and lateral stability, and control properties can be markedly reduced (Wagner et al., 1997). Flights thus become very dangerous, and safety is compromised, thus there is a need to evaluate the change in the aerodynamic characteristics of aircraft components during icing conditions.

Aircraft engines can also be affected. Ice accretion that occurs on the inlet of an engine nacelle can cause distortion of the inlet air flow, which in turn, may cause the engine to flame-out, or may induce fan stall or compressor surge. Further, any ice that is shed, either from the engine nacelle inlet itself or from any other aircraft surface, and is subsequently ingested by the engine, can cause substantial damage to the fan blades and / or the compressor blades.

Flight testing in icing conditions is very expensive and very dangerous. Thus, the use of scale models in icing wind tunnels is an attractive alternative. However, the in-flight ice accretion process is complex and valid simulations of it in icing wind tunnels require that certain scaling requirements be satisfied. Unfortunately, it is not entirely clear at the present time what all of these scaling requirements are, or if, in fact, all of the requirements can be simultaneously satisfied during testing. In icing wind tunnel tests, as in other types of scale model tests, there may be conflicts between some of the scaling requirements if the model scale is less than that of the full scale icing surface, that is, if reduced scale testing is considered. However, reduced scale tests are very desirable since icing wind tunnels are of limited size. One possible way of alleviating conflicts between the scaling requirements is to

manipulate or adjust one or more of the physical parameters that are involved. Manipulation of the surface tension of the spray water was investigated in the present thesis work.

The approach used was to test circular cylinders of two different diameters with a spray consisting of water (H_2O) and with sprays consisting of water / 1-propanol solutions. The 1-propanol ($\text{CH}_3\text{CH}_2\text{CH}_2\text{OH}$) served to reduce the surface tension of the spray water. The icing wind tunnel tests were carried out in the Altitude Icing Wind Tunnel (AIWT) test facility at the National Research Council of Canada (NRC).

Chapter 2 of this thesis presents background information and a literature review of ice accretion, including a description of the in-flight ice accretion process as presently understood. Chapter 3 presents an outline of similarity requirements for icing scaling including a description of the interaction between the water droplets and the surface. A literature review of past ice accretion scaling methods is included in Chapter 3. Chapter 4 presents the experimental procedure that was used to determine the surface tension of the water / 1-propanol solutions, and the results. The experimental procedure and the results of the icing wind tunnel tests are presented in Chapter 5. Finally the conclusions and recommendations are presented in Chapters 6 and 7 respectively.

2 BACKGROUND INFORMATION AND LITERATURE REVIEW

2.1 Description of the Ice Accretion Process

Water droplets can exist in a supercooled liquid condition well below the freezing temperature for extended periods of time due to the absence of a freezing nucleus (Wagner et al., 1997). Clouds can thus exist with a liquid water content (*LWC*) of several grams of supercooled water droplets per cubic metre of air. When these droplets are in the vicinity of the leading edge of an aircraft, they will tend to deviate from the curvature of the streamlines of the air flow due to inertia forces. The larger droplets tend to deviate more from the streamlines and have less curved trajectories than the smaller droplets; thus, the droplets will either flow around the aircraft or impact upon it depending on their size. During most icing conditions, the median volume diameter (*MVD*) of the supercooled water droplets is rarely more than approximately 20 microns (Wagner et al., 1997). As a result, a diameter of 20 microns has become a standard for experimental, analytical, and numerical work.

Upon impact, if the surface temperature of the aircraft is at the freezing temperature or below, the water droplets lose their supercooled condition and will either freeze completely or freeze partially. As the droplets freeze, the temperature of the icing surface, which includes the aircraft surface and the accreted ice, is raised towards the freezing temperature due to the release of latent heat of fusion. The equilibrium temperature that is achieved is

determined by the balance between the rate at which the latent heat of fusion is released from the freezing droplets and the rate at which it can be dissipated to the environment by forced convection, and evaporation or sublimation.

The icing surface temperature cannot exceed the freezing temperature when icing is occurring, due to the freezing of the droplets; thus, for a given ambient temperature, air speed, and aircraft geometry, there is a critical liquid water content for which all of the accreted droplets will just freeze. When the liquid water content is below the critical value, all of the accreted droplets freeze completely and the equilibrium icing surface temperature is below the freezing temperature. This corresponds to a freezing fraction of one, where the freezing fraction, defined by Messenger (1953), is a measure of the mass fraction of the impinging water that freezes immediately upon impact. When the liquid water content is above the critical value, only some of the impinging water freezes and the equilibrium icing surface temperature is at the freezing temperature. This corresponds to a freezing fraction of less than one. The remaining unfrozen water runs back along the icing surface until enough heat is lost for it to freeze, or it may run back until some or all of it is blown off the surface (Bilanin, 1991).

2.2 In-Flight Ice Accretion Types

There are three generic types of ice accretions for which the freezing fraction has a distinct significance in their formation. When the freezing fraction has a value of one, which corresponds to ambient temperatures of roughly -20°C or less, coupled with lower liquid water contents, rime ice accretions occur. When the freezing fraction has a value close to zero, which corresponds to ambient temperatures nearer the freezing temperature, coupled with higher liquid water contents, glaze ice accretions occur. Finally, when the freezing fraction has a value between approximately 0.3 and 1.0, mixed ice accretions occur, which have the characteristics of both rime ice accretions and glaze ice accretions (Ruff, 1986). The

following discussions of the characteristics of ice accretion are based on the observations of Hansman et al. (1993).

2.2.1 Rime Ice Accretions

Rime ice accretions are characterized by a relatively streamlined, but rough, ice shape which is restricted to the impingement zone and protrudes forward into the local airstream (Figure 7). The general shape of rime ice accretions does not change with accretion time. It grows forward parallel to the local airstream and can act as an aerodynamic "nose flap", which, especially at high angles of attack, can add camber to the aerofoil and thus actually improve some of the aerodynamic characteristics (Gray and von Glahn, 1958). Rime ice accretions are relatively white and opaque, believed to be caused by the presence of microscopic air bubbles frozen within the individual water droplets rather than air trapped between the frozen water droplets (Macklin, 1962).

Rime ice often gives rise to feather growth in the off-stagnation regions. The feathers grow on local roughness elements that act as nucleation sites. It appears that the feathers start to grow once the roughness elements penetrate further into the turbulent boundary layer where the local air velocity is greater (Hansman et al., 1993). This results in higher local collection efficiencies and higher convective heat transfer coefficients. The feathers are usually very brittle and tend to break if they grow too large or too far above the surface. The density of the feathers in rime ice accretions tends to be less than that in other ice accretions as the tips of the feathers tend to merge, leaving voids near their roots (Hansman et al., 1993).

2.2.2 Glaze Ice Accretions

Glaze ice accretions are characterised, in general, by a well-defined double horned ice shape that tends to protrude radially outwards from the icing surface normal to the local

airstream (Figure 8). The ice is very wet and is clear in appearance as there is little or no air entrapped within it (Macklin, 1962). The upper horn acts like a spoiler by increasing the drag and reducing the lift, whereas the lower horn usually has relatively little effect due to the low local air speeds (Wilder, 1977). During glaze icing, the surface is very wet as the freezing fraction is fairly close to zero, thus a considerable amount of water runs back along the icing surface and freezes when the heat transfer is great enough to remove the latent heat of fusion. The horn growth is initiated at the downstream boundary of this run-back region (Hansman et al., 1993). The high local air velocity over the tips of the horns enhances the convective heat transfer, promoting the continued growth of the horns. As they grow, the local collection efficiency also increases, further promoting the growth (Ruff, 1986). As the icing time is increased, the projected frontal area of the ice accretion is substantially increased.

2.2.3 Mixed Ice Accretions

Mixed ice accretions are characterised by glaze ice in the stagnation region and rime ice in the off-stagnation regions. The size of the glaze ice accretion in the stagnation region will diminish as the freezing fraction approaches one. Feathers are also present during mixed ice accretions in the off-stagnation regions. They are initiated at the location at which the run-back water freezes, which acts as a nucleation point (Hansman et al., 1993). The feathers rapidly grow forward into the airstream. However, the density of the feathers in mixed ice accretions is greater than that in rime ice accretions, as once the feather growth has been initiated, the unfrozen water running back from the stagnation region tends to fill the gaps between the feathers and freezes. Olsen and Walker (1986) have observed that this results in the accretion having streaks of clear and opaque ice, as the run-back water tends to freeze slowly, causing it to be clear and transparent. Characteristic of mixed ice accretions, and for unknown reasons, the growth of the feathers tends to slow once they have reached the upstream boundary of the ice accretion, which is believed to be due to the interaction between the feathers and the run-back water (Hansman et al., 1993). This leads to a fairly flat leading edge profile.

When there are higher liquid water contents and larger water droplets under otherwise similar conditions, mixed ice accretions can be characterised by horns that protrude forward into the airstream (Hansman et al., 1993). This type of ice accretion also has feather growth. However, the feather growth does not slow once it has reached the upstream boundary of the ice accretion. The reason for the difference between the two ice accretions is not clear, however it is believed that this type of ice accretion could be a later evolution of mixed ice accretions (Hansman et al., 1993).

2.3 Modelling of Ice Accretion

The danger that is presented from in-flight icing has forced the civil certification authorities, the Joint Airworthiness Authority (JAA) in Europe and the Federal Aviation Administration (FAA) in the United States, to establish icing certification requirements that aircraft manufacturers must comply with. Aircraft manufacturers must demonstrate that their aircraft meet these requirements. This normally requires that the aircraft be equipped with ice protection systems (i.e. de-icing or anti-icing systems). Aircraft that do not meet these requirements are not permitted to fly into known icing conditions.

To obtain certification, aircraft manufacturers must demonstrate that safe flight can be maintained during icing conditions. This is either done through flight tests, or done through testing of scale models in icing wind tunnels and computer simulation. Flight testing in natural icing conditions gives the most realistic results; however, it is very expensive and can be very dangerous. Further, conducting successful icing flight tests requires specific meteorological conditions; however, neither the meteorological conditions nor the location at which they can be encountered are precisely known ahead of time. Thus, much flight time can be wasted and icing flight tests tend to be conducted in conditions that are not always as severe as required. Some icing flight tests, however, must be conducted. They are conducted in order to verify that the shapes of the ice accretions that the aircraft will experience are similar to those that have been predicted in icing wind tunnels or by computer simulation, and

to evaluate the degradation of aerodynamic performance and handling characteristics. If the critical ice accretion shapes can be predicted in icing wind tunnels or by computer simulation, artificial models of these shapes can then be attached to the aircraft surfaces to assess the effects of ice accretion on performance and handling qualities by flight in dry air.

Full scale testing of complete aircraft in icing wind tunnels is not an option due to limitations in their size. Thus, when icing wind tunnels are used, only certain components of an aircraft can be tested at any one time, or reduced scale testing must be carried out. Many models, both physical and computational, for simulating or analysing the ice accretion process have been developed. Some of these have been used for research and development, for the design of aircraft, and have also been used for proving compliance with the icing requirements set out by regulatory authorities. All models must begin with certain input variables. These are usually the meteorological conditions that have been found to influence ice accretion, the flight speed, the physical description of the icing surface geometry, and the icing surface orientation. The models are used to predict the ice shape, the ice mass, and the aerodynamic characteristics of the accreted ice.

As the shapes of the accreted ice are usually complex, most of the work in the field of ice accretion modelling has been done on simple body shapes, such as cylinders, plates, and aerofoils, where there is information available on the flow field and the heat transfer characteristics (Lozowski and Gates, 1991). However, even for simple shapes, as the ice accretion process progresses in time, the geometry of the accreted ice becomes increasingly complex.

Ice accretion models for aircraft perhaps have the longest history. There are some unique features in aircraft icing, namely viscous heating, and, if flight speeds are high, adiabatic compression and expansion. The flow itself is also unique, as it ranges from the quasi-two-dimensional cylinder and aerofoil to the fully three-dimensional fuselage. In addition, for aircraft, there is more concern for the accreted ice's effect on lift, stability, and

the operation of control surfaces, than concern for the mass of the ice itself. Further, as mentioned in Chapter 1, there is also concern for ice that is shed from the aircraft and is subsequently ingested by engines.

Aircraft manufacturers, such as Douglas Aircraft Co., Lockheed Aircraft Corp., Boeing Airplane Co., and British Aircraft Corp. have all developed their own computational models of the ice accretion process (Ruff, 1986). Various other methods are in use for scaling and interpretation of physical model tests. These include the ONERA scaling analysis of Armand et al. (1977) and the AEDC scaling analysis of Ruff (1986).

Computational models include SIMICE, which was developed from the results of Ruff (1986), and LEWICE, which is the NASA Lewis ice accretion prediction code. Several researchers have developed and modified the LEWICE code in order to improve the results. They include Hansman et al. (1991), and Al-Khalil et al. (1994). Other computational models that have been developed include INTERICE (Paraschivoiu et al., 1993) and FENSAP-ICE (Habashi et al., 1997).

Unfortunately, the physics behind the ice accretion process are not fully understood. Thus, not all of the physical details that the computational models or scaling analyses require are known. Because of this, assumptions must be introduced into the models which can cause them to be of restricted usefulness and can cause errors to be introduced. This is especially evident by the number of different ice accretion scaling practices that have been developed to guide and interpret physical modelling. Many of these practices have been tested by Ruff (1986) and Anderson (1994), who have shown that although most of the practices could produce similar rime ice accretions, none could reliably produce satisfactory mixed or glaze ice accretions.

3 REVIEW OF SIMILARITY REQUIREMENTS AND SCALING PRACTICES

The purpose of icing testing is to reproduce, as realistically as possible, natural in-flight icing conditions. In order to properly scale the ice accretion process, the model scale conditions must be dynamically similar to the full scale conditions. The term dynamically similar refers to the model test conditions being properly scaled such that the test results are representative of the full scale results. Reduced scale testing becomes a necessity due to the size limitations of icing wind tunnel facilities; however, Anderson (1994) and Kind (1997) have found that researchers are often faced with icing wind tunnel and meteorological limitations. The icing wind tunnel can often only operate over a limited range of air speeds and water spray conditions. This often forces researchers to assess the icing behaviour of one set of meteorological conditions by using a different set of meteorological conditions in the icing wind tunnel. The similarity requirements of the ice accretion process are a consideration of the physical phenomena involved (Kind, 1997).

3.1 The Buckingham II Theorem

Bilanin (1991) attempted, through dimensional analysis, to develop a list of independent parameters that would govern dynamic similarity of the ice accretion process. He started with a list of the variables that are assumed to affect the ice accretion process (reproduced in Table 1). Evaporation and condensation from the icing surface are neglected

as the air in icing conditions is nearly saturated, and the heat capacity of the icing surface is neglected as it is assumed to be at steady state (no temperature change). If the Buckingham II theorem is applied to the list of variables in Table 1 then we will find that there are 18 nondimensional parameters that affect the ice accretion process (Table 2).

The first two parameters, π_1 and π_2 , are independent. Parameters π_3 and π_4 require that if the characteristic length in the model scale is reduced from the full scale then the water droplet size and the mean spacing between water droplets in the model scale must also be reduced by the same factor. Parameters π_5 through π_{13} are ratios of the properties of the air and the liquid. These parameters can easily be matched by using the same substances, air and water, for the model scale tests as used for the full scale tests. The requirement of π_{14} is that the ratio of freezing temperature to free stream static temperature is held constant. This is the same as requiring a constant temperature difference between the freezing temperature and the free stream static temperature if water and air are the substances being used in the model scale. In other words, all of the model scale tests must be done at the same free stream static temperature as the full scale tests. When this is done, π_{15} is automatically held constant.

The last three parameters, π_{16} through π_{18} , are the Mach number, M , the free stream Reynolds number based on characteristic length, Re_L , and the Weber number, We , respectively. These three parameters require that the free stream velocity varies as:

$$U_\infty = \text{const}, \quad U_\infty \propto \frac{1}{L}, \quad U_\infty \propto \frac{1}{\sqrt{L}}.$$

Thus it is impossible to match the Mach number, the free stream Reynolds number based on characteristic length, and the Weber number in the model scale tests if reduced scale testing is to be considered, and the Buckingham II theorem has failed to give a suitable scaling methodology.

In view of the conflicts between some of the above scaling requirements, a more detailed look at the physical understanding of the ice accretion process is needed in the hope of simplifying the scaling requirements. Reasonable compromises and approximations must be identified.

3.2 Review of Similarity and Scaling Requirements

The following discussion of scaling requirements is based on the reviews by Ruff (1986) and Kind (1997). As stated earlier, ice accretion usually occurs when an aircraft enters a region of air containing supercooled water droplets. The droplets follow trajectories determined by the viscous drag and inertia forces that act upon them, and will either flow around the aircraft or impinge upon it. If the droplets impinge on the aircraft, they will either freeze in place, run back along the surface and freeze in another location, or run back along the surface and, perhaps, as suggested by Bilanin (1991), some or all of them will be blown off the surface. The shape of the ice accretion is a result of the distribution of the droplets impinging on the aircraft, the location at which they freeze, and the type of ice formed. Further, the ice growth is an accretion process. Thus, each layer of ice builds up on the previous layer. Thus, provided the accretion starts with a similar icing surface with similar surface characteristics, the ice accretion process will continue similarly in both the model scale and the full scale.

From this description, the physical phenomena of the ice accretion process that must be considered in an icing model can be identified. These are: the flow field around the icing surface, including the accreted ice, the droplet trajectories and impingement characteristics, the total mass of water impinging on the icing surface, and the thermodynamics and the fluid dynamics of the run-back water, and the freezing processes. Each of these will be considered in turn in order to identify the scaling requirements used in this study.

3.2.1 Flow Field Scaling Requirements

For flow field similarity it is required that the model scale and the full scale icing surfaces have scaled geometries. The aerodynamic pressure, force, and moment coefficients will be matched if this is done. Further, the Mach number, if compressibility effects are significant, and the free stream Reynolds number based on characteristic length should also be matched. As already mentioned this cannot be done. However, for most aircraft, icing conditions are encountered at relatively low Mach numbers; thus, the Mach number can be excluded from the scaling requirements. Matching the free stream Reynolds number based on characteristic length will put stringent limitations on the test conditions. These will, in general, not be compatible with the other scaling parameters. However, in most aerodynamic testing, there are well-established methods for dealing with this problem in so far as scaling of aerodynamic pressures, forces, and moments are concerned. Further, Anderson (1994) states that the free stream Reynolds number may not need to be matched as icing occurs predominately at the leading edge of the body where the boundary layer is still thin.

From the above discussion, the requirement for producing similar flow field characteristics is that the model scale and the full scale icing surfaces must have scaled geometries.

3.2.2 Droplet Trajectory Scaling Requirements

It is also required that the trajectories of the water droplets that are present in the flow field be similar. Thus a scaling parameter that will produce similar regions of impingement and similar impingement mass distributions on the surfaces of the scaled icing surfaces is needed.

The following discussion of the scaling requirements of droplet trajectories is based on Bragg (1982), Ruff (1986), and Kind (1997). Classical particle trajectory equations can

be used for the calculation of the droplet trajectories if the flow field has been accurately predicted. By using these equations it is assumed that the concentration of the water droplets is small, that is, less than 700 particles per cubic centimetre. Thus two-phase flow effects, and droplet collision and break up can be neglected (Ruff, 1986).

By applying Newton's Second Law of motion to a single spherical particle moving relative to its surroundings, the differential equation for the droplet trajectory can be derived. There are many forces that act upon the droplet; however, for most applications only the viscous drag force and the inertia forces need to be considered. Thus, the differential equation describing the droplet trajectory is

$$m \frac{d^2 \bar{x}}{dt^2} = \bar{D} + m \bar{g}. \quad (1)$$

Although the gravity force is included in Equation (1), it will be shown below that it is generally negligible. By approximating the droplets as rigid spheres, Stokes' equation for the drag of a sphere can be used

$$\bar{D}_{stokes} = 3\pi\mu_a d(\bar{U}_a - \bar{U}_d). \quad (2)$$

However, Stokes' equation is only valid for flows where the relative Reynolds number based on droplet diameter is less than one (Figure 9). The flows that are usually encountered during icing conditions are outside of this range. Therefore, a correction factor must be used in Equation (2). The correction factor is given by

$$\frac{C_D Re_{rel}}{24} = f[Re, d], \quad (3)$$

where Re_{rel} is the relative Reynolds number based on droplet diameter, which is given by

$$Re_{rel} = \frac{\rho_a d U_\infty |\bar{U}'_a - \bar{U}'_d|}{\mu_a},$$

where $\overline{U_a'}$ is the dimensionless air velocity vector, and $\overline{U_d'}$ is the dimensionless droplet velocity vector. The correction factor, in Equation (3), equals one when Stokes law is valid; however, it is a function of the relative Reynolds number based on droplet diameter in general. By multiplying Equation (2) by the correction factor, the corrected equation for the drag of a sphere becomes

$$\overline{D} = 3\pi\mu_a d \left(\frac{C_D Re_{rel}}{24} \right) (\overline{U_a'} - \overline{U_d'}). \quad (4)$$

When Stokes law is valid Equation (4) reduces to Equation (2). At all other conditions, the correction factor is less than one, which accounts for the deviation from Stokes law. By substituting Equation (4) into Equation (1) and then making the equation dimensionless, the following equation results

$$K \left(\frac{d^2 \overline{U_d'}}{dt'^2} \right) = \left(\frac{C_D Re_{rel}}{24} \right) (\overline{U_a'} - \overline{U_d'}) + \frac{K}{Fr^2}, \quad (5)$$

where t' is the dimensionless time. There are two other dimensionless parameters in Equation (5), the inertia parameter, K , and the Froude number, Fr . These are given by

$$K = \frac{\rho_l d^2 U_\infty}{18L\mu_a},$$

and

$$Fr = \frac{U_\infty}{\sqrt{Lg}}.$$

As the diameters of the supercooled water droplets are usually in the order of 10–50 microns during in-flight icing, the gravity force is considered negligible compared to the viscous drag; thus, the trajectories of the droplets are dependent only upon the viscous drag and the inertia forces (Kind, 1997), and the second term on the right-hand side of Equation (5) becomes negligible compared to the first term. The sphere drag law can then be expressed as a

function of only the relative Reynolds number based on droplet diameter which is related to the free stream Reynolds number based on droplet diameter, Re_d , by

$$Re_{rel} = Re_d \left| \overline{U'_a} - \overline{U'_d} \right|.$$

Thus from the Stokes' law correction factor comes the third similarity parameter,

$$Re_d = \frac{\rho_a U_\infty d}{\mu_a}.$$

The droplet trajectory is thus a function of three parameters; the inertia parameter, the Froude number, and the free stream Reynolds number based on droplet diameter. However, as mentioned previously the gravity term is negligible compared to the viscous drag term, thus the Froude number does not need to be matched.

This leaves only two parameters that must be matched. However, there are still conflicts with the scaling requirements as only the free stream velocity and the droplet diameter can be varied. The inertia parameter and the free stream Reynolds number based on droplet diameter require that the free stream velocity varies as:

$$U_\infty \propto \frac{1}{d^2}, \quad U_\infty \propto \frac{1}{d}.$$

The work of Bragg (1982) will be used in order to solve this problem. His work is the most thorough and gives the best results (Kind, 1997). Taking the inertia parameter and dividing it by the correction factor from Stokes' law gives

$$\frac{4}{3} \frac{\rho_l d}{\rho_a L} \frac{1}{C_D \left| \overline{U'_a} - \overline{U'_d} \right|}.$$

If this ratio is kept constant then there is one scaling parameter, assuming that the flow field has already been scaled. However, this term is not constant throughout the trajectory of the droplet since the relative Reynolds number based on droplet diameter is based on the relative velocity between the droplet and the air. Thus a representative value that is unique for a

given trajectory is needed. Bragg assumed that the Stokes' law parameter is a function of only the relative Reynolds number based on droplet diameter,

$$\frac{C_D Re_{rel}}{24} = c Re_{rel}^\lambda, \quad (6)$$

where c and λ are constants. Taking the logarithm of Equation (6) gives

$$\log\left(\frac{C_D Re_{rel}}{24}\right) = \log c + \lambda \log Re_{rel}.$$

This gives a straight line in log-log coordinates. Figure 10 shows the comparison of Bragg's approximation with a standard curve of $C_D Re_{rel}/24$ vs. Re_{rel} using the values of $c=0.845$ and $\lambda=0.35$ for the constants. The trajectory equation, Equation 5, then becomes

$$\left(\frac{d^2 \overline{U'_d}}{dt'^2}\right) = c \left(\frac{Re_d^\lambda}{K}\right) \left|\overline{U'_a} - \overline{U'_d}\right|^\lambda (\overline{U'_a} - \overline{U'_d}). \quad (7)$$

From this Bragg defined the trajectory scaling parameter, $\overline{K}$, where

$$\overline{K} = \frac{K}{Re_d^\lambda}. \quad (8)$$

Since λ occurs in both the $1/\overline{K}$ term and the $|\overline{U'_a} - \overline{U'_d}|^\lambda$ term in Equation (7), λ cannot, in general, be a function of the free stream Reynolds number based on droplet diameter. Therefore a value for λ must be chosen that forms a best fit for all of the droplets over the range of Reynolds numbers that will be experienced. Bragg (1982) recommends a value of 0.35 for λ . There is now a simple parameter that combines K and Re_d and thus the trajectory equation becomes a function of $\overline{K}$ only.

Matching the trajectory scaling parameter is much less restrictive than that which dimensional analysis would lead to. However, it does entail an approximation. An approximate fit to the drag law, Equation (6), must be used. However Bragg (1982) has shown that matching the trajectory scaling parameter gives excellent scaling of the droplet trajectories. Figure 11 shows the collapse of the local collection efficiency for $\overline{K}$ and also for

the parameter K_o , which was defined by Langmuir and Blodgett (1946) and is an average of $24K/C_D Re_d$ over the Reynolds number range from 0 to $\rho_d d U_d / \mu_a$ (Kind, 1997).

Thus the requirement for scaling the droplet trajectories is matching the trajectory scaling parameter, Equation (8), in the model scale and full scale tests.

3.2.3 Impingement-Freezing Process Scaling Requirements

The impingement-freezing process is the most difficult to scale. This is due to the complex dynamic, capillary, and thermal phenomena, including heat and mass transfer, that are involved. The impingement-freezing process can be divided into two sections. These are the scaling to obtain the correct distribution of the volume of impinging water (accumulation scaling requirements), and the scaling to obtain the correct freezing fraction of impinging water (thermodynamic scaling requirements).

3.2.3.1 Accumulation Scaling Requirements

The scaling requirements in Section 3.2.2 ensured that the trajectories of the impinging water are similar. Thus for ice accretions formed on two geometrically scaled icing surfaces to be similar, the total volume of impinging water per unit area, V'' , must be scaled. This is done by requiring that

$$V''_m = S V''_f \quad (9)$$

where S is the model scale factor defined by

$$S = \frac{L_m}{L_f} \quad (10)$$

L_m and L_f are the characteristic lengths for the model scale and the full scale icing surfaces respectively. If Equation (10) is substituted into Equation (9), the following equation results

$$\left(\frac{V''}{L} \right)_m = \left(\frac{V''}{L} \right)_f \quad (11)$$

The total volume of impinging water per unit area on the icing surface during a time interval, t , is given by

$$V'' = \frac{LWC U_\infty \beta t}{\rho_l}, \quad (12)$$

where LWC is the liquid water content, and β is the local collection efficiency which is defined as

$$\beta = \frac{dy_o}{ds}$$

where y_o is the vertical distance between the upper surface impingement limit and lower surface impingement limit (Figure 12). By substituting Equation (12) into Equation (11) a relationship that will scale the total volume of impinging water per unit area at each point on the geometrically scaled objects is achieved

$$\left(\frac{LWC U_\infty \beta t}{\rho_l L} \right)_m = \left(\frac{LWC U_\infty \beta t}{\rho_l L} \right)_f \quad (13)$$

Since the trajectory scaling parameter has ensured that the local collection efficiency at each location on the icing surface is the same, it can be removed from both sides of Equation (13) to give

$$\left(\frac{LWC U_\infty t}{\rho_l L} \right)_m = \left(\frac{LWC U_\infty t}{\rho_l L} \right)_f \quad (14)$$

The parameter given on both sides of Equation (14) is called the accumulation parameter, A_c . It can be thought of as a time scaling equation and will give us some flexibility in our choice of liquid water content and free stream velocity (Kind, 1997).

Therefore the requirement for scaling the total mass of water per unit area that impinges on the surface is matching the accumulation parameter given by Equation (14).

3.2.3.2 Thermodynamic Scaling Requirements

It is now required to scale the thermodynamics of the system so that the type, the surface characteristics, and the density of the ice accretion are similar in the full scale and the model scale. In order to formulate a mathematical expression that will define the thermodynamic scaling parameters, it is necessary to develop a physical model of the ice accretion process (Ruff, 1986). The assumption was made in Section 3.2.1 that if the geometries are scaled, the normalized pressure and air temperature distributions in the region of droplet impingement will be similar. With the scaling of the trajectory scaling parameter, the distribution of mass impingement on the surface of the scaled icing surfaces has been scaled. The distribution of the thermodynamic characteristics should also be similar in the full scale and model scale and this imposes additional scaling requirements.

The traditional approach to the thermodynamics of icing introduced by Messenger (1953) will be used. Starting with the quasi-steady state heat balance equation, which is based on the assumption that the accretion is in thermal equilibrium, the value of the steady state temperature of the substrate, T_{surf} is dependent on the energy balance of the quantities shown in Figure 13. The rate of heat loss due to convection

$$q_c = hA_r(T_{surf} - T_\infty),$$

where h is the convective heat transfer coefficient, and A_r is the surface area. The rate of heat loss due to evaporation or sublimation of water vapour

$$q_e = 2.90 hA_r \frac{h_{fg}}{p_\infty} (p_{vap,s} - p_{vap,\infty}) \quad (15)$$

where h_{fg} is the latent heat of evaporation, p_∞ the free stream pressure, and $p_{vap,s}$ and $p_{vap,\infty}$ are the vapour pressure of the solid and the free stream vapour pressure respectively. When the freezing fraction, n , equals one (rime icing) the latent heat of evaporation should be replaced with the latent heat of sublimation, h_{sg} . The value of 2.90 that appears in Equation (15) is an empirical constant that relates the mass transfer to the convection heat transfer. The sensible

heat required to raise the temperature of the impinging water droplets due to the temperature rise from T_∞ to T_{surf}

$$q_w = \dot{m}'' A_r c_{p,l} (T_{surf} - T_\infty)$$

where $\dot{m}''$ is the rate of water catch per unit of surface area. The heat gain due to the release of the latent heat of fusion as the supercooled water droplets impinge and freeze, and then as a solid cool to the icing surface temperature

$$q_f = \dot{m}'' A_r n (h_{fs} - c_{p,s} (T_{surf} - T_\infty))$$

however as $h_{fs} \gg c_{p,s} (T_{surf} - T_\infty)$ this simplifies to

$$q_f = \dot{m}'' A_r n h_{fs}. \quad (16)$$

The heat gain due to the viscous or frictional heating in the boundary layer

$$q_v = h A_r r \frac{U_\infty^2}{2 c_{p,a}}$$

The recovery factor, r , represents the ratio of the frictional temperature increase to that due to adiabatic compression, $U_\infty^2 / 2 c_{p,a}$ (Schlichting, 1979). Finally, the equivalent heat gain due to the conversion of kinetic energy of the water droplets as they strike the icing surface

$$q_K = \dot{m}'' A_r \frac{U_\infty^2}{2}$$

The complete heat balance equation can then be written as

$$q_c + q_e + q_w - q_f - q_v - q_K = 0. \quad (17)$$

The quantity n , in Equation (16), is the freezing fraction.

For situations when the icing conditions are such that the heat loss terms exceed the heat gain terms, all the droplets freeze immediately upon impact which results in a rime ice accretion. Recall that rime ice is characterized by a stagnation point freezing fraction equal to one. When the icing conditions are such that the heat gain terms exceed the heat loss terms

(i.e. when the liquid water content is relatively high and the free stream temperature is close to the freezing temperature), some of the impinging water will not freeze, but will remain as a liquid and run back along the substrate. Recall that in this case the value of the freezing fraction will be less than one. When this happens, the heat quantity in Equation (15), h_{fs} , corresponds to the latent heat of evaporation rather than the latent heat of sublimation, even though a large portion of the impinging water may be present as ice.

The discussion of the freezing fraction and its significance in the formation of ice accretions has led to the requirement that the model scale and full scale freezing fractions must have the same values at corresponding positions.

Consider any control volume in the ice accretion region. It has been found that when the ambient air is saturated, as in icing conditions, the heat loss by evaporation is roughly equal to the heat loss by convection, or $q_e/q_c \sim 1$ (Kind, 1997). It is also found that the heat gain due to the viscous or frictional heating in the boundary layer and the equivalent heat gain due to the kinetic energy of the water droplets as they strike the icing surface are normally negligible in glaze icing conditions. Equation (17) then becomes

$$q_c + \frac{q_e}{q_c} q_c + q_w - q_f = 0. \quad (18)$$

By substituting the various heat terms into Equation (18) the following approximate heat balance equation is achieved

$$\left(1 + \frac{q_e}{q_c} \right) h A_r (T_{surf} - T_\infty) + \dot{m}'' A_r c_{p,l} (T_{surf} - T_\infty) - \dot{m}'' A_r n h_{fs} = 0. \quad (19)$$

Solving Equation (19) for the freezing fraction gives

$$n = \left(\frac{\left(1 + \frac{q_e}{q_c} \right) h (T_{surf} - T_\infty)}{\dot{m}'' h_{fs}} \right) + \left(\frac{c_{p,l} (T_{surf} - T_\infty)}{h_{fs}} \right) \quad (20)$$

noting that

$$\dot{m}'' = LWC \beta U_{\infty}.$$

Thus Equation (20) becomes

$$n = \left(\frac{\left(1 + \frac{q_e}{q_c} \right) h (T_{surf} - T_{\infty})}{LWC \beta U_{\infty} h_{fs}} \right) + \left(\frac{c_{p,l} (T_{surf} - T_{\infty})}{h_{fs}} \right). \quad (21)$$

This implies that the freezing fraction distribution will be correctly matched if the following two parameters are matched for full scale and model scale,

$$A = \frac{c_{p,l} (T_{surf} - T_{\infty})}{h_{fs}} \quad (22)$$

and

$$B = \frac{\left(1 + \frac{q_e}{q_c} \right) h (T_{surf} - T_{\infty})}{LWC U_{\infty} h_{fs}}, \quad (23)$$

where B is called the convective / latent heat ratio. Instead of A , b can be matched, where b is called the relative heat factor and is defined as follows, taking note that as previously mentioned the heat loss by evaporation is roughly equal to the heat loss by convection, or $q_e/q_c \sim 1$,

$$b = 2 \beta \frac{A}{B} = \frac{LWC U_{\infty} \beta c_{p,l}}{h}. \quad (24)$$

Kind (1997) suggests that it is more important to match the parameter B than either A or b . This is because the term $c_{p,l}/h_{fs}$ is only $0.012/^{\circ}\text{C}$ for water. Thus, the last term in Equation (21) will be relatively small when compared to the other terms. The parameter B represents the ratio of convective heat loss to potential for latent heat release. A value of 0.5 for B represents the approximate boundary between rime icing and glaze icing, with rime icing

occurring for values of B greater than 0.5 and glaze or mixed icing occurring for values of B less than 0.5.

It is very difficult to achieve the desired value for the convective heat transfer coefficient, h , that is contained in Equation (23) at all locations in the ice accretion region (Kind, 1997). This is due to the complex functional dependence on the thermal conductivity of the air, the free stream Reynolds number based on characteristic length, the Prandtl number of the air, the position on the icing surface, and the roughness of the icing surface. The thermal conductivity of the air and the Prandtl number of the air will remain unchanged in the model scale; however, if reduced scale icing tests are to be conducted, the free stream Reynolds number based on characteristic length will most likely be less than the full scale value. The dependence of the convective heat transfer coefficient on the free stream Reynolds number based on characteristic length is

$$h \propto Re_L^x. \quad (25)$$

The value for the exponent x , in Equation (25), can range from 0.330 to 0.805 and above depending on the free stream Reynolds number based on characteristic length (Holman, 1990). Typically, values for x between 0.5 and 0.8 are used. Furthermore, the convective heat transfer coefficient is strongly affected by roughness. It has been shown that rough cylinders can have convective heat transfer coefficients as high as 7.5 times that of smooth cylinders (Kind, 1997). As mentioned in Section 2.2, glaze ice accretions are strongly affected by roughness. However, there is very little data available on the effects of roughness on the convective heat transfer coefficient (Kind, 1997).

Thus, the requirements for producing similar thermodynamic characteristics are by matching the parameter B given by Equation (23), and if possible by matching either the parameter A or the parameter b given by Equations (22) and (24) respectively. Further, a reasonable choice for the convective heat transfer coefficient must be made when evaluating these parameters for the model and full scale cases.

3.2.4 Scaling Requirements for Droplet-Surface Interactions and Water Movement

Recent works carried out by Olsen and Walker (1986), Hansman and Turnock (1989), and Hansman et al. (1991) have shown the detailed behaviour of the run back water during glaze ice accretions through the use of close-up cameras.

During glaze ice accretions, Olsen and Walker (1986) found that initially the surface of the stagnation region was quickly covered by large rapidly growing liquid water drops. As the drops grew in size, the larger drops began to move away from the stagnation region under the effects of aerodynamic forces. After a short period of time the liquid water drops in the stagnation region stopped moving as roughness on the surface greatly increased the surface tension adhesion forces and prevented the aerodynamic forces from further moving the drops. The liquid water drops then collected in the stagnation region, replacing it with a thin liquid film of water with a thin ice layer and hills growing underneath. Outside of the stagnation region very large stationary ice hills were growing. The width of the thin liquid film in the stagnation region decreased with time. Olsen and Walker (1986) stated that it appears that the ice hills in the stagnation region are wet and have smooth tops, whereas the ice hills in the off-stagnation region are not covered with water and are rough.

The shape of glaze ice formation is affected by the initial flow of water on the surface of the icing surface. The shape of the ice formation and the roughness also affect the local air flow which affects the local droplet catch, which in turn further affects the shape of the ice formation. Thus, the transportation of the water in glaze ice accretions has a direct influence on the shape of the ice formation. The behaviour of the transport of the water is influenced by the surface tension forces, and by aerodynamic and body forces (Hansman and Turnock, 1989). Surface tension forces minimize the surface area of the liquid, causing the liquid to form beads or rivulets, and oppose the flow of water along the surface caused by

aerodynamic forces. Thus it would appear that surface tension forces play an important role in glaze ice accretions and must also be considered in the similarity requirements.

Tests conducted by Hansman and Turnock (1989) in which a surfactant, Photoflo, was added to the spray water in icing tests produced very different ice accretions than those in which where no surfactant was added. This showed that the surface tension forces do play an important role in glaze ice accretions.

The following discussion of the droplet-surface interaction is based on Defay and Prigogine (1966), and Padday (1969). When two fluids are in contact with each other, they are separated by a thin interfacial layer. The properties of the interfacial layer are different from that of either of the two bulk fluid phases. Mechanically it is as though the two fluids are separated by a contractile skin of infinitesimal thickness (Defay and Prigogine, 1966). The existence of the contractile skin is further shown by the fact that work has to be done to create new surface area. The work required to create the new surface area must be done against a real force, that of the tension of the contractile skin (Padday, 1969).

The real system is shown in Figure 14. The two bulk phases BB' and AA' are separated by the interfacial layer, or surface layer, $A'B'$. However, a simplified model is achieved when the real system is replaced by a system where the two bulk phases are separated by only a geometric surface of tension, as shown in Figure 15. In Figure 14, between A and A' there is a homogeneous fluid on either side of the plane AB . Thus, the only mechanical force is the hydrostatic pressure p'' . Similarly between B' and B , the only force is the hydrostatic pressure p' . However, between A' and B' is the non-uniform interfacial layer where the forces vary according to an unknown law. Now consider Figure 15. Here the bulk phases remain homogeneous right up to the surface of tension. Thus the hydrostatic pressure p'' acts between A and C , and the hydrostatic pressure p' acts between C and B . Further, we attribute a tension, σ , at the surface of separation such that the model is

mechanically equivalent to the real system (Defay and Prigogine, 1966). This tension, σ , is known as the surface tension.

Consider any point P on a surface as shown in Figure 16. For any pair of orthogonal lines, AB and CD , on the surface, there will be a corresponding pair of radii of curvature, R_1 and R_2 . Mechanical equilibrium will be achieved if

$$p'' - p' = \sigma \left(\frac{1}{R_1} + \frac{1}{R_2} \right). \quad (26)$$

This equation is known as Laplace's formula and relates p'' , p' , R_1 , R_2 , and σ .

As a solid does not have mobility at its surface, a solid / liquid interfacial layer does not have the same characteristics as a liquid / liquid interfacial layer. Thus, in general, an experimental determination of its surface tension cannot be made (Defay and Prigogine, 1966). Consider the line of contact between a liquid / gas interface and a solid surface, as shown in Figure 17. If the solid / gas and solid / liquid interface exerted no force on the line of contact, then the system could not be in equilibrium as there is the force $\sigma^g \cos \gamma$ acting on this line, where σ^g is the liquid / gas interfacial surface tension and γ is the contact angle (Defay and Prigogine, 1966). Thus there must be surface tension forces, or forces of a similar nature, that act on the line of contact that are associated with the solid / gas and solid / liquid interfaces. By denoting these forces as σ^s and σ^l respectively, the following equation can be written

$$\sigma^g \cos \gamma = \sigma^s - \sigma^l$$

This equation relates the contact angle to the surface tensions of the three interfaces. The liquid / gas interfacial surface tension, σ^g , can be measured and thus the contact angle becomes a measure of the solid / gas and solid / liquid interfacial surface tensions.

Thus, it is also desirable to include the surface tension effects and the contact angle in the similarity requirements. The contact angle was introduced in the dimensional analysis

carried out in Section 3.1, and is already a dimensionless quantity. Thus, it should, by itself, be matched. The surface tension was also introduced in Section 3.1. It was contained within the Weber number

$$We = \frac{\rho_a U_\infty^2 L}{\sigma^{lg}}. \quad (27)$$

The Weber number represents the ratio of inertial or aerodynamic forces to surface tension forces. However, the surface tension also appears in another dimensionless parameter, namely the Capillary number, which is given by

$$Ca = \frac{\mu_l U_\infty}{\sigma^{lg}}, \quad (28)$$

where μ_l is the absolute viscosity of the liquid. The Capillary number represents the ratio of viscous forces to surface tension forces.

From the discussion above, the requirements for scaling the droplet-surface interactions are to match the contact angle, γ , and to match, if possible, both the Weber number and the Capillary number given in Equations (27) and (28) respectively.

3.3 Concluding Remarks on Scaling Requirements

After a more detailed look at the physical understanding of the ice accretion process, it is still seen that not all of the scaling requirements can be met. Conflicts still exist between some of the requirements. However, in conclusion, the scaling requirements that should be met during glaze or mixed icing tests would be to match the following parameters as discussed in the preceding sections:

For flow field similarity the icing surfaces must have scaled geometries. It would also be advantageous to match the free stream Reynolds number based on characteristic length,

$$Re_L = \frac{\rho_a L U_\infty}{\mu_a},$$

and the Mach number,

$$M = \frac{U_\infty}{c_{p,a} T_\infty}.$$

As previously mentioned it is often not possible to do this. This is especially true when reduced scale testing is contemplated. However, since ice accretion occurs at relatively low Mach numbers for most aircraft, the Mach number can be excluded from the scaling requirements. The same cannot be said of the free stream Reynolds number based on characteristic length. In view of the discussion on the convective heat transfer coefficient, there could be large errors if it is not matched. Droplet trajectory similarity is satisfied by matching the trajectory scaling parameter

$$\bar{K} = \frac{K}{Re_d^\lambda},$$

and matching the accumulation parameter

$$\left(\frac{LWC U_\infty t}{\rho_l L} \right)_m = \left(\frac{LWC U_\infty t}{\rho_l L} \right)_f,$$

satisfies the accumulation scaling requirements.

Whereas the previous scaling requirements are all that are required in order to satisfactorily scale rime icing tests, for scaling during glaze or mixed icing tests the following parameters should be matched in addition. In order to satisfy the thermodynamic scaling requirements, the convective / latent heat ratio parameter

$$B = \frac{\left(1 + \frac{q_e}{q_c} \right) h (T_{surf} - T_\infty)}{LWC U_\infty h_{fs}},$$

must be matched, taking note that as previously mentioned the heat loss by evaporation is roughly equal to the heat loss by convection, or $q_e/q_c \sim 1$, and if possible either the parameter A ,

$$A = \frac{c_{p,l}(T_{surf} - T_{\infty})}{h_{fs}},$$

or the relative heat factor,

$$b = 2\beta \frac{A}{B} = \frac{LWC U_{\infty} \beta c_{p,l}}{h},$$

should be matched. However, priority should be given to the convective / latent heat ratio, B . Finally, for correct scaling of the droplet-surface interactions the contact angle, γ , should be matched and, if possible, both the Weber number,

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

and the Capillary number,

$$Ca = \frac{\mu_l U_{\infty}}{\sigma^{lg}},$$

should be matched.

3.4 Past Scaling Methodologies

As mentioned in Section 2.3, many models for simulating or analysing the ice accretion process have been developed. A recent summary of past scaling methods was presented by Anderson (1994). The three methods that Anderson tested in the NASA Lewis Icing Research Tunnel (IRC) are discussed below; the discussion is based on the review of Kind (1997).

3.4.1 Method 1: A_c Matched

In this scaling method, Anderson only allowed the liquid water content and the icing time to vary such that the accumulation parameter, A_c (Equation (14)), is matched in the model scale and the full scale, or that $LWC \times t = \text{const}$. This method is the most restrictive that Anderson tested, as the characteristic length, free stream velocity, static pressure, static temperature, and droplet diameter are all matched in the model scale and the full scale. As a result, this method also happens to match the Mach number, the free stream Reynolds number, the droplet trajectories, and the Weber number. However, it also has the disadvantage that reduced scale testing cannot be carried out. Figure 18 shows the results that Anderson achieved. The results show that ice accretions could not be scaled satisfactorily except during rime icing conditions. This is the result of changing the liquid water content, which as stated in Section 2.1, has a significant effect on the surface heat balance. Thus it is also required to match the surface heat balance in the model scale and the full scale in order to achieve scaled ice accretions (Anderson, 1994). In other words, the liquid water content and the icing time must each be matched (Kind, 1997).

3.4.2 Method 2: $\bar{K}$ and A_c Matched

This scaling method was developed by a joint Swedish / Russian group. In addition to matching the accumulation parameter, this method also requires that the trajectory scaling parameter, $\bar{K}$, be matched with the exponent, λ , in Equation (8) having a value of $\lambda=0$. In this method the liquid water content and the temperature are matched in the model scale and the full scale. The characteristic length and the free stream velocity are chosen in the model scale, and the static pressure is determined by the free stream velocity and the ambient pressure, as it could not be controlled in the icing wind tunnel test facility. The droplet diameter and the icing time are determined such that $\bar{K}$ and the accumulation parameter, A_c , are matched. However, this method makes no attempt to match the freezing fraction. Anderson's results are shown in Figure 19. This method produced good results for rime icing, however the

results for mixed and glaze icing are not entirely satisfactory for reduced scale testing (Kind, 1997).

3.4.3 Method 3: $\bar{K}$, A_c , n , and b Matched

This method was first published by Charpin and Fasso in 1972, with the derivation of this method by Armand et al. (1977). As in method 2, the characteristic length and the free stream velocity are chosen in the model scale, and the static pressure is determined by the free stream velocity and the ambient pressure. Further, the droplet diameter and the icing time are determined such that $\bar{K}$, with the exponent, λ , in Equation (8) having a value of $\lambda=0.39$, and the accumulation parameter are matched. The static temperature is determined such that the freezing fraction, n , is matched; however, this is equivalent to matching the convective / latent heat ratio, B , defined in Equation (23) (Kind, 1997). Finally the liquid water content is determined such that the relative heat factor, b , is matched. The equation

$$h = \frac{0.333 Re_L^{0.8} k_a}{L}$$

was used for the convective heat transfer coefficient. Similar to method 2, this method produced good results for rime icing, however the results for mixed and glaze icing are again not entirely satisfactory (Figure 19).

3.4.4 Discussion

For all the three methods tested by Anderson good results were achieved for rime icing. However, the results achieved for glaze icing were not as good. The similarity requirements for rime icing and glaze icing are different, as mentioned in Section 3.3. In order to scale rime ice accretions the similarity requirements that should be matched are: flow field similarity, droplet trajectory similarity (Equation (8)), and scaling of the accumulation of impinging water (Equation (14)). For glaze ice accretions the similarity requirements that

should be matched, in addition to the similarity requirements that are matched for rime ice accretions, are: thermodynamic similarity (Equation (23), and if possible either Equation (22) or Equation (24)), and droplet-surface interactions (Equation (27) and / or Equation (28)). Thus the scaling requirements for rime ice accretions are less stringent and do not require scaling of the complex thermodynamic phenomena including heat and mass transfer that occurs during glaze icing, and the surface tension effects. Thus, it is found that the similarity requirements for rime icing can be satisfied without undo difficulty and give good results, even at reduced scale (Kind, 1997). However, the same cannot be said about glaze icing where the similarity requirements present difficulties at reduced scale and good results have not been achieved as can be seen from these results.

3.4.5 Recent Developments

Bilanin and Anderson (1995) studied the effect of scaling the droplet-surface interactions and water movement. They carried out two tests. In the first test, a surfactant, Liqui-Nox, was added to the spray bar water supply of the NASA Lewis Icing Research Tunnel (IRT) such that the entire spray had reduced surface tension. In the second test another surfactant, Kodak Photo-Flo 600, was added to the spray of a single nozzle which was directed at the centre of the icing surface. These methods allowed the Weber number, We , to be scaled. The tests were carried out on $\frac{1}{2}$ and $\frac{1}{3}$ scale cylinders. The results, shown in Figure 20, were very promising, which shows that scaling of the droplet-surface interactions is important.

4 AXISYMMETRIC DROP SHAPE ANALYSIS (ADSA)

This chapter describes the method used to measure the surface tension of the water / 1-propanol and the water / 2-propanol solutions. The water used in these experiments was doubly distilled and de-ionized. There are many methods that researchers have used to measure the surface tension of a liquid / liquid or liquid / gas interface. A review of these techniques is presented by Padday (1969). One method is to analyse the shape of a pendant or a sessile drop. The shape of the drop is determined by the combination of the tensile force at the surface and the gravitational force. When these two forces are comparable, one can determine the surface tension from the shape of the drop. The following discussion is based on Lahooti et al. (1996).

As introduced in Section 3.2.4, the equation that is used for the relationship between the surface forces and gravitational forces is the Laplace equation of capillarity, Equation (26), repeated below.

$$p''-p'=\sigma\left(\frac{1}{R_1}+\frac{1}{R_2}\right) \quad (26)$$

The Laplace equation relates the surface tension, σ , and the curvature of a surface to the pressure difference across that curved surface. In Equation (26), R_1 and R_2 are the two principal radii of curvature, and $p''-p'$ is the pressure difference across the surface. If only

the gravitational force is considered then the pressure difference across the surface can be written as

$$p'' - p' = \Delta p_0 + (\Delta \rho)gz,$$

where Δp_0 is the pressure difference across the surface at the reference plane, $\Delta \rho$ is the density difference between the fluids on either side of the surface, and z is the vertical height from the reference plane. Thus, the surface tension can be determined if the shape of the drop is known; that is, if the two principal radii of curvature are known.

4.1 Theoretical Background

The technique used for measuring the surface tension in this thesis was Axisymmetric Drop Shape Analysis (ADSA), which was developed by Rotenberg et al. (1983). One particular version, Axisymmetric Drop Shape Analysis - Profile (ADSA-P), was used to analyse the shape of a pendant drop. The technique fits a curve to a series of points extracted from along the profile of a measured drop. An objective function is then formed that describes the deviation of the experimental points extracted from along the profile of the measured drop to the theoretical curve as a sum of the squares of the normal distances between the points. The objective function is then minimized through the use of the Newton-Raphson method until the required convergence is achieved. The ADSA-P output includes the surface tension, the surface area of the drop, the volume of the drop, and the principle radius of curvature (a sample ADSA-P output is contained in Appendix I).

4.2 Experimental Apparatus and Outline of Experimental Method

The experimental apparatus used for the ADSA-P experiments at The University of Toronto is shown in Figure 21. For liquid / gas pendant drop experiments, which were the subject in these experiments, the specimen solution is fed through a Teflon tube by use of a syringe. The drops are formed inside a sealed quartz cuvette which minimizes evaporation

and isolates the drop from vibrations. The cuvette is located inside an environmental chamber which controls the pressure and temperature at which the experiments are being conducted. A few drops of the specimen solution are allowed to fall to the bottom of the cuvette. This forms an equilibrium vapour environment. The drops are illuminated from behind with a white light source which is diffused through frosted glass. The frosted glass minimizes the heat transfer to the drop and provides a uniformly bright light source.

A fixed CCD video camera then captures an image of the drop and an analog signal of the drop is sent to an image processor for digitization. The digitized image is in the form of an array consisting of pixels with the intensity, or grey-level, of each pixel represented by a real number from 0, representing black, to 255, representing white. Once the image of the drop is obtained, ADSA-P finds the drop profile coordinates, from which the surface tension is obtained. A detailed description of ADSA is given in Lahooti et al. (1996).

4.3 Scope of the Measurements

The solutions tested in this thesis project were mixtures of doubly distilled and de-ionized water with either 1-propanol or 2-propanol. The source and purity of the 1-propanol and 2-propanol are listed in Appendix II. The addition of 1-propanol or 2-propanol served to reduce the surface tension from that of pure water, 72.14 g/s^2 at 25°C (Jasper, 1972). The addition of 1-propanol or 2-propanol has the advantage that when mixed with water the solutions are homogeneous mixtures, that is, there is not a preferential migration of one of the liquids in the mixture to the free surface. Thus when used in the icing wind tunnel, the surface tension of the droplets could be expected to be identical to that of the bulk mixture.

For each of the water / 1-propanol and the water / 2-propanol solutions, the concentrations tested were 0.5, 1, 2, 3, 5, 7, 10, and 15 percent 1-propanol or 2-propanol by volume. Four samples of each concentration were tested. A portion of each sample was used to measure its density as outlined below, and the remainder was used to create drops in

determining its surface tension. The density is required as one of the inputs for the ADSA-P algorithm. Six drops could be created from each sample. Thus a total of 24 drops were used in the determination of the surface tension for each of the concentrations of the specimen solutions. The 24 drops were labelled drop A through drop X, with drops A through F taken from sample 1, drops G through L from sample 2, drops M through R from sample 3, and drops S through X from sample 4. Finally, for each drop sixty-one separate images were taken and analysed, with the first image taken at time $t=0$, and the following 60 images taken every 10 seconds apart thereafter. The average surface tension was calculated for each drop over the 61 images.

The surface tension of the doubly distilled and de-ionized water was also determined through the ADSA-P algorithm. For these experiments, as with the water / 1-propanol and the water / 2-propanol solutions, four samples were used with each sample providing six drops each.

4.4 ADSA-P Surface Tension Experiments

The inputs required for the ADSA-P experimental method are the local gravitational acceleration and the densities of the two bulk phases. The local gravitational acceleration, and the densities of water and air are known and are listed in Table 3.

The ADSA-P algorithm also requires spatial calibration through the use of a calibration grid and a plumb line. A calibration grid is a glass slide with horizontal and vertical lines printed on one of its faces. The distance between the lines is known. The calibration grid is used for scaling the captured images, as the digitized image is only recognized as an array of pixels. Four corners of a rectangle are selected as the boundary on the digitized image. These points, along with the number of horizontal and vertical spaces between the lines making up the four sides of the rectangle, and the actual distance between the lines, are used as inputs. A plumb line is also required to correct for any rotation of the

camera. The two end points of the plumb line are selected and are also used as inputs. All measurements were taken with the environmental chamber set at 25°C. An image of a water drop is shown in Figure 22.

4.5 Discussion

4.5.1 Density of the 1-Propanol and 2-Propanol Solutions

The densities of the various solutions of water / 1-propanol and water / 2-propanol were not known and had to be measured. The measurements were carried out at The University of Toronto and are listed in Tables 4 and 5 for the water / 1-propanol and water / 2-propanol solutions respectively. A small volume of the sample mixture was used to fill a glass oscillator. The glass oscillator consisted of two coaxial tubes that had a heat conducting gas between them. This ensured a rapid temperature equilibrium. The entire apparatus was further kept at a constant temperature of 25°C through the use of a water heater. The glass oscillator was excited and a quartz clock measured its period which was then used to calculate the density.

The densities of the solutions decreased as the ratio of 1-propanol or 2-propanol to water was increased. However, the percent difference from the value of pure water, 0.9971 g/cm³ at 25°C (Streeter and Wylie, 1985), is low. For a 15% 1-propanol or 2-propanol solution, the percent difference is 1.88% and 2.78% respectively, and for a 1% solution it is only 0.15% and 0.16% respectively. The average density of the 4 samples for each concentration, listed in Tables 4 and 5, was used in the ADSA-P algorithm for the determination of the surface tension.

4.5.2 Surface Tension of Pure Water

Table 6 shows the results of the surface tension measurements for the doubly distilled and de-ionized water. The resulting average, 71.26 g/s^2 , is slightly less than the published value of 72.14 g/s^2 at 25°C (Jasper, 1972). However, the percent difference between the two values is only 1.2%. The difference is most likely caused by impurities in the test samples, such as dust particles. The addition of only traces of impurities can noticeably alter the surface tension. Further, the spray water used in the icing wind tunnel will collect impurities as it interacts with the air flow.

4.5.3 Surface Tension of the 1-Propanol and 2-Propanol Solutions

Tables 7 and 8 show the results of the surface tension measurements for the water / 1-propanol and the water / 2-propanol solutions respectively. As the ratio of 1-propanol or 2-propanol to water is increased, the effect of the addition of either 1-propanol or 2-propanol on the surface tension is reduced (Figure 23). Thus the concentrations chosen for the specimen solutions were those with lower concentrations of 1-propanol or 2-propanol. Further, as the ratio of 1-propanol or 2-propanol to water is increased, the other properties of pure water that were not measured, such as the latent heat of fusion, would increase calculation errors. Thus it was advantageous to keep the percent of 1-propanol or 2-propanol to a minimum.

On average, the 1-propanol had a greater effect in reducing the surface tension of pure water as shown in Figure 23. Thus, for a given required surface tension, less 1-propanol would be required. It was thus decided to use only the water / 1-propanol solutions for the icing wind tunnel experiments.

5 ICING WIND TUNNEL EXPERIMENTS

This chapter describes the icing wind tunnel test facility at the National Research Council of Canada, outlines the experimental method used, and presents the results of the tests.

5.1 Altitude Icing Wind Tunnel Test Facility

The icing tests were conducted in the Altitude Icing Wind Tunnel (AIWT) test facility at the National Research Council of Canada, in Ottawa, Canada (Figure 24). The facility is a closed loop wind tunnel with a working section of 0.57m by 0.57m square. It can produce air velocities from approximately 5m/s to 160m/s, and can simulate altitudes from ground level to 5000m (16400 feet). The static air temperature can range from approximately -35°C to 40°C. The spray is produced by air / water nozzles attached to spray bars that are mounted across the span of the wind tunnel. The spray bars are located upstream of the tunnel contraction. The liquid water content, LWC , of the spray can range from 0.1g/m³ to 1.7g/m³, and the median volume diameter, MVD , or droplet diameter, d , from approximately 8µm to 35µm.

Two sources for the spray supply were used during the experiments. A secondary spray supply had to be installed for the water / 1-propanol solutions so that the test facility

distilled water supply would not get contaminated. Recall that in Section 4.5.3 it was decided to use the water / 1-propanol solutions rather than the water / 2-propanol solutions as the surface tension was reduced a greater amount for a given concentration. The secondary spray supply was tapped into the test facility pipe network and by-passed the test facility distilled water supply. Thus, depending upon the test, either the test facility distilled water supply or the secondary spray supply could be selected. When the pure water spray was selected, the test facility distilled water supply was used, and when the water / 1-propanol solution was selected, the secondary spray supply was used. However, as both spray supplies shared the same pipe network, the pipes had to be purged each time the spray supply was changed.

5.2 Outline of Experimental Method

Two solid aluminum cylinders were used for the tests, one with a diameter of 45mm and the other with a diameter of 20mm. The larger cylinder was chosen such that blockage effects would be unimportant. Both cylinders had a span of 0.57m, that is, the width of the tunnel test section, and were fitted with a thermocouple at mid-span in their cores so that the temperature could be monitored. Cylinders were chosen as the test icing surfaces for the ease of manufacturing as well as the known relationships for the heat transfer coefficient. As icing occurs predominately in the stagnation region, the results can be assumed to be representative of the ice accretion that would be realized if aerofoils were used. This is due to the fact that the differences in the flow field at the trailing edge of the cylinder would not propagate far enough upstream to strongly influence the ice shapes.

The larger cylinder, diameter of 45mm, was used as the reference case. The reference tests were done with the free stream total temperature at 5, 10, and 15°C below the freezing temperature of the chosen spray liquid under otherwise identical conditions: free stream velocity $U_\infty=50\text{m/s}$, liquid water content $LWC=1\text{g/m}^3$, droplet diameter $d=35\mu\text{m}$, and run time $t=900\text{s}$. Each reference test was repeated; that is, for each free stream total temperature two test runs were performed (Table 9).

For each test run the velocity and the total air temperature were allowed to stabilize, during which time the temperature at the core of the test cylinder would drop such that it approximately equalled the total air temperature. The spray was set, by selecting the required supply air pressure to the spray bars and the required spray flow rate, to achieve the desired liquid water content and droplet diameter. The liquid water content and droplet diameter were set during the tests according to existing calibration sheets for the test facility distilled water supply. The spray was turned on, which represented $t=0$, and shut off when the desired icing time was reached.

During the ice accretion tests, a VHS format video cassette recorder was used to record the ice growth through time. Photographs were also taken during the test using a laser light sheet to highlight the profile of the ice accretion. At the end of the test, the cross section of the ice accretion at mid-span was recorded by melting a thin gap into it and tracing the profile onto a stiff template. The tracings of the ice shapes were compared to the photographs. These tracings constitute the main experimental results.

5.3 Icing Wind Tunnel Experiments

Six additional test runs were performed with the 20mm diameter cylinder for each of the three free stream total temperatures. These six test runs consisted of two additional runs using pure water, and two runs for each of a 99% water / 1-propanol and a 95% water / 5% 1-propanol solution (Table 10). Through matching either the Weber number, Equation (27), or the Capillary number, Equation (28), the velocity for the reduced scale test could be found, as the characteristic length (the cylinder diameter) and the spray supply, and thus the surface tension, were already chosen. The liquid water content could then be found by matching the accumulation parameter, Equation (14). The droplet diameter, d (i.e. the median volume diameter), was set by matching the droplet trajectory scaling parameter, Equation (8), and finally through matching the convective / latent heat ratio, Equation (23),

the icing time was determined. The relation used for the determination of the convective heat transfer coefficient, Equation (25), is given by

$$h = C \frac{k_a}{L} Re_L^x Pr_a^{\frac{1}{3}}, \quad (29)$$

where C and x are constants that are determined by the value of the Reynolds number based on characteristic length, and Pr is the Prandtl number. Equation (29) is from Holman (1990). For Reynolds numbers in the range of 4.0×10^5 to 4.0×10^6 , C and x take the values of 0.0266 and 0.805 respectively. This correlation for the heat transfer coefficient is an average value for a cylinder in cross flow, and was chosen for its ease of use. As discussed in Section 3.3, the Reynolds number and the contact angle should also be matched. Matching the Reynolds number was not possible, but as stated in Section 3.2.1, this is usually not a serious problem. Recent reports by Hansman and Turnock (1989) have stated that as the icing surface is quickly covered by a layer of ice, the initial surface condition has little or no effect on the final ice accretion shape. The relevant contact angle is thus that between the spray water and the accreted ice and is automatically matched, at least when pure water spray is used.

The remaining variables, the properties of the air and the spray, are listed in Table 11 (references provided with table). The density for the water / 1-propanol solutions were taken from the density measurements conducted during the surface tension measurements (Table 4). It was assumed that the ratio of the density of the accreted ice to the density of the spray in liquid form was the same for pure water and for the water / 1-propanol solutions. Thus the densities of the ice formed by the water / 1-propanol solutions could be calculated. The freezing temperatures of the water / 1-propanol solutions were found by allowing a liquid / solid mixture in a beaker to stabilize at the equilibrium freezing temperature. The values of the freezing temperatures thus found are in Table 12. The latent heat of fusion and the viscosity of the water / 1-propanol solutions were not measured. The values for pure water were used instead. Since the concentration of the 1-propanol is small, the values for the water / 1-propanol solutions should differ only slightly from those for pure water.

For the test cases designated C, D, and E (see Table 9) the Weber number, $\rho_a U_\infty^2 L / \sigma^g$, was matched. The three sprays used were pure water, a 99% water / 1% 1-propanol solution, and a 95% water / 5% 1-propanol solution respectively. Similarly, for test cases F, G, and H the Capillary number, $\mu_l U_\infty / \sigma^g$ was matched. Each of these test cases were performed for the three free stream total temperatures, 5, 10, and 15°C below the freezing temperature of the selected spray liquid.

5.4 Discussion

The results were assumed to be scaled if the model scale ice shape represented that of the reference scale. The method to determine whether the ice shapes were representative or not is very subjective. Anderson (1996) refers to this and states that the assessment of scaling methods will continue to be subjective in the absence of either a quantitative description or the identification of critical qualities of the ice shapes. In this thesis project, the ice shapes were said to be representative if the relative quantity of ice was similar, and if the relative shape and size of the ice were similar.

The results for the icing wind tunnel tests are shown in Figures 25, 26, and 27 for the 5, 10, and 15°C total air temperature differences respectively. As mentioned previously the reference cases, with the 45mm diameter cylinder, were repeated for each of the total air temperature differences. Thus the repeatability of the test cases can be observed. It can be seen from Figures 25 through 27 that the repeatability is fairly good; however, there are some differences between the two cases, especially when the total air temperature difference is 15°C. Given this, it would be advantageous to conduct more tests such that repeatability could be better studied.

For the 5°C total air temperature difference, the reduced scale ice accretion shapes matched the reference ice accretion shapes quite well when the Capillary number was matched, especially for test cases F and G where pure water and the 99% water / 1% 1-

propanol solution were used respectively. For test case H, where the 95% water / 5% 1-propanol solution was used, the ice accretion shape is not representative of the reference case. Test cases C, D, and E, in which the Weber number was matched, did not scale as well as test cases F, G, and H, in which the Capillary number was matched.

Similarly, for the 10°C total air temperature difference, the scaling results were better when the Capillary number was matched. This is especially true for the 99% water / 1% 1-propanol solution (test case G). However unlike for the 5°C total air temperature difference, test case F does not match quite as well. Test case E exhibits fairly good matching; however, as will be discussed later the 95% water / 5% 1-propanol solution did not exhibit the same freezing characteristics as the other sprays.

When the total air temperature difference was increased to 15°C the difference between the test cases in which the Capillary number was matched and in which the Weber number was matched was not quite as distinct. However the test cases in which the Capillary number was matched still reproduced the reference case better than when the Weber number was matched. Again, as was the case when the total air temperature difference was either 5°C or 10°C, when the 95% water / 5% 1-propanol solution was used, scaling was not good.

The ice formed when the 95% water / 5% 1-propanol solution was used tended to be somewhat mushy. Further, the ice tended to break apart during test runs due to aerodynamic forces; thus the ice accretion would lose the fine details of its shape. As mentioned in Section 5.2, the liquid water content and median volume diameter were set according to the tunnel calibration figures for pure water. Unfortunately, due to time constraints, the water / 1-propanol solutions could not be calibrated. Bilanin and Anderson (1995) have reported that when the surface tension is reduced by one half, the droplet size can be expected to decrease by up to 25%. Thus there is some uncertainty regarding the droplet size during the water / 1-propanol solution test cases; however, the results also

include reduced scale test cases with pure water spray which also support the requirement to match the Capillary number.

The physical properties of the water / 1-propanol solutions that were required for the scaling requirements have been discussed in previous sections. However, the physical properties of the 1-propanol itself have not been discussed. Although the boiling point of 1-propanol is close to that of pure water, the vapour pressure is not. Thus there is a preferential evaporation of the 1-propanol from the solutions. As the time from when the liquid exits the spray nozzles to when it impinges on the icing surface is short, it can be assumed that there would not be any preferential evaporation of the 1-propanol from the solution during this time. However, once the liquid impinges on the icing surface there would be a relative lack of 1-propanol in the solution as the freezing time during glaze and mixed icing is long. This would affect the physical properties of the solution, including the surface tension. Thus, the properties of the solution are, in fact, unknown. However, it is unclear at this time whether this would be undesirable or not, as the frozen liquid would have a relatively higher percentage of water, and thus, the ice would be more closely representative of the physical properties of pure ice.

During glaze icing, a water film is present in the stagnation region that moves downstream along the icing surface under aerodynamic forces. Thus, it is reasonable to expect that both viscous effects and aerodynamic or shear effects are important in this process. This would require matching both the Capillary number and the Weber number. It is thus postulated that the length scale that is used in the Weber number should be the thickness of the water film (Kind et al., 1998). Further, for flow field scaling requirements the icing surfaces must have scaled geometries, thus, having identical pressure and shear stresses at corresponding locations on the surface. Therefore, it is expected that the water bead size or rivulet size be identical at corresponding locations on the icing surfaces. Thus, the length scale would be the same in the reference scale as in the model scale, and thus, the Weber number would automatically be matched.

6 CONCLUSIONS

From the results presented in Chapter 5, it appears that viscous effects in the liquid water film or rivulets are important in the scaling analysis during glaze icing. This requires that the Capillary number, $\mu_l U_\infty / \sigma^g$, be matched in glaze icing tests. Further, Kind et al. (1998) hypothesize that the relevant Weber number, with a length scale representing the thickness of the water film or the size of the rivulets or water beads, would automatically be matched if the Capillary number is matched.

If tests with reduced surface tension are to be carried out, the concentration of the solute must be low. When the concentration of 1-propanol was 5% by volume the physical properties of the ice were markedly different from that of pure water; in particular the mechanical strength of the ice was insufficient to withstand the prevailing aerodynamic forces without parts of the accretions breaking off during test runs. Thus, the feasible reduction in surface tension is limited by the need to have low concentrations of solute. However, reduced surface tension tests may not actually be required. The conclusions of this thesis project are also supported by the reduced scale test cases using pure water. Thus, it appears that reduced scale testing is possible using pure water spray when the Capillary number, $\mu_l U_\infty / \sigma^g$, is matched. This has a clear advantage in that the properties of the spray water and the ice are then identical in both the reference case and the reduced scale case.

7 RECOMMENDATIONS

If reduced surface tension tests are to be continued, there are many areas where improvements can be made. First, and foremost, is the requirement to calibrate the icing wind tunnel spray system for the solution. As previously discussed, when the surface tension is reduced, the droplet diameters may be reduced by as much as 25%. Thus without proper calibration data, there remains the uncertainty of the actual value for the droplet diameter used in icing tests. Another possibility is further studying the freezing process of solutions. A better understanding in this area may assist in finding an optimal solute to reduce the surface tension without altering the physical properties of the spray. Further, the physical properties that are used in the scaling analysis, such as the latent heat of fusion, should be measured for the solution.

Further tests should be conducted for repeatability. As no two ice accretions are alike, perhaps a 'mean' or 'average' of two or three samples might help in the decision of whether the test cases were scaled adequately. It would also be very useful to conduct tests to determine the most appropriate relation for the convective heat transfer coefficient as it strongly influences the freezing process, especially during glaze icing tests.

Table 1. List of Variables Used in Dimensional Analysis.
(Bilanin, 1991)

Nomenclature	Description	Units
δ	ice thickness	L
d	droplet diameter	L
l	mean distance between droplets	L
L	characteristic length	L
ρ_a	density of the air	M/L^3
ρ_l	density of the liquid	M/L^3
ρ_s	density of the solid	M/L^3
ν_a	kinematic viscosity of the air	L^2/T
ν_l	kinematic viscosity of the liquid	L^2/T
k_a	thermal conductivity of the air	$ML/T^3\circ$
k_l	thermal conductivity of the liquid	$ML/T^3\circ$
k_s	thermal conductivity of the solid	$ML/T^3\circ$
$c_{p,a}$	specific heat at constant pressure of the air	$L^2/T^2\circ$
$c_{p,l}$	specific heat at constant pressure of the liquid	$L^2/T^2\circ$
$c_{p,s}$	specific heat at constant pressure of the solid	$L^2/T^2\circ$
h_{fs}	latent heat of fusion	L^2/T^2
T_∞	free stream temperature	$\circ$
T_{fr}	freezing temperature	$\circ$
σ^{lg}	liquid / air surface tension	M/T^2
γ	contact angle of the liquid with the icing surface	
U_∞	free stream velocity	L/T
s	distance along the icing surface	L
t	time	T

Table 2. Non-dimensional Parameters from Dimensional Analysis.

(Bilanin, 1991)

$$\begin{array}{lll}
\pi_1 = \frac{tU_\infty}{L}, & \pi_2 = \frac{s}{L}, & \pi_3 = \frac{d}{L}, \\
\pi_4 = \frac{d}{l}, & \pi_5 = \frac{\rho_a}{\rho_l}, & \pi_6 = \frac{\rho_l}{\rho_s}, \\
\pi_7 = \frac{c_{p,a}}{c_{p,l}}, & \pi_8 = \frac{c_{p,l}}{c_{p,s}}, & \pi_9 = \frac{k_a}{k_l}, \\
\pi_{10} = \frac{k_l}{k_s}, & \pi_{11} = \frac{v_a}{v_l}, & \pi_{12} = \gamma, \\
\pi_{13} = \frac{c_{p,a} v_a \rho_a}{k_a}, & \pi_{14} = \frac{T_{jr}}{T_\infty}, & \pi_{15} = \frac{h_{fs}}{c_{p,a} T_\infty}, \\
\pi_{16} = \frac{U_\infty^2}{c_{p,a} T_\infty}, & \pi_{17} = \frac{U_\infty L}{v_a}, & \pi_{18} = \frac{\rho_a U_\infty^2 L}{\sigma^{lg}}.
\end{array}$$

Table 3. Local Constants Used During ADSA-P Experiments.

[1. University of Toronto data, 2. Holman (1990)]

gravitational acceleration ¹	980.43 cm/s ²
density of pure water (@25°C) ²	0.9971 g/cm ³
density of air (@25°C) ²	0.001185 g/cm ³

Table 4. Density of Water / 1-Propanol Solutions.

(Values taken at 25 °C)

% 1-Propanol by Volume	Sample A (g/m ³)	Sample B (g/m ³)	Sample C (g/m ³)	Sample D (g/m ³)	Average (g/m ³)
0.5%	0.9959	0.9959	0.9963	0.9963	0.9961
1.0%	0.9955	0.9953	0.9955	0.9953	0.9954
2.0%	0.9941	0.9922	0.9940	0.9945	0.9937
3.0%	0.9923	0.9923	0.9930	0.9931	0.9927
5.0%	0.9904	0.9896	0.9904	0.9904	0.9902
7.0%	0.9880	0.9880	0.9880	0.9875	0.9879
10.0%	0.9831	0.9838	0.9843	0.9848	0.9840
15.0%	0.9786	0.9786	0.9784	0.9789	0.9786

Table 5. Density of Water / 2-Propanol Solutions.

(Values taken at 25 °C)

% 2-Propanol by Volume	Sample A (g/m ³)	Sample B (g/m ³)	Sample C (g/m ³)	Sample D (g/m ³)	Average (g/m ³)
0.5%	0.9963	0.9960	0.9958	0.9959	0.9960
1.0%	0.9954	0.9954	0.9951	0.9953	0.9953
2.0%	0.9939	0.9937	0.9939	0.9937	0.9938
3.0%	0.9926	0.9919	0.9904	0.9924	0.9918
5.0%	0.9865	0.9891	0.9891	0.9886	0.9883
7.0%	0.9859	0.9846	0.9870	0.9867	0.9861
10.0%	0.9829	0.9834	0.9787	0.9832	0.9821
15.0%	0.9700	0.9682	0.9674	0.9749	0.9701

Table 6. Surface Tension of Doubly Distilled and De-Ionized Water.

Sample A	Sample B	Sample C	Sample D	Average
(g/s ²)	(g/s ²)	(g/s ²)	(g/s ²)	(g/s ²)
70.90	72.15	70.23	71.88	71.26

Table 7. Surface Tension of Water / 1-Propanol Solutions.

% 1-Propanol by Volume	Sample A	Sample B	Sample C	Sample D	Average
	(g/s ²)	(g/s ²)	(g/s ²)	(g/s ²)	(g/s ²)
0.5%	67.59	66.80	67.84	68.06	67.57
1.0%	61.99	62.28	63.55	62.23	62.54
2.0%	57.83	56.96	57.22	57.88	57.47
3.0%	53.44	52.84	54.09	53.56	53.48
5.0%	46.26	46.40	45.68	46.57	46.23
7.0%	43.12	43.30	42.90	43.36	43.17
10.0%	38.50	37.38	38.71	38.80	38.35
15.0%	28.49	32.53	31.09	31.75	30.97

Table 8. Surface Tension of Water / 2-Propanol Solutions.

% 2-Propanol by Volume	Sample A	Sample B	Sample C	Sample D	Average
	(g/s ²)	(g/s ²)	(g/s ²)	(g/s ²)	(g/s ²)
0.5%	68.28	67.58	66.84	66.25	67.23
1.0%	63.08	62.91	64.56	63.36	63.48
2.0%	58.50	58.58	57.52	59.18	58.45
3.0%	54.92	55.57	55.19	55.04	55.18
5.0%	48.13	49.32	49.31	50.02	49.20
7.0%	45.92	46.46	45.23	45.92	45.88
10.0%	40.98	41.14	40.98	41.08	41.04
15.0%	35.78	36.00	35.12	35.64	35.63

Table 9. Icing Wind Tunnel Test Cases.

Designation	Spray (% 1-propanol)	Cylinder Diameter (mm)	Description of Test
A	0	45	reference
B	0	45	reference
C	0	20	Weber number matched
D	1	20	Weber number matched
E	5	20	Weber number matched
F	0	20	Capillary number matched
G	1	20	Capillary number matched
H	5	20	Capillary number matched

Table 10. Similarity Requirements for Icing Wind Tunnel Test Cases.

Test case	U_∞ (m/s)	L (mm)	σ (mN/m)	LWC (g/m ³)	d (μ m)	t (s)
A	50.0	45	71.26	1.0	35.0	900
B	50.0	45	71.26	1.0	35.0	900
C	75.0	20	71.26	1.1	18.2	246
D	69.9	20	62.54	1.1	18.8	261
E	60.1	20	46.23	1.1	20.0	299
F	50.0	20	71.26	1.2	21.4	341
G	43.4	20	62.54	1.2	22.6	383
H	32.1	20	46.23	1.3	25.5	488

Test case	B	K	A_c	Re_L	Ca_l	We_L
A	1.016E-01	8.091E-01	1.091	1.733E-05	1.25	2015
B	1.016E-01	8.091E-01	1.091	1.733E-05	1.25	2015
C	1.016E-01	8.091E-01	1.091	1.155E-05	1.86	2015
D	1.016E-01	8.091E-01	1.091	1.077E-05	2.00	2015
E	1.016E-01	8.091E-01	1.091	9.257E-04	2.33	2015
F	1.016E-01	8.091E-01	1.091	7.701E-04	1.25	896
G	1.016E-01	8.091E-01	1.091	6.685E-04	1.25	777
H	1.016E-01	8.091E-01	1.091	4.944E-04	1.25	575

Table 11. Physical Properties of Air and Water.

[1. Holman (1990), 2. Streeter and Wylie (1985), 3. Van Wylen and Sonntag (1985)]

Air	Water
$\mu_a = 16.75 \text{ } \mu\text{Pa/s (@} 0^\circ\text{C)}^1$	$\mu_w = 1790 \text{ } \mu\text{Pa/s (@} 0^\circ\text{C)}^1$
$\rho_a = 1.29 \text{ kg/m}^3 \text{ (@} 25^\circ\text{C)}^1$	$\rho_w = 997.1 \text{ kg/m}^3 \text{ (@} 25^\circ\text{C)}^2$
$c_{p,a} = 1.005 \text{ kJ/kg}^\circ\text{C (@} -5^\circ\text{C)}^1$	$\rho_i = 916.8 \text{ kg/m}^3 \text{ (@} 0.01^\circ\text{C)}^3$
$k_a = 0.0194 \text{ W/m}^\circ\text{C (@} -5^\circ\text{C)}^1$	$h_{fs} = 333.4 \text{ kJ/kg (@} 0.01^\circ\text{C)}^3$
$Pr_a = 0.718 \text{ (@} -5^\circ\text{C)}^1$	

Table 12. Measured Physical Properties of Water / 1-Propanol Solutions.

1% 1-Propanol by Volume
 $T_{fr} = -0.4^\circ\text{C}$

5% 1-Propanol by Volume
 $T_{fr} = -1.3^\circ\text{C}$

Figure 1. Rime Ice Accretion on a Post at Cairngorm, Scotland (1220 m).
(Lozowski and Gates, 1991)

Figure 2. Ice Accretion on a Transmission Line, Observed During
a Three-Day Episode of Natural Icing Near Grenoble, France.
(Lozowski and Gates, 1991)

Figure 3. Ice Accretion on the Bow of the Chemical Tanker Anna Broere.
(Lozowski and Gates, 1991)

Figure 4. Cross-section (in Reflected Light) of a Giant Hailstone Which
Fell Near Cedoux, Saskatchewan, August 27, 1973.
(Lozowski and Gates, 1991)

Figure 5. AS 332 Super Puma Following a Natural Icing Encounter
(Lozowski and Gates, 1991)

Figure 6. Ice Accretion on an Oil Cooler Air Intake
(Ashwood and Swift, 1977)

Figure 7. Typical Rime Ice Accretion.
(Wilder, 1977)

Figure 8. Typical Glaze Ice Accretion.
(Wilder, 1977)

Figure 9. Drag Coefficients for Spheres and Circular Disks.
(Streeter and Wylie, 1985)

Figure 10. Standard Sphere Drag Curve and Approximation.
(Bragg, 1982)

Figure 11. Comparison of K_0 and $\bar{K}$ in Scaling the Droplet Impingement Efficiency on an Aerofoil.
(Bragg, 1982)

s_u = UPPER SURFACE IMPINGEMENT LIMIT

s_l = LOWER SURFACE IMPINGEMENT LIMIT

$$\beta = \frac{dy_0}{ds}$$

Figure 12. Definition of the Local Collection Efficiency (2-Dimensional Case).
(Bilanin, 1991)

Figure 13. Modes of Energy Transfer for an Unheated Aerofoil in Icing Conditions.
(Messinger, 1953)

Figure 14. Schematic Representation of the Distribution of Pressure in an Interfacial Layer.
(Defay and Prigogine, 1966)

Figure 15. Model of a Mechanically Equivalent Surface Layer.
(Defay and Prigogine, 1966)

Figure 16. Equilibrium of a Non-Spherical Cap.
(Defay and Prigogine, 1966)

Figure 17. Definition of Contact Angle.
(Defay and Prigogine, 1966)

Figure 18. Scaling with $LWC \times t = \text{const.}$
Velocity, 94 m/s; $LWC \times t$, 10.15 g min/m³.
(Anderson, 1994)

Figure 19A. Scaling with Swedish / Russian and French Laws.
Rime Ice Conditions.
(Anderson, 1994)

Figure 19B. Scaling with Swedish / Russian and French Laws.
Mixed Ice Conditions.
(Anderson, 1994)

Figure 19C. Scaling with Swedish / Russian and French Laws.
Glaze Ice Conditions.
(Anderson, 1994)

Figure 20A. Scaling with Constant Weber Number.
reference scale
1/2 scale
(Bilanin and Anderson, 1995)

Figure 20B. Scaling with Constant Weber Number.

——— reference scale

..... $\frac{1}{2}$ scale

(Bilanin and Anderson, 1995)

Figure 20C. Scaling with Constant Weber Number.

——— reference scale

..... $\frac{1}{2}$ scale

(Bilanin and Anderson, 1995)

Figure 20D. Scaling with Constant Weber Number.

————— reference scale
 - - - - - $\frac{2}{3}$ scale
 $\frac{1}{3}$ scale
 (Bilanin and Anderson, 1995)

Figure 20E. Scaling with Constant Weber Number.

————— reference scale
 - - - - - $\frac{2}{3}$ scale
 $\frac{1}{3}$ scale
 (Bilanin and Anderson, 1995)

Figure 21. ADSA-P Experimental Apparatus for Measuring Pendant Drops.
(ADSA User's Manual)

Figure 22. Image of a Drop of Doubly Distilled and De-Ionized Water from ADSA-P.

Figure 23. Change in Surface Tension by Percent Volume for Water / 1-Propanol and Water / 2-Propanol Solutions.

Figure 24. Altitude Icing Wind Tunnel (AIWT), National Research Council of Canada.
(Courtesy of Myron Oleskiw, N.R.C.)

Test Case A - Reference.

Test Case B - Reference.

Test Case C - We Matched.

Test Case F - Ca Matched.

Test Case D - We Matched.

Test Case G - Ca Matched.

Test Case E - We Matched.

Test Case H - Ca Matched.

Figure 25. Scaling with Free Stream Total Temperature 5°C Below the Freezing Temperature.

Test Case A - Reference.

Test Case B - Reference.

Test Case C - We Matched.

Test Case F - Ca Matched.

Test Case D - We Matched.

Test Case G - Ca Matched.

Test Case E - We Matched.

Test Case H - Ca Matched.

Figure 26. Scaling with Free Stream Total Temperature 10°C Below the Freezing Temperature.

Test Case A - Reference.

Test Case B - Reference.

Test Case C - We Matched.

Test Case F - Ca Matched.

Test Case D - We Matched.

Test Case G - Ca Matched.

Test Case E - We Matched.

Test Case H - Ca Matched.

Figure 27. Scaling with Free Stream Total Temperature 15°C Below the Freezing Temperature.

APPENDIX I

Table A1. Sample ADSA-P Output Data for Doubly Distilled and De-Ionized Water.

File Name	Surface Tension (mJ/m**2)	Surface Area (cm**2)	Volume (cc)	Radius of Curvature (cm)
h2o_a000.00.	72.440191	0.2049408	0.4611951	0.0306323
h2o_a010.01.	72.441769	0.0856079	0.4611095	0.0306284
h2o_a020.01.	72.485061	0.1225858	0.4610957	0.0306242
h2o_a030.02.	72.398168	0.0895064	0.4614293	0.0306344
h2o_a040.02.	72.432989	0.1001372	0.4613571	0.0306307
h2o_a050.01.	72.435552	0.1036664	0.4611108	0.0306184
h2o_a060.02.	72.423923	0.0922332	0.4613099	0.0306250
h2o_a070.02.	72.507964	0.0923196	0.4610569	0.0306167
h2o_a080.02.	72.441306	0.0806315	0.4612008	0.0306189
h2o_a090.01.	72.354225	0.0989642	0.4612597	0.0306168
h2o_a100.02.	72.394990	0.0920935	0.4611585	0.0306126
h2o_a110.02.	72.389006	0.1035052	0.4611496	0.0306115
h2o_a120.02.	72.425100	0.0920447	0.4610233	0.0306070
h2o_a130.01.	72.481581	0.0681366	0.4608489	0.0305985
h2o_a140.02.	72.407561	0.0840043	0.4611472	0.0306131
h2o_a150.01.	72.411580	0.1287186	0.4610314	0.0306057
h2o_a160.02.	72.437476	0.1002755	0.4607680	0.0305921
h2o_a170.02.	72.402863	0.0859050	0.4607970	0.0305919
h2o_a180.01.	72.463282	0.0951430	0.4608616	0.0305973
h2o_a190.02.	72.351793	0.0914800	0.4609694	0.0305948
h2o_a200.01.	72.457041	0.0893022	0.4607810	0.0305867
h2o_a210.01.	72.392896	0.0715511	0.4605751	0.0305757
h2o_a220.01.	72.428837	0.0927079	0.4606555	0.0305775
h2o_a230.01.	72.382855	0.0935965	0.4607138	0.0305777
h2o_a240.02.	72.410333	0.0795433	0.4604146	0.0305654
h2o_a250.02.	72.492100	0.0857461	0.4604967	0.0305734
h2o_a260.01.	72.409263	0.0951956	0.4605466	0.0305681
h2o_a270.01.	72.393692	0.1033777	0.4603307	0.0305584
h2o_a280.01.	72.413177	0.0993406	0.4603143	0.0305561
h2o_a290.01.	72.376121	0.0922577	0.4603098	0.0305534
h2o_a300.02.	72.399414	0.0959017	0.4603830	0.0305587
h2o_a310.02.	72.420706	0.0950103	0.4605043	0.0305658
h2o_a320.01.	72.416539	0.0722525	0.4604273	0.0305590
h2o_a330.01.	72.401433	0.0905580	0.4604098	0.0305608
h2o_a340.01.	72.470798	0.0897358	0.4604233	0.0305617
h2o_a350.02.	72.401268	0.0933531	0.4601289	0.0305433
h2o_a360.02.	72.431330	0.0864053	0.4602105	0.0305466
h2o_a370.01.	72.420786	0.0829458	0.4602308	0.0305472
h2o_a380.01.	72.392533	0.0850358	0.4600278	0.0305366
h2o_a390.02.	72.397184	0.0912185	0.4602346	0.0305459
h2o_a400.02.	72.380950	0.0915769	0.4602085	0.0305413
h2o_a410.02.	72.439122	0.0845452	0.4601568	0.0305421
h2o_a420.02.	72.425337	0.0871021	0.4601261	0.0305395
h2o_a430.01.	72.433970	0.0921482	0.4600568	0.0305366
h2o_a440.01.	72.400176	0.0796567	0.4601347	0.0305368
h2o_a450.01.	72.419644	0.0993834	0.4601250	0.0305386
h2o_a460.02.	72.410420	0.1016233	0.4599059	0.0305274
h2o_a470.01.	72.394293	0.0810319	0.4601493	0.0305368
h2o_a480.01.	72.428714	0.0965598	0.4600427	0.0305338
h2o_a490.01.	72.405043	0.0906727	0.4598356	0.0305206
h2o_a500.01.	72.371439	0.0817093	0.4600791	0.0305294
h2o_a510.01.	72.444690	0.0856053	0.4600393	0.0305332
h2o_a520.02.	72.409452	0.0915712	0.4599658	0.0305276
h2o_a530.01.	72.394382	0.0801595	0.4600538	0.0305277
h2o_a540.01.	72.394165	0.0618995	0.4599496	0.0305245
h2o_a550.02.	72.405816	0.0749868	0.4599789	0.0305254
h2o_a560.01.	72.412968	0.0831917	0.4599342	0.0305257
h2o_a570.01.	72.379274	0.1015014	0.4599348	0.0305206
h2o_a580.01.	72.390477	0.0839541	0.4598528	0.0305178
h2o_a590.01.	72.410076	0.0814820	0.4598807	0.0305193
h2o_a600.02.	72.371242	0.0857823	0.4599216	0.0305195

APPENDIX II

1-Propanol Source and Purity

1-Propanol 99.5+% A.C.S. reagent

[Aldrich Cat. Number 40,289-3 and Lot Number 00256AR]

2-Propanol Source and Purity

2-Propanol 99.5+% A.C.S. reagent

[Aldrich Cat. Number 19,076-4 and Lot Number 05145KQ]

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IMAGE EVALUATION TEST TARGET (QA-3)

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