INVESTIGATION OF ICING SENSOR AND WIND ICING SCALE FOR METEOROLOGICAL TOWERS

By

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ABSTRACT

There is an urgent need by the wind industry for an accurate assessment of icing conditions in cold climates that can be correlated to a wind icing scale. There is currently no instrumentation mounted on meteorological towers that can detect icing and measure its severity reliably. Thus icing data, important to regions prone to severe icing, is unavailable. Wind farms located in northern climates, where wind penetration is severe, are prone to failure under severe icing conditions. This reduces grid reliability and leads to more duplication of power generation infrastructure. Instrumentation mounted on meteorological towers near wind farms must not only measure wind speed but also icing severity. This research proposes a method for correlating ice sensor output to a wind icing scale by developing and testing an icing sensor that can measure changes in capacitance and resistance between electrodes in relation to ice thickness as well as ice mass and volume accumulation rate. Experiments are performed to measure capacitance changes over time between probes in the University of Manitoba Icing Tunnel Complex (UMITC) under simulated weather conditions that produce rime, glaze, and rime-glaze mixture ice growth. Results are tabulated and compared to theoretical values of capacitance for ice between parallel cylinders. Suggested improvements to current design are then described to improve the overall performance and efficiency of the probes for future testing purposes.
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1 INTRODUCTION

1.1 Project Objectives

The objectives of this research investigation are to develop and test an icing sensor based on capacitance and resistance principles that can correlate its output to a wind icing scale—specifically correlating the changes in capacitance and resistance to measure ice thickness, ice weight per unit area per unit time, and ice accumulation rate on structures. It will be necessary to examine the current state-of-the-art sensors that regulate ice accumulation on meteorological towers and to discuss the limitations of these sensors; commenting on the research efforts aimed at improving the robustness and reliability of these instruments.

2. LITERATURE REVIEW

2.1 Introduction

This section provides an insight into the types of icing conditions and their effect on instrumentation such as anemometers, which are used to measure wind speed and direction, as well as the mechanics and dynamics of ice accretion. This section will also describe several methods for measuring and controlling ice build-up as well as the current probe designs used in the market.

2.2 Atmospheric Icing

Icing is the process by which snow or ice grows on a structure exposed to the atmosphere. It occurs when the relative humidity of the ambient air is over 95% and the temperature is below $0^\circ$C [Cost 727 2007]. The type of ice formation is mainly dependent
on the process by which the cloud is formed in the atmosphere and is affected by several factors including ambient air temperature, barometric pressure, relative humidity, wind speed, air density, altitude as well as the temperature of the surface with which the icing comes in contact. In-cloud icing is the most severe type and occurs when super cooled cloud droplets collide with cold surfaces. The higher the wind speed, the more intense the ice accretion becomes. Specific icing types such as in-cloud icing or rime aggregation, icing precipitation, wet snow accumulation, and icing as a result of sea water spray have been identified by The Finnish Meteorological Institute [Ahti 2005]. Damaging icing effects caused by freezing of persistent fog clouds [Chaîné 1974] have also been known to occur in northern climates. Ice accretion on surfaces has been known to form in two different ways: rime and glaze and even a mixture of the two.

### 2.2.1 Rime Icing

Rime icing forms in low humidity air when super cooled water droplets freeze into particles of ice upon colliding with the surface of the structure, thus forming an opaque, low density, feathery ice build up. Rime ice tends to form on structures with surface temperatures in the range of -4°C to -12°C [Bose 1992].
2.2.2 Glaze Icing

Glaze icing occurs in air with a high humidity or liquid content at temperatures just below freezing, 0°C to -4°C [Bose 1992]. When water droplets collide with the surface of the structure, some freeze on impact while others run along the surface before freezing. As a result, a smooth, high density, semi-clear lumping ice forms on the surface.
[Kraj 2007]. Seen below is the formation of glaze icing on aerial cables used to support a light standard after a freezing rain event in Slovenia [Makkonen 2000].

Figure 2-3: Glaze ice on aerial cable [Makkonen 2000]

Figure 2-4: Glaze ice formation [Makkonen 2000]
2.3 Icing on the Accuracy of Wind Speed Readings

Instruments used to measure ambient air temperature, humidity, barometric pressure, solar radiation, wind speed and direction can be mounted onto meteorological towers and located strategically near wind turbine turbines to regulate and optimize their operation. Severe environmental conditions, such as icing, however, hamper the operation of these instruments and impede the collection of reliable data.

There are several types of anemometers currently used to measure wind speed, including cup, windmill, hot-wire, laser Doppler, and sonic anemometers. In northern climates, the accuracy of instrumentation readings can be seriously affected by icing and ice accretion. In order to maintain optimum accuracy of the measurements obtained from the instrumentation, there must be a continuous and proper observation of the icing accumulation and the rate of the icing growth.

The types of anemometers listed previously, fall into two categories, heated and unheated. When icing or precipitation is not present the two types of anemometers record the same wind speed. A test performed at the Tauren Wind Park [Seifert 2004] on both heated and unheated cup anemometers showed ambiguous results during instances when icing and snowfall was significant. The snow melted, as expected, on a heated anemometer’s hot cups and the water was pushed to the outer portions of the cups by centrifugal forces. The ‘forced convection’ induced by high wind speed and low air temperature caused ‘refreezing’ of the melted snow and ice on the outer radius of the cups. The resulting increase in inertia and drag caused the anemometer to rotate at a reduced speed and give a faulty wind speed indication. On the other hand the unheated
anemometer remained cold. The snow and ice hitting the cups was reflected (bounced off) by centrifugal forces. As a result there was no notably large effect on wind speed.

![Ice anemometer in wind tunnel test](image)

**Figure 2-5: Ice anemometer in wind tunnel test [NEMO 2 1998]**

### 2.4 The Mechanics of Ice Accretion

In order to fully understand the mechanisms behind ice accretion, a closer look at the heat transfer and particle dynamics of the ice upon impact must be examined.

Super-cooled water droplets that collide and build up on the surface of objects undergo a series of solid to liquid phase changes that depend on a combination of both droplet kinetic energy and convective heat transfer between the object and the droplets [Kraj 2007, Naterer 2003].

Icing rate is primarily dependant on the flux of water particles (concentration multiplied by velocity) in the area of projection of the object with respect to wind direction [Laakso 2003]. Because the icing particles exist at different sizes and inertias, those with low inertia follow the air stream and pass over the structures while those with large inertia will collide and stick to the instrumentation. There are also those particles
that will collide and bounce off the surfaces and not increase total ice mass as seen in the following simplified figure for flow over a cylinder:

![Figure 2-6: Air streamlines and droplet trajectories around a cylindrical object [Makkonen 2000]](image)

Consider a long cylinder in a wind tunnel exposed to air flow at a velocity $U$, temperature $T_a$, pressure $P_a$, that contains super cooled droplets with radius $r$ and liquid water content (LWC) $W$ [Mazin et al. 2000]. The air flow direction is assumed to be perpendicular to the axis of the cylinder. The temperature of the droplets is the same as the ambient air temperature. The droplets will hit the cylinder within a range, represented by polar angles $\varphi_o$ and $\phi_o$ along the frontal projection surface of the cylindrical, as shown below:
These angles are a function of droplet radius, cylinder radius, airspeed, air temperature, and pressure [Mazin 1957, Mazin et al. 2000]. Any droplets outside the range of these angles will not hit the object and will pass over the object along streamlines. The shape of the ice accretion depends on the airspeed, droplet size, LWC, air temperature, and other parameters [Mazin et al. 2000]. The schematic below shows the heat fluxes to and from a cylinder undergoing testing for the build up of rime ice in a wind tunnel:
According to a study performed at the Technical Research Centre of Finland (VTT) [Makkonen 2000], the rate of icing can be characterized as:

\[
\frac{dM}{dt} = \alpha_1 \alpha_2 \alpha_3 \omega v A, \tag{Eq. 2.1}
\]

where \(A\) is the cross sectional area of the object relative to the direction of the particle velocity vector \(v\). The variables \(\alpha_1, \alpha_2,\) and \(\alpha_3\) are correction factors which vary between zero and one.

Factor \(\alpha_1\) represents the collision efficiency of the particles. In other words \(\alpha_1\) is the ratio of the flux density, \(F\), of the particles that collide with the object to the maximum flux density, \(F_m\). The flux density is the product of the mass concentration of the particles, \(w\), and the velocity, \(v\), of the particles relative to the object. When air flows over the object the collision efficiency drops because the smaller particles will be
deflected from their path towards the object and follow the air streamlines [Makkonen 2000].

Factor $\alpha_2$ represents the efficiency of the particles that impact and stick to the object to the total flux density of the particles that hit the object. In other words, $\alpha_2$, represents the ‘sticking efficiency’. This parameter is reduced when the particles bounce off the object after impact. The degree of adhesion is not only affected by force of impact but also by the exchange of heat with the surface to which the particles are hitting.

Factor $\alpha_3$ represents the ice accretion efficiency, or the ratio of the rate of icing to the flux density of the particles that stick to the surface [Makkonen 2000]. This efficiency drops when the heat flux from accretion is insufficient to cause freezing resulting in loss of mass flux of particles from the surface caused by water run-off. The heat flux from the surface to the surroundings also determines whether the colliding ice particles freeze on impact forming rime ice, or form a thin watery film referred to as glaze ice [Laakso 2003]. When the efficiency of accretion is zero, $\alpha_3 = 1$, the process forms ‘dry growth’ or rime ice and when this factor is less than one, the process forms ‘wet growth’ or glaze ice.

2.4.1 Collision Efficiency:

Assuming a cylindrical icing object, the collision efficiency for airflow around the object can be characterized by two dimensionless parameters:

$$K = \frac{\rho_a d^2}{9 \mu D}, \quad \text{(Eq. 2-2a)}$$

$$\phi = \frac{\text{Re}^2}{K}, \quad \text{(Eq. 2-2b)}$$

Where $\text{Re}$ represents the droplet Reynolds number, $d$ is the droplet diameter, $D$ the cylinder diameter, and $\rho_a$ the air density. The droplet Reynolds number as a function of the free stream velocity can be represented by:
\[ \text{Re} = \frac{\rho_d d v}{\mu}, \quad \text{(Eq. 2-3)} \]

[Finstad et al. 1988] developed the empirical fit for the collision efficiency:

\[
\alpha_1 = A - 0.028 - C(B - 0.0454) \quad \text{(Eq. 2-4, a:d)}
\]

\[
A = 1.066 K^{-0.00616} \exp\left(-1.103 K^{-0.688}\right)
\]

\[
B = 3.641 K^{-0.498} \exp\left(-1.497 K^{-0.694}\right)
\]

\[
C = 0.00637 (\phi - 100)^{0.381}
\]

### 2.4.2 Sticking Efficiency:

When super cooled water droplets collide with a solid surface they can either freeze upon impact, ultimately forming rime ice or spread along the surface forming glaze ice. In either case the particles do not bounce and thus for water droplets it can be assumed that the sticking efficiency, also known as the ‘collection efficiency’, \( \alpha_2 \) is approximately equal to one [Makkonen 2000]. Snow particles, on the other hand, bounce off the surface of the object quite profoundly upon impact [Wakahama et al. 1977]. For dry snow, \( \alpha_2 \) becomes zero. The higher the temperature of both the particles and object surface temperature the higher the collection efficiency.

Experiments for determining approximation methods for the collection efficiency on cylindrical objects performed by [Admirat et al. 1988], showed that:

\[
\alpha_2 = \frac{1}{v}, \quad \text{(Eq. 2-5)}
\]

where \( v \) represents the wind speed. When \( v < 1 \), \( \alpha_2 = 1 \). Apart from temperature and velocity, the collection efficiency is affected by humidity. But there is not enough...
consistent data to take them into account [Makkonen 2000]. When the wet-bulb
temperature falls below zero degrees Celsius the snow cannot stick to the object’s surface
effectively [Makkonen 1989]. Thus the collection efficiency can only be greater than zero
if the snow particle surface is wet.

2.4.3 Accretion Efficiency:

During rime ice growth all super cooled water droplets freeze upon impact with
the object’s surface and the accretion efficiency, $\alpha_3$, is equal to one. In glaze ice growth,
the rate of heat loss by both the water droplets as well as the surface of the object during
the freezing process determines the freezing rate. The remaining water that does not
freeze tends to run along the surface or is removed by gravity or wind drag.

For glaze ice growth the heat balance equation becomes:

$$Q_f + Q_v = Q_c + Q_e + Q_1 + Q_s,$$

(Eq. 2-6)

where $Q_f$ is the latent heat released during freezing, $Q_v$ is the frictional heating of air, $Q_c$
is the loss of sensible heat to air, $Q_e$ is the heat loss due to evaporation, $Q_1$ is the heat loss
in the warming of the impinging super cooled water to the freezing temperature, and $Q_s$ is
the heat loss due to radiation [Makkonen 2000].

In glaze ice, there is a negative temperature gradient ahead of the growing ice
caused by trapped water within the layers of ice during formation [Makkonen 2000]. The
heat released during freezing moves from the ice-water interface through the liquid water
into the air. The unfrozen water can be trapped without releasing any latent heat thus $Q_f$
becomes:
\[ Q_f = (1 - \lambda)\alpha S F L_f, \quad \text{(Eq. 2-7)} \]

where \( F \) is the flux density of water to the surface, as shown previously, and \( \lambda \) is the liquid fraction of the accretion. Theoretical and experimental attempts to determine the liquid fraction have concluded that \( \lambda \) is highly dependent on the growth conditions and that a value of \( \lambda = 0.3 \) is a reasonable approximation [Makkonen 2000].

The heat conduction into the ice is negligible for the heat balance equation because the ice and water mixture is at a uniform 0°C [Makkonen 2000].

The frictional heating of air is small and can be characterized by:

\[ Q_v = \frac{hrv^2}{(2C_p)}, \quad \text{(Eq. 2-8)} \]

where \( h \) is the convective heat transfer coefficient, \( r \) is the recovery factor for viscous heating (\( r = 0.79 \) for a cylinder), \( v \) is the wind speed, and \( C_p \) is the specific heat of air.

The convective heat transfer is characterized by:

\[ Q_c = h(t_s - t_a), \quad \text{(Eq. 2-9)} \]

where \( t_s \) is the icing surface temperature (\( t_s = 0°C \) for pure water), and \( t_a \) is the air temperature.

The heat loss due to evaporation is characterized by:

\[ Q_e = h\varepsilon L_e \left( e_s - e_a \right) / (C_p p), \quad \text{(Eq. 2-10)} \]

where \( \varepsilon \) is the ratio of the molecular weights of the dry air and water vapour (\( \varepsilon = 0.622 \)), \( L_e \) is the latent heat of vaporization, \( e_s \) is the saturation water vapour pressure over the accretion surface, \( e_a \) is the ambient vapour pressure in the air stream, and \( p \) is the air pressure. The ambient vapour pressure is a function of the temperature and relative humidity of ambient air but is used as a constant here (6.17 mbar).
The heat loss in the warming of the impinging super cooled water to the freezing temperature, $Q_1$, is caused by the temperature difference between the super cooled water droplets and the surface of the icing object as shown below:

$$Q_1 = F C_w (t_s - t_d)$$

(Eq. 2-11)

where $C_w$ is the specific heat of water, and $t_d$ is the temperature of the droplets at impact. It can be assumed that $t_d = t_a$ for cloud droplets because their terminal velocity is very small.

The heat loss caused by long-wave radiation is characterized by:

$$Q_s = \sigma a (t_s - t_a)$$

(Eq. 2-12)

where $\sigma$ is the Stefan-Boltzmann constant ($5.67 \times 10^{-8} \text{ Wm}^{-2}\text{K}^{-4}$), and $a$ is the radiation linearization constant ($8.1 \times 10^7 \text{ K}^3$). This equation does not take into consideration the short wave radiation. It also assumes uniform emissivities for both the icing surface and the environment. The Sun’s short-wave radiation is neglected because icing tends to only occur in cloudy weather [Makkonen 2000].

Substituting all of these values into the heat balance equation and rearranging to solve for the accretion efficiency:

$$\alpha_3 = \frac{1}{F(1-\lambda)L_f} \left[ (h + 6a)(t_s - t_a) + \frac{h e L_s}{C_p p}(e_s - e_a) - \frac{h r v^2}{2C_p} + FC_w(t_s - t_d) \right]$$

(Eq. 2-13)

The convective heat transfer coefficient $h$ in the above equation is dependent on surface roughness and has been studied in detail [Makkonen 1985]. The factors that control the roughness of ice accretion and growth on the surface of the object are not well known. Thus empirical estimates of surface roughness must be included in the modelling process.
2.5 Instrumentation for Measuring and Regulating Ice Accretion

There have been several attempts to develop sensors that can accurately detect ice accretion and ice loads on meteorological towers and instrumentation. Most measurements of ice accretion to date have been derived from empirical data collected at various weather stations. Described below are the most commonly used types of icing sensors in the market today, which are used to detect the onset of ice growth and determine the overall ice accumulation.

2.5.1 Labko Ice Detector 3210C

Labko Oy, a Finnish company has developed an ice sensor called LID (Labko Ice Detector) 3210C specifically for arctic wind power applications that uses a special ultrasonic sensitive wire that can detect icing conditions within time intervals between heating and cooling of the wire. An ice warning signal is given via a digitally controlled sensor signal programmed within preset limits. The sensor data is presented both as a standard DC signal (4 to 20 mA DC) and a serial output (RS-232). Ice accumulation rate can be derived as an amplitude damping rate if the RS-232 output is used. The frequency of the ice alarms indicates the accumulation rate of the ice. In other words, solid ice attenuates the signal more than water or other non solid substances [Labko 2006].

2.5.2 Instrumar Limited Ice Sensor IM101

Another sensor which detects early formations of ice is the Instrumar Limited ice sensor IM101 which measures the surface electrical impedance and temperature of a ceramic probe. This data is used to determine the surface conditions of the probe. An
‘icing window’ can be programmed into the probe so that when the parameters fall within this window, a signal is triggered. The probe itself contains a solid state switch that closes when icing is detected and remains closed for a set period of time. The closure can be used to control devices such as alarms, heaters or even turn on/off low power devices [Laakso 2003, Instrumar 2006].

2.5.3 Rosemount Model 0871LH1 Icing Sensor

Among several types of sensors, Goodrich Deicing Systems has developed the Model 0871LH1 ice detector that works on the principle of ‘magnetostriction’ [Laakso 2003]. A detection probe vibrates ultrasonically at a resonant frequency of 40 kHz. As ice collects on the probe, the total mass of the probe increases causing its resonant frequency to decrease. When the frequency reaches an equivalent to 0.508 mm (0.020 inch) of ice thickness an ice signal is triggered for a 60-second duration. The detector then simultaneously, undergoes a self-deicing cycle that removes the ice from the probe. Another icing event detected within that 60 seconds resets the timer to zero and the ice signal remains activated for an additional 60 seconds [Goodrich 2006].

2.6 Ice Accretion Simulation Software

To simulate natural wind icing conditions on structures, two major software tools have been created, TURBICE, and LEWICE. Both utilize particle dynamics theory and heat transfer to simulate the growth of ice on surfaces and the change in aerodynamic profile of the objects during icing events. This section will outline the two software programs giving a short description of both.
2.6.1 TURBICE

TURBICE has been under development at the Technical Research Institute of Finland (VTT) since 1991 and has been specifically developed for modelling ice accretion on turbine blades. In short, it uses a numerical model to accrete ice on a 2D airfoil section in a potential flow field directed perpendicular to the airfoil axis by integrating the steady-state equation of motion to determine droplet trajectories [Tammelin 2001]. This modelling tool simulates both glaze and rime icing. The simulations have been compared and verified with data from icing wind tunnel experiments for aircraft wing sections and from a field study of natural wind turbine icing. These simulations have shown to be in good agreement with actual data [Makkonen 2001].

2.6.2 LEWICE 2.0

LEWICE 2.0 was developed by the icing branch at the NASA Glenn Research Center in Cleveland, Ohio. It uses codes to predict ice accretion by applying a time stepping procedure to calculate the shape of an ice accretion. It cannot, however, predict reduced efficiency in aerodynamic performances as a result of icing; rather, it analyzes the thermodynamics of the freezing process that occurs when super cooled droplets impinge on a body. The primary use of this software tool is for evaluating icing on aircraft but can be adapted to work on other applications. The ice growth rate on the surface of the body is calculated from the icing model that was first developed by Messinger [Wright 1999, Messinger 1953]. This is an iterative process where an ice
thickness is added to a body through the ice growth rate. The procedure is then repeated for a specific duration of time. Both dry and wet (glaze) ice growth can be modeled by LEWICE. The modeling program also incorporates a thermal anti-icing function which calculates the power density required to prevent the formation of ice on the body. The main purpose of LEWICE is to obtain anti-icing values but can also be used to generate data on droplet trajectories, collection efficiencies, impingement limits, energy and mass balances, ice accretion shape and thickness [Wright 1999].

3 CAPACITIVE AND RESISTIVE ICING PROBE DEVELOPMENT

The following sections will discuss the experimental stage of the thesis where several designs were developed to best test the relationship between change in capacitance and resistance and icing thickness. The apparatuses consisted of a set of capacitive and resistive probes, first in the form of aluminium rods and subsequently aluminium plates that were tested both in the University of Manitoba Icing Tunnel Facility (UMITF) as well as in a controlled environment to simulate icing effects. This section will begin with a description of the calculation of capacitance and resistance using theoretical models of cylinders and flat plates as well as a brief description on the capacitance and resistivity of ice. It will then go into detail about the preliminary probe designs, experimental procedures, data collection, and the flaws encountered during testing.
3.1 Calculation of Capacitance:

Capacitance is the measure of the electric charge stored between two oppositely charged electrodes separated by a given distance. The two conducting electrodes are insulated from one another through this separation and the potential difference between these two electrodes is represented by the voltage across the electrodes. Capacitance can be characterized by the equation:

\[ C = \frac{Q}{V}, \]  

(Eq. 2-14)

where \( Q \) is the charge on each electrode and \( V \) is the voltage across the electrodes—[Capacitance Wikipedia]—the higher the charge on each electrode, the higher the capacitance. The amount of charge an electrode can hold is dependent also on its surface area of the electrodes and the distance between them. For flat plate electrodes, the larger the surface area of the electrode the more charge it can hold. The simplest representation would be a pair of electrodes in the form of flat plates. Consider an ideal circuit with a voltage source and two flat plate electrodes touching. Also assume that the wires and electrodes have no resistance. The current flows through the wires and the electrodes effortlessly:

![Figure 3-1: Capacitor with flat plates touching](image)

Figure 3-1: Capacitor with flat plates touching
Because the electrodes are in contact the distance between them is assumed to be zero and the capacitance is zero. This is obvious because there is no ‘build-up’ of charge between the plates. The current flows effortlessly across the plates. Now assume that the plates are spaced apart by a distance $d$:

![Figure 3-2: Capacitor with flat plates spaced apart](image)

Since there now exists an insulated gap of air between the two plates, both positive and negative charges begin to build-up between the plates. The tendency for the charge to jump from one plate to the next is dependant on the permittivity of the insulator, in this case air. The permittivity of any material is usually represented relative to that of a vacuum, in the form of the relative permittivity $\varepsilon_r$, also known as the dielectric constant. The permittivity is a measure of the ability of a material to polarize in response to an electric field or to transmit an electric field. Thus by definition, the dielectric constant of a vacuum is equal to one. For air, $\varepsilon_r = 1.00054$. These constants are dimensionless. For this thesis, the dielectric constant of water and ice is: $\varepsilon_r = 80$ and $3.2$ respectively [Dielectric Constant Wikipedia]. The dielectric constant of a material is a measure of the material’s ability to concentrate lines of electrostatic flux. The higher this concentration
the easier it is for the material to polarize in the electric field and the easier it is for electrons to pass from one electrode to the other. This results in a higher charge build up leading to a higher capacitance between electrodes [Electrostatics, Wikipedia]:

![Figure 3-3: Concentration of electrostatic lines of flux between electrodes](image)

Thus for flat plates the capacitance equation becomes:

\[
C = \varepsilon_r \varepsilon_0 \frac{A}{d},
\]

(Eq. 2-15)

where \( \varepsilon_r \) is the relative permittivity, also known as the dielectric constant of the material—which is dimensionless, \( \varepsilon_0 \) is the permittivity of free space (~8.85x10^{-12} F/m), \( A \) is the surface area of the plates and \( d \) is the distance between the plates.

To calculate the capacitance of parallel rods, it is necessary to apply the theory of capacitance for parallel wires [Capacitor S&E Encyclopaedia, Chen 2005]:

31
\[
C(F/m) = \frac{\pi \varepsilon_r \varepsilon_o}{\cosh^{-1} \left( \frac{s}{d} \right)} , \quad \text{(Eq. 2-16)}
\]

where \( \varepsilon_r \) is the dielectric constant of the insulator between the rods, in this case air, water, and ice, \( \varepsilon_o \) is the permittivity of free space, \( s \) is the distance between the centers of the rods, and \( d \) is the diameter of the rods (see Appendix B for closer analysis of capacitance for cylinders):

![Figure 3-4: Parallel wire capacitance](image)

The capacitance between electrodes can be measured using a capacitor meter or indirectly through the use of a combination of a voltmeter, ammeter, and function generator. This will be discussed later in the section describing initial design concepts. The mechanics behind the capacitance of ice will be discussed later in the results and discussion section.

### 3.2 Calculation of Resistance:

The resistivity of any material is a measure of how strongly it opposes the flow of electric current. Resistance of a material is simply the voltage across the material divided by the current through it and is a rearrangement of Ohm’s Law:

\[
R = \frac{V}{I} , \quad \text{(Eq. 2-17)}
\]
In an ideal circuit, the resistance of the wires and electrodes is negligible, but in reality, all wires contain some degree of resistance. This must be taken into account when calculating the change in resistance between probes during ice build-up. Resistivity of a material is given by:

\[ \rho = \frac{R A}{l}, \]  

(Eq. 2-18)

where \( R \) is the electrical resistance of the material, \( A \) is the cross sectional area of the specimen, and \( l \) is the length of the specimen [Resistivity Wikipedia]. The resistance of any object is also dependent on its material properties. The electrical resistance of air is very high. In other words, air acts as an excellent insulator. In an ideal circuit, when two electrodes are spaced apart by a gap of air, the circuit is essentially severed and the resistance across those electrodes is assumed to be infinite. The resistance between the electrodes remains infinite until the gap is closed at which the resistance falls to zero. Based on this simple observation it can be assumed that the resistance is either infinite or a single value between zero and infinite. This value is based on the resistance of the insulator between the two electrodes. Both ice and water have a specific resistivity. This resistivity is mainly dependant on the material properties of water, specifically on the concentration of impurities and the pH of the water. Tap water and rain water are slightly acidic and contain several impurities which affect its resistivity. In other words, this type of water can carry a current to a certain degree. Distilled water, on the other hand, has a pH value of exactly seven and contains no impurities that allow current to pass through it. Thus, in ideal cases the resistance across a specimen of ice or water that is distilled is infinite. Because the change in resistance is not gradual across an air gap, it can be concluded that the change in resistance during ice build-up is constant up until the
occurrence of ‘bridging’ when the resistance will fall rapidly to a value pertaining to the resistance of the ice. As a result, resistance is not an effective method for measuring ice build-up over time but rather an indication of the exact time when ‘bridging’ occurs. This applies to all geometries of electrodes.

3.3 **Initial Design Concepts**

The following sections will discuss initial design concepts for capacitive and resistive electrodes that could calculate change in capacitance and resistance during ice build-up in the UMITC.

The first concept was based on the notion of a series of electrodes spaced apart at interval distances. Initially it was proposed that flat plates were to be arranged in such a way as to stack them at interval distances so that their largest surface area was parallel to the wind direction. They would be held by a strip of non conducting acrylic:

![Figure 3-5: Flat plate design](image-url)

**Figure 3-5: Flat plate design**
This method would have been easiest to calculate the capacitance during icing by using the concept of flat plates. The problem lies in the formation of ice around a flat plate during testing. Based on the behaviour of rime and ice growth, in both rime and glaze ice tests, the ice would build-up primarily on the front small edge of the plate. Low density rime ice will begin to build on the smallest face and grow outwards. Glaze ice, on the other hand will form on the sides of the plate, but not evenly because of the direction the plates are facing:

Therefore it was concluded that the use of flat plates in this arrangement is not effective for calculated capacitance because of the non-uniform ice build-up between plates.

Based on this initial setup it was assumed that the problem was in the shape of the electrodes and not in their arrangement. It was proposed that to achieve a uniform ice build-up around the electrodes, cylindrical rods were to be used. This led to the development of the first tested concept. This concept included the arrangement of six, 6 inch long 0.5 inch diameter cylindrical steel rods, drilled and threaded on each end and
fastened to a strip of non conducting acrylic. They were to be spaced at specific distances so that the effect of spacing on capacitance could be taken into account during testing:

![Figure 3-7: Schematics for rod design](image)

The growth of ice around cylinders is much more evenly distributed:

![Glaze ice growth over time](image)

![Rime ice growth over time](image)

Figure 3-8: Expected ice growth on rod design
For this design, the measurement of capacitance becomes more difficult because the concept of flat plate electrodes no longer applies. The measurement of capacitance for this design will be discussed in the subsequent sections describing the experimental setup and procedure.

The steel rods were later replaced by aluminium rods because the rods used were construction grade steel and were coated with a thin layer of oxidized steel whose resistivity is not zero. In order to test the effects of ice build-up on resistivity, this coating would have to be removed, thus exposing the steel to the icing effects resulting in prominent rust stains. This justified the change to aluminium which is not only lighter in mass but also less resistive to electric current than steel.

### 3.4 Cylindrical Electrode Design Experiment

This section outlines the calibration of the University of Manitoba Wind Icing Tunnel and describes the procedural setup and testing of the preliminary design of the cylindrical rod electrodes. A description of the measurement procedure for capacitance of the cylindrical rods will also be given as well as the problems encountered during and after testing.

#### 3.4.1 Facility

The University of Manitoba is home to the UMITC or University of Manitoba Icing Tunnel Complex, located in Engineering Building 3, built for the purpose of simulating real weather conditions on stationary airfoils. These airfoils are placed within
an inner duct that guides air flow and water spray via a series of spray nozzles located upstream from the testing chamber:

![Image of spray bar centered in inner duct](image1)

Figure 3-9: Spray bar centered in inner duct

![Image of UMITC Schematic](image2)

Figure 3-10: UMITC Schematic [Naterer 2001]

This spray system contains a high pressured air nozzle that atomizes water flow into the air which is subsequently carried by the wind produced by a powerful fan. The
temperature in the wind tunnel is carefully controlled by a heat exchanger and monitored by three separate thermocouples located at different ends of the tunnel system. The nozzles in place during the experimentation allowed water droplet diameters to range anywhere between 10^{-3} to 10^{-5} m. In low temperature tests the nozzles must be heated to prevent clogging, via an external heating source.

3.4.2 Wind Tunnel Calibration

Due to time constraints of this thesis the wind tunnel had already undergone calibrations to test under the conditions for rime ice and glaze ice to form effectively on the testing apparatus within the inner duct.

To calibrate the wind tunnel, normally, a series of tests are performed at varying temperatures to obtain data on wind speeds [Kraj 2007]. A three-cup manometer is placed downstream of the inner duct of the icing tunnel while a pitot-tube manometer is placed upstream behind the water nozzles. This is to test the accuracy in the frequency of the fan and to calibrate it for producing the correct wind speeds at these given temperatures. The calibration parameters set for the icing tests required a range of motor frequencies between 8 and 40 Hz (3 to 24 m/s), and a temperature range between -30°C and 25°C. For details on the results for this type of calibration, please refer to [Kraj 2007].

3.4.3 Experimental Objective

The purpose of the experiment to test the cylindrical electrode approach was to measure the change in capacitance and resistance for specified distances between electrodes, on the build-up of ice over time.
3.4.4 Scope

There have been several attempts to create a successful probe based of the capacitive and resistive approach to measure and control the build-up of ice on instrumentation and structures. Some of these include:

- U.S. Pat. No. 4766369: Ice Detector
- U.S. Pat. No. 5874672: Apparatus and method for determining the existence of ice or water on a surface from the capacitance between electrodes on said surface.
- U.S. Pat No. 6384611: Ice Thickness Detector
- U.S. Pat No. 5551288: Measuring ice distribution profiles on a surface with attached capacitance electrodes

The majority of these designs deal with calculating ice thicknesses on airfoils of wings on aircraft at high altitudes and at extreme wind conditions (see Appendix D for details). This experiment will attempt to simulate weathering effects in cold climates but at altitudes close to ground level. Two distinct ice types: rime and glaze, will be simulated by adjusting the overall temperature of the wind icing tunnel. A summary of the parameters that are going to be considered during testing are outlined in the following section.

3.4.5 Experimental Parameters

To achieve ideal conditions for the formation of rime and glaze ice in this experiment, the wind tunnel motor was set to a frequency of 11.5 Hz which translated to a wind speed of 20k/hr or approximately 5.55 m/s. For stationary meteorological towers this wind speed seemed reasonable for cold climate conditions. The flow rate of water through the nozzles was set to 2 gallons per hour or approximately 7.57 litres per hour for all four nozzles. The maximum mass flow rate of water in the tunnel is 4 gal/hr. This
would cause the liquid water content (LWC) to be too high for the formation of either type of ice. An imbalance in LWC would cause the ice formation to be too “wet” or “dry” [Kraj 2007]. Because glaze ice and rime ice both form at temperatures below 0°C, the water intake into the nozzles was heated to around 35.9°F or 2.17°C to prevent clogging of the nozzles due to premature freezing. For conditions of glaze ice temperatures must be in a range of 0°C to -4°C. The wind tunnel was to be set to and average -2°C. For rime ice the temperature range falls between -4°C to -12°C, so the wind tunnel was set to achieve a temperature of -10°C. These temperatures were chosen taking into account a margin of error in the wind tunnel’s thermocouple accuracy. To obtain optimal temperatures near the specimen a thermocouple was attached just above the position of the specimen and connected to a data acquisitions system that would record the temperature each second. A summary of the wind icing tunnel parameters is as shown:

### Table 3-1: Experimental parameters

<table>
<thead>
<tr>
<th>Preliminary Wind Tunnel Conditions</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind Tunnel Set Motor Frequency (Hz)</td>
<td>11.5</td>
</tr>
<tr>
<td>Spray Nozzle Bar Water Temperature (°C)</td>
<td>2.17</td>
</tr>
<tr>
<td>Spray Nozzle Bar Air Pressure (MPa)</td>
<td>0.325</td>
</tr>
<tr>
<td>Spray Nozzle Bar Water Flow Rate (m³/s)</td>
<td>2.10E-06</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Rime Icing Conditions</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Free Stream Temperature (°C)</td>
<td>-2</td>
</tr>
<tr>
<td>Free Stream Pressure (MPa)</td>
<td>0.1013</td>
</tr>
<tr>
<td>Local Wind Velocity (m/s)</td>
<td>5.55</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Glaze Icing Conditions</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Free Stream Temperature (°C)</td>
<td>-10</td>
</tr>
<tr>
<td>Free Stream Pressure (MPa)</td>
<td>0.1013</td>
</tr>
<tr>
<td>Local Wind Velocity (m/s)</td>
<td>5.55</td>
</tr>
</tbody>
</table>

### 3.4.6 Procedure

The following sections will discuss the apparatus setup and configuration for the two types of wind tunnel tests. This section will describe the methods used to measure both capacitance and resistance during testing.
3.4.7 Preparation

To effectively measure the resistance and capacitance across the aluminium rods, wires were connected via small set screws drilled into the back of the rods:

![Figure 3-11: Set screws drilled into back of rods](image)

The aluminium wires, normally used in strain gauges, were used to connect the rods to the electronic equipment that would measure capacitance and resistance. The wires were bundled and labelled to avoid confusion during testing:

![Figure 3-12a: Bundled wires leading to apparatus in testing chamber](image)  ![Figure 3-12b: Wire labeling](image)
At the time, a meter that could measure capacitance could not be obtained. As a result it was necessary to measure capacitance indirectly through the measurement of voltage and current flow across the probes. This was done by connecting the rods into an AC circuit along with a function generator, and two digital multimeters:

![Capacitance measurement setup](image)

In alternating current (AC) circuits, the ratio of voltage to current is called Impedance, rather than resistance which occurs in DC (direct current) circuits. The function generator was set to produce a sine wave voltage starting at 60 Hz at a peak to peak voltage of 4V. The voltmeter would read the RMS equivalent of 1.414 volts:

$$V_{RMS} = \frac{V_{P-P}}{2} \times 0.707 \quad \text{(Eq. 2-19)}$$

To check to see if the circuit was working, the voltage drops to zero once the rods are connected via a wire. This means that the resistance drops to zero. Similarly the ammeter that reads the current is expected to remain equal to zero until the ice bridges between the two electrodes (circuit is incomplete until bridging). The capacitance would then be calculated via the impedance:
\[ X_c = \frac{V_c}{I} = \frac{1}{\omega C}, \]  

(Eq. 2-20)

where \( \omega \) is equal to the angular frequency \( (\omega = 2\pi f) \), \( f \) is the frequency set by frequency generator, and \( C \) is the capacitance across the electrodes. Because the multimeters did not have multiple leads, manual switching for each pair of rods had to be performed for both multimeters. Also, a data acquisition system for reading voltage and current was not available. This would introduce slight delays in data readings.

3.4.7.1 Problems Encountered During Setup

When the ammeter and voltmeter were connected to the apparatus and function generator, a series of tests were done to ensure that the circuit was functioning properly. Initially the voltmeter was tested without the ammeter connected. The voltage dropped to zero, as expected, once the probes were connected together via wiring (resistance drops to zero). The ammeter was then connected in addition to the voltmeter and tested. The current remained equal to zero even when the rods were connected. It was assumed that the ammeter’s range was insufficient to detect any current through the wiring. In an attempt to measure some current through the circuit the voltage amplitude of the function generator was maxed out and the frequency was continuously increased until a reading could be made. A very small current reading in the range of 0.001mA was made at a frequency of 20kHz and a max peak to peak voltage of 20V. It was concluded that among several problems, the current method of calculating the capacitance using the function generator, voltmeter, and ammeter was not effective for the apparatus. The range of the ammeter was insufficient to detect any current through the rods even when they were connected with an aluminium wire.
The function generator was disconnected and the measurement of capacitance was abandoned for the test. It was concluded that for the current design capacitance would have to be measured directly using a capacitance meter. The apparatus was then setup to measure resistance because only one multimeter is required without a voltage supply.

3.4.8 Test Procedure

After setting up the apparatus in the test chamber, the first set of probes spaced one millimetre apart were connected to the multimeter. The first test would be to simulate the effects of glaze ice build-up on the apparatus. The wind icing tunnel was set to reach a temperature of -2°C. It took an hour to reach this temperature which was continuously monitored via thermocouple located just above the apparatus in the testing chamber and connected to a temperature data acquisition system:

Once the temperature was reached the water nozzle was activated and a timer was started. Readings of resistances were to be read every five minutes, allowing a 15 second window of time to manually switch between each pair of probes to read the resistances. It was proposed that once bridging occurred at the first pair of probes (those that were spaced
closest together) it was no longer necessary to record resistances for that pair. This would apply to bridging of subsequent pairs of electrodes.

Although it was concluded earlier that resistance is not an effective method of measuring real time ice growth it could be used to estimate it by measuring the time for bridging for each set of distances under given icing conditions and then calculating ice growth by comparing bridging times to separation distances.

3.4.8.1 Problems Encountered During Testing

After approximately ten minutes into the testing phase it was observed that the ice growth rate was not as expected. Because the temperature of the chamber was set to only -2°C, the heated nozzle water droplets did not reach this expected temperature upon impact onto the rods. In other words the thermocouple above the apparatus was reading temperatures between -1°C and +1°C. As a result the glaze ice forming on the apparatus was being melted by the warmer water droplets. To offset these effects, it was concluded that the temperature of the chamber would be lowered by one degree. This would still be in range of the formation of glaze ice under the current conditions. Unfortunately the chamber does not gradually drop in temperature. After five minutes the chamber had dropped ten degrees to -10°C and then began to slowly rise to the desired -3°C. This changed the formation of ice from glaze to rime which subsequently began to form rapidly around the leading edge of the rods, building straight outwards and then fanning out the sides. This had drastically affected the experiment. Unfortunately this was not the largest problem encountered. Once bridging occurred at the closest pair of electrodes, the multimeter read a zero resistance. It was assumed that there was fault in the wiring but
the wiring was tested afterwards and worked perfectly. The fault lay in the fact that the icing tunnel uses distilled water. Distilled water has no impurities thus acting as a perfect insulator. The method for determining the effects of ice growth on resistance between probes could not be applied or tested in this icing tunnel. At this point in testing, the following suggestions could be made:

1) Test resistance using tap water in a controlled environment, i.e. a freezer separate from the icing tunnel with no wind conditions.

2) Obtain a capacitor meter that could measure capacitance across the probes in the icing tunnel. Capacitance can still be measured for distilled water but will require a very sensitive meter that could measure in the pico to femto-Farad range.

3) Obtain a function generator with a very large voltage source in the range of 200-400V. This could pose as a safety concern and will need the supervision of an experienced technician to oversee its usage to prevent serious harm to the student. Current will still flow through distilled water but will require an ammeter with a very low range to measure effectively.

4) Change the apparatus back to the idea of flat plates and space them very close together so that the low voltage function generator can be used safely to determine capacitance.

3.5 REVISED CAPACITANCE EXPERIMENT
For the final set of tests a capacitance meter was obtained and used to determine the capacitance during icing between pairs of rods, specifically between rods 1 and 2, 2 and 3, as well as 4 and 5, and finally 5 and 6 as shown below:

![Figure 3-15: Numbered aluminium rods](image)

<table>
<thead>
<tr>
<th>Table 3-2: Rod pair gap widths</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rods</td>
</tr>
<tr>
<td>------</td>
</tr>
<tr>
<td>5-6</td>
</tr>
<tr>
<td>4-5</td>
</tr>
<tr>
<td>1-2</td>
</tr>
<tr>
<td>2-3</td>
</tr>
</tbody>
</table>

There were three icing tests performed, each to simulate a different type of icing: Rime, Glaze, and a Rime-Glaze mixture. Each test will be discussed below.

### 3.5.1 RIME ICE TEST

#### 3.5.1.1 Experimental Setup

Three separate icing events were simulated in the wind icing tunnel and capacitance was recorded for each. The first test simulated the growth of rime ice. Rime ice forms at temperatures between -4°C to -12°C when the liquid to water content (LWC) is low. To simulate this, the wind icing tunnel was set to maintain a temperature of -10°C with a water nozzle mass flow rate of 2 gal/hr or 7.57 litres/hr. The fan motor was set to
11.5 Hz which provided a constant wind speed of 20km/hr. The wind speed was kept constant throughout the three icing events.

Because wires themselves have a capacitance it was recommended to use as short a wire as possible between the meter and the apparatus. Since it was not safe to operate the capacitance meter in the wind tunnel itself long lead wires had to be used. Before attaching the lead wires to the rods, their capacitance was measured for each designated pair of rods:

<table>
<thead>
<tr>
<th>Wires Pairs</th>
<th>Capacitance [pF]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2</td>
<td>126.3</td>
</tr>
<tr>
<td>2-3</td>
<td>128.2</td>
</tr>
<tr>
<td>4-5</td>
<td>120.5</td>
</tr>
<tr>
<td>5-6</td>
<td>104.6</td>
</tr>
</tbody>
</table>

These values would later be subtracted from the capacitance readings for each pair of rods during the testing. These values are considered constant through each of the three icing tests.

The apparatus was mounted on a bar that spanned the length of the inner ducts so that it sat in the direct path of the oncoming water spray. This was to ensure even distribution of ice growth on all the bars. A thermocouple was mounted at the mouth of the duct leading down to the apparatus to read the temperature of the oncoming wind and water spray via a data acquisition system:
A second thermocouple was mounted further down the wind tunnel behind the apparatus and was monitored by a wall mounted meter.

3.5.1.2 Test Procedure

Data was taken every two minutes so that an accurate trend could be established. Because the capacitance meter had only two leads and there was no data acquisition system available, a coaxial cable with two alligator clips was used to connect to each pair of wires manually in succession every two minutes while recording the capacitance. A fifteen second window of time was incorporated into the measurements to allow time to switch between pairs of leads. This setup is shown below:
This setup would be used for each experiment. The apparatus would be cleaned and degreased after each test and the capacitance of the rods without ice build-up would be tested individually to ensure consistency between tests.

3.5.1.3 Test Results

A summary of the parameters used during the experiment as well as a plot of the capacitance change over time as ice built up between and around the rods is shown below:

Table 3-4: Rime ice growth experimental parameters

<table>
<thead>
<tr>
<th>Rime Growth</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Temp (°C)</td>
<td>-10</td>
</tr>
<tr>
<td>Water mass flow rate (gal/hr)</td>
<td>2</td>
</tr>
<tr>
<td>Wind Speed (km/hr)</td>
<td>20</td>
</tr>
<tr>
<td>Nozzle Water Pressure (kPa)</td>
<td>325</td>
</tr>
<tr>
<td>Nozzle Air Pressure (kPa)</td>
<td>350</td>
</tr>
</tbody>
</table>
Figure 3-18: Change in capacitance over time during rime ice growth

A summary of this data can be seen in Appendix A.

3.5.1.4 Discussion of Results

Because rime icing conditions call for low liquid water content and cold temperatures the resulting growth formation is very feathery, white and low density. Instead of ice growing evenly around the rods, frost forms at the leading edge of the rod and grows straight outwards. Little or no ice forms between and behind the rods:
The low density ice formation results in a low measurement of capacitance for each pair of rods. This is caused by the air trapped in between the frozen water particles. The capacitance of air is very low. This is because the dielectric constant of air is very close to that of a vacuum $\varepsilon_r = 1.00054$. The graph does however clearly show a trend for each set of rods. Looking back at the definition for capacitance between parallel cylinders, the greater the distance between the rods the lower the capacitance. This is evident in the plot of capacitance over time. The capacitance for each pair of rods changes in the same manner regardless of distance between rods, except for the closest pair. A linear increase in capacitance is evident in the 15 to 55 minute marks for all four pairs of rods. A line of best fit curve can be applied to this trend, as shown in Figure 7-C4 in Appendix C, to estimate the growth rate of ice (dM/dt) with respect to the changes in capacitance over
time. Around the 35 minute mark the capacitance between rods five and six jump and then begin to normalize while the capacitance of the other rods continue to grow. This jump can be correlated to a complete bridging of ice between the rods. It should be noted that bridging is assumed to occur evenly throughout the length of the rods because of the position of the apparatus in the inner duct allows for even distribution of water droplets. The normalization, however, may be caused by complete encasing of rods five and six. Based on the definition of electrostatic fields and the behaviour of a dielectric medium, discussed in a previous section, it can be concluded that any ice that forms outside the highest concentration of electrostatic flux between the rods, does not greatly affect the capacitance readings:

![Figure 3-20: Movement of electrons across electrostatic lines of flux upon bridging](image)

It can be difficult to observe bridging during rime icing tests because of the low density ice formation between the rods, especially for those pairs that are closest together.
Although the rods may appear to be bridged from a distance, large cavities of air can still form between the rods. This may cause a fluctuation in capacitance readings.

![Figure 3-21: Movement of electrons around air gaps](image)

Figure 3-21: Movement of electrons around air gaps

Also, because of the growth behaviour of rime ice, bridging may not occur directly between rods. Electrons will still travel through the medium with a higher dielectric constant, in this case ice. This is evident in the pairs of rods spaced farthest apart, particularly pairs 1-2 and 2-3 (6.35 mm and 12.7 mm respectively):
At around 55 minutes into testing it is clear from the charts that the remaining three pairs of rods reach maximum capacitance after which the readings normalize. As seen in the above figures, once bridging occurs, the gap is blocked and any more ice that builds upon the pair of rods past the point of highest concentration of electrostatic lines, does not affect the capacitance.

It can be concluded that normalization of capacitance is not necessarily an indication of the exact time of bridging but rather the maximum amount of ice built up that will affect capacitance. Because the apparatus is setup in such a way that the ice builds evenly along the length of each rod it can also be concluded that, based on theory, the maximum reading of capacitance indicates the exact time of bridging. Upon bridging the electrons will begin to pass through the ice rather than the air causing a jump in capacitance.

If we were to look at the relationship between separation distance and diameter of rods and their effect on the behaviour of capacitance, as shown in Figure 7-B6 in Appendix B, an optimal rod spacing could be determined for best results in this test.
The maximum capacitance was harder to measure because of the number of readings taken. If a data acquisition system was available, more readings per minute could be read and an indication of the exact time of bridging could be determined.

3.5.2 GLAZE ICE TEST

3.5.2.1 Experimental Setup

The Glaze ice test experimental setup was very similar to that of the rime test. Once the rime test was completed the apparatus was cleaned and the capacitance of the rods were re-measured so that a reading at $t = 0$ could be established. To properly simulate glaze ice the temperature was increased to -2°C. Normally a temperature at the freezing point of water would be ideal, 0°C. The pressurized water entering the nozzles is heated to just above freezing to prevent clogging during the tests. This offset in temperature was taken into account and dropped the temperature of the water droplets hitting the apparatus to 0°C. Glaze ice tends to be a density, high liquid to water content formation that is clear and lumpy. The mass flow rate of water through the nozzles was increased from 2 gal/hr (7.571 L/hr) to 5 gal/hr (18.927 L/hr). This would result in a more ‘wet’ type of growth. The fan speed was kept constant at 11.5 Hz (20 km/hr wind speed).

3.5.2.2 Test Procedure

The procedure for testing was the same as the rime test.

3.5.2.3 Test Results
A Summary of the test results and data in the form of a plot of Capacitance vs. Time for each pair of rod is shown below:

Table 3-5: Glaze ice growth experimental parameters

<table>
<thead>
<tr>
<th>Glaze Growth</th>
<th>Temp (°C)</th>
<th>-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water mass flow rate (gal/hr)</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Wind Speed (km/hr)</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Nozzle Water Pressure (kPa)</td>
<td>325</td>
<td></td>
</tr>
<tr>
<td>Nozzle Air Pressure (kPa)</td>
<td>350</td>
<td></td>
</tr>
</tbody>
</table>

Figure 3-23: Change in capacitance over time for glaze ice growth

A summary of this data can be seen in Appendix A
3.5.2.4 Discussion of Results

Upon first inspecting the graphs for rod pair 5-6 it is evident that there is a large jump in capacitance at the beginning of testing. Because the conditions for glaze ice calls for a very high liquid water content the capacitor meter began reading spikes in capacitance due to water build-up between the rods. The high concentration of water hitting the apparatus at the beginning of the testing did not yet have time to freeze and thus caused bridging between the closest pair of rods with water. In other words, the water droplets collected on the surface of the rods were large enough to bridge the gap between the closest pair of rods. Because the dielectric constant for water is much larger than ice (80 compared to 3.2) the capacitance readings jumped considerably at the beginning of the experiment. This was also somewhat evident in the next largest spaced rods. But in the case of rods four and five the capacitance did not drop as much after spiking. This can be the result of two situations: First, water may have pooled at the base of the rods to the point where the pools of water around each rod touched causing the increase in capacitance and then subsequently failed to freeze causing the capacitance to remain constant. Secondly, due to sensitivity of the temperature there could have still been pockets of water in between rod pair four and five causing the capacitance to remain around that of water.

Capacitance measurements between rod pairs 1-2, and 2-3 showed similar behaviour primarily due to the large spacing between them. Looking at the graph, the capacitance shows a relatively flat trend throughout the experiment. This is due to the slow growth rate of glaze ice. Because glaze forms uniformly around the rods and is very dense, its growth rate is slow. Unlike rime ice it is much more difficult to determine the
bridging time through changes in capacitance in this experiment, but much easier through visual observations. Normalization appears to occur at the start of experimentation, much sooner than in the rime test. Again this is difficult to confirm due to the insufficient number of measurements taken over the short period of time. To accurately measure a trend in capacitance for glaze ice between the largest spaced rods, it is necessary to substantially increase the duration of the test.

Water pooling and bridging did not affect the measurements of capacitance for rod pairs 1-2 and 2-3 early in the experiment:

![Glaze ice build-up between rods 1, 2, & 3](image)

Figure 3-24: Glaze ice build-up between rods 1, 2, & 3
Figure 3-25: Considerable glaze ice growth in apparatus

It is evident through the diagram above that the high water content causes icicles to form and drip down from the top of the apparatus before freezing. Much of this water also pooled at the base of the apparatus, some of which froze the apparatus to the support bar.

It can be concluded that the spiking in the capacitance measurements early in the experiment cannot be a good indication of maximum capacitance and bridging because of the high ratio of water to ice. Due to its slow growth rate, it would be much easier to determine the bridging time if more measurements per minute were taken via a data acquisition system.

### 3.5.3 RIME-GLAZE MIXED ICE TEST

#### 3.5.3.1 Experimental Setup

The final test was to adjust the environmental conditions so that a combination of rime and glaze could form. To do this, the water nozzle flow rate and temperature were
adjusted to be between those of rime and glaze conditions. The water flow rate was
adjusted to 3 gal/hr (11.36 L/hr) and the temperature was dropped down to -4°C. These
conditions would produce a wet snow type of growth. The wind speed was kept constant
at 20 km/hr. The apparatus was cleaned and readings for capacitance at t=0 were retaken.

3.5.3.2 Test Procedure

The test procedure is the same as the Rime and Glaze tests.

3.5.3.3 Test Results

A summary of the experimental parameters and plot of capacitance vs. time for
each pair of rods is shown below:

<table>
<thead>
<tr>
<th>Table 3-6: Glaze-Rime mixed ice growth experimental parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Glaze-Rime Mixed Growth</strong></td>
</tr>
<tr>
<td>Temp (°C)</td>
</tr>
<tr>
<td>Water mass flow rate (gal/hr)</td>
</tr>
<tr>
<td>Wind Speed (km/hr)</td>
</tr>
<tr>
<td>Nozzle Water Pressure (kPa)</td>
</tr>
<tr>
<td>Nozzle Air Pressure (kPa)</td>
</tr>
</tbody>
</table>
Figure 3-26: Change in capacitance over time for Glaze-Rime mixed ice growth

The data for this plot can be seen in Appendix A

3.5.3.4 Discussion of Results

All four pairs of rods showed very similar results for increases and decreases in capacitance over time. All four pairs appear to have reached peak capacitance and began normalizing at the same time. This may be the result of an agreeable median between the two types of ice. The consistency of ice is just enough that it doesn’t pool water and doesn’t grow rapidly outwards from the leading edge. Although the data seems clear, it is obvious that all four pairs cannot bridge at the same time because their spacing isn’t constant. According to the data is seems as if all four pairs of rods bridge at around 50 minutes (maximum capacitance reading).
The data does however have some similarities with the plots of rime and glaze ice. The capacitance values for all four pairs of rods lie between the measurements for rime and glaze ice. This is consistent with the fact that the liquid water content of this mixture should be between that of rime and glaze. All four pairs of rods exhibit a spike in capacitance readings at the start which is similar but less intense that that of the glaze test. Also, there is a clear dip in capacitance for all four rods around the 30 minute mark which is also evident in the rime ice growth test (around the 10-15 minute mark). Because these anomalies in the testing are common to all four pairs of rods, it can be assumed that they are caused not by the ice growth on the rods themselves but a change originating from the capacitor meter itself or the water flow from the nozzle. A clear trend in capacitance is displayed between the 10 and 40 minute marks. Again a trend line can be used to estimate the ice growth rate \( dM/dt \) based on changes in capacitance over time, as shown in Figure 7-C6, in Appendix C. It would be feasible however to take more capacitance measurements to understand the source of the anomalies in the readings.

It can be concluded that although the results seem in agreement in comparison to those of the rime and glaze tests, it is obviously unclear when bridging occurs for each pair of rods. Normalization does occur however at around 50 minutes into the testing, but this again only indicates when the rod pairs are encased in ice, at an undetermined amount of time after bridging occurs.

### 3.6 Uncertainties and Possible Sources of Error

Due to time constraints, proper equipment for these experiments could not be obtained. As a result much of the data collection had to be done manually. For example, a
data acquisition system for measuring capacitance could have been used to better indicate bridging time for each pair of rods. It is normally recommended that in order to measure capacitance accurately, the lead wires from the meter to the apparatus must be as short and as closely tied together as possible to reduce movement and interference from other objects which can change the capacitance of the wiring. For this experiment a combination of a coaxial cable and aluminium wiring were used connected by alligator clips. Slight movement of the wiring during testing caused by wind in the wind tunnel produced slight fluctuations in the readings of capacitance.

The manuals switching of the alligator clips from one pair of rods to the next may have caused some error in the readings because of the window of time required as well as gradual decimation of wiring caused by repeated attachment and detachment of alligator clips. To improve this, it would be necessary to acquire a capacitance meter with multiple leads and a switch to change between them.

3.7 Theoretical Capacitance in Relation to Experimentation

To get a better idea of the maximum capacitance for ice between the rod pairs, it is necessary to look back at the definition of capacitance between parallel cylinders. Previously, it was established that capacitance between parallel cylinders per meter was defined by:

\[ C[F/m] = \frac{\pi \varepsilon_r \varepsilon_o}{\cosh^{-1}(S/d)} \]

where \( \varepsilon_o \) is the permittivity of free space \( (\varepsilon_o \approx 8.85 \times 10^{-12} \text{ F/m}) \), \( \varepsilon_r \) is the relative permittivity or dielectric constant of the material separating the cylinders, in this case ice \( (\varepsilon_r = 3.2) \), \( S \) is the center-to-center separation distance between the cylinders, and \( d \) is the
diameter of the cylinders. Each cylinder is 6 inches or 0.1524m long. The following is a summary of the capacitance calculation for each pair of rods:

Table 3-7: Theoretical capacitance calculations for ice

<table>
<thead>
<tr>
<th>Rod pairs</th>
<th>1-2</th>
<th>2-3</th>
<th>4-5</th>
<th>5-6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gap width (mm)</td>
<td>6.35</td>
<td>12.7</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>S (mm)</td>
<td>19.05</td>
<td>25.4</td>
<td>14.7</td>
<td>13.7</td>
</tr>
<tr>
<td>d (mm)</td>
<td>12.7</td>
<td>12.7</td>
<td>12.7</td>
<td>12.7</td>
</tr>
<tr>
<td>C (when completely iced) [pF]</td>
<td>14.09</td>
<td>10.30</td>
<td>24.48</td>
<td>34.39</td>
</tr>
</tbody>
</table>

According to the data from each of the three experiments these values most closely resemble the normalization measurements for capacitance in glaze growth. This is understandable because glaze has the highest water content with little room for air (see Appendix A for experimental data). The average capacitance measurements during normalization for all three types of ice growth for each pair of rods are as follows:

Table 3-8a: Summary of average capacitance measurements during normalization of icing

<table>
<thead>
<tr>
<th>Capacitance [rod] (pF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2</td>
</tr>
<tr>
<td>Glaze</td>
</tr>
<tr>
<td>Rime</td>
</tr>
<tr>
<td>Rime&amp;Glaze</td>
</tr>
</tbody>
</table>

The % difference between the experimental normalization measurements and the theoretical calculations is as follows:

Table 3-8b: Summary of % error between experimental and calculated maximum capacitance

<table>
<thead>
<tr>
<th>% Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2</td>
</tr>
<tr>
<td>Glaze</td>
</tr>
<tr>
<td>Rime</td>
</tr>
<tr>
<td>Rime&amp;Glaze</td>
</tr>
</tbody>
</table>
4 Conclusions

The purpose of this thesis was to develop and test a method for correlating changes in capacitance and resistance between probes to ice growth rate. Based on experimental data, it has been clear that capacitance between probes changes dynamically as ice builds on their surfaces. These changes occur in real time and allow the growth rate of ice to be mapped over a period of time. Resistance on the other hand does not change dynamically as ice grows, rather it drops immediately when ice bridging occurs between electrodes. Thus, resistance can be used to determine the exact time that bridging occurs. If ice growth on surfaces is to be mapped accurately it is recommended that a data acquisition system in conjunction with a modern capacitance meter be used. The more readings that are taken, the better chance of determining point of bridging and exact time of normalization. Also, capacitance can be used to determine melting rate in terms of mass loss during de-icing periods to further enhance the effectiveness of the probes.

4.1 Recommendations for Future Analysis

There are several ways to improve the efficiency of the probe design to eliminate all possible sources of error and to measure capacitance accurately. These include:

- Obtaining a data acquisition system to measure more capacitance readings per minute for each icing test to give a more accurate picture of the behaviour of ice during the tests.
- Perform more experiments with more variables which include varying the diameter and length of the rods. Different wind speeds and nozzle flow rates should also be tested.
- Use an ohmmeter in conjunction with a capacitance meter to indicate bridging time while analysing growth rate. This would allow effecting tracking of different icing events during testing.
- Use suspended probes to eliminate mis-readings in capacitance due to water pooling.
- Increase duration of testing for glaze ice formation.
• Use a multi-lead capacitance meter with switch to eliminate manual switching.
• Run the experiment during melting to determine mass loss over time for de-icing applications
• Integrate a de-icing mechanism and look at the heat required to melt the ice. A measurement of the change in capacitance and resistance during de-icing can also be analysed

4.2 Suggested Improvements to Design

To eliminate the possibility of uneven growth in the rime and rime-glaze mixture growth types, it may be feasible to bundle the electrodes in groups of three in the shape of a triangular prism or even have the electrode pairs rotate to allow even distribution of ice on the surfaces. This can be shown below:

![Figure 4-1: Rotating Triangular Probe Design](image)

Another improvement may involve modifying the current design to eliminate pooling at the base of the rods during testing by coating the base of the rods with a thin layer of magnetic oxidation that is resistant to current.
This design as well as the rotating triangular prism design can be placed on a scale to measure mass accumulation dynamically during testing via a data acquisition system. This way, not only can the capacitance be measured dynamically but also the mass accumulation rate so that a relationship can be established between the capacitance and ice accumulation rate in real time during the experiment.
5 REFERENCES


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7 APPENDICES

A. COLLECTED DATA FOR REVISED EXPERIMENT
B. THEORETICAL CAPACITANCE CALCULATIONS
C. MEASUREMENT OF MASS ACCUMULATION ON RODS
D. CURRENT PROBE DESIGNS UNDER US PATENTS
APPENDIX A

COLLECTED DATA FOR REVISED EXPERIMENT
### Rime Growth

<table>
<thead>
<tr>
<th>Temp (°C)</th>
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</tr>
</thead>
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<td>Water mass flow rate (gal/hr)</td>
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</tr>
<tr>
<td>Wind Speed (km/hr)</td>
<td>20</td>
</tr>
<tr>
<td>Nozzle Water Pressure (kPa)</td>
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<tr>
<td>Nozzle Air Pressure (kPa)</td>
<td>350</td>
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</tbody>
</table>

<table>
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<th>Time (mins)</th>
<th>Capacitance [rod] (pF)</th>
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<td>68</td>
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<td>70</td>
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### Glaze Growth

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<th>Temp (°C)</th>
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</thead>
<tbody>
<tr>
<td>Water mass flow rate (gal/hr)</td>
<td>5</td>
</tr>
<tr>
<td>Wind Speed (km/hr)</td>
<td>20</td>
</tr>
<tr>
<td>Nozzle Water Pressure (kPa)</td>
<td>325</td>
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<tr>
<td>Nozzle Air Pressure (kPa)</td>
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</table>

<table>
<thead>
<tr>
<th>Time (mins)</th>
<th>Capacitance [rod] (pF)</th>
</tr>
</thead>
<tbody>
<tr>
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<td></td>
</tr>
<tr>
<td>5</td>
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<tr>
<td>10</td>
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### Glaze-Rime Mixed Growth

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<tr>
<th>Temp (°C)</th>
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<td>Water mass flow rate (gal/hr)</td>
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<td>Wind Speed (km/hr)</td>
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<tr>
<td>Nozzle Water Pressure (kPa)</td>
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<tr>
<td>Nozzle Air Pressure (kPa)</td>
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<table>
<thead>
<tr>
<th>Time (mins)</th>
<th>Capacitance [rod] (pF)</th>
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<tr>
<td>0</td>
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APPENDIX B

THEORETICAL CAPACITANCE ANALYSIS & CALCULATIONS
In order to accurately describe the behaviour of capacitance for each pair of rods during ice build-up, it is necessary to analyse the behaviour of capacitance based on theory. Thus, for parallel cylinders, the capacitance equation is:

\[ C \left[ F/m \right] = \frac{\pi \varepsilon \varepsilon_0}{\cosh^{-1}(S/d)} \]  

(Eq. 2-16)

where,

\[ S \]

\[ d \]

The denominator: \( \cosh^{-1}(S/d) \) can be rewritten as:

\[ \cosh^{-1}(S/d) = \log\left(\frac{S}{d} + \sqrt{\left(\frac{S}{d}\right)^2 - 1}\right) \]  

(Eq. 7-B1)

When the ratio \( S/d \) is plotted against \( \cosh^{-1}(S/d) \) for the range \( 1 \leq (S/d) \leq 3 \) the following graph is produced:

![Figure 7-B1: Plot of \( \cosh^{-1}(S/d) \) to \( S/d \)](image)

If the diameter of the rods are kept constant and the spacing continuously increases \( (S \text{ continuously increases}) \), the function \( \cosh^{-1}(S/d) \) will continue to rise to infinite and the capacitance will fall to zero:
This is quite evident if the behaviour of the electrostatics field is observed. The more spaced apart the rods, the lower the concentration of electrostatic lines of flux. Thus there is less of a chance electrons have of traveling from one rod to the other, lowering the chances of the material in between the rods to polarize, and thus lowering the capacitance.

If the spacing is kept constant and the diameter is increased to the point of the two rods touching $S=d$, the capacitance will continue to rise because the ratio $S/d$ increases to a value of one whereby $\cosh^{-1}(S/d)$ becomes zero and theoretical capacitance is infinite:

The concentration of electrostatic lines of flux increases as the spacing between the rods begins to shrink caused by increasing the diameters:
Finally by keeping the distance between the rods constant but changing the diameters and spacing between centers such that \( S = d+x \), where \( x \) is the gap distance:

![Diagram of varying gap spacing](image)

**Figure 7-B5: Varying gap spacing**

The ratio \( S/d \) will vary according to \((d+x)/d\), which becomes the equation of a straight line with slope \( x/d \), as shown below:

\[
\frac{S}{d} = \frac{x}{d} + 1, \quad \text{(Eq. 7-B2)}
\]

noting that \( S-d = x \). Varying \( d \) from one to ten units of measure and graphing the results for different values of \( x \), starting at \( x = 1 \) unit of measure a trend can be seen, as shown below:

![Plot of S/d over varying diameter for different gap distances](image)

**Figure 7-B6: Plot of S/d over varying diameter for different gap distances**

Based on this graph it is clear that as the gap between the rods increases (\( x \) increases), the larger \( S/d \) becomes for a specific diameter, and the larger \( \cosh^{-1}(S/d) \) becomes, lowering the capacitance. Also, for increasing diameters, it is evident that the limit of the ratio \( S/d \) approaches a single value regardless of gap distance. In other words, increasingly large
diameter rods will cause the ratio S/d to approach one at which time \( \cosh^{-1}(S/d) \) becomes equal to zero. The capacitance thus becomes infinite. This is because the rods touch at S/d = 1.

It would be reasonable to choose a pair of rods with as large a diameter as possible, and spaced as closely as possible, up to a particular diameter. Around a diameter of ten units, the optimal range for spacing would be between 1 and 2 units of measure. This ratio is independent of ice type and length of bars.

Sample Calculation for Capacitance between rods five and six spaced one millimetre apart:

Diameter of rods: 0.5 inches = 12.7mm = 0.0127 m
Length of rods: 6 inches = 152.4 mm = 0.1524 m
Permittivity of free space: \( \varepsilon_0 \approx 8.85 \times 10^{-12} \text{ F/m} \)
Dielectric constant of ice: \( \varepsilon_r = 3.2 \)

\[
C[F/m] = \frac{\pi \varepsilon_r \varepsilon_0}{\cosh^{-1}(S/d)} = \frac{\pi (3.2)(8.85 \times 10^{-12} \text{ F/m})}{\cosh^{-1}(13.7/12.7)} = 2.256 \times 10^{-10} \text{ F/m} \\
C[F] = (2.256 \times 10^{-10} \text{ F/m}) \times 0.1524m = 3.4389 \times 10^{-11} \text{ F} = 34.4 \text{ pF}
\]

To test the accuracy of the capacitor meter to values calculated through theory, a similar test was performed for capacitance of water between the rods in a controlled environment prior to the icing tunnel experiments.

A large plastic tub was filled with two inches of water, and the apparatus was placed inside face down so that rods were submerged but the set screws were just above the water:
Each pair of rods was then attached to a short wire with alligator clips to the capacitor meter and the capacitance of the rods in water was measured:

A summary of the measurements is shown below:

<table>
<thead>
<tr>
<th>Capacitance (pF)</th>
<th>Rods</th>
<th>wires &amp; clips</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rods</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1-2</td>
<td>219</td>
<td>11.9</td>
</tr>
<tr>
<td>2-3</td>
<td>142</td>
<td></td>
</tr>
<tr>
<td>4-5</td>
<td>462</td>
<td></td>
</tr>
<tr>
<td>5-6</td>
<td>776</td>
<td></td>
</tr>
</tbody>
</table>

The capacitance of the wires is subtracted from the readings for each pair:
Rods 5-6 (1mm) → 764.1 pF
Rods 4-5 (2mm) → 450.1 pF
Rods 1-2 (6.35mm) → 207.1 pF
Rods 2-3 (12.7mm) → 130.1 pF

According to the theory the capacitance for water with a dielectric constant \( \varepsilon_r = 80 \), the capacitance of each rod becomes:

Table 7-B2: Theoretical capacitance calculated for water & % error

<table>
<thead>
<tr>
<th>Rods</th>
<th>1-2</th>
<th>2-3</th>
<th>4-5</th>
<th>5-6</th>
</tr>
</thead>
<tbody>
<tr>
<td>S (mm)</td>
<td>19.05</td>
<td>25.4</td>
<td>14.7</td>
<td>13.7</td>
</tr>
<tr>
<td>d (mm)</td>
<td>12.7</td>
<td>12.7</td>
<td>12.7</td>
<td>12.7</td>
</tr>
<tr>
<td>L (m)</td>
<td>0.1524</td>
<td>0.1524</td>
<td>0.1524</td>
<td>0.1524</td>
</tr>
<tr>
<td>C (pF)</td>
<td>352.21</td>
<td>257.39</td>
<td>611.76</td>
<td>859.73</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Rods</th>
<th>1-2</th>
<th>2-3</th>
<th>4-5</th>
<th>5-6</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Error</td>
<td>41.2</td>
<td>49.5</td>
<td>26.4</td>
<td>11.1</td>
</tr>
</tbody>
</table>

There is a fairly large % error between the theoretical values and the measured values for the largest spaced rods. The main source of error lies in the fact that the water used during the test was de-ionized and distilled. This may contribute to the lower values of capacitance for each pair of rods. Also, the surface on which the bucket was placed may not have been completely flat, causing the water level around the rods to be lower than intended, thus exposing them to air.
APPENDIX C

MEASUREMENT OF MASS ACCUMULATION ON RODS
After each of the three capacitance icing tests, the ice that had accumulated onto the rods was weighed so that an average value for ice mass accumulation rate could be established:

![Figure 7-C1: Containers holding ice accumulated on rods](image)

The picture above shows the ice accumulated for the rime icing test. The first container held the ice that had accumulated onto rod three, while container two and three held the ice accreted onto rods 1-2 together and 4-5-6 together respectively. A summary of the mass values and pictures of glaze ice weighing are shown below:

![Figure 7-C2: Glaze Ice accumulation on rods 1, 2 & 3 being weighed](image)

<table>
<thead>
<tr>
<th>Rods</th>
<th>Mass (g)</th>
<th>Rime</th>
<th>Rime &amp; Glaze Mixture</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>13.8</td>
<td></td>
<td>17</td>
</tr>
<tr>
<td>1-2</td>
<td>27.25</td>
<td></td>
<td>34.86</td>
</tr>
<tr>
<td>4-5-6</td>
<td>17</td>
<td></td>
<td>61.25</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rime</td>
<td>37.6</td>
</tr>
<tr>
<td>1-2-3</td>
<td>89.2</td>
<td></td>
<td>89.2</td>
</tr>
<tr>
<td>4-5-6</td>
<td>57.8</td>
<td>Glaze</td>
<td>57.8</td>
</tr>
</tbody>
</table>

Table 7-C1: Summary of mass accumulation readings for each icing test
Each rod weighs approximately 52 g. Looking at the geometries of the apparatus and the mass readings, as well as the mass flow rate of air and water, a mass accumulation rate could be established.

**Determination of Mass Accumulation Rate:**

Roughly looking at the length of growth from the rime test off of the leading edge of rod three and taking into consideration the mass accumulation on that rod, it is safe to estimate the average growth rate over the entire duration of that test:

Length of growth off leading edge: \( \sim 1.25 \text{ inches} = 31.75 \text{ mm} \)

The mass of rime ice accreted onto rod three during the test: 13.8 g

Time duration of Rime Test: 65 minutes

Thus Average growth rate:

\[
\text{Mass flow rate} = \frac{13.8 \text{ g}}{65 \text{ min}} \times \frac{1 \text{ min}}{60 \text{ sec}} = 0.00354 \text{ g/s}
\]

Assuming no ice growth on sides or back, which is evident in much of the rime icing experiment:

\[
\text{Volume flow rate} = \frac{31.75 \times 12.7 \times 152.4 \text{ mm}}{65 \text{ min}} \times \frac{1 \text{ min}}{60 \text{ sec}} = 15.76 \text{ mm}^3/\text{s}
\]

If we were to correlate this growth rate to the linear trend in the Rime Ice test plot of capacitance, a relationship between capacitance and growth rate could be established:
Summarizing the slopes of each trend:

Table 7-C2: Summary of trendline slopes for Rime Ice test

<table>
<thead>
<tr>
<th>Rod Pairs</th>
<th>1-2</th>
<th>2-3</th>
<th>4-5</th>
<th>5-6</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{dC/dt} )</td>
<td>0.0544</td>
<td>0.0516</td>
<td>0.0631</td>
<td>0.0613</td>
</tr>
</tbody>
</table>

Based on these findings, a correlation between dC/dt and dM/dt could be made.

Similarly, for the **Glaze test**:

Rods 1-2-3 (Glaze):

\[
\text{Mass accumulation rate} = \frac{89.2 \text{g}}{44 \text{ min}} \times \frac{1 \text{ min}}{60 \text{ sec}} = 0.0338 \text{ g/s}
\]

Rods 4-5-6 (Glaze):
Due to the slow rate of ice accumulation for glaze ice, and the difficulty in isolating the ice growth per bar, neither the accumulation rate nor any trend lines can be made accurately for the glaze ice test to determine a correlation between capacitance and mass accumulation of ice. More tests would have to be performed.

For the **Rime-Glaze mixture test:**

Estimated mass accumulation rate per bar:

\[
\text{Mass accumulation rate} = \frac{34.86 \text{g}}{70 \text{ min}} \times \frac{1 \text{ min}}{60 \text{ sec}} = 0.0083 \text{ g/s}
\]

Estimated volumetric accumulation rate per bar:

\[
\text{Volume accumulation rate} = \frac{38.1 \times 12.7 \times 152.4 \text{mm}}{70 \text{ min}} \times \frac{1 \text{ min}}{60 \text{ sec}} = 17.56 \text{mm}^3/\text{s}
\]

---

**Figure 7-C5: Length of Rime-Glaze mixture growth off leading edge of rod**
Glaze-Rime Ice Mixed Growth

$$y = 0.0913x + 20.432$$

$$y = 0.1003x + 15.606$$

$$y = 0.0809x + 8.388$$

$$y = 0.0743x + 5.0076$$

Figure 7-C6: Rime-Glaze Mixture Ice capacitance trendlines

Summarizing the slopes of each trend:

Table 7-C3: Summary of trendline slopes for Rime-Glaze Mixture Ice test

<table>
<thead>
<tr>
<th>Rod Pairs</th>
<th>1-2</th>
<th>2-3</th>
<th>4-5</th>
<th>5-6</th>
</tr>
</thead>
<tbody>
<tr>
<td>dC/dt</td>
<td>0.0809</td>
<td>0.0743</td>
<td>0.1003</td>
<td>0.0913</td>
</tr>
</tbody>
</table>

Again, a correlation can be made between the change in capacitance over time, dC/dt, and the mass accumulation or even volumetric accumulation rate of ice, dM/dt & dV/dt. Further experimentation could increase the accuracy of these relationships.
APPENDIX D

CURRENT PROBE DESIGNS UNDER US PATENTS
There has been extensive research done in the field of capacitive and resistive ice probe design, specifically targeted towards the aerospace industry for use in commercial and military aircraft. These probes measure the onset of ice growth and ice accumulation on the surface of aircraft and aircraft wings and can be used in conjunction with other measurement devices to improve the safety of structural stability of these aircraft.

Some probes currently in the design and development stage that can correlate capacitance and resistance output to map ice growth rate on surfaces of objects include:

1) U.S. Pat. No. 4766369: Ice Detector
2) U.S. Pat. No. 5874672: Apparatus and method for determining the existence of ice or water on a surface from the capacitance between electrodes on said surface.
3) U.S. Pat No. 6384611: Ice Thickness Detector
4) U.S. Pat No. 5551288: Measuring ice distribution profiles on a surface with attached capacitance electrodes

The following are summaries of the patent abstracts found on www.patentstorm.us:

**U.S. Patent No. 4766369: Ice Detector:**

This particular detector is used to determine the thickness of ice on an outer surface of an object independent of temperature and ice composition. It consists of two capacitance gauges, and a temperature measuring circuit which measures an output voltage, embedded slightly below the outer surface of the object. The embedded is flush with outer surface to prevent undesirable drag. The two capacitive gauges and temperature gauge are connected to first and second capacitance measuring circuit and temperature measuring circuit respectively. The geometry of the first and second capacitive gauges is such that ratio of the output voltages of the first and second capacitance circuits is proportional to the thickness of ice regardless of temperature or composition. The ratio is determined by an offset and dividing circuit.

**U.S. Patent No. 5874672: Apparatus and method for determining the existence of ice or water on a surface from the capacitance between electrodes on said surface:**

This ice detector measures non-uniform, heterogeneous ice that accretes onto the leading edges of aircraft wings as well as on top of the wing surfaces. The probe design is very similar to the one designed in this thesis in that it consists of a series of capacitive sensors whose electrodes are spaced at different interval distances. The sensors measure the ice thickness by measuring changes in capacitance between the electrodes in the presence of ice or water. Electronic guarding techniques are employed to minimize baseline and parasitic capacitances to decrease the noise level and thus increase the signal to noise ratio. The use of guard enables distributed capacitive measurements to be made over large or complex areas, independent of temperature or location, due to the capability of manipulating the electric field lines associated with the capacitive sensors.
U.S. Patent No. 6384611: Ice Thickness Detector:

This design uses a pair of electrodes connected by leads to control unit that measures admittance between leads to sense the presence of ice. This detector measures the onset of ice growth rather than the accumulation rate itself. The electrodes are integrated into a patch which can be placed at difference locations on an aircraft.

U.S. Patent No. 5551288: Measuring ice distribution profiles on a surface with attached capacitance electrodes:

This patent is an older version of Patent No. 5874672, shown above. This patent was filed in 1996 while the one above was an updated version filed in 1999.

The probe design in this thesis most closely resembles US. Pat. No. 5874672, in that it uses the method of multiple parallel electrode located at increasing interval spacing.