Numerical Modelling of Icing on Power Lines

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Abstract

Atmospheric icing arises from precipitation icing, or due to suspended supercooled water droplets in a fog or cloud. It can cause extensive damage to overhead power lines. Data from icing events are scarce or unavailable, therefore physical modelling of the icing process is required for power line design purposes or the development of anti-icing and de-icing systems. There are many numerical icing models in existence, however they are all fundamentally similar. This seminar presents the basic considerations needed to construct such a model, with a focus on the models of Lasse Makonnen and Ping Fu.

In the first section of the seminar the different types of atmospheric icing, their properties and the conditions, under which they occur, are described. The following section describes the determination of the mass flux of the impinging water particles onto the conductor and the thermodynamic heat balance which dictates the amount of available water that freezes. The last sections briefly presents the results from the two models under discussion.
1 Introduction

The consequences of ice storms can have disastrous proportions, as it is evident from ice storms such as those in Canada in 1998 and Slovenia in 2014. One of the outcomes of these events was extensive damage to electrical infrastructure. A proposed method to prevent ice build-up or to de-ice an overhead conductor is to heat the conductor by means of Joule losses [1, 2]. Field data from icing events required to determine the appropriate current to employ such a method is scarce, since these events occur rarely. Therefore, appropriate physical modeling is required to predict the conductor surface temperature in order to develop such anti-icing and de-icing systems. Forecasting ice loads from atmospheric parameters using icing models can also be used for design purposes of power equipment and for the understanding of the icing process itself.

In the 1950’s, several simple analytical models based on strong assumptions or empirical data were developed to estimate ice loads [3, 2]. In the 1980’s, when computers became widely available, it also became possible to predict ice loads using time dependant numerical models. Many assumptions of these models, however, still relied on empirical relationships. Since then, enhanced models that are more complete in terms of accounting for the physical processes of icing started to emerge. State of the art models directly simulate physical processes that were previously described by empirical relations [2]. Many of these models emerged from aircraft icing models that were specifically adapted for icing on power lines.

This seminar presents a brief overview on how to approach the construction of a numerical model used to predict the accretion of ice on overhead power lines based on atmospheric parameters, without delving too deep on the specifics. There are many icing models in existence. This seminar focuses on the models of Lasse Makonnen [4] and Ping Fu [5]. Details about some other models can be found in [6, 7, 8, 9]. While there are differences among these models, they are all fundamentally similar [2].

2 Atmospheric Icing

In general, we encounter a number of different types of ice and snow deposits as there are different mechanisms for their formation. According to [10] atmospheric icing can be classified as in cloud icing or precipitation icing. The first refers to icing due to suspended water droplets inside a cloud or fog and the latter to icing due to the precipitation, such as freezing rain or snow. The different classes of icing differ in their color and apperance, shape, density, adhesion and cohesion properties. All these factors influence the hazard they pose to overhead power lines. In general, glaze ice, rime ice, snow and hoar frost can form under different atmospheric conditions [10].
Glaze ice occurs in a temperature inversion situation, where the raindrops from the warm (above 0°C) region fall through the region with sub-zero temperatures. In this manner, the raindrops become super-cooled, i.e., still in the liquid phase but at sub-zero temperatures. The temperature of such raindrops is typically between −1°C and −5°C. As the supercooled raindrop impinges onto the conductor, it quickly freezes with virtually no air trapped inside the accretion. Glaze ice is transparent and has a density of about 900 kg/m³. Icicles might also form on the bottom side of the conductor. Glaze ice can also occur in in-cloud situations, if the in-flux of cloud water is high enough.

![Glaze ice sample](image1.png)

Figure 1: Rime icing (left) and glaze ice sample (right) [10].

Rime ice forms when small (≈ 10 µm) supercooled water droplets in a cloud or fog collide with the conductor and freeze. It typically occurs at temperatures between −5°C and −15°C. The freezing time of such droplets is very short due to low temperatures and low impact velocity of the droplets, therefore air bubbles get trapped and can present a significant portion of the accretion. Consequently, the density of rime ice varies and is typically much lower than that of glaze ice. At higher temperatures we encounter hard rime, which is difficult to remove, with a density ranging from about 300-700 kg/m³. Soft rime is not as hazardous, since it’s density varies between 150-300 kg/m³. Rime ice can be highly asymmetric, with leading vanes in the wind direction.

The accretion of wet snow occurs at temperatures slightly above freezing (≈0.5°C - 2°C). It can be encountered for a wide range of wind velocities. Wet snow has a very low adhesion above the freezing temperature. However, the adhesion forces become much stronger if the temperature drops below freezing. This scenario is quite common, when there is snowfall during the day with air temperature just over freezing and the temperature then drops below zero during the night. The deposit of snow can be compacted over time due to wind, so the density can reach as high as 850 kg/m³. Dry snow is encountered at sub-zero temperatures and in low wind (≈2 m/s), it has low density and weak adhesion.

Hoar frost occurs when water vapour in air sublimes to a solid state. This can occur, when the temperature of the conductor is below the freezing point. Hoar frost takes the shape of small ice crystals with a very low density (≈100 kg/m³). It can also easily be blown away by wind, so it generally does not pose a hazard to power lines.
2.1 Ice Accretion Process

There are two scenarios of ice growth, depending if the surface is covered with a liquid water layer or not. These two growth modes are called dry growth and wet growth. Dry growth occurs, when the freezing rate is greater than the impingement rate [10]. In this scenario, the impinging droplets rapidly freeze, leaving no permanent liquid surface layer on the deposit. In this manner, pockets of air can get trapped inside the accretion, so the resultant ice has an opaque appearance and a density that can be substantially lower than that of frozen water. The resultant ice deposit of the dry growth process is called rime ice [10, 2]. In wet growth, the impinging rate is greater than the freezing rate. As a result not all water freezes on impingement, thus a liquid surface layer is formed. A significant amount of liquid water can get trapped inside the accretion, but this is rarely detected, as the trapped water also freezes after a certain amount of time [2, 3]. This scenario results in glaze ice, which has a density close to the density of pure water in solid state and is transparent in appearance. Both growth modes are schematically presented on figure (3).

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The rate of change of the ice mass accumulated on the object is proportional to the product of the mass flux density of the impinging particles and the effective cross-sectional area of the object, as seen by the incoming water particles [2, 4]:

\[
\frac{dM_{ice}}{dt} = \rho_{water} \cdot \beta \cdot A_{eff} \cdot \rho_{water} \cdot \beta
\]

where:\n- \(dM_{ice}/dt\) is the rate of change of ice mass \(\text{g/s}\)\n- \(\rho_{water}\) is the density of water \(\text{kg/m}^3\)\n- \(\beta\) is the mass flux density of water \(\text{kg/m}^2\cdot\text{s}\)\n- \(A_{eff}\) is the effective cross-sectional area of the object \(\text{m}^2\)
\[
\frac{dM}{dt} = E_n w v A,
\]

(3.1)

where \( M \) is the accreted ice mass, \( w \) is the content of liquid water per unit volume of air, \( v \) is the velocity of incoming particles and \( A \) is the effective cross-sectional area of the accreting object. In the product of \( wv \) we recognise the aerial mass flux density of water droplets. In natural conditions the incoming particles will be of different sizes, therefore \( v \) has to be calculated as a mass-weighted mean velocity of the incoming particles. Similarly, the effective cross-sectional area \( A \) is the mass-weighted average cross-sectional area seen by each particle.

Factors \( E \) and \( n \) represent processes that may reduce \( dM/dt \) from its maximum potential value, so they lie on an interval between 0 and 1. \( E \) is called the collection efficiency. It is defined as the ratio of the mass flux that collides with the icing object to the total aerial mass flux. The collection efficiency may be considerably less than unity, since small particles tend to follow the air streamlines and may be deflected around the object.

The freezing fraction \( n \) (sometimes also referred to as the accretion efficiency) is the ratio of the mass flux density which accretes onto the object as ice, to the mass flux density that impinges onto the object. It is determined from the thermodynamic heat balance on the icing surface.

Equation (3.1) can also be multiplied by an additional factor called the mean coalescence efficiency \([2]\). This factor takes into account those particles that hit the object, but bounce from the surface. When a supercooled water droplet hits a surface in the dry ice process, it rapidly freezes and, typically, does not bounce. When a liquid layer sits on the surface, the droplet tends to spread on the surface and again there is, typically, no bouncing. It is reasonable to assume, that for water droplets, the coalescence efficiency is approximately 1 \([2]\).

For modeling of icing in 1 dimension (where radial accretion is assumed), the effective cross-sectional area \( A \) is the diameter of the ice deposit \( D \). Equation (3.1) also holds for icing in 2 or 3 dimensions. In the latter two cases, the right side terms can be computed for each small enough surface element of the icing surface \([5]\). In this manner, the shape of the ice deposit can also be calculated.

In order to determine the radius of the accretion, the density (particularly for rime ice) of the deposit at time \( t + dt \) needs to be evaluated. For this purpose we can use empirical formulas based on experimental studies, such as those of Bain and Gayet \([11]\). They proposed the following relation for obtaining the density (in units of g/cm\(^{-3}\)) of the ice deposit as a function of droplet diameter, droplet impact velocity and the surface temperature of the object:

\[
\rho = \begin{cases} 
0.11R^{0.76}, & R \leq 10 \\
R(R + 5.61)^{-1}, & 10 < R \leq 60 \\
0.92, & R > 60
\end{cases}
\]

(3.2)

where \( R = -v_0d/t_s \) is the Maclin parameter, \( v_0 \) is the droplet impact velocity, \( d \) is the droplet diameter and \( t_s \) is the surface temperature.

Having determined all the relevant quantities for each time step, we can then integrate equation (3.1) and output the accreted mass, density and accretion dimensions as a function of time.

### 3.1 Collection Efficiency

The collection efficiency \( E \) of a cylinder is defined as the ratio of the mass flux of impinging particles on the upstream side of the cylinder, to the mass flux that would be experienced by the surface if the particles had not been deflected by the air stream \([5]\). Because of their small momentum, small cloud or fog droplets tend to closely follow the airflow streamlines. Thus, \( E \) can approach 0 for small enough droplets. Larger droplets, on the other hand, because of their higher momentum, tend to impinge on the icing object without substantial deflection. The collision efficiency is also smaller for larger obstacles, because streamlines deviate relatively farther in front of large obstacles than small ones. With a higher wind velocity \( E \) increases, because the droplets then possess a greater momentum. It is worth mentioning, however, that in the case of precipitation, even in no wind there is still a downward flux of water onto the object \([6]\).
A numerical algorithm can be constructed to compute $E$ [5]. For this purpose, the trajectories of a large number of droplets ($\sim 200$) need to be computed. Neglecting gravity and buoyancy, the dimensionless equation of motion for a droplet in an airflow is [4]:

$$K \frac{dv'_d}{d\tau} = \frac{c_D Re_d (v'_a - v'_d)}{24},$$  \hfill (3.3)

where $\tau$ is time, $v'_d = v_d/v$ is the dimensionless velocity of the droplet in units of the free stream velocity far from the obstacle $v$, $v'_a = v_a/v$ is the dimensionless velocity vector of the airflow and $c_D$ is the drag coefficient of the droplet. The inertia parameter $K$ is defined as

$$K = \frac{\rho_w dv'^2}{9 \mu D},$$  \hfill (3.4)

where $\rho_w$ is the density of water, $d$ is the droplet diameter, $\mu$ is the dynamic viscosity of air and $D$ is the characteristic length of the obstacle. The droplet Reynolds number $Re_d$ based on the relative droplet velocity to the air stream is

$$Re_d = \frac{\rho_a dv'_a - v'_d}{\mu},$$  \hfill (3.5)

where $\rho_a$ denotes the air density. In order to solve equation (3.3), the airflow velocity vector $v'_a$ needs to be determined. Such calculations can be exceedingly difficult and computationally intensive, since air is a compressible viscous fluid. A good approximation is to treat air flow as a steady, incompressible, irrotational fluid flow, where potential fluid flow theory can be applied [8]. The effects of viscosity are limited to a thin layer around the object, known as the velocity boundary layer. Similarly, when the temperature of the air stream and that of the object differ, a thermal boundary layer, where heat transfer from the object to the airstream takes place, also forms. A combination of potential flow with boundary layer can also be implemented, such as in [5].

A closed form solution exists for a potential flow around a cylinder. For this case, Langmuir and Blodgett have numerically solved equation (3.3) to obtain the trajectories of droplets with a given diameter $d$ and calculated the collection efficiency for a cylinder with a given diameter $D$ [12]. A fit in terms of the inertia parameter $K$ and the free stream Reynolds number $Re = \rho_a dv/\mu$ can then be applied to the tabulated numerical data. Such fits can then be used to calculate the collection efficiency $E$ and droplet impact velocity $v_0$.

In natural conditions, cloud or rain droplets are not all of the same size, but have a certain size distribution. In principle, the calculation of $E$ should be performed separately for each size category and then sum these collection efficiencies multiplied by the fraction of the total liquid water content represented by that size [2, 4]. However, it is a sufficiently accurate approximation, if one evaluates the collection efficiency using the Median Volume Diameter of the size distribution (MVD) [2, 4].


### 3.2 Freezing Fraction

In the dry growth process, all impinging droplets freeze, i.e., the freezing fraction \( n = 1 \). In the wet growth regime, the latent heat released during freezing must balance the other heat sources or sinks at the icing surface \( q_i \), i.e.,

\[
q_f = (1 - \lambda)n FL_f = \sum q_i,
\]

where \( L_f \) is the latent heat of fusion of water and \( F = E_{wv} \) is the mass flux of the impinging droplets. \( \lambda \) accounts for the possibility of unfrozen water being trapped inside the accreting ice. Based on experimental and theoretical studies, a value of \( \lambda = 0.3 \) is proposed, since \( \lambda \) can be rather insensitive to the growth conditions [2].

A list of heat balance terms (in units of W/m\(^2\)) is given in [2]:

- heat exchange due to convection
  \[
  q_c = h(T_s - T_a),
  \]
  where \( h \) is the convective heat transfer coefficient (HTC), \( T_s \) is the surface temperature and \( T_a \) is the ambient air temperature.

- heat loss due to the evaporation
  \[
  q_e = \frac{\epsilon h L_v}{p c_p} (p_{sat,s} - H p_{sat,a}),
  \]
  where \( \epsilon = 0.622 \) is the ratio of the molecular weights of water vapour and dry air, \( L_v \) is the specific latent heat of vaporization (in wet icing where we have a water film, in dry icing it needs to be replaced by the specific latent heat of sublimation), \( p \) is the ambient air pressure, \( c_p \) is the specific heat of air, \( p_{sat,s/a} \) is the saturated vapor pressure of water at the surface temperature \( T_s \) or ambient temperature \( T_a \) respectively and \( H \) is the relative humidity of ambient air.

- heat loss due to warming the impinging supercooled water to the freezing temperature
  \[
  q_l = F c_w (T_s - T_a),
  \]
  where \( F = E_{wv} \) is the mass flux of the impinging droplets and \( c_w \) is the specific heat of water.

- radiative heat exchange
  \[
  q_s = \sigma (T_s^4 - T_a^4),
  \]
  where \( \sigma \) is the Stefan-Boltzmann constant and \( T_{s/a} \) is the surface/ambient temperature, respectively. In some models, [4], the Stefan law is linearized in the form of \( q_s = a \sigma (T_s - T_a) \), where \( a \) is a linearization constant, to account only for the long-wave radiation. Shortwave radiation from the sun can be neglected, because atmospheric icing tends to occur in cloudy weather with much diminished solar irradiances [2].

- frictional and compressive heating by the airstream
  \[
  q_v = \frac{h r v^2}{2 c_p},
  \]
  where \( h \) is the convective heat transfer coefficient, \( r \) is the recovery factor (\( r = 0.79 \) for a cylinder), \( v \) is the wind speed and \( c_p \) is the specific heat capacity of air.
heating due to Joule losses in the conductor

\[ q_j = I^2 R_c / (\pi D_c), \]  

(3.12)

where \( I \) is the current through the conductor, \( R_c \) is the resistivity per length of the conductor and \( D_c \) is the conductor diameter.

Some models incorporate a slightly different heat balance \([5, 6]\), or can use a slightly different parametrization of certain heat balance terms, particularly the evaporative term \([6]\). An overview of the magnitudes of the different heat balance terms for different values of meteorological variables in the ranges typical to icing events, is presented on figure (5). The biggest contribution comes from the release of the latent heat of fusion during freezing and from convective and evaporative terms. The latter two terms both depend on the convective heat transfer coefficient. Consequently, the overall accuracy of the model is mostly dependent on the accuracy of \( h \).

![Figure 5: Comparison of heat flux terms in typical freezing-rain conditions \([6]\): Standard conditions (black symbols) for the parameters are \( v = 3 \) m/s, \( T_a = -3^\circ \text{C}, H = 0.90 \), precipitation rate \( P = 3 \) mm/h, diffuse solar irradiance \( S = 100 \) W/m, wire diameter \( D = 3 \) cm. In each plot one or two of these parameters is varied about the standard conditions as follows: a) \( 0 < v < 10 \) m/s, b) \( -6 < T_a < -0.5^\circ \text{C}, c) \) \( 0.5 < P < 10 \) mm/h, d) \( 0.5 < D < 10 \) cm, e) \( 0.80 < H < 1.00 \) and \( 0 < S < 200 \) W/m. Key: \( e \) - evaporative cooling, \( c \) - convective cooling, \( I \) - longwave cooling, \( w \) - cooling from warming water, \( s \) - shortwave solar heating, \( f \) - heat of fusion, \( v \) - viscous heating, \( k \) - kinetic heating.

The heat equation, describing the heat transfer in a fluid flow can be expressed as \([9]\)

\[ \rho c_p \frac{\partial T}{\partial t} + \nabla(-k_f \nabla T) = Q - \rho c_p \nu_a \nabla T, \]  

(3.13)

where \( \rho \) denotes the density of the fluid, \( c_p \) the specific heat, \( k_f \) is the thermal conductivity, \( \nu_a \) is the velocity field vector and \( Q \) are the heat sources/sinks. The second term on the left represents heat conduction, while the second term on the right represents the heat transfer due to convection.

Direct modelling of the heat transfer can be difficult and computationally intensive, however it can be avoided by using experimentally or theoretically determined heat transfer coefficients. It is a very efficient and accurate method for most engineering applications \([9]\).

The dimensionless Nusselt number is commonly used to describe the heat transfer properties of a fluid. It is defined as the ratio of convective to conductive heat transfer normal to a surface \([9]\):

\[ Nu = \frac{hL}{k_f}, \]  

(3.14)
where $h$ is the heat transfer coefficient, $L$ is the characteristic length of the object and $k_f$ is the thermal conductivity of the fluid. Having determined the Nusselt number, the heat transfer coefficient can then also be evaluated. Many different empirical and theoretical formulas used to determine the Nusselt number for a given geometry and other conditions can be found in literature. For forced convection, the Nusselt number is a function of the Reynolds number $Re$, and the Prandtl number $Pr$ [6]. The latter describes the ratio of viscous to thermal diffusion rate. For instance, the parametrization used by Makonnen [4] is a numerical fit based on experimental data of an airflow around a cylinder and is expressed as $Nu = 0.032Re^{0.85}$.

After obtaining the value of $h$, equation (3.6) can then be solved to obtain the freezing fraction $n$. First, we assume a wet regime, where the surface temperature $T_s = 0^\circ C$. The resultant $n$ should lie between 0 and 1. If we obtain a different result, the assumption of wet growth is proven to be false in which case the growth mode is dry. In this case the freezing fraction $n = 1$ and we can then solve equation (3.6) for the unknown surface temperature $T_s$.

4 Model Results

This section briefly presents the features and output of two among a number of existing icing models. The first one is a 1D model of in-cloud icing developed by Lasse Makkonen in 1984 [4], and the other is a more comprehensive 2D model developed by Ping Fu in 2004 [5].

4.1 Makonnen model

The model [4] takes the wind velocity, air temperature, liquid water content of air, air pressure and the droplet diameter as input, and outputs the effective radius of the accretion, ice mass per length, surface temperature and ice density as functions of time. A radial accretion of ice is assumed. Makonnen justifies this assumption on account of the conductor being highly flexible and thus able to rotate around its axis due to the torque, as soon as the accretion grows asymmetric. This exposes the portion of the conductor, that was on the leeward side before rotation to incoming water droplets. The model is capable to account for both wet and dry growth modes. It is also mentioned that the model is not suitable for freezing rain during low wind speeds. In such conditions icicles can form, which considerably contribute to the total ice deposit mass. Later, the model was expanded with a separate icicle growth model, which, including the atmospheric conditions, accepts the excess water assumed to be shed in wet growth as input parameters [3].

An example of model output for given values of input parameters is presented in figure (6, left). As we have seen, the terms $E$, $n$ and $A$ in equation (3.1) are all coupled in a nonlinear fashion. Thus, the model output can vary greatly for different values of input parameters. However, a number of conclusions on the ice growth process can be reached.

In dry growth, the growth rate ($dM/dt$) first increases and then decreases with time, while in wet growth, the growth rate increases with time. The growth mode can change from wet to dry growth conditions, even for constant values of input parameters (figure 6, right). When the growth mode changes from dry to wet, the ice deposit density begins to decrease. This affects the radius of the accretion, which then in turn affects the collection efficiency and the heat transfer coefficient. With decreasing ambient air temperature, the total ice load may either decrease or increase, depending on the other atmospheric parameters. The model is also sensitive to the size of the droplets, which is difficult to obtain.
Figure 6: Example model [4] output. Time dependences of ice mass $M$, diameter $D$, ice density $\rho$, mean ice density of the total ice deposit $\bar{\rho}$, and icing intensity $I = \frac{dM}{dt}/A$. (Left) The time dependencies of freezing fraction $n$ and collection efficiency $E$. (Right) The values of atmospheric parameters are equal in both graphs: wind speed $v = 20$ m/s, ambient air temperature $T_a = -1^\circ C$, liquid water content $w = 0.3 \text{ g/m}$ and droplet median volume diameter $d = 25\mu m$.

4.2 Fu model

The model presented in [5] numerically simulates more phenomena of the icing process, relying less on empirical formulas. It simulates ice accretion around a two dimensional object. Thus, the profile of the accretion can be of arbitrary shape.

The flowchart depicting the algorithm employed by the model is presented on figure (7). Initially at each time step, the airflow velocity field is treated as a potential flow with boundary layer is calculated using the boundary element method. Obtaining the airflow velocity field enables the calculation of the trajectories of individual droplets, which in turn yields the local collection efficiency on each element of the icing surface. The velocity field is also needed to determine the temperature distribution around the icing surface and to obtain the local heat transfer coefficient. Both the local collision and heat transfer coefficients are spatially dependant and thus influence the overall shape of the icing surface.

The surface water film, that forms in wet icing conditions, also has a considerable effect on the icing surface shape. The portion of water, that does not freeze on impact, can flow on the icing surface and freeze elsewhere on the surface. The motion of the water film is governed by gravity and wind shear stress. The model assumes the water film is thin compared to the dimension of each surface element, so it can be treated as a laminar flow over a flat plate. The total collected water for a specific element is the sum of directly impinging water and the water flowing from adjacent elements. By taking into account also the conservation of mass, the water surface layer thickness and velocity distribution can be obtained. As in the Makonnen model, the density of ice is estimated using Bain and Gayet’s formula (3.2). Finally, the heat balance is used to determine the portion of available water that freezes on each surface element. The algorithm then outputs the ice shape, total ice load and the ice density distribution.
The model can treat the conductor as being fixed, or flexible and allowed to rotate around its axis. In the latter case, the gravitational torque due to an asymmetric ice load is also calculated at each time step. It is then possible to account for the rotation of the conductor.

Figure 8: Comparison of calculated and experimental measurements of the ice accretion shape [5]. Left: icing of a fixed conductor for values of parameters \( v = 5 \text{ m/s}, T_a = -5^\circ C, \text{MVD} = 26 \mu m, D = 34.9 \text{ cm} \). The experimental data was obtained via a wind tunnel experiment. Right: icing of a rotating conductor, for values of parameters \( v = 10 \text{ m/s}, T_a = -15^\circ C, \text{MVD} = 15 \mu m, D = 1.57 \text{ cm} \). The experimental shapes were obtained by Gayet et al. in 1988.

5 Conclusion

Modeling the ice accretion process in the manner presented in this seminar has shown some success. Many fundamental aspects of the state-of-the-art theory of ice accretion on structures have indeed been successfully verified [2]. There are, however, several poorly understood areas that require more verification and development. The general unavailability of field data hinders the thorough verification of icing models. Many crucial parameters such as the droplet size distribution or liquid water content are not routinely measured; the measurements of atmospheric parameters can also take place a large distance away from the location of interest. Other difficulties include the lack of data on surface roughness of the ice deposit [2]. Surface roughness affects the heat transfer at
the surface and that in turn influences the overall result of the calculation. Also, when the collision efficiency is very small ($E < 0.1$), the theory tends to underestimate the actual values.

References


