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Conductor icing: Comparison of a glaze icing model with experiments under severe laboratory conditions with moderate wind speed

E.B. Lébatto [a,b,*], M. Farzaneh [a,b,1], E.P. Lozowski [c]

[a] NSERC/Hydro-Quebec/UQAC Industrial Chair on Atmospheric Icing of Power Network Equipment (CIGELE), Université du Québec à Chicoutimi, Chicoutimi, Québec G7H 2B1, Canada
[b] Canada Research Chair on Engineering of Power Network Atmospheric Icing (INGIVRE), Université du Québec à Chicoutimi, Chicoutimi, Québec G7H 2B1, Canada
[c] Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton TG6 2E3, Canada

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ABSTRACT

The purpose of this paper is to compare the results of a 3D numerical, morphogenetic model of glaze ice accretion on a non-rotating unheated cylinder with experimental data. The numerical method is a stochastic model capable of predicting the mass of ice accretion and its shape as a function of the associated weather conditions. The experimental tests were undertaken in the CIGELE Atmospheric Icing Laboratory at the University of Quebec in Chicoutimi. The influences of air temperature and precipitation rate are investigated. The main goal of this work is to compare the numerical results with laboratory experimental results of severe icing conditions with moderate wind speed. The model is able to predict arrays of icicles, even if they are too long and thin while the total mass is underpredicted.

1. Introduction

The atmospheric icing of power line conductors is one of the major problems that have to be taken into account in planning, constructing and operating overhead power lines in cold regions with ice storms. Its socioeconomic impacts can be catastrophic. Glaze ice accreted during freezing rain is harmful to the power network equipment. It can cause failure of power line conductors and towers or modify their aerodynamic characteristics, leading to galloping (oscillations with amplitudes reaching several metres). These events affect the reliability of service by causing disturbances or disruptions of electric power transmission (Abley, 1998; Lecomte et al., 1998). They sometimes entail repair expenses of hundreds of thousands of dollars. Service disruptions during cold weather must be avoided because of the vital importance of the electric power supply. Consequently, it is important to prevent ice accretion or to mitigate its effects on power line conductors.

One solution would be to increase the conductor dimensions so that they can hold greater ice loads. But the costs of this solution are significant. A realistic forecast of icing would allow some de-icing procedures to be performed before the formation of extreme ice loads. The challenges are to find a way to estimate icing intensity over a wide range of meteorological conditions and to predict the formation of extreme ice loads. Accretion is a complex natural phenomenon and no simpler model has yet been able to accurately predict both the accreted ice mass and the details of its shape (including icicles). Several models predict the accreted ice mass. But the accreted ice shape and the icicle shape are crucial too, inasmuch as they determine the accreting cross-section and hence the impinging flux of droplets. In the presence of wind, they also affect the aerodynamics of the conductors. In 2009, Musilek et al. made some preliminary advances in this endeavour (Pytlak et al., 2010).

Stochastic numerical modelling (morphogenetic) can predict ice accretion and relevant physical processes such icicle growth and their interactions (Lozowski and Makkonen, 2005) as well. It also adds some "realistic" stochastic variability to ice accretion shapes, in agreement with wind tunnel experiments and field observations. This occurs because each simulation is slightly different when a different sequence of random numbers is used, even though the external conditions may be identical. Smooth circular cylinder icing is used as a first approximation to power line conductor and ground wire icing to make the computing easier. Existing computer models of ice accretion on a cylinder, while useful in the past, are in need of improvement. Icicles may considerably contribute to the total ice load on a cylinder (Makkonen, 1998). Indeed, they greatly increase the surface of the capture area of the deposit and increase the wind load when the wind speed is high (Lozowski and Makkonen, 2005). Therefore, one of the objectives of the present work is to develop a 3D model of ice accretion on a non-rotating unheated

* Corresponding author at: 2402 3rd Avenue, Cold Lake, Alberta T9M 0A4, Canada. Tel.: +1 780 813 3000, +1 418 545 5044; fax: +1 418 545 5032.
E-mail address: elielebatto@gmail.com (E.B. Lébatto).
URL: http://cigele.ca (E.B. Lébatto).
[1] Tel.: +1 418 545 5044; fax: +1 418 545 5032.

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cylinder. This numerical model simulates the shape and load of the accreted ice. The other objective is to compare the numerical results with laboratory experimental results under severe icing conditions with moderate wind speed.

A number of standard approaches to predict glaze ice accretion on a cylinder exist. However, we have adopted a unique approach to represent ice formation physics. A stochastic model was introduced into the research on atmospheric icing by Szilder (1993, 1994). The models derived from this unique approach are called morphogenetic models (Rudzinski et al., 2005; Lébatto et al. (2005).

This method allows the simulation of wet icing, when unfrozen water flows along the surface of the ice accretion before it freezes. Typically, such wet icing is the result of freezing rain. The quintessence of this approach is that an ice accretion is built up by means of discrete particles, accreting one at a time. Depending upon their size, these discrete particles can be considered to be either individual droplets or ensembles of droplets that behave in unison.

Morphogenetic models do not yet solve the classical physico-mathematical equations that govern icing. As this type of modelling is still in its infancy, a comparison with experimental data will facilitate the initial development of rigorous theoretical underpinnings, in order to quantify the physical and mathematical basis of morphogenetic modelling.

2. Numerical model

The morphogenetic 3D model presented here is intended for freezing rain applications with conductors. The model attempts to predict the shape and the mass of ice accretion on a non-rotating, unheated, smooth cylinder because of a freezing rain. A transmission conductor of 35 mm in diameter is used in this work. The choice of this diameter was lead by its availability for the experiments. The experiments used a conductor sample. After the first stages of the icing process the assembly consisting of the conductor and the ice is cylindrical in shape. It is difficult to numerically implement the surface of a conductor. Therefore, the model used a circular cylinder as an approximation of a conductor sample. We assumed that if the model can predict the shape and the mass of ice accretion on a cylinder of a given diameter the model should be able to simulate the ice accretion on any cylinder of different diameters. A smooth cylinder is preferred at this stage of the work to make the model simple. Reproducing the strands of the conductor numerically would take some time to implement. Simplify the model now and make it complex is the chosen approach. For the same purpose, the power supply and the torsion rigidity of the cylinder are also ignored. This model is an improvement of the model described by Lébatto et al. (2005).

The domain of the model is a three-dimensional, rectangular lattice with cubic cells. This 3D lattice consists of 500 by 1000 by 1000 cells, each with 1 mm sides. The choice of 1 mm as the grid size is based on

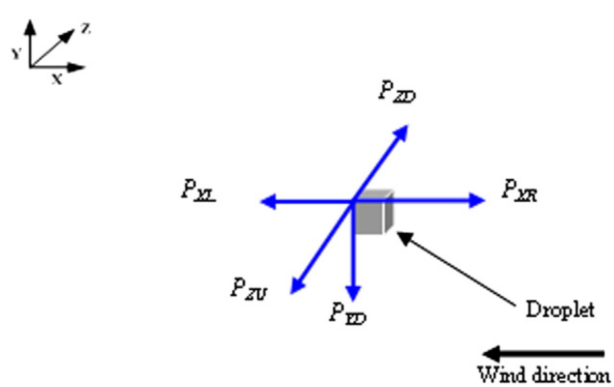

Fig. 1. Directions of allowed droplet motion on the model's cubic lattice.

a compromise between resolution and computing time. We felt that 1 mm was perhaps the coarsest resolution we could consider for a phenomenon whose overall dimensions are measured in centimetres. During ice accretion, the cells may be empty, occupied by cylinder cells, or by particles (liquid or solid). Each cell can hold a single particle. The cylinder is defined by filling up appropriate cells. The total precipitation of freezing rain is divided into fluid elements (particles). Each fluid element is specified to have a volume of 1 mm^3 after freezing. For each particle, we compute its trajectory before it hits the surface of ice already formed on the cylinder. A fluid element may also hit part of the cylinder where freezing has not occurred yet. The fluid elements are fired from random locations on the upper boundary of the lattice, in order to simulate a flux of freezing raindrops. Prior to their impact, the particles follow straight-line trajectories with angle of impact, $\Phi(°)$. The value of this angle is derived from experimental tests. The intersection of the particle trajectory with the cylinder or ice accretion determines the impact location of a particle.

Once a fluid element has impacted, it begins a solitary random walk. Its motion is called a random walk because the particle's behaviour is determined stochastically. We assumed that, since the acceleration of surface liquid flow is typically small, its fluid dynamics consists of quasi-equilibrium behaviour, involving a balance of gravitational, viscous, surface tension and wind stress forces. In addition, heat transfer can lead to freezing. However, we assumed that the cylinder surface temperature was 273 K during the ice accretion. The heat transfer is treated further in this paper.

At each time step during the random walk, a fluid element has eight possible alternatives: i) move towards the left; ii) move towards the right; iii) move downstream; iv) move upstream; v) move downward; vi) move leave the ice-covered cylinder; vii) freeze or viii) remain where it is. Diagonal motion is not allowed. If the diagonal motion is allowed the liquid particles will need more time to reach the bottom of the conductor where they can leave the surface of the cylinder by shedding if they are not frozen. The longer the liquid particles stay on the upper surface of the ice-covered conductor the higher their probability to freeze is. This will lead to more mass accreted. To simplify the model, any diagonal motion is prohibited. A probability is associated with each event and will be defined later. However, the particle is not allowed to walk away from the cylinder or the ice already formed. While moving along the surface, a particle's behaviour has two possible outcomes; either it merges with the existing accretion when it freezes, or it drips from the accretion. Particle freezing occurs on drawing a random number whose value is within the freezing probability interval. However, a fluid element will not necessarily freeze in its present lattice cell. A “cradle” location is sought for this element, in the neighbourhood of its current cell. The size of this neighbourhood is determined by the freezing range parameter, n. The range parameter controls the porosity of the ice accretion (Szilder, 1993, 1994; Szilder and Lozowski, 1994). When it is equal to zero (the effect of the surface tension is turned off); an unrealistic, porous ice accretion is obtained (Szilder et al., 1999). When it is equal to one, a compact ice accretion is obtained (Szilder and Lozowski, 1995; Szilder et al., 1999). For values greater than two, the ice accretion surface is smooth (Szilder and Lozowski, 1995). Therefore the range parameter was set to two in order to yield a reasonable porosity for the accretion (Szilder and Lozowski, 1995). Therefore, the search neighbourhood is a cube of side $2n + 1$ cells. Within this volume, the particle moves to the empty cell with the greatest number of adjacent occupied cells. If several cells meet this condition, the final location is chosen randomly among them. This process emulates the effect of the surface tension force that tends to minimize the local surface area.

The progress of each liquid particle is ended, either by freezing or by dripping, processes governed by the freezing probability and the shedding parameter. The freezing probability specifies when a fluid element freezes during its random walk. Particle freezing occurs on drawing a random number whose value is within the freezing probability